Modelling actual and potential wind erosion risk by using readily available data on weather elements and GIS

"A pilot study from Denmark and Switzerland"

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Dedicated to my wife,

Hamideh

And my daughter,

Sarina

Those that are a great source of my inspiration and motivation and to my family especially my beloved mother and the loving memory of my father.

Also dedicated to Dr. Jafar keyvani and Mrs. Forouzandeh Saadatmand for their kindness and fully support; and finally, to all those who believe “where there's a will there's a way”.

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ABSTRACT

Wind erosion is a complex process which is affected generally by the combined impact of wind erosivity and soil erodibility. According to the complexity of the wind erosion process, the main aim of this research was to design a practical model to predict potential and actual wind erosion risk based on spatial distribution of wind erosivity and soil erodibility. For representation of the potential and actual wind erosion risk in this study, two pilot countries with very different environmental settings were selected; Denmark and Switzerland. In order to be able to implement the model even in areas with minimal data availability, the structure of the GIS-based model was designed for a limited number of key parameters, which can be easily accessed even in regions with inadequate data. Three basic aspects distinguish the proposed model from other models:

1) Separation of wet- and dry-times is taken into account for the wind data analysis;

2) The impact of climate change is considered for factors that are used in the model;

3) Running the model for given return periods based on extreme wind velocity analysis.

The soil moisture content is one of the most important and dynamic factors determining soil resistance to wind erosion, because it affects threshold wind velocities for particle detachment. Presence or absence of moisture in the soil should therefore, be included in wind erosion risk assessments. In order to include soil moisture conditions into the wind data analysis, a sub-model was developed to separate wet and dry periods in weather time series. Weather data and soil moisture content collected during one year in Foulum were used to calibrate the model.

The reason why soil moisture conditions were considered for the wind data analysis was the theory that using wind data for calculation of wind frequency distributions regardless of the status of soil moisture would lead to an overestimation of wind erosion. To confirm or reject this hypothesis, the frequency distribution of wind velocity in conventional method (all-times) and proposed method (dry-times) was compared by using the pairwise Wilcoxon test. The results showed that in 99.6% and 97.1% of tests the difference between two distributions were significant at 99% confidence level for Denmark and Switzerland respectively. Change detection analysis of wind erosivity maps, revealed that 56.02% and

30.63% of the territory of Denmark and Switzerland experience an overestimation of wind erosivity, if the conventional approach would be used. However, underestimation was also observes in considerable parts of these countries, but almost all of these areas were located in regions, which are not prone to wind erosion.

To investigate the impact of climate change on various wind factors, the Mann-Kendall trend test and the Sen's slope estimator method for detecting the trend and estimating its magnitude were used. The results revealed that, in general, most wind factors experience a slightly decreasing trend in both countries. The median of trends of each input factor was considered to assess the impact of climate change on wind erosion risk modeling.

For running the model according to a given return period it was necessary to analyzed extreme wind velocities and to extract return levels for desired return periods. For this goal the Peak Over Threshold (POT) method was considered and the time series was fitted by the Generalized Pareto distribution (GPD) model. To ensure the independence of the extracted extreme values, a peak over threshold identifier algorithm was designed based on the detection of windiness of periods.

According to the results of above mentioned investigations, a GIS-based model was designed and successfully implemented to generate spatio-temporal distributions of potential and actual wind erosion risk by using a two-dimensional minimum curvature spline technique to spatially interpolate data, as well as a fuzzy overlay technique to combine fuzzy membership rasters.

The results of model in Switzerland confirmed that, wind erosion is not a threat in this country and only in limited areas of croplands (1.7% of croplands) the risk of wind erosion was estimated to be high. In Denmark 11.48% of total land surface was ranked in the class of high actual wind erosion risk, which are generally located in the north-west and south-west of Jutland peninsula as well as north of Vendsyssel-Thy and Zealand.

The spatial distribution of actual wind erosion risk in Denmark revealed that almost all of the estimated high risks occurs in "Croplands" and "barren or sparsely vegetated" lands, which included 18.4% and 10.3% of these land types respectively. Therefore, it should be emphasized that the role of human activities can have a significant impact on the increase or decrease of wind erosion risk in both countries.

Key words: wind erosivity, soil erodibility, Modeling, wind erosion, Potential risk, climate change, Mann-Kendall test, extreme wind velocity, Denmark, Switzerland

List of abbreviations used in the thesis

Acronym	***Definition***
AUSLEM	Australian Land Erodibility Model
CNDC	National Climatic Data Center
EPIC	Environmental Policy Integrated Climate
EVA	Extreme Value Analysis
EWPD	Erosive Wind Power Density
GEV	Generalized Extreme Value
GIS	Geographic information system
GP	Generalized Pareto
GPD	Generalized Pareto Distribution
ILSWE	Index of Land Susceptibility to Wind Erosion
ILSWE	Index of Land Susceptibility to Wind Erosion
IWEMS	Integrated Wind Erosion Modeling System
LUCAS	Land use and Land Cover Area Frame Survey
MAD	Median Absolut Deviation
MASH	multivariate analysis of series for homogenization
mle	maximum likelihood estimator
MSE	Mean Squared Error
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
POT	Peaks Over Threshold
R^2	coefficient of determination
RMSE	Root Mean Squared Error
RS	Remote sensing
RWEQ	Revised Wind Erosion Equation
SNHT	the standard normal homogeneity test
TEAM	The Texas Tech Wind Erosion Analysis Model
TPR	two-phase regression
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WA^SP	Wind Atlas Analysis and Application Program.
WE	Wind Erosion
WEAM	Wind Erosion Assessment Model
WEELS	Wind Erosion on European Light Soils
WEPS	Wind Erosion Prediction System
WEQ	Wind Erosion Equation
WESS	Wind Erosion Stochastic Simulator
WPD	Wind Power Density

“A thinker sees his own actions as experiments and questions -as attempts to find out something. Success and failure are for him answers above all.”

~ Friedrich Nietzsche (1844-1900)

INTRODUCTION

Wind erosion is defined as movement of soil particles by wind force and involves the entrainment, transport and deposition of portable soil grains by the airflow. This process is an environmental mechanism which is influenced by geological and climatic variations as well as human activities. In fact, this type of soil erosion is a complex process that is affected by many environmental parameters which include atmospheric conditions (e.g. wind speed and direction, temperature, precipitation, evaporation), soil surface properties (e.g. soil texture, soil type, soil moisture content), land surface characteristics (e.g. topography, roughness, percentage of vegetation cover and non-erodible elements) and land use applications (e.g. farming, grazing, mining) (Yaping Shao, 2008).

Soil erosion by wind is a worldwide concern, especially in arid and semi-arid regions (Borrelli, Ballabio, Panagos, & Montanarella, 2014; Buschiazzo & Zobeck, 2008; Hagen, 1991; Wolfe & Nickling, 1993). Based on the most important factors of wind erosion, it can be said that, the wind erosion process depends on wind force, the granular structure of the soil surface, the moisture content of the soil, as well as the density of the vegetation cover or non-erodible elements. This phenomenon leads to land degradation, especially in arid, semi-arid and agricultural areas during the fallow stage. The negative effects of wind erosion can be separated into on-site effects and off-site effects. The on-site effects are for example the removal of the most fertile component of the topsoil particles as well as damaging agricultural products and vegetation cover. In contrast, off-site effects are for example the negative influence on air quality, nutrient and pollutant export into other ecosystems, and effects on infrastructure. In addition, the emitted dust emission is a major source of atmospheric aerosols which influence the global radiation budgets and climate. Due to the climate change and human activities in recent decades, wind erosion has been one of the major problems and sources of pollution and dust emission in the world, for instance in the Middle East (e.g., dust is often observed moving from south-eastern Iran into the Indus Delta along Makran Mountains (Prospero, 2002), China (Husar et al., 2001), Australia (Chan, Mctainsh, Leys, Mcgowan, & Tews, 2005) as well as the Great Plains of the United States (Yaping Shao, 2008).

The wind erosion process is a complex phenomenon which is affected by the combined impact of wind erosivity and soil erodibility (Chepil & Woodruff, 1963). Wind erosivity is the potential of wind force to generate erosion (Yaping Shao, 2008), while soil erodibility describes the stability of the soil aggregates against the force of the wind.

Many different factors influence the wind erosivity and soil erodibility. One of the most important soil erodibility factors, which directly affect the stability of soil aggregates to the wind power, is the soil moisture content. It is the dominant factor that governs the initiation of soil movement by wind (Cornelis & Gabriels, 2003). According to wind tunnel tests (Weinan, Zhibao, Zhenshan, & Zuotao, 1996), “the threshold velocity for soil particle movement by wind increases with increasing soil moisture by a power function.” The main reason for the increased threshold velocity and thus, increased soil stability due to amount of soil moisture content, is the cohesive forces between the soil particles and absorbed water films. The water films around the particles can also increase the weight of the particles, and thus making them heavier and less prone to detachment (Cornelis & Gabriels, 2003).

The physics of the wind erosion process is very complicated and as mentioned before, it involves various aspects of atmospheric, soil and geomorphologic conditions, which are not yet fully understood. Its study requires the knowledge of a wide range of other physical and environmental sciences such as atmospheric science (e.g. meteorology, climatology, remote sensing), fluid dynamics, soil physics, surface hydrology, ecology, agricultural science, and land management (Yaping Shao, 2008).

1.1. Background and research questions

As mentioned above, the soil moisture content is one of the most important soil parameters, because it has a direct impact on the wind erosion threshold friction velocity (Weinan et al., 1996), so an increase of the soil moisture content immediately leads to a reduction of wind erosion and it significantly affects the transport of sediment by wind (Cornelis & Gabriels, 2003). However, despite its importance, it is usually not recorded along with wind speed and wind direction in conventional meteorological measurement stations. As a consequence, the soil moisture content cannot be directly obtained from standardized daily weather reports. Since the exact soil moisture content is generally not available, it would be very important to at least know whether the soil surface has been wet or dry during a wind erosion event. It can actually be assumed, that because of a higher threshold friction velocity, the soil surface is protected against the wind during wet periods. Hagen (2007) tried to determine if the frequency distribution of wind speeds during dry and wet periods is similar or not. The results from the analysis of 46 observation stations in the western U.S. showed that the frequency distributions of dry and wet periods are different. Therefore, the calculation of potential soil loss by wind erosion would most probably lead to an overestimation, if all-day wind speed distributions are being used and wet times were not accounted for. He concluded that, "at many locations, accuracy of physically based wind erosion simulation models could be modestly improved by accounting for differences in wind speed distributions on wet days and dry days" (Hagen, 2007). This finding is especially important for humid and sub-humid areas, because in these regions the differences in the frequency distributions of wind speeds for wet and dry days are most probably more pronounced than in arid or semi-arid regions. Thus, overestimating wind erosion in this kind of regions seems to be obvious when wind erosion estimation is based on using a model that does not account wet and dry times at the wind velocity distributions. As a consequence, the first issue which is necessary to investigate can be expressed as follows:

Issue I:

Using wind time series to compute wind erosion rates without considering wet and dry periods, most probably leads to an overestimation (Hagen, 2007), especially in humid and sub-humid areas. In order to improve wind erosion risk assessments, the influence of wet periods on the frequency distributions of wind velocities needs to be better understood and it is necessary to include them into wind erosion prediction models (Borrelli, Panagos, et al., 2014).

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Climate change is a phenomenon that can be observed in climate data of many regions of the world (IPCC, 2007a). For conservation planning and protection of natural resources it would be very helpful to know about the influences of climate change on regional wind patterns and their effects on the rate of wind erosion. However, this factor is often neglected in wind erosion models, because the time series being used do not include a proper trend analysis to account for changes in future climate.

Especially in GIS-based models it would be important to use this kind of information as a separate data layer to verify if the actual wind erosion risk is the same than it will be in the future. Based on this information, conservation plans and mitigation measures could be adjusted to different future scenarios. Consequently, the second scientific challenge, which this thesis tries to investigate, can be described as follows:

Issue II:

The estimated potential wind erosion risk is, usually, only reflecting the risk according to present or past wind patterns. In order to improve the quality of the risk assessments it is necessary to include future climate trends into the process.

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Wind erosion is extremely variable in space and very intermittent in time (Yaping Shao, 2008). Therefore, its prediction is a very complex process, which requires an indepth knowledge of processes involved and a huge amount of information on meteorological, hydrological, and soil data (Borrelli, Panagos, et al., 2014; Böhner, Schäfer, Conrad, Gross, & Ringeler, 2003; Yaping Shao, 2008). The quality of model predictions usually increases with increasing amount of available input data. However, herein lays one of the biggest problems of modelling environmental processes, which is data availability.

During the past decades, quite some good wind erosion models have been designed, for different scales (plot, field, catchment, regional as well as global) and observation periods (event based or mean annual estimations)(Borrelli, Ballabio, et al., 2014; Böhner et al., 2003; Fryrear, Sutherland, Davis, Hardee, & Dollar, 1999; L.J. Hagen, 1991; Wagner & Throckmorton Hall, 1996). None of these models is perfect for every research question, but if chosen wisely, most of them deliver satisfactory and acceptable results (Wagner & Throckmorton Hall, 1996; Webb, McGowan, Phinn, Leys, & McTainsh, 2009; Zobeck, Baddock, Scott Van Pelt, Tatarko, & Acosta-Martinez, 2013). However, what they all have in common is that their performance improves with the amount and quality of data that is available for model calibration. In fact, to run these models, access to several datasets are necessary, such as meteorological data, crop management practices, and soil data (Gao, Wagner, & Fox, 2013). However, wind erosion models are often used in regions where both the amount and the quality of data is limited and access to existing data is difficult, such as deserts, drylands or other remote places. Even in places where one would expect to be able to get most of the necessary input data like central Europe or the USA, it is often very difficult and expensive to obtain all necessary input data. The main reason for this problem is that the necessary data are not continuously measured in existing meteorological or hydrological measurement networks. Instead, scientists usually have to set up own measurement networks to record for example infiltration rates or the above mention, very important soil moisture content.

Issue III:

Data limitation and high complexity of conventional soil erosion models diminishes their usability for wind erosion risk assessments in remote areas with poor availability of data. In order to be able to accomplish proper risk assessments under these limitations, a less complex approach using readily available meteorological data is needed.

Based on the above mentioned issues, the following research questions need to be addressed:

1- Is it necessary to separate wet and dry periods, or in other words, are there significant differences between using the conventional method (calculation of wind patterns for all-times) and separation of dry and wet periods?

2- How is it possible to separate wet and dry periods in standard historic wind data time series by using easy to access data on weather elements, such as precipitation, temperature and relative humidity, without data on soil moisture content?

3- What could be the possible impacts of climate change on wind factors in a region of interest and does it differ depending on the method applied (conventional versus dry/wet method)?

4- Is there a quick, easy to use, and reliable method in order to predict potential and actual wind erosion risk for areas without sufficient or low quality data?

1.2. Aims and objectives

Based on the open research questions above, the aims of this research are to develop and test a new model that is able to assess the potential wind erosion risk for regions, where neither enough nor adequate input data are available for existing wind erosion models. The proposed model is supposed to fill the large gap between the highly complex and data demanding research models and the relatively basic methods that only use historical wind and soil texture data to produce maps of wind erosion risk. The new GIS-based model should be able to use readily available meteorological data to enable its use for almost every region of the world, where such data are recorded. By including a climate trend analysis and the differentiation between dry and wet times, it should be possible to produce reliable maps of potential wind erosion risk with better accuracy and quality than it was possible with the conventional statistical method. By accessing other layers of information with a GIS, for example soil texture data, the estimation of the actual wind erosion risk for a given region would also be possible. In comparison to the complex wind erosion models, this new model should be easier to use and could, because of the reduced amount of input parameters, be applied by a much larger user community, not just by wind erosion specialists or modelers. Being able to create a quick but reliable overview of the potential wind erosion risk of a region could be helpful for many other applications, for example environmental management, agricultural use or landscape planning, and not only for research on wind erosion.

In order to successfully achieve this model development and to answer the above mentioned research questions, following objectives have to be met consecutively:

1- Designing and testing of a dynamic database and data generator program. In combination, they have to be capable of importing data of varying sources and formats and to be able to compute specific parameters, such as Wind Power Density (WPD) and Erosive Wind Power Density (EWPD). Moreover, it is necessary that the extracted data can be imported into a GIS program for further processing;

2- Development of a method to distinguish and separate wet and dry times in a time series, based on standard meteorological data records;

3- Comparison of the quality of the results between the conventional (use of all-times) and the new method (separation of wet/dry times) to calculate wind speed frequency distributions;

4- Homogenization and statistical analysis of historical wind data to study the impact of climate change on wind parameters for both the conventional and the dry/wet approach;

5- Detection of return period of extreme wind velocities to incorporate their analysis into the wind erosion risk assessment;

6- Compilation of a potential and actual wind erosion risk map by taking into account climate change impact and the dry/wet approach.

All of the above mentioned data selection and preparations, data analysis and computations, model testing and compilation of maps were done for two exemplary test regions, Denmark and Switzerland. A reasoning why these specific countries were chosen as test subjects is given in sub-chapter 1.4. The overall process of the research is summarized in Figure 1-1.

Issues

- Using wind time series to compute wind erosion rates without considering wet and dry periods, most probably lead to an overestimation;
- To improve the quality of the risk assessments it is necessary to include future climate trends into the process;
- Data limitation and high complexity of conventional soil erosion models diminishes their usability for wind erosion risk assessments in remote areas with poor availability of data.

Questions

- How is it possible to separate wet and dry periods in historic wind data time series without data on soil moisture content?
- Is the separation of wet and dry periods necessary?
- What could be the possible impacts of climate change on wind factors ?
- Is there a quick, easy to use, and reliable method in order to predict potential and actual wind erosion risk for areas without sufficient or low quality data?

Main Aim

- To develop and test a new model that is able assess the potential wind erosion risk for regions, where neither enough nor adequate input data are available for existing wind erosion models.

Objectives

- Designing and testing of a dynamic database and data generator programfor data mining and to extract climatic time series;
- Development of a method to distinguish and separate wet and dry times in a time series, based on standard meteorological data records;
- Comparison of the quality of the results between the conventional and the new method to calculate wind speed frequency distributions;
- Statistical analysis of historical wind data to study the impact of climate change on wind parameters for both the conventional and the dry/wet approach;
- Detection of return period of extreme wind velocities to incorporate their analysis into the wind erosion risk assessment;
- Compilation of a potential and actual wind erosion risk map by taking into account climate change impact and the dry/wet approach.

Figure 1-1: The overall process of the research in this thesis

1.3. The research strategy

The research strategy focused on the analysis of historical time series of weather elements such as wind speed, temperature, precipitation, and relative humidity to predict land susceptibility to wind erosion.

According to this strategy, the aim of this thesis is to design a GIS-based model to estimate potential and actual wind erosion risk by taking into account the impact of climate change and soil surface moisture on wind erosion. Therefore, the final outcome of the research will be a GIS-based model for mapping potential and actual wind erosion risk on a regional scale. It should be noted that the potential wind erosion (WE) risk in this research indicates the spatial distribution of wind power regardless of the sensitivity of topsoil, while the more commonly used meaning of actual WE risk would include a combination of both, wind erosivity and soil erodibility. To achieve this goal of an actual wind erosion risk map in this research, the actual WE risk map will be derived from potential WE risk map by taking into account the erodible fraction of soils (EF) to compute the soil erodibility (Borrelli, Ballabio, et al., 2014; Fryrear et al., 2000).

1.4. Selection of test sites

Denmark is a Nordic country, located in northern Europe between Sweden, Norway and Germany, that consists of a peninsula, Jutland, and the archipelago of 443 named islands in the Baltic Sea, around 72 of which are inhabited (as of 1 January 2007, Statistics Denmark). The country is relatively flat with an average elevation of 31 meters and a highest natural point of 171 m in Møllehøj (Crolla & McKeating, 2009). The weather in this country is often windy and the occurrence of calm wind is usually rare. Consequently, the wind flow is a key factor of daily life in the country (Cappelen & Jørgensen, 1999). According to the frequency of wind speed distribution, the prevalent wind direction in Denmark is westerly (Mette, Jørgensen, & Cappelen, n.d.). North winds have the lowest frequency across the country. Generally, Denmark’s weather is quite mild and its climate is temperate, which is characterized by mild winters and cool summers. The average precipitation is 712 mm/a, with an average 121 days of precipitation per year. Autumn is the wettest season and spring is the driest.

Generally, the eastern parts of the country have a continental climate and the western parts experience a more Atlantic climate.

There are several reasons for choosing Denmark as one of the study areas in this research. First of all, the country is strongly affected by wind. For example, 23% of observed wind speeds at Fouloum climate station were higher than 11 knots (equivalent to 5.66 m/s) during 2000-2013). This is also the reason why Denmark has the highest concentration of wind turbines per capita in the world (Mason, 2007).

Secondly, Danish soils are very sandy and loosely aggregated (Odgaard & Rydén Rømer, 2009). This is why they are generally very prone to wind erosion. Historical evidence and huge erosion events in the 18th and 19th century as well as in the mid-twentieth century indicate that wind erosion is important, if land use and agricultural management practices are not adjusted to the environmental conditions and high vulnerability of the soils (Deumlich, Funk, Frielinghaus, Schmidt, & Nitzsche, 2006). Due to new law enforcements and improved protection measures during the last decades of the 20th century, the rate of wind erosion has been decreased to an amount that can be considered as almost negligible (Schjønning, Heckrath, & Christensen, 2009). There are two main factors that could be able to change this situation though. First of all, there is a tendency to change the crop production from cereals to maize and energy crops, which can be used to produce biofuel. These kinds of crops, in comparison to other crops, promote wind erosion, because of low ground coverage during most parts of the year. Due to this development and the general trend to increasing field sizes and machinery sizes to improve profitability of agriculture (Riksen & De Graaff, 2001), it could happen that wind erosion rates in the near future reach alarming proportions again. The second factor that might lead to increasing wind erosion rates in Denmark is climate change.

Observational and modelling evidence reported by IPCC (2013) indicates that extreme precipitation events over most of the mid-latitude land will very likely become more intense and more frequent by the end of 21st century, as global mean surface temperature increases(Stocker et al., 2014). So according to this report Denmark will also experience a gradual temperature increase over the next centuries as well as an increase in annual rainfall. Increased evapotranspiration due to higher temperatures in combination with more accentuated rainfall events, stronger but shorter rainfall events with longer periods of no rain in-between, could very likely increase the threat of wind erosion again in this country.

Based on these two issues it seems to be very important to assess the wind erosion susceptibility in Denmark and to produce a spatially distributed wind erosion risk map. Because of this need for a map of high quality, the above mentioned new model development could be very advantageous, especially if the new model is capable of including the effects of climate change and dry and wet time period separation.

Another factor why Denmark was chosen is the representativeness of its landscape and environmental setting to large parts of northern Europe. Due to the development during and after the Pleistocene, the topography and the soils in the south-eastern parts of Great Britain, The Netherlands, northern Germany, northern Poland, the Baltic States, and southern Scandinavia are very similar.

The final reason was the possibility to set up a reference weather station that recorded weather and soil moisture contents simultaneously. This very precise dataset was needed in order to be able to calibrate and test the proposed new wind erosion risk model, especially the capability to separate dry from wet periods.

The second country that was chosen is Switzerland. It seems that in this country wind erosion is not yet a major issue, but due to similar climate change scenarios and agricultural management practice changes, the possibility that agricultural areas like the Swiss Central Plateau could experience wind erosion events, is present.

The main reasons why Switzerland was chosen are the differences in climate, topography and soil distribution. In comparison to the maritime climate in Denmark, Switzerland is sort of a transition climate that experiences both, maritime and continental influences. In addition, the Alps act as a climate barrier between the northern and southern parts of the country. As a consequence, the climate in the north and east (Basel, Luzern, St. Gallen, and Zurich) is moderate whereas the southern part of the country is mainly influenced by the Mediterranean climate, which is characterized by much milder winters than North (MeteoSwiss, 2014). This complexity is even further increased by the huge differences in relief (average altitude 580 m, highest altitude Monte Rosa 4634 m (Crolla & McKeating, 2009)), which often is the reason for very different climatic conditions in neighboring regions. In comparison, Denmark is a flat country with an average altitude of 31 meters and a highest point of just near to 171 meters above sea level.

The weather is, therefore, much more variable than in Denmark and it will be very interesting to see, if the designed model to separate dry and wet times also works out in such a complex climatic and topographic environment.

1.5. Thesis structure

This thesis contains 6 chapters and is structured as follows (see Figure 1-2):

Chapter 2 covers a literature review, including a thematic and chronological overview of past investigations in wind erosion studies.

Chapter 3 includes “Data mining”, “Modeling of wet and dry periods” and also introduces various methods used in each part of the study. In data mining, different types of climatic time series which are necessary for our research are described and the methods to extract and compute the wind parameters are introduced. The structure of the model to separate wet and dry periods is also presented in this chapter, since it is based on weather elements and is related to the data mining. Also this chapter describes various methods used in each part of the study. The algorithms, which are designed for each part of research, will also be described in this chapter of the thesis.

Chapter 4 covers the results of the study, which include wind pattern analysis, trend maps of different climatic elements, extreme wind speed analysis, and finally potential and actual wind erosion risk maps for Denmark and Switzerland.

Chapter 5 of the thesis is the discussion part. The results of the presented model will be compared against previous investigations in the literature and advantages and disadvantages of the model will be described.

Finally, chapter 6 will summarize the conclusions of each part of the research and assess whether the overall aims of the research have been achieved. The end of this chapter will be concerned with the application of the method as well as presenting some recommendations and suggestions for the future use of the method. Figure 1-2 shows the structure of the thesis and the relationship between each part of study.

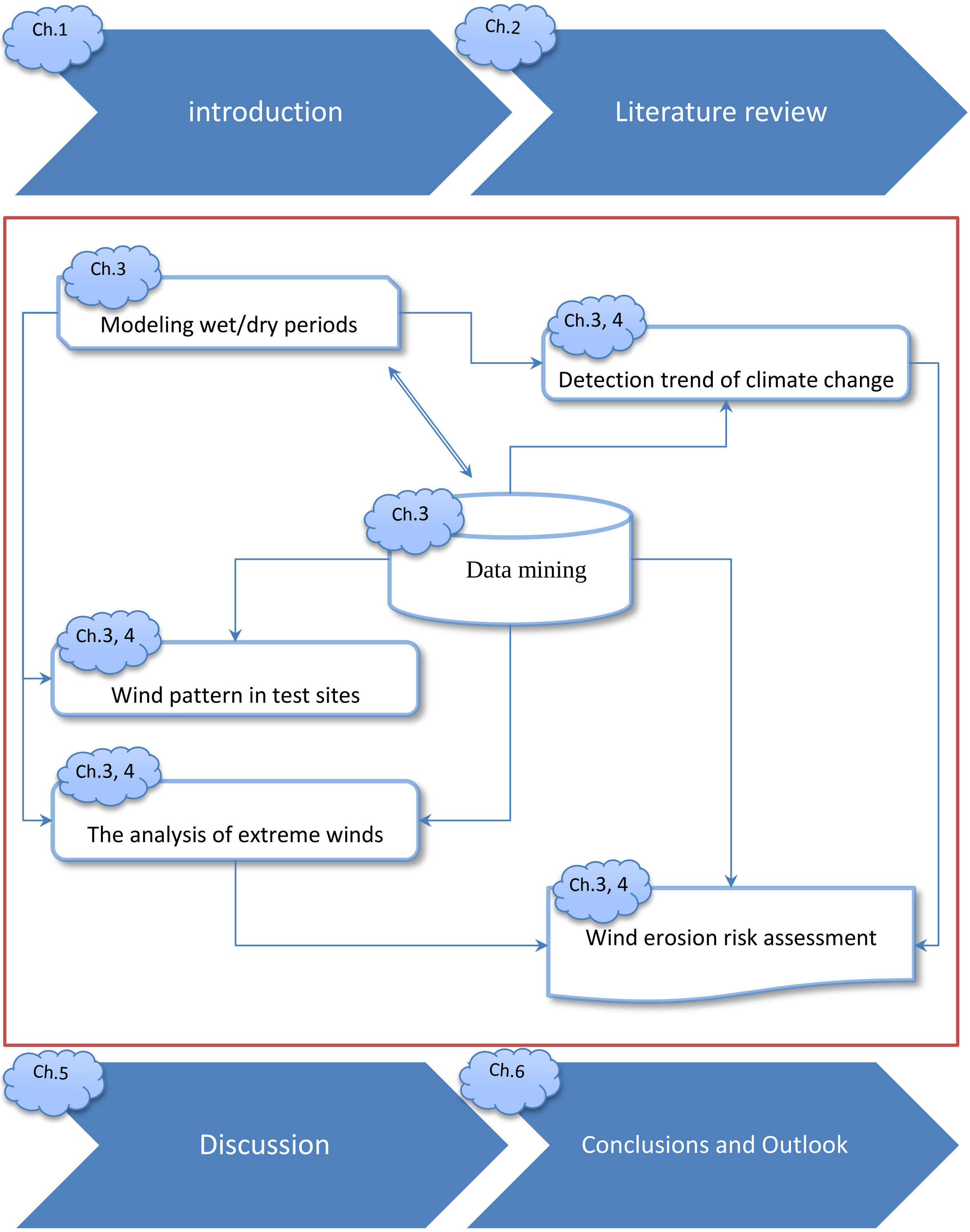


Figure 1-2: The structure of the thesis and the relationship between each chapter

"We know very little, and yet it is astonishing that we know so much, and still more astonishing that so little knowledge can give us so much power."

~ Bertrand Russell (1872-1970)

LITERATURE REVIEW

After the second half of the twentieth century, numerous studies have been conducted on various aspects of wind erosion process. With the advancement of technology and the use of new techniques, investigations in this field not only accelerated but also became much more accurate than before.

By using the results from other investigations, this research attempts to design a GIS-based model to predict potential wind erosion risk on a large scale and assist Policymakers with better and faster decision making. To achieve this goal, various aspects of wind erosion studies were used in this research and an overview of each aspect is summarized in this chapter.

It is worth mentioning that, the provided literature review in this chapter initially organized thematically and then within each issue Attempts to respect the chronology between conducted researches.

2.1. The effects of soil moisture on the wind erosion process

The wind erosion process is a complex phenomenon which is affected by the combined impact of wind erosivity and soil erodibility (Chepil & Woodruff, 1963). Many different factors of wind erosivity and soil erodibility contribute to the occurrence of this phenomenon. One of the most significant soil erodibility factor, which affects the stability of soil aggregates to the wind power, is soil moisture content, that governs the initiation of soil movement by wind (Cornelis & Gabriels, 2003).

According to wind tunnel tests (Weinan et al., 1996) the wind threshold velocity for soil particle movement increases with increasing soil moisture by a power function. The main reason for this increasing threshold velocity and thus, increase in soil stability due to amount of soil moisture content, is the adhesion between soil particles and soil moisture. The water films around particles can also increase the weight of particles, and thus making them heavier and less prone to detachment (Cornelis & Gabriels, 2003).

Physically, soil erosion by wind occurs when the wind speed is greater than a specific threshold value, which is sufficient to overcome the stability of soil particles, to allow detachment and movement (Ravi, Zobeck, & Over, 2006). The threshold wind velocity depends on the physical characteristics of the soil surface, such as soil surface roughness, amount of soil clay content, size and shape of the soil aggregates as well as near surface soil water content (Chepil, 1945). This threshold value begins to increase linearly when the soil surface moisture content exceeds about 25% at 1.5 MPa moisture tension (Hagen, 2007). McKenna et al. (1989) tested a theoretical model in a wind tunnel to study the small amount of water on the threshold shear velocity of sand particles. They concluded that, most of the sand particles appear to be extremely resistant to wind erosion at gravimetric moisture contents above around 0.2 percent or at moisture tensions below 10 MPa. According to Weinan et al., (1996) research, in sandy loam soils, there was a negative exponential relationship between soil moisture content and the wind erosion rate. Thus, by increasing the soil moisture content, the decrease in the wind erosion rate was relatively quick. When soil moisture contents reached more than 4%, the rate of reduction in wind erosion was slower and approximately constant with successive increase of moisture.

By comparing distributions of dry days and all days at 46 stations in the western U.S, based on a Kolmogorov-Smirnov test, Hagen (2007) found that 87% of the distributions were significantly different at 0.10 significance levels, and concluded that the "use of an all-day wind speed distribution likely leads to an overestimation of potential soil loss by wind erosion." Thus, elimination of time periods in which the soil is affected by moisture, could most probably lead to better estimates of soil loss.

2.2. Estimation of soil moisture contents

The soil moisture content cannot be directly obtained from standard daily weather reports but it can be calculated by using other weather elements like precipitation, evaporation and relative humidity. The atmospheric humidity plays an important role in determining the soil surface moisture content and the threshold wind velocity (Ravi et al., 2006).

Shang et al. (2007) developed a model to calculate the surface soil moisture content in China by using precipitation and evaporation. In this study precipitation was directly obtained from weather reports, while evaporation was indirectly calculated by using meteorological elements according to the Penman formula (Chen & Chen, 1993).

One of the most important factor that has a great impact on wind erosion is threshold friction velocity of soil surface which depends on field surface conditions, surface roughness, size and shape of the soil aggregates and soil clay content (Ravi et al., 2006). Soil erosion occurs when the wind speed is sufficient to overcome the resistance of soil particles to detachment and removal by the wind. Many studies have been carried out to estimate this factor in different soils with different surface conditions such as the presence or absence of soil moisture content and soil surface roughness. Gregory & Darwish, (1990) found that threshold friction velocity was affected by air humidity and suggested that atmospheric variables such as temperature and specific humidity could be more easily used to predict soil erodibility than surface soil moisture, due to the difficulties that are commonly experienced in the accurate measurement of surface soil water content. Ravi, et.al., (2006) showed that the threshold shear velocity decreases with increasing values of relative humidity for values of relative humidity between about 40 to 65 percent, while above and below this range, the threshold shear velocity increases with air humidity. These results can be explained on the basis of the theory of wet bonding forces and their effect on the threshold velocity. As they have mentioned, in air-dry soils (RH<65%), the adsorptive component dominates the wet bonding forces because the soils are too dry for the existence of liquid bridge bond. However in higher humidity conditions (RH>65%), water condenses into liquid bridges between soil grains and then, the liquid bridge bonding dominates the wet bonding forces (Ravi et al., 2006).

2.3. Homogenization of surface climate data

The records of time series from weather stations are very important to climate change studies. Since these data are collected over long periods of time, data homogenization is necessary for improving the quality and homogeneity of selected time series. However, “Many related research in climate change still use original data without homogenization, which leads to large uncertainty in the conclusions of the studies. Therefore, it is still an important task in climate change research to study the homogeneity testing and adjustment methods for various elements of climate data” (Cao & Yan, 2012).

Homogenization in climate change research means the removal of non-climatic changes from a time series which are usually affected by relocations or changes in instrumentation. Several solutions have been proposed to apply statistical homogeneity tests to climatological time series. Aguilar te al. (2003) referred to at least 14 different approaches for homogenization developed and applied by various authors. Li te al. (2003) summarized the more commonly used nine homogeneity test methods. Reeves et al. (2007) analyzed and compared eight methods and Costa & Soares (2009) summarized nine homogeneity test methods. In total, two groups of homogeneity testing techniques can be distinguished, which can be referred to as “absolute” and “relative” methods based on whether to use the reference station time series or not (Cao & Yan, 2012). In the relative approach, the candidate station is compared to a reference time series based on one or more neighboring stations but in the absolute approach the statistical test is applied to each independent station. Some of the more commonly used homogenization methods, without considering absolute or relative procedures, can be listed as follows:

- the Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1984, 1986);
- Two-Phase Regression (TPR) (Easterling & Peterson, 1995a, 1995b; Solow, 1987);
- Multivariate Analysis of Series for Homogenization (MASH) (Szentimrey,1996,1999,2000);
- Multiple linear regression (Gullett, Vincent, & Malone, 1991; Vincent, 1998);
- Buishand range test (Buishand, 1982);
- Pettit test (Pettitt, 1979).

Tuomenvirta (2002) used SNHT for testing and adjusting the homogeneity process applied to temperature, precipitation and air pressure time series in Finland and concluded that homogenization procedures are essential for ensuring the reliability and suitability of long-term time series for the studies of climatic changes and variations.

For the homogeneity test of time series, some tools have been developed such as Climatol (Guijarro, 2011) package in R which is designed based on SNHT test; RHtestsV3 (Wang & Feng, 2004) software package also in R environment, designed based on the penalized maximal t-test (PMT) (Wang et al., 2007), the penalized maximal F-test (PMFT) (Xiaolan L.Wang, 2008) and multiple-phase linear regression algorithm. This package has the ability to homogenize data with a reference series, by using the penalized maximal *t* test, or without a reference series, based on the penalized maximal F test. Similarly, the homogeneity tests tool in XLSTAT, which is an add-Ins software in Excel, can be employed. By using this tool, the homogeneity test based on SNHT, Buishand's test, Pettit's test as well as von Neumann's ratio test are possible.

Table 2-1: A summary of some widely used methods for testing homogeneity and homogenization

#	Method	Details	source
1	Pettit test	a non-parametric rank test. The test statistic is related to the Mann–Whitney statistics.	(Pettitt, 1979)
2	Buishand range test	When a time series is homogeneous the values of this test will fluctuate around zero	(Buishand, 1982)
3	multiple linear regression	The test is based on four regression models to test homogeneity, trend, a single step, trends before or after a step. The procedure consists of the successive application of these four models	(Gullett et al., 1991; Vincent, 1998)
4	multivariate analysis of series for homogenization (MASH)	This method is a relative homogeneity test procedure with a multiple break points detection technique that does not assume that the reference series are homogeneous.	(Szentimrey, 1996, 1999, 2000)
5	two-phase regression (TPR)	In this method, a linear regression is fitted to the part of the difference series before the year that is being tested and other linear regression after this year.	(Easterling & Peterson, 1995a, 1995b; Solow, 1987)
6	the standard normal homogeneity test (SNHT) *	The SNHT is a likelihood ratio test that is usually performed on a ratio or difference series between the candidate station and a composite reference series.	(Alexandersson, 1984, 1986)

Note: Methods marked with an asterisk are used in the research

2.4. Review and synthesis of climate change induced global wind velocity trends

In recent years, many studies (Dinpashoh et al., 2011; Gocic & Trajkovic, 2013; Kousari et al., 2010; Sicard, Mangin et al., 2010; Tabari et al., 2011; Wang et al., 2012; Yue & Wang, 2002) have been performed to find trends of different climatic elements by applying nonparametric statistical tests such as Kendall's τ, Mann–Kendall's as well as Mann–Whitney's tests. Gocic & Trajkovic, (2013) studied the annual and seasonal trends of seven meteorological variables for twelve weather stations in Serbia during 1980–2010 by using Mann-Kendall and Sen's slope methods. They concluded that the results of applying Mann-Kendall and Sen's slope tests demonstrate a good result in the detection of the trend for meteorological variables.

Pirazzoli & Tomasin (2003) used linear regression to study the trends of change in wind direction and velocity at 17 coastal stations in Italy. They reported near surface wind speeds decreased significantly from 1951 to the mid-1970s and that a decline trend was also observed since 1980. Tuller (2004) found that, the annual and winter mean wind velocities at stations along the west coast of Canada decreased from the late 1940s to the mid-1990s. Also, a reduction in wind speed was reported for 88% of the weather stations in Australia between 1975 and 2006, with an average trend of -0.009 m/s per year (McVicar et al., 2008). The increase in wind velocity has also been reported in other regions. For instance, in the Baltic region, the annual mean wind speed increased significantly over the period 1953 to 1999 (Pryor & Barthelmie, 2003), as well as at the Atlantic and Mediterranean Coasts (Recio et al., 2009), and in the north west (Duero Valley) of Spain (Moratiel et al., 2011).

In many investigations conducted in China, the trend of wind velocity has been examined in the past 50 years (Fu et al., 2011; Guo et al., 2010; Jiang et al., 2010). In almost all investigations, decreasing trend has been observed, especially in the northwest of China during winter. Jiang et al. (2010) analyzed wind speed changes based on two observational datasets in China from 1956 to 2004 and reported a decreasing trend of the annual mean wind velocity, days of strong winds as well as maximum wind velocities over broad areas of China. They concluded that the main reason for the decreasing trend in wind speed is the change of atmospheric circulation. Guo et al. (2010), by using a new dataset consisting of 652 stations, found that most stations in China experienced a significant decrease in annual and seasonal mean wind velocity during 1969-2005. Xiaomei et al. (2012) analyzed Daily wind velocity from 110 stations in southwestern China to determine annual and seasonal trends, spatial differences and possible causes. Their results showed that there was statistically a significant decrease of 0.24 m/s per decade in the annual mean wind velocity during the period 1969-2009.

Vautard et al. (2010) analyzed the extent and potential cause of changes in global surface wind velocities by using data from 822 surface weather stations. They concluded that wind velocities have decreased around 5-15% over almost all continental areas in the northern mid-latitudes between 1979 and 2008. It is important to note that, the widely reported decrease of surface wind speed is not only associated with the large-scale circulation change, but also with the urbanization-induced change in observational settings around the meteorological stations (Xiaomei et al., 2012).

In Table 2-2, results from various studies carried out in Europe are summarized. As these studies reveal, decreasing wind velocities can be observed almost everywhere in Europe. Only a few investigations in Spain found positive trends of wind velocity. It should be noted that, to provide for a comparison of the results of all investigations, the resulting trend has been recalculated in units of meters per second per annum ($\boldsymbol{m\,s^{-1}a^{-1}}$).

Table 2-2: A summary of observed near-surface terrestrial wind speed trends in Europe. The anemometer height above ground-level is specified in parenthesis in the 'Study Details' column. n/s means 'not specified'.

#	Trend $ms^{-1}a^{-1}$	Location (site position/domain)	Study details	source
1	-0.038	Estonia, Pakri Peninsula (59°N, 24°E)	1970-1991, 1 site, (10 m)	(Keevallik & Soomere, 2009)
2	-0.021	Ireland (51-56˚N, 6-11˚W)	1961-1978, 12 sites (10-12 m)	(Haslett & Raftery, 1989)
3	+0.043	The Netherlands, De Kooy (53˚N, 5˚E)	1985-1992, 1 site, (10 m)	(Coelingh, Wijk, & Holtslag, 1996)
4	-0.010	Europe (30-75˚N, 20˚W-40˚E)	1979-2008, 276 sites, (10 m)	(Vautard et al., 2010)
5	-0.009	The Netherlands, (51-53˚N, 4-7˚E)	1970-2010, 5 sites, (10 m)	(Cusack, 2012)
6	-0.001	Germany (47-55˚N, 6-15˚E)	1951-2001, 73-113 sites,(10m)	(Walter et al., 2006)
7	-0.002	Germany (47-55˚N, 6-15˚E)	~1888-2006, 6 sites, (10 m)	(Bormann, 2010)
8	-0.008	Czech Republic (48-51˚N, 12-19˚E)	1961-2005, 23 sites, (10 m)	(Brázdil, Chromá, Dobrovolný, & Tolasz, 2009)
9	-0.009	Switzerland (46-48˚N, 6-10˚E)	1983-2006, 25 sites, (10 m)	(McVicar et al., 2010)
10	-0.005	France (43-51˚N, 5˚W-8˚E)	1984-2003, 51 sites (10 m)	(Najac, Lac, & Terray, 2011)
11	-0.031	Italy, Trieste (45˚N, 14˚E)	1951-1996, 1 site, (10 m)	(Pirazzoli & Tomasin, 1999)
12	-0.009	Spain, north east, Comunidad Foral de Navarra mountainous area (42-43˚N, 1-2˚W)	1992-2005, 14 sites, (10 m)	(Jiménez, González-Rouco, Navarro, Montávez, & García-Bustamante, 2010)
13	+0.040	Spain, Vigo, Atlantic coast (42˚N, 8˚W)	1995-2005, 1 site, (n/s)	(Recio et al., 2009)
14	+0.017	Spain, north west, Duero Valley (40-43˚N, 1-7˚W)	1980-2009, 8 sites, (10 m)	(Moratiel et al., 2011)
15	-0.013	Italy (35-45˚N, 9-18˚E)	~1955-~1996, 17 sites, (10 m)	(Pirazzoli & Tomasin, 2003)
16	-0.022	Greece, Lesvos Island (39˚N, 26-27˚E)	2003-~2009, 4 sites (10 m)	(Palaiologou, Kalabokidis, Haralambopoulos, Feidas, & Polatidis, 2011)
17	-0.005	Spain, south, Andalusia area (37-39˚N, 1-7˚W)	~1967-2005, 8 sites, (10 m)	(Espadafor, Lorite, Gavilán, & Berengena, 2011)
18	-0.001	Greece (35-41˚N, 20-28˚E)	1959-2001, 20 sites (2 m)	(Papaioannou, Kitsara, & Athanasatos, 2011)
19	+0.118	Spain, Malaga, Mediterranean coast (36˚N, 4˚W)	1991-2006, 1 site, (n/s)	(Recio et al., 2009)
20	-0.040	Cyprus (34-35˚N, 32-34˚E)	~1982-~2002, 5 sites, (~8.5m)	(Jacovides, Theophilou, Tymvios, & Pashiardes, 2002)

Source: McVicar et al., 2012, pp. 186–187

Decreasing trend not only in mean wind speed but also in other wind elements has been observed. For example, the frequency trend of moderate wind events (occurring on average 10 times per year) and strong wind events (occurring on average twice a year) in the Netherlands during 1962-2002 indicate a decrease in storminess (Smits et al., 2005).

According to the IPCC (2007) reports, confidence in future changes in windiness is relatively low, but it seems that there will be an increase in average and extreme wind speeds in northern Europe. According to this report, several model studies have reported increasing average and extreme wind speeds in northern and central Europe, but as mentioned before, most of the observations show the opposite direction.

McVicar et al. (2010) by investigation Monthly average wind velocity data (ms^{-1}) in China and Switzerland (1960-2006) acquired some evidence from two mountainous regions that near-surface wind speeds are declining more rapidly at higher elevations than lower elevations. According to this research from 1983–2006 the annual wind velocity trend decreased by −0.0086 $ms^{-1}a^{-1}$ in Switzerland.

2.5. Extreme wind velocity analysis

The purpose of extreme wind velocity analysis in this research is to find reliable estimates of the return period of extreme wind velocities.

In literature, two approaches are referred for extreme value analysis. The first approach is based on block maxima series and the second relies on extracting Peak Over Threshold (POT) values. In the first method, it is customary to extract the annual maxima time series and fitting by GEV distribution. But in the second method, from a continuous record, any records with values exceeding a certain threshold will be selected. This process could lead to the extraction of several records or no record at all in a given year. Finally, the extracted POT values will be fitted with a GPD model in this method. Both approaches have been used extensively for the analysis of extreme winds. Some recent investigations are summarized in Table 2-3.

Table 2-3: A summary of extreme wind velocity investigations in recent decades. The anemometer height above ground-level is specified in parenthesis in the 'Study Details' column. n/s means 'not specified'

#	Location (site position/domain)	Study details	Study method	source
1	--	A review of methods	Describe Classical method based on the Generalized Extreme Value and Peak-over-threshold methods with the GPD	(Palutikof, Brabson, Lister, & Adcock, 1999)
2	Denmark (Skjern, Kegnæs, Sprog, Tystofte)	7-20 yr time period, 4 sites, wind speed analysis, (10m)	WA^{S}P cleaning and geostrophic mapping, use the ranking procedure	(Kristensen, Rathmann, & Hansen, 2000)
3	Sweden (55-70 ˚N, 11-25˚E)	1961–1990, 12 site, using wind speed database provided by SMHI, (n/s)	Weibull-Gumbel and the annual maxima methods	(Perrin, Rootzén, & Taesler, 2006)
4	The Eastern North Atlantic and Europe (35-73˚N, 35˚W-35˚E)	1957-2002, ERA-40 wind gust data, (10m), the 850hPa geostrophic wind speed	classical peak over threshold (POT) extreme value analysis techniques, modelled using a Generalized Pareto Distribution (GPD)	(Della-Marta, Mathis, Frei, Liniger, & Appenzeller, 2007)
5	Selected 7site in South of Spain, North of France, Korea,Colorado,Denmark, Netherlands, Minnesota	5-10 yr time period, 7site, maximum wind speeds and squared maximum wind speed,(n/s)	Gumbel, IEC, EWTS methods	(Langreder & Hojstrup, 2007)
6	Australia, Sydney region	~1939-2005, 23 site, max. daily wind speed and max. daily wind gust,(n/s)	the Generalised Pareto Distribution (GPD)	(Sanabria & Cechet, 2007)
7	Switzerland (46-48˚N, 6-10˚E)	1981-2007, 55 sites, wind gust analysis, (n/s)	POT method, Block Maxima approach	(P Ceppi, Della-Marta, & Appenzeller, 2008)
8	Iran, Isfahan province	1983–1998, 1 site, analysis prevalent westerly annual maximum wind speeds,(10m)	Generalized Extreme Value (GEV) distribution	(Rajabi & Modarres, 2008)
9	Europe (35-73˚N, 35˚W-35˚E)	ERA-40 reanalysis data, wind gust and wind speed, (10 m), 200 European winter wind storms	classical peak over threshold (POT) extreme value analysis (EVA) techniques to the EWI and grid-point wind data	(Della-Marta & Mathis, 2009)
10	United States (NewOrleans, Miami, New England)	3 sites, using historical data and a set of synthetic storms generated using a recently published downscaling technique,(n/s)	Empirical probability density functions for normalized hurricane wind speeds, extreme-value theory with parameter fitting using a peaks-over-threshold model	(Emanuel & Jagger, 2010)
11	Denmark, three meteorological masts located in Lammefjord	Using a time series of two days (July 12 and July 13), (30m)	Present models to analyzing large wind speeds on small time scales, establish a conditional model for exceedances over a time-dependent threshold	(Steinkohl, Davis, & Klüppelberg, 2013)
12	Schiphol airport in the Netherlands	1957–2002, using surrogates of the actual and reanalysis data, (10m)	the block maxima method, introduce the quantile calibration method	(Anastasiades & McSharry, 2014)

WA^{S}P: Wind Atlas Analysis and Application Program.

In recent years, the production and development of practical application tools and software for statistical extreme modeling has been accelerated, particularly in open source environments such as R (R Development Core Team, 2012). Consequently, some effort must be made in finding the proper tool for a particular work (Gilleland, Ribatet, & Stephenson, 2012). Table 2-4 introduces some R software packages that have been written for modeling extreme values. It should be noted, packages marked with an asterisk are used in current research which has been explained in more details in materials and methods (chapter3) under the title "Extreme wind Analysis" (page 81).

Table 2-4: A summary of some R software packages for extreme value analysis

#	Package name	Modeling approach	Parameters estimation method	source
1	evd*	BM, POT	MLE	(Stephenson, 2002)
2	evdbayes	BM, POT	Bayesian	(Stephenson & Ribatet, 2010)
3	evir	BM, POT	MLE	(McNeil & Stephenson, 2011)
4	fExtremes	BM, POT	MLE, PWM	(Wuertz, 2006)
5	Ismev*	BM, POT	MLE, LM	(Stephenson, 2012)
6	lmom	BM, POT	LM	(Hosking & Hosking, 2014)
7	lmomRFA	BM, POT	LM	(Hosking, 2009)
8	lmomco	BM, POT	LM	(Asquith, 2007)
9	POT*	POT	MLE, PMLE, PWMU, PWMB, MDPD, Pickands ,…	(Mathieu Ribatet, 2012)
10	SpatialExtremes	BM, POT	MLE,MCLE, Bayesian	(M Ribatet, Singleton, & Team, 2011)
11	texmex	POT	MLE,PMLE, Bayesian	(Southworth & Heffernan, 2012)
12	VGAM	BM, POT	MLE, BFA	(Yee, 2009)

BM: block maxima, POT: peak over threshold, MLE: maximum likelihood estimation, LM: L-moments estimation, PWM: probability weighted moments estimation, PMLE: penalized maximum likelihood estimation, MCLE: maximum composite likelihood estimation, BFA: backfitting algorithm, PWMU: unbiased probability weighted moments, PWMB: biased probability weigthed moments, MDPD: minimum density power divergence.
Note: packages marked with an asterisk are used in the research.

2.6. Efforts to wind erosion modeling

Although investigations carried out in the field of wind erosion modeling are not as extensive as in water erosion, some valuable studies have been conducted and will be briefly described in the following.

The fundamental basis of modern wind erosion prediction models largely began with the publication of Bagnold's classic book titled "The Physics of Blown Sand and Desert Dunes" (Ralph A Bagnold, 1941). More than two decades later, the use of wind tunnels and field studies led to the development of the first wind erosion mode, the wind erosion equation (WEQ) (Woodruff & Siddoway, 1965), which is the most widely applied method for assessing long-term annual soil loss by wind per unit area from agricultural fields.

Since the inception of the WEQ, there have been many efforts to improve its accuracy. Some of these modifications were suggested by Woodruff & Armbrust (1968), Skidmore & Woodruff (1968), Bondy et al., (1980), Lyles (1983) and Skidmore & Nelson (1992). Also, there have been many reports to validate and calibrate the revised wind erosion equation (RWEQ) such as, Fryrear et al., (2000), Vanpelt et al., (2004) and Youssef et al., (2012). The output of the WEQ is the average soil erosion by wind, expressed in mass per unit area per annum, that could occur from a given field length (Woodruff & Siddoway, 1965). Determination of the WEQ factors are described in detail in a certified National Agronomy Manual released by NRCS-USDA in 2002 (Li, Lobb, & Tiessen, 2013; USDA-NRCS, 2002).

However, despite all efforts and investigations that have been devoted to the improvement and development of the WEQ, it was impossible to adapt the model to many problems (Wagner & Throckmorton Hall, 1996). Therefore As an empirical model, it has many limitations and is capable to estimate only long-term average of annual wind erosion rates (Gao et al., 2013). For this reason, the United States Department of Agriculture (USDA) attempted combining the latest investigations in wind erosion science and technology to develop a Wind Erosion Prediction System (WEPS) as a replacement for the WEQ.

WEPS is a physical process-based, daily time-step model that simulates weather, field conditions as well as wind erosion (Wagner & Throckmorton Hall, 1996). The output of this model contains the total amount of erosion, suspension and PM10 (particulate matter with aerodynamic diameter less than 10 µm) emission into the atmosphere for a single field (Gao et al., 2013).

There are numerous challenges to modify proposed field-scale models for using on large areas (Feng & Sharratt, 2007; Hagen, 2010; Zobeck, Parker, Haskell, & Guoding, 2000). Hence, in addition to the development of previously mentioned models many new approaches have been provided by the use of new technologies and the occurrence of extensive developments in GIS and RS techniques. For instance, Borrelli, et al. (2014) proposed an integrated mapping approach to estimate soil susceptibility in order to gain a better understanding of the spatial distribution of wind erosion processes in Europe. This approach was also used in this thesis especially for computing soil erodibility index and mapping the soil susceptibility and actual wind erosion risk. Table 2-5 a summary of the most widely used wind erosion models are presented.

Table 2-5: A summary of the most widely used wind erosion models in the world

#	Model	Scale	Model type	Details	Reference
1	WEQ	Field-Scale	process-based	The empirical Wind Erosion Equation (WEQ) is the most widely used model in the world for assessing long-term annual soil loss by wind per unit area(L J Hagen, 2010) from agricultural fields.	(Woodruff & Siddoway, 1965)
2	WEPS	Field-Scale	process-based, daily time-step model	The Wind Erosion Prediction System (WEPS) can calculate soil movement, estimate plant damage by wind, and predict PM-10 emissions from agricultural fields (Wagner & Throckmorton Hall, 1996) The structure of WEPS is modular and consists of a user interface, a science model including seven sub-models, and four databases.	(L.J. Hagen, 1991)
3	WEAM	Regional	Physically-based	Wind Erosion Assessment Model (WEAM) simulates sand entrainment from different sites. It is based on the Owen equation for simulating saltation flux and dust entrainment. This model is more suitable to describe sand particle entrainment and not much for dust transport and deposition (Blanco-Canqui & Lal, 2008).	(Y Shao, Raupach, & Short, 1994)
4	RWEQ	Field-Scale	a combination of empirical and process based modeling	The Revised Wind Erosion Equation (RWEQ) estimates mean soil loss per unit area for measurement period. It is a single event wind erosion model that includes climatic factors for wind and rainfall, soil roughness, the erodible fraction of soil surface, crusting, and surface residues (Vanpelt et al., 2004)	(D W Fryrear et al., 2000; D.W. Fryrear et al., 1998)
5	TEAM	Plot and Field-Scale	process-based	The Texas Tech Wind Erosion Analysis Model (TEAM) is an integration of many mathematical models and generally predicts the rate and amount of detachment, movement, and deposition of soil particles associated with wind processes. This model also is able to simulate the suspension and movement of dust above and downwind from eroding sites (James M Gregory, Vining, Peck, & Wofford, 1999; Singh, Gregory, & Wilson, 1997).	(J. Gregory, Wilson, Singh, & Darwish, 2004; James M Gregory et al., 1999)
6	IWEMS	Field, Regional	Physically-based	Integrated Wind Erosion Modeling System (IWEMS) produce quantitative predictions of wind erosion on scales from local to global. This model attempt to combine atmospheric and land-surface data for large-scale wind-erosion assessment	(H. Lu & Shao, 2001)
7	WEELS	Regional	GIS-based	The Wind Erosion on European Light Soils (WEELS) is designed and implemented to predict the long-term spatial distribution of wind erosion risks in terms of erosion hours and wind-induced soil loss.	(Böhner et al., 2003)
8	AUSLEM	Field, Regional, National	Physical condition based	Australian Land Erodibility Model (AUSLEM) predicts wind-driven soil loss under various climate and land use regimes (Böhner et al., 2003) The model incorporates several modules for predicting wind erosivity, soil moisture, surface roughness, land use and soil erodibility but has limitation to recognize the dynamic nature of soil erodibility (Webb, McGowan, Phinn, & McTainsh, 2006).	(Böhner et al., 2003)
9	WESS	Field-Scale	process-based, single event	The Wind Erosion Stochastic Simulator (WESS) is a module of the environmental policy integrated climate (EPIC) model. This model has the ability to simulate wind erosion on an event basis	(Vanpelt et al., 2004)

2.7. Potential wind erosion risk assessment

In recent years, a range of studies has been performed to investigate potential and actual soil erosion risk in the world. However, in almost all of these studies, the focus has been placed on water erosion and the issue of soil erosion by wind has not been investigated adequately. For instance, in the "Soil erosion risk assessment in Europe" (Van der Knijff et al., 2000) the annual actual and potential soil erosion risk was assessed only for water erosion by running the empirical Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) model, based on the assumption that there is a total absence of soil cover. Hence in this investigation, the meaning of the term 'soil erosion' is merely water erosion and it does not include wind erosion estimations.

In general, reviewing literature revealed significant gaps and the lack of researches, especially at the region scales, about the land surface susceptibility to wind erosion (Borrelli, Panagos, et al., 2014). However, a comprehensive study still has not been conducted in this field of research, despite of all the efforts and studies that have been carried out to accomplish wind risk assessments. Quine (2000) proposed a method for the estimation of mean wind climate and probability of strong winds for wind risk assessment. The proposed method was based on the estimation of Weibull parameters, Fisher-Tippett type I extreme value distribution and the tatter flag technique. He developed a quantitative classification of wind risk by define a method to estimate the probability of strong winds. In recent studies, the use of new technologies such as remote sensing (RS) and GIS has been very common, especially for large-scale analysis. This approach increased the speed of studies and also led to increased accuracy. For example, (Borrelli, Ballabio, et al., 2014; Borrelli, Panagos, et al., 2014; Feng & Sharratt, 2007; Klik, 2004; Palaiologou et al., 2011).

Model based approaches, for example by using WEPS and RWEQ, were also employed for the assessment of wind erosion risk. Some examples are given in Coen et al. (2004), Feng & Sharratt (2007), and Mendez & Buschiazzo (2010).

Feng & Sharratt (2007) used WEPS and GIS to simulate soil loss and PM10 (particulate matter $\leqslant$ 10 μ) emissions. They indicated that wind erosion assessments and inventories can be performed by scaling from field to region using WEPS and GIS. Funk, Hoffmann, & Reiche (2014) used remote sensing and GIS procedures to represent wind erosion and dust deposition areas for large landscape units in steppe regions. In order to achieve a better understanding of the spatial distribution of wind erosion processes in Europe, Borrelli, Ballabio, et al. (2014) applied an integrated digital soil mapping approach to estimate soil susceptibility to wind erosion. They used the wind-erodible fraction of soil (EF) (Fryrear et al., 1994) and the soil crust factor (SCF) (Fryrear et al., 2000) as key parameters for estimating the soil erodibility to wind erosion within the 34 European countries. To calculate EF in this research the soil characteristics were obtained for 18,730 geo-referenced topsoil samples from Union Land Use/Land Cover Area frame statistical Survey (LUCAS) (Tóth te al., 2013) for the whole European Union.

2.8. Linking state of the art with present research topics

Despite comprehensive studies in various aspects of wind erosion investigations, there are still many problems and gaps which need to be addressed. For instance, most of models developed in the field of wind erosion are field-scale models and operating them requires many parameters, which are not generally available in every region. Data limitation and high complexity of conventional soil erosion models diminishes their usability for wind erosion risk assessments in remote areas with poor availability of data. In order to be able to accomplish proper risk assessments under these limitations, a less complex approach using readily available meteorological data is needed. In current models, generally there is not a good link between the impact of climate change and the estimated parameters by models. The establishment of such connection provides the ability to perform temporal analysis that would be very helpful for many applications, such as environmental management, agricultural use or landscape planning.

Separation of wet and dry periods in time series without soil moisture data and actually using that separation to compute wind velocity distributions is another problem in most models, which can lead to overestimation of wind erosion, especially in humid and semi-humid regions. Based on these problems, as mentioned before in the introduction, the main aim of this research is to develop and test a new GIS-based model that is able to assess the potential wind erosion risk for regions, where neither enough nor adequate input data are available for existing wind erosion model.

"Everything must be made as simple as possible. But not simpler."

~ Albert Einstein (1879-1955)

MATERIALS AND METHODS

The development and the actual modelling of wind erosion risk for the two selected countries are the main aims of this study. Thus, other parts of this research, such as the analysis of the climate change impact and the extreme winds analysis, are carried out to produce layers of information that are necessary to run the proposed model. This chapter primarily presents and explains the structure of the proposed model. In addition, the methods which have been used to produce required layers of information are described. Overall, this chapter could also be seen as a roadmap or guideline for similar studies that might be done in the future.

3.1. Data mining

Observational time series data are essential for statistical forecasting models. By analyzing the behavior of past data and finding patterns that govern them, forecasting and providing an image of the future would be possible.

Although historical time series are very important and valuable, one of the major issues that researchers are faced with is accessing this kind of reliable and up-to-date data. In fact, the lack of access to reliable data, in many cases has led to using non-homogenous data in numerous published studies, especially in climate change trend analysis, which has in turn resulted in erroneous results (Cao & Yan, 2012). On the other hand, in many studies, due to the cost and problems of data access, the statistical period, which is selected for the research is not up-to-date and often between one to five years of recent data are not included, depending to the time of study and its publication.

Due to these problems, the proposed method for data mining in this research has several advantages, among which the most important can be addressed as follows:

1- Access to the data is free and almost available for all countries in the world;

2- Usually, if the weather station is still recording data, obtaining data right from the setup of the station until two or three days before current time is possible;

3- Although the raw data gathered by using National Oceanic and Atmospheric Administration (NOAA) data center are in fact hourly/sub hourly and daily time series of weather elements, accessing the different climatic time series such as monthly, seasonal and annual time series is possible by using the designed data generator program;

4- Standardizing data, based on standard hours of observations for synoptic purposes (The standard times for surface synoptic observations are 0000, 0300 0600, 0900, 1200, 1500, 1800, 2100 GMT);

5- Separating data based on day and night by using sunrise and sunset definition, in accordance with current astronomical equations;

6- Separating observed weather elements, especially wind elements, based on wet/dry periods.

Figure 3-1 schematically indicates the structure of the designed data generator which has been used for data mining and extracting climatic data from weather time series.

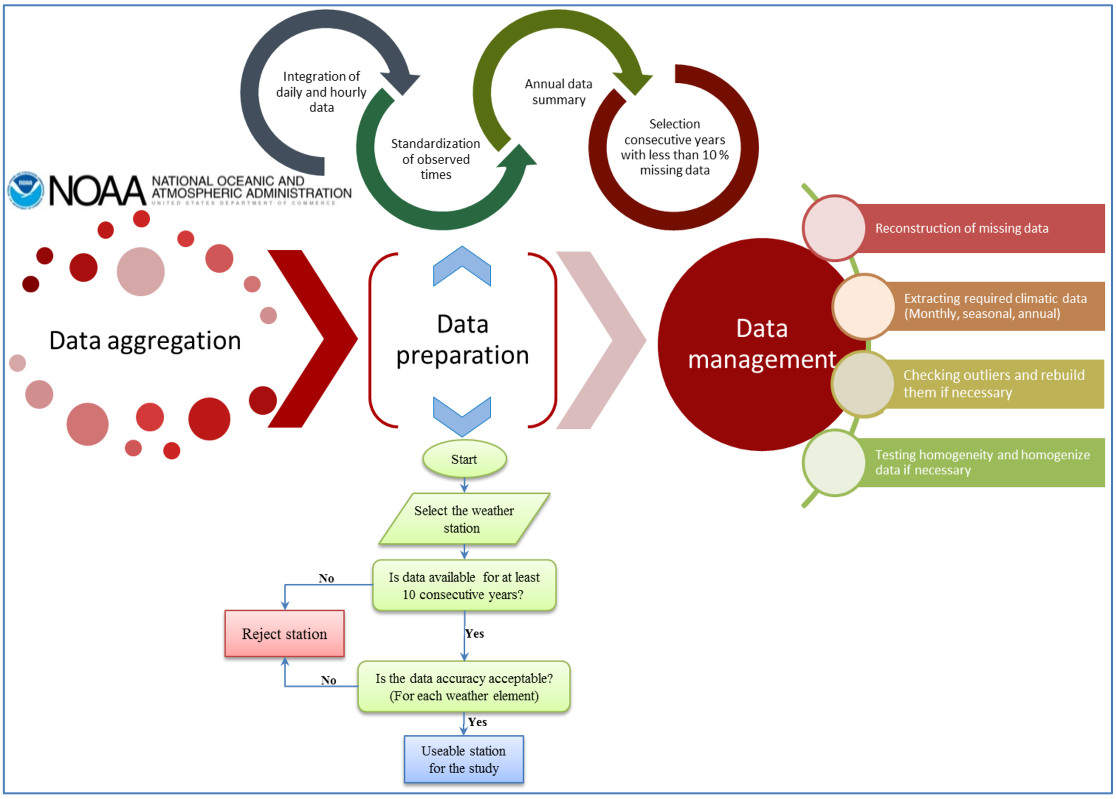


Figure 3-1: The proposed method for preparing data for different climatic time series analysis

In order to perform data mining for this research, three steps have been considered which are respectively: Raw data aggregation, data preparation and finally data management (Figure 3-1). Each of these steps has been discussed in more details in the following sub-chapters:

3.1.1. Data aggregation

The first step of the method used for data mining, is data aggregation. In this step hourly/sub hourly and daily time series of available weather elements were collected by using the national climatic data center of NOAA (National Oceanic and Atmospheric Administration) available from: http://www.climate.gov/data/maps-and-data or directly from: http://gis.ncdc.noaa.gov

The collection of the data was carried out for daily precipitation and also hourly or sub-hourly temperature, relative humidity, dew point temperature, wind speed and wind direction. The required data was downloaded for all available synoptic weather stations of World Meteorological Organization (WMO) in Denmark and Switzerland since the beginning of their founding to the end of 2013. Generally, three types of text files were downloaded for each weather station as follows:

1- Weather station characteristics (geographic and spatial information);
2- Global summary of daily observational data including mean temperature, mean wind speed as well as precipitation amount.
3- Hourly/ sub-hourly observational data which includes weather elements such as Air Temperature, Relative Humidity, Dew point Temperature, Wind Speed and Wind Direction.

Table 3-1 provides a summary of some the available data in each text file with their related units. In addition, in Figure 3-2, the header of text files downloaded from NOAA/National climatic data center for each weather station are illustrated as an example.

Table 3-1: Summary of some the available data in the NOAA ASCII files

File	Element	Abbreviation	Unit
File I: Geographic and spatial information of station	Station name	--	--
	Station number	USAF-WBAN_ID	--
	Altitude	--	Decimal degree
	Latitude	--	Decimal degree
	Height	--	Tenths of meters
File II: Hourly/ sub-hourly observational data	Air Temperature	TEMP	Degrees Celsius
	Dew Point Temperature	DEWPT	Degrees Celsius
	Relative Humidity	RHX	Percent
	Wind Speed	WIND Dir	Meters per Second
	Wind Direction	WIND Spd	Angular Degrees
	Sea Level Pressure	SLP	Hectopascals
	Visibility	VISBY	Meters
File III: Daily observational data	Precipitation	PRCP	Inches
	Daily Mean Temperature	TEMP	0.1 Fahrenheit
	Daily Maximum Temperature	MAX	0.1 Fahrenheit
	Daily Minimum Temperature	MIN	0.1 Fahrenheit
	Maximum wind speed	MXSPD	knots to tenths
	Daily Mean station pressure	STP	Tenths of millibars

2047956918381stn.txt | CDO5089776918385.txt | 2047956918381dat.txt

```
USAF-WBAN_ID STATION NAME                   COUNTRY                                      STATE LATITUDE LONGITUDE ELEVATION
------------ ------------------------------ -------------------------------------------- -------- --------- ---------
060690 99999 FOULUM                         DENMARK                                            +56.500  +009.567   +0058.0
```

A) Weather station characteristics

2047956918381stn.txt | CDO5089776918385.txt | 2047956918381dat.txt

```
STN---,WBAN , YEARMODA,   TEMP,  ,   DEWP,  ,  SLP   ,  ,  STP   , , VISIB,  ,  WDSP,  , MXSPD,  GUST,   MAX  ,  MIN  ,
060690,99999, 19881001,   47.4, 7,   43.0, 7, 1032.1, 7, 9999.9, 0, 999.9, 0,  12.5, 7,  15.5, 999.9,   55.0 ,  41.0 ,
060690,99999, 19881002,   49.5, 8,   44.7, 8, 1032.0, 8, 9999.9, 0, 999.9, 0,  16.5, 8,  21.4, 999.9,   56.8 ,  43.9 ,
060690,99999, 19881003,   48.1, 7,   46.4, 7, 1026.6, 7, 9999.9, 0, 999.9, 0,  15.8, 7,  23.3, 999.9,   59.0 ,  42.6 ,
060690,99999, 19881004,   52.1, 5,   51.6, 5, 1016.6, 5, 9999.9, 0, 999.9, 0,   9.7, 5,  11.7, 999.9,   54.1 ,  43.7 ,
060690,99999, 19881005,   53.2, 8,   52.1, 8, 1006.7, 8, 9999.9, 0, 999.9, 0,  15.3, 8,  21.4, 999.9,   56.7 ,  50.5 ,
060690,99999, 19881006,   50.4, 8,   49.4, 8,  989.0, 8, 9999.9, 0, 999.9, 0,  23.1, 8,  38.9,  41.0,   55.6 ,  44.2*,
060690,99999, 19881007,   45.8, 7,   45.2, 7,  974.8, 7, 9999.9, 0, 999.9, 0,  25.5, 7,  31.1,  39.0,   50.0 ,  43.0 ,
060690,99999, 19881008,   49.2, 6,   48.0, 6,  984.9, 6, 9999.9, 0, 999.9, 0,  22.7, 6,  31.1,  36.9,   53.2 ,  46.4 ,
060690,99999, 19881009,   50.6, 7,   48.3, 7,  985.0, 7, 9999.9, 0, 999.9, 0,  31.6, 7,  40.8, 999.9,   55.9 ,  46.2 ,
060690,99999, 19881010,   47.9, 8,   43.9, 8,  998.6, 8, 9999.9, 0, 999.9, 0,  21.6, 8,  31.1, 999.9,   52.5 ,  42.1*,
060690,99999, 19881011,   44.0, 7,   39.8, 7, 1019.2, 7, 9999.9, 0, 999.9, 0,  10.8, 7,  13.6, 999.9,   52.9 ,  36.5 ,
060690,99999, 19881012,   47.3, 4,   47.0, 4, 1016.3, 4, 9999.9, 0, 999.9, 0,  32.5, 4,  36.9, 999.9,   47.7 ,  42.6 ,
060690,99999, 19881013,   50.9, 7,   50.7, 7, 1014.3, 7, 9999.9, 0, 999.9, 0,  16.6, 7,  31.1, 999.9,   53.4 ,  46.0 ,
060690,99999, 19881014,   47.7, 7,   47.7, 7, 1022.3, 7, 9999.9, 0, 999.9, 0,  10.3, 7,  15.5, 999.9,   51.4*,  41.5 ,
060690,99999, 19881015,   48.4, 5,   48.2, 5, 1029.1, 5, 9999.9, 0, 999.9, 0,   6.6, 5,   7.8, 999.9,   53.1*,  45.9
```

B) Daily observational data

2047956918381stn.txt | CDO5089776918385.txt | 2047956918381dat.txt

```
Identification                               WIND              CEILING      VISIBILITY   TEMP      DEWPT     SLP       RHX
USAF   NCDC  Date      HrMn I Type  QCP  Dir Q I Spd   Q Hgt   Q I I Visby  Q I Q Temp   Q Dewpt  Q Slp     Q Rhx
060690,99999,19881001,0300,4,FM-12,    ,240,1,N,  6.0,1,99999,9,9,9,      ,9,N,9,   5.5,1,   4.7,1,1029.3,1, 95,
060690,99999,19881001,0600,4,FM-12,    ,240,1,N,  5.0,1,99999,9,9,9,      ,9,N,9,   5.5,1,   4.6,1,1031.0,1, 94,
060690,99999,19881001,0900,4,FM-12,    ,230,1,N,  5.0,1,99999,9,9,9,      ,9,N,9,   9.2,1,   6.4,1,1032.6,1, 83,
060690,99999,19881001,1200,4,FM-12,    ,250,1,N,  8.0,1,99999,9,9,9,      ,9,N,9,  11.4,1,   6.2,1,1033.1,1, 70,
060690,99999,19881001,1500,4,FM-12,    ,250,1,N,  8.0,1,99999,9,9,9,      ,9,N,9,  11.9,1,   6.4,1,1032.6,1, 69,
060690,99999,19881001,1800,4,FM-12,    ,200,1,N,  6.0,1,99999,9,9,9,      ,9,N,9,   8.7,1,   7.1,1,1033.0,1, 90,
060690,99999,19881001,2100,4,FM-12,    ,180,1,N,  7.0,1,99999,9,9,9,      ,9,N,9,   7.8,1,   7.5,1,1032.9,1, 98,
060690,99999,19881002,0000,4,FM-12,    ,190,1,N,  8.0,1,99999,9,9,9,      ,9,N,9,   7.2,1,   7.0,1,1033.0,1, 99,
060690,99999,19881002,0300,4,FM-12,    ,190,1,N,  8.0,1,99999,9,9,9,      ,9,N,9,   8.0,1,   7.3,1,1032.7,1, 95,
060690,99999,19881002,0600,4,FM-12,    ,180,1,N,  9.0,1,99999,9,9,9,      ,9,N,9,   8.3,1,   6.1,1,1032.2,1, 86,
060690,99999,19881002,0900,4,FM-12,    ,190,1,N, 10.0,1,99999,9,9,9,      ,9,N,9,  11.8,1,   7.4,1,1032.8,1, 74,
060690,99999,19881002,1200,4,FM-12,    ,210,1,N, 11.0,1,99999,9,9,9,      ,9,N,9,  13.1,1,   6.8,1,1032.3,1, 66,
060690,99999,19881002,1500,4,FM-12,    ,190,1,N,  9.0,1,99999,9,9,9,      ,9,N,9,  13.3,1,   7.2,1,1031.0,1, 67,
060690,99999,19881002,1800,4,FM-12,    ,160,1,N,  7.0,1,99999,9,9,9,      ,9,N,9,   8.7,1,   7.7,1,1031.1,1, 93,
060690,99999,19881002,2100,4,FM-12,    ,170,1,N,  6.0,1,99999,9,9,9,      ,9,N,9,   7.4,1,   6.9,1,1031.1,1, 97,
```

C) Hourly/sub-hourly observational data

Figure 3-2: The header of text files downloaded from NOAA/National data center for each weather station

3.1.2. Data preparation

Data preparation is defined as the second step of data mining in the research. In this step, the accuracy and adequacy of the data will be controlled. After selecting the appropriate weather stations, the data will be imported into a dynamic database which has been designed for data mining purposes in a data generator program. By importing daily and hourly time series into the database, the information gathered will be merged together based on the common times. It should be mentioned that, before importing data into the database, the adequacy of data for each station was checked and all weather stations with less than nine years data was excluded from the study.

In this step, several works were performed such as data quality control, designing a dynamic database and consequently, a climatic data generator as well as data standardization which will be discussed respectively in more detail in the following:

3.1.2.1. Data quality control

The raw data, which are obtained from NOAA/NCDC, are quality controlled and the result of quality control is presented by using quality codes after each observation. The concept of codes selected for each element is mentioned in a metadata file and is sent along with the ordered data. For instance, Figure 3-3 shows a part of this metadata that denotes the quality status of wind speed.

```

Q: WIND-OBSERVATION speed quality code

    The code that denotes a quality status of a reported WIND-OBSERVATION speed
    rate.
    Length:1
    Default Value:9
    Table of Values:

    0: Passed gross limits check
    1: Passed all quality control checks
    2: Suspect
    3: Erroneous
    4: Passed gross limits check , data originate from an NCDC data source
    5: Passed all quality control checks, data originate from an NCDC data source
    6: Suspect, data originate from an NCDC data source
    7: Erroneous, data originate from an NCDC data source
    9: Passed gross limits check if element is present

```

Figure 3-3: Part of the information contained in the metadata file which is displayed along with an hourly elements data file of NOAA/NCDC

3.1.2.2. Designing a dynamic database

Although a quality control of the data has already been performed by NOAA/NCDC, the data is not ready yet to operate the analysis that is expected. In fact, dealing with this type of data is not easy because:

1- The raw data which is collected by NOAA/NCDC is presented in an ASCII format and consequently, it is very difficult to get statistical reports and there is a high probability of error in the calculations;

2- Daily and hourly observational data have been reported in two separate files and hence, there is no relationship or any connection between them;

3- It is unclear what percentage of whole data in each year is missing or incomplete, to select an appropriate statistical time period (e.g. all data must be at least 2920 records per year for a temporal resolution of 3 hours, considering eight records per day);

4- The units of measurement are different in hourly and daily observational data (in hourly data, the unit measurement is metric (SI) whereas in daily data files, the US customary measurement system has been used);

5- Analyzing data based on dry/wet periods is not possible because there is no field to show this status; and

6- Separating the data based on days, nights and seasons is complicated even by importing data into a spreadsheet program such as Excel.

Consequently, to solve these problems and to facilitate the calculations and analysis, a database was designed based on the information which is available in the hourly and daily text files. The structure of the designed database contains four tables and several queries. Figure 3-4 shows the relationship between tables in the database.

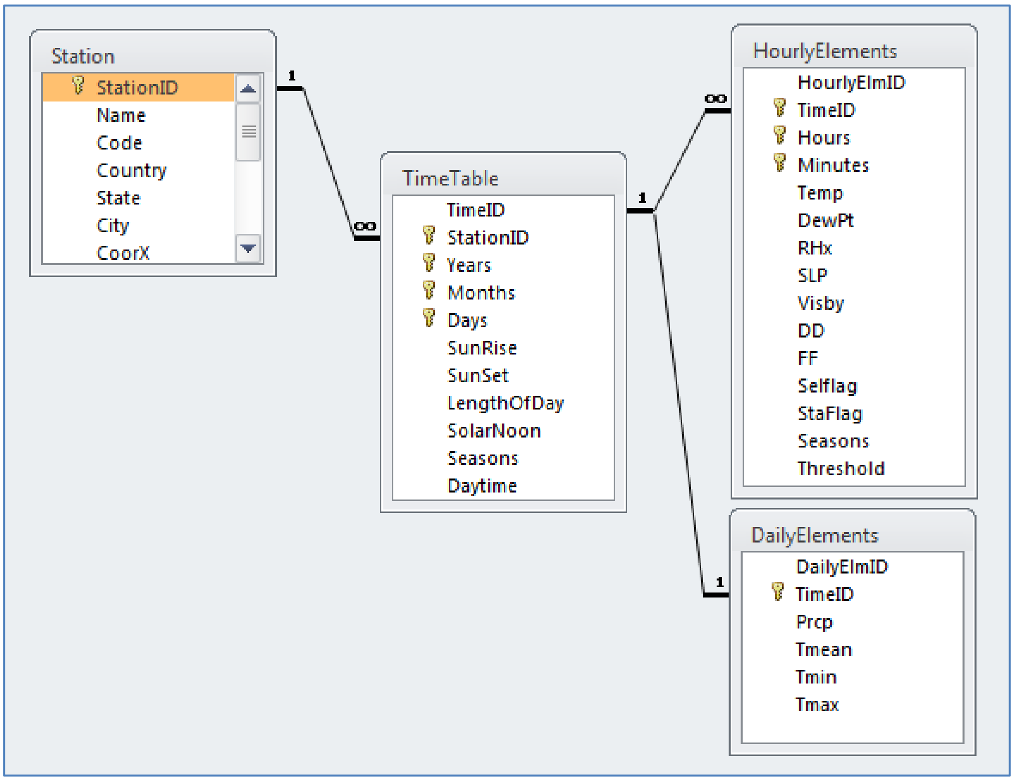


Figure 3-4: The structure of the designed database and the type of relationships between tables

It should be mentioned that, to establish a connection between user and provided database, a program, named Climatic Data Generator, was written in visual basic 2012 language to import hourly and daily observational weather elements, which are available in ASCII formats, to the database. Also by using the program access to the following information was provided: extraction of any desired time series (annual, seasonal and monthly), frequency distribution table of wind velocities in different geographical directions as well as a descriptive statistics of imported weather elements.

3.1.2.3. Data standardization

Almost in all selected weather stations of both test sites, the scales of observational data elements are different even within a single station over time. This is especially the case with stations with a long term records, usually more than ten years, because they have been faced with changing the type of stations (e.g. becoming a synoptic station). For example, at some stations during the first years of observations, the temporal resolution of data was three hours, that means registering eight observations per day. But, the data which has been recorded in recent years is generally hourly, with at least one record per hour or even sub-hourly (e.g. recording each 30 or 15 minutes).To remove the temporal non-homogeneity between data records and enhance a statistical return period for each selected stations, the data was reanalyzed based on the synoptic and intermediate synoptic hours which are: 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 GMT.

Although, using data standardization causes loss of information, but reanalyzing and normalizing of data (standardization) will cause that climatic time series extracted exactly at the same times in all studied stations. Thus, comparing the results, due to the same observations, would be statistically more reasonable and acceptable.

3.1.2.4. Creation of a network of weather stations

To create an appropriate network of weather stations in selected test sites, first of all, a statistical summary of weather elements was calculated for each available weather station. Following, based on data availability for at least eight consecutive years, the appropriate stations with probably sufficient data were selected primarily and weather stations with less than eight years of data were excluded from the investigation.

Data standardization and the estimation of the percentage of missing data were the next step for the decision-making procedure (Figure 3-5) to create a network of weather stations. At this stage, those stations that had at least eight consecutive years with less than 15 percent missing or incomplete data in each year were selected. Finally, by checking the accuracy of data, all usable stations in both selected test sites in Denmark and Switzerland were formed into a network of stations for this study.

It should be mentioned that, in Denmark 95 stations were controlled but only 15 stations were diagnosed suitable for the study, and in Switzerland after controlling 163 stations, a final 54 stations were selected. In Table 3-2, the final selected stations in Denmark are listed. Similarly the appropriate stations in Switzerland are presented in Table 3-3.

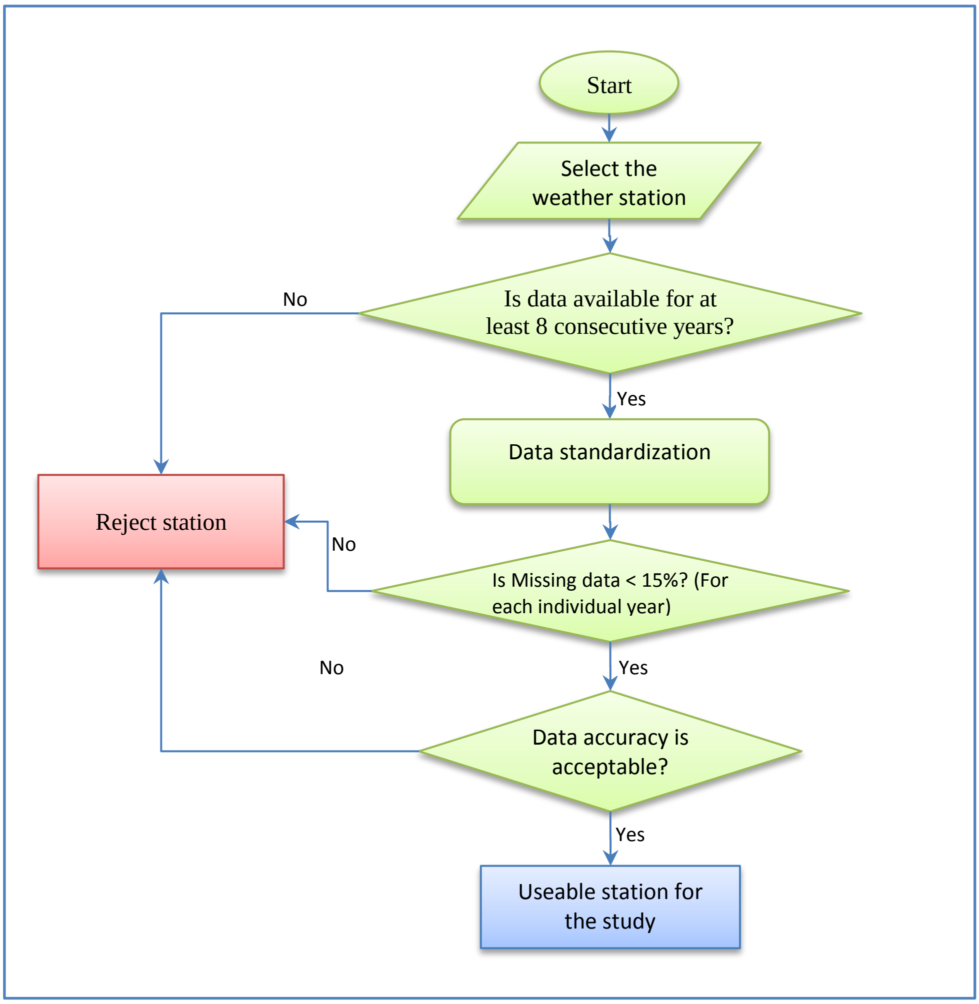


Figure 3-5: The decision-making procedure to select an appropriate station in the study

Given that, the establishment of weather stations varies in both pilot countries and they have been considered independently, thus inevitably, the statistical period of the time series at each selected weather station is different. The length of the statistical periods at the weather stations varies between 9 to 40 years in Denmark (Table 3-2) and 12 to 48 years in Switzerland (Table 3-3).

Table 3-2: Spatial information of selected synoptic weather stations along with the duration of data availability in Denmark

#	STATION NAME	LAT	LON	ELEV (Meter)	Start Year	Periode (Year)
1	AARHUS LUFTHAVN	56.317	10.633	23	1974	40
2	AARHUS SYD	56.083	10.133	55	2003	11
3	ABED	54.833	11.333	9	2002	12
4	BILLUND	55.733	9.167	80	1976	38
5	FLYVESTATION AALBOR	57.1	9.85	13	1976	38
6	FOULUM	56.5	9.567	58	2000	14
7	GEDSER ODDE	54.567	11.967	8	2003	11
8	HOLBAEK	55.733	11.6	13	2002	12
9	KARUP	56.3	9.117	53	1993	21
10	ROSKILDE_TUNE	55.583	12.133	43	1988	26
11	SKAGEN	57.733	10.633	5	1973	41
12	SKRYDSTRUP	55.233	9.267	47	1993	21
13	TESSEBOELLE	55.4	12.15	21	2005	9
14	TYLSTRUP	57.183	9.95	9	2005	9
15	TYSOFTE	55.25	11.333	14	2005	9

Table 3-3: Spatial information of selected synoptic weather stations along with the duration of data availability in Switzerland

#	STATION NAME	LAT	LON	ELEV (Meter)	Periode (Year)	#	STATION NAME	LAT	LON	ELEV (Meter)	Periode (Year)
1	AADORF-TAENIKO	47.48	8.90	536	12	**28**	NAPF	47.00	7.93	1406	30
2	ACQUAROSSA-COMPROVA	46.47	8.93	552	23	**29**	NEUCHATEL	47.00	6.95	487	32
3	ADELBODEN	46.50	7.57	1320	12	**30**	NYON _ CHANGINS	46.40	6.23	430	12
4	AIGLE	46.33	6.92	383	32	**31**	PAYERNE	46.82	6.95	491	48
5	ALTDORF	46.87	8.63	451	34	**32**	PILATUS MTN	46.98	8.25	2110	12
6	BASEL BINNINGEN	47.55	7.58	316	12	**33**	PIOTTA	46.52	8.68	1016	34
7	BERN-ZOLLIKOFE	46.98	7.47	565	12	**34**	PIZ CORVATSCH	46.42	9.82	3299	34
8	BUCHS-SUHR	47.38	8.08	387	12	**35**	PLAFFEIEN-OBERSCHRO	46.75	7.27	1041	23
9	BULLET-LA-FRETAZ	46.83	6.58	1202	12	**36**	POSCHIAVO-ROBBIA	46.35	10.07	1078	35
10	CHASSERAL	47.13	7.07	1599	12	**37**	ROBIEI	46.45	8.52	1898	12
11	CHUR-EMS	46.87	9.53	556	33	**38**	RUENENBERG	47.43	7.88	610	12
12	CIMETTA	46.20	8.80	1648	32	**39**	SAENTIS	47.25	9.35	2500	36
13	DAVOS	46.82	9.85	1590	12	**40**	SAMEDAM	46.53	9.88	1706	33
14	ENGELBERG	46.82	8.42	1035	12	**41**	S BERNARDINO	46.47	9.18	1638	31
15	GENEVE-COINTRIN	46.25	6.13	416	48	**42**	SCHAFFHAUSEN	47.68	8.62	437	12
16	GLARUS	47.03	9.07	515	12	**43**	SCUOL	46.80	10.28	1298	12
17	GRIMSEL-HOSPIZ	46.57	8.33	1980	12	**44**	SION	46.22	7.33	481	48
18	GUETSCH OB ANDERMAT	46.65	8.62	2284	48	**45**	ST. GALLEN	47.43	9.40	791	31
19	GUTTINGEN	47.60	9.28	440	12	**46**	ULRICHEN	46.50	8.32	1345	12
20	INTERLAKEN	46.67	7.87	579	31	**47**	VISP	46.30	7.85	640	12
21	LA CHAUX-DE-FONDS	47.08	6.80	1019	33	**48**	WADENSWIL	47.22	8.68	463	12
22	LE MOLESO	46.55	7.02	1972	12	**49**	WEISSFLUHJOCH	46.83	9.82	2690	12
23	LOCARNO-MAGADINO	46.17	8.88	198	48	**50**	WYNAU	47.25	7.78	416	36
24	LOCARNO-MONTI	46.17	8.78	380	36	**51**	ZERMATT	46.03	7.75	1638	12
25	LUGANO	46.00	8.97	276	36	**52**	ZUERICH-AFFOLTER	47.43	8.52	443	12
26	LUZERN	47.03	8.30	456	12	**53**	ZUERICH-FLUNTER	47.38	8.57	569	36
27	MONTANA	46.30	7.47	1508	34	**54**	ZURICH-KLOTEN	47.48	8.53	432	48

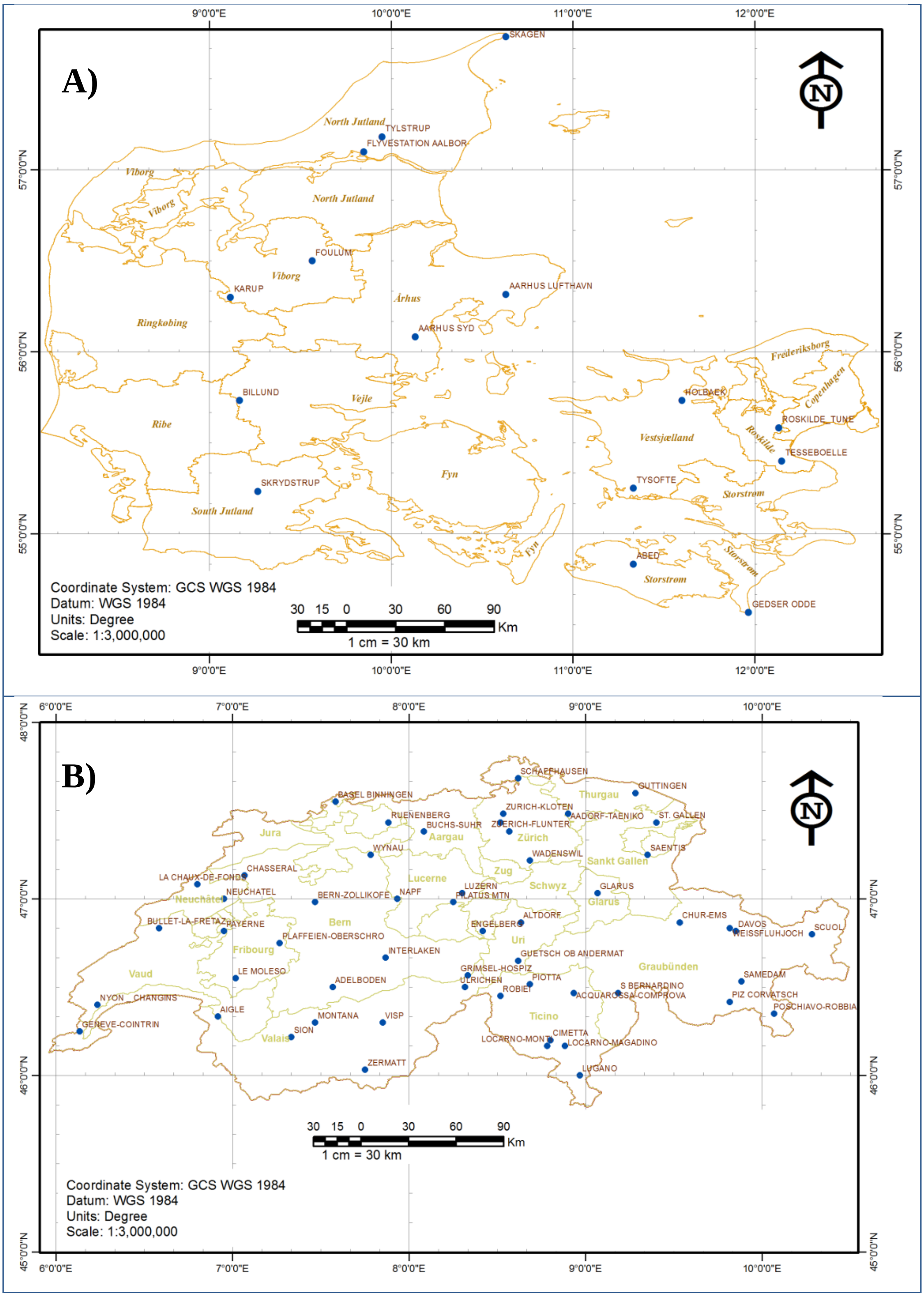


Figure 3-6: Spatial distribution of stations used in this research A) in Denmark B) in Switzerland

3.1.3. Data management

All data collected and downloaded from NOAA/NCDC are daily and hourly/sub-hourly records of weather elements from observational time series. The preparation and standardization of data, which was described in previous sub-chapters, was carried out using these time series. However, before the actual model development can get started, the needed climatic data parameters had to be extracted from the whole dataset.

In this research, a wide range of time series of climatic parameters was examined. For example, for climate change trend analysis, three different climatological data (annual, seasonal, and monthly time series) were used for more than 30 parameters that the most important of which is listed in Table 3-4.

Table 3-4: List of presented parameters for which the different type of time series is extracted

#	Notation	Definition	Unit
1	T_{max}	Maximum Temperature	Degree centigrade (˚C)
2	T_{mean}	Mean Temperature	Degree centigrade (˚C)
3	RH_{mean}	Mean Relative humidity	Dimensionless
4	$DewP_{max}$	Maximum dew point temperature	Degree centigrade (˚C)
5	$DewP_{mean}$	Mean dew point temperature	Degree centigrade (˚C)
6	PN	Number of precipitation	Dimensionless
7	P	Precipitation	millimeter
8	NDT	Number of dry times	Dimensionless
9	D_{mean}	Mean of wind direction	degrees clockwise from true North
10	V_{max}_Gust	Maximum wind speed in all observations	knot
11	V_{max}	Maximum wind speed in standard times	knot
12	V_{mean}	Mean wind speed	knot
13	Vt_{mean}	Mean winds more than threshold (7.0 m/s)	knot
14	NEW	Number of erosive winds	Dimensionless
15	NED	Number of erosive Days	Dimensionless
16	WPD	Wind power density	watts per square meter ($^{w}/_{m^2}$)
17	EWPD	Erosive wind power density	watts per square meter ($^{w}/_{m^2}$)

Since in the study dry or wet soil surface has also been considered then, some of the parameters, especially wind factors, has been investigated in two different approaches which include conventional way (study total observations) and also, study according to wet/dry periods.

In the data management stage, the main focus is on extracting, controlling and reconstructing different types of climatic time series that will be used in the other parts of study (e.g. trend analysis, extreme value analysis, etc.). The data management generally involves the following steps:

1- Modeling wet/dry periods to extract climatic time series of wind parameters based on dry times;
2- Extracting the required climatic data, which include monthly, seasonal and annual time series;
3- Reconstructing the missing data in each time series;
4- Checking outliers and rebuilding them if necessary;
5- Testing the data homogeneity and homogenizing the data if required.

3.1.3.1. Extracting required climatic data

In this research, the different types of climatic time series used were extracted directly from publicly available weather element databases. During the process of data mining, all available weather elements for each station were imported to a dynamic database. To generate and extract all necessary climatic data, a program (Climatic Data Generator) was written using visual.net and SQL language. In the program, the generated climatic time series of each station can be saved in a Comma Separated Values file (.CSV) in order to provide easy transferability to R and Excel.

To extract climatological time series, the maximum or average of required weather elements was calculated for each desired time (month, season or year) based on synoptic times of observations (0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 GMT). These time intervals have been selected to standardize the dataset and enable further analysis.

The method that has been used to generate desired climatic elements is similar in all elements except for the time series of wind direction. In this element the average was calculated like other elements and then, the calculated average was categorized in 36 different directions. The range of each direction was 10 degree and the median of each sector was attributed to the all calculated average directions which involve the range of that sector. For example, when a calculated average direction is greater or equal to 355 and less than five degree, it will be considered as north direction therefore, the value of all average directions which are in this range will be 360 degree.

Figure 3-7 illustrates the structure of the Climatic Data Generator program to extract different types of climatic time series. As is schematically represented, the input data in this program contains just two text files. The first file is daily precipitation and the second file contains other weather elements with higher resolutions (hourly/sub-hourly). In contrast, the output of the program is very flexible and covers a wide range of climatic data that can be extracted according to the user request for different studies.

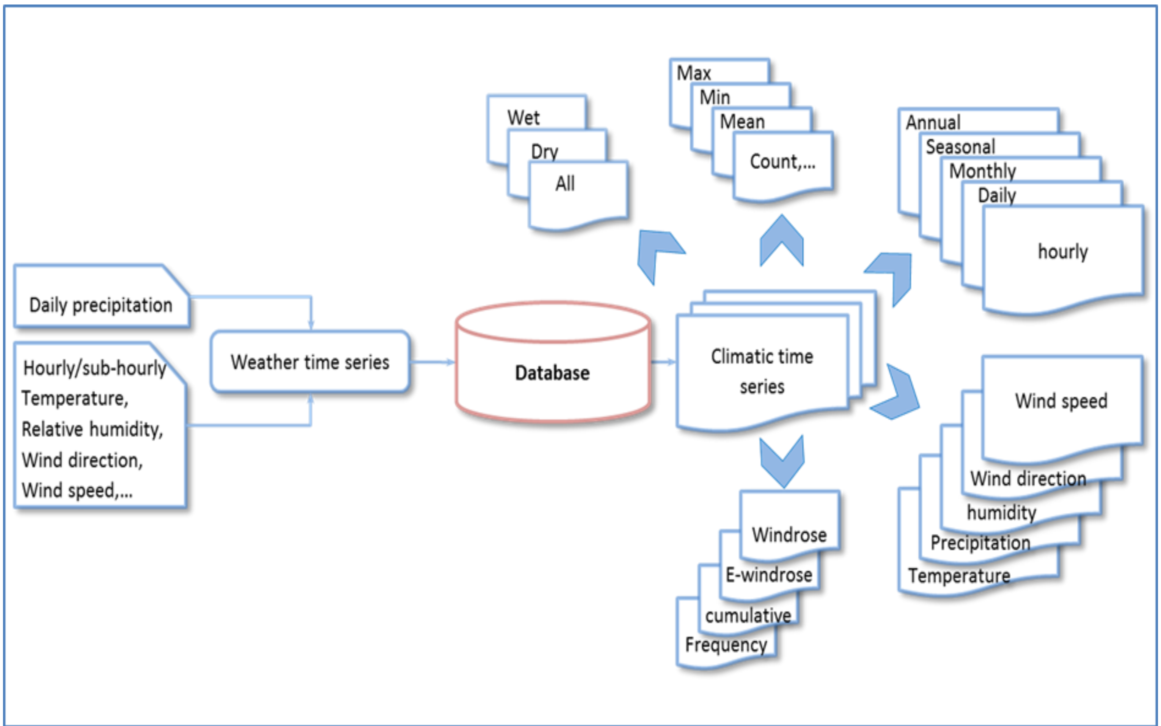


Figure 3-7: The structure of the Climatic Data generator program to extract different types of climatic time series

In Figure 3-8 and Figure 3-9 some dialog forms of designed Climatic Data Generator program to extract climatic time series according to the intended restrictions has been presented.

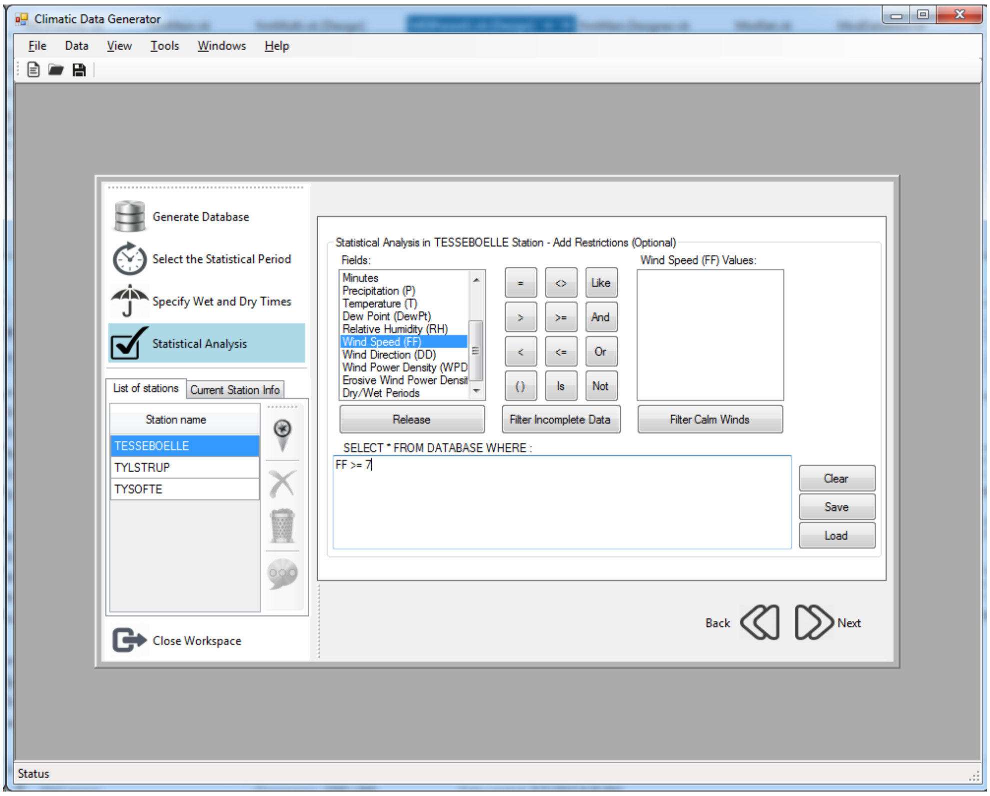


Figure 3-8: A view of designed Climatic Data generator program (Add restrictions dialog form)

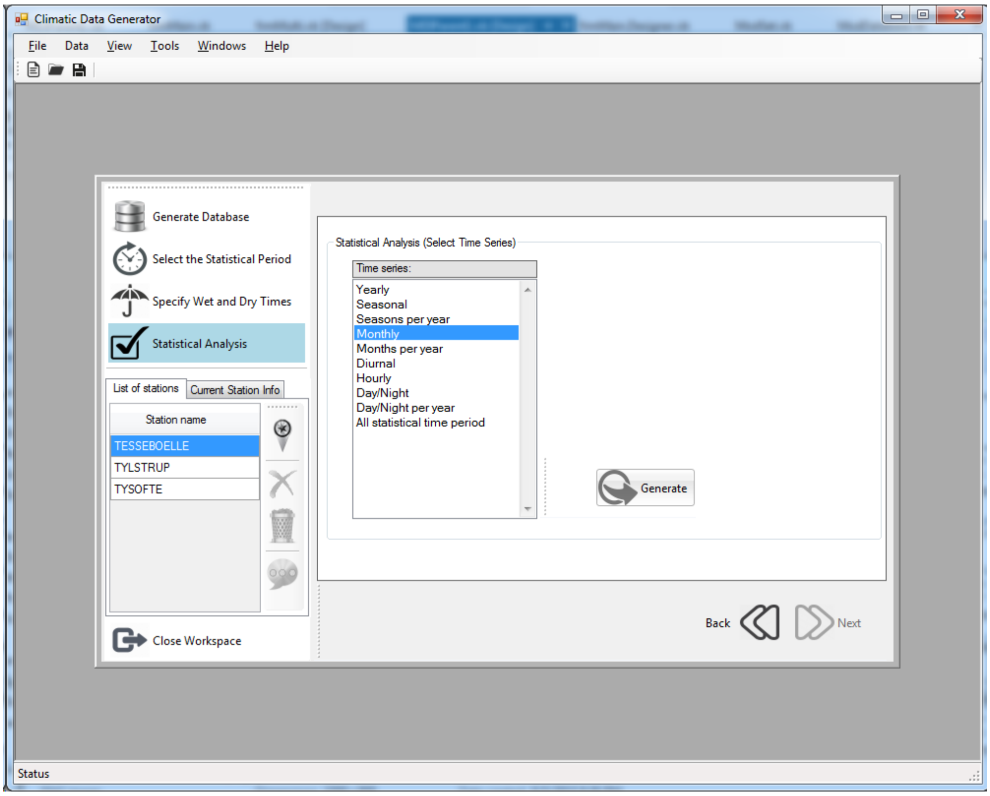


Figure 3-9: A view of designed Climatic Data generator program to extract climatic time series

3.1.3.2. Checking outliers, detecting and removing

In statistics, an outlier is an observational data that seems unusual and very far away from other observed values (Grubbs, 1969). Outliers can simply occur by mechanical faults, instrument error, human error, changes in system behavior or a special error that disrupted the observed phenomenon (Hodge & Austin, 2004). In such cases, the outliers must be either corrected or discarded from the observations before doing any descriptive analysis, modeling as well as predicting (Osborne & Overbay, 2004). It is, therefore, very important to identify them, e.g., by using some tests such as Grubbs or Dixon tests, flag them in the reports (in tables or graphical representations), and finally delete them. An alternative to ignoring them would be to use robust statistics, which are not or less sensitive to outliers, such as using for instance a median value instead of a mean value.

In this research, the classical Grubbs test (Grubbs, 1950) was used to identify if there are outliers present in the time series. If the null hypothesis of this test was rejected, then all suspected outliers were detected by using the modified Z-scores method (Iglewicz & Hoaglin, 1993) in a second step. All detected outliers were then removed from the time series in the database. These outliers were labeled as 'missing values' in the next step of data management.

- ***Grubb's tests***

Grubb's test, also known as the maximum normed residual test, is a statistical test used to detect a single outlier in a univariate dataset that follows an approximately normal distributed population. The test is based on the assumption of normality and it is defined by:

$$G = \frac{\max_{i=1,\dots,N}|Y_i - \bar{Y}|}{s} \qquad (3\text{-}1)$$

Where: $\bar{Y}$ and S denoting the sample mean and standard deviation respectively.

For two-sided test, the null (H_0) and alternative (H_a) hypothesis are given by:

H_0: there are no outliers in the dataset

H_a: there is at least one outlier in the dataset

An approximation of the critical value for a given significant level α (typically 5%) for rejecting the null hypothesis is given by:

$$G_c(n, \alpha) \approx \frac{(n-1)t_{n-2,\alpha/k}}{\sqrt{n(n-2+t^2_{n-2,\alpha/k})}} \quad (3\text{-}2)$$

Where $t_{n-2,\alpha/k}$ denoting the upper critical value of the t student distribution with n-2 degree of freedom and a significant level of α/k, where k is equal to n for one-sided tests and 2n for the two-sided test.

The classical Grubb's test can only detect one outlier at a time and it has been used in this study only to identify the presence of an outlier in the dataset. Consequently, in the case of rejecting the null hypothesis of the Grubb's test, the modified z-scores method is used to detect and remove outliers in the dataset.

- ***Modified z-scores***

Z-scores, also called Z-values, standard scores or normal scores, are a dimensionless quantity which indicates the number of standard deviations that an observation is above the mean. This score is obtained by subtracting the mean of the population from an individual raw score and then dividing the difference by the standard deviation of the population. It can be represented mathematically as:

$$Z_i = \frac{x_i - \mu}{\sigma} \quad (i=1,2,\ldots,n) \quad (3\text{-}3)$$

Where:

μ is the mean of the population;

σ is the standard deviation of the population.

This score corresponds to the standardized sample and can be helpful to identify potential outliers. Iglewicz & Hoaglin, (1993) recommend using the modified z-score, in order to improve outlier detection. The formula is:

$$M_i = \frac{0.6745(x_i - m)}{MAD} \quad (MAD \neq 0 \quad , i = 1,2,3,\ldots,n) \quad (3\text{-}4)$$

Where, the MAD is the Median Absolut Deviation and m denoting the median.

In this recommended method, modified z-scores with an absolute value of greater than 3.5 would be considered as potential outliers. In this study, to identify potential outliers, if the MAD value was greater than zero, the modified z-scores method was used. Otherwise, the z-scores method was applied to identify outliers. The algorithm of detection of potential outliers was written in Excel by using VBA and it was implemented before reconstruction of missing data and testing data homogeneity.

3.1.3.3. Reconstruction of missing data

The appearance of missing values in a climatic time series means that, no observation is registered for the element within a desired timeframe, which can be a day, month, season or even year. The reasons for missing data are manifold. They can include mechanical faults, stop registering data because of cessation of activities or stop reporting observations to the data processing authorities due to policy changes.

As previously pointed out, only consecutive time periods with less than 15 percent missing or incomplete data in each year have been selected. In order to fill the remaining gaps of data, missing values were computed by using the longtime average of the same periods. For instance, when missing data occur in January of a given year, the missing data have been replaced with the average of desired element in January of the other years.

Due to the large number of weather stations as well as great variety of examined climatic time series, a macro in Excel was written using Visual Basic for Application (VBA) to verify the existence of missing data and to reconstruct them. The results of this process were directly added to the climatic time series extracted by climatic data generator.

3.1.3.4. Breakpoint detection and homogeneity adjustments

There are many factors that could lead to inhomogeneity in climatological and meteorological time series. Some of the most important non-climatic factors that can lead to inhomogeneity are: changes or error incident in instruments, station or instrument relocation, change in observation methods or observation times, as well as the effects of urbanization (Cao & Yan, 2012). Thus, using original climatic time series without considering their homogeneity might probably lead to uncertain, inconsistent or even wrong conclusions, especially in trend analysis and climate change investigations.

In homogenous climate time series, the variations between data is just based on weather or climate variations (Cao & Yan, 2012), but when the data is non-homogenous other factors are the cause. Therefore, it is recommended that, "besides routine quality control, the homogeneity of data should be evaluated before performing studies of climatic changes" (Tuomenvirta, 2002).

Unfortunately, many studies in climate change are still using original time series without concern about the homogenization, so, this neglect produces large uncertainty in the results of investigations (Cao & Yan, 2012). As an example, in Figure 3-10, it is quite clear that, by using original data, the trend of monthly wind speeds is negative, but after detecting breakpoints and data adjustment, a slight positive trend can be seen.

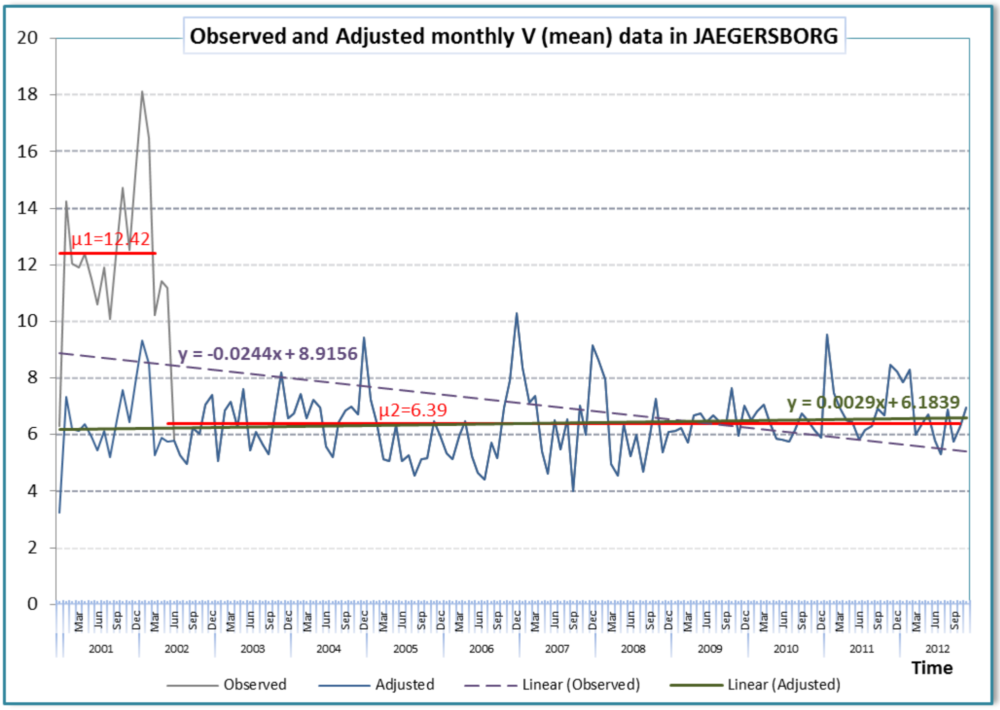


Figure 3-10: Example of data series adjustment because of data inhomogeneity. Shown are monthly averages of wind speeds in JAEGERSBORG.

To test the homogeneity of time series, the Standard Normal Homogeneity Test (Alexandersson's SNHT test), using XLSTAT time series tool in Excel environment, was used. This test was developed by Alexandersson (1986) at first, to detect a change in a series of rainfall data, but it is now widely used for the time series of different climate elements.

After detecting a breakpoint by applying the SNHT test, the average of time series before and after the detected breakpoint was calculated. The dataset was then adjusted by using the following method:

$$A_i^b = \begin{cases} O_i^b \times \frac{\mu^a}{\mu^b} & if\ L^b < L^a \\ O_i^b & \end{cases} \quad , \quad A_i^a = \begin{cases} O_i^a \times \frac{\mu^b}{\mu^a} & if\ L^a < L^b \\ O_i^a & \end{cases} \qquad (5)$$

Where, a and b refer to time series located after or before detected breakpoint respectively; A, O, L and μ are adjusted data, original data, length of time series, and average of data respectively, before or after detected breakpoint.

After adjusting data and removing detected breakpoint, the SNHT was repeated again to detect further breakpoints, if they exist. This repetitive process was applied until all breakpoints were detected and adjusted.

3.2. Modeling wet and dry periods

In humid and sub-humid areas the soil surface is moist for a long period of time thus, because of its direct impact on the rate of wind erosion threshold velocity, the amount of soil erosion by wind is negligible or actually zero during wet periods. However it needs to be emphasized that the estimation of wind erosion risk in humid areas should include a differentiation of dry and wet times. If this is not taken into account, the estimation of wind erosion risk would most probably lead to an overestimation.

As mentioned before, one of the objectives of this research is modeling wet and dry periods by using appropriate weather elements such as precipitation, relative humidity, temperature as well as dew point temperature. The proposed model in this study is based on some easy to access weather elements and physical facts between these elements and soil surface moisture.

3.2.1. Structure of model

A few investigations have been carried out into wind erosion studies based on wind observations in dry periods. One of the first studies in this field was performed by Hagen (2007). He compare ratios of erosive wind energies on dry-days and all-days in the Western United States and came to the conclusion that the first hour of precipitation along with the 23 succeeding hours should be placed in wet day distribution classes. The problem involved in this approach is that precipitation records of standard meteorological weather stations are usually reported on a daily basis, so it is not clear when the first hour of precipitation has occurred. Given that, surface soil moisture will remain in the soil for a few hours after each precipitation, it was attempted to design a model to separate wet and dry periods based on daily precipitation records and some other hourly or sub-hourly weather elements (relative humidity, temperature, dew point temperature) as well as spatial information (latitude and longitude) and physical reality (e.g., altitude) of the weather stations in the study area. As indicated in Figure 3-11 briefly, four stages can be considered in the proposed model:

1- Estimating initial time of precipitation in days with recorded rainfall;
2- Calculating the duration of rainfall effect on the soil surface;
3- Estimating solid state times (e.g. snow);
4- Evaluating the dew formation time prediction.

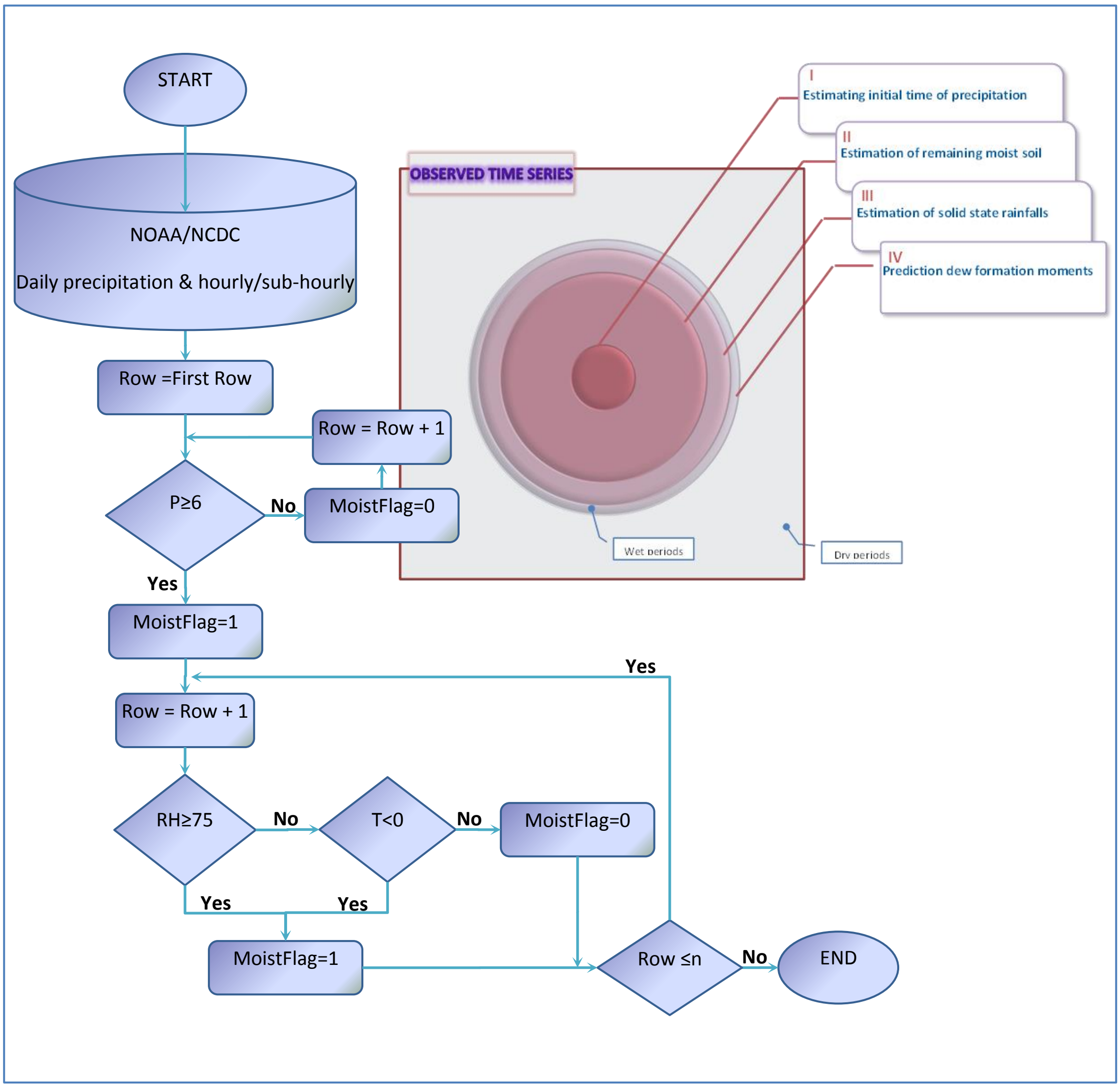


Figure 3-11: Flowchart and the conceptual plan of Wet/dry time separation method (P: Precipitation, RH: Relative Humidity, T: Temperature, MoistFlag: a Boolean flag defined to separate wet and dry times. in this flag 0 means dry time and the 1 refer to wet time, n: total number of records)

- ***Estimating initial time of precipitation***

The first step of the proposed model is estimating initial time of precipitation in days with daily precipitation more than 6 mm. This amount of daily rainfall is obtained based on model calibration results (the highest estimated accuracy and the lowest RMSE among all scenarios, Table 3-8), which has been discussed in the "Measuring the model accuracy" (page 61).

To find out the first hours of rainfall in each selected days, the amount of relative humidity was examined and when its value was greater than 95 percent (based on model calibration, see page 61) the corresponding time was considered as the first hours of precipitation. Hence, the beginning times of precipitation can be formulated by using the following sign function:

$$S_i = \begin{cases} 1 & P_i \geq 6 \, {}^{mm}/_{day} \;, \quad RH_i \geq 95 \\ 0 & RH_i < 95 \end{cases} \;, i = 1,2,3, \dots, n \tag{3-6}$$

Where:

S_i: is a Boolean or logical data type that its value can be zero or one, according to the amount of relative humidity in i'th time. The zero means that, in the desired time, the soil surface has been dry and the concept of number one is having wet soil in the corresponding time. P_i and RH_i are Precipitation and Relative Humidity in i'th time, respectively.

- ***Calculating the duration of rainfall effect on the soil surface***

Staying topsoil wet after each precipitation is related to many environmental and meteorological parameters, which include the soil texture, infiltration rate of the soil, ambient temperature, the amount of vegetation cover, exposure of soil to the wind as well as the amount and duration of sunshine.

This part of the model was designed with the assumption that, the soil moisture is in equilibrium with the relative humidity in the atmosphere. According to recent investigations by Ravi, Zobeck, & Over (2006), the threshold friction velocity increases when the air humidity is more than 65 percent. This increase of the threshold friction velocity occurs, because the particles of water vapor will condense into liquid bridges between the soil grains. Accordingly, the lower limit of relative humidity, which defines the duration of rainfall effect on the soil surface, was initially selected at 65 percent. However, after calibrating the model and measuring the model accuracy in different scenarios, with the weather and soil moisture data from our own installed weather station, the final value of this parameter was selected at 85 percent based on the highest estimated accuracy and the lowest RMSE (Root Mean Squared Error) among all scenarios.

Based on the direct relationship between relative humidity and soil surface moisture it was assumed that the soil surface is still moist, if the percent of relative humidity was higher or equal to 85 percent. Upon reduction of relative humidity below 85 percent, it is inferred that the wet phase of the soil has ended and from there onwards no influence on wind erosion could be expected anymore. The decision matrix for the implementation of this stage of proposed model can be formulated as follows:

$$S_i = \begin{cases} 1 & (S_i < S_{i-1} \quad , \quad RH_i \geq 85) \\ 0 & (S_i < S_{i-1} \quad , \quad RH_i < 85) \end{cases} \qquad i = 1,2,3,\dots,n \qquad (3\text{-}7)$$

- ***Estimating solid state times***

The solid state times of precipitation refer to the times, during which snowfall can be assumed. This type of precipitation provides a cover on the soil surface to protect it against the wind erosion. The decision matrix to estimate solid state times is defined as follow:

$$S_i = \begin{cases} 1 & (S_i < S_{i-1} \quad , \quad T_i < 0) \\ 0 & (S_i < S_{i-1} \quad , \quad T_i > 0) \end{cases} \qquad i = 1,2,3,\dots,n \qquad (3\text{-}8)$$

Where:

T_i : Temperature in i'th time.

As describe in the decision matrix above, this function is only applied for times which follow immediately after a wet period. If the observed temperature was less than zero during this time, then days with snow cover would be added to the wet period. Assuming that, the snow cover melts relatively quickly after temperature has increased above zero degrees again. And thus, the protective effect of snow ends.

- ***Evaluating the dew formation times prediction***

Another weather phenomenon, which increases the soil moisture content, is dew formation. Dew formation generally occurs at nightfall, when the humidity is at saturation level (RH = 100%). Therefore, it was important to include both factors, dew point and day and night separation, into the model. To achieve this objective, the exact time of sunrise and sunset was computed for each day by using astronomical relations and then, the dew times were estimated during night periods based on saturated air humidity. The sign function of this part of proposed model can be formulated as follow:

$$S_i = \begin{cases} 1 & (RH_i = 100, \quad DL_i = 0) \\ 0 & (RH_i < 100, \quad DL_i = 0) \\ 0 & \qquad\qquad (DL_i = 1) \end{cases} \quad , i = 1, 2,3, \dots , n \tag{3-9}$$

Where;

DL_i: A sign function which indicates that the desired time has been located during the day or night. As already mentioned, this indicator function is defined based on sunrise and sunset calculation that can be given by:

$$DL_i = \begin{cases} 1 & (S_i \geq S_r \quad , \quad S_i \leq S_s) \\ \\ 0 & (S_i \leq S_r \quad , \quad S_i \geq S_s) \end{cases} \quad , i = 1, 2, \dots , n \tag{3-10}$$

Where:

S_r And S_s are sunrise and sunset respectively and can be calculated by:

$$\omega_s = arccos[-tan(\varphi)tan(\delta)] \tag{3-11}$$

Where:

ω_s: The hour angle at either sunrise or sunset;

φ: The latitude of the location on the earth;

δ: The solar declination that can be calculated in radians by following equation:

$$\delta = 23.45 \frac{\pi}{180} \left(2\pi \left(\frac{284+J}{365} \right) \right) \tag{3-12}$$

Where:

J: The calendar yearly day which starts from 1 to 366.

It is worth mentioning that, the range of solar declination is from 0.409 at summer solstice to -0.409 at winter solstice in radians.

Since the earth rotates at an angular velocity of $15°/hour$ therefore, $\omega_s/15°$ gives the interval of time before and after local solar noon that sunrise or sunset will occur. So according to this fact, the sunrise (S_r) and sunset (S_s) can be calculated respectively by the following equations:

$$S_r = 12 - \frac{1}{15^\circ}\omega_s + \frac{TC}{60} \qquad (3\text{-}13)$$

$$S_s = 12 + \frac{1}{15^\circ}\omega_s + \frac{TC}{60} \qquad (3\text{-}14)$$

Where:

TC: is the time correction factor, in minutes, which takes into account the variation of Local Solar Time (LST) in a given time zone, due to the longitude variations within the time zone, and also Equation of Time (ET). This factor can be computed as follow:

$$TC = 4(L - LSTM) + ET \qquad (3\text{-}15)$$

Where:

L: longitude;

LSTM: Local Standard Time Meridian;

ET: Equation of Time in minute.

Also, the coefficient of 4 minutes comes from this fact that the Earth rotates 1° every 4 minutes.

$$LSTM = \frac{360^\circ}{24} + \Delta T_{GMT} \qquad (3\text{-}16)$$

Where:

ΔT_{GMT}: is the difference of the Local Time (LT) from Greenwich Mean Time (GMT) in hours.

Finally, the Equation of Time (ET) can be calculated by the following formula in minute.

$$ET = 9.87\sin(2b) - 7.53\cos(b) - 1.5\sin(b) \qquad (3\text{-}17)$$

$$b = \frac{360}{365}(j - 81) \qquad (3\text{-}18)$$

Where:

J: is the number of days since the start of the year. So, its range is [1-366].

Although, the probability of dew formation occurrence is very low in many areas, estimation of this phenomenon causes the proposed model to be more accurate and the times which the topsoil is protected by this phenomenon can also be considered.

3.2.2. Model Calibration

Model calibration is the process of adjusting and modifying the input parameters to obtain the best estimate of the model and match it better to an observed set of data (Woody, 2006). In order to obtain a high quality dataset for calibration of the proposed model, a weather station was temporarily installed on a farm near Foulum in Denmark (latitude $56° \ 30' \ 06'' \ N$ and longitude $9° \ 35' \ 00'' \ E$). The recorded weather elements are summarized in table 3-5. The dataset covers the period from 3/10/2012 to 30/09/2013 with a temporal resolution of 30 minutes (in total 17520 records). The used weather station was a potable HOBO® Weather Station Data Logger - H21-001 with a 10HS soil moisture smart sensor (model: S-SMD-M005).

Table 3-5: Observational weather elements in the installed weather station.

#	Weather element	Unit
1	Temperature	Degree centigrade (°C)
2	Relative humidity	Dimensionless
3	Wind speed	Meter per second
4	Gust speed	Meter per second
5	Wind direction	Degrees clockwise from true North
6	Water Content	m^3/m^3
7	Rain	Millimeter
8	Solar Radiation	W/m^2
9	Air Pressure	Millibar

By using this one year dataset, especially the rainfall and soil moisture data, the initial selection of threshold criteria for start of rainfall (95% relative humidity) and end of moisture influence on wind erosion (65% relative humidity) could be evaluated.

The soil water content is a quantity of water contained in the soil which is expressed as a ratio of water volume to the soil volume and can theoretically range from zero (completely dry) to saturation, when all pores are filled with water. In reality, this range is much less for natural soils (Dingman, 2002). Four specific water content levels can be distinguished (Table 3-6).

Table 3-6: Specifications and characteristics of standard water contents

Stage name	Suction pressure (J/kg or kPa)	Water content (vol/vol)	Conditions
Saturated water content	0	0.2–0.5	Fully saturated soil, equivalent to effective porosity
Field capacity	-33	0.1–0.35	Amount of soil moisture 2–3 days after a precipitation or irrigation
Permanent wilting point	-1500	0.01–0.25	Minimum soil moisture at which a plant wilts
Residual water content	-∞	0.001–0.1	Remaining water in soil at high tension

Source: (Dingman, 2002; Saxton, Rawls, Romberger, & Papendick, 1986)

During times with saturated as well as field capacity conditions, it can be expected that the presence of water in the soil will lead to higher wind erosion thresholds and consequently, to reduced wind erosion. The water content in the soil in saturated condition can vary between 0.2 and 0.5 m^3/m^3 (Table 3-6) depending on the texture and soil type. However, to be able to determine in the model whether at a given time the soil surface has been truly wet or at least at field capacity, it was assumed that the soil surface is wet when the water content of the soil is greater than or equal to 0.3 m^3/m^3.

To evaluate if the selected threshold values are adequate to separate wet from dry periods, the proposed model was run with 392 different parameter combinations for daily precipitation and relative humidity. The values for relative humidity ranged from 65 to 95 percent with 5 percent steps sizes (seven different cases) and the values for precipitation ranged from one to nine millimeters of daily rainfall with step size of one millimeter (eight different cases). It should be mentioned that, the values for relative humidity was adjusted in two different parts of model structure with 5 percent step size (Figure 3-11).

To implement this model and extracting estimated data in all 392 scenarios, a program in visual basic 2012 was written and the results of observed and estimated data was stored in a *.CSV file format to compare and measure the model accuracy.

3.2.3. Measuring the model accuracy

Models actually are an attempt to describe data. Ideally, this description of data should be accurate and reliable, thus, allowing to make predictions on future development of the parameters. A model is accurate when its predictions are close to the measured data.

In total, 17520 data points were recorded for the different parameters over the one year period and have been used to calibrate the proposed model. Based on the described approach (relative humidity > 65% and rainfall > 1mm), 10875 records (62.1%) were selected as dry conditions and consequently, 6645 records (37.9%) were categorized as wet. Table 3-7 presents a random selection of the results based on the different parameter ranges for relative humidity and rainfall. The specified parameters of each scenario combination are described in the column named ‘Model Status’. The first value is the amount of precipitation (e.g. P3 = 3 mm rainfall), the second one is the relative humidity for estimating starting time of rainfall (e.g. RHp65 = 65% relative humidity), and the third one is the relative humidity to estimate the stopping time of rainfall. The columns ‘overlap’ and ‘inaccurate’ indicate, if the measured values from the climate station dataset correspond to the predicted values of the model. Obviously, the more overlap the better is the model accuracy.

In order to be able to see which model parametrization shows best results, some statistical parameters such as Mean Squared Error (MSE), Root Mean Squared Error (RMSE), coefficient of determination (R^2) as well as the percentage of model accuracy, have been calculated for all 392 different scenarios. The results are shown in Table 3-8. The structure of the table is the same as in table 3-7, with the first row labelling the scenario number and the second row specifying the scenario parameter combinations.

Table 3-7: The results of specifying wet and dry times in some scenarios (note: the results of all scenarios are presented in the digital appendix of the thesis)

#	Model Status	Records	Dry			Wet		
			Estimated	Overlap	Inaccurate	Estimated	Overlap	Inaccurate
1	P1_RHp65_RH65	17520	6802	5830	972	10718	5673	5045
2	P1_RHp65_RH70	17520	7127	6109	1018	10393	5627	4766
3	P2_RHp65_RH80	17520	10188	7655	2533	7332	4112	3220
4	P2_RHp65_RH85	17520	10930	7951	2979	6590	3666	2924
5	P3_RHp70_RH70	17520	8057	6856	1201	9463	5444	4019
6	P3_RHp70_RH75	17520	9114	7719	1395	8406	5250	3156
7	P4_RHp70_RH70	17520	8559	7284	1275	8961	5370	3591
8	P4_RHp70_RH75	17520	9480	8050	1430	8040	5215	2825
9	P5_RHp70_RH70	17520	8818	7428	1390	8702	5255	3447
10	P5_RHp70_RH75	17520	9732	8188	1544	7788	5101	2687
11	P6_RHp70_RH65	17520	8680	7451	1229	8840	5416	3424
12	P6_RHp95_RH65	17520	9130	[illegible]	1408	8390	5237	3153
381	P6_RHp95_RH70	17520	[illegible]	8018	[illegible]	[illegible]	[illegible]	[illegible]
382	P6_RHp95_RH75	17520	10516	8778	1738	7004	4907	2097
383	P6_RHp95_RH80	17520	12998	9416	3582	4522	3063	1459
384	P6_RHp65_RH95	17520	15461	9995	5466	2059	1179	880
385	P7_RHp95_RH70	17520	9714	8147	1567	7806	5078	2728
386	P7_RHp95_RH75	17520	10658	8858	1800	6862	4845	2017
387	P7_RHp95_RH80	17520	14069	9566	4503	3451	2142	1309
388	P7_RHp75_RH85	17520	14024	9383	4641	3496	2004	1492
389	P7_RHp80_RH85	17520	14080	9430	4650	3440	1995	1445
390	P7_RHp65_RH95	17520	15732	10058	5674	1788	971	817
391	P8_RHp95_RH80	17520	14404	9654	4750	3116	1895	1221
392	P8_RHp95_RH85	17520	14772	9766	5006	2748	1639	1109

Table 3-8: Selecting the best model status based on accuracy and reliability (note: the results of all scenarios are presented in the digital appendix of the thesis)

#	Model Status	Accuracy			MSE	RMSE	R.squared	R.Pearson
		Wet	Dry	Total				
1	P1_RHp65_RH65	85.37	53.61	65.66	0.34	0.59	0.15	0.39
2	P1_RHp65_RH70	84.68	56.17	66.99	0.33	0.57	0.16	0.40
3	P2_RHp65_RH80	61.88	70.39	67.16	0.33	0.57	0.10	0.32
4	P2_RHp65_RH85	55.17	73.11	66.31	0.34	0.58	0.08	0.28
5	P3_RHp70_RH70	81.93	63.04	70.21	0.30	0.55	0.19	0.44
6	P3_RHp70_RH75	79.01	70.98	74.02	0.26	0.51	0.24	0.49
7	P4_RHp70_RH70	80.81	66.98	72.23	0.28	0.53	0.22	0.46
8	P4_RHp70_RH75	78.48	74.02	75.71	0.24	0.49	0.26	0.51
9	P5_RHp70_RH70	79.08	68.30	72.39	0.28	0.53	0.21	0.46
10	P5_RHp70_RH75	76.76	75.29	75.85	0.24	0.49	0.26	0.51
11	P6_RHp70_RH65	81.50	68.51	73.44	0.27	0.52	0.24	0.49
12	[illegible]	[illegible]	71.01	[illegible]	0.26	0.51	[illegible]	0.48
381	P6_RHp95_RH70	76.49	73.73	74.78	0.25	0.50	0.24	0.49
382	P6_RHp95_RH75	73.84	80.72	78.11	0.22	0.47	0.29	0.54
383	P6_RHp95_RH80	46.09	86.58	71.23	0.29	0.54	0.13	0.36
384	P6_RHp65_RH95	17.74	91.91	63.78	0.36	0.60	0.02	0.15
385	P7_RHp95_RH70	76.42	74.91	75.49	0.25	0.50	0.25	0.50
386	P7_RHp95_RH75	72.91	80.45	78.01	0.22	0.47	0.29	0.54
387	P7_RHp95_RH80	32.23	87.96	66.83	0.33	0.58	0.06	0.25
388	P7_RHp75_RH85	30.16	86.28	64.99	0.35	0.59	0.04	0.20
389	P7_RHp80_RH85	30.02	86.71	65.21	0.35	0.59	0.04	0.20
390	P7_RHp65_RH95	14.61	92.49	62.95	0.37	0.61	0.01	0.11
391	P8_RHp95_RH80	28.52	88.77	65.92	0.34	0.58	0.05	0.22
392	P8_RHp95_RH85	24.67	89.80	65.10	0.35	0.59	0.04	0.19

According to the statistical results from the comparison of observed and estimated accuracy values (table 3-8), the best parameter combination to separate wet and dry periods is the following (row number 382):

- Initial definition as wet days by precipitation per day (wet period): days with more than or equal to six millimeters of rainfall
- Estimation of exact starting time of rainfall: relative humidity more than 95 %
- Estimation of duration of rainfall effect on soil surface (increased threshold velocity): relative humidity more than or equal to 75 %.

The best parameter selection shows a total accuracy of 78.1% for the separation between wet and dry periods. In comparison, the total accuracy with the initial assumptions is only 65.7 %. More important for wind erosion research than the total accuracy, is the accuracy for dry-times, which is around 81% in the best scenario and 53.6% in the initial assumption. Obviously, the calculated accuracy of the model depends largely on the accuracy of the registered time series from the weather station. But, it should be mentioned that the accuracy of the model could perhaps be further improved, if a different threshold value for the definition of soil saturation (higher or equal to 0.3 m^3/m^3) would be used. As mentioned above, this soil moisture threshold value was selected based on the assumption that the soil surface is definitely wet, and the soil is nearly water saturated. So, by running the model with this threshold, certain periods of time with slightly lower water contents than saturation are excluded, although these water levels could still be high enough to reduce wind erosion on the surface.

With this explanation can be concluded that in many observation times which seems, compare to the selected real water content level, are identified incorrectly wet also the soil is in fact wet but its wetness is less than saturated water content level. Since, the accuracy of model to specify wet and dry periods would be even more than what has been estimated here (78% in total).

3.3. Wind pattern studies

In order to assess the wind pattern in Denmark and Switzerland, several methods were used. First of all, in accordance with the conventional way in these fields, the wind rose of each station was plotted and the frequency distribution of all observed winds was calculated for each station. By spatially distributing the plotted wind roses on maps of Denmark and Switzerland, a general view of the wind pattern in both countries is presented.

Secondly, by introducing a special type of wind rose, which is named effective-wind rose (E-wind rose), only the pattern of erosive winds were examined. As it was done for the wind rose, a spatially distributed map for both countries was prepared.

A comparison of wind patterns obtained by the conventional way (all wind data analysis regardless of wet or dry times of soil surface) and for the dry-times (based on proposed dry/wet model) was one of the main reasons for carrying out this part of research. In fact, it is very important to know for the later part of this study, if the wind pattern during dry periods is significantly different from the annual one.

To better understand the difference between all-times and dry-times, statistical tests like t-test and Wilcoxon test were performed and their results will be discussed in the result chapter.

3.3.1. Wind rose (wind pattern indicator)

Wind rose is one of the most practical diagrams, which has been used to display how wind speed and its direction are typically distributed at a particular location and to describe the wind pattern in the region. This graphical model is a conventional way to summarize the information about wind and gives the frequency of winds with higher velocities than one knot in different directions. In other words, a wind rose is the frequency distribution of wind speed classes (generally based on the Beaufort scale) in different directions.

The wind rose has many useful applications, for instance, determining the prevailing wind direction in a study area. This is very important in wind erosion studies, especially in the movement of sand dunes, design of wind breaks, finger-printing of wind transported sediments and so on. Figure 3-12 illustrates a wind rose with the introduction of its constituent parts.

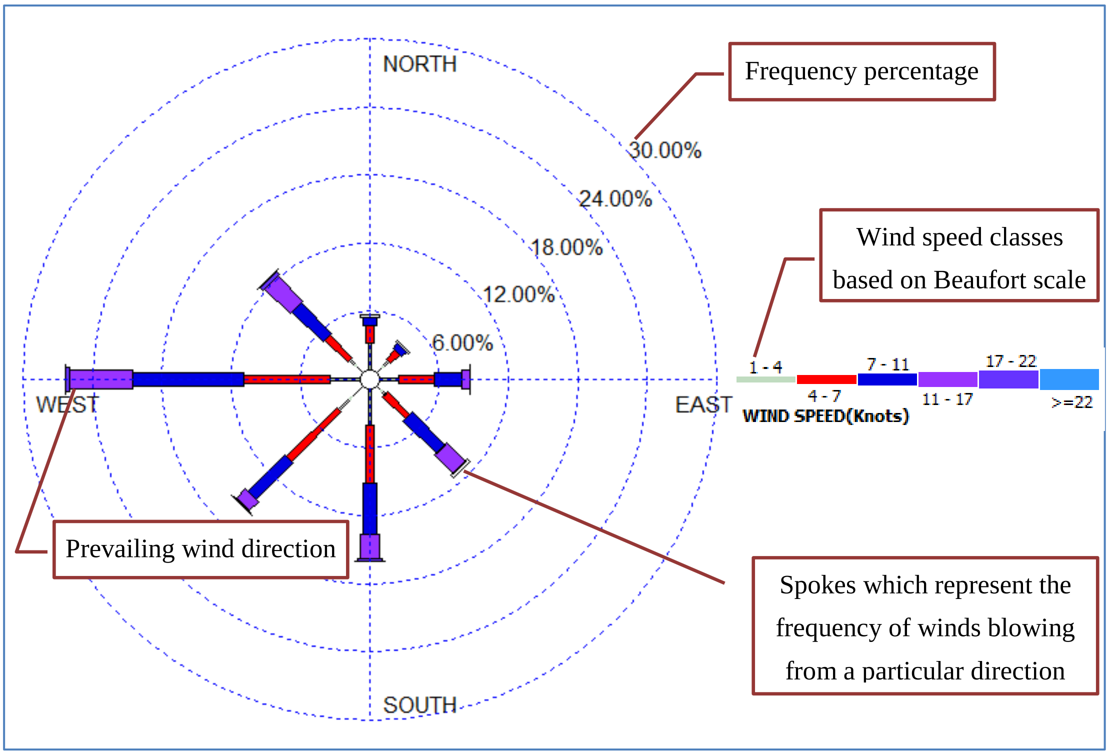


Figure 3-12: An exemplary annual wind rose plot along with the introduction of its constituent parts

3.3.2. E-windrose (erosive wind pattern indicator)

Although a wind rose is practical in many fields of research and helps to identify wind conditions in a particular location, it is not good enough for wind erosivity studies. To achieve this goal, another diagram was defined which is named E-wind rose or effective wind rose. This diagram creates a relationship between the windiness in a desired location in relation to the soil surface conditions. An E-wind rose, instead of presenting the frequency of all winds exceeding one knot, only the winds with velocities higher than the threshold velocity will be considered. Therefore, winds with speeds less than the threshold velocity are defined as non-effective winds in this diagram.

It should be noted that, the purpose of this thesis was not to investigate the relationship between soil surface conditions and windiness of each location. Hence, E-wind rose was used only to highlight the pattern of erosive winds over Denmark and Switzerland with the assumption that all soil types have the same sensitivity to the wind erosion and consequently the threshold friction velocity was selected as constant (7.0 m/s) in both studied countries similar to Borrelli, Panagos, et al. (2014).

E-wind rose is a very flexible diagram and can be adjusted depending on the type of application. For example if the aim is to investigate storms in a specific area, the frequency of winds greater than 48 knots (according to Beaufort scale) can be considered and the diagram can be identified as storm-rose.

As the aim of this research is to study wind erosion, the frequency of winds greater than the wind erosion threshold velocity were used to calculate the effective-wind roses. Since the obtained diagram refers to erosive winds, this type of effective-wind rose can also be called erosive-wind rose.

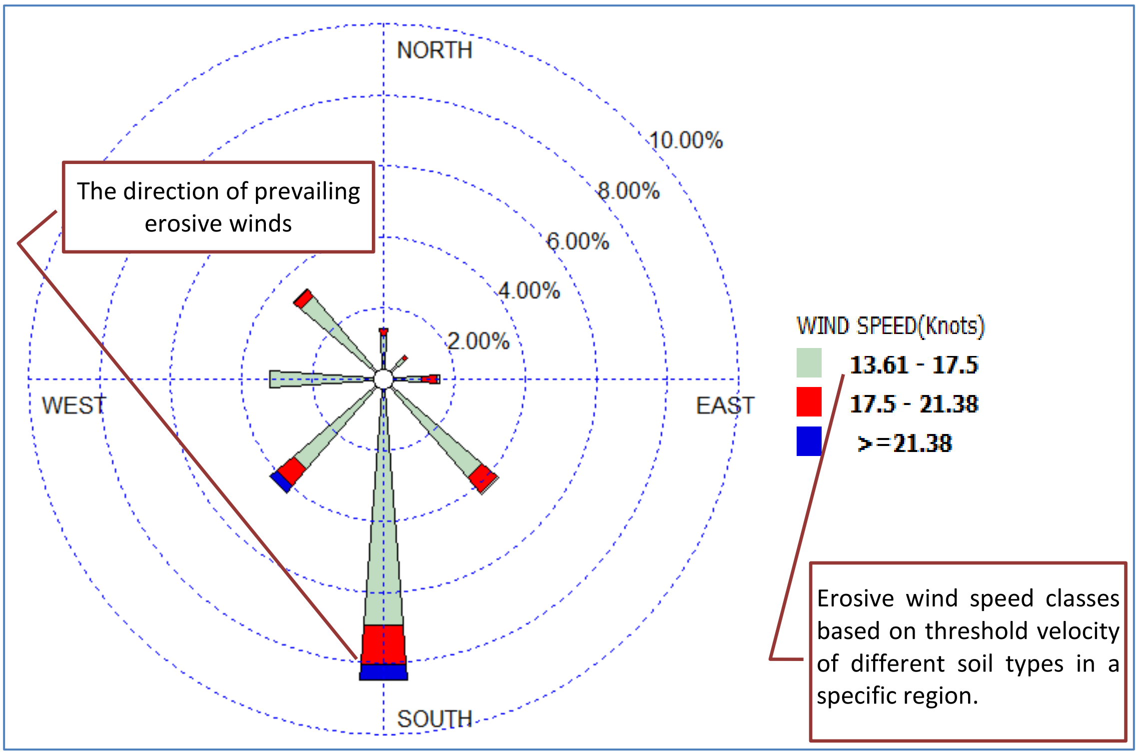


Figure 3-13: An exemplary annual e-wind rose plot along with the introduction of its constituent parts

3.4. Structure of the proposed model

The model proposed is a GIS-based model, which includes aspects that are usually not considered in other wind erosion risk models, for example the climate trend analysis and the specification of wet and dry periods. For implementation of this model, several layers of information are necessary (See Figure 3-14). The most important layers can be listed as follows:

1- Wind Power Density (WPD);
2- Erosive Wind Power Density (EWPD);
3- The trend of wind parameters due to the climate change;
4- Maximum wind speed in different return periods;
5- Digital Elevation Model (DEM);
6- Soil surface database;
7- Land cover.

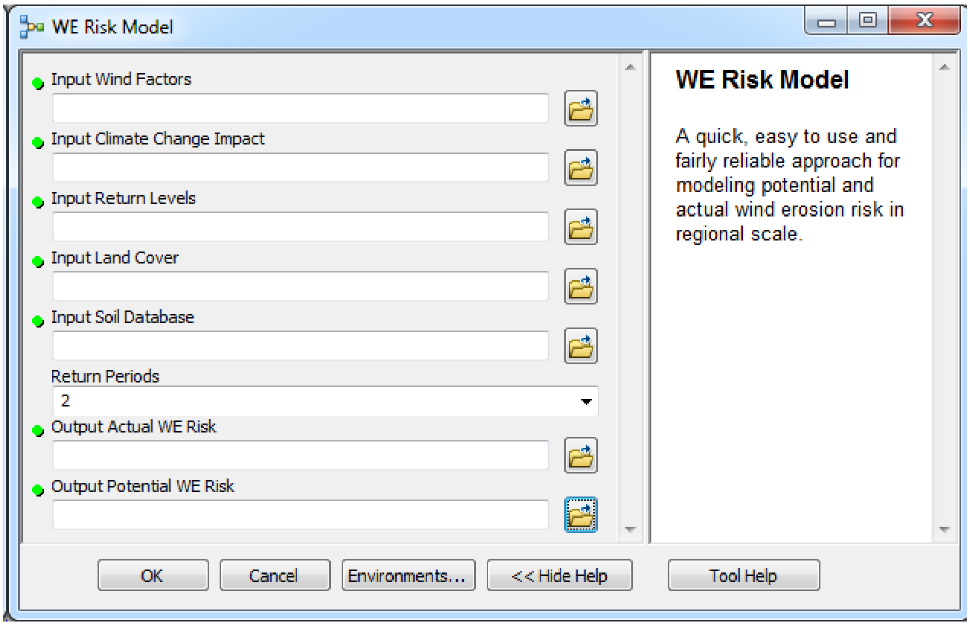


Figure 3-14: The dialog form of proposed wind erosion risk model tool in ArcGIS 10.0 invironment

Calculations or estimations of the first four items are based on historical time series of some weather elements, obtained from NOAA/NCDC, which will be discussed in more details later in this chapter.

The DEM used in the proposed model is the ASTER GDEM Version 2, which was obtained through the Global Data Explorer (GDEx) of USGS website (http://gdex.cr.usgs.gov/gdex/). In addition and in order to access the land cover of Denmark and Switzerland, the Collection 5 MODIS Global Land Cover Type product was downloaded from the URL of USGS for the year 2012. The soil surface database selected for this model is the Harmonized World Soil Database (HWSD) (Nachtergaele et al., 2012).

To implement the proposed model and assess potential and actual wind erosion risk, various programs were applied. In database programing SQL language and Visual.Net 2012 were used and a dynamic database was designed to import and combine daily and hourly weather elements (see chapter 3). Furthermore, to generate and extract climate time series from the database, a Climatic Data Generator program was written to provide a rapid appraisal of climate data for different parts of study. Most of the statistical analysis was performed in R environment and finally, after providing the necessary resources and data layers, the model was implemented in ArcGIS by using Model builder and also scripting in Python language.

To analyse the probability of wind erosion events and to investigate the relationship between the memberships of multiple sets, the Fuzzy overlay technique was used in the proposed wind erosion risk model. To combine reclassified wind data layers based on fuzzy set theory (Zadeh, 1965), the Fuzzy Gamma type with gamma = 0.8 was selected as the best choice based on sensitive analysis of outputs according to land cover layer and some selected reference points in literature (Borrelli, Panagos, et al., 2014; Veihe, Hasholt, & Schiøtz, 2003) as well as expert judgment. The Fuzzy Gamma type is an algebraic function of Fuzzy Product and Fuzzy Sum, which are both raised to the power of gamma and then multiplied to each other. Finally, the generated wind layer map was overlaid with land cover map to obtain potential wind erosion risk map of the study area.

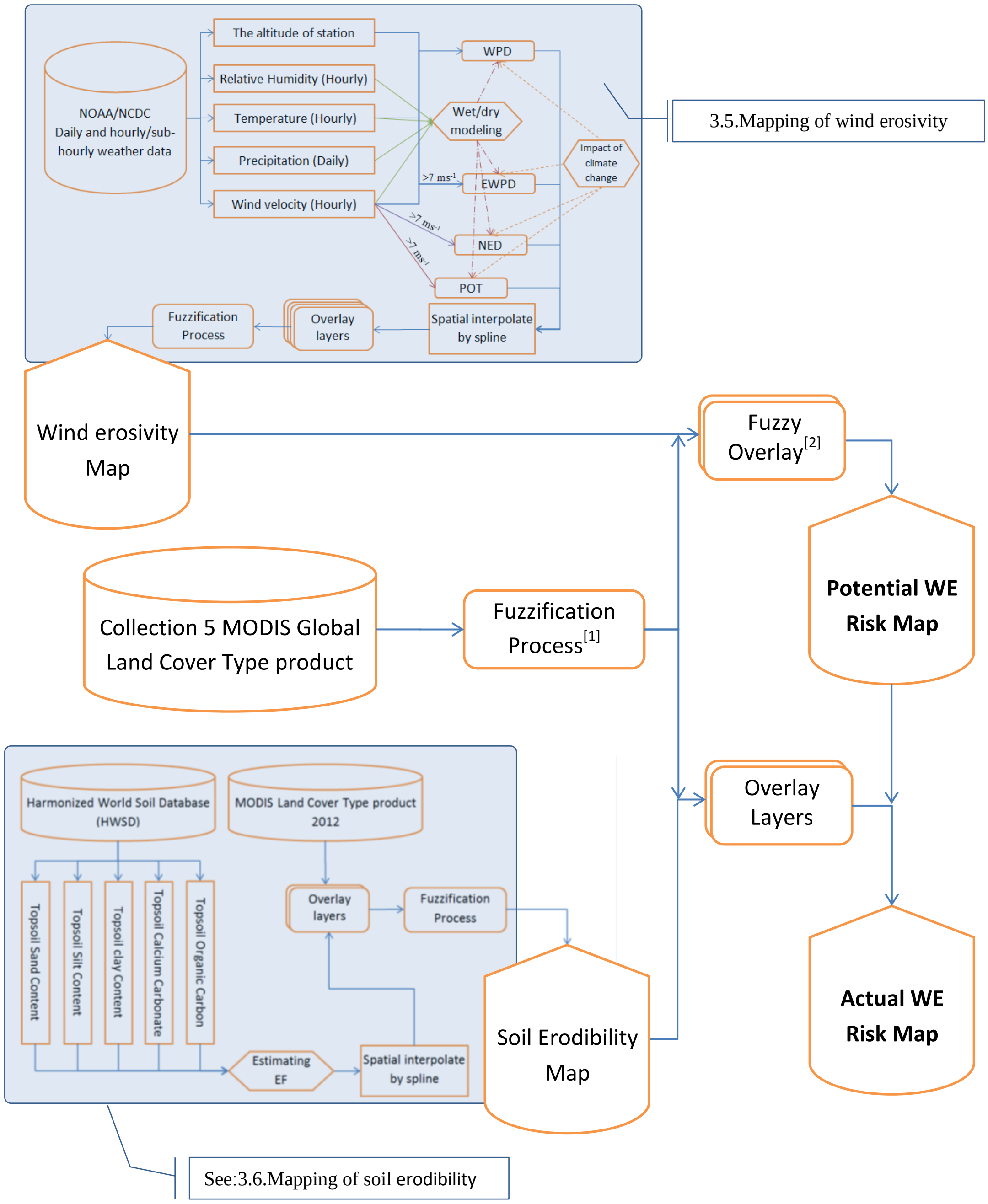
The potential wind erosion risk was ranked according to fuzzy logic techniques and the degree of membership was allocated by using a fuzzy membership function in ArcGIS 10.0, which reform values between zero and one [0,1]. The value 1 indicates that the object is entirely belonging to the fuzzy set and zero shows that the object is not owned by the fuzzy set at all (Casper, Gemmar, Gronz, Johst, & Stüber, 2007). It should be noted that a fuzzy set as defined by Zadeh (1965) is a “class of objects with a continuum of grades of membership”.

Based on these basic principles, the obtained risk score 0 indicates that there is ‘no risk’ in this area and the score 1 indicates that the risk can be ‘critical’. The closer the risk score is to the value 1, the higher is the erosion risk. The risk scores were categorized into 5 wind erosion risk classes to provide a more tangible expression of the severity of the risk.

- 0 = ‘No risk’
- 0 < 0.3 = ‘very low’
- 0.3 < 0.5 = ‘low’
- 0.5 < 0.6 = ‘moderate’
- ≥ 0.6 = ‘high’

As mentioned above, the value 1 can represent critical areas, but since there are no such values present in our studied test sites we did not consider this class in this classification. The range of each class was determined considering the situation of erosive winds in the region and has been verified with values of soil susceptibility to wind erosion from literature(Borrelli, Panagos, et al., 2014).

Figure 3-15 illustrates a simplified scheme of the model structure. As it is shown in this simplified schematic figure, the model is basically composed of two main parts, namely soil erodibility and wind erosivity. The different parts will be discussed in more detail in following sub-chapters:



[1] Fuzzification Process: The input raster is transformed into a 0 to 1 scale by using fuzzy membership algorithms. A value of 1 indicates full membership in the fuzzy set. A zero value indicates that the value is not a member of the fuzzy set. This process is done by using "Fuzzy Membership" toolbox in ArcGIS 10.0.

[2] Fuzzy Overlay: Combine fuzzy membership rasters data together, based on selected overlay type.

Figure 3-15: A simplified scheme of the proposed model structure

3.5. Mapping of wind erosivity

The wind erosivity expresses the impact of wind power on the soil and it is the wind energy component of mass transport equations (Greeley & Iversen, 1987; Guo, Chang, & Wang, 2013). As wind energy increases with the third power of wind velocity (Böhner et al., 2003), the wind velocity factor has the most important role for wind erosivity.

To estimate wind erosivity different methods have been used in wind erosion models, which are generally based on wind energy. In the RWEQ (Revised Wind Erosion Equation) (Fryrear, Saleh, & Bilbro, 1998), wind erosivity is computed by using the definition of a weather factor which is a function of wind, snow and soil wetness (Blanco-Canqui & Lal, 2008). In the WEELS model (Wind Erosion on European Light Soils) (Böhner et al., 2003), wind erosivity is first defined in terms of number of erosive hours and then measured by the wind-induced potential mass transport, based on the (Ralph Alger Bagnold, 1966) sediment transport formula.

In this thesis the wind erosivity was computed by using Erosive Wind Power Density (EWPD) which was improved by using other parameters including WPD (Wind Power Density), Number of Erosive Days (NED) as well as Peak Over Threshold (POT) wind velocity analysis output. The computation of wind erosivity for the two test countries also takes into account the impact of climate change and the results of the wet/dry modeling. All necessary weather data were imported from the NOAA database (see chapter3).

It should be noted, that following a simplified approach, the threshold wind velocity was assumed to be a constant of 7.0 m s^{-1} similar to Borrelli, Panagos, et al. (2014) investigation in European countries. Spatial distribution of parameters was interpolated by a two-dimensional minimum curvature spline technique in ArcGIS 10.0.

The resulting spatial layers were overlaid by multiplying each layer by its given weight and summing them together. The weight of each layer was selected according to its degree of importance on the wind erosivity and they were obtained by taking into account the correlation between overlaid parameters in the selected weather stations. Therefore, to overlay EWPD and WPD the weight was considered 0.8 and 0.2 respectively and the result of this overlaying was again overlaid with NED and POT by 0.7, 0.2 and 0.1 respectively.

The weight of the layers was obtained by sensitivity analysis of each data layer according to their control values in selected weather station points. In the structure of model the EWPD was selected as a main layer of data to estimate wind erosivity. So, it was tried to adjust the EWPD, which is the representative of wind erosivity in the proposed model, by other related layers. By this, the placement of wind erosivity in a completely wrong class was prevented.

Finally the wind erosivity map was linearly reclassified through predefined fuzzy membership functions as proposed by Borrelli, Panagos, et al. (2014).

As shown in Figure 3-16, several layers of information are necessary including wind power density, the trend of climate change impact, extreme winds in different return periods to compute the wind erosivity map. The preparation of these layers will be discussed in more detail in the following sections:

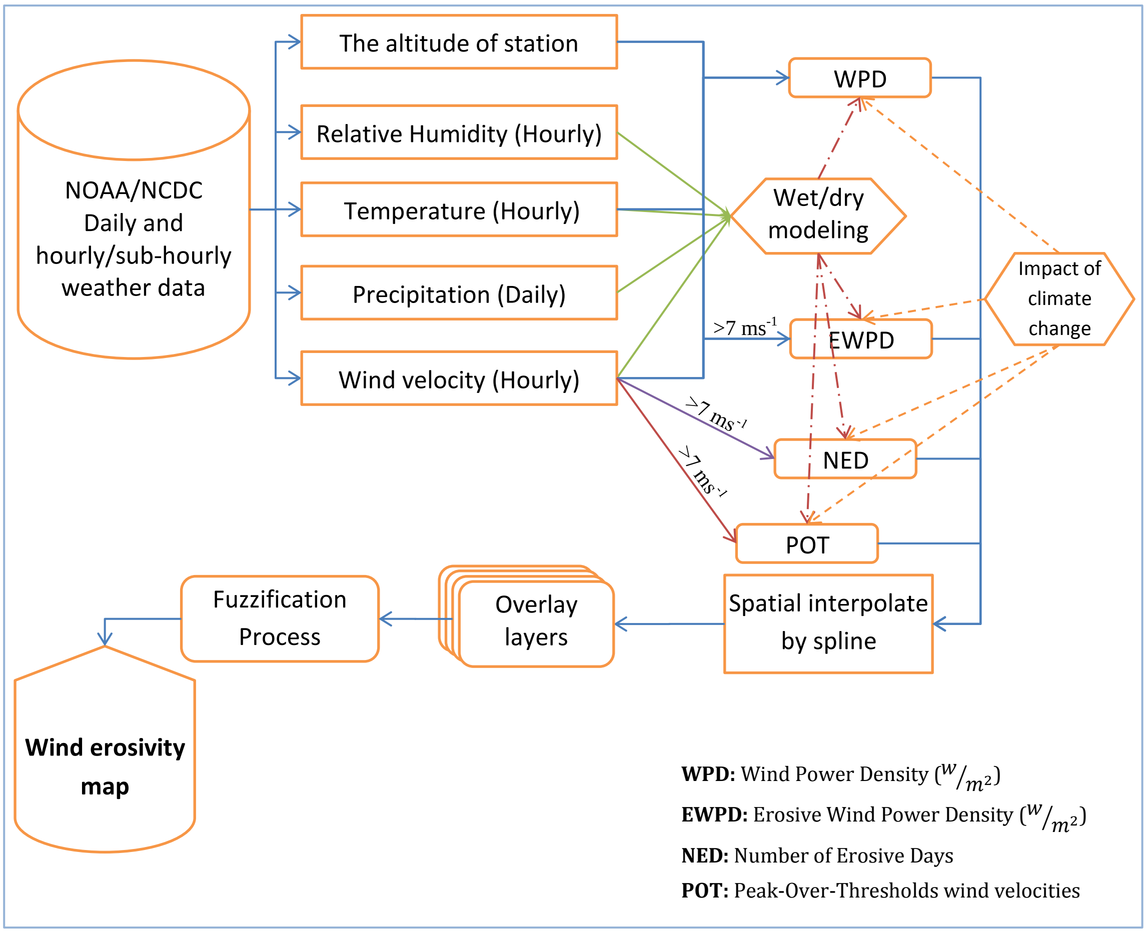


Figure 3-16: The workflow of the mapping of wind erosivity in the proposed wind erosion risk model

3.5.1. Wind Power Density (WPD) and Erosive Wind Power Density (EWPD)

The wind power density, measured in watts per square meter, indicates, on average, how much energy there is in each square meter of wind profile. This factor is directly related to the wind velocity and air density, because "its value combines the effect of a site's wind speed distribution and its dependence on air density and wind speed" (Bailey, McDonald, & Bernadett, 1997).

In this thesis, WPD was calculated based on all observed wind velocities in the time series. EWPD was obtained by just taking into account the winds above the threshold friction velocity, which was 7.0 m/s for dry periods and 9.0 m/s for wet periods. The definition of WPD and EWPD that is used in this research follows the one by Bailey et al. (1997) and Donk et al. (2005):

$$WPD = \frac{1}{2n}\sum_{i=1}^{n}\rho(v_i)^3 \qquad (3\text{-}19)$$

$$EWPD = \begin{cases} \frac{1}{2n}\sum_{i=1}^{n}\rho(v_i - v_*)(v_i)^2 & v_i > v_* \\ 0 & v_i \leq v_* \end{cases} \qquad (3\text{-}20)$$

Where:

n: the number of records;

v_i: the i[th] wind speed value (m/s);

ρ: the air density ($^{kg}/_{m^3}$) which is related to the air pressure, ambient temperature and elevation of the station when the site pressure is not available and can be estimated by the following function:

$$\rho = \left(\frac{P_0}{R.T}\right) exp^{-\left(\frac{g.z}{R.T}\right)} \qquad (3\text{-}21)$$

Where:

P_0: The standard sea level atmospheric pressure which is about 101.325 kPa;

R: the specific gas constant for air (287 $^{J}/_{kg.K}$);

T: the ambient air temperature in degrees Kelvin ($^\circ C + 273.15$);

g: the gravitation constant (9.8 $m/_{s^2}$); and

z: the site elevation above the sea level (m).

By substituting the numerical values, the final function to estimate air density will be as follows:

$$\rho = \left(\frac{353.05}{T}\right) exp^{-0.034\left(\frac{z}{T}\right)} \qquad (3\text{-}22)$$

As is evident by the summation sign in WPD and EWPD equations, these equations should only be used for all wind speed values that are recorded hourly/sub hourly during a selected time period and not for a single long term average (e.g., monthly, yearly). The reason is based on the normal variability of the wind velocity and the cubic wind speed relationship (Bailey et al., 1997).

It should be noted that, since EWPD indicates the wind power of erosive winds (V>7 ms^{-1}) and WPD states the wind power of all winds then the weight of EWPD has been considered higher than WPD at the time of overlaying layers and mapping wind erosivity.

3.5.2. Impact of climate change

To study the impact of climate change in Denmark and Switzerland other climatic elements, such as temperature, precipitation as well as relative humidity, were considered, in addition to the investigation of wind factors. In this part of the study, the trend of mentioned climatic elements was investigated to obtain evidence of climate change in each element for each of the selected climate stations. Subsequently, the magnitude of obtained trends in each climatic element was computed by using the Theil-Sen estimator. In order to investigate the general trend, Mann-Kendall and Seasonal Mann-Kendall trend tests were applied, depending on the type of time series. In fact, three different types of time series (monthly, seasonal and annual) were used for investigation. Three different significance levels (0.01, 0.05 and 0.1) were used and the magnitude of trends was computed if the results were significance at one of these levels. Figure 3-17 describes the stepwise approach that was used to specify the trend.

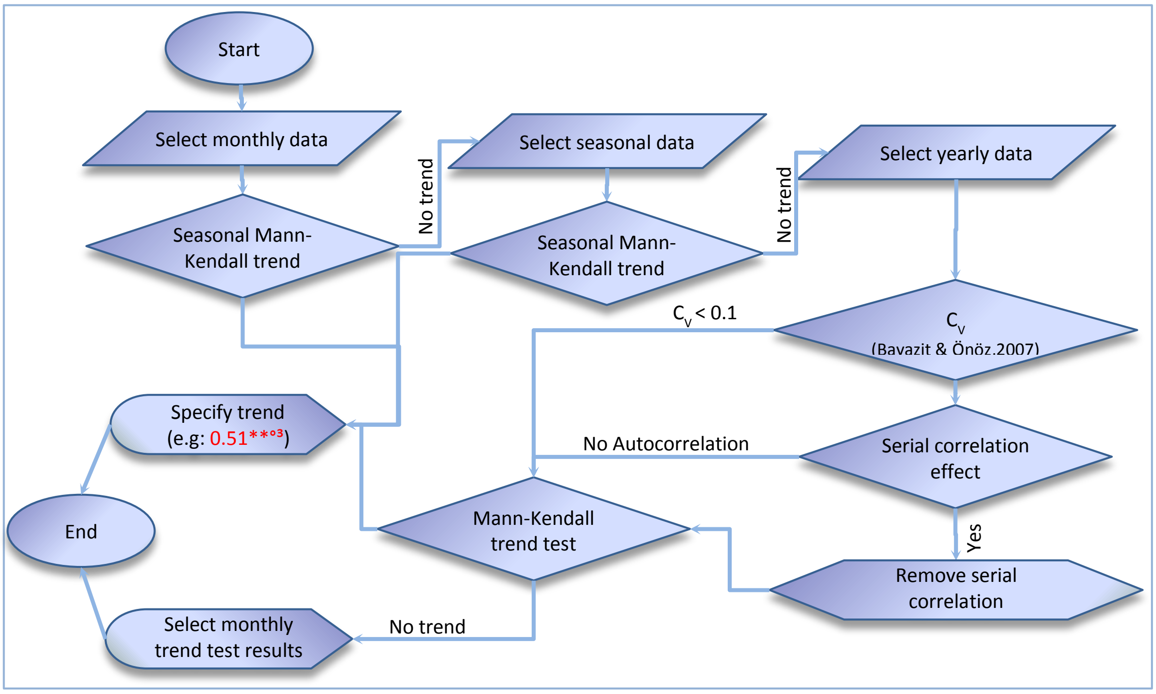


Figure 3-17: The flowchart of trend analysis method according to monthly, seasonal and annual time series

It should be noted that, the methods and tools utilized to estimate monotonic trend and its magnitude were different based on used climatic data time series. Annual time series were analyzed by using the "zyp" package (Bronaugh & Werner, 2013) in R to implement the Man-Kendall trend test but, for monthly and seasonal data time series, the “rkt” package (Marchetto, 2014) was applyed. This package is using the seasonal and regional Kendall test for trend and the Theil-Sen’s slope estimator to assess magnitude of the trend.

3.5.2.1. Mann-Kendall trend test

There are various statistical tests to identify and quantify the monotonic trend in time series. These tests can be classified as parametric and non-parametric methods. Parametric trend tests require data to be independent and normally distributed, while non-parametric trend tests only require the data to be independent (Gocic & Trajkovic, 2013). In this study, the non-parametric Mann-Kendall test was selected to detect the meteorological variable trends because this test is one of the widely used non-parametric tests to quantify the significant trends in hydrological and meteorological time series and is recommended by the World Meteorological Organization (WMO) (Gocic & Trajkovic, 2013; Sicard et al., 2010; Tabari et al., 2011)

The nonparametric Mann-Kendall trend test is a monotonic trend test, which has first been proposed by Mann (1945), then further studied by Kendall (1975) and improved by Hirsch et all.(1982, 1984) to take into account the seasonality of time series. The *S* statistic used for the test is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{3-23}$$

Where n is the number of observations, x_k and x_j are the independent observations in time k and j ($k < j$), respectively and $sgn(x_j - x_k)$ is the sign function that has been defined by:

$$sgn(x_j - x_k) = \begin{cases} 1 & if\ x_j - x_k > 0 \\ 0 & if\ x_j - x_k = 0 \\ -1 & if\ x_j - x_k < 0 \end{cases} \tag{3-24}$$

S, in fact, indicates the number of positive differences minus the number of negative differences. When S is a positive value it means that the trend of observations is positive and when it is negative indicates a negative trend. The variance of S is computed by:

$$Var(s) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)}{18} \tag{3-25}$$

Where:

n is the number of observations, q is the number of tied groups, that a tied group is a set of sample data which have the same value and t_p is the number of observations in the p^{th} group. In cases where the sample size is more than 10 observations, the standard normal test statistic, *Z*, is calculated by the following equation.

$$Z = \begin{cases} \frac{s-1}{\sqrt{var(s)}} & if\ s > 0 \\ 0 & if\ s = 0 \\ \frac{s+1}{\sqrt{var(s)}} & if\ s < 0 \end{cases} \tag{3-26}$$

Similar to *S*, a positive (negative) values of *Z* indicates that the data tend to increase (decrease) with time.

The null hypothesis, H_0, for this test is that there is no monotonic trend in the series versus the alternative hypothesis, H_1, that there is a monotonic trend in examined data which can be positive or negative. In this test, it is assumed that the data are independent and randomly ordered (Hamed & Ramachandra Rao, 1998a).

3.5.2.2. Seasonal Mann-Kendall trend test

The seasonal Mann-Kendall trend test was improved by Hirsch et al. (1982); Hirsch & Slack (1984). In the case of Mann-Kendall test the seasonality of time series will be considered. This means that, for example, in monthly data with seasonality of 12 months, the test will not try to find a trend in the overall dataset, but it will examine whether from one month of January to another January, or from one month February to another February, and so on, there is a trend or not.

To carry out seasonal Mann-Kendall test in this research, the time series toolbox of XLSTAT software was used, which is an add-ins based on Microsoft Excel. In this software the Kendall's tau is calculated for each season and afterwards, an average Kendall's tau is computed.

Also in this program, the variance of time series can be calculated assuming that the seasonal time series are independent (e.g. values of January and February are independent) or dependent, which requires the calculation of a covariance.

3.5.2.3. Serial correlation effect

The Mann-Kendall trend test assumes that the observations are independent and randomly ordered (Hamed & Ramachandra Rao, 1998b; Yue & Wang, 2004). Thus, the correlation between time series with themselves, in their first lag, should not be significant.

According to many investigations (Bayazit & Önöz, 2007; Hamed & Ramachandra Rao, 1998a; Von Storch, 1995; Yue & Wang, 2002b), the existence of positive serial correlation increases the probability of rejecting the null hypothesis of the Mann-Kendall trend test when there is actually no trend (Type I error) in the time series. To eliminate the serial correlation effect, Von Storch, (1995) proposed a procedure called pre-whitening. "Pre-whitening is the most commonly used procedure to eliminate the effect of serial correlation in trend analysis. It efficiently removes the possibility of finding a significant trend in the Mann-Kendall test when actually there is no trend."(Bayazit & Önöz, 2007)

For pre-whitening to eliminate the effect of serial correlation, the lag-one autocorrelation coefficient of time series can be computed by:

$$r_1 = \frac{\frac{1}{n-1}\sum_{i=1}^{n-1}\left(x_i - E(x_i)\right).\left(x_{i+1} - E(x_i)\right)}{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - E(x_i)\right)^2} \qquad (3\text{-}27)$$

Where, n is the sample size and $E(x_i)$ is the mean of desired time series.

$$E(x_i) = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (3\text{-}28)$$

The critical value for r_1 was computed according to Anderson, (1942) and Salas, et all. (1980) as follows:

$$r_1 = \begin{cases} \frac{-1+1.645\sqrt{n-2}}{n-1}, & one - tailed\ test \\ \frac{-1\pm 1.96\sqrt{n-2}}{n-1}, & two - tailed\ test \end{cases} \qquad (3\text{-}29)$$

Which in this research, a two-tailed test is used to calculate lag-1 serial correlation.

The pre-whitening procedure decreases the rejection rate of the null hypothesis, which is not desirable when there is a trend in time series (Bayazit & Önöz, 2007). In fact, this procedure is only appropriate for eliminating the influence of autocorrelation on the Mann-Kendall test when there is no trend (Yue & Wang, 2002b). Also, Bayazit & Önöz, (2007) concluded that pre-whitening data should be avoided when the coefficient of variation is very low (less than 0.1) for all sample sizes.

The pre-whitening procedure performed in this research was based on Yue & Wang, (2004) by using the Mann-Kendall trend test in XLSTAT time series tool, but it was ignored when the coefficient of variation of data was less than 0.1 or there was no trend in the time series (see Figure 3-17).

3.5.2.4. Theil-Sen estimator

Theil-Sen estimator or Sen's slope estimator is a non-parametric statistical method, which has been developed by Sen (1968) to estimate the magnitude of any significant trend. It computes the slopes of all possible pairs of observations and takes the median value as slope (Ohlson & Kim, 2014). This estimator is "the most popular nonparametric technique for estimating a linear trend" (Holland & Sirois, 2006), which can be estimated by using three following stages:

Stage I: calculates the slope of all possible pairs of observations by using the following equation:

$$Q_i = \frac{X_j - X_k}{j-k}, \; i = 1,\ 2,\ \ldots,\ N \tag{3-30}$$

Where: X_j and X_k are the data values at times *j* and *k*, (*j* > *k*), respectively and *N* is the number of pairs of points. If there is only one value in each time period, then $N = \frac{n(n-1)}{2}$, where n is the number of observations.

Stage II: ranks the *N* values of Q_i from smallest to largest.

Stage III: computes the median of ranked slopes as Theil-Sen estimator by:

$$Q_{med} = \begin{cases} Q_{\left[(N+1)/2\right]}, & if\ N\ is\ odd \\ \frac{Q_{\left[N/2\right]} + Q_{\left[(N+2)/2\right]}}{2}, & if\ N\ is\ even \end{cases} \tag{3-31}$$

The Theil-Sen estimator is "not influenced by the outlier and well represents the increasing trend" (Ohlson & Kim, 2014) and it can be significantly more accurate than simple linear regression.

3.5.3. Extreme Wind Analysis

Extreme value theory is a powerful and yet fairly robust technique to analyze the tail behavior of distributions which has been applied extensively in different branches of science such as: hydrology, climatology as well as economic studies and the financial industry, including banking and insurance (Embrechts, Resnick, & Samorodnitsky, 1999). The main purpose of using Extreme Value Analysis (EVA) in this study is to find reliable estimates of extreme values (here wind speeds) in different return periods. There are two approaches for practical EVA; the first method relies on using block maxima series (e.g. annual maxima series) which in this research was analyzed by using Generalized Extreme Value (GEV) distributions. The second method relies on extracting Peak-Over-Threshold (POT) values which has been fitted with a Generalized Pareto Distribution (GPD).

There is very strong evidence in scientific literature which recommends the use of the GEV distribution and GPD, to fit extreme values. For example, in extreme wind speed analysis the flowing articles can be cited: (Ceppi et al., 2008; Della-Marta et al., 2007; Langreder & Hojstrup, 2007; Sanabria & Cechet, 2007)

To increase the fitting accuracy of the GEV distribution and the GPD, the time series of extreme events must be sufficiently long. Cook (1985) advises that at least ten years of observation is needed for classical analysis of extreme hourly wind speeds by using the GEV distribution. But for POT methods, having five to six years of data may be sufficient (Coles & Walshaw, 1994).

At first, fitting block maxima by GEV was implemented by programming in R based on “evd” (Stephenson, 2002) and “ismev” (Stephenson, 2012) packages, but in some of the weather stations, there was not enough data for running the model with this approach. Therefore the POT approach was also performed, by using “POT” (Mathieu Ribatet, 2012) package in R. At the end all return periods were derived according to this “POT” approach.

Extreme wind velocity analysis in POT approach was performed with the following steps:

1- Choose an appropriate threshold value (here 13 knots has been selected based on the most sensitive soils to the wind erosion);

2- Extract all independence maximum values above the threshold into a sample;

3- Estimate scale and shape parameters of GPD by using the maximum likelihood estimator (mle) method;

4- Fit a GPD model to Peaks Over a Threshold data;

5- Draw diagnostic plots (probability plot, density plot, quantile-quantile plot as well as return period plot) to verify the accuracy of the fitted model;

6- Plot return level and extract extreme wind velocities of desired return periods.

3.5.3.1. Generalized Extreme Value (GEV) distribution

Classical Extreme Value Analysis describes how the maxima of samples can be fitted to one of three basic distribution functions which are known as Gumbel (Type I), Fisher-Tippett, Fréchet (Type II) and Weibull (Type III) distribution families.

These three families of distributions were combined into a single distribution by Von Mises (1936, in French), which is universally known as the Generalized Extreme Value (GEV) distribution (Palutikof et al., 1999). The cumulative distribution function of the GEV distribution is:

$$F_{(x;\varphi,\delta,\varepsilon)} = \begin{cases} exp\left(-\left[1+\mu\left(\frac{x-\varphi}{\delta}\right)\right]^{-1/\varepsilon}\right) & \varepsilon \neq 0 \\ exp\left[-exp\left(-\frac{x-\varphi}{\delta}\right)\right] & \varepsilon = 0 \end{cases} \qquad (3\text{-}32)$$

Where; μ is a shape parameter which determines the type of extreme value distribution. If $\varepsilon = 0$, the distribution is Type I (Gumble) and it has a short tailed (Palutikof et al., 1999). Fréchet distribution (Type II) has a positive value of ε but in Type III (Weibull) this value is negative (Embrechts et al., 1999).

φ is the location parameter which is the mode of the extreme value distribution and δ is the dispersion or scale parameter (Palutikof et al., 1999).

The implementation of the GEV distribution, in this research, was performed in the R statistical software, based on "evd" and "ismev" packages (Stephenson, 2002, 2012). Although, it should be noted that, the required block maxima datasets were obtained before by using Climatic Data Generator software which is mentioned chapter 3.

3.5.3.2. Generalized Pareto Distribution (GPD)

The Generalized Pareto Distribution (GPD) is also specified like the GEV, by three parameters: location φ, scale δ, and shape ε. Although in some scientific literature, it is defined by only scale and shape (Hosking & Wallis, 1987). The cumulative distribution function (cdf) of this continuous probability distribution is:

$$F_{(x;\varphi,\delta,\varepsilon)} = \begin{cases} 1 - \left[1 + \frac{\varepsilon(x-\varphi)}{\delta}\right] & , \quad \varepsilon \neq 0 \\ 1 - exp\left(-\frac{x-\varphi}{\delta}\right) & , \quad \varepsilon = 0 \end{cases} \tag{3-33}$$

For $x \geq \varphi$ when $\varepsilon \geq 0$ and $\varphi \leq x \leq \varphi - {}^{\delta}/_{\varepsilon}$ when $\varepsilon < 0$

And its probability density function (pdf) is:

$$f_{(x;\varphi,\delta,\varepsilon)} = \frac{1}{\delta}\left(1 + \frac{\varepsilon(x-\varphi)}{\delta}\right)^{\left(-\frac{1}{\varepsilon}-1\right)} = \frac{\delta^{\frac{1}{\varepsilon}}}{[\delta+\varepsilon(x-\varphi)]^{\frac{1}{\varepsilon}+1}} \tag{3-34}$$

Again, for $x \geq \varphi$ when $\varepsilon \geq 0$ and $\varphi \leq x \leq \varphi - \delta / \varepsilon$ when $\varepsilon < 0$

With shape $\varepsilon > 0$ and location $\varphi = \delta / \varepsilon$ the GPD is equivalent to the Pareto distribution and if the shape and location are both zero, the GPD is equivalent to the exponential distribution.

3.5.3.3. Peak-Over-Threshold (POT) methods with the GPD

The Generalized Pareto distribution (GPD) is used in a method, the so-called Peak-Over-Threshold (POT), to describe the behavior of the events above the specified threshold. In this case, the location φ parameter is equal to the selected threshold (Palutikof et al., 1999).

In POT methods, usually it is customary to consider a minimum separation time to ensure the independence of the extreme events. In many studies, for European wind climates, this separation time is selected to be 48 hours (e.g. Cook, 1985; Gusclla, 1991). In this study, to ensure the independence of the extracted extremes, a peak over threshold identifier algorithm was written in C sharp (C#), based on the detection of windiness periods. The proposed method contains at least the following four steps:

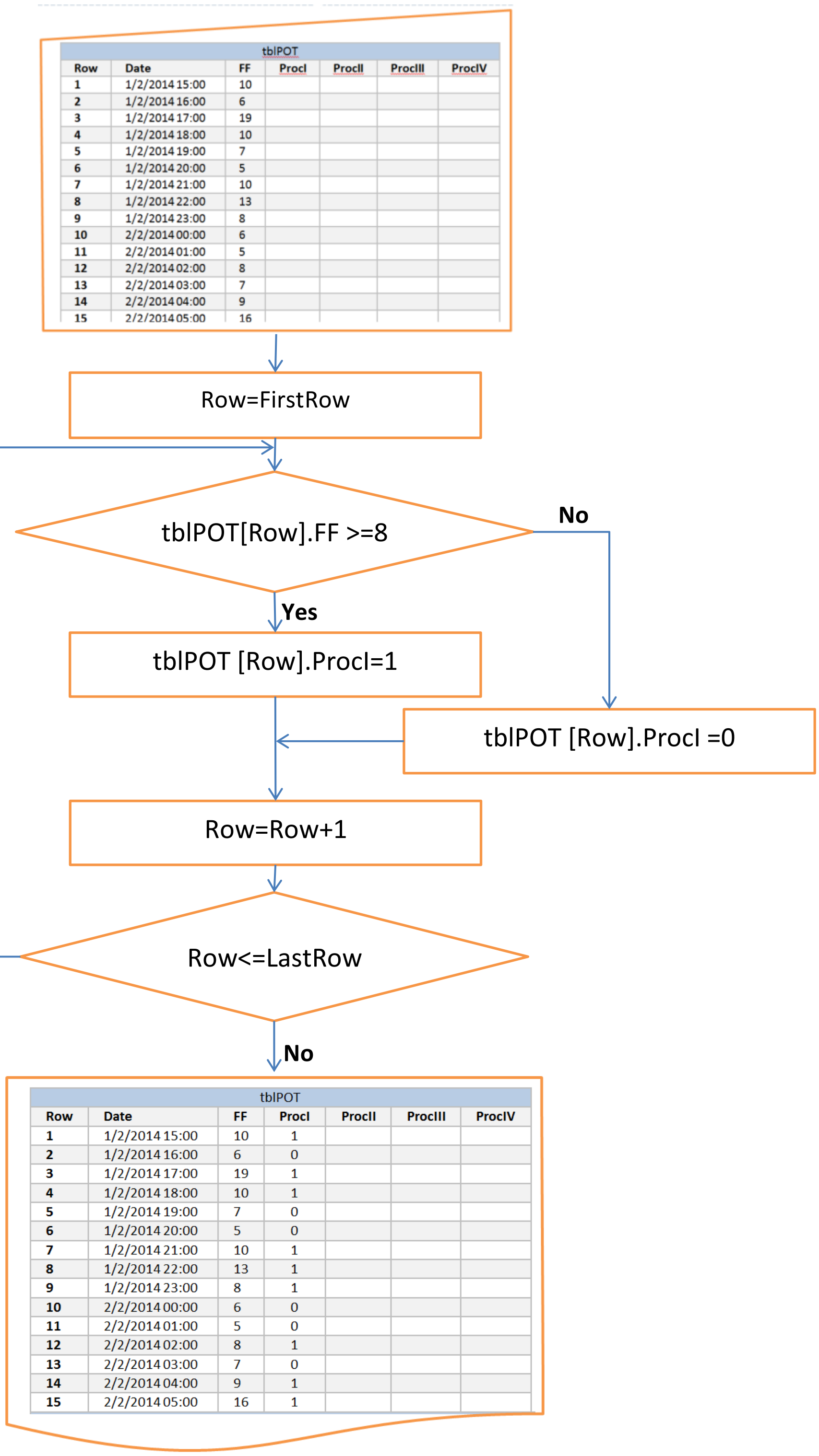
Step I: Determination of wind blowing periods;

Step II: Calculation of maximum wind velocity of each specified wind period;

Step III: Selection of maxima of winds greater than or equal to the selected threshold velocity;

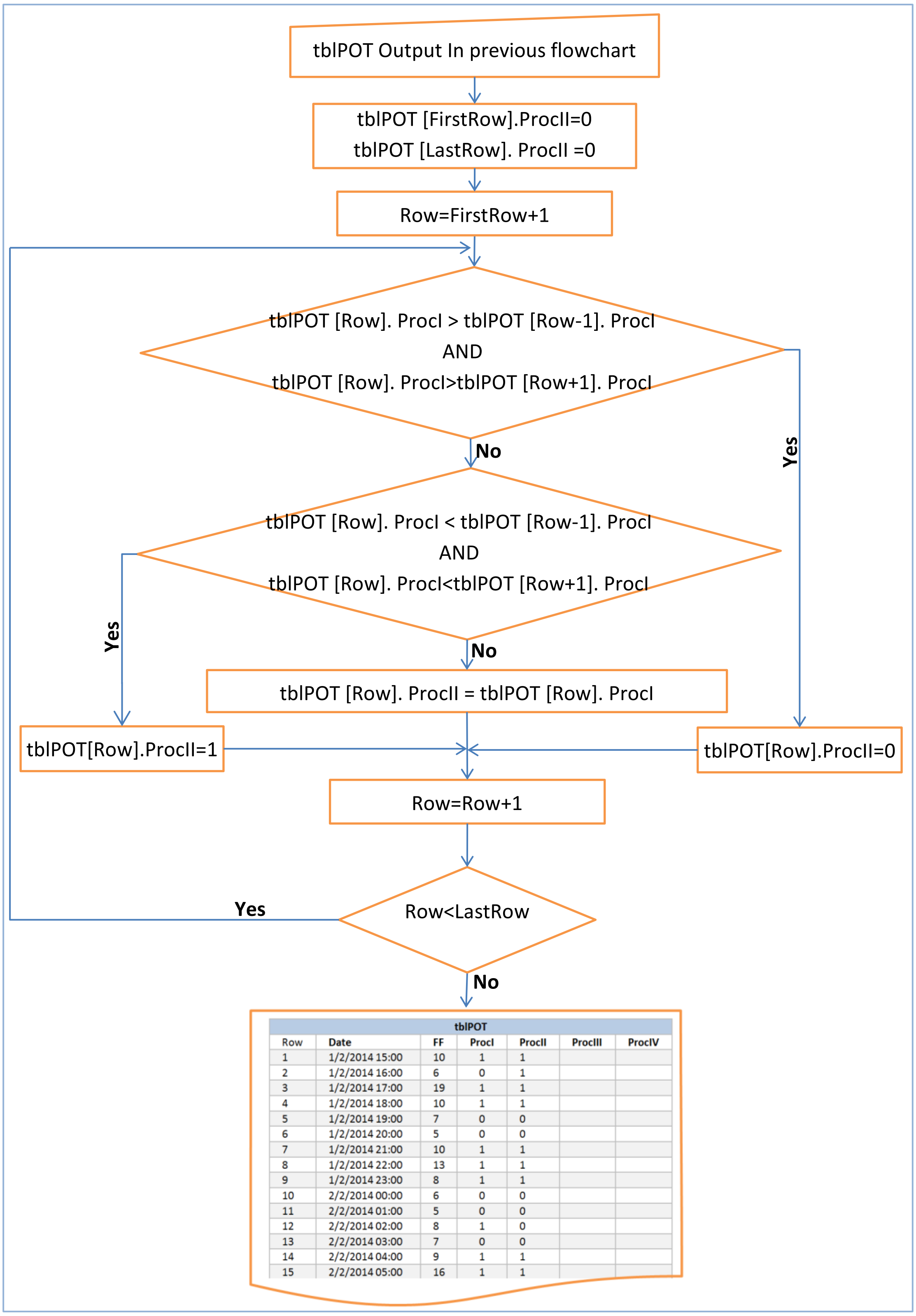
Step IV: Selection of the first maxima of wind velocity in the days that estimated more than one record.

To illustrate how the structure of designed program works, the flowchart of each step is given in Figure 3-18 until Figure 3-22. For better understanding of each process, a numerical example was included to the flowcharts to display input and output of every single step.



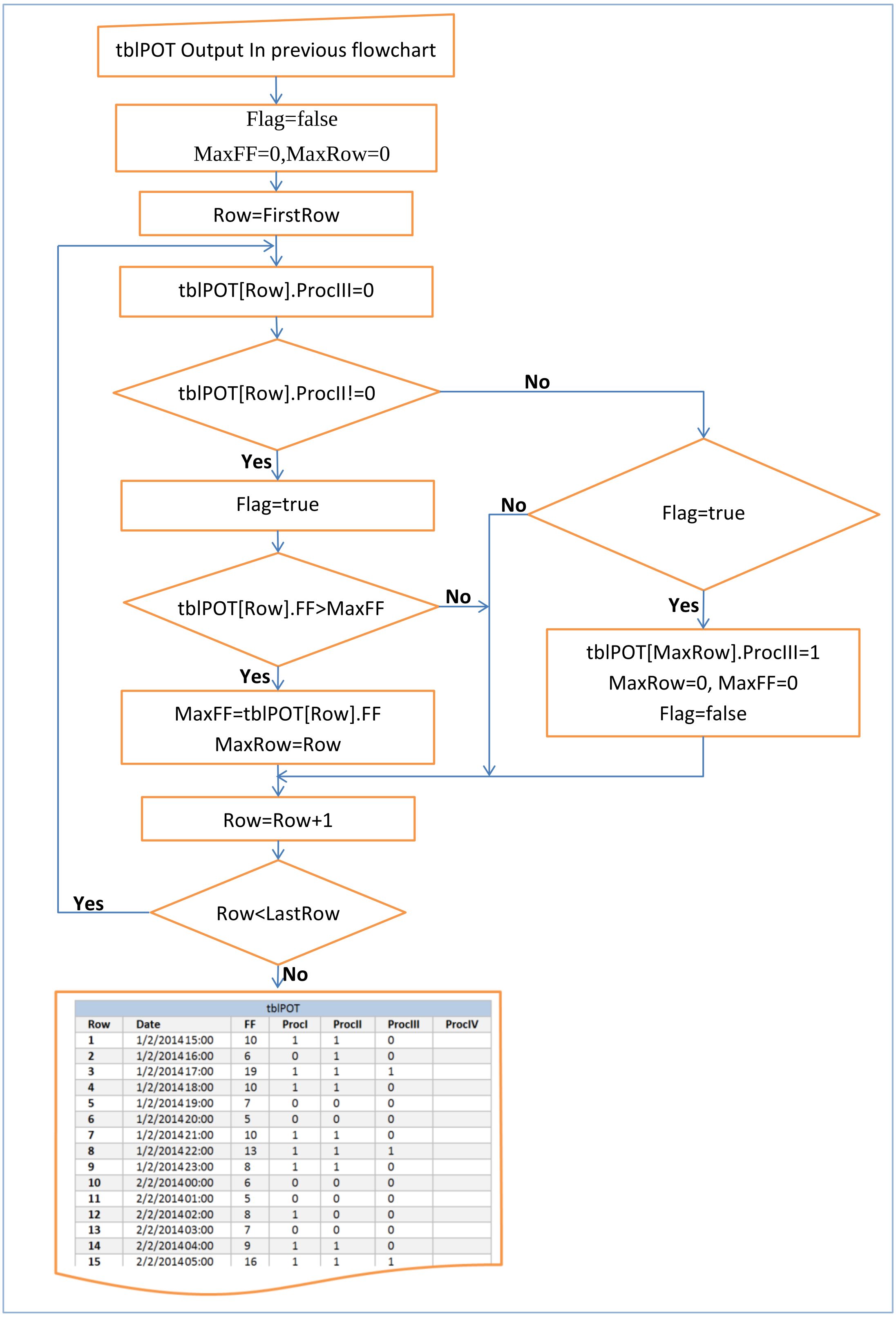
tblPOT: The name of weather elements table in the database;
ProcI: A field to save the results of the implementation of the first process;
FF: wind velocity field in the database;
Row: Number of records.

Figure 3-18: The flowchart of definition first step of independence peak over threshold wind velocities (Step I)



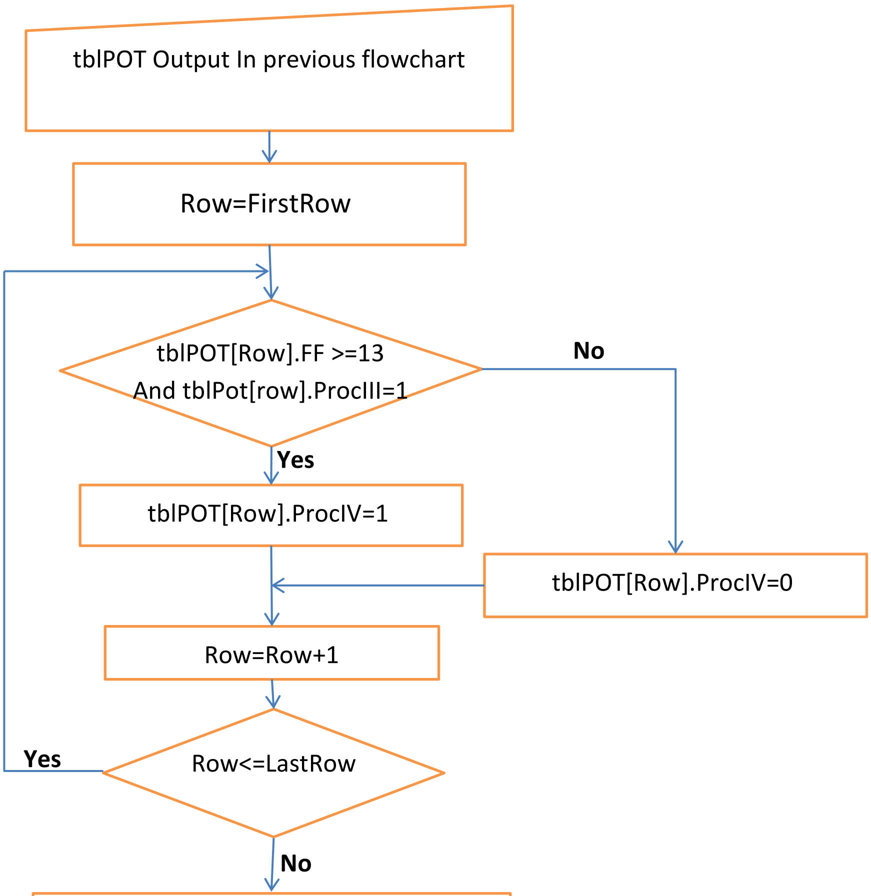
Row	Date	FF	ProcI	ProcII	ProcIII	ProcIV
1	1/2/2014 15:00	10	1	1		
2	1/2/2014 16:00	6	0	1		
3	1/2/2014 17:00	19	1	1		
4	1/2/2014 18:00	10	1	1		
5	1/2/2014 19:00	7	0	0		
6	1/2/2014 20:00	5	0	0		
7	1/2/2014 21:00	10	1	1		
8	1/2/2014 22:00	13	1	1		
9	1/2/2014 23:00	8	1	1		
10	2/2/2014 00:00	6	0	0		
11	2/2/2014 01:00	5	0	0		
12	2/2/2014 02:00	8	1	0		
13	2/2/2014 03:00	7	0	0		
14	2/2/2014 04:00	9	1	1		
15	2/2/2014 05:00	16	1	1		

Figure 3-19: The flowchart of eliminate wind fluctuations in determined wind periods (continued step I)



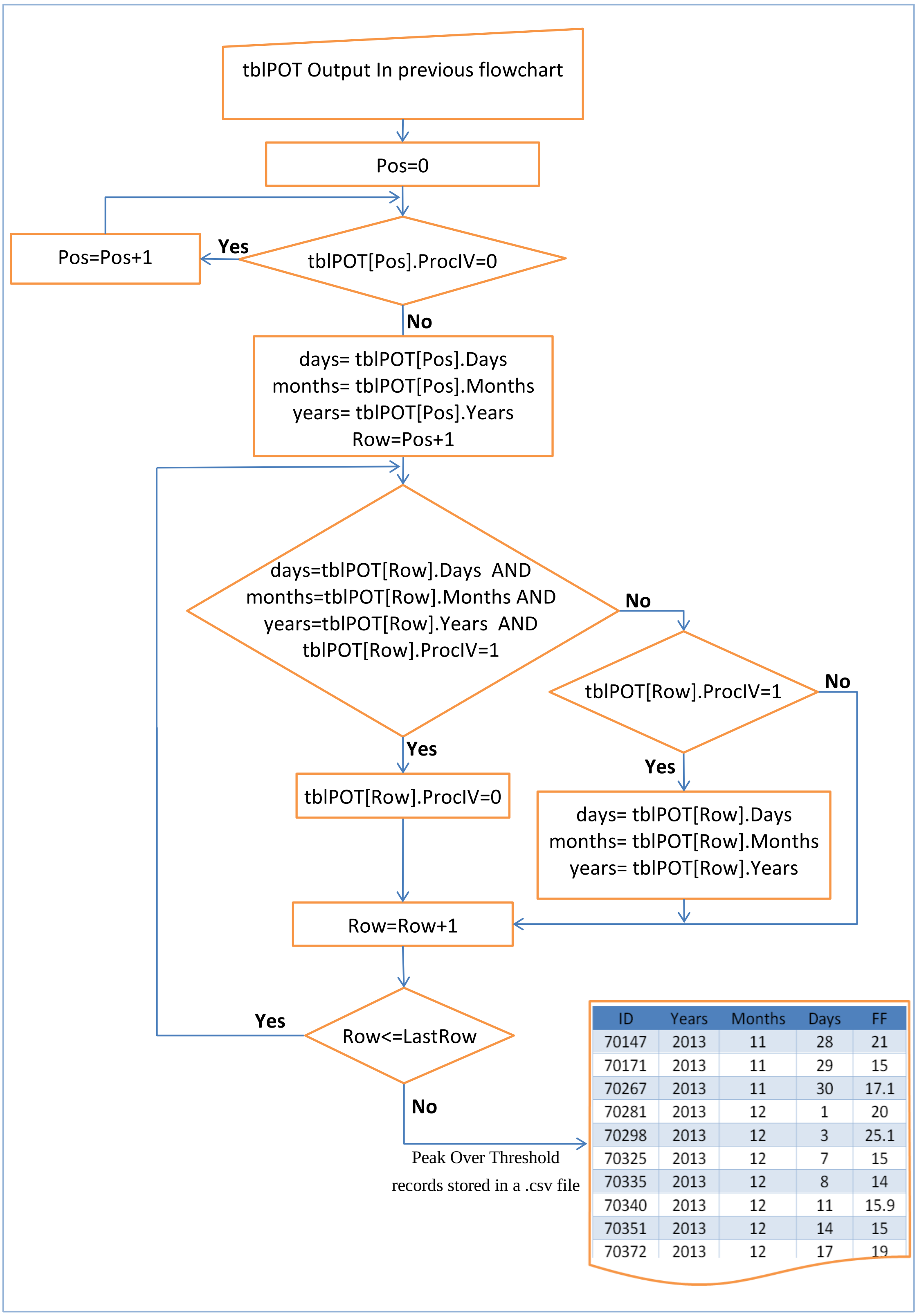
tblPOT						
Row	**Date**	**FF**	**ProcI**	**ProcII**	**ProcIII**	**ProcIV**
1	1/2/2014 15:00	10	1	1	0	
2	1/2/2014 16:00	6	0	1	0	
3	1/2/2014 17:00	19	1	1	1	
4	1/2/2014 18:00	10	1	1	0	
5	1/2/2014 19:00	7	0	0	0	
6	1/2/2014 20:00	5	0	0	0	
7	1/2/2014 21:00	10	1	1	0	
8	1/2/2014 22:00	13	1	1	1	
9	1/2/2014 23:00	8	1	1	0	
10	2/2/2014 00:00	6	0	0	0	
11	2/2/2014 01:00	5	0	0	0	
12	2/2/2014 02:00	8	1	0	0	
13	2/2/2014 03:00	7	0	0	0	
14	2/2/2014 04:00	9	1	1	0	
15	2/2/2014 05:00	16	1	1	1	

Figure 3-20: The flowchart of Calculation maximum wind velocity of each specified wind period (Step II)



tblPOT						
Row	**Date**	**FF**	**ProcI**	**ProcII**	**ProcIII**	**ProcIV**
1	1/2/2014 15:00	10	1	1	0	0
2	1/2/2014 16:00	6	0	1	0	0
3	1/2/2014 17:00	19	1	1	1	1
4	1/2/2014 18:00	10	1	1	0	0
5	1/2/2014 19:00	7	0	0	0	0
6	1/2/2014 20:00	5	0	0	0	0
7	1/2/2014 21:00	10	1	1	0	0
8	1/2/2014 22:00	13	1	1	1	0
9	1/2/2014 23:00	8	1	1	0	0
10	2/2/2014 00:00	6	0	0	0	0
11	2/2/2014 01:00	5	0	0	0	0
12	2/2/2014 02:00	8	1	0	0	0
13	2/2/2014 03:00	7	0	0	0	0
14	2/2/2014 04:00	9	1	1	0	0
15	2/2/2014 05:00	16	1	1	1	1

Figure 3-21: The flowchart of Select maxima winds greater than or equal to the selected threshold velocity (Step III)



ID	Years	Months	Days	FF
70147	2013	11	28	21
70171	2013	11	29	15
70267	2013	11	30	17.1
70281	2013	12	1	20
70298	2013	12	3	25.1
70325	2013	12	7	15
70335	2013	12	8	14
70340	2013	12	11	15.9
70351	2013	12	14	15
70372	2013	12	17	19

Figure 3-22: The flowchart of Select maxima winds greater than or equal to the selected threshold velocity (Step IV)

3.6. Mapping of soil erodibility

Wind erosion occurs when the wind friction velocity exceed threshold friction velocity. In fact, at this moment, the shear wind force on the ground exceeds the energy that is required to mobilize the soil aggregates (Borrelli, Panagos, et al., 2014; Yaping Shao, 2008). Soil erodibility represents the stability of the soil aggregates against the erosive power of the wind (Böhner et al., 2003). The determination and characterization of soil erodibility is an essential task in any modeling of wind erosion. Several factors have been proposed to calculate soil erodibility, such as the K-factor, a dimensionless soil erodibility factor used in the Universal Soil Loss Equation (USLE). The K-factor describes the intrinsic susceptibility of a dry and freshly cultivated sandy soil to wind erosion when the soil surface is not affected by any soil cover, roughness, crusting or soil moisture (Böhner et al., 2003). Another factor that was proposed to reflect the relationship between soil loss by wind and the characteristics of the soil surface is the wind erodible fraction of soils (EF) (Woodruff & Siddoway, 1965).

The wind erodible fraction of soils (EF) is commonly accepted and widely applied to measure soil erodibility by wind (Borrelli, Panagos, et al., 2014; Fryrear et al., 2000; Woodruff & Siddoway, 1965). Hence, in this research this factor was also used to determine soil erodibility in the proposed wind erosion risk model.

The wind erodible fraction of soils (EF) can be computed by the following equation based on the soil's texture and chemical properties:

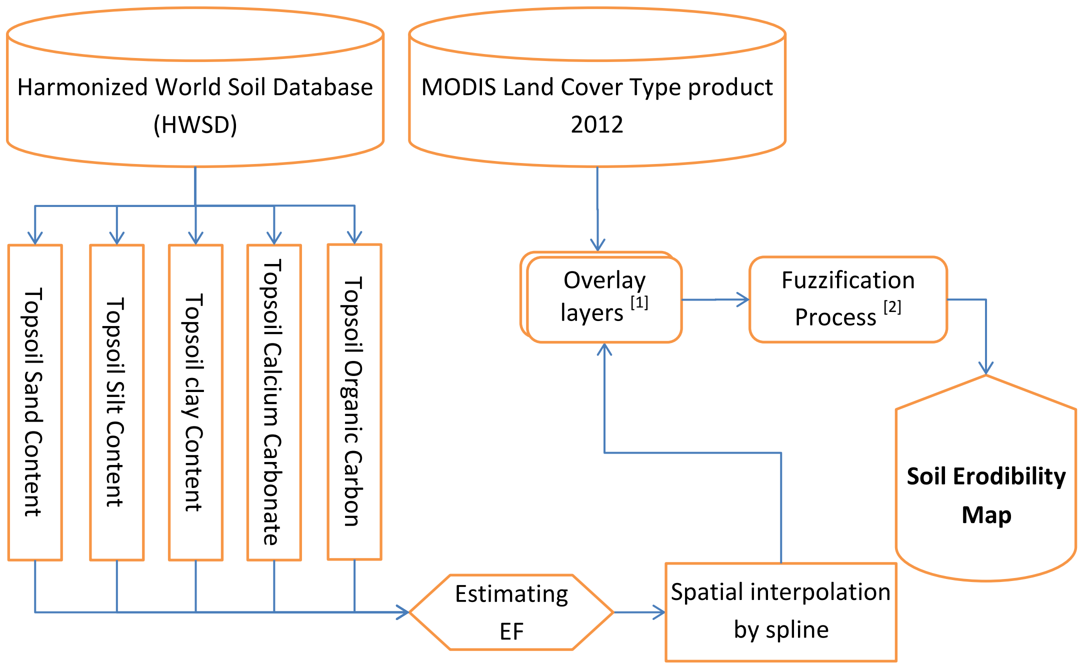
$$EF = \frac{29.09+0.31S_a+0.17S_i+0.33S_c-2.59OM-0.95CaCO_3}{100} \qquad (3\text{-}35)$$

Where:

S_a is the soil sand content, S_a: the soil silt content, S_c: the ration of sand to clay contents, OM: the organic matter content that in this research derived from organic carbon (OC) content by multiplying to 1.7, $CaCO_3$: the calcium carbonate content.

It should be noted that all variables in this formula are expressed in percentage and that the susceptibility of the particular soil is higher, the larger the EF factor becomes. Despite some limitations of the above equation (López, De Dios Herrero, Hevia, Gracia, & Buschiazzo, 2007), it is still one of the most robust and widely used equations that has been introduced in the literature, in order to assess the intrinsic susceptibility of the soil surface to wind erosion (Borrelli, Panagos, et al., 2014).

Figure 3-1 shows the workflow to estimate the soil erodibility in the proposed wind erosion risk model. As indicated in this figure, the Harmonized World Soil Database (HWSD) was used to estimate EF. All the calculations and mapping was implemented in ArcGIS 10.0. The results of estimating EF was interpolated by spline method and the output layer was overlaid with MODIS Land Cover Type Product 2012 to eliminate land types such as water, urban and built-up, forest as well as snow and ice zones as non-erodible surfaces in studied countries.



[1]: Overlay analysis is a technique for combining information from one GIS layer with another GIS layer to derive or infer an attribute for one of the layers

[2]: Fuzzification Process transforms the input raster into a 0 to 1 scale by using fuzzy membership algorithm. A value of 1 indicates full membership in the fuzzy set and decreasing to 0 indicating it is not a member of

Figure 3-23: The workflow of the mapping soil erodibility in the proposed WE risk model

“I am saying that all predictions concerning climate are highly uncertain.”

~ Freeman Dyson (1923-)

RESULTS

Due to the required different layers of information in the proposed wind erosion risk model, the research covers various aspects of wind data analysis. According to this various aspects the results chapter includes the following parts:

- Investigation and description of present wind patterns;
- Investigation of the impact of climate change on wind;
- Extreme wind velocity analysis;
- Assessment of the potential wind erosion risk.

Before an analysis of extremes and future climate trends can be done, it is necessary to evaluate and describe present wind patterns in Denmark and Switzerland. In this part of study, not only the frequency of all observed winds but also the frequency of erosive winds, winds with velocities above the threshold friction velocity of 7.0 m/s, was calculated. Thus, in addition to the prevailing wind direction the prevailing wind direction of erosive winds was determined. The wind patterns were computed using the conventional method (all wind data included regardless of soil moisture conditions) and the proposed method (selection of wind data based on modelling of dry-times). For better understanding if any significant differences between the two methods exist, the results of both methods have been compared to each other.

By proving a significant difference between the conventional method and new method, the impact of climate change, the trend and its magnitude, in both approaches was investigated with emphasis on wind parameters. Using the rate of trend in all studied weather stations and integrating them in one database facilitated predicting wind erosion risk based on climate change.

The analysis of extreme winds is another part of this study and includes the fitting of statistical extreme value models to a maximum wind velocity time series to determine their return period. The final sub-chapter provides a quick and easy to access potential wind erosion risk assessment model, which is based on the results of previous parts of this study. As already mentioned, the main aim of this research is to develop a simple, quick and reliable GIS-based model to estimate potential wind erosion risk by using readily available weather elements, so that it can be applied in areas without adequate data availability.

Since all algorithms and methods presented in this study are based on publicly available data, e.g. NOAA/NCDC meteorological observations and Harmonized World Soil Database (HWSD) (Nachtergaele et al., 2012), the implementation of proposed model or any sub-studies is possible for many other countries. In this research, Denmark and Switzerland were selected as pilot countries and the results presented here are based on these two countries.

4.1. Wind patterns in Denmark and Switzerland

To illustrate the pattern of the winds and erosive winds in Denmark and Switzerland, the frequency distribution of all observed winds (more than one knots) as well as winds greater than the considered threshold velocity (7.0 m/s) was calculated. The wind rose and e-wind rose of all selected stations were plotted in both cases, for seasonal and annual periods.

In this part of the study, the wind rose and e-wind rose were plotted for two different situations based on wet/dry modeling results. One for all observed winds, regardless of soil moisture situation (conventional method) and the other for the winds recorded during the dry times (new method). In order to better perceive significant differences between wind pattern of two methods, the Wilcoxon, Kolmogorov–Smirnov test as well as the t-test were performed to accept or reject the null hypothesis which is: “two populations have the same continuous distribution”.

4.1.1. Annual patterns of all winds and erosive winds

To indicate how the patterns of erosive winds perform in each station, the frequency distribution of all winds and erosive winds (winds with velocity more than the estimated threshold velocity) were calculated. In this study, three different threshold friction velocities are being used (7.0, 9.0, 11.0 m/s) and it is assumed that the more erosion susceptible soils fall within this range. The threshold friction velocity of the most sensitive soil to wind erosion is selected at 7.0 m/s (13.6 knots) as selected also by (Borrelli, Panagos, et al., 2014) to investigate land susceptibility to wind erosion in 34 European countries.

In Figure 4-1, an exemplary annual wind rose and E-windrose of the FOULUM station has been illustrated for both all-times and dry-times. Comparing these two graphical models shows that around 30 percent of winds in this station are westerly but, only less than 1.5 percent of the winds (according to E-windrose) are erosive winds capable of transporting soil particles and causing dust emissions, especially in dry times.

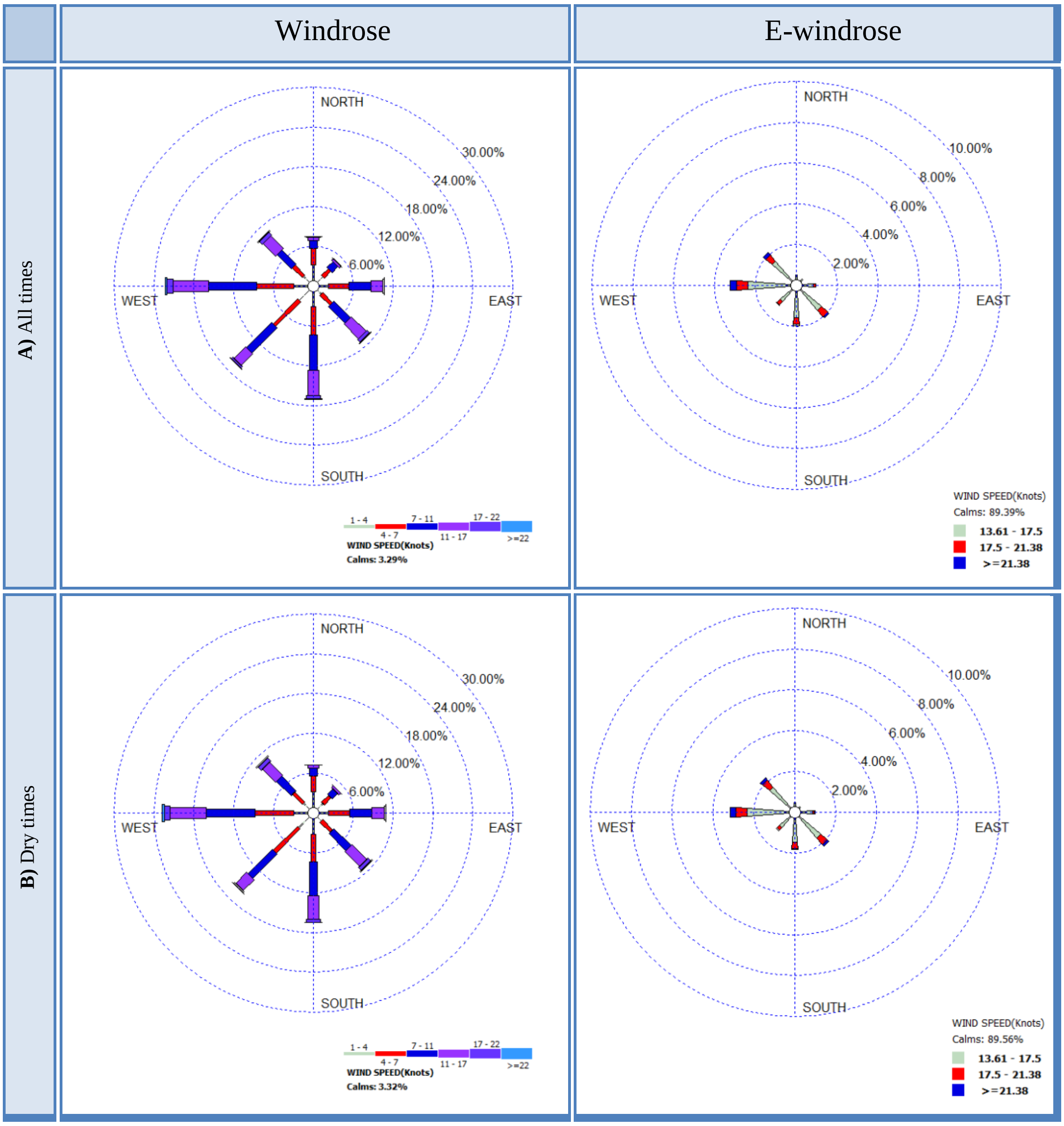


Figure 4-1: An exemplary annual windrose and E-windrose of the FOULUM station in all times and dry times (note: Windrose and E-windrose of other stations can be seen in the spatial distribution wind rose maps. Also, the high resolution of all diagrams are enclosed in the digital appendix of the thesis)

Just by using a visual interpretation of the wind rose and e-wind rose in all-times and dry-times at this exemplary weather station in Foulum, it appears that there is no significant difference between all-times and dry-times wind velocity distributions. The main reason for this is not that there is no difference, it is just not visible because of the huge amount of data and the scale of the graph. Thus, some statistical tests (Wilcoxon, t-test) were conducted to better understand the differences. The details of this statistical comparison for all weather stations are presented in sub-chapter 4.1.3.

The above mentioned annual wind rose and E-windrose were plotted for all selected stations in Denmark and Switzerland. According to the spatial distribution of the selected stations, wind and erosive wind pattern maps were produced for both countries (Figure 4-2 and Figure 4-3).As illustrated in Figure 4-2, the wind regime of the selected stations in Denmark are very similar and the prevailing wind direction is almost predominantly westerly or southwesterly in all stations, and northerly winds are the least frequent winds in the country. Clearly the strongest winds occur in general in the northern and western parts of the country. The spatial distribution of E-wind roses in Denmark indicates that the prevailing erosive wind in almost all stations is westerly with a frequency of less than 5 percent. Only in a few stations in the North and East of Denmark (SKAGEN, SINDAL, SILSTRUP and GEDSER ODDE), this frequency is near to 10 percent of the total wind observations. In FOULUM, AARHUS SYD, TYLSTRUP and TESSEBOELLE, the frequency of erosive wind is less than 2 percent in the predominant direction. Comparing E-windrose in different stations indicates that after the west direction, the frequency of erosive winds from north-west and south-west is greater than in other directions. Erosive winds coming from the north are almost not present in Denmark. Because of the almost impossible visual differentiation between all-time and dry-time wind velocity distributions, this question is discussed in sub-chapter 5.1.3 together with the statistical analysis.

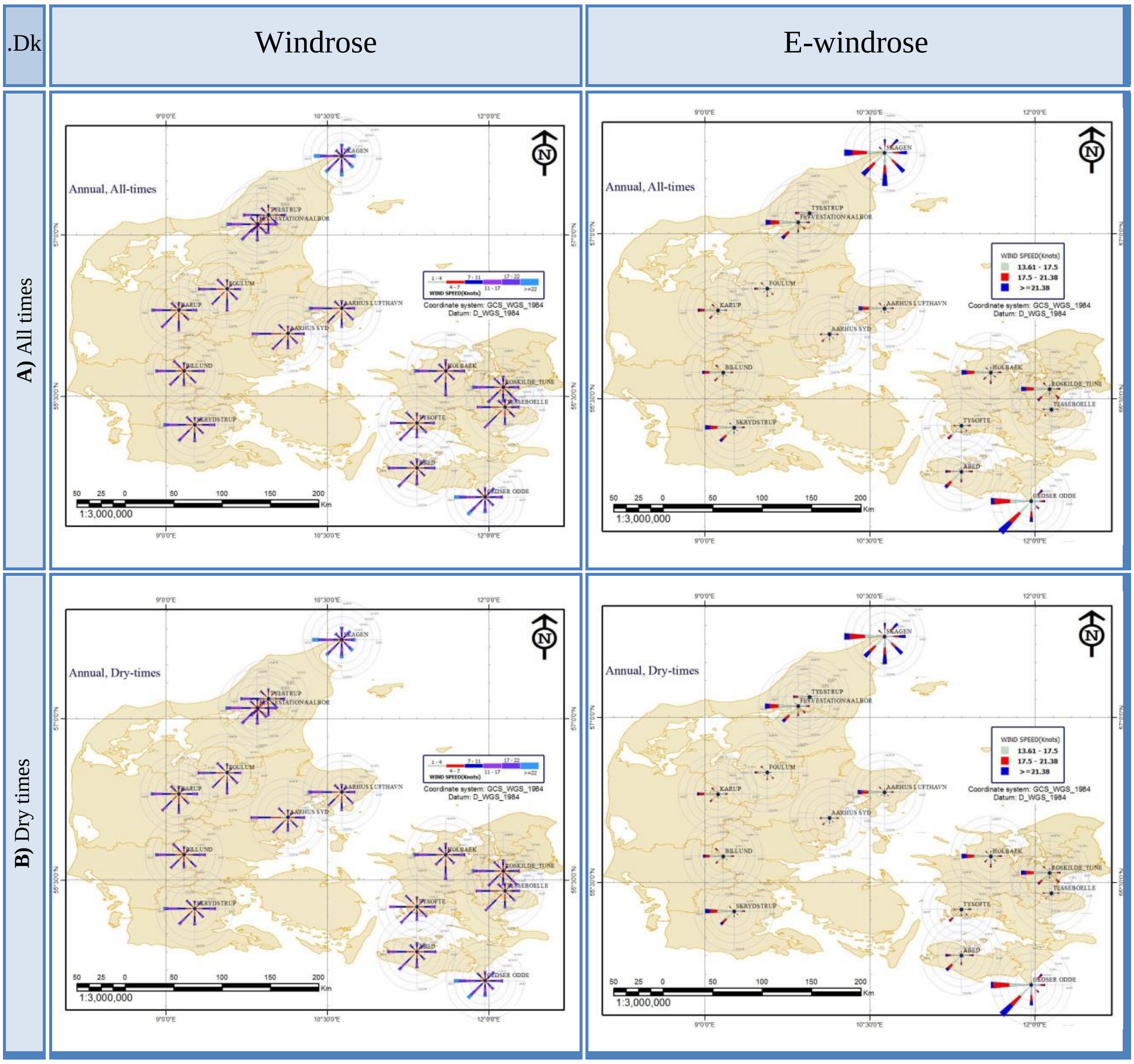


Figure 4-2: Spatial distribution of windrose and E-windrose of Denmark stations used in this study based on all-times and dry-times. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

The spatial distribution of wind roses in Switzerland indicates (Figure 4-3), the wind pattern in Switzerland is much more diverse than in Denmark. One reason among many others is the strong influence by the topography of the region. In fact, the mountainous character is responsible for the huge differences in the climate among different regions and the existence of Alps, acting as a climatic barrier in this country, lead winds into natural wind corridors across the mountains. For example the Föhn wind system is a very common meteorological phenomenon that induces mild and dry weather conditions on the respective lee side of the mountains. Because of this diversity it is impossible to find a prevailing wind direction for the whole country. Depending on the position of the weather station in relation a mountain ridge (luv or lee), or the height above sea level, the wind velocity distribution is very different. As mentioned above, these differences were among the reasons, why these two countries were selected and it will be interesting to see, if this difference is reflected in the quality of the model results.

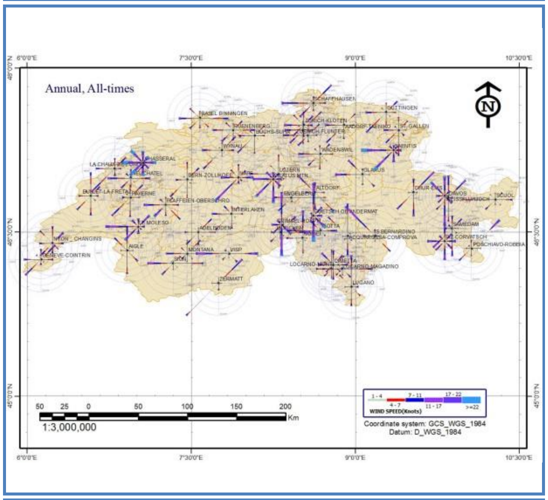
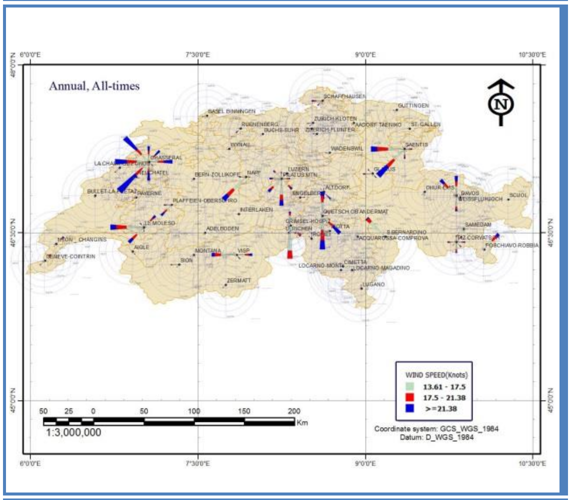
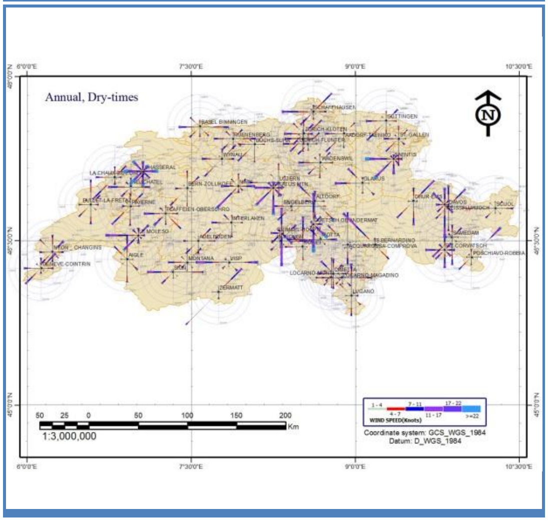
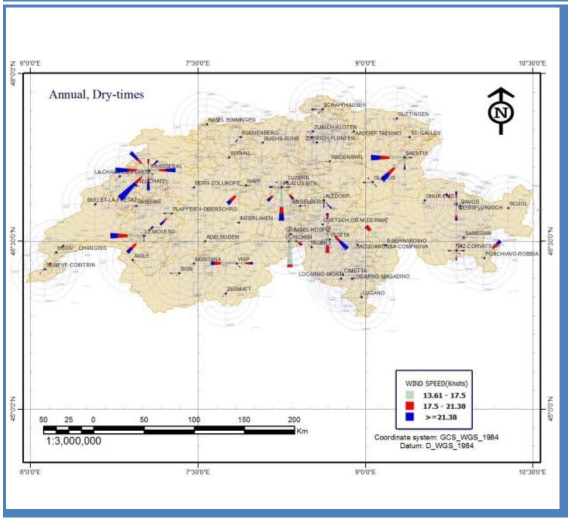
.CH	Windrose	E-windrose
A) All times		
B) Dry times		

Figure 4-3: Spatial distribution of windrose and E-windrose of Switzerland stations used in this study based on all-times and dry-times. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

4.1.2. Seasonal patterns of all winds and erosive winds

For a more detailed analysis of wind patterns in Denmark and Switzerland, their temporal distribution was investigated for the four different seasons of the year. The method of study in this section was the same as annual pattern studies with the exception that, in this part only, wind data recorded in the same season were analyzed. The beginning and end of each season was selected in accordance with astronomical calculations. Since both countries are located in the northern hemisphere the data for the seasons is in accordance with Table 4-1

Table 4-1: The data of seasons in accordance with astronomical calendar

Season	From	To
Spring	20 March	21 June
Summer	21 June	22 September
Autumn	22 September	21 December
Winter	21 December	20 March

The seasonal frequency distribution of wind and erosive wind velocity were calculated in each station for both all-times and dry-times conditions and then, their wind rose and e-wind rose were plotted. In Figure 4-4, as an example, wind rose and e-wind rose of the FOULUM station are presented.

As illustrated in Figure 4-4, in spring, summer and winter, the westerly winds are predominant in this station. The frequency of winds from this direction is more than 20 percent in these seasons and even more than 25 percent in spring and summer. However, in autumn, winds from the south are more frequent (more than 23 percent of all records).

The Evaluation of the frequency of erosive winds in the FOULUM station, by using E-wind rose, indicates that, the frequency of erosive winds in winter is greater than in other seasons and that in summer, their frequency is lowest. The prevailing wind direction of erosive winds is similar to all winds.

As mentioned above, the differentiation between all-time and dry-time seasonal wind velocity distributions is discussed in pages 106-112 with supporting statistical results.

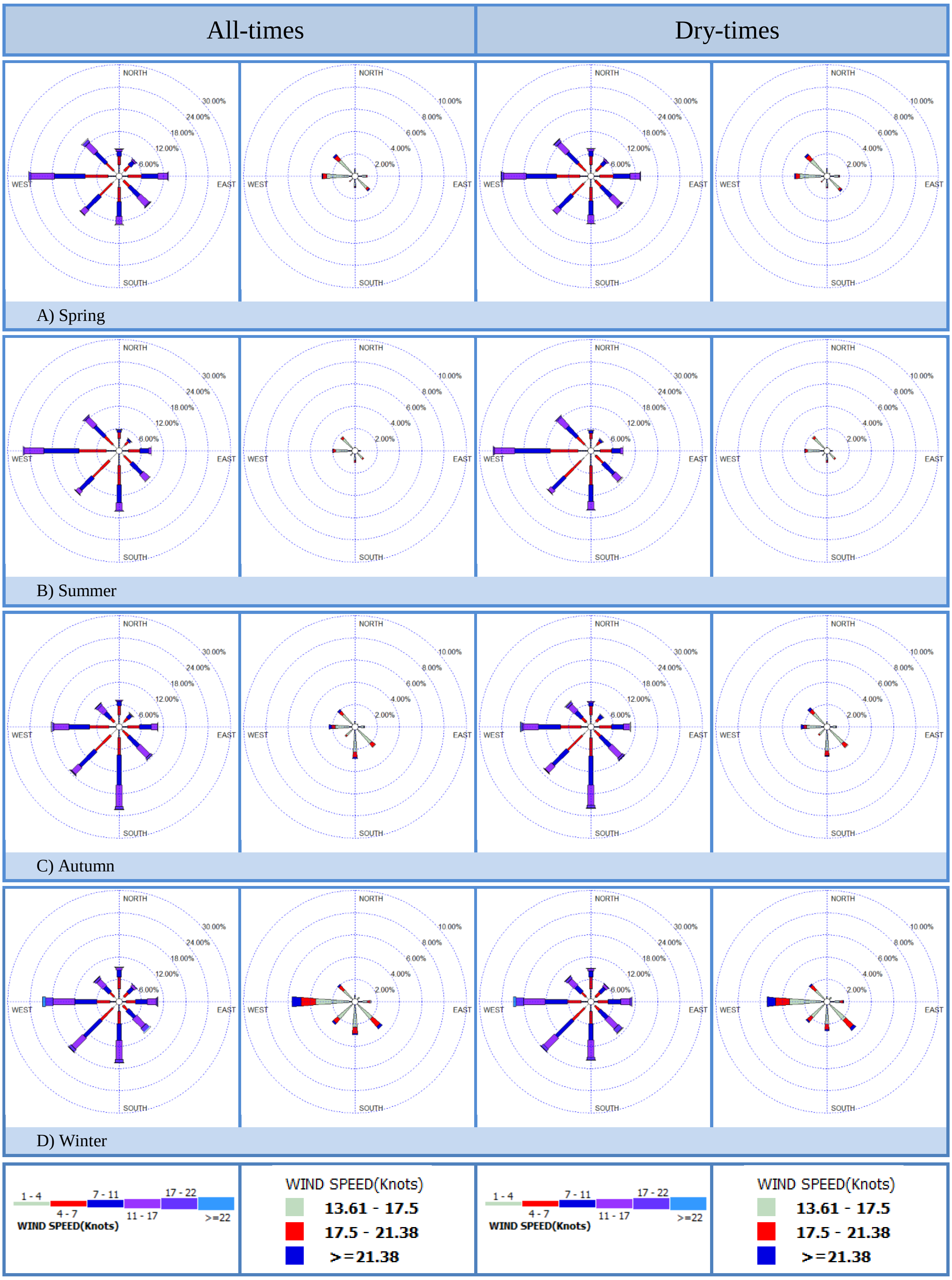


Figure 4-4: Windrose and E-windrose of different seasons in all-times and dry-times at the FOULUM Station, Denmark (Note: High resolution of seasonal diagrams for all different climate stations are enclosed in the digital appendix of the thesis)

Similar to the FOULUM station, a seasonal wind rose and E-wind rose was plotted for all studied weather stations in Denmark and Switzerland. The seasonal wind roses for all other climate stations are included in the digital appendix to this thesis. As it was done with the annual wind roses, the spatial distribution map of wind roses and E-wind roses was prepared as illustrated in Figure 4-5 and Figure 4-6 for Denmark and Switzerland, respectively.

Based on Figure 4-5, it can be said that, in almost all seasons the predominant wind direction (also for erosive winds) is westerly in all of Denmark. Based on the similarity of the wind patterns, spring and summer seasons can be grouped together as well as autumn and winter seasons.

With regards to the E-wind rose maps it can be observed that the frequency of erosive winds in winter is the highest and that, in the other seasons, except of a few stations such as SKAGEN, GEDSER ODDE and partly FLYVESTATION AALBOR, the frequency of erosive winds is not very noticeable, especially in central Jutland peninsula.

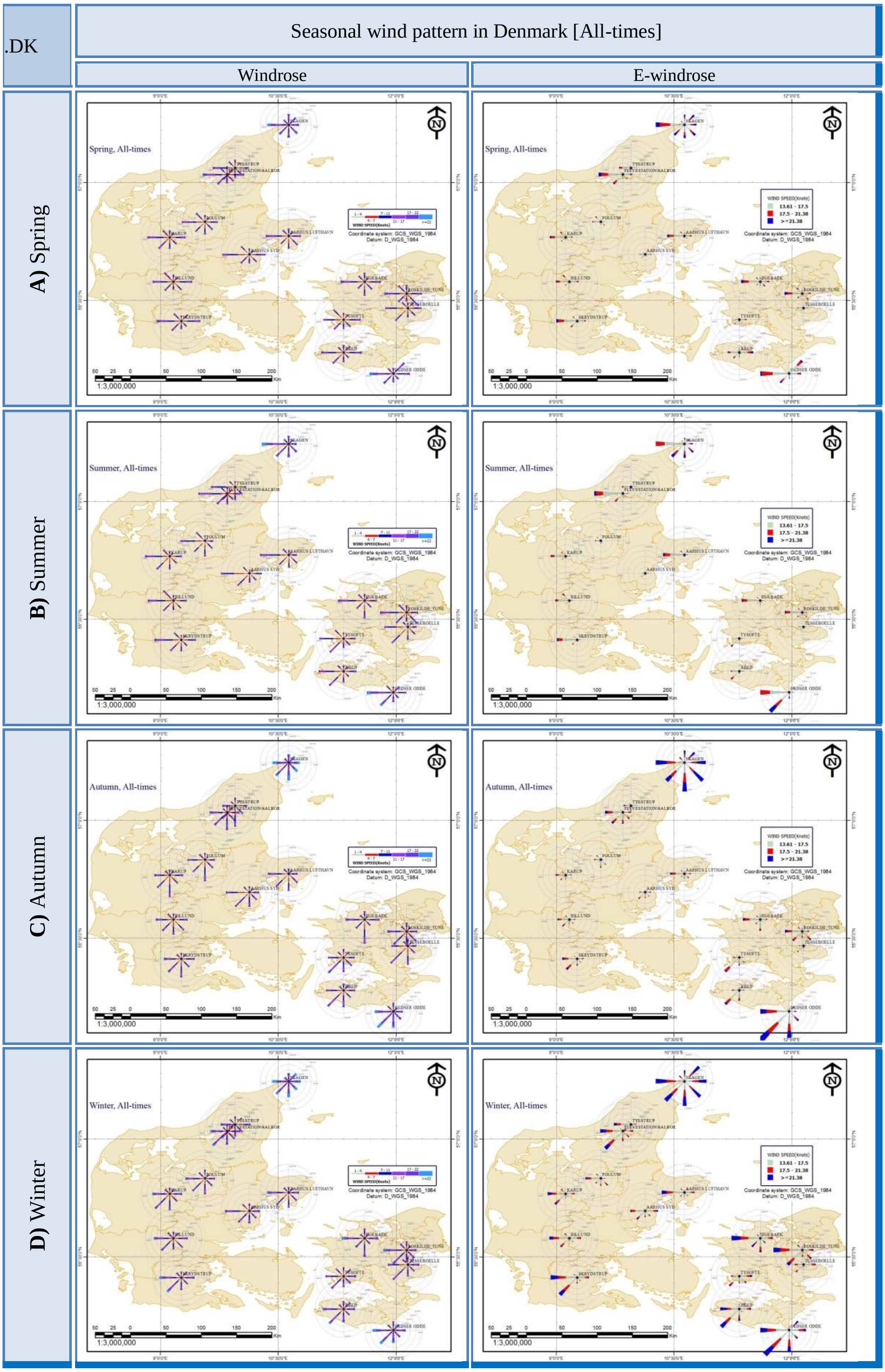


Figure 4-5: Seasonal wind map to illustrate speed and direction of wind in Denmark. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

The seasonal analysis of wind distribution (Figure 4-6) shows more or less the same diversity as the annual distribution (Figure 4-3) for Switzerland. Also the very low probability of occurrence for erosive winds can be confirmed, especially the very low one during summer. Only in a small number of stations, such as CHASSERAL, SAENTIS, LUZERN PILATUS and NAPF, the frequency of erosive winds is partly remarkable in this season. It should be noted that in Switzerland, erosive winds most often occur in central and western parts of the country and some in the eastern parts. The respective stations are often situated in higher altitudes, so the topography is probably again one of the most important factors for the occurrence of erosive winds.

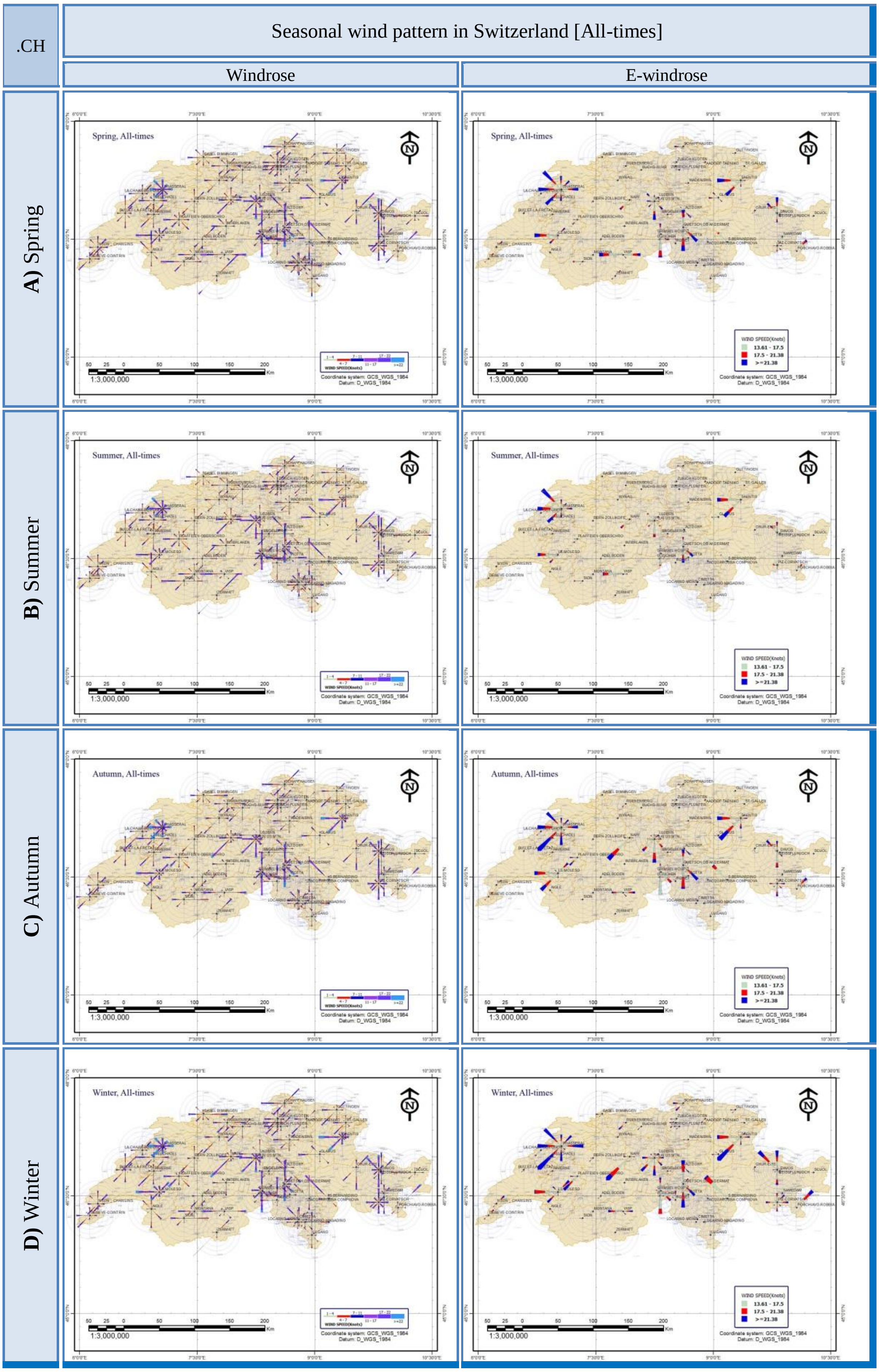


Figure 4-6: Seasonal wind map to illustrate speed and direction of wind in Switzerland. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

4.1.3. Comparison of all-times and dry-times wind speed frequency distributions

One of the features that have been considered in the proposed model is using wind data regarding to the status of surface soil moisture. Before applying this structure in the model, the frequency distribution of winds in the conventional method (all-times) and new approach (dry-times) were compared by using statistical tests. For this purpose, the frequency of winds was extracted for all studied stations. For example, Table 4-2 and Table 4-3 show the frequency of wind in different periods for the FOULUM station in Denmark.

Table 4-2: Annual, seasonal, day time and night time wind speed frequency distributions in the FOULUM station

Wind Speed Class (knots)	Annual		Day time		Night time		Spring		Summer		Fall		Winter	
	Dry	All	Dry	All	Dry	All	Dry	All	Dry	All	Dry	All	Dry	All
1	890	1761	207	618	683	1143	213	368	242	501	220	476	215	416
2	2127	4036	645	1524	1482	2512	621	970	707	1311	433	973	366	782
3	3231	6409	1044	2471	2187	3938	1074	1721	961	1978	616	1503	580	1207
4	3877	7627	1446	3188	2431	4439	1283	2012	1113	2292	746	1859	735	1464
5	3902	8022	1719	3779	2183	4243	1373	2196	1145	2342	672	1893	712	1591
6	3605	8160	1808	4100	1797	4060	1251	2131	1068	2288	659	2080	627	1661
7	3629	8007	2008	4265	1621	3742	1273	2128	1034	2074	686	2096	636	1709
8	3307	7166	2032	4151	1275	3015	1214	1906	945	1907	526	1715	622	1638
9	2988	6662	1918	3966	1070	2696	1117	1763	778	1621	449	1588	644	1690
10	2610	5818	1727	3543	883	2275	970	1537	726	1370	410	1402	504	1509
11	2226	4934	1536	3079	690	1855	821	1279	622	1114	355	1185	428	1356
12	1857	4136	1290	2553	567	1583	690	1047	456	800	309	1010	402	1279
13	1441	3296	1009	2003	432	1293	568	829	326	575	220	786	327	1106
14	1052	2487	756	1508	296	979	414	610	223	395	186	633	229	849
15	799	1927	573	1146	226	781	324	444	158	267	117	486	200	730
16	630	1512	468	901	162	611	263	369	117	201	94	369	156	573
17	408	1078	290	627	118	451	146	219	74	114	69	275	119	470
18	283	747	188	431	95	316	100	151	38	77	47	179	98	340
19	177	527	111	277	66	250	57	87	24	48	24	133	72	259
20	123	364	78	194	45	170	30	44	22	32	18	75	53	213
21	90	298	55	152	35	146	24	33	12	14	9	62	45	189
22	70	188	40	87	30	101	21	24	4	5	9	39	36	120
23	48	145	32	80	16	65	16	24	4	4	10	33	18	84
24	33	83	20	40	13	43	10	12	4	4	4	15	15	52
25	25	59	13	29	12	30	8	10	0	1	7	15	10	33
26	22	46	16	28	6	18	9	12	0	0	4	6	9	28
27	14	22	9	13	5	9	5	6	0	0	1	2	8	14
28	3	9	1	4	2	5	0	0	0	0	1	3	2	6
29	11	19	6	11	5	8	3	3	0	0	1	2	7	14
30	2	7	0	3	2	4	0	0	0	0	1	1	1	6
31	2	5	2	4	0	1	0	0	0	0	1	2	1	3
32	0	4	0	2	0	2	0	0	0	0	0	0	0	4
33	1	3	0	1	1	2	0	0	0	1	0	0	1	2
34	0	3	0	1	0	2	0	0	0	0	0	0	0	3
35	0	4	0	1	0	3	0	0	0	0	0	0	0	4
36	1	1	0	0	1	1	0	0	0	0	0	0	1	1

Table 4-3: Monthly wind speed frequency distributions in the FOULUM station

Wind Speed Class	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	Dry	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**	**Dry**	**All**
1	83	139	74	129	35	129	81	121	80	125	63	132	93	199	76	157	74	135	105	207	40	111	86	177
2	129	241	122	239	119	298	221	291	218	333	203	345	231	470	225	437	238	386	230	421	71	274	120	301
3	182	356	211	414	211	459	369	510	400	626	295	566	352	715	294	677	335	599	260	580	130	379	192	528
4	283	494	204	439	291	524	428	616	429	665	381	717	451	877	313	767	372	702	320	707	173	488	232	631
5	257	530	228	522	348	620	424	644	475	764	390	714	446	883	318	745	411	795	250	705	175	531	180	569
6	232	570	220	560	314	628	387	590	409	740	390	767	382	768	326	745	379	848	242	751	156	634	168	559
7	224	571	210	577	321	624	387	616	432	732	387	758	352	676	295	619	418	815	280	799	154	690	169	530
8	215	525	204	526	285	612	363	536	406	659	410	732	351	636	275	585	322	673	214	611	138	611	124	460
9	242	575	197	530	287	627	334	513	365	604	366	630	302	545	215	479	246	571	187	551	126	602	121	435
10	182	529	155	453	223	525	284	443	343	539	319	549	237	437	230	417	248	499	138	452	146	551	105	424
11	149	476	111	389	215	483	259	383	278	433	285	484	232	361	184	316	154	351	129	403	130	477	100	378
12	137	454	112	388	196	423	227	325	223	343	216	364	124	203	173	276	149	303	109	314	98	386	93	357
13	98	382	102	345	156	351	195	262	189	271	165	288	85	129	119	172	114	243	72	230	75	341	71	282
14	73	307	65	254	121	291	163	222	134	199	101	154	46	80	82	131	88	190	57	192	78	277	44	190
15	65	281	47	221	112	207	124	163	94	128	93	146	32	50	50	78	64	117	40	155	56	229	22	152
16	41	210	49	189	79	190	102	127	91	121	47	87	33	41	44	60	38	90	37	108	31	161	38	128
17	36	168	42	172	57	138	59	87	40	60	33	51	19	27	17	20	35	59	23	80	28	122	19	94
18	33	119	36	124	29	90	42	51	31	44	19	46	5	10	11	17	20	42	21	65	18	69	18	70
19	30	112	26	79	23	63	19	27	21	30	5	12	2	7	9	11	13	26	11	45	8	49	10	66
20	12	70	23	74	21	64	14	15	7	11	3	8	3	6	9	9	10	15	9	23	8	31	4	38
21	12	70	19	68	17	46	13	17	4	4	0	2	0	1	7	7	5	7	3	13	4	20	6	43
22	11	44	16	39	12	30	10	11	2	2	1	1	0	0	3	3	1	2	3	11	4	15	7	30
23	7	44	6	23	11	22	5	7	2	4	0	2	1	1	1	1	2	3	3	6	2	9	8	23
24	11	35	1	7	3	8	5	5	2	3	1	1	0	0	1	1	3	3	1	3	2	7	3	10
25	3	16	4	9	5	10	3	3	1	3	1	1	0	0	0	0	0	1	0	2	4	6	4	8
26	5	18	1	6	6	8	4	5	0	1	1	1	0	0	0	0	0	0	0	1	4	4	1	2
27	1	5	1	2	1	3	4	4	1	1	0	0	0	0	0	0	0	0	0	0	0	0	6	7
28	0	3	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	1	1
29	4	8	1	1	1	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4
30	1	4	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
31	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0
32	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
34	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

In order to see if the calculation of wind velocity distributions for dry-times shows different results than for all-times, the Wilcoxon test was selected. The Wilcoxon Rank Sum test is a nonparametric statistical test that can be applied by the null hypothesis of “two populations have the same continuous distribution”, so it is appropriate to determine whether two samples can be considered identical or not (on the basis of their ranks). Since our data is paired data, for all-time and dry-time, it is important to use only a paired sample mode of the t-test or Wilcoxon test. Using a paired sample mode means that dry-time and all-time frequency distributions are only comparable for a given wind speed class. It is obvious that, the order of the pairing is important in paired data as opposed to unpaired data.

The pairwise Wilcoxon test was implemented in R environment by using the Wilcox.test function with argument Paired=T. It should be mentioned that in this research, at first, three methods of two-sample tests were selected to compare pair of wind speed distributions, which were: the Wilcoxon test, t-test and Kolmogorov–Smirnov test (K-S test). Since, there is no paired-wise K-S test, therefore, using K-S test was rejected from our studies as it is not appropriate for testing our desired data.

The Wilcoxon test was separately implemented for two different cases: all winds ($V \geq 1$ knot) and erosive winds ($V \geq 13.5$ knot). As presented in the above tables, for each station, 19 statistical tests were performed, which include 17 tests for monthly, seasonal and annual samples and two tests for day and night periods. Thus, in Denmark with 15 appropriate weather stations, 570 pairs of frequency distribution were tested and in Switzerland exactly 2052 tests were performed for 54 selected weather stations. The interpretation of obtained p-values, computed by using the pairwise Wilcoxon test and after correction for multiple testing by using the BH method (Benjamini & Hochberg, 1995), is presented in Figure 4-7 and Figure 4-8, respectively for Denmark and Switzerland.

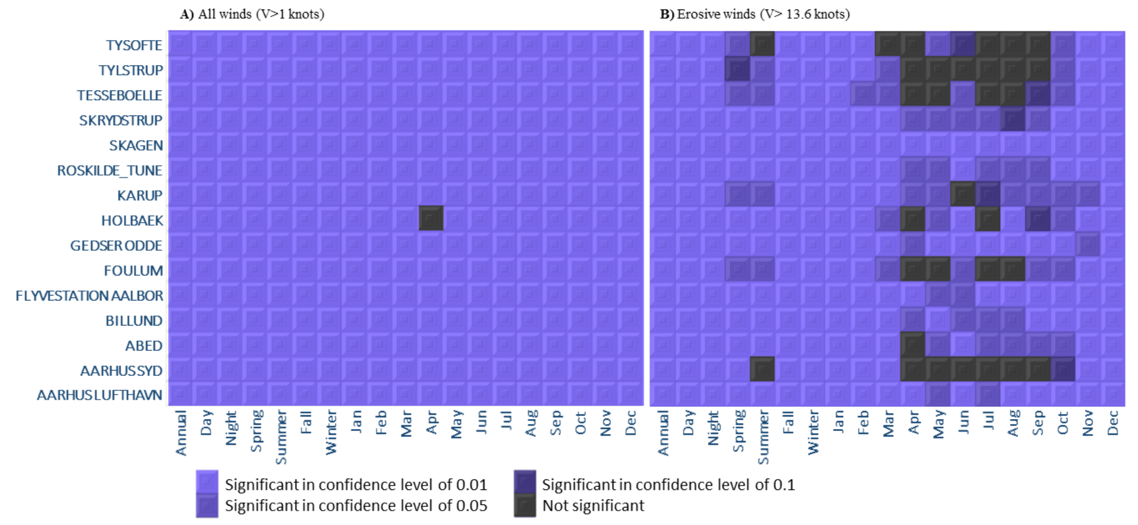


Figure 4-7: The Wilcoxon test results of comparison of dry-times and all-times frequency distribution of wind speeds for 19 different scenarios at selected stations in Denmark

The results of the Wilcoxon test for Denmark are presented in figure 5-7. As the legend of this heat-map indicates, the color of each cell reflects the p-value situation of each test. The lighter blue cells indicate that the difference between two compared frequency distributions is more significant and the black cells denote that the difference is not significant, which means that the frequency distribution of wind speed classes in both situation (dry-time and all-time) have been the same.

As shown in the heat-map on the left for all winds, only in HOLBAEK in April, the difference has not been significant. In other cases and with confidence levels of 99%, the difference between dry-time and all-time frequency distribution of wind speed classes has been significant. In other words, by implementing the dry/wet approach, the resulting wind velocity distributions are significantly different in almost all stations. This actually proves the initial assumption that a calculation of wind velocity distributions should be accomplished separately for dry and wet times, because they can be very different.

The heat-map on the right for erosive winds indicates that in eight weather stations, in the months from March to October, for at least one month (KARUP) and a maximum of six months (TYSOFT, TYLSTRUP, AARHUS SYD), the test was not significant. The reason for this is the actual occurrence, or better the lack of erosive wind events at these weather stations. The Wilcoxon test shows also no significant differences, if actually no erosive winds occurred at these stations, which was the case in most of these scenarios. This coincides with the very low frequency of erosive winds especially during the summer months, which is visible in Figure 4-5. In total, out of 285 erosive wind tests 254 tests (89.1%) are significant, at least at the 90% confidence level.

The Wilcoxon test was also performed in the same way for the weather stations in Switzerland. The results are presented in Figure 4-8. The heat map on the left displays the results for all winds. In 30 out of 1026 tests (2.9%) the differences between all-day and dry-day frequency distributions were non-significant, as for example in SCUOL and BUCHS-SUHR weather stations. In all other situations the test was significant at 99% confidence level.

Comparing the frequency distribution for erosive winds, it is visible that in about 11 stations the difference is significant in all 19 scenarios, but the rest of the stations show no differences in at least one scenario.

By controlling the frequency distribution of the stations where the difference was not significant, it was determined that both compared frequencies were identical for two main reasons. First of all, the occurrence of erosive winds in the desired stations has been negligible. Secondly, the length of wet times was very short, consequently that caused almost the entire period to be considered as dry situation.

Figure 4-8: The Wilcoxon test results of comparison of dry-times and all-times frequency distribution of wind speeds for 19 different scenarios at selected stations in Switzerland

4.2. Impact of climate change

The evidence which has been obtained from various studies indicates that the Earth's climate is changing mainly due to the wide range of human activities and increases in the amount of greenhouse gases released in the world. However, these evidences are strongly related to the used data source, the research method and the situation of the studied location (IPCC, 2007a).

In the foll owing sub-chapters the outcome of the climate change assessment for Denmark and Switzerland are specified. At first the more conventional climate indicators, such as temperature and humidity were investigated (Figure 4-9). These parameters were followed by 'normal' wind factors (Figure 4-10) and the three erosive wind factors (Figure 4-11).

4.2.1. Trend of climate variables

For all of the ten investigated climatic factors, the trend of climate change was separately evaluated for the two different time periods with different to soil moisture conditions. The maps on the left were computed using the all-times approach and the ones on the right using the dry-times. To find a monotonic trend in each climatic factor, the non-parametric Mann-Kendall trend test was selected. This test has been discussed earlier in chapter 3 (see page 77). The intensive data preparation and homogenization for the climate trend analysis has also been explained in detail in previous chapter 3 (sub-chapter 3.1). Detailed tables with all results of the trend analysis (including significance values) of ten selected climatic variables for all climate stations in Denmark and Switzerland are attached in the appendix. To improve readability and display the spatial pattern of trends in the countries, the most important parameters for this study were displayed in maps, using the ArcGIS 10.0. The different parameters are categorized into three different groups: (1) air temperature, precipitation, dry time period, and relative humidity (Figure 4-9); (2) wind factors including maximum and average wind velocity (Figure 4-10), and (3) erosive wind factors (Figure 4-11)

4.2.1.1. Trend of climate variables in Denmark

The trend analysis of air temperature in Denmark (Figure 4-9, A) reveals a biased pattern. More than half of the stations in Jutland show increasing temperature trends and all of the stations on the eastern islands show no or negative temperature trends. Apart from very few differences, this observation is valid also for the trend analysis in dry-periods. It should be emphasized that in all maps the significant trends are presented with blue and red triangles according to the trend direction (red shows increasing and blue decreasing trend). Non-significant trends have been considered also as no trend and were illustrated by green circles. The lack of a trend for some stations does not necessarily mean that there is no trend in this region. It could also be possible that the time record at these stations is just not long enough to enable detecting a trend. For example in FOULUM and TYSOFT with respectively 14 and 9 years statistical period the trend was not significant in most cases.

Changes in precipitation are harder to measure according to the existing records, because of the greater difficulty in sampling precipitation and also it is expected that precipitation will have a smaller fractional change as the climate warms (Stocker et al., 2014). In our study also it was not possible to find a clear countrywide evidence for a positive or negative trend for precipitation (Figure 4-9, B left). An increasing trend was only observed at two stations (FOULUM and AARHUS LUFTHAVN) and a decreasing trend was perceived in SKAGEN and FLYVESTATION AALBOR. For the number of dry times, (Figure 4-9, B right) an increasing trend can be seen in six out of 15 stations and only two show a decreasing trend. An increase of dry periods would underline the argumentation from previous chapter, that dry-times should be considered when wind velocity distributions for wind erosion studies are calculated. It seems that using this factor instead of precipitation could be even more important for wind erosion research than just the amount of precipitation.

As described in previous chapters, soil humidity is an important reference parameter, which can be used to estimate the influence of soil moisture on wind erosion, like it is done in this study for calculating dry-times (Figure 4-9, C). The trend of relative humidity in Denmark does not show a clear pattern, especially when all observed data are included in the analysis. Some stations like FOULUM and GEDSER ODDE increase and some others decrease (KARUP, TYSOFT) or show no trend at all (e.g., BILUND, ABED, SKAGEN). For dry times, however, this indifferent pattern turns a little bit and shows increasing humidity over the years in more stations. This observation indicates that the proposed model would increase the number of days, which are excluded from the wind erosion risk assessment, since more humidity leads to less erodible soil surfaces (see model description in sub-chapter 3.2).

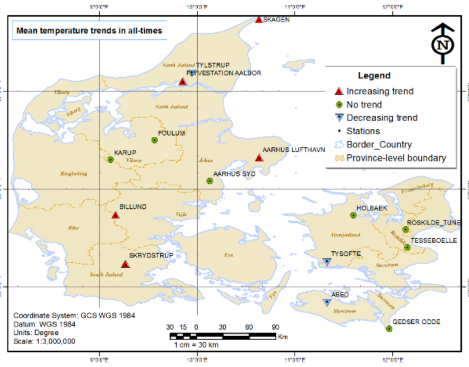
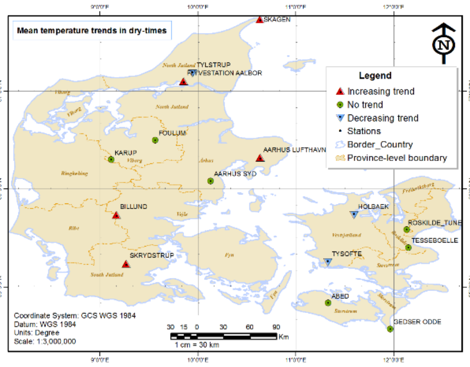
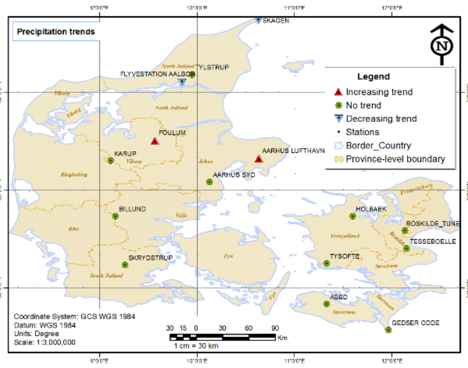
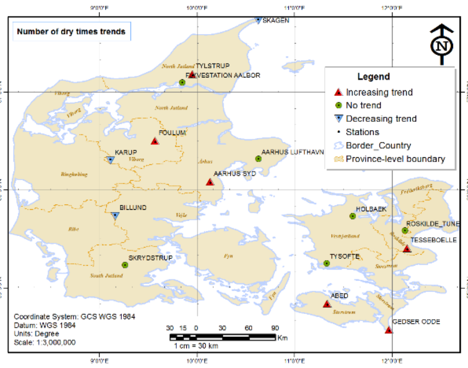
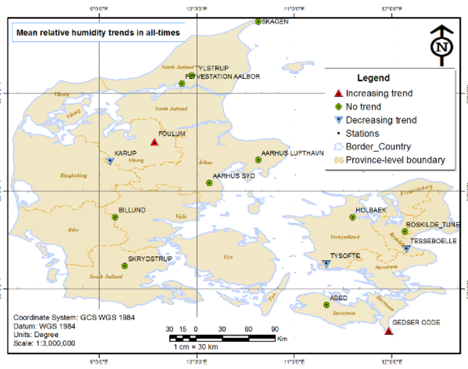
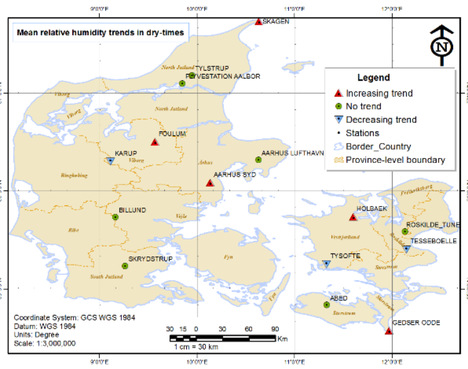
.Dk	Annual climatic factors in Denmark	
	All-times	Dry-times
A) Mean air temperature		
B) Precipitation (left) dry-time periods(right)		
C) Relative humidity		

Figure 4-9: The trend of different climatic elements in both dry and all times, Denmark (Note: High resolution maps are enclosed in the digital appendix of the thesis)

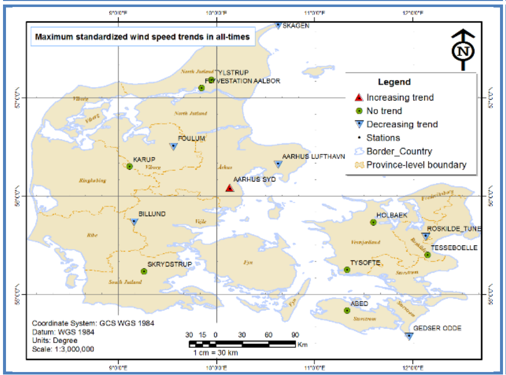
The analysis of the impact of climate change on selected wind factors revealed that the behavior of wind in nature is very complex and, therefore, only weak tendencies could be found. The maximum wind speed in both all-times and dry-times decreased in five stations and only in AARHUS SYD a positive trend was detected (Figure 4-10, A). This is very interesting to see, because a probable decrease in maximum wind velocities would decrease the threat of wind erosion for Denmark in the future. For mean wind velocity, prevailing wind direction and wind power density no clear trend could be found, neither for all-times nor dry-times. Since the maximum wind speed is the most important factor for wind erosion, it can be assumed that the possible risk of wind erosion decreases in future. This trend, however, is not that strong that it can be expected to have a major impact on land management in the near future.

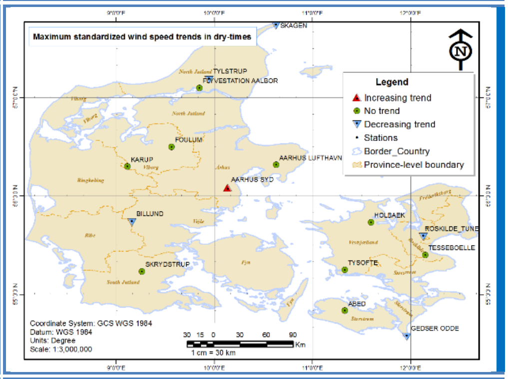
.Dk

Annual wind factors in Denmark

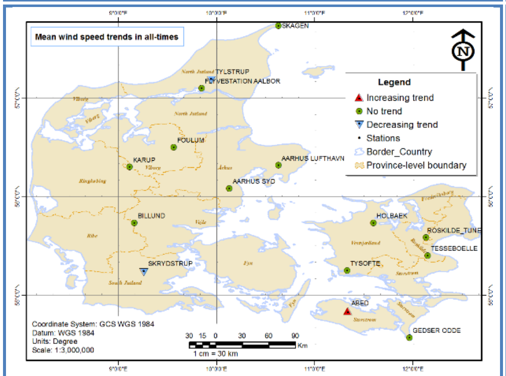
All-times | Dry-times

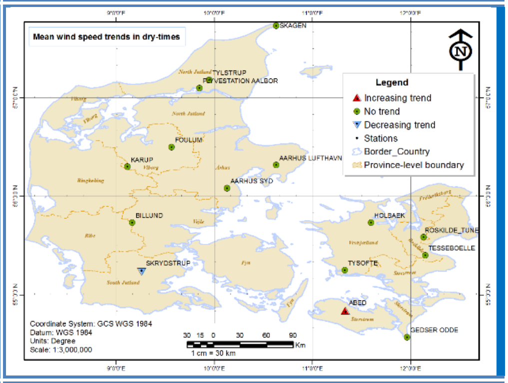
A) Maximum wind speed



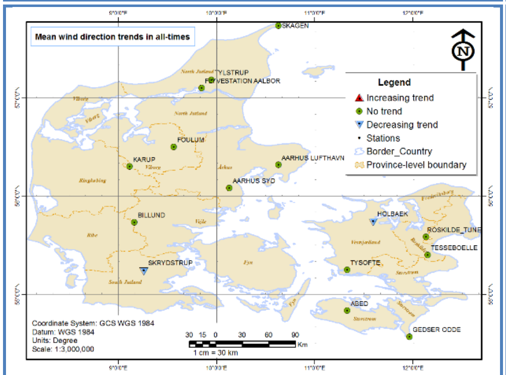


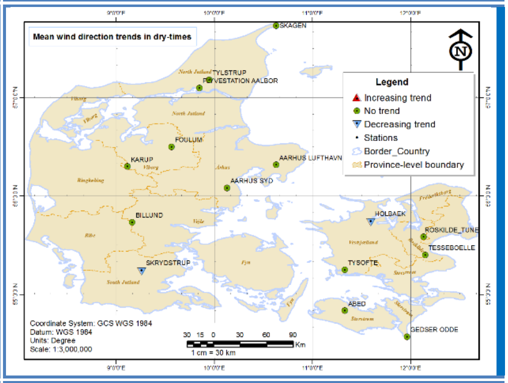
B) Mean wind speed



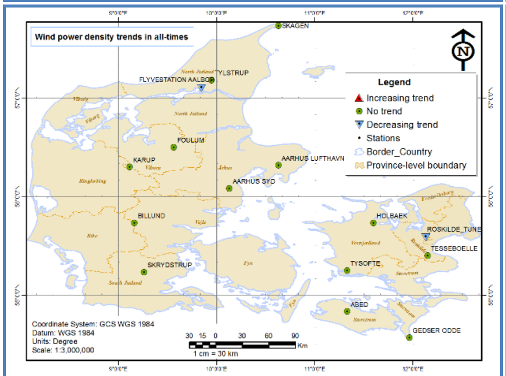


C) Wind direction





D) Wind Power Density



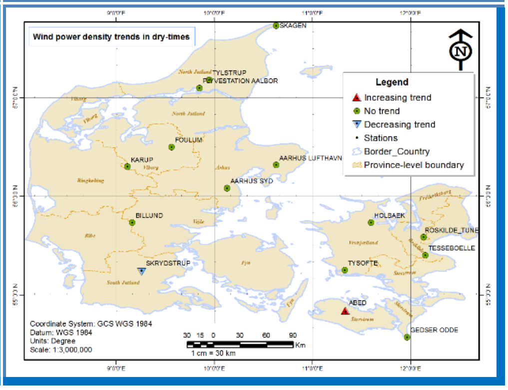


Figure 4-10: The trend of various studied wind factors in both dry and all times, Denmark. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

Regarding annual erosive winds in Denmark, three different factors were examined which are the number of erosive winds, mean wind velocities above the threshold wind velocity as well as Erosive Wind Power Density (EWPD). As illustrated in Figure 4-11, the trend of number of erosive winds was negative at five stations in all-times, but in dry-times the pattern changed significantly. Only one station still experienced a decreasing trend (SKRYDSTRUP) and five stations showed instead an increasing trend. This development of increasing number of dry days is especially prevalent for the eastern Islands. Similarly, the trend analysis of mean wind velocities above the threshold wind velocity revealed that in both approaches, at three stations (exactly the same stations), a negative trend was observed and in one station (ABED in all-times, and AARHUS SYD station in dry-times), the trend was increasing. For all other stations the trend was not significant. For EWPD almost the same stations show a similar decreasing trend, but no stations with increasing trends exist.

Based on all analyzed climate parameters it can be concluded that the trend patterns are not clearly pointing in a specific direction and it is, therefore, not possible to tell if wind erosion in future will decrease or increase in Denmark. For example the effect of a likely decrease in maximum wind velocities together with an increase in relative humidity stands against a trend to more dry days during the year. Which one of these factors is more important is not possible to say at this moment. Especially the lack of trends in most stations creates a hindrance to get a clear pattern. As mentioned above, the missing trends do not necessarily mean that there are no trends. The reason could be contradicting monthly or seasonal trends or too short time series.

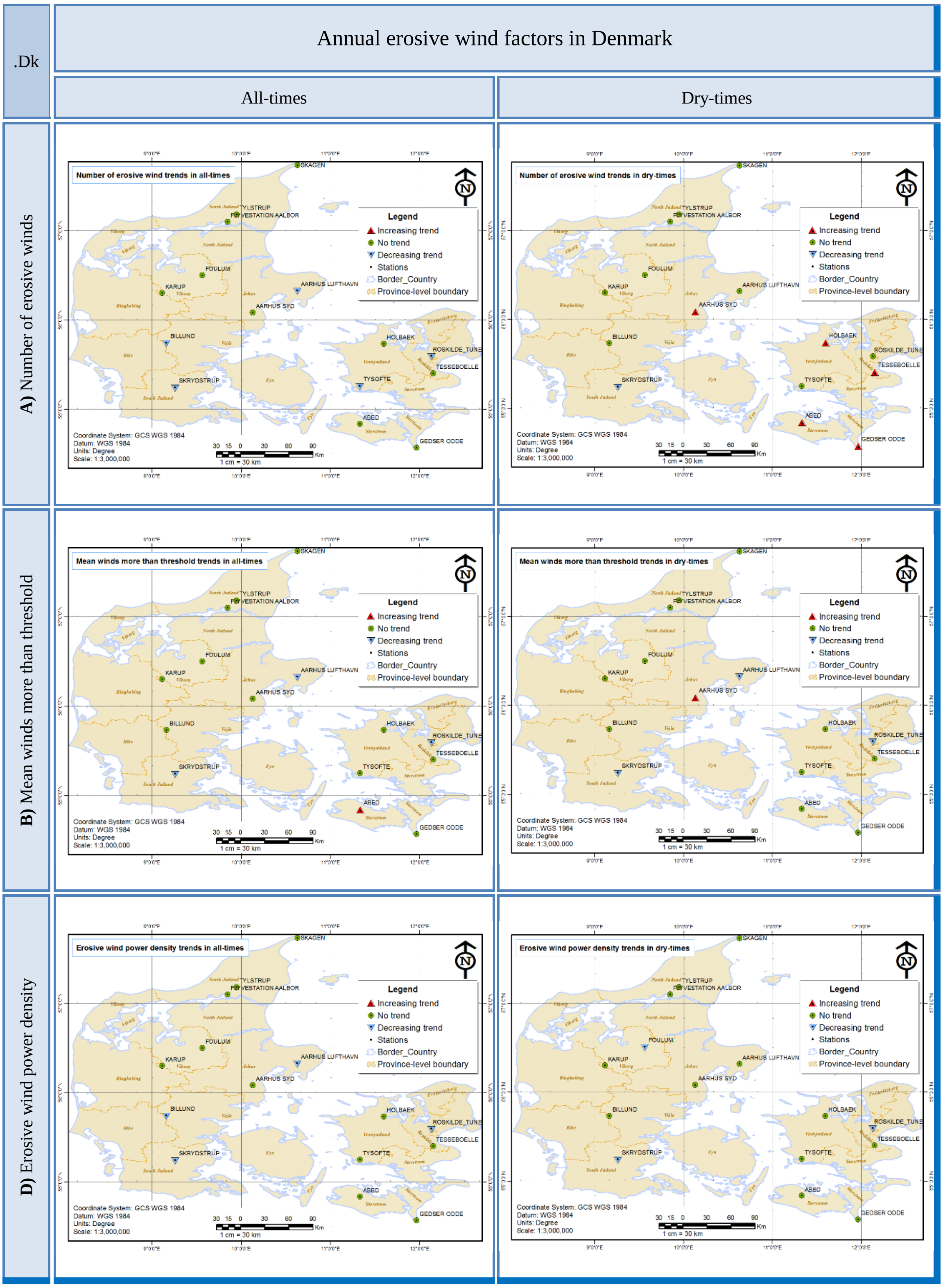


Figure 4-11: The trend of erosive wind factors in both dry and all times, Denmark. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

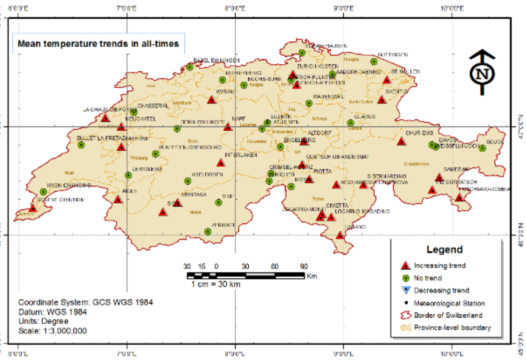
4.2.1.2. Trend of climate variables in Switzerland

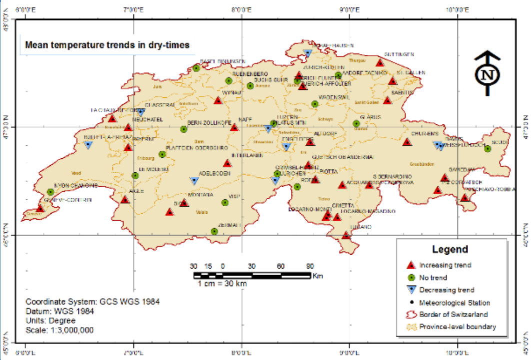
In Switzerland, the trend of climate change was investigated in 54 appropriate weather stations. As illustrated in Figure 4-12, the impact of climate change on ambient air temperature was very clear. An increasing trend was observed across the country with a significance level of at least 90%. Nine of the stations that did not show a trend for all-times, showed a decreasing trend for dry-times. In contrast to Denmark, no regional differentiation was possible. Main reasons for this are most probably the dominating influence of topography and the lack of contrast between maritime and continental influences, as they are present in Denmark.

Like in Denmark, the trend for precipitation was less pronounced than the trend of dry time periods. A majority of the stations in the Central Plateau and the central Alps show this trend of more dry times in the year and most of the stations that experience an increase of precipitation are situated in the southern and eastern parts of the country. Only very few stations simultaneously experience an increase of precipitations and an increase of number of dry times (LE MOLESO, ZERMATT, CIMETTA). This means that, at these stations, although the amount of precipitation is increasing, the frequency of rainfall is decreasing. Consequently, it can be assumed that the few rainfall events that occurred, must have had higher return periods (stronger events). The pattern for relative humidity is not that distinct as for the other factors, but at least for the dry-times a more positive trend can be observed as well. The general trends of temperature, precipitation, number of dry times and relative humidity are more pronounced, but point into the same direction than the ones in Denmark.

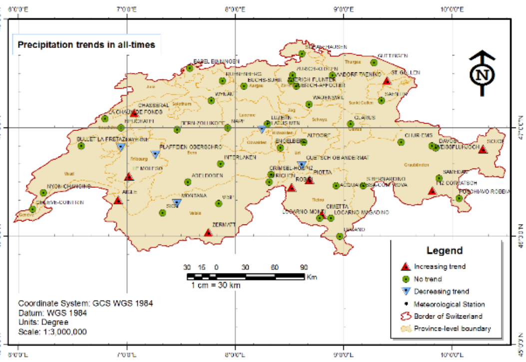
.CH	Annual climatic factors in Switzerland	
	All-times	Dry-times

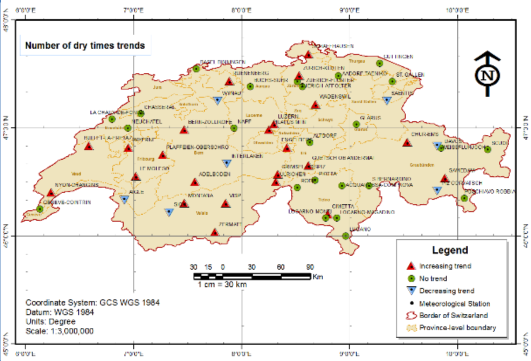
A) Mean air temperature



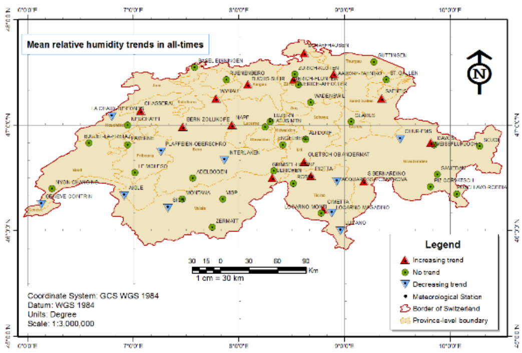


B) Precipitation (left), dry-time periods (right)





C) Relative humidity



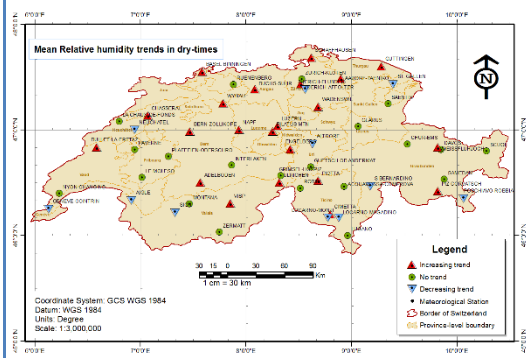


Figure 4-12: The trend of different annual climatic factors in both dry and all times, Switzerland. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

Despite the much longer time series in Switzerland than in Denmark, the trend pattern for the investigated wind factors shows no trend for most of the stations. The trends that can be observed also show a rather heterogeneous distribution of increasing and decreasing trends. Maximum wind velocities seem to decrease in the Northwest. However, this is not present for mean wind velocities. Like for all other factors, the differences between all-, and dry-times are rather minimal in Switzerland. The wind direction, like in Denmark, showed no trend at all for most of the stations. The wind power density (WPD) was statistically significant in more weather stations, but like other wind factor, the observed trend was mostly decreasing. Only seven out of all investigated stations showed increasing WPD's (Figure 4-13, D).

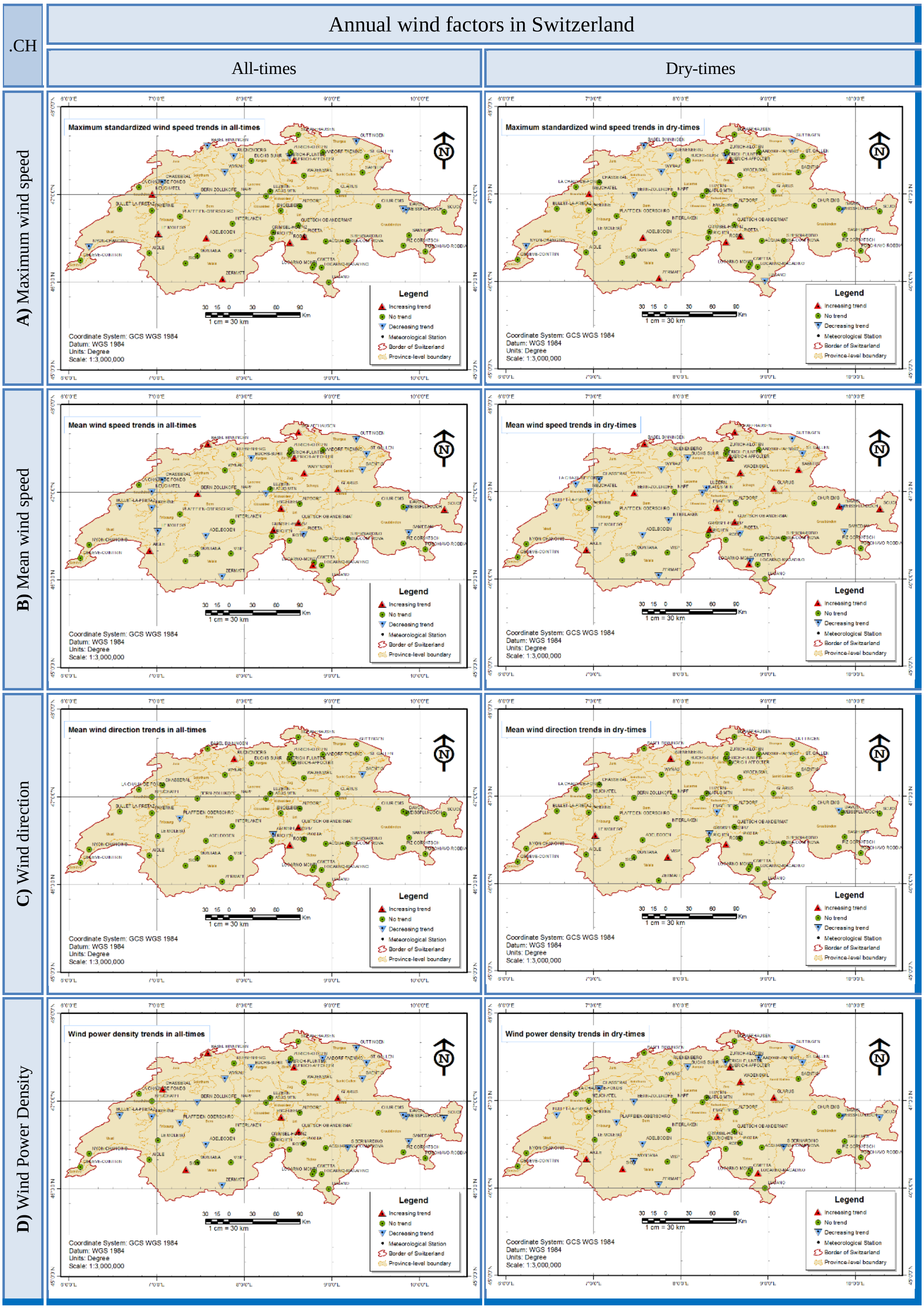


Figure 4-13: The trend of various studied wind factors in both dry and all times, Switzerland. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

As illustrated in Figure 4-14, the trend of erosive wind factors was not significant in most of the analyzed weather stations. Only in a few stations, the trend was statistically significant at least in 90% confidence level with some stations showing increasing and others decreasing trends. Only the stations GRIMSEL-HOSPIZ (increase) and S BERNARDINO (decrease) show the same trend for all investigated erosive wind factors. Thus, as reported by Reddaway & Bigg (1996) and Evans, Smith, & Oglesby (2004), this is presumably the result of complex mesoscale atmospheric circulation in this area. The main reason for the lack of significant trend in most of stations can be associated with the low frequency of erosive winds in these regions.

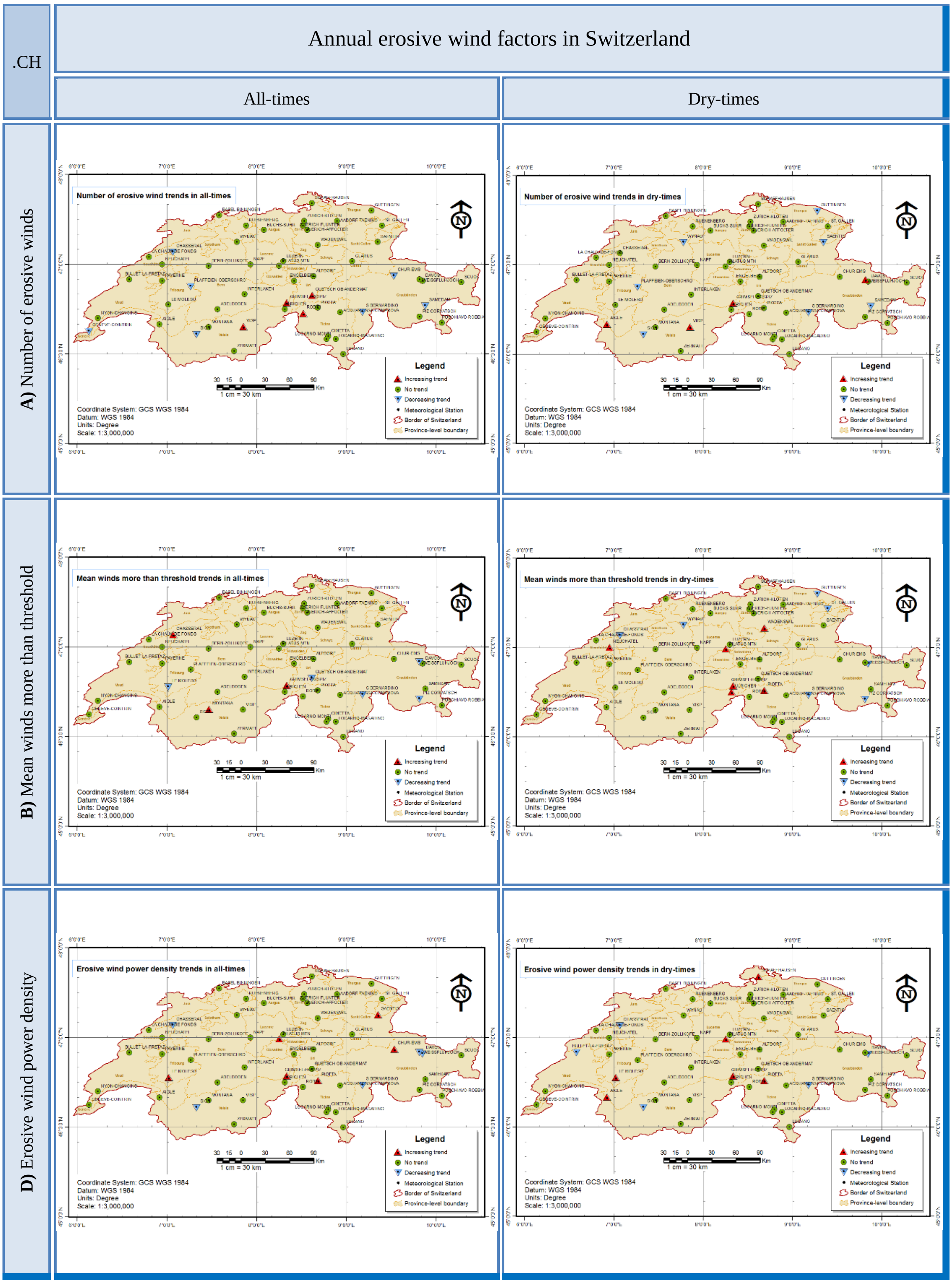


Figure 4-14: The trend of erosive wind factors in both dry and all times, Switzerland. (Note: High resolution maps are enclosed in the digital appendix of the thesis)

4.2.2. Magnitudes of change in meteorological variables

As part of the effort to understand the impact of climate changes, several studies in recent years have examined the trend of wind speed in regions around the world, but it can certainly be said that, there is not yet enough knowledge about the trend of this phenomenon. “The main reason for this lack of information is that the quality of the observational records of near-surface wind is generally too poor for assessing changes in the wind climate” (Smits et al., 2005), thus only a few stations specified a systematic change in wind variables on the basis of near-surface wind speed and wind direction observations.

On a global scale, the average trend of wind speed is calculated $-0.011\,m\,s^{-1}a^{-1}$ with a standard deviation of $0.026\,m\,s^{-1}a^{-1}$ by using the 852 stations located across the globe from 1979-2010 (Peterson et al. , 2011). This global mean value of trend is an arithmetic mean, without weighting applied. Furthermore, Peterson et al. (2011) reported a value of $-0.0093\,m\,s^{-1}a^{-1}$ as a global wind velocity trend which was weighted according to local station density using a standard National Climatic Data Center area averaging approach.

McVicar et al. (2012), by reviewing 146 regional studies, concluded that declines in terrestrial wind velocity are geographically wide spread, with declines reported in the tropics and mid-latitudes of both hemispheres, and increases reported at high-latitudes (i.e. latitudes almost greater than 70°) also in both hemispheres.

In addition to this widespread latitudinal dependence of wind velocity trend, there are some remarkable exception, as for instance in several studies increasing wind speed in coastal regions has been observed, which agrees with increasing wind velocities on oceans, measured by both in situ systems (anemometers located on ships or buoys) and remote sensing techniques (McVicar et al., 2012).

As described in the methods chapter, the monotonic Mann-Kendall trend test was used to quantify the significance of trends and it could not calculate the magnitude of change in desired variables. Thus, to estimate the magnitude of trend, the Sen’s slope estimator method was used in this research and results presented in this section for both Denmark and Switzerland. Table 4-4 show the magnitude of trends estimated by the Sen’s slope estimator for ten climatic variables in studied weather stations of Denmark in both all-times (conventional method) and dry-times. The numbers in the table refer to the magnitude of trend of each variable in its unit per annum and the asterisks above the numbers show the confidence level of the trend which is 99%, 95% and 90%, respectively for three, two and one asterisks. Furthermore, above each number, a small number can also be found which refers to the type of time series that have been used to calculate the trend. Therefore [“1”], [“2”] as well as [“3”,] respectively are representing an annual, monthly and seasonal time series. For example trend slope of maximum and mean temperature in FOULUM estimated 0.11 and -0.05 respectively that the amount of maximum temperature was significant but the mean temperature was not significant.

Table 4-4: The magnitude of trends estimated by the Theil-Sen estimator method for several climatic variables of selected weather stations in Denmark

	Stations	T_{max}	T_{mean}	RH_{mean}	$DewP_{mean}$	V_{max}	V_{mean}	Vt_{mean}	NEW	WPD	EWPD
		$°C\,a^{-1}$	$°C\,a^{-1}$	$\%\,a^{-1}$	$°C\,a^{-1}$	$m\,s^{-1}a^{-1}$	$m\,s^{-1}a^{-1}$	$m\,s^{-1}a^{-1}$	$Record\,a^{-1}$	$w\,m^{-2}a^{-1}$	$w\,m^{-2}a^{-1}$
All-times (Conventional way)	AARHUS LUFTHAVN	0.01^{3}	0.03^{***1}	-0.11^{3}	0.00^{3}	0.00^{3}	0.00^{3}	-0.01^{**2}	-0.2^{**1}	-0.33^{3}	-1.31^{***2}
	AARHUS SYD	0.07^{3}	-0.01^{3}	-0.57^{3}	0.01^{3}	0.21^{**2}	0.01^{3}	0.05^{3}	2.1^{3}	0.4^{3}	4.9^{3}
	ABED	0.06^{3}	0.00^{3}	0.06^{3}	-0.04^{3}	-0.06^{3}	0.04^{*1}	0.04^{*3}	6.46^{3}	1.74^{3}	4.75^{3}
	BILLUND	0.03^{***1}	0.04^{***1}	-0.06^{3}	0.04^{***1}	-0.01^{***1}	-0.01^{3}	0.00^{3}	0.00^{3}	-0.05^{3}	0.00^{3}
	FLYVESTATION	0.05^{***1}	0.05^{***1}	0.00^{3}	0.05^{***1}	0.04^{3}	-0.02^{3}	-0.01^{3}	0.33^{3}	0.00^{3}	0.32^{3}
	FOULUM	0.11^{*3}	-0.05^{3}	0.2^{***1}	0.02^{3}	0.00^{3}	0.00^{3}	-0.02^{3}	-6^{3}	0.09^{3}	-3.38^{3}
	GEDSER ODDE	-0.05^{3}	-0.08^{3}	0.13^{*1}	-0.05^{3}	-1.21^{***3}	0.02^{3}	0.02^{3}	12.12^{3}	1.42^{3}	0.83^{3}
	HOLBAEK	-0.05^{3}	-0.03^{3}	-0.11^{3}	-0.01^{3}	-0.51^{3}	0.01^{3}	0.01^{3}	0.12^{3}	-0.09^{3}	1.14^{3}
	KARUP	0.04^{3}	0.01^{3}	0.00^{3}	-0.05^{3}	0.00^{3}	-0.01^{3}	-0.01^{3}	-0.58^{3}	0.06^{3}	-0.33^{3}
	ROSKILDE_TUNE	-0.04^{3}	0.00^{3}	-0.07^{3}	0.08^{***1}	-0.09^{***1}	-0.01^{3}	-0.02^{***2}	-1.46^{***2}	-1.24^{***2}	-1.62^{**2}
	SKAGEN	0.00^{3}	0.02^{***1}	0.04^{3}	0.00^{3}	-0.17^{**3}	0.00^{3}	0.00^{3}	-0.24^{3}	-0.03^{3}	-0.5^{3}
	SKRYDSTRUP	0.02^{3}	0.03^{**1}	-0.06^{3}	0.03^{*1}	-0.08^{3}	-0.05^{***2}	0.00^{3}	0.00^{3}	-0.74^{3}	-5.3^{**3}
	TESSEBOELLE	-0.01^{3}	-0.14^{3}	-0.23^{***1}	-0.12^{**1}	0.42^{3}	-0.03^{3}	0.04^{3}	-11.67^{3}	0.51^{3}	-3.85^{3}
	TYLSTRUP	-0.2^{**1}	-0.2^{**3}	-0.01^{3}	0.00^{3}	-1.09^{3}	0.00^{3}	0.06^{3}	-23.38^{3}	-3.91^{3}	2.57^{3}
	TYSOFTE	-0.17^{**1}	-0.22^{**3}	-0.28^{***1}	-0.19^{***1}	0.05^{3}	0.03^{3}	0.07^{3}	0.00^{3}	1.67^{3}	9.39^{3}
Dry-times	AARHUS LUFTHAVN	0.02^{*2}	0.03^{***1}	-0.08^{3}	0.00^{3}	-0.09^{3}	0.00^{3}	-0.01^{**2}	-0.97^{3}	-0.31^{3}	-0.57^{3}
	AARHUS SYD	0.07^{3}	0.06^{3}	0.24^{**1}	-0.06^{3}	0.16^{*1}	0.02^{3}	0.05^{*3}	0.5^{**1}	0.79^{3}	5.03^{3}
	ABED	0.06^{3}	-0.19^{3}	0.14^{3}	-0.13^{3}	-0.11^{3}	0.06^{*1}	0.04^{3}	2^{**2}	1.89^{*2}	4.16^{3}
	BILLUND	0.04^{***1}	0.04^{***1}	-0.01^{3}	0.04^{***1}	-0.02^{**1}	0.00^{3}	0.00^{3}	-1.22^{3}	0.00^{3}	-0.21^{3}
	FLYVESTATION	0.05^{***1}	0.05^{***1}	0.00^{3}	0.05^{***1}	0.00^{3}	-0.02^{3}	-0.01^{3}	2.37^{3}	-0.36^{3}	0.51^{3}
	FOULUM	0.11^{*3}	-0.03^{3}	0.16^{***1}	0.00^{3}	-0.17^{3}	0.00^{3}	-0.01^{3}	-2.37^{3}	0.37^{3}	-2.89^{**1}
	GEDSER ODDE	-0.05^{3}	0.11^{3}	0.21^{**1}	-0.09^{3}	0.00^{3}	0.06^{3}	0.03^{3}	5.93^{**2}	4.17^{3}	4.21^{3}
	HOLBAEK	-0.05^{3}	0.00^{3}	0.14^{*1}	-0.08^{3}	-0.18^{3}	0.03^{3}	0.01^{3}	1.79^{**2}	0.55^{3}	1.07^{3}
	KARUP	0.04^{3}	-0.04^{3}	-0.09^{**1}	-0.06^{3}	0.00^{3}	0.00^{3}	0.00^{3}	3.89^{3}	0.06^{3}	0.38^{3}
	ROSKILDE_TUNE	-0.04^{3}	0.00^{3}	-0.04^{3}	0.07^{***1}	0.00^{3}	-0.01^{3}	-0.02^{***2}	-2.39^{3}	-0.3^{3}	-1.57^{**2}
	SKAGEN	0.00^{3}	0.02^{***1}	0.04^{***1}	-0.02^{3}	0.00^{3}	0.01^{3}	0.00^{3}	2.1^{3}	0.39^{3}	-0.84^{3}
	SKRYDSTRUP	0.04^{*1}	0.03^{*1}	-0.07^{3}	-0.02^{3}	-0.1^{3}	-0.05^{***2}	0.00^{3}	-1.11^{**2}	-1.08^{**2}	-5.38^{**3}
	TESSEBOELLE	-0.01^{3}	-0.14^{3}	-0.23^{***1}	-0.11^{**1}	0.44^{3}	0.04^{3}	0.08^{3}	2^{**2}	1.7^{3}	7.23^{3}
	TYLSTRUP	0.00^{3}	0.00^{3}	-0.08^{3}	-0.15^{**2}	0.00^{3}	-0.06^{3}	0.01^{3}	-11.16^{3}	-2.1^{3}	1.3^{3}
	TYSOFTE	0.12^{3}	-0.32^{**3}	-0.26^{**1}	-0.12^{**1}	0.59^{3}	0.01^{3}	0.08^{3}	-12.4^{3}	0.1^{3}	2.06^{3}

T: temperature, RH: relative humidity, DewP: dew point, V: wind speed in synoptic times, Vt: wind speed in all records, NEW: number of erosive winds, WPD: wind power density, EWPD: erosive wind power density.
^{1}: Calculations based on monthly data ^{2}: Calculations based on seasonal data ^{3}: Calculations based on annual data
***: The trend statistically significant at 99% level **: The trend statistically significant at 95% level
*: The trend statistically significant at 90% level.

Table 4-5: The magnitude of climatic variable trends estimated byTheil-Sen estimator method in Switzerland for all-times.

Stations	T_{max}	T_{mean}	RH_{mean}	$DewP_{mean}$	V_{max}	V_{mean}	Vt_{mean}	NEW	WPD	EWPD
	$^{\circ}C\,a^{-1}$	$^{\circ}C\,a^{-1}$	$\%\,a^{-1}$	$^{\circ}C\,a^{-1}$	$m\,s^{-1}a^{-1}$	$m\,s^{-1}a^{-1}$	$m\,s^{-1}a^{-1}$	$Record\,a^{-1}$	$w\,m^{-2}a^{-1}$	$w\,m^{-2}a^{-1}$
AADORF-TAENIKO	0.17**[1]	-0.01[3]	0.21***[1]	0.02[3]	0.00[3]	0.00[3]	0.01[3]	0.00**[1]	-0.33***[2]	0.00**[1]
ACQUAROSSA-COMPROVA	0.04*[1]	0.02*[2]	-0.11**[1]	0.06***[1]	0.08[3]	0.00[3]	0.01[3]	-0.31[3]	0.13[3]	0.08[3]
ADELBODEN	0.07[3]	-0.07[3]	0.15[3]	0.01[3]	0.66*[3]	-0.05**[3]	-0.02[3]	0.63[3]	-0.15**[1]	4.5[3]
AIGLE	0.05***[1]	0.04***[1]	0.00[3]	0.04***[1]	0.00[3]	0.01***[1]	-0.05[3]	-0.02[3]	2.7[3]	0.00[3]
ALTDORF	0.05***[1]	0.04***[1]	0.02[3]	0.03***[1]	-0.11[3]	0.00[3]	-0.02[3]	0.29[3]	-0.44[3]	-3.06[3]
BASELBINNINGEN	0.08[3]	-0.03[3]	0.06[3]	0.01[3]	-0.44***[2]	0.03**[1]	0.00***[1]	0.63[3]	0.37*[2]	0.00**[1]
BERN-ZOLLIKOFE	0.08[3]	-0.06[3]	0.21**[1]	0.00[3]	-0.43**[3]	0.04***[1]	-0.07[3]	0.00*[1]	-0.17**[3]	0.00***[1]
BUCHS-SUHR	0.05[3]	-0.07[3]	0.2**[1]	-0.02[3]	0.08[3]	-0.04***[2]	0.00[3]	0.00*[1]	-0.14**[2]	0.58[3]
BULLET-LA-FRETAZ	-0.19[3]	-0.08[3]	0.08[3]	0.03[3]	-0.01[3]	0.00[3]	-0.12[3]	0.58[3]	0.00[3]	0.00*[1]
CHASSERAL	0.1*[1]	-0.1[3]	0.15***[3]	0.67[3]	-0.27**[3]	-0.16***[2]	0.06**[1]	0.00[3]	4.89*[1]	-18.06***[2]
CHUR-EMS	0.07***[1]	0.05***[1]	-0.04**[1]	0.06***[1]	0.01[3]	0.01[3]	0.01[3]	-0.03**[1]	0.28[3]	0.82*[3]
CIMETTA	0.07***[1]	0.03***[1]	0.14***[2]	0.07***[1]	0.04[3]	0.00[3]	0.01[3]	0.21[3]	-0.13[3]	-0.46[3]
DAVOS	0.00[3]	-0.03[3]	-0.12[3]	0.02[3]	-0.43**[3]	-0.04***[1]	0.00[3]	-2.71[3]	-0.53***[2]	0.00[3]
ENGELBERG	-0.01[3]	-0.05[3]	0.06[3]	-0.03[3]	-0.06[3]	0.03**[1]	0.00[3]	2.93[3]	0.25**[1]	-1.11[3]
GENEVE-COINTRIN	0.06***[1]	0.05***[1]	0.00[3]	0.02***[1]	0.01[3]	0.00[3]	0.00[3]	0.00[3]	0.00[3]	0.38[3]
GLARUS	0.07[3]	0.05[3]	0.00[3]	46.45**[3]	0.07[3]	0.04**[1]	0.81[3]	8.67[3]	0.52*[1]	0.00[3]
GRIMSEL-HOSPIZ	-0.01[3]	-0.04[3]	-0.01[3]	0.00[3]	-1.3[3]	0.12**[2]	0.07***[1]	1**[1]	-0.47[3]	3.01***[1]
GUETSCHOBANDERMAT	0.02***[1]	0.04***[1]	0.04**[1]	0.03***[1]	0.07[3]	0.02**[2]	0.00[3]	0.57*[2]	0.86***[1]	-1.88[3]
GUTTINGEN	0.15**[1]	0.23[3]	0.00[3]	0.12***[1]	0.00[3]	0.00[3]	-2.5[3]	0.00**[1]	-0.36***[1]	0.00**[1]
INTERLAKEN	0.06***[1]	0.04***[1]	-0.04**[1]	0.06***[1]	0.00*[1]	0.00**[1]	0.00[3]	0.01[3]	0.04[3]	0.00***[1]
LACHAUX-DE-FONDS	0.06***[1]	0.04***[1]	0.00[3]	0.03***[1]	-0.03[3]	0.00[3]	0.00[3]	-0.76[3]	-0.09[3]	-0.33[3]
LEMOLESO	0.12*[1]	-0.01[3]	0.02[3]	-0.03[3]	0.33*[2]	-0.11**[1]	-0.07**[1]	-3.69[3]	0.00[3]	10.44*[2]
LOCARNO-MAGADINO	0.04***[1]	0.04***[1]	-0.05**[1]	0.03***[1]	0.00[3]	0.00[3]	0.00[3]	-0.14[3]	-0.01[3]	0.26[3]
LOCARNO-MONTI	0.07***[1]	0.04***[1]	-0.04[3]	0.02***[1]	0.00[3]	0.01**[2]	0.00[3]	0.00[3]	0.03[3]	0.65[3]
LUGANO	0.06***[1]	0.05***[1]	-0.09***[1]	0.03***[1]	0.06[3]	0.00[3]	0.00[3]	-0.22[3]	-0.05[3]	0.34[3]
LUZERN	0.00[3]	-0.02[3]	-0.01[3]	11.89[3]	0.02[3]	-0.18[3]	-0.12[3]	4.45[3]	0.00[3]	0.00**[1]
MONTANA	0.06***[1]	0.04***[1]	0.05[3]	0.05***[1]	0.00**[1]	0.00*[3]	0.02*[3]	0.02[3]	-0.04[3]	0.42[3]
NAPF	0.05***[1]	0.03**[1]	0.12**[3]	0.05***[1]	-0.07[3]	0.01[3]	-0.02[3]	0.46[3]	0.21[3]	-1.19[3]
NEUCHATEL	0.04***[1]	0.02**[1]	0.04[3]	0.02*[1]	0.06**[3]	-0.01**[2]	0.01[3]	-0.21[3]	-0.08[3]	0.67[3]
NYON.CHANGINS	-0.08[3]	-0.05[3]	0.06[3]	-0.03[3]	0.00[3]	0.01[3]	-0.04[3]	-2.8[3]	-0.04[3]	-3.39[3]
PAYERNE	0.04***[1]	0.04***[1]	-0.01[3]	0.01**[1]	0.00*[2]	-0.01**[2]	0.00**[1]	-0.14[3]	-0.06**[1]	-0.55[3]
PILATUSMTN	-0.04[3]	-0.05[3]	-0.02[3]	-0.01[3]	0.26[3]	0.00[3]	0.04[3]	-48.16[3]	-4.1[3]	12.44**[3]
PIOTTA	0.03**[1]	0.03***[1]	0.08**[2]	0.05***[1]	0.03***[2]	-0.01***[1]	0.01[3]	0.14[3]	0.01[3]	0.5***[2]
PIZCORVATSCH	0.00[3]	0.02**[1]	0.03[3]	0.08***[1]	-0.04[3]	0.02[3]	-0.02***[2]	1.14[3]	-0.14[3]	-0.11[3]
PLAFFEIEN-OBERSCHRO	0.05**[1]	0.01[3]	0.00[3]	0.00[3]	0.11[3]	-0.02[3]	-0.02[3]	0.00[3]	-1.16**[3]	-3.25[3]
POSCHIAVO-ROBBIA	0.05***[1]	0.04***[1]	0.01[3]	0.04***[1]	0.02[3]	0.00[3]	0.00[3]	0.62[3]	-0.18[3]	0.19[3]
ROBIEI	-0.14[3]	-0.01[3]	0.00[3]	0.00[3]	0.17**[1]	0.00[3]	-0.01[3]	0.09*[1]	0.06[3]	-1.7[3]
RUENENBERG	0.08[3]	-0.04[3]	-0.02[3]	0.00[3]	-0.27***[1]	0.00[3]	-0.09[3]	-1.52[3]	-0.28[3]	0.00**[1]
SAENTIS	0.03**[1]	0.04***[1]	0.05*[3]	0.04***[1]	0.08[3]	0.00[3]	0.01[3]	-0.7[3]	0.00[3]	2.27*[3]
SAMEDAM	0.03**[1]	0.04***[1]	0.03[3]	0.07***[1]	0.02[3]	-0.01**[1]	0.00[3]	-0.02**[1]	0.00[3]	0.28[3]
SBERNARDINO	0.06***[1]	0.03***[1]	0.08**[2]	0.06***[1]	-0.07[3]	-0.01[3]	-0.03***[2]	-0.38***[1]	-0.34***[1]	-1.13***[1]
SCHAFFHAUSEN	-0.05[3]	0.06[3]	0.16*[1]	1.22[3]	0.03[3]	0.04**[1]	-0.88[3]	-0.05[3]	-7.81[3]	0.00[3]
SCUOL	0.08[3]	-0.02[3]	0.01[3]	0.03[3]	0.00[3]	0.01**[1]	0.01[3]	0.00[3]	-0.08**[1]	0.42[3]
SION	0.03***[1]	0.05***[1]	-0.03**[1]	0.03***[1]	0.00**[1]	0.00[3]	0.00[3]	-0.08**[2]	0.08**[2]	-0.09**[1]
ST.GALLEN	0.05***[1]	0.04***[1]	-0.04[3]	0.03***[1]	-0.04[3]	-0.01***[1]	-0.01[3]	-0.25[3]	-0.09***[2]	-1.31[3]
ULRICHEN	0.13[3]	0.07[3]	0.27***[1]	0.08**[1]	0.24[3]	-0.05[3]	0.07[3]	-2.6[3]	-0.74[3]	4.09[3]
VISP	-0.13[3]	0.03[3]	0.22[3]	0.07*[1]	0.02[3]	0.04[3]	0.01[3]	1**[1]	-0.56[3]	0.16[3]
WADENSWIL	-0.03[3]	0.00[3]	-0.01[3]	0.51[3]	0.00[3]	0.19**[3]	0.23[3]	0.00[3]	1.29[3]	0.00[3]
WEISSFLUHJOCH	0.2[3]	-0.04[3]	0.24*[1]	0.05[3]	0.00[3]	-0.04[3]	-0.06***[2]	12.34[3]	0.00[3]	-8.13***[2]
WYNAU	0.07***[1]	0.04***[1]	0.05***[1]	0.05***[1]	-0.05***[2]	0.00[3]	-0.01[3]	0.00[3]	-0.11***[2]	-0.71[3]
ZERMATT	0.13[3]	-0.03[3]	0.04[3]	0.01[3]	0.41*[3]	-0.05***[1]	0.07[3]	-1.32[3]	-0.38***[1]	5.38[3]
ZUERICH-AFFOLTER	-0.04[3]	-0.06[3]	0.26***[1]	0.01[3]	-0.26**[2]	0.02[3]	-0.12[3]	0.00**[1]	-0.53***[2]	-5.06[3]
ZUERICH-FLUNTER	0.06***[1]	0.04***[1]	-0.03[3]	0.04***[1]	0.03*[1]	0.01**[1]	0.00[3]	-0.12[3]	0.06**[1]	1.09[3]
ZURICH-KLOTEN	0.05***[1]	0.04***[1]	-0.01[3]	0.02***[1]	0.03[3]	0.00[3]	0.00[3]	0.13[3]	0.04[3]	-0.08[3]

T: temperature, RH: relative humidity, DewP: dew point, V: wind speed in synoptic times, Vt: wind speed in all records, NEW: number of erosive winds, WPD: wind power density, EWPD: erosive wind power density.

[1]: Calculations based on monthly data [2]: Calculations based on seasonal data [3]: Calculations based on annual data

***: The trend statistically significant at 99% level **: The trend statistically significant at 95% level

*: The trend statistically significant at 90% level.

Table 4-6: The magnitude of trend estimated by Theil-Sen estimator method in Switzerland for dry-time periods.

Stations	T_{max}	T_{mean}	RH_{mean}	$DewP_{mean}$	V_{max}	V_{mean}	Vt_{mean}	NEW	WPD	EWPD
	$°C\,a^{-1}$	$°C\,a^{-1}$	$\%\,a^{-1}$	$°C\,a^{-1}$	$m\,s^{-1}a^{-1}$	$m\,s^{-1}a^{-1}$	$m\,s^{-1}a^{-1}$	$Record\,a^{-1}$	$w\,m^{-2}a^{-1}$	$w\,m^{-2}a^{-1}$
AADORF-TAENIKO	0.18***[1]	0.04[3]	0.19***[1]	-0.03[3]	0.00[3]	0.01[3]	0.01[3]	0.00***[1]	-0.32***[2]	0.00**[1]
ACQUAROSSA-COMPROVA	0.04*[1]	0.03**[1]	-0.08[3]	0.06***[1]	0.08[3]	0.00[3]	0.00[3]	-0.24[3]	0.11[3]	0.00*[1]
ADELBODEN	0.07[3]	0.00[3]	0.24**[2]	-0.01[3]	0.66*[3]	-0.05**[3]	-0.03[3]	0.68[3]	-0.2**[1]	4.5[3]
AIGLE	0.05***[1]	0.04***[1]	0.00[3]	0.04***[1]	0.01[3]	0.01***[1]	0.00[3]	0.08***[2]	0.05**[1]	1.33**[2]
ALTDORF	0.05***[1]	0.04***[1]	0.00[3]	0.03***[1]	-0.11[3]	0.00[3]	-0.02[3]	0.33[3]	-0.36[3]	-2.74[3]
BASELBINNINGEN	0.08[3]	-0.02[3]	0.15*[2]	0.05[3]	-0.44***[2]	0.03**[1]	0.00***[1]	0.49[3]	0.36[3]	0.00**[1]
BERN-ZOLLIKOFE	0.08[3]	-0.08[3]	0.25***[1]	0.03[3]	-0.43**[3]	0.04***[1]	-0.06[3]	0.00**[1]	0.00[3]	0.00***[1]
BUCHS-SUHR	0.05[3]	-0.01[3]	0.16*[2]	0.02[3]	0.08[3]	-0.03**[2]	0.01[3]	0.3[3]	0.00[3]	0.58[3]
BULLET-LA-FRETAZ	-0.19[3]	0.00[3]	0.4**[2]	-0.03[3]	0.17[3]	-0.03**[1]	-0.05[3]	0.63[3]	-0.35**[1]	0.00[3]
CHASSERAL	0.1*[1]	-0.11**[1]	0.43***[2]	0.00[3]	-0.12[3]	0.00[3]	-0.12***[2]	-11.71[3]	-10.97***[1]	-18.45**[2]
CHUR-EMS	0.07***[1]	0.05***[1]	-0.03[3]	0.06***[1]	0.04[3]	0.01[3]	0.01[3]	1.74[3]	0.34[3]	-0.4[3]
CIMETTA	0.07***[1]	0.04***[1]	0.09**[1]	0.06***[1]	-0.01[3]	-0.02***[3]	0.00[3]	0.05[3]	-0.03[3]	0.33[3]
DAVOS	0.00[3]	0.00[3]	0.01[3]	-0.11**[3]	-0.15**[1]	-0.03***[1]	-0.07**[2]	0.00*[1]	-0.47**[1]	0.00[3]
ENGELBERG	-0.01[3]	0.00[3]	0.4***[2]	-0.07[3]	-0.06[3]	0.05**[2]	-0.1[3]	2.94[3]	0.21*[1]	-1.08[3]
GENEVE-COINTRIN	0.06***[1]	0.05***[1]	-0.03**[1]	0.03***[1]	0.01[3]	0.00[3]	0.00[3]	-0.02[3]	0.00[3]	0.29[3]
GLARUS	-0.04[3]	0.04[3]	0.11[3]	0.19[3]	0.07[3]	0.04**[1]	0.37[3]	10.88[3]	0.61*[1]	0.45[3]
GRIMSEL-HOSPIZ	-0.01[3]	-0.08[3]	0.29[3]	-0.08[3]	-0.52[3]	0.12*[1]	0.05**[1]	1.18***[1]	-2.02[3]	3.2**[2]
GUETSCHOBANDERMAT	0.02***[1]	0.03***[1]	-0.02[3]	0.03***[1]	0.09[3]	0.02*[2]	0.01[3]	0.14[3]	0.54[3]	-1.76[3]
GUTTINGEN	0.15**[1]	0.38*[3]	0.65***[2]	0.12***[1]	0.00[3]	-0.03**[2]	0.00[3]	-0.25**[2]	-0.59***[2]	0.00**[1]
INTERLAKEN	0.06***[1]	0.05***[1]	0.02[3]	0.05***[1]	0.00*[2]	-0.01***[2]	0.00[3]	0.00***[1]	-0.02[3]	0.00***[1]
LACHAUX-DE-FONDS	0.06***[1]	0.03***[1]	0.02[3]	0.04***[1]	-0.02[3]	-0.01**[2]	0.00*[1]	0.00**[1]	0.04[3]	-0.92[3]
LEMOLESO	0.11*[1]	-0.01[3]	0.05[3]	-0.04[3]	0.54[3]	0.00[3]	0.11[3]	0.2[3]	0.79[3]	16.09**[2]
LOCARNO-MAGADINO	0.04***[1]	0.04***[1]	-0.07***[1]	0.02***[1]	0.00[3]	0.00[3]	0.00[3]	-0.15[3]	0.05*[2]	0.25[3]
LOCARNO-MONTI	0.07***[1]	0.05***[1]	-0.07**[1]	0.02*[1]	0.00[3]	0.01**[2]	0.00[3]	0.01[3]	-0.01[3]	0.44[3]
LUGANO	0.06***[1]	0.05***[1]	0.00[3]	0.02**[1]	0.00[3]	0.00[3]	0.00[3]	-0.16[3]	-0.04[3]	0.29[3]
LUZERN	0.00[3]	0.05[3]	0.2**[1]	-0.03[3]	0.03[3]	-0.01**[1]	-0.15[3]	4.44[3]	7.68[3]	0.00**[1]
MONTANA	0.06***[1]	0.04***[1]	0.07[3]	0.05***[1]	-0.03[3]	0.00[3]	0.02[3]	0.03[3]	-0.07***[2]	0.42[3]
NAPF	0.05***[1]	0.02**[1]	0.07**[2]	0.04***[1]	0.01[3]	0.01[3]	-0.02[3]	-0.39[3]	-0.03[3]	-1.22[3]
NEUCHATEL	0.04***[1]	0.02**[1]	-0.05**[1]	0.02[3]	0.07**[3]	0.00[3]	0.01*[3]	-0.22[3]	-0.05[3]	0.68[3]
NYON.CHANGINS	-0.08[3]	-0.06[3]	0.34[3]	-0.02[3]	0.00[3]	0.01[3]	-0.04[3]	-2.3[3]	-0.07[3]	-3.06[3]
PAYERNE	0.04***[1]	0.03***[1]	-0.01[3]	0.01*[1]	0.00[3]	0.00[3]	0.00*[1]	0.00[3]	-0.03[3]	-0.26[3]
PILATUSMTN	-0.04[3]	-0.1**[1]	0.51***[1]	-0.17**[3]	0.00[3]	0.00[3]	0.12**[3]	-40.18[3]	2.51[3]	11.71**[3]
PIOTTA	0.03**[1]	0.03***[1]	0.06*[2]	0.05***[1]	0.04***[2]	-0.01**[1]	0.01**[2]	0.06[3]	0.01[3]	0.53**[2]
PIZCORVATSCH	0.00[3]	0.03***[1]	0.14***[2]	0.06***[1]	-0.04[3]	0.02[3]	-0.02**[2]	0.5[3]	0.33[3]	0.83[3]
PLAFFEIEN-OBERSCHRO	0.05**[1]	0.02[3]	-0.02[3]	0.01[3]	0.00[3]	-0.02[3]	-0.02[3]	0.00[3]	-1.32***[3]	-2.53[3]
POSCHIAVO-ROBBIA	0.05***[1]	0.04***[1]	0.00[3]	0.04***[1]	0.03[3]	0.01[3]	0.00[3]	0.71[3]	-0.04[3]	0.2[3]
ROBIEI	-0.14[3]	-0.03[3]	0.19[3]	0.00[3]	0.23*[2]	0.02[3]	-0.02[3]	0.00**[1]	0.43[3]	-1.78[3]
RUENENBERG	0.08[3]	-0.05[3]	-0.01[3]	-0.01[3]	-0.27***[1]	0.00[3]	-0.09[3]	0.00*[1]	-1.07[3]	0.00**[1]
SAENTIS	0.02[3]	0.02**[1]	0.06[3]	0.02**[1]	0.01[3]	0.02**[2]	0.00[3]	0.00[3]	-0.42[3]	-1.42[3]
SAMEDAM	0.03**[1]	0.04***[1]	0.01[3]	0.07***[1]	0.03[3]	0.00[3]	0.00[3]	-0.02**[1]	-0.04[3]	0.25[3]
SBERNARDINO	0.06***[1]	0.04***[1]	0.00[3]	0.06***[1]	-0.06[3]	-0.01[3]	-0.03***[2]	-0.33***[1]	-0.36***[1]	-1.16***[1]
SCHAFFHAUSEN	0.01[3]	-0.1**[3]	0.2**[1]	-0.03[3]	0.04[3]	0.04**[1]	0.00[3]	-0.01[3]	-4.86[3]	22**[3]
SCUOL	0.08[3]	-0.05[3]	0.22[3]	0.06**[1]	0.00[3]	0.01*[1]	0.01[3]	0.00[3]	-0.09**[1]	0.42[3]
SION	0.03***[1]	0.04***[1]	-0.08***[2]	0.03***[1]	0.00*[1]	0.00[3]	0.00[3]	-0.08**[2]	0.08**[2]	-0.05**[1]
ST.GALLEN	0.05***[1]	0.04***[1]	0.00[3]	0.02***[1]	-0.04[3]	-0.01***[1]	-0.02**[3]	-0.14[3]	-0.08**[2]	-1.26[3]
ULRICHEN	0.13[3]	0.00[3]	0.26***[1]	0.02[3]	0.24[3]	-0.06[3]	0.03**[3]	-1.69[3]	0.00[3]	2.32[3]
VISP	-0.13[3]	-0.02[3]	0.22***[1]	0.06*[1]	0.02[3]	0.04[3]	0.01[3]	1**[1]	-0.5[3]	0.18[3]
WADENSWIL	0.04[3]	-0.02[3]	0.25***[1]	0.01[3]	0.00[3]	0.19*[3]	0.14**[2]	0.03[3]	12.52**[3]	3.57[3]
WEISSFLUHJOCH	0.2[3]	-0.13***[1]	0.58***[2]	-0.33[3]	0.00[3]	0.1***[1]	-0.06[3]	2.5*[2]	3.14[3]	-3.01[3]
WYNAU	0.07***[1]	0.04***[1]	0.02*[1]	0.05***[1]	-0.05***[2]	-0.01**[1]	0.00[3]	0.00[3]	-0.03[3]	-0.66[3]
ZERMATT	0.13[3]	-0.04[3]	0.09[3]	0.00[3]	0.41*[3]	-0.06***[1]	0.07[3]	-1.12[3]	-0.42***[1]	5.37[3]
ZUERICH-AFFOLTER	-0.04[3]	0.00[3]	0.21***[1]	0.06[3]	-0.26**[2]	0.02[3]	-0.12[3]	0.00**[1]	-0.53***[2]	-5.29[3]
ZUERICH-FLUNTER	0.06***[1]	0.04***[1]	0.00[3]	0.04***[1]	0.03**[1]	0.01**[1]	-0.01[3]	-0.27[3]	0.07**[1]	-1.14[3]
ZURICH-KLOTEN	0.05***[1]	0.03***[1]	-0.02[3]	0.01**[1]	0.00*[1]	0.00*[1]	0.00[3]	0.08[3]	-0.02[3]	-0.41[3]

T: temperature, RH: relative humidity, DewP: dew point, V: wind speed in synoptic times, Vt: wind speed in all records, NEW: number of erosive winds, WPD: wind power density, EWPD: erosive wind power density.
[1]: Calculations based on monthly data [2]: Calculations based on seasonal data [3]: Calculations based on annual data
***: The trend statistically significant at 99% level **: The trend statistically significant at 95% level
*: The trend statistically significant at 90% level.

In order to simplify the implementation of the model and also prevent the errors caused by outliers, the median value of significant annual trend slopes of studied climatic elements in weather stations was used in the structure of the model as an indicator of the impact of climate change. These results have been presented in Table 4-7 which have been derived from Table 4-5 for Denmark and Table 4-6 and Table 4-7 for Switzerland. For example the mean wind velocity is decreasing by -0.05 and -0.01 degrees per annum in Denmark and Switzerland respectively, based on analysis of all records without considering wet and dry periods. Also an annual change for WPD is also decreasing in both countries which are -0.86 and -0.14 watt per square per annum respectively for Denmark and Switzerland.

In comparison to the global average trend of wind speed ($-0.011\, m\, s^{-1} a^{-1}$) calculated by Peterson et al. (2011), the average trend of wind speed estimated according to all-times for Denmark is five times more than global and in Switzerland it is similar to the global. But based on dry-times, the estimated trend for Denmark slightly increased and for Switzerland it increased to five times more than the global trend.

Table 4-7: The median value of estimated annual slope for different climatic elements in Denmark and Switzerland

Test site	Status	T_{max} $°C\, a^{-1}$	T_{mean} $°C\, a^{-1}$	RH_{mean} $\%\, a^{-1}$	$DewP_{mean}$ $°C\, a^{-1}$	V_{max} $m\, s^{-1} a^{-1}$	V_{mean} $m\, s^{-1} a^{-1}$	Vt_{mean} $m\, s^{-1} a^{-1}$	NEW $Record\, a^{-1}$	WPD $w\, m^{-2} a^{-1}$	EWPD $w\, m^{-2} a^{-1}$
Denmark	**Dry-times**	0.04	0.025	0.09	-0.035	-0.075	0.005	-0.015	1.895	0.405	-2.89
	All-times	0.03	0.025	-0.14	0.03	-0.1	-0.05	-0.015	-0.89	-0.86	-1.465
Switzerland	**Dry-times**	0.05	0.03	0.15	0.04	0.01	-0.05	-0.01	-0.01	-0.08	-0.2
	All-times	0.05	0.04	0.05	0.04	-0.2	-0.01	-0.02	-0.02	-0.14	0.5

T: temperature, RH: relative humidity, DewP: dew point, V: wind speed in synoptic times, Vt: wind speed in all records, NEW: number of erosive winds, WPD: wind power density, EWPD: erosive wind power density

4.2.3. Monthly trend analysis

In addition to the assessment of climate change on an annual basis, it was necessary to also investigate the time series based on monthly observations. As described in the chapters above, it could be possible that monthly trends influence the annual trend in a way that no trend can be found anymore. Another reason why monthly trends are very important is the fact, that the actual wind erosion is not present during all of the year. Its occurrence is limited to times with low vegetation cover, dry conditions and strong winds, which in their combination are most prevalent during spring and summer season. Due to the large number of results in this part of trend analysis, the results of monthly trend analysis of wind factors have been listed in Annexes A and B respectively for Denmark and Switzerland and here the median of estimated monthly trends of studied weather stations have been presented. In order to remove the effects of outliers, the median of significant trend slopes was considered as an indicator of climate change impact on desired wind factor. In Table 4-8 and Table 4-9 the results of trend analysis for Denmark and Switzerland were presented, respectively. It should be emphasized that each number in these tables implies an increase or decrease of the desired parameter during a year. The results show for both countries in most months of the year a decreasing trend for wind parameters for both approaches. Comparing the results of the two countries for March, the trend of all wind parameters is negative in Denmark but in Switzerland this trend is positive in all parameters. In Denmark a decreasing trend in all parameters can be observed in most months but in Switzerland just in January, April and August the trend of all parameters is negative.

Table 4-8: The median of estimated monthly slope for some wind factors in Denmark

	Wind factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Conventional method	Vmax	NA	NA	-0.25	-0.15	-0.13	-0.17	-0.23	-0.09	-0.25	-0.115	-0.13	0.15
	Vmean	-0.085	-0.13	-0.09	-0.045	-0.05	-0.05	-0.05	-0.05	0.02	-0.08	-0.44	-0.1
	WPD	-7.02	-8.225	-4.95	-1.88	-2.27	-3.17	-1.02	-1.15	-4.28	-1.89	-5.2	-10.26
	EWPD	NA	NA	-9.19	-3.01	NA	-7.08	-3.65	NA	-9.73	-3.985	-4.11	13.52
New method	Vmax	-1.35	NA	-0.29	-0.145	-0.1	-0.17	-0.3	-0.1	-0.435	-0.12	-0.1	0.495
	Vmean	NA	-0.15	-0.09	-0.04	-0.045	-0.07	-0.06	-0.05	-0.08	0.12	NA	0.325
	WPD	-3.745	2.425	-3.89	-0.83	-1.46	-3.16	-1.23	-1.98	-7.6	-1.78	-10.53	-13.45
	EWPD	NA	NA	-9.845	-2.86	4.9	-6.35	-3.65	-4.14	-9.78	-3.67	NA	-8.53

NA: no trend has been available in all studied stations.

Table 4-9: The median value of estimated monthly slope for some wind factors in Switzerland

	Wind factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Conventional method	Vmax	-1.13	-0.19	0.11	-0.43	-0.64	-0.46	0.01	-0.25	0.425	-0.08	-0.135	-0.13
	Vmean	-0.155	-0.06	0.14	-0.06	0.01	0.04	-0.025	-0.06	-0.02	-0.02	-0.02	-0.02
	WPD	-1.125	-0.14	0.57	-1.04	0.25	-0.105	-0.12	-0.095	-0.035	1.075	0.345	-0.095
New method	Vmax	-0.82	0.1	0.11	-0.64	-0.62	-0.46	0.08	-0.185	0.54	0.245	-0.16	0.96
	Vmean	-0.16	-0.07	0.065	-0.05	0.01	-0.02	-0.06	-0.01	-0.02	-0.01	NA	-0.04
	WPD	-1.185	0.965	0.46	-0.72	-0.045	-0.08	-0.14	-0.235	0.02	0.2	-0.715	-0.535

NA: no trend has been available in all studied stations.

4.3. Extreme wind analysis

In order to model the potential wind erosion risk, access to data for extreme wind velocities in different return periods is necessary. To achieve this type of data layer as input for the proposed GIS-based model, the statistical extreme value theory was considered and extreme wind velocities of all selected weather stations in Denmark and Switzerland were analyzed by using both approaches, either using block maxima series fitted by GEV (Generalized Extreme Value) or POT (Peaks Over Threshold) fitted with GPD (Generalized Pareto Distribution).

Before performing extreme value analysis based on POT approach, the descriptive statistics of obtained POT data was calculated for each studied weather stations by using the R package “fBasics” (Wuertz, Setz, & Chalabi, 2014), which results are presented in Table A and Table B in the Appendix for Denmark and Switzerland, respectively.

Based on basic descriptive statistics, the average of POT wind velocities in Denmark is at least 16.64 knot (8.6 m/s) in the TESSEBOELLE station and in Switzerland, the minimum average was observed in the PIOTTA station (15.4 knot). In addition, the skewness and kurtosis were observed positive in all studied stations which indicate that the tail on the right side is longer or fatter than on the left side and the shape of probability distribution is a leptokurtic distribution.

As already mentioned in materials and methods, GP distribution is specified by three parameters: location, scale and shape. In order to use this distribution to analyze POT values, the location parameter is considered equivalent to the desired threshold wind velocity and the two other parameters have been estimated.

To estimate shape and scale parameters of GPD, several estimator methods were examined and compared and finally, the Maximum Likelihood estimator (mle) was found better to estimate GPD parameters(Figure 4-15).

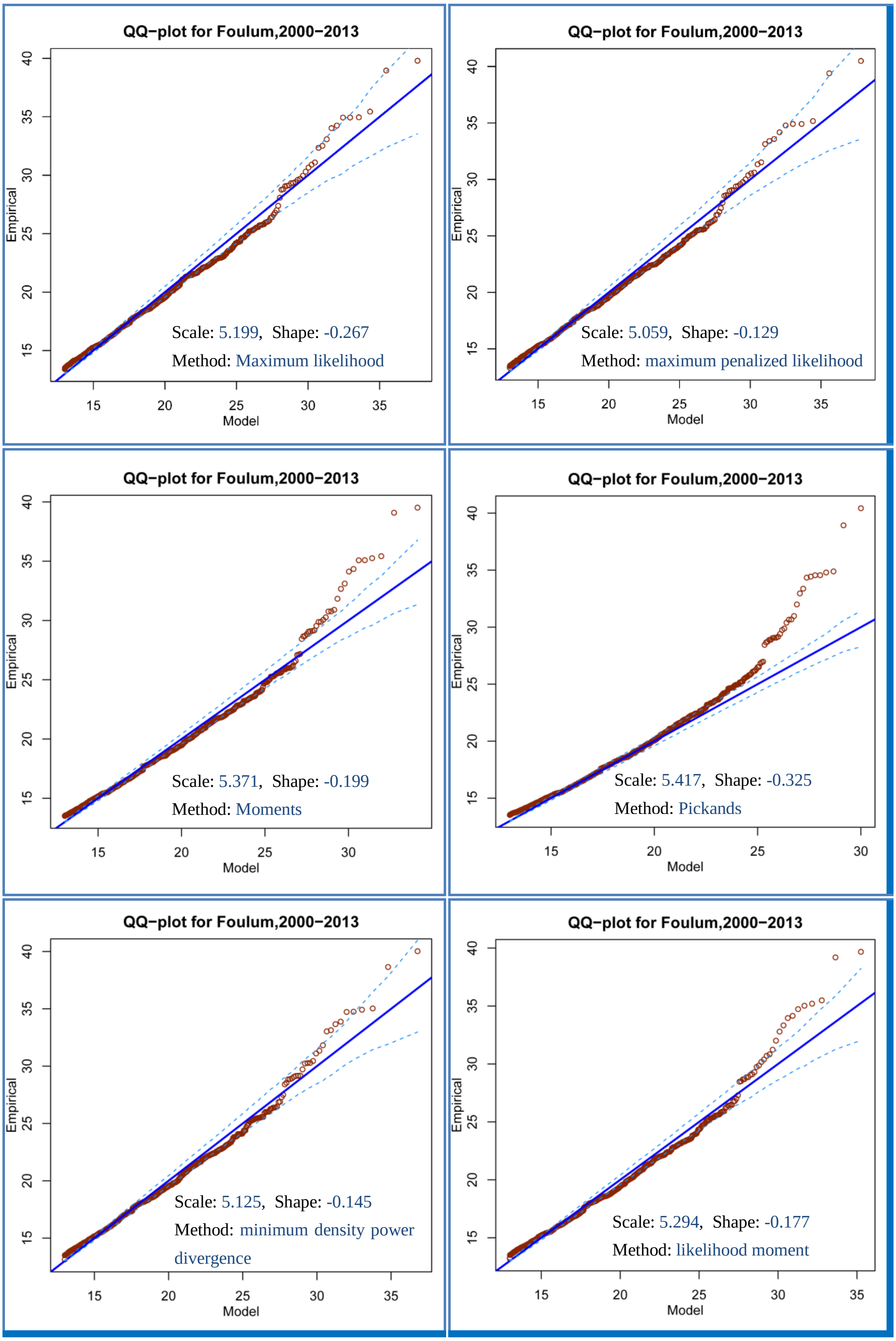


Figure 4-15: The trend of erosive wind factors in both dry and all times, Denmark

After selecting the best method to estimate the scale and shape parameters of the GPD model, the model was performed for all studied weather stations in both selected countries. As an exemplary, the diagnostic plots of FOULUM station in Denmark have been illustrated in Figure 4-16 . It should be note that, the diagnostic plots of other stations are enclosed in the digital appendix of the thesis. The return level plot illustrated in the downright of this figure shows the estimated return period of each maximum wind speed (knots) in FOULUM station.

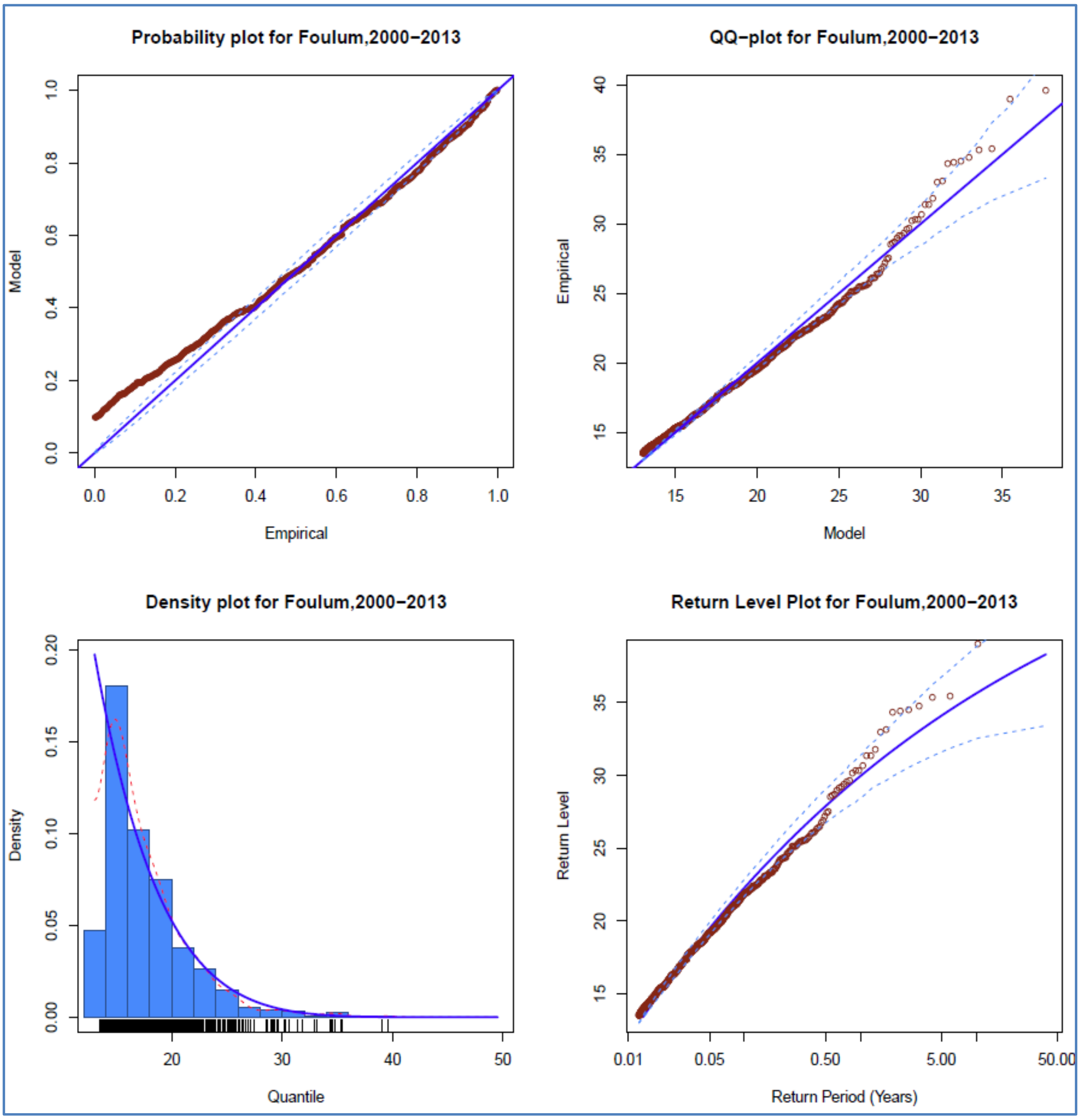


Figure 4-16: As an exemplary the diagnostic plots of fitting GPD to the POT values of the FOULUM station in Denmark

The main objective of extreme wind velocity analysis was to obtain the extreme wind velocity in different return periods for using its results in the proposed model to estimate potential and actual wind erosion risk. For this purpose, the wind velocity of 2, 5, 10, 25, 50 as well as 100 year return periods was extracted from the fitted GPD model. In Table 4-10 and Table 4-11 the wind speed value (knots) of each return period has been listed for studied weather stations of Denmark and Switzerland, respectively.

Table 4-10: Estimated wind velocities (knots) in different return periods for desired weather stations in Denmark

Station Name	Return periods (years)					
	2	**5**	**10**	**25**	**50**	**100**
AARHUS LUFTHAVN	39.48	43.03	45.57	48.75	51.02	53.18
AARHUS SYD	30.03	31.96	33.25	34.77	35.79	36.71
ABED	40.64	45.34	48.88	53.55	57.07	60.59
BILLUND	35.52	38.31	40.27	42.68	44.39	45.99
FLYVESTATION AALBOR	40.57	43.76	45.96	48.64	50.50	52.22
FOULUM	31.84	34.09	35.63	37.45	38.70	39.84
GEDSER ODDE	45.15	47.75	49.39	51.21	52.36	53.34
HOLBAEK	42.12	46.80	50.29	54.83	58.22	61.57
KARUP	35.77	38.51	40.42	42.77	44.42	45.95
ROSKILDE TUNE	37.34	39.82	41.50	43.49	44.83	46.04
SKAGEN	54.64	58.54	61.04	63.85	65.66	67.23
SKRYDSTRUP	39.89	43.30	45.73	48.74	50.88	52.90
TESSEBOELLE	27.52	29.19	30.31	31.62	32.49	33.28
TYLSTRUP	30.32	32.44	33.87	35.55	36.69	37.71
TYSOFTE	28.82	30.12	30.93	31.82	32.37	32.84

Table 4-11: Estimated wind velocities in different return periods for desired weather stations in Switzerland

Station Name	Return periods (years)					
	2	5	10	25	50	100
AADORF-TAENIKO	26.76	30.41	33.19	36.86	39.65	42.45
ACQUAROSSA-COMPROVA	24.67	26.74	28.19	29.99	31.25	32.43
ADELBODEN	29.04	33.62	37.28	42.38	46.47	50.74
AIGLE	26.29	28.39	29.79	31.41	32.48	33.44
ALTDORF	38.78	41.80	43.82	46.19	47.78	49.21
BASELBINNINGEN	33.29	38.29	42.19	47.50	51.65	55.90
BERN-ZOLLIKOFE	30.37	35.88	40.44	47.03	52.48	58.35
BUCHS-SUHR	25.49	29.46	32.55	36.75	40.02	43.37
BULLET-LA-FRETAZ	28.41	32.04	34.81	38.50	41.33	44.18
CHASSERAL	76.40	83.58	88.54	94.55	98.71	102.56
CHUR-EMS	27.11	29.78	31.82	34.52	36.58	38.64
CIMETTA	31.38	34.05	35.90	38.17	39.74	41.20
DAVOS	30.65	34.16	36.84	40.42	43.15	45.90
ENGELBERG	30.99	34.41	36.76	39.58	41.52	43.31
GENEVE-COINTRIN	34.49	37.83	40.26	43.35	45.60	47.78
GLARUS	40.24	44.74	48.15	52.65	56.06	59.47
GRIMSEL-HOSPIZ	44.50	49.93	54.07	59.61	63.84	68.11
GUETSCHOBANDERMAT	62.02	68.85	73.78	80.01	84.52	88.85
GUTTINGEN	30.60	34.91	38.26	42.81	46.34	49.95
INTERLAKEN	23.82	26.29	28.07	30.32	31.95	33.52
LACHAUX-DE-FONDS	27.60	30.56	32.76	35.62	37.74	39.83
LEMOLESO	53.25	58.15	61.58	65.79	68.75	71.52
LOCARNO-MAGADINO	26.17	28.84	30.72	33.05	34.69	36.24
LOCARNO-MONTI	17.55	19.42	20.61	21.93	22.77	23.49
LUGANO	28.48	31.07	32.88	35.09	36.63	38.07
LUZERN	29.17	32.10	34.14	36.63	38.37	39.98
MONTANA	19.08	20.49	21.37	22.35	22.96	23.48
NAPF	40.94	45.40	48.67	52.88	55.98	59.00
NEUCHATEL	26.51	28.31	29.52	30.94	31.90	32.76
NYON.CHANGINS	34.47	37.84	40.26	43.28	45.46	47.53
PAYERNE	24.99	26.79	27.98	29.34	30.24	31.04
PILATUSMTN	43.03	46.43	48.76	51.54	53.45	55.19
PIOTTA	21.75	23.05	23.93	24.96	25.66	26.30
PIZCORVATSCH	44.17	49.20	52.95	57.83	61.47	65.07
PLAFFEIEN-OBERSCHRO	39.41	42.26	44.10	46.17	47.51	48.67
POSCHIAVO-ROBBIA	34.92	37.15	38.54	40.08	41.04	41.86
ROBIEI	31.86	35.20	37.62	40.68	42.89	45.03
RUENENBERG	38.66	44.32	48.64	54.37	58.73	63.11
SAENTIS	58.29	63.41	66.94	71.22	74.17	76.91
SAMEDAM	24.09	25.33	26.16	27.14	27.79	28.38
SBERNARDINO	28.59	30.31	31.44	32.74	33.59	34.34
SCHAFFHAUSEN	41.70	47.10	51.21	56.69	60.86	65.05
SCUOL	22.23	24.49	26.12	28.20	29.71	31.17
SION	28.11	30.13	31.55	33.27	34.48	35.60
ST.GALLEN	24.30	26.47	27.94	29.69	30.89	31.97
ULRICHEN	32.25	35.32	37.56	40.40	42.47	44.46
VISP	39.06	41.92	43.89	46.27	47.92	49.43
WADENSWIL	30.23	33.67	36.19	39.42	41.78	44.08
WEISSFLUHJOCH	55.43	61.89	66.72	73.02	77.73	82.38
WYNAU	22.52	23.91	24.78	25.75	26.36	26.88
ZERMATT	32.09	35.71	38.46	42.11	44.87	47.64
ZUERICH-AFFOLTER	34.75	41.26	46.64	54.42	60.86	67.82
ZUERICH-FLUNTER	29.41	32.24	34.17	36.45	38.00	39.42
ZURICH-KLOTEN	31.25	33.79	35.57	37.74	39.26	40.68

4.4. Wind erosivity

The wind erosivity maps, for Denmark and Switzerland, were obtained based on a combination of WPD, EWPD, extreme wind velocities in desired return period (in this study was selected), as well as the number of erosive days (NED).

The return period of extreme wind velocities was selected for two years, because in almost all stations the wind velocity with a two year return period (Table 4-10 and Table 4-11) already exceeded the threshold friction wind velocity (13.6 knots). According to the results of dry/wet time modeling, wind erosivity was estimated for both conventional and new method.

As the wind erosivity maps in Denmark show, Figure 4-17, the wind erosivity in Jutland peninsula is gradually increasing from central Denmark to all directions. The closer to the coastlines, the higher is the wind velocity and consequently the wind erosivity. The lowest wind erosivity can be seen in the lee parts of Jutland, Fyn, and central Zeeland. Highest values above 400 W/m^2 are reached in the north of Vendsyssel-Thy in surrounding area of Skagen. When both maps for conventional and proposed approach are visually compared, no evident difference can be seen, because of the large scale. In order to make differences between the two approaches more comprehensible and easier to see, the two methods were compared using change detection techniques.

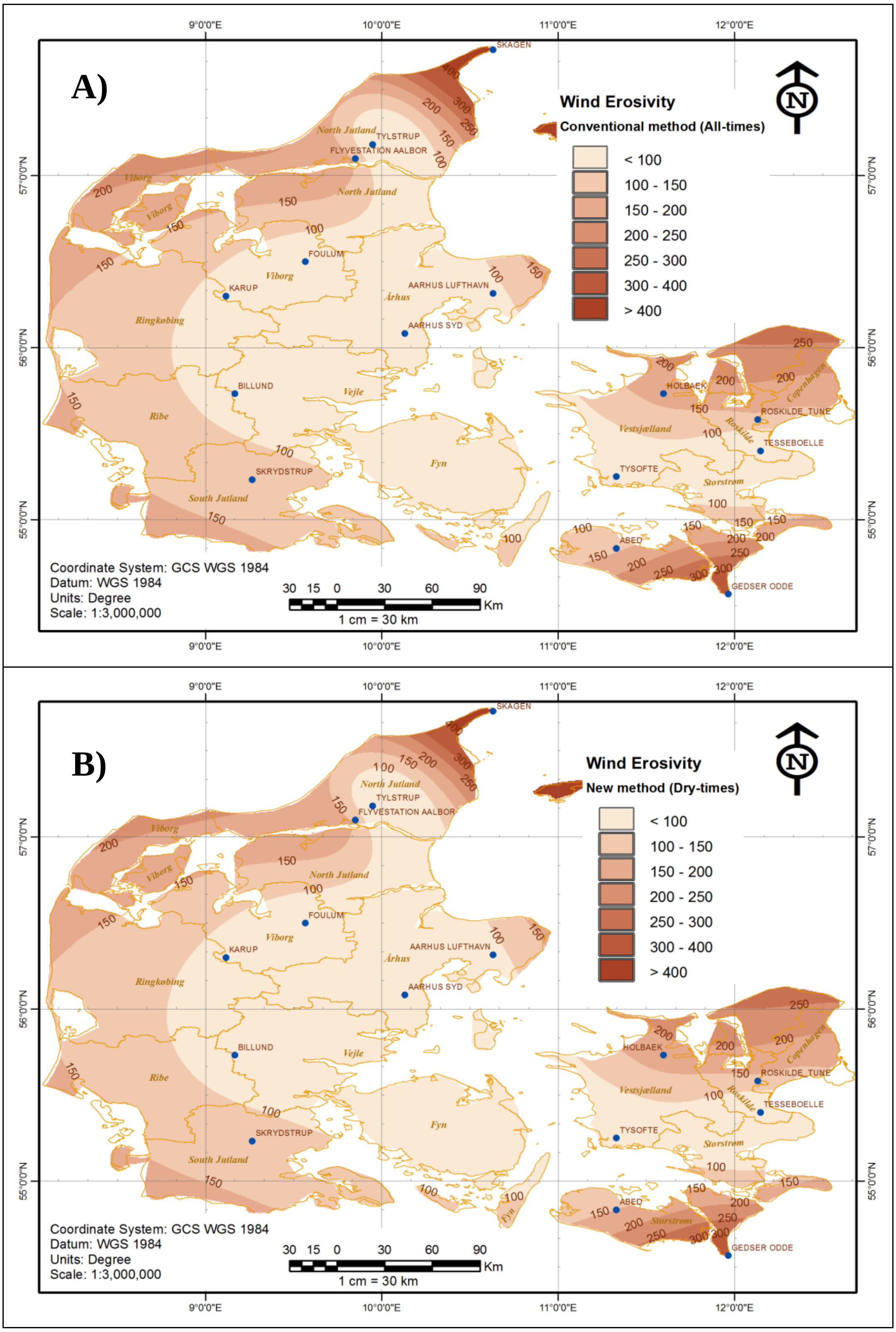


Figure 4-17: The erosivity of wind ($^{W}/_{m^2}$) in Denmark A) Conventional method (all-times) and B) new method (Dry-times)

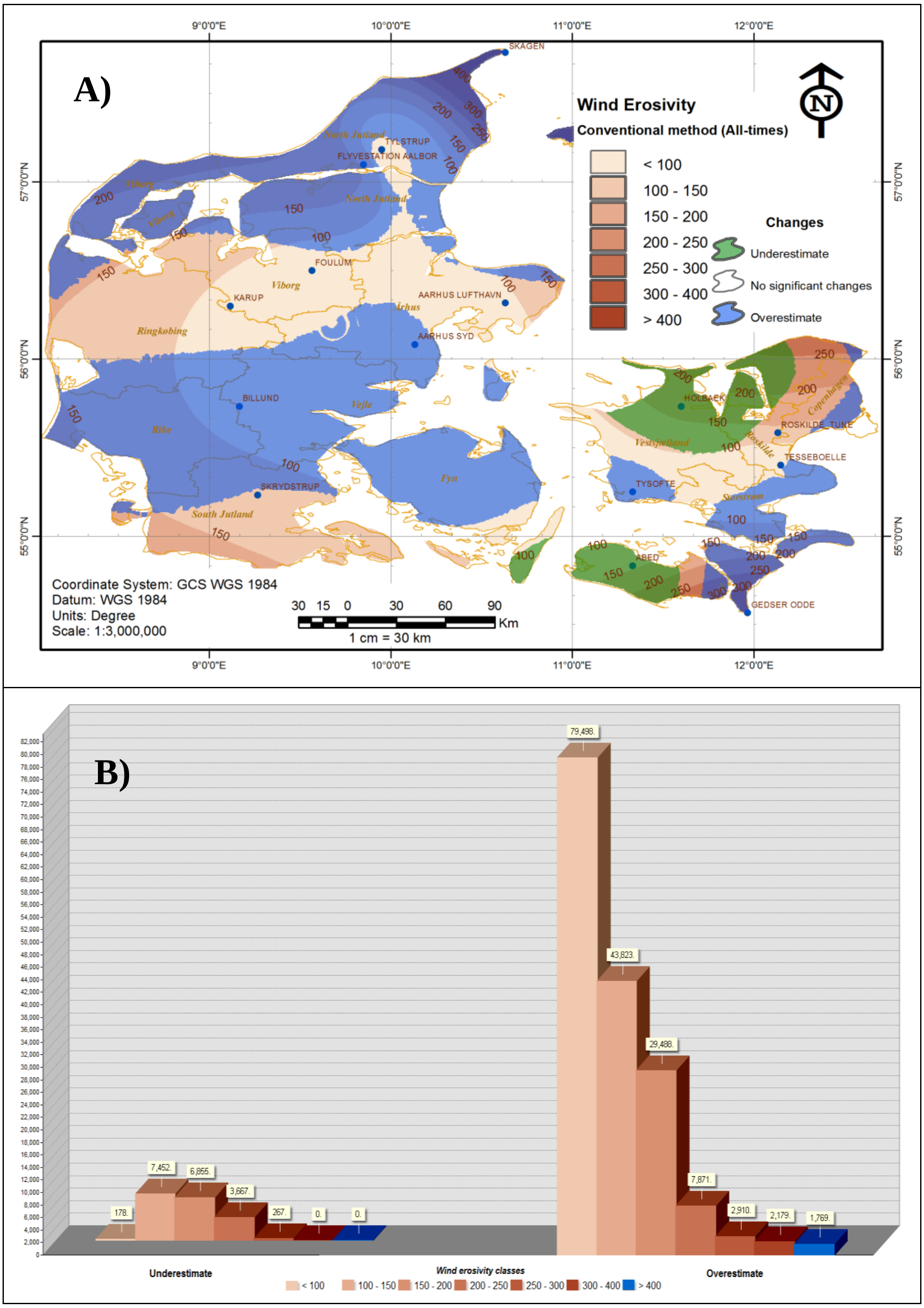


Figure 4-18: Spatial distribution of change detection analysis of conventional and new method (A), and the frequency distribution of overestimation and underestimation in different wind erosivity classes (B) in Denmark

The change map (Figure 4-18) shows that using the conventional approach (all times) to calculate the wind velocity distributions, leads to an overestimation for most parts of Jutland, Fyn and east Denmark. Only in the north of Zealand and west of Lolland it would lead to an underestimation of the wind velocity distribution. To evaluate the wind erosivity estimation in more detail, the frequency distribution of over- and under-predictions were calculated for specific wind erosivity classes. The resulting figure (Figure 4-18, B) illustrates that for the two highest wind erosivity classes (300-400 W/m^2 and >400 W/m^2) all changes were overestimations. Also in all other classes the dominating proportion of detected changes was overestimations. Since the higher classes are the most important for wind erosion risk estimations, it can be said that, the calculation of wind velocity distributions and hence wind erosivity, will lead to an overestimation of the wind erosion risk, if the conventional method without separation of wet and dry times is used. Table 4-12 summarizes the amount of over- or underestimations for both countries. It can be seen that in Denmark about 56% of all wind erosivity values are overestimated, if the conventional method is applied and only 6% are underestimated.

Table 4-12: The results of change detection in case of using conventional method

Change status	Denmark [%]	Switzerland [%]
underestimate	6.16	15.86
overestimate	56.02	30.63
not significant	37.82	53.51

As more or less expected, the lack of coastlines and the more complex climate and topographical situation in Switzerland generate a different pattern of wind erosivity (Figure 4-19). Most of the country has very low wind erosivity. Only a few hot spots, dominantly at weather stations in mountainous regions, like PILATUS, SAENTIS, CHASSERAL, and LE MOLESON, show high wind erosivities above 250-300 W/m^2. This corresponds to the shown wind patterns at the beginning of this chapter (Figure 4-3).

It is important to note, that these relative isolated high erosivity stations produce some artifacts to the whole distribution, which need to be considered for interpretation. For example the very large area of high erositvity in the Jura Mountains is only that big, because there are no other weather stations, so that the high value of CHASSERAL can dominate this region. Something similar occurred with the SAENTS climate station. The south-eastern end of this high erosivity region is only a relict from the spatial interpolation between the SAENTIS and its neighboring climate stations. The interpolation is also the reason, why the maximum wind erosivity is not directly at the PILATUS station, but a little bit to the southwest where actually not station exists. These minor problems show that the spatial accuracy of the distribution maps very much relies on the amount of available weather stations and that this method should not be used on a very local scale.

The visual comparison of the all-times versus the dry-times approach is, like for Denmark, not very meaningful. The only different that is visible in the maps is a reduction of about one wind erosivity class at most of the hot spot stations. For better visibility of the differences, a change-map and frequency distribution of the over- and under-predictions was also computed for the different erosivity classes (Figure 4-20).

Because of the more complex system, the spatial distribution of over- and underestimations does not show such a straightforward distribution as in Denmark. Main areas of overestimation are the Jura, Bernese, Engadin, St. Gallen, Napf, and Central Alps regions. Underestimations can be found in various regions, such as Lucerne, Visp etc.

As shown in Table 4-12, the overestimation of wind erosivity in Switzerland (31%) because of the use of the conventional methods is about 25% lower than in Denmark (56%). On the other hand, the number of underestimations increased to about 16%. Especially the values with no significant difference are much higher (54%) than in Denmark (38%). Like in Denmark, the two highest wind erosivity classes (300-400 W/m^2 and >400 W/m^2) are solely overestimations and in all other classes the dominating proportion of detected changes are overestimations as well. Therefore it can be assumed, that the dry/wet differentiation when calculating wind velocity distributions is also very important for more complex environments, like Switzerland.

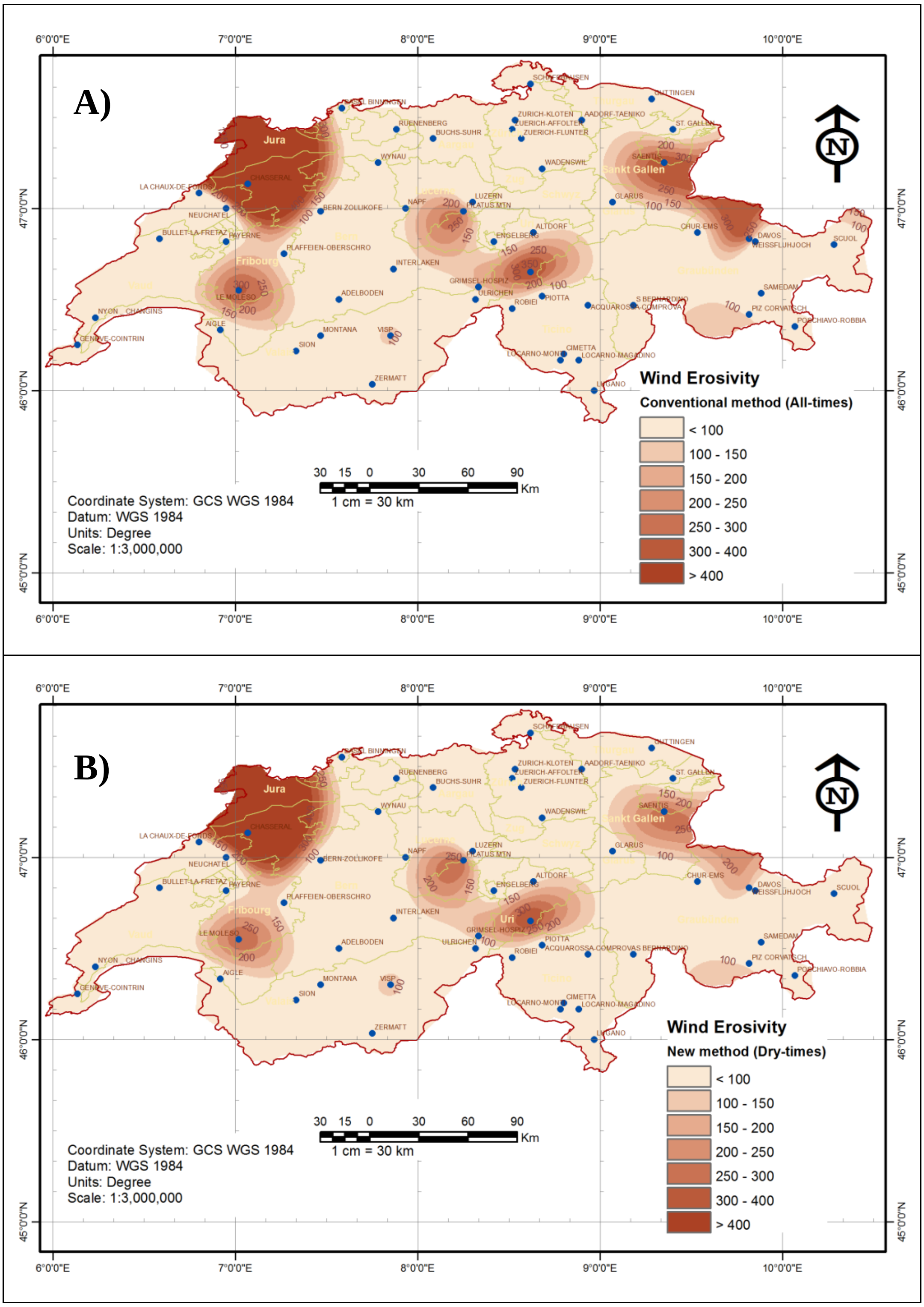


Figure 4-19: The erosivity of wind ($^{W}/_{m^2}$) in Switzerland A) Conventional method (all-times) and B) new method (dry-times)

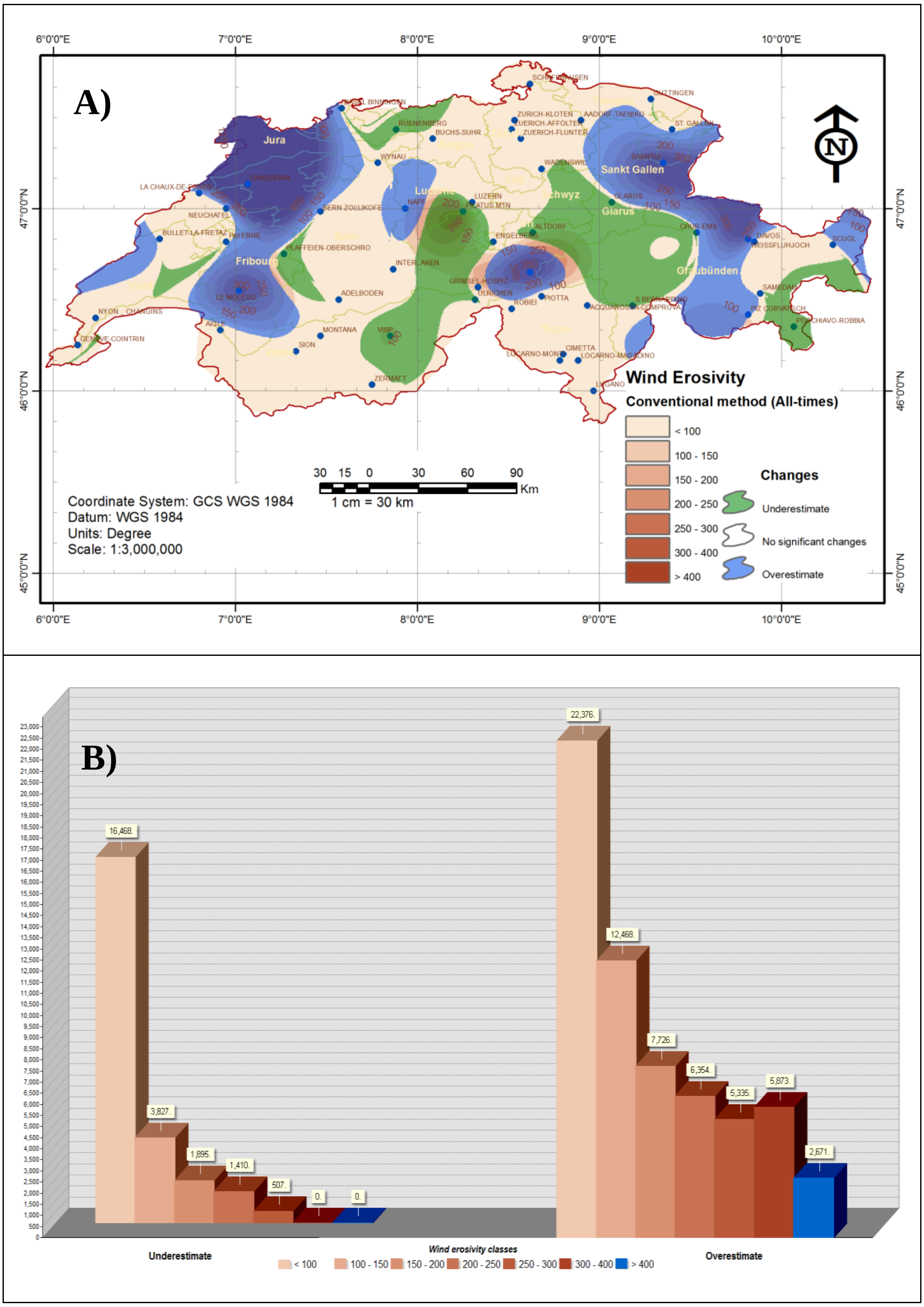


Figure 4-20: Spatial distribution of change detection analysis of conventional and new method (A), and the frequency distribution of overestimations and underestimations in different wind erosivity classes (B) in Switzerland

4.5. Soil erodibility

In order to calculate soil erodibility in the proposed model, the soil texture and its chemical characteristics were used to estimate the wind-erodible fraction of soil (EF) (Borrelli, Ballabio, et al., 2014; Borrelli, Panagos, et al., 2014; Fryrear et al., 2000), as mentioned in materials and methods (see page 90) which is a simplified method of Chepil (1941) performed by the U.S Department of Agriculture Wind Erosion Unit (USDA-ARS) (Woodruff & Siddoway, 1965). The necessary input data for topsoil layers (texture and chemical characteristics) were retrieved from the Harmonized World Soil Database (version 1.2) (Nachtergaele et al., 2012). The computed soil erodibility values were classified into three categories (slight, moderate, high; see also Table 4-14) according to Borrelli et al. (2014a; 2014b) and spatially visualized in Figure 4-21. Table 4-13 presents the descriptive statistics of estimated EF values in Denmark and Switzerland.

Table 4-13: Descriptive statistics of the wind-erodible fraction of soils (EF) by wind in Denmark and Switzerland

Test site	Min.	Max.	Mean	Standard deviation	Coefficient of variation
Denmark	25	52	39.32	10.08	0.26
Switzerland	8	48	31.25	9.67	0.31

The category ‘non-erodible’ in the soil erosion maps was not derived from the soil database. Instead it was computed data for 2012 from the MODIS Land Cover Type product (Friedl et al., 2010). The non-erodible areas, which cover about 17% of the total territory of Denmark and 58% of Switzerland, consist of land types such as water, urban, forest, and ice zones.

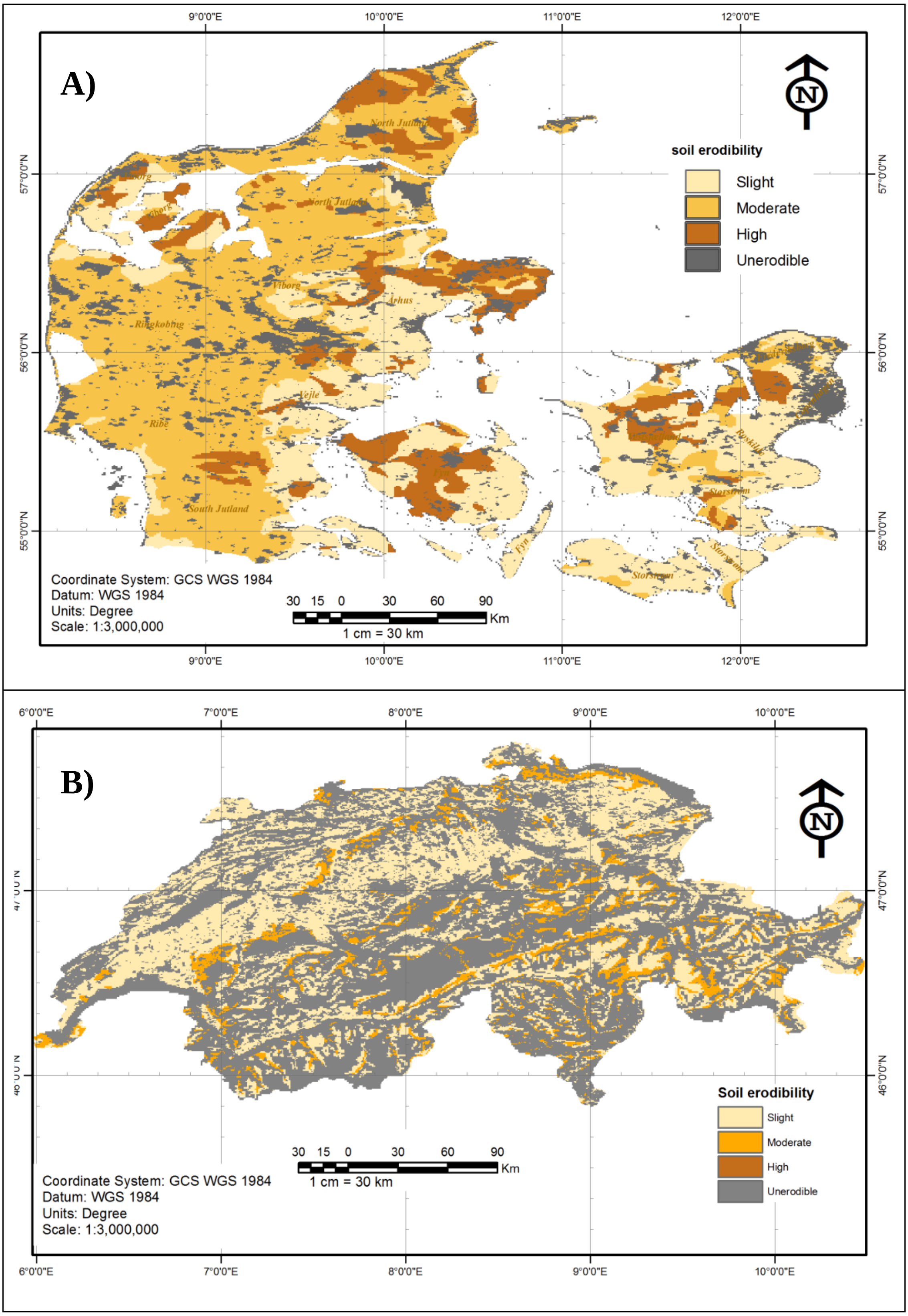


Figure 4-21: Map of soil erodibility by wind with 500 m spatial resolution based on the estimation of wind-erodible fraction of the soil (EF) factor in A) Denmark B) Switzerland

The highest soil erodibility can be found in areas, which were glaciated during the last ice age, for example northern and eastern Jutland, Fyn, and Zeeland. The glacial sediments in these areas have a dominantly loamy and fine sandy texture (for more details see: www.jggj.dk/torpjord.htm) and are, therefore, very prone to wind erosion. Almost all of western Jutland is classified as area with 'moderate' erodibility. The high degree of uniformity can be explained, again, by its development during the last ice age. These coarse sandy areas are the so-called outwash plains in front of the glaciated areas, where the meltwater from the glaciers passed by on their way to the North Sea. Further reasons for this uniformity of soil erodibility in Denmark are most likely the intensive agriculture, which keeps most of the country free of forests and the low relief.

Following Table 4-14 was extracted from the soil erodibility maps to get some quantitative information about the actual land coverage of the different classes. In total about 54% of Denmark's territory can be classified as high and moderately erodible, 31% as slightly, and only 17% as non-erodible. In comparison to Switzerland, especially this low percentage of non-erodible area is, at first sight, somehow surprising. But considering the dominant land use in the two different countries and the different environmental setting with a lot of flat areas or gentle hills in Denmark and huge, steep mountains in Switzerland, this difference is not so surprising anymore. The highest class of erodibility is not at all present in Switzerland and the moderate class with only about 8% is also not very prominent. Moderate erodibility can mostly be found in areas with loess substrate or sandy glacial or fluvial deposits. Judging based on the soil erodibility distribution, the soils in Denmark are much more susceptible to wind erosion than the soils in Switzerland.

Table 4-14: The percentage frequency of EF classes in Denmark and Switzerland

Class		Denmark [%]	Switzerland [%]
Slight	(EF<40)	30.50	34.74
Moderate	(40<EF<50)	40.90	8.14
High	(EF>50)	12.77	0.00
Unerodible		16.99	57.49

4.6. Potential wind erosion risk assessment

The potential wind erosion risk is based on the computed wind erosivity map (sub-chapter 4.4, page 139) and land cover information from the MODIS land cover database (Friedl et al., 2010). The resulting map shows the potential power of erosive winds in a region regardless of the actual susceptibility of the soil surface to wind erosion.

Although the potential wind erosion risk was computed for both approaches (conventional and dry-times) only the maps based on wind velocity distribution in dry times is presented (Figure 4-22). This selection was done, because it has been proven in sub-chapter 4.4 that the conventional method leads to an overestimation of high wind erosivity classes, which would undoubtedly also lead to an overestimation of the potential wind erosion risk.

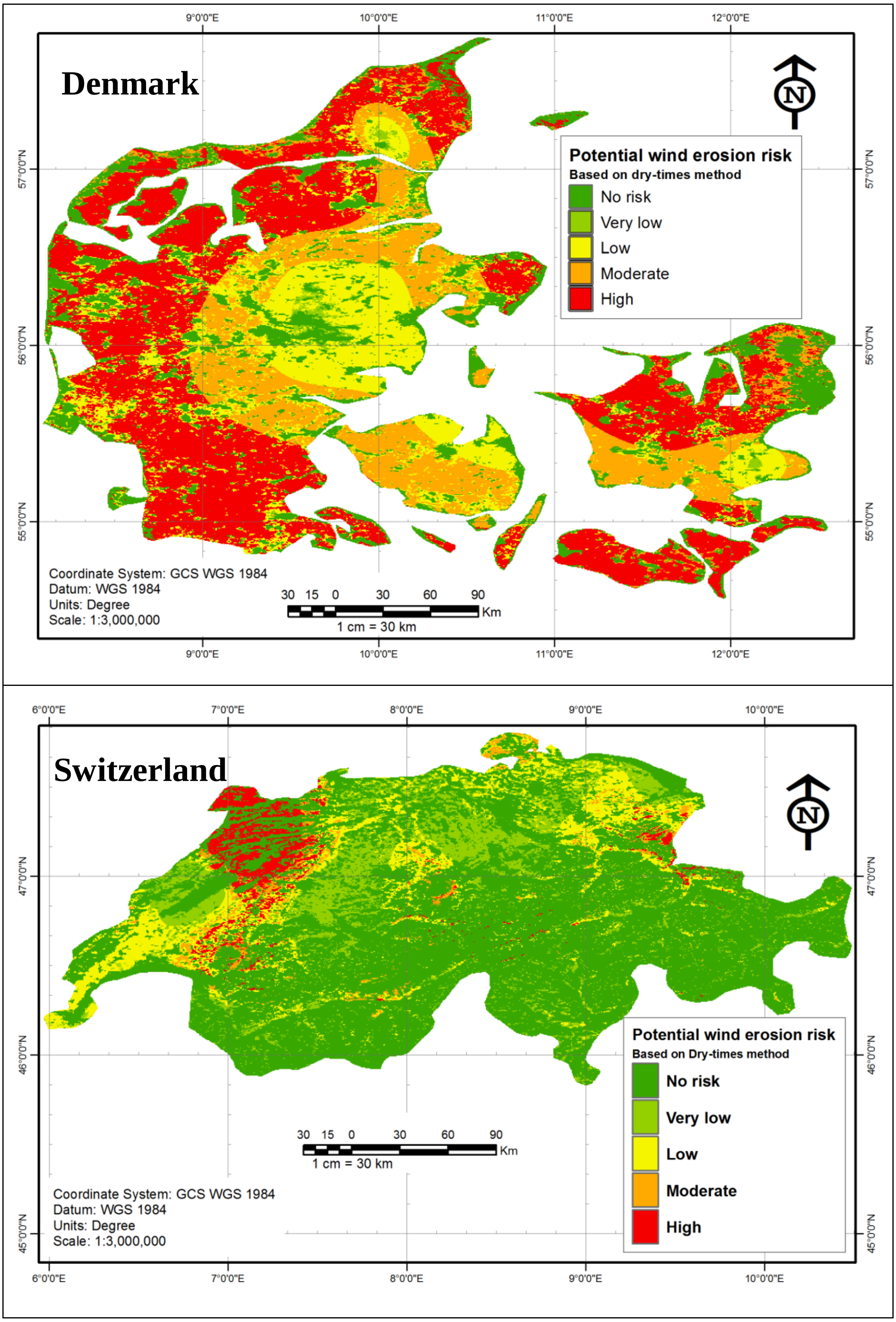


Figure 4-22: Potential wind erosion risk in Denmark and Switzerland based on dry-times method

The potential wind erosion risk in large parts of Denmark can be considered as high (38%) and moderate (19%). The overall pattern is quite similar to the one of the wind erosivity distribution, with low and moderate risk in eastern parts of Jutland, Fyn and southern Zeeland. The main differences are produced by the non-erodible areas, which were defined in sub-chapter 4.5 based on the land cover type. The calculation of the total area covered by each risk class is shown for Denmark and Switzerland in Table 4-15. The spatial pattern of potential wind erosion risk in Switzerland shows that wind erosion is no major threat in most parts of the country. Only about 6% of the country can be designated as moderate or high potential risk erosion areas. Logically, these areas are directly correlated with the areas of high wind erosivity and are located in the Jura, Bernese, St. Gallen, Lucerne, Napf, and Visp regions. Relatively prominent on the map are also the low risk areas along the alpine valleys.

Table 4-15: The percentage frequency of potential wind erosion risk classes estimated in Denmark and Switzerland

Risk class	Denmark [%]	Switzerland [%]
No risk	21.40	69.83
Very low	0.98	12.27
Low	20.27	11.89
Moderate	19.30	2.15
High	38.06	3.86

In order to see which land cover types are most severely threatened by potential wind erosion, the frequency of the potential wind erosion risk classes for each land cover type was computed. The results are listed in Table 4-16. These results clearly demonstrate that, “croplands” and “barren or sparsely vegetated” land cover types are mostly probably affected by wind erosion. Generally, because of the higher wind velocities, the different land cover types show higher risk classes in Denmark.

Table 4-16: The frequency of various potential wind erosion risk classes for each land cover type in Denmark and Switzerland

	Land type	No risk	Very low	Low	Moderate	High
				[%]		
Denmark	Forest	100.0	0.0	0.0	0.0	0.0
	Shrub lands	5.6	41.6	45.6	7.2	0.0
	Grasslands	100.0	0.0	0.0	0.0	0.0
	Croplands	0.0	0.1	12.0	27.1	60.7
	Cropland/Natural vegetation	0.0	4.3	79.5	14.9	1.3
	Barren or sparsely vegetated	0.0	0.0	0.0	13.6	86.4
	Others	100.0	0.0	0.0	0.0	0.0
Switzerland	Forest	100.0	0.0	0.0	0.0	0.0
	Shrub lands	0.4	95.5	4.1	0.0	0.0
	Grasslands	100.0	0.0	0.0	0.0	0.0
	Croplands	0.0	18.9	42.9	13.0	25.2
	Cropland/Natural vegetation	0.0	46.8	41.3	4.5	7.4
	Barren or sparsely vegetated	0.0	17.9	40.4	28.2	13.5
	Others	100.0	0.0	0.0	0.0	0.0

4.7. Actual wind erosion risk assessment

Actual wind erosion risk was derived from the potential wind erosion risk map by taking into account the erodible fraction of soils (EF) or in other words, soil erodibility based on the soil's texture and chemical properties (Borrelli, Ballabio, et al., 2014; Fryrear et al., 2000).

The results of spatial distribution of actual wind erosion risk in Denmark and Switzerland are presented in Table 4-17. In Denmark, the percentage of area that belonged to the highest wind erosion risk class dropped quite significantly and all other classes gained in comparison to the potential wind erosion risk distribution. Especially the class ‘very low’ increased (up to 18%), because large areas with high or moderate potential wind erosion risk were located in areas with soils that have relatively low soil erodibility. This is valid for large parts of the coarse sandy soils in western Jutland, the island of Fyn and the south-eastern islands. For Switzerland the erosion risk dropped even further by including soil erodibility into the model and the areas with high or moderate actual wind erosion risk are almost negligible (both < 1%). Although the spatial distribution is still the same, even the potential high risk area in the Jura region have dropped to moderate or even low actual wind erosion risk classes.

Table 4-17: The percentage frequency of actual WE risk classes in Denmark and Switzerland

Risk class	Denmark [%]	Switzerland [%]
No risk	22.12	70.14
Very low	17.69	22.49
Low	27.79	4.97
Moderate	20.69	0.61
High	11.48	0.17

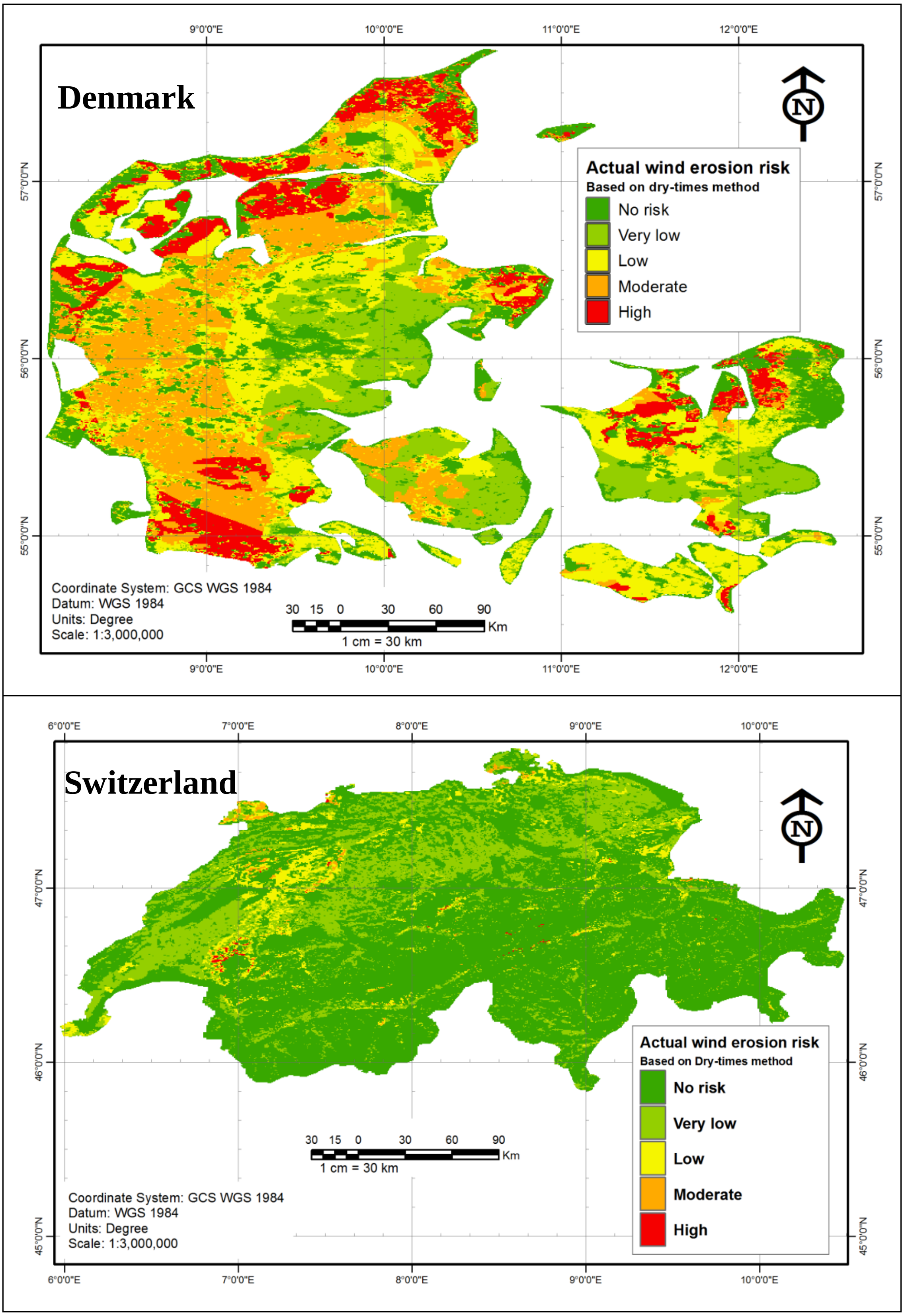


Figure 4-23: Actual wind erosion risk in Denmark and Switzerland based dry-times method

After analyzing the potential wind erosion risk for Denmark and Switzerland, it can be concluded, that the risk for Denmark is quite prominent, but it is almost negligible in Switzerland, for most land cover types. However, in the frequency distribution of the risk classes for different land uses (Table 4-18) can be seen that cropland and barren land still pose a moderate threat in some areas. Therefore, the role of future human activities can be very important. Depending on the crop rotation and the amount of land that is used for grassland or shrubs the human activities can actually quite significantly increase the erosion risk, for example if they decide to start growing crops on grass- or shrub-land. Since the general trend for wind velocity is stable or decreasing, an increased erosion risk because of the climate change effect cannot be expected at the moment.

Table 4-18: The frequency of various actual WE risk classes in different land use types in Denmark and Switzerland

	Land type	No risk	Very low	Low	Moderate	High
				[%]		
Denmark	Forest	100.0	0.0	0.0	0.0	0.0
	Shrub lands	10.4	77.4	12.2	0.0	0.0
	Grasslands	100.0	0.0	0.0	0.0	0.0
	Croplands	0.8	19.1	29.7	31.9	18.4
	Cropland/Natural vegetation	1.1	35.0	58.5	5.3	0.1
	Barren or sparsely vegetated	48.3	10.3	10.3	20.7	10.3
	Others	100.0	0.0	0.0	0.0	0.0
Switzerland	Forest	100.0	0.0	0.0	0.0	0.0
	Shrub lands	22.6	76.6	0.9	0.0	0.0
	Grasslands	100.0	0.0	0.0	0.0	0.0
	Croplands	3.9	59.4	29.2	5.8	1.7
	Cropland/Natural vegetation	3.6	84.5	11.6	0.2	0.0
	Barren or sparsely vegetated	92.9	2.3	3.5	1.3	0.0
	Others	100.0	0.0	0.0	0.0	0.0

"I was not predicting the future, I was trying to prevent it."

~ Ray Bradbury (1920-2012)

DISCUSSION

It is generally accepted that wind erosion occurs when at least these three conditions are provided: the wind power is strong enough, the soil surface is dry and sufficiently susceptible to wind erosion, and there is no soil surface protection (e.g. vegetation cover, residues, desert pavement, snow) present (Shao & Leslie, 1997). The proposed wind erosion risk model aimed to use a limited number of key wind erosion parameters, which are readily accessible at any synoptic weather station, to predict the potential and the actual wind erosion risk.

In the structure of the proposed model it was tried to address at least two main aspects, which are usually not considered in existing wind erosion models. In short, the aspects to be considered are:

1- Taking into account soil moisture condition already for the wind data analysis to estimate wind frequency distributions and consequently wind erosivity, for periods of time when the soil surface is dry, or in other words, susceptible to wind erosion;
2- Considering the possible impacts of climate change on wind patterns in the model and involving them in the estimation of temporal changes of wind erosion risk.

5.1. Considering soil moisture condition in wind data analysis

Since dryness and susceptibility of soil surfaces are requisites of aeolian erosion, taking into account the soil moisture state of the soil surface was one of the main objectives of our modeling approach. To achieve this goal, a wet/dry separator model was designed, based on easy to access weather elements, for example mean and maximum wind velocity, air temperature, relative humidity and so on. By implementing these data, it can be determined whether the soil surface had been wet or dry at the time of wind direction and velocity registration. By providing the ability to separate wind data based on soil moisture status, it was possible to test our hypothesis: the use of wind time series, regardless of the status of soil moisture, will lead to an overestimation of wind erosion.

The results of the wind velocity frequency distributions for all-times (conventional approach) and dry-times (proposed approach) showed, that almost in all scenarios in Denmark and at confidence level of 99%, the difference were significant in almost all stations. Sole exception was the station HOLBAEK, where the difference was not significant in April. For Switzerland, the difference between the two compared wind speed frequencies was not significant in only 30 test scenarios out of 1026. Therefore, in 97.1% of tests, the difference between the two frequency distributions was significant at 99% confidence level. In addition to the calculation based on all winds, the same test was conducted by using only the data for erosive winds (periods of time when wind velocity exceeded the threshold wind velocity of 7 m/s). The statistical analysis revealed that 89.1% of the distributions for Denmark were significantly different at 99% confidence level. In Switzerland however, the analysis of erosive winds did not show significant differences between the two frequencies, because the actual occurrence of erosive winds was very rare in many stations.

The results of this investigation reveal that using all-time wind velocity time series in wind erosion studies most likely cause an overestimation of potential soil loss in wind erosion risk assessments. The only other study (Hagen 2007) that has tried to investigate this research problem so far, came to similar conclusions. By comparing data from 46 weather stations in the western U.S.A, Hagen (2007) observed that 87% of the distributions were significantly different at 90% confidence level. Nevertheless, since the results, for example for the erosive days in Switzerland, are not always conclusive, further research, to compare spatial distribution of wind erosivity maps, will be necessary to proof the hypothesis. This research has been discussed in more detail in section 5.3

Böhner et al (2003) used a simplified topsoil moisture model for the prediction of the water content in the uppermost soil layer (ca. 2 cm) of sandy soils and integrated it into the structure of the WEELS model. This soil moisture model provides a continuous, daily, soil water balance based on the daily actual evapotranspiration according to (Haude, 1954). The model is able to calculate the days with dry soil surface during the periods without vegetation soil cover. While our proposed model is able to predict the wetness of soil surface hourly or sub-hourly. Borrelli, Panagos, et al. (2014) also used (Böhner et al., 2003) method for modeling soil moisture in their GIS-based proposed model.

5.2. The impact of climate change on wind patterns

The impact of climate change is used to validate the capability of our proposed model to analyze wind erosion risk according to the rate of wind parameter changes. Although many studies have examined the trend of wind velocity in different regions around the world, there is not yet enough knowledge about the trend for this phenomenon under the influence of climate change. "The main reason for this lack of information is that, the quality of the observational records of near-surface wind is generally too poor for assessing changes in the wind climate" (Smits et al., 2005). Thus, only a few stations specified a systematic change in wind variables on the basis of near-surface wind velocity and wind direction observations.

On a global scale, the average trend of wind speed is calculated $-0.011\, m\, s^{-1} a^{-1}$ with a standard deviation of $0.026\, m\, s^{-1} a^{-1}$ by using the 852 stations located across the globe from 1979-2010 (Peterson et al., 2011). This global mean value of trend is an arithmetic mean, without weighting applied. Also, Peterson et al. (2011) reported a value of $-0.0093\, m\, s^{-1} a^{-1}$ as a global wind velocity trends which was weighted according to local station density using a standard National Climatic Data Center area averaging approach. McVicar et al. (2012) by review 146 regional studies concluded that declines in terrestrial wind velocity are geographically wide spread. Although not only are decreases reported in the tropics and mid-latitudes of both hemispheres, but increases are also observed at high-latitudes (i.e. latitudes almost greater than 70°) in both hemispheres.

In this thesis, the results of trend analysis of desired wind factors reviled that finding a good evidence of climate change in many stations of studied countries was not possible. Possible reasons are insufficient data or the complexity of the parameters, which are intensively influenced by many other climatic parameters. However, according to the median of significant trends obtained in studied stations a negative trend was confirmed similar to the mentioned literature above. Based on the median trend, the magnitude of mean wind velocity trend was obtained 0.015 and -0.01$m\, s^{-1} a^{-1}$ in Denmark and Switzerland, respectively which is similar to the average trend of this parameter obtained by Peterson et al. (2011)

In addition to the mean wind velocity, the trends of other wind factors, which have not been studied in the literature so far (e.g., Wind Power Density, Erosive Wind Power Density, Number of Erosive Winds), were also evaluated. According to the median of trends it can be concluded that observed trends are not explicit, but they seem to have more a tendency towards reduction than increase. For more details see Table 4-7.

Several reasons have been reported to explain the reduction of observed near-surface wind velocities, especially for mid-latitudes and non-coastal regions. Some of these reasons are as follows:

1- Changes in mesoscale circulation in regions, as for instance, mesoscales associated with the strength of El Niño (St. George & Wolfe, 2009) and change in patterns of tropical monsoonal circulation (Vecchi & Soden, 2007; Xu et al., 2006);
2- Poleward expansions of the Hadley cell (Lu, Vecchi, & Reichler, 2007; Seidel, Fu, Randel, & Reichler, 2008);
3- The movement of massive storms towards polar latitudes due to climate change and global warming (Frederiksen & Frederiksen, 2007; Lorenz & DeWeaver, 2007; Yin, 2005);
4- Increasing land surface roughness (Vautard et al., 2010) or vegetation cover due to the release of agricultural land, increases in air temperature (Nemani, Keeling, & Hashimoto, 2003) and atmospheric CO_2 concentrations which cause the enhancement of vegetation growth (Donohue, McVICAR, & Roderick, 2009) as well as the development of urban spaces;

5- Astronomical variations related to day-length changes due to the exchange of angular momentum between the lithosphere and atmosphere (Lambeck & Cazenave, 1976; Mazzarella, 2006);
6- Due to global warming, polar latitudes are started heating more rapidly than tropical and sub-tropical latitudes (Lorenz & DeWeaver, 2007), thus weakening the thermal difference of the equatorial-polar and is expected to lead to a reduction in wind velocity in equatorial and mid-latitude (Ren, 2010).

As mentioned, wind parameters are strongly affected by other climatic elements, hence the trend of other climatic elements such as temperature and relative humidity was also investigated. In increasing trend was observed in both countries. Especially in Switzerland this positive trend was fairly strong and no negative trend in temperature was observed in the studied stations. These results were similar to Ceppi et al. (2012) who found only positive and mostly significant trends. He reported an annual average warming rate of 0.04 $^{\circ}C/year$. According to the median of significant trends, the obtained trend in this study was a little bit higher. The observed positive trend mean air temperature in Denmark was not as strong as in Switzerland but the results are in accordance to the reported value ranges in the IPCC reports about global warming (IPCC, 2007a).

5.3. Overestimation of wind erosivity by use of the conventional method

Experimental investigations showed that wind erosivity can be expressed as the cubic measure of annual average of wind velocity (Skidmore, 1986) and it is related to other climate-related factors such as air pressure, temperature as well as relative humidity. Therefore, the interaction of many related parameters lead to determine the intensity, frequency and duration of wind erosion events (Borrelli, Panagos, et al., 2014).

To investigate the effects of soil moisture conditions in wind data analysis, the spatial distribution of wind erosivity was computed using two approaches. One based on all observed times of wind velocity (conventional method) and the other, using wind data just in dry-times (new method). Comparing the obtained two maps indicates that the wind erosivity computed with both methods has a similar spatial pattern, but with different frequencies of occurrence. According to the computed two different wind erosivity maps, with regard and regardless of considering the situation of topsoil moisture, an evaluation of the previously raised hypothesis (using wind time series regardless of the status of soil moisture will lead to the overestimation of wind erosion) was provided. Hence, to compare the two applied methods, the changes between conventional method and proposed method were detected pixel by pixel by using a change detection technique in ArcGIS 10.0 (ESRI, 2011). The results of change detection showed both overestimation and underestimation are possible by using the conventional method and analyzing wind data without considering soil moisture situation. However, a very important interesting point to note is that, wind erosivities above 300 W/m^2 (two final classes), will lead to overestimation if the conventional method is used. All observed underestimations were in regions that are not affected by wind erosion at all. These results in both test sites (Denmark and Switzerland) were similar. Thus, the change detection results confirmed the hypothesis that was mentioned above and also the results obtained by Hagen (2007), based on simulations of soil loss using the WEPS model with dry-day and all-day wind speed distributions. He predicted ratios of monthly dry-day to all-day soil losses for bare fields with two different soil textures and concluded that, at many locations, accuracy of physically based wind erosion models could be improved by accounting the differences in wind speed distributions on wet days and dry days.

5.4. Potential and actual wind erosion risk

Mapping the spatial distribution of potential and actual WE risk was the main objective of this study. To achieve this goal, a GIS-based model was designed and successfully implemented.

To validate and check the quality of results that were obtained by the proposed model, the wind erosion risk maps for Denmark and Switzerland were compared with the Index of Land Susceptibility to Wind Erosion (ILSWE) estimated by Borrelli, Panagos, et al. (2014) and the wind erosion map of EEA (2012). Based on the patterns of these maps it can be said that the zoning of wind erosivity in our proposed model was similar to these maps, especially in comparison with Borrelli, Panagos, et al. (2014). They used ILSWE for predicting wind erosion susceptibility. According to their results, in Denmark, 16.2% and 32.6% of the country were classified in high and moderate susceptibility to wind erosion, respectively. The areas with high susceptibility were located in the west of the country, generally in coastal margins. In ILSWE almost no high erosion was observed in Switzerland and just about 1.7% moderate erosion observed in the country.

The results of our proposed model showed that according to the results of potential wind erosion risk 38.1% and 19.3% of the land surface in Denmark was classified as high and moderate respectively that in was reduced to 11.5% and 20.7% in actual wind erosion risk. The results of the model for Switzerland also showed that wind erosion is not a threat in this country and according to the actual wind erosion risk the high and moderate risk of wind erosion contain only 0.2 and 0.6 percent of land surface.

Considering that the findings in the literature are very heterogeneous in methods and scales, and that generally no quantitative measures were reported, comparison of results to evaluate the model is a considerable challenge. For instance the wind erosion map released by EEA (2012) was computed by number of erosive days per year, based on wind velocity and soil texture. The number of erosive days per year that were estimated was less than what was expected. Even for the highest class of estimated wind erosion the model considered more than 2 days per year, while Borrelli, Panagos, et al. (2014) estimated much higher erosive days. The EEA also admitted that the validation of erosion data can be challenging, this is why they validate their results through comparison with national datasets and by expert judgement. Despite this difference in the scale, the pattern of obtained wind erosion risk in the EEA map was partly similar to our results. The EEA map also showed that wind erosion in Denmark ranges from moderate to high in large areas and high wind erosion mostly present in the West and Northwest. For Switzerland, no erosion was observed by this investigation as well.

Spatial distribution of potential and actual wind erosion risk in Denmark showed that arable land in north-west and south of Jutland peninsula as well as north of Vendsyssel-Thy and Zealand is affected by wind erosion and that the actual wind erosion risk in these regions are fairly high (Figure 4-23). Although 18.4% of croplands are predicted susceptible to wind erosion (Table 4-18) but according to potential wind erosion risk, around 88% of croplands potentially can be affected by wind erosion in this country. Denmark is predicted to have a moderate (27.1%) and high (60.7%) potential erosion risk (Table 4-16). Therefore, human activities can be very effective in reducing or increasing the risk of wind erosion in agricultural lands. Using wind breaks around arable fields is highly recommended, especially in the West and North-West of the country. Also, ploughing in the right direction (perpendicular to the prevailing wind direction) especially in fallow periods can play an important role in reducing soil loss and dust emission.

According to the literature and to the results, it can be concluded that wind erosion in Switzerland is not a threat, although in some parts of Switzerland, particularly in the Jura and in the north of Bern canton, potentially high risk areas were observed. Based on the distribution of wind erosion class for each land type, all estimated high wind erosion risk areas are located in croplands. In Switzerland, about 1.7% of the total croplands are threatened by wind erosion (Table 4-18). The size of this area is not very impressive, but it indicates that the role of human land management is and most likely will be the main driver for in the occurrence of wind erosion in the future. So it should be emphasized that land management is also very important in this country. A lack of attention could in the worst case lead to soil loss by wind in more than 25% of the croplands in Switzerland, because they are potentially susceptible to high wind erosion risk (Table 4-16).

“If the facts don't fit the theory, change the facts.”

~ Albert Einstein (1879-1955)

CONCLUSIONS AND OUTLOOK

6.1. Conclusions

Wind erosion is a phenomenon that seriously affects large areas of the world and can have a serious impact to human life, but unfortunately, there is still no effective management strategy to identify land susceptibility to wind erosion. As described in the introduction, the main aim of this research was to design an easy to use, quick and reliable model to estimate potential and actual wind erosion risk by using a number of easy to access weather elements so that it can be applied in regions without adequate information. The model that was designed for this purpose is a GIS-based model.

The implementation of the model required finding a solution for at least three basic issues, mentioned in the introduction. Therefore, in order to eliminate these gaps of knowledge, the following research questions were tried to be answered:

1- Is it necessary to separate wet and dry periods, or in other words, are there significant differences between using the conventional method (calculation of wind patterns for all-times) and separation of dry and wet periods?

2- How is it possible to separate wet and dry periods in historic wind data time series by using easy to access data on weather elements, such as precipitation, temperature and relative humidity, without data on soil moisture content?

3- What could be the possible impacts of climate change on wind factors in a region of interest (here Denmark and Switzerland) and does it differ depending on the method applied (conventional versus dry/wet method)?

4- Is there a quick, easy to use, and reliable method in order to predict potential and actual wind erosion risk for areas without sufficient or low quality data?

Therefore, according to the investigations in this thesis, following responses can be summarized to each research question:

Question 1: Is it necessary to separate wet and dry periods?

In order to answer this question, the velocity frequency distributions of winds in all-times (conventional approach) and dry-times (excluding wet days) were compared for two different wind velocity thresholds; (1) for all winds ($V \geq 1$ knot) and (2) for erosive winds ($V \geq 13.6$ knots). The results of the Pairwise Wilcoxon test for the exemplary test regions (Denmark and Switzerland) clearly showed for all winds (1) that the differences between the two wind velocity frequency distributions are significant for 99% of the tested combinations in Denmark ($P<0.01$) and about 97% in Switzerland ($P<0.01$). The outcome for erosive winds (2) in both regions was less clear, but the results still indicated that the difference between all-time and dry-time velocity distributions should be considered in wind erosion studies.

Since these tests only showed that differences between the two approaches exist, but do not show what kind of differences there are and how big these differences are, it was decided to calculate the future trends of selected climate variables for the modelling of wind erosion risk by using both approaches. It was expected that the differences in the periods of time (dry vs. all) would cause differences in the observed trends. The results, however, were not that explicit. For some parameters the observed trends from all-times were a little bit stronger it calculated for dry-times, but there were many other parameters that didn’t show differences at all between the two approaches. Since the trends are generally more pronounced in Switzerland, also the effect of dry-times can be seen much better in these data. For example the parameters temperature, precipitation, number of dry days, and relative humidity showed quite some increase in the number of stations, which showed a positive trend. As was mentioned in the corresponding section, one of the major problems with this data analysis could have been the relatively short series of time available for some of the data stations. If the data series is too short to include a trend, then it does not matter if the trend analysis is done for all-times or just for dry-times, since both will not be able to find a trend.

The final test to verify if the separation of dry and wet times is relevant was done for the wind erosivity maps. The wind erosivity maps were compiled based on the wind velocity frequency distributions of all- and dry times, following the two different approaches. Unfortunately, the scale of the maps was not detailed enough to see any differences between the two approaches, therefore the two layers were subtracted from each other using change detection techniques. The resulting change maps showed significant differences (areas with over- and underestimation of wind frequency) for large parts of the test countries between the two separate approaches. The visual difference could be seen in the maps, but in order to have quantitative information about the relevance, the frequency distribution of over- and underestimations were calculated. The main result showed that for about 56% of the territory of Denmark and 31% of territory of Switzerland the wind erosivity was overestimated and in 6.2% and 16% for Denmark and Switzerland respectively, the values were underestimated. Since all of the differences for high wind erosivity classes were overestimations, it can be concluded that estimations of wind erosion risk for Denmark and Switzerland produces an overestimation of the wind erosion risk, if the dry-times are not taken into account. Based on these findings, the raised question of this section can be clearly answered; It is very important to include the dry/wet separation into the data analysis for wind frequency analysis, wind erosivity calculations and wind erosion risk assessments.

Question 2: How to separate wet/dry periods based on standard historic wind data time series?

Usually, in a time series of wind factors, the wetness or dryness of soil surface is not recorded with wind factors. To specify wet days, Hagen (2007) assumed that “the first hour of precipitation along with the 23 succeeding hours were placed in wet day distribution classes”. However, in this thesis, instead of using Hagen’s method to specify wet days and dry days, it was attempted to design a model to separate wet and dry periods based on daily precipitation records and other hourly or sub-hourly weather elements (relative humidity, temperature, dew point temperature) as well as spatial information and physical reality of desired weather stations in the study area. In general, the structure of the proposed sub-model can be divided into four stages:

1- Estimating initial time of precipitation in days with precipitation more than 6mm;

2- Calculating the duration of rainfall effect on the soil surface;

3- Estimating solid state times;

4- Evaluating the dew formation time prediction.

Before applying the proposed model and specifying wet/dry periods in studied weather stations, the model was calibrated by installing a portable weather station in Denmark for monitoring weather elements and soil moisture (water content) at least for one year and with a temporal resolution of 30 min. After calibrating the model and measuring its accuracy, the model was implemented for all selected stations in Denmark and Switzerland. In fact, by running this sub-model, a Boolean flag field was added to the database and thus, the separation of wet/dry periods was possible.

Question 3: What could be the impact of climate change on wind factors in Denmark and Switzerland?

To identify the impact of climate change, particularly for wind factors, is not an easy task and requires the consideration of some principles. For example, before investigating the trend of climatic factors, it is essential that the time series should be homogenous and the outliers in time series controlled. The existence of such errors has a great influence on the rate and direction of the calculated trend and consequently, if these errors are not excluded, the results can not reflect the impact of climate change.

The trend analysis of all selected weather stations in Denmark and Switzerland revealed that, in almost all studied wind factors, a decreasing trend is more apparent than an increasing one. This result is in accordance with many other studies (Brázdil et al., 2009; Cusack, 2012; Jiménez et al., 2010; McVicar et al., 2010; Najac et al., 2011; Papaioannou et al., 2011; Pirazzoli & Tomasin, 2003; Vautard et al., 2010; Walter et al., 2006). Several reasons have been reported to describe the reduction of observed near-surface wind velocity as for instance, changes in mesoscale circulation in regions, increasing land surface roughness as well as the movement of massive storms towards polar latitudes due to climate change (see sub-chapter 5.2 for more details).

It should be noted that the method used in this part of study was defined as very strict and tried to detect trends only due to climate change. This rigidity provoked that for many stations, which had inadequate or inappropriate data, it was not possible to detect a trend. However, the trend failure in these stations does not necessarily imply the absence of climate change in the region.

Question 4: How to estimate actual and potential wind erosion risk in a quick, simple and reliable method in an area without sufficient data?

Finding a quick, simple and reliable way for mapping potential wind erosion risk was in fact the main objective of the current research. Therefore, studies such as the investigation of the impacts of climate change as well as extreme wind velocity analysis were performed in order to generate the required data necessary in this part of research.

The way that was adopted for the implementation of the model was according to GIS techniques, Fuzzy logic and somewhat univariate statistics. To reduce the complexity of the model, spline technique was used to interpolate a raster surface from point maps. Also, for overlaying layers, the Fuzzy overlay tool in the spatial analyst toolbox of ArcGIS 10.0 was applied to combine fuzzy membership raster data, according to the gamma value of 0.8 in overlay type.

Since the proposed model is a GIS-based model and its workflows containing a sequence of tools, thus, the model was automated by scripting in Payton and created a model tool in ArcGIS desktop 10.0 which can be easily handled by users by simply possessing a set of input data created by other related investigative parts in this thesis. These input data include Digital Elevation Model (DEM) and land cover obtained through the Global Data Explorer (GDEx) of USGS website (http://gdex.cr.usgs.gov/gdex/); data tables such as wind factors, the impact of climate change on wind elements as well as extreme winds in different return levels. It should be noted that all these data tables are obtained based on reanalyzing weather elements from NOAA/NCDC.

Finally, the model implementation led to the creation of potential and actual wind erosion risk maps using the results of the wet/dry sub-modeling as well as the computation of the climate change impacts on wind factors.

6.2. Limitations of the study

First of all, it is very important to note that the aim of this research was to design a model to assess wind erosion risk, even in areas with minimal weather and soil information. Therefore, other factors that could also be very important to model the wind erosion process, but are unfortunately not publicly available everywhere, were ignored. In order to make the model uncomplicated, quick and easy to run, some parameters are not included in the model such as vegetation cover, soil surface roughness as well as agricultural land management.

Lack of access to adequate and appropriate time series of desired weather elements is one of the most significant challenges in this research and will have a detrimental effect on the model output. Selecting suitable weather stations, correcting and reconstructing the weather time series as well as running a data homogenization process is very time-consuming, but an essential undertaking. However, neglecting this series of processes of data homogenization will lead to reduced accuracy of the modelling.

Another limitation of this research was the unavailability of the actual status of wind erosion risk in the study areas to validate the accuracy of the model. Hence, the output of the model was compared with the results of other wind erosion models which had been carried out for European countries in the literature (Borrelli, Ballabio, et al., 2014; Borrelli, Panagos, et al., 2014).

Finally, with the proposed model we tried to estimate the potential and actual risk of wind erosion. Nevertheless, it must be understood that no scientific model can be designed to explain every detail of a natural phenomenon and that some uncertainties cannot be eliminated. Our proposed model is also no exception to this rule and the predicted values could be far from reality, depending on the accuracy of input data.

6.3. Further research suggestions

Arising from the previously mentioned limitations of the study, some future research suggestions can be presented as follows:

In order to simplify the model, we assumed that the threshold wind velocity is identical for all soil types (7 ms-1 at 10m height above ground) and only dependent on soil moisture situation. It can be assumed that under real natural conditions, the threshold values are variable in time on the same plot and spatially, because of different soil types or soil texture. During wet periods of the year for example, the threshold velocity would have been considered much higher. Therefore, it is recommended estimating the threshold wind velocity at least according to soil types in future modeling approaches.

Unfortunately, in almost all weather stations, wind factors and soil moisture status are not recorded simultaneously along with wind data observations. Therefore, determining the state of soil surface moisture, exactly in each recording time of observations in a time series, is simply not possible. Hence, with technical advancements nowadays, it is highly recommended to start recording wind data and soil moisture content simultaneously, at least in synoptic weather stations. With long-term hydrological and meteorological datasets, modelling of wind erosion risk is far more accurate and can be verified much easier.

Since the physics of wind erosion is very complex, therefore many factors of soil surface as well as atmospheric conditions must be taken into account for modeling wind erosion with increased reliability. However, in this research the main focus was the status of weather elements and soil moisture. It has to be evaluated, if further parameters should be included in modeling approaches, such as surface roughness, presence or absence of windbreaks, agricultural field irrigation periods, times of tillage and fallow in agricultural lands as well as the amount of vegetation cover at different times of the year. Since the structure of the proposed model is GIS-based, and the modeling approach is a pixel-oriented, integrating other layers of information and running the model in different scales would be feasible.

Finally, due to the availability and open access on raw data almost across the globe, the model implementation is possible in any country. Running the model in other countries with different climate and topography can be useful to identify the effects of changes in topography and climate on potential wind erosion risk.

6.4. Research achievements and outlook

The main achievement resulting from this research was to provide a quick, easy to use and fairly reliable approach for modeling potential and actual wind erosion risk in regions with few information. In addition to this main goal, other achievements were successfully accomplished. The most important achievements of this thesis can be listed as follows:

1- Offering a dynamic database for the integration of daily and hourly/sub-hourly weather element observations, obtained from NOAA/NCDC. In addition, importing downloaded ASCII files to this database renders the reanalysis and data management much easier;

2- Designing a climatic data generator program for the reanalysis of weather element time series and the extraction of climatic data;

3- Modeling wet/dry periods in wind time series, based on standard weather elements;

4- Developing a strict method for the homogenization of climatic time series, trend analysis and estimating the slope of trend of each desired climatic elements based on SNHT, the Mann-Kendall trend test as well as Sen's slope estimator, respectively;

5- Designing an algorithm to select independent peak over threshold data in a wind time series;

6- Offering an effective wind rose diagram (E-wind rose) in order to show the frequency of erosive winds in a region. Using E-windrose will provide a better representation of affecting erosive winds in a region and will be useful for future studies on wind erosion and desertification;

7- Accelerating the analysis of extreme wind velocity by using and developing extreme value analysis methods in R environment;

8- Allowing a rapid calculation of climate change impact on different climatic elements by using and developing trend analysis packages in R, as well as extracting appropriate outputs of data for using in GIS environments.

This investigation was more or less able to show that the proposed model fulfills the set requirements, that the developed statistical routines work, and that the designed and programmed software packages can be used for their purpose. For the near future it is planned to add some easy to use GUI (Geographic User Interface) to the developed software and data tools and to make them publicly available, because they could be of some help for other researcher in their own field of research. The first tools to be released will most probably be the data generator and the dynamic database for analysis and rearrangement of weather data. In addition, the E-windrose program will definitely be published as an option to the conventional wind roses. Finally, after further verification and implementation of some likely improvements and the development of a user friendly front end input platform, the wind erosion risk model will be made publicly available. Being able to create a quick but reliable overview of the potential wind erosion risk of a region, could be helpful for many other applications, for example environmental management, agricultural use or landscape planning, and, last but not least, wind erosion research.

Something that is not intended is to try to include much more, without any doubt, important factors into the model to improve its accuracy and quality of prediction. It was the intention from the beginning, to have a model that works with standard meteorological weather data and some other, publicly available data sources, like the Collection 5 MODIS Global Land Cover Type product and the Harmonized World Soil Database (HWSD). In order to improve the model without increasing its complexity and the problem of data availability too much, carefully selected parameters will be included, as for example the vegetation cover (e.g., NDVI maps), soil roughness and perhaps land management.

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“Det bedste er det godste fiende.”
English equivalent: ”Better is the enemy of good.”
~ Danish proverb

APPENDIX A:

Denmark

1. Wind frequency distributions
2. Impact of climate change
3. Extreme wind analysis

1. Wind frequency distributions

Note: As an exemplary the results of one station (FOULUM) has been presented here. The results of other stations also enclosed to the thesis in a digital appendix.

Table A-1: An exemplary of frequency distribution of wind speed classes in different directions regardless of wet/dry situation (Foulum, synoptic times of 2000-2013)

#	Directions	Wind Speed Classes (Knots)						Total
		1-4	4-7	7-11	11-17	17-22	>=22	
1	N	910	921	474	176	34	3	2518
2	NE	448	549	465	150	8	0	1620
3	E	522	1195	1262	687	76	11	3753
4	SE	299	814	1347	1185	223	37	3905
5	S	857	1640	2044	1426	194	26	6187
6	SW	820	2018	2067	928	121	19	5973
7	W	797	2135	2772	2054	337	116	8211
8	NW	465	818	1143	1025	236	53	3740
	Sub Total	5118	10090	11574	7631	1229	265	35907
	Calms							1220
	Incomplete Data							2495
	Total							39622

Table A-2: An exemplary of frequency distribution of wind speed classes in different directions based on dry-times (Foulum, synoptic times of 2000-2013)

#	Directions	Wind Speed Classes (Knots)						Total
		1-4	4-7	7-11	11-17	17-22	>=22	
1	N	824	786	416	141	24	2	2193
2	NE	410	486	413	126	6	0	1441
3	E	480	1103	1153	643	74	11	3464
4	SE	276	737	1245	1085	210	36	3589
5	S	792	1450	1745	1195	159	18	5359
6	SW	758	1753	1798	793	96	14	5212
7	W	714	1989	2554	1858	291	95	7501
8	NW	421	741	1056	962	226	51	3457
	Sub Total	4675	9045	10380	6803	1086	227	32216
	Calms							1107
	Incomplete Data							2494
	Total							35817

Table A-3: An exemplary of frequency distribution of erosive wind speed classes in different directions regardless of wet/dry situation (Foulum, synoptic times of 2000-2013)

#	Directions	Wind Speed Classes (Knots)			Total
		13.61-17.5	17.5-21.38	>=21.38	
1	N	72	16	3	91
2	NE	39	3	0	42
3	E	207	39	11	257
4	SE	504	150	37	691
5	S	497	124	26	647
6	SW	292	75	19	386
7	W	804	212	116	1132
8	NW	489	153	53	695
	Sub Total	2904	772	265	3941
	Non-erosive				33186
	Incomplete Data				2495
	Total				39622

Table A-4: An exemplary of frequency distribution of erosive wind speed classes in different directions based on dry-times (Foulum, synoptic times of 2000-2013)

#	Directions	Wind Speed Classes (Knots)			Total
		13.61-17.5	17.5-21.38	>=21.38	
1	N	60	9	2	71
2	NE	31	3	0	34
3	E	194	38	11	243
4	SE	467	142	36	645
5	S	409	101	18	528
6	SW	237	61	14	312
7	W	707	185	95	987
8	NW	460	149	51	660
	Sub Total	2565	688	227	3480
	Non-erosive				29843
	Incomplete Data				2494
	Total				35817

2. Impact of climate change

Table A-5: Annual trend analysis of climatic variables in Denmark

	Stations	T_{max}	T_{mean}	RH_{mean}	$DewP_{mean}$	V_{max}	V_{mean}	Vt_{mean}	NEW	WPD	EWPD
All-times (Conventional way)	AARHUS LUFTHAVN	0.05°1	0.15***°1	0.05^1	-0.03°1	-0.21*°3	-0.01^1	-0.14**°2	-0.08**^1	-0.04^1	-0.15***°2
	AARHUS SYD	-0.03°1	-0.08°1	0.11°1	0.03°1	0.24**°2	0.05°1	0.07°1	0.08°1	0.05°1	0.07°1
	ABED	-0.08°1	-0.11*°1	0.08°1	-0.07°1	0.08°1	0.11*°1	0.39*°3	0.06°1	0.1°1	0.05°1
	BILLUND	0.11***°1	0.19***°1	0.05°1	0.21***°1	-0.09***°1	0.01^1	-0.02°1	-0.11*^2	-0.01^1	-0.09*°2
	FLYVESTATION AALBOR	0.16***°1	0.23***°1	-0.01°1	0.24***°1	-0.03°1	-0.01^1	-0.02^1	0.02^1	-0.11*°2	0.01°1
	FOULUM	0.36*^3	-0.06°1	0.22***°1	0.03°1	-0.1*°1	-0.04^1	-0.09°1	-0.09^1	-0.03^1	-0.03^1
	GEDSER ODDE	-0.06°1	-0.09°1	0.12*°1	-0.03°1	-0.69***°3	0.03°1	-0.02°1	0.03°1	0.01°1	0.02°1
	HOLBAEK	-0.02°1	-0.08°1	0.06°1	-0.08°1	-0.02°1	0.08°1	0.01°1	0.03^1	0.05°1	-0.02°1
	KARUP	0.05°1	0.06°1	-0.15*°2	0.05°1	-0.06°1	0.02^1	-0.01°1	0.04^1	0.03^1	-0.03°1
	ROSKILDE_TUNE	0°1	0.05°1	-0.06^1	0.2***°1	-0.13***°1	0.03^1	-0.22***°2	-0.24***°2	-0.27***°2	-0.15**°2
	SKAGEN	0.04°1	0.14***°1	-0.02^1	0°1	-0.25**°3	0.04^1	0.01^1	0.02^1	0^1	-0.01^1
	SKRYDSTRUP	0.07°1	0.09**°1	-0.02°1	0.08*°1	-0.06°1	-0.25***°2	-0.08*°1	-0.15*°2	0.05^1	-0.33**°3
	TESSEBOELLE	-0.04°1	-0.09°1	-0.24***°1	-0.16**°1	0°1	0.04°1	-0.02°1	0.09°1	0.1°1	-0.01°1
	TYLSTRUP	-0.16**°1	-0.71**°3	-0.12°1	-0.14*°1	-0.09°1	-0.15*°1	0.02°1	-0.08°1	-0.07°1	-0.02°1
	TYSOFTE	-0.16**°1	-0.71**°3	-0.23***°1	-0.22***°1	-0.02°1	-0.02°1	-0.08°1	-0.57*°3	-0.01°1	-0.05°1
Dry-times	AARHUS LUFTHAVN	0.09*°2	0.15***°1	-0.05^1	-0.03°1	0.02^1	0^1	-0.13**°2	-0.04^1	-0.03^1	0.03^1
	AARHUS SYD	-0.01°1	-0.06°1	0.15**°1	0.05°1	0.13*°1	0.08°1	0.47*°3	0.15**°1	0.07°1	0.07°1
	ABED	-0.09°1	-0.08°1	0.01°1	-0.09°1	0.09°1	0.12*°1	0.05°1	0.23**°2	0.21*°2	0.07°1
	BILLUND	0.13***°1	0.19***°1	0.02°1	0.21***°1	-0.08**°1	0.01^1	0°1	-0.04^1	0^1	-0.05°1
	FLYVESTATION AALBOR	0.16***°1	0.24***°1	-0.03°1	0.24***°1	-0.03°1	0^1	-0.01^1	0.05^1	0.05^1	0.01°1
	FOULUM	0.36*^3	-0.07°1	0.17***°1	0.02°1	-0.08°1	-0.02^1	-0.09°1	-0.09°1	-0.02^1	-0.13**°1
	GEDSER ODDE	-0.04°1	-0.1°1	0.17**°1	-0.01°1	-0.43*°3	0.05°1	0.02^1	0.28**°2	0.04°1	0.05°1
	HOLBAEK	0.04°1	-0.45*°3	0.12*°1	-0.04°1	0.02°1	0.06°1	-0.02°1	0.22**°2	0.06°1	0.01°1
	KARUP	0.07°1	0.07°1	-0.11**°1	0.05°1	-0.03°1	0.02^1	0°1	-0.03^1	0.02^1	-0.02°1
	ROSKILDE_TUNE	-0.02°1	0.05°1	-0.04^1	0.2***°1	-0.13*°2	0.03^1	-0.22***°2	0.06^1	0.04^1	-0.16**°2
	SKAGEN	0.04°1	0.1***°1	0.09***^1	-0.01°1	-0.2*°3	0.03^1	0.02^1	-0.03°1	0^1	0^1
	SKRYDSTRUP	0.08*°1	0.08*°1	-0.04°1	0.07°1	0.04^1	-0.25***°2	-0.15*°2	-0.18**°2	-0.18**°2	-0.38**°3
	TESSEBOELLE	-0.05°1	-0.08°1	-0.23***°1	-0.16**°1	0.03°1	0.11°1	-0.07°1	0.3**°2	0.08°1	-0.04°1
	TYLSTRUP	-0.23*°2	-0.14*°1	-0.05°1	-0.28**°2	-0.15*°1	-0.13°1	0.01°1	-0.04°1	-0.08°1	-0.05°1
	TYSOFTE	-0.1°1	-0.71**°3	-0.17**°1	-0.18**°1	-0.01°1	-0.06°1	-0.11°1	-0.09°1	-0.02°1	-0.09°1

T: temperature, RH: relative humidity, DewP: dew point, V: wind speed in synoptic times, Vt: wind speed in all records, NEW: number of erosive winds, WPD: wind power density, EWPD: erosive wind power density.
°: Homogenous data ^: Adjusted data to remove inhomogeneity
¹: Calculations based on monthly data 2: Calculations based on seasonal data 3: Calculations based on annual data
***: The trend statistically significant at 99% level **: The trend statistically significant at 95% level
*: The trend statistically significant at 90% level.

Note: As an exemplary monthly trend of mean wind speed has been presented here. The trend of other parameters enclosed to the thesis in a digital appendix.

Table A-6: Monthly trend of mean wind speed in Denmark in all-times and dry-time approaches

	Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
All-times (Conventional way)	AARHUS LUFTHAVN	0.08^	-0.13°	0.05^	-0.08^	0.04^	-0.11°	0.04^	0.04^	-0.06^	-0.01^	-0.05^	-0.01^
	AARHUS SYD	-0.09°	0.2°	0.38°	0.33°	0.05°	-0.09°	-0.11°	0.05°	0.09°	0.2°	-0.24°	0.2°
	ABED	-0.12°	0.21°	0.12°	-0.09°	0.06°	0.02°	-0.09°	0.06°	-0.18^	0.3°	-0.09°	0.15°
	BILLUND	-0.02°	-0.05°	0.08^	0.12^	-0.1°	-0.14°	-0.02^	0.01^	-0.02^	0.05^	-0.02^	-0.02^
	FLYVESTATION AALBOR	0.01°	-0.04°	-0.11°	-0.1°	0.05°	0.06°	-0.22*°	0.01°	-0.1°	-0.11°	-0.11°	-0.16°
	FOULUM	-0.25°	-0.12°	0.18°	0.08°	-0.18°	-0.31°	-0.05°	-0.21°	0.01°	-0.03°	-0.27°	0.1°
	GEDSER ODDE	-0.13°	0.2°	0.16°	-0.05°	0.16°	-0.2°	-0.02°	-0.38°	0.24°	0.2°	-0.02°	-0.09°
	HOLBAEK	-0.24°	0.06°	0.09°	0.09°	-0.21°	-0.09°	-0.06°	0.06°	0.39*°	0.24°	-0.27°	0.09°
	KARUP	-0.14°	-0.42**°	-0.22°	-0.2°	-0.16°	-0.36**°	-0.22°	-0.24°	-0.22°	-0.37**°	-0.19°	0.06°
	ROSKILDE_TUNE	-0.29**°	-0.31**°	-0.31**°	-0.27*°	-0.27*°	-0.01°	-0.3**°	-0.28**°	-0.13°	-0.09°	-0.05°	-0.05°
	SKAGEN	-0.2*°	0.01°	-0.09°	-0.21*°	-0.09°	-0.18°	-0.31***°	-0.14°	-0.37***°	-0.17°	-0.17°	-0.31***°
	SKRYDSTRUP	-0.16°	-0.31**°	-0.23°	-0.24°	-0.11°	-0.16°	-0.13°	-0.1°	-0.07°	-0.19°	-0.13°	0.05°
	TESSEBOELLE	-0.29°	-0.36°	0.36°	0.11°	0.06°	0°	-0.17°	-0.11°	-0.06°	0.44°	-0.64**°	0.17°
	TYLSTRUP	-0.5°	-0.29°	-0.14°	0°	-0.28°	-0.17°	-0.39°	-0.39°	-0.22°	0.22°	-0.44°	-0.06°
	TYSOFTE	-0.36°	-0.36°	0°	0.36°	-0.11°	0.11°	-0.36°	-0.11°	0.06°	0.33°	-0.43°	0.17°
Dry-times	AARHUS LUFTHAVN	0.08^	-0.13°	0.05^	-0.08^	-0.23**^	-0.12°	0.02^	0.03^	-0.08^	0.04^	-0.01^	0.04^
	AARHUS SYD	-0.33°	0.2°	0.2^	0.42^	-0.05°	-0.02°	-0.07°	-0.02°	0.13°	0.24°	-0.02°	0.31°
	ABED	-0.35°	0.64***°	0.24°	-0.15°	-0.36^	0.09°	-0.05°	0.12°	-0.06^	0.33°	-0.24°	-0.05^
	BILLUND	-0.02°	-0.03°	-0.19°	-0.23**°	-0.13°	-0.05°	-0.01^	0.02^	-0.07^	-0.16°	-0.18°	-0.08°
	FLYVESTATION AALBOR	0.01°	-0.03°	-0.11°	-0.1°	0.05°	0.08°	-0.23**°	0.02°	-0.07°	-0.13°	-0.05°	-0.1°
	FOULUM	-0.27°	-0.19°	0.18°	0.05°	-0.13°	-0.3°	-0.03°	-0.21°	-0.03°	0.13°	-0.21°	0.1°
	GEDSER ODDE	-0.05°	0.38°	-0.11°	-0.05°	0.13°	-0.07°	-0.02°	-0.42°	0.24°	0.24°	0.02°	-0.02°
	HOLBAEK	-0.06°	0.15°	0.06°	0.09°	-0.24°	0.05°	-0.06°	0.06°	0.36°	0.21°	-0.15°	-0.02°
	KARUP	-0.18°	-0.38**°	-0.19°	-0.27*°	-0.16°	-0.31**°	-0.18°	-0.28*°	-0.16°	-0.37**°	-0.2°	0.24°
	ROSKILDE_TUNE	-0.18°	-0.33**°	-0.31**°	-0.25*°	-0.3**°	-0.01°	-0.32**°	-0.29**°	-0.12°	-0.03°	-0.03°	-0.03°
	SKAGEN	-0.07°	0.04°	-0.08°	-0.2*°	-0.06°	-0.17°	-0.28***°	-0.15°	-0.39***°	-0.1°	0.03°	-0.32***°
	SKRYDSTRUP	-0.1°	-0.33**°	-0.08°	-0.21°	-0.1°	-0.17°	-0.12°	-0.09°	0.07°	-0.2°	-0.16°	0.04°
	TESSEBOELLE	-0.29°	0.14°	0.29°	0.29°	0°	-0.06°	-0.11°	-0.22°	0°	0.64**°	-0.29°	0.29°
	TYLSTRUP	-0.14°	0°	-0.21°	0.06°	-0.28°	-0.06°	-0.39°	-0.28°	-0.22°	0°	-0.28°	0.29°
	TYSOFTE	-0.11°	-0.43°	0.07°	0.07°	-0.11°	0.11°	-0.43°	-0.08°	0°	0.33°	-0.33°	0.64**°

°: Homogenous data ^: Adjusted data to remove inhomogeneity
***: The trend statistically significant at 99% level **: The trend statistically significant at 95% level
*: The trend statistically significant at 90% level.

Table A-7: The magnitude of monthly trends of mean wind speed estimated by the Theil-Sen estimator in Denmark

	Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
All-times (Conventional way)	AARHUS LUFTHAVN	0.02	-0.04	0.01	-0.02	0.00	-0.02	0.01	0.01	-0.01	0.00	-0.01	0.00
	AARHUS SYD	-0.07	0.17	0.14	0.12	0.01	-0.02	-0.03	0.01	0.05	0.14	-0.32	0.1
	ABED	-0.04	0.13	0.07	-0.06	0.03	0.01	0.00	0.01	-0.03	0.11	-0.12	0.07
	BILLUND	-0.01	-0.02	0.01	0.01	-0.01	-0.01	0.00	0.00	0.00	0.01	0.00	0.00
	FLYVESTATION AALBOR	0.00	-0.01	-0.03	-0.02	0.01	0.01	-0.04**	0.00	-0.02	-0.02	-0.02	-0.04
	FOULUM	-0.09	-0.13	0.06	0.02	-0.11	-0.08	0.00	-0.05	0.00	-0.06	-0.05	0.09
	GEDSER ODDE	-0.18	0.23	0.19	-0.03	0.07	-0.2	-0.08	-0.19	0.34	0.24	-0.04	-0.1
	HOLBAEK	-0.38	0.13	0.03	0.06	-0.16	-0.03	-0.02	0.04	0.12**	0.08	-0.28	0.05
	KARUP	-0.11	-0.21**	-0.12	-0.06	-0.03	-0.05**	-0.03	-0.05	-0.06	-0.08**	-0.06	0.04
	ROSKILDE_TUNE	-0.11**	-0.13**	-0.09**	-0.04**	-0.05**	0.00	-0.05**	-0.05**	-0.03	-0.02	-0.01	-0.03
	SKAGEN	-0.06**	0.00	-0.04	-0.05**	-0.01	-0.04	-0.06**	-0.03	-0.08**	-0.04	-0.05	-0.1**
	SKRYDSTRUP	-0.11	-0.13**	-0.06	-0.05	-0.02	-0.05	-0.03	-0.02	-0.01	-0.05	-0.06	0.03
	TESSEBOELLE	-0.44	-0.55	0.18	0.05	0.01	0.02	-0.04	-0.09	-0.02	0.16	-0.44**	0.13
	TYLSTRUP	-0.73	-0.51	-0.14	0.02	-0.11	-0.03	-0.07	-0.19	-0.16	0.04	-0.17	-0.01
	TYSOFTE	-0.65	-0.54	0.00	0.02	-0.06	0.09	-0.1	-0.03	0.04	0.17	-0.27	0.2
Dry-times	AARHUS LUFTHAVN	0.02	-0.04	0.01	-0.01	-0.03**	-0.02	0.00	0.00	-0.01	0.00	0.00	0.01
	AARHUS SYD	-0.15	0.18	0.06	0.12	-0.02	0.00	-0.01	0.00	0.04	0.22	-0.04	0.1
	ABED	-0.26	0.38**	0.11	-0.07	-0.07	0.02	-0.02	0.03	-0.03	0.15	-0.16	-0.04
	BILLUND	-0.01	-0.01	-0.03	-0.02**	-0.02	-0.01	0.00	0.00	-0.01	-0.03	-0.03	-0.01
	FLYVESTATION AALBOR	0.00	-0.01	-0.03	-0.02	0.01	0.01	-0.04**	0.00	-0.01	-0.02	-0.01	-0.02
	FOULUM	-0.14	-0.13	0.1	0.02	-0.07	-0.09	0.00	-0.02	0.00	0.09	-0.09	0.06
	GEDSER ODDE	-0.09	0.23	-0.04	-0.04	0.11	-0.06	-0.05	-0.16	0.25	0.26	0.02	-0.02
	HOLBAEK	-0.12	0.17	0.02	0.04	-0.2	0.06	-0.01	0.03	0.12	0.08	-0.12	-0.02
	KARUP	-0.12	-0.2**	-0.1	-0.07**	-0.02	-0.07**	-0.03	-0.05**	-0.06	-0.06**	-0.05	0.12
	ROSKILDE_TUNE	-0.09	-0.17**	-0.09**	-0.04**	-0.06**	0.00	-0.06**	-0.05**	-0.02	-0.01	-0.02	-0.01
	SKAGEN	-0.03	0.04	-0.04	-0.04**	-0.01	-0.04	-0.06**	-0.03	-0.08**	-0.03	0.01	-0.13**
	SKRYDSTRUP	-0.1	-0.13**	-0.04	-0.05	-0.02	-0.06	-0.03	-0.01	0.01	-0.05	-0.04	0.03
	TESSEBOELLE	-0.13	0.05	0.12	0.1	-0.01	-0.04	-0.06	-0.09	-0.01	0.3**	-0.22	1.23
	TYLSTRUP	-0.49	0.3	-0.19	0.04	-0.14	-0.03	-0.1	-0.19	-0.21	0.03	-0.14	0.64
	TYSOFTE	-0.17	-0.68	0.03	0.03	-0.08	0.08	-0.31	-0.02	0.00	0.22	-0.23	0.78**

***: The trend statistically significant at 99% level **: The trend statistically significant at 95% level
*: The trend statistically significant at 90% level.

3. Extreme wind analysis

Table A-8: Basic descriptive statistics of POT wind velocities for desired weather stations in Denmark

Station Name	nobs	Min	Max	1st Qu.	3rd Qu.	Mean	Median	Var.	Stdev	Skew.	Kurtosis
AARHUS LUFTHAVN	4620	13.39	64.86	15.05	20.45	18.48	17.09	23.74	4.87	2.25	9.76
AARHUS SYD	883	13.51	38.71	14.70	18.63	17.18	16.17	11.51	3.39	1.69	4.12
ABED	1256	13.12	69.83	15.00	19.73	18.20	16.81	26.70	5.17	3.67	23.06
BILLUND	4731	13.34	61.26	14.93	19.43	17.76	16.62	15.94	3.99	2.17	9.13
FLYVESTATION AALBOR	4775	13.13	63.95	15.27	21.34	19.01	17.77	25.28	5.03	1.85	6.20
FOULUM	1139	13.51	39.62	14.74	19.13	17.49	16.35	14.28	3.78	1.84	4.75
GEDSER ODDE	1147	13.50	56.13	16.12	25.68	21.54	20.26	41.55	6.45	1.02	1.31
HOLBAEK	1321	13.26	81.37	15.15	20.42	18.56	17.03	28.68	5.36	3.46	23.95
KARUP	2632	13.50	47.46	14.86	19.51	17.86	16.57	17.80	4.22	2.09	6.76
ROSKILDE TUNE	3398	13.50	48.53	15.06	20.66	18.54	17.19	21.48	4.63	1.65	3.85
SKAGEN	3412	13.30	75.48	17.74	28.82	24.10	22.79	62.67	7.92	1.02	1.93
SKRYDSTRUP	2722	13.50	64.62	15.23	20.41	18.55	17.16	23.20	4.82	2.31	9.98
TESSEBOELLE	646	13.50	34.93	14.46	18.10	16.64	15.79	8.55	2.92	1.71	4.16
TYLSTRUP	564	13.52	37.81	14.72	19.10	17.37	16.24	13.11	3.62	1.72	4.06
TYSOFTE	757	13.50	31.96	14.72	19.22	17.34	16.23	11.49	3.39	1.26	1.44

Table A-9: Estimated parameters of fitting GPD over POTs for desired weather stations in Denmark

Station Name	Estimated parameters		Standard errors	
	Scale	Shape	Scale	Shape
AARHUS LUFTHAVN	5.845676	-0.06966	0.100762	0.009041
AARHUS SYD	4.772719	-0.14821	0.183866	0.019406
ABED	5.214608	-0.00305	0.177791	0.019138
BILLUND	5.160265	-0.08859	0.081637	0.006374
FLYVESTATION AALBOR	6.620697	-0.10776	0.106394	0.007158
FOULUM	5.057556	-0.12998	0.181148	0.020488
GEDSER ODDE	10.29092	-0.22255	0.324964	0.013019
HOLBAEK	5.660314	-0.01768	0.184756	0.017568
KARUP	5.311363	-0.09608	0.124802	0.013255
ROSKILDE TUNE	6.292766	-0.13983	0.127576	0.011068
SKAGEN	13.04876	-0.20161	0.229293	0.005424
SKRYDSTRUP	5.966809	-0.0783	0.130985	0.010807
TESSEBOELLE	4.170201	-0.1526	0.18672	0.022203
TYLSTRUP	4.983777	-0.14482	0.250201	0.028009
TYSOFTE	5.333534	-0.23731	0.230065	0.024783

"Who cares about every little feather should not make the bed."

~ Swiss Proverb

APPENDIX B:

Switzerland

1. Impact of climate change
2. Extreme wind analysis

1. Impact of climate change

Table B-1: Annual trend analysis of climatic variables in Switzerland based on all-times

	T_{max}	T_{mean}	RH_{mean}	$DewP_{mean}$	V_{max}	V_{mean}	Vt_{mean}	NEW	WPD	EWPD
AADORF-TAENIKO	0.16**°1	0.03°1	0.2***°1	0.07°1	0^1	0.03^1	-0.04^1	-0.13**°1	-0.43***°2	-0.13**°1
ACQUAROSSA-COMPROVA	0.08*°1	0.13*°2	-0.09**^1	0.14***°1	-0.01^1	0°1	0^1	-0.02^1	0.02°1	0.07°1
ADELBODEN	0.06°1	-0.02°1	0.02°1	-0.01°1	0.45*°3	-0.53**°3	0.03^1	-0.03°1	-0.14**°1	-0.01°1
AIGLE	0.16***°1	0.18***°1	-0.07*°1	0.15***°1	0^1	0.13***°1	0.03°1	0.03^1	0.05^1	0.05^1
ALTDORF	0.14***°1	0.16***°1	-0.03°1	0.18***°1	-0.02°1	-0.01^1	-0.04°1	-0.01°1	-0.02°1	-0.05°1
BASELBINNINGEN	0.06°1	-0.01°1	0.06°1	0.03°1	-0.3***°2	0.14**^1	-0.17***^1	-0.05^1	0.21*^2	-0.12**^1
BERN-ZOLLIKOFE	0.07°1	-0.04°1	0.16**°1	0.03°1	-0.6**°3	0.25***^1	-0.05^1	-0.11*^1	-0.53**°3	-0.2***°1
BUCHS-SUHR	0.06°1	-0.09°1	0.15**°1	0.03°1	0.05^1	-0.32***°2	-0.05^1	-0.08*°1	-0.22**°2	-0.05°1
BULLET-LA-FRETAZ	0.07°1	-0.06°1	0.08°1	0.05°1	0.04^1	-0.21*°2	-0.08^1	0.02^1	-0.22*°2	-0.11*°1
CHASSERAL	0.12*°1	-0.01°1	0.78***°3	0.05°1	-0.49**°3	-0.33***°2	0.13**^1	-0.11*^1	0.11*^1	-0.33***°2
CHUR-EMS	0.18***°1	0.2***°1	-0.08**^1	0.26***°1	0.05^1	-0.02^1	0^1	-0.08**^1	0^1	0.21*^3
CIMETTA	0.17***°1	0.12***°1	0.18***°2	0.21***°1	-0.06°1	-0.02^1	-0.01°1	0.03^1	-0.02^1	-0.04^1
DAVOS	0.03°1	0°1	-0.07°1	-0.07°1	-0.61**°3	-0.19***°1	-0.09^1	-0.04^1	-0.36***°2	-0.11*°1
ENGELBERG	0.03°1	-0.02°1	0.07°1	0.03°1	0.08^1	0.14**^1	0.03^1	0.02°1	0.15**°1	0.01^1
GENEVE-COINTRIN	0.21***°1	0.28***°1	-0.05*^1	0.13***°1	0^1	0.03^1	0.01^1	-0.05*^1	-0.02^1	-0.02^1
GLARUS	0.06°1	-0.04°1	0.05°1	0.6**°3	-0.04°1	0.15**^1	-0.01°1	-0.03°1	0.12*^1	0°1
GRIMSEL-HOSPIZ	-0.09°1	-0.01°1	-0.03°1	-0.22*°2	0.06°1	0.27**^2	0.21***°1	0.13**^1	0.03°1	0.2***°1
GUETSCHOBANDERMAT	0.08***°1	0.18***°1	0.07**^1	0.15***°1	0.02°1	0.1**°2	-0.19*°3	0.09*°2	0.08***^1	0°1
GUTTINGEN	0.17**°1	0°1	0.05^1	0.19***°1	-0.19*°2	-0.21*°2	-0.05^1	-0.15**°1	-0.23***°1	-0.13**^1
INTERLAKEN	0.15***°1	0.18***°1	-0.08**^1	0.24***°1	-0.06*^1	-0.07**^1	-0.02°1	-0.05^1	-0.03^1	-0.11***°1
LACHAUX-DE-FONDS	0.14***°1	0.15***°1	-0.12*°2	0.14***°1	0.04^1	0^1	0.03^1	-0.02^1	0.01^1	0.02^1
LEMOLESO	0.12*°1	0.04°1	-0.03°1	0.01°1	0.21*°2	-0.15**°1	-0.14**^1	-0.05^1	-0.03°1	0.22*°2
LOCARNO-MAGADINO	0.17***°1	0.25***°1	-0.07**°1	0.14***°1	0^1	0.02^1	-0.02^1	-0.04^1	0^1	-0.04^1
LOCARNO-MONTI	0.2***°1	0.24***°1	-0.05^1	0.09***°1	0.04^1	0.12**^2	0^1	0°1	0.03^1	0°1
LUGANO	0.18***°1	0.27***°1	-0.11***°1	0.13***°1	0.03^1	-0.02^1	0.02°1	0^1	-0.02^1	-0.03^1
LUZERN	-0.19*°2	-0.02°1	0.1°1	0.03°1	-0.02°1	-0.08°1	0.02^1	-0.05°1	-0.05°1	-0.13**°1
MONTANA	0.17***°1	0.13***°1	0.04°1	0.22***°1	-0.07**^1	0.2*^3	0.2*°3	-0.03°1	-0.03^1	-0.02°1
NAPF	0.11***°1	0.09**°1	0.28**°3	0.19***°1	0.01°1	0.02°1	-0.01°1	0°1	-0.02°1	0.02°1
NEUCHATEL	0.12***°1	0.08**°1	-0.06°1	0.07*°1	0.28**°3	-0.14**°2	-0.03^1	-0.01°1	-0.05°1	0.01°1
NYON.CHANGINS	0.07°1	-0.04°1	-0.02°1	-0.01°1	-0.2*°2	0^1	-0.1^1	-0.05°1	-0.03^1	-0.1°1
PAYERNE	0.16***°1	0.18***°1	-0.03^1	0.06**°1	-0.09*°2	-0.1**^2	-0.07**°1	0°1	-0.08**°1	-0.03°1
PILATUSMTN	0.09°1	0.02°1	0.04°1	0.03°1	0.04^1	-0.45*°3	0.03^1	-0.08^1	-0.07^1	0.49**^3
PIOTTA	0.08**°1	0.14***°1	0.15**°2	0.19***°1	0.16***°2	-0.11***^1	0.03°1	0.03°1	-0.03^1	0.16***°2
PIZCORVATSCH	0.01°1	0.08**°1	0.01^1	0.26***°1	-0.05°1	0.01^1	-0.16***°2	0^1	-0.03^1	0.02^1
PLAFFEIEN-OBERSCHRO	0.1**°1	0.06°1	-0.13*°2	0.03°1	-0.03°1	-0.01°1	-0.05°1	-0.07*°1	-0.39**°3	0°1
POSCHIAVO-ROBBIA	0.12***°1	0.2***°1	0.01°1	0.14***°1	0.01°1	0.02°1	0.02^1	0.04°1	-0.01°1	0.01^1
ROBIEI	0°1	0.02°1	0.01°1	0.05°1	0.13**^1	-0.05^1	0.01^1	0.12*°1	0°1	0.05°1
RUENENBERG	0.1°1	-0.01°1	0.05°1	0.05°1	-0.17***°1	0.04°1	-0.04^1	-0.1°1	-0.01°1	-0.12**°1
SAENTIS	0.08**°1	0.13***°1	0.2*°3	0.17***°1	0°1	-0.11*^2	0.03^1	0.04^1	-0.06*^1	0.2*^3
SAMEDAM	0.08**°1	0.17***°1	0.05^1	0.25***°1	-0.03^1	-0.08**°1	0.02^1	-0.08**^1	-0.06*^1	0.03^1
SBERNARDINO	0.13***°1	0.13***°1	0.13**°2	0.2***°1	-0.05^1	-0.01^1	-0.34***°2	-0.21***^1	-0.12***^1	-0.13***^1
SCHAFFHAUSEN	0.08°1	-0.05°1	0.12*°1	0.02°1	-0.09°1	0.13**°1	-0.09°1	-0.04°1	-0.03°1	-0.08°1
SCUOL	0.04°1	0°1	-0.04°1	0.08°1	0.03^1	0.14**^1	-0.07°1	-0.01°1	-0.13**°1	-0.07°1
SION	0.12***°1	0.24***°1	-0.08**^1	0.18***°1	-0.06**^1	-0.04^1	-0.04^1	-0.12**^2	0.12**^2	-0.06**^1
ST.GALLEN	0.13***°1	0.12***°1	-0.04°1	0.12***°1	-0.03°1	-0.1***°1	-0.05°1	0.02°1	-0.22***°2	0.02°1
ULRICHEN	0.03°1	0.02°1	0.18***°1	0.14**°1	0.03°1	-0.07^1	0.04°1	-0.06°1	-0.04°1	0.04°1
VISP	-0.01°1	0.02°1	0.1°1	0.12*°1	-0.03^1	0.04°1	-0.01^1	0.13**°1	-0.03^1	0.02^1
WADENSWIL	0.05°1	-0.02°1	0.11°1	0.07°1	0.02°1	0.49**°3	0.05^1	0.01°1	-0.03°1	-0.01°1
WEISSFLUHJOCH	0°1	0.05°1	0.11*°1	0.07°1	-0.19*°2	0.06^1	-0.31***°2	0.03^1	-0.21*°2	-0.32***°2
WYNAU	0.21***°1	0.18***°1	0.11***°1	0.24***°1	-0.16***^2	0.05^1	-0.04°1	0.01°1	-0.16***°2	-0.03°1
ZERMATT	0.02°1	0°1	0.03°1	0.05°1	0.44*°3	-0.31***^1	-0.03^1	-0.04°1	-0.23***°1	-0.06°1
ZUERICH-AFFOLTER	0.07°1	-0.06°1	0.19***°1	0.06°1	-0.22**°2	0.06^1	-0.07^1	-0.12**°1	-0.44***°2	-0.07°1
ZUERICH-FLUNTER	0.18***°1	0.16***°1	-0.03°1	0.17***°1	0.06*^1	0.08**^1	-0.03°1	0.05°1	0.08**^1	0.01°1
ZURICH-KLOTEN	0.16***°1	0.18***°1	0.02^1	0.09***°1	0.04^1	0.03^1	0^1	0.01^1	0.01^1	0^1

T: temperature, RH: relative humidity, DewP: dew point, V: wind speed in synoptic times, Vt: wind speed in all records, NEW: number of erosive winds, WPD: wind power density, EWPD: erosive wind power density.

°: Homogenous data ^: Adjusted data to remove inhomogeneity, ***: The trend statistically significant at 99% level

**: The trend statistically significant at 95% level, *: The trend statistically significant at 90% level.

1: Calculations based on monthly data 2: Calculations based on seasonal data 3: Calculations based on annual data

Table B-2: Annual climatic variables trend analysis in Switzerland based on dry-times

Stations	T_{max}	T_{mean}	RH_{mean}	$DewP_{mean}$	V_{max}	V_{mean}	Vt_{mean}	NEW	WPD	EWPD
AADORF-TAENIKO	0.17***°1	0.04°1	0.2***°1	0.09°1	0.03^1	0.02^1	-0.05^1	-0.14***°1	-0.35***°2	-0.13**°1
ACQUAROSSA-COMPROVA	0.08*°1	0.09**°1	-0.06^1	0.14***°1	-0.01^1	-0.01°1	0^1	-0.03^1	0.02°1	0.07*°1
ADELBODEN	0.06°1	-0.21*°2	0.25**°2	-0.04°1	0.45*°3	-0.56**°3	0.04^1	-0.03°1	-0.16**°1	-0.01°1
AIGLE	0.16***°1	0.18***°1	-0.07*°1	0.16***°1	0.02^1	0.16***°1	0.01°1	0.19***°2	0.07**^1	0.12**°2
ALTDORF	0.14***°1	0.17***°1	-0.06*°1	0.18***°1	-0.02°1	0.02^1	-0.04°1	0°1	-0.02°1	-0.04°1
BASELBINNINGEN	0.06°1	-0.01°1	0.22*°2	0.03°1	-0.3***°2	0.13**^1	-0.17***^1	-0.06^1	0.06^1	-0.12**^1
BERN-ZOLLIKOFE	0.08°1	-0.04°1	0.18***°1	0.06°1	-0.6**°3	0.26***^1	-0.05^1	-0.11**^1	-0.42*°3	-0.19***°1
BUCHS-SUHR	0.07°1	-0.02°1	0.21*°2	0.03°1	0.04^1	-0.29**°2	-0.05^1	-0.05°1	-0.19*°2	-0.05°1
BULLET-LA-FRETAZ	0.07°1	-0.11*°1	0.28**°2	0.04°1	-0.1°1	-0.13**°1	0.03^1	-0.09°1	-0.16**°1	-0.19*°2
CHASSERAL	0.11*°1	-0.14**°1	0.34***°2	0.01°1	0.01°1	-0.21*°2	-0.33***°2	0.1°1	-0.17***°1	-0.28**°2
CHUR-EMS	0.18***°1	0.19***°1	0.06°1	0.26***°1	0.05^1	-0.01^1	0^1	-0.04^1	0^1	-0.03^1
CIMETTA	0.17***°1	0.13***°1	0.09**°1	0.19***°1	-0.06°1	-0.48***°3	0.04°1	-0.02^1	-0.03^1	-0.04°1
DAVOS	0.03°1	-0.39*°3	0.03°1	-0.49**°3	-0.16**°1	-0.17***°1	-0.29**°2	-0.11*°1	-0.17**°1	-0.2*°2
ENGELBERG	0.03°1	-0.2*°2	0.35***°2	-0.01°1	0.07^1	0.29**°2	0.02^1	-0.01°1	0.12*°1	-0.01^1
GENEVE-COINTRIN	0.21***°1	0.28***°1	-0.06**^1	0.14***°1	0.01^1	0.03^1	0.01^1	-0.05^1	-0.01^1	-0.02^1
GLARUS	0.06°1	-0.05°1	0.08°1	0.02°1	-0.02°1	0.16**^1	-0.02°1	0.03°1	0.12*^1	0.03°1
GRIMSEL-HOSPIZ	-0.08°1	-0.07°1	0.08°1	-0.08°1	0.08°1	0.12*^1	0.16**°1	0.2***^1	-0.03°1	0.24**°2
GUETSCHOBANDERMAT	0.08***°1	0.14***°1	-0.01°1	0.13***°1	0.03°1	0.09*°2	0.01^1	0.01^1	0.03°1	-0.01°1
GUTTINGEN	0.15**°1	0.45*^3	0.58***°2	0.2***°1	-0.2*°2	-0.24**°2	-0.45*°3	-0.25**°2	-0.35***°2	-0.14**^1
INTERLAKEN	0.14***°1	0.18***°1	0.03°1	0.22***°1	-0.12*°2	-0.19***°2	-0.03°1	-0.12***°1	-0.01^1	-0.1***°1
LACHAUX-DE-FONDS	0.14***°1	0.13***°1	0.01°1	0.16***°1	0.01^1	-0.13**^2	-0.06*°1	-0.09**^1	0.02^1	0.02^1
LEMOLESO	0.11*°1	-0.02°1	0.02°1	-0.07°1	-0.06^1	-0.12*°1	-0.08^1	0.03^1	0°1	0.27**°2
LOCARNO-MAGADINO	0.17***°1	0.26***°1	-0.13***°1	0.11***°1	-0.01^1	0.01^1	-0.02^1	-0.04^1	0.09*^2	-0.05^1
LOCARNO-MONTI	0.2***°1	0.25***°1	-0.09**^1	0.07*°1	0.05^1	0.13**^2	0^1	0°1	0.01^1	0°1
LUGANO	0.19***°1	0.3***°1	-0.03^1	0.08**°1	-0.06*^1	0.04^1	0.02°1	0^1	-0.02^1	-0.03^1
LUZERN	-0.19*°2	-0.03°1	0.16**°1	0.04°1	-0.02°1	-0.13**°1	0.02^1	-0.05°1	-0.07°1	-0.12**°1
MONTANA	0.17***°1	0.13***°1	0^1	0.21***°1	-0.04^1	-0.02^1	0^1	-0.02°1	-0.17***°2	-0.01°1
NAPF	0.1***°1	0.08**^1	0.13**°2	0.17***°1	-0.01°1	0.04°1	-0.04°1	-0.02°1	-0.02°1	-0.02°1
NEUCHATEL	0.12***°1	0.08**°1	-0.08**°1	0.05°1	0.27**°3	-0.07*°1	0.21*^3	0°1	-0.05°1	0.01°1
NYON.CHANGINS	0.06°1	-0.06°1	0.05°1	0°1	-0.21*°2	-0.08°1	-0.1^1	-0.07°1	-0.1°1	-0.08°1
PAYERNE	0.16***°1	0.18***°1	-0.03^1	0.06*°1	0°1	0^1	-0.05*°1	0.04°1	0.01^1	-0.01°1
PILATUSMTN	0.07°1	-0.13**°1	0.17***°1	-0.49**°3	-0.04^1	-0.45*°3	0.53**^3	-0.07^1	-0.09^1	0.49**^3
PIOTTA	0.08**°1	0.14***°1	0.1*°2	0.19***°1	0.16***°2	-0.09**^1	0.13**°2	0.03°1	-0.02^1	0.15**°2
PIZCORVATSCH	-0.01°1	0.1***°1	0.16***°2	0.19***°1	0^1	-0.02^1	-0.12**°2	-0.04°1	-0.02°1	-0.01^1
PLAFFEIEN-OBERSCHRO	0.1**°1	0.07°1	-0.02°1	0.03°1	-0.04°1	0°1	-0.06°1	-0.29*°3	-0.41***°3	-0.01°1
POSCHIAVO-ROBBIA	0.12***°1	0.21***°1	-0.06*°1	0.12***°1	0.01°1	0.04°1	0.02^1	0.04°1	0.01°1	0.01^1
ROBIEI	0°1	0.03°1	0.05°1	0.04°1	0.19*°2	0.03^1	0.01^1	0.13**°1	0.05°1	0.07°1
RUENENBERG	0.1°1	-0.03°1	0.1°1	0.03°1	-0.17***°1	-0.01°1	-0.04^1	-0.1*°1	-0.07°1	-0.12**°1
SAENTIS	0.05°1	0.08**°1	0.01^1	0.07**°1	-0.02^1	0.12**^2	-0.01^1	-0.1*^2	-0.05^1	-0.02^1
SAMEDAM	0.08**°1	0.17***°1	0.02^1	0.25***°1	-0.01^1	-0.06*°1	0.02^1	-0.08**^1	-0.04^1	0.03^1
SBERNARDINO	0.13***°1	0.13***°1	-0.07*^1	0.2***°1	-0.04^1	-0.03^1	-0.33***°2	-0.2***^1	-0.11***^1	-0.15***^1
SCHAFFHAUSEN	0.09°1	-0.48**°3	0.15**°1	0.04°1	-0.05°1	0.15**°1	-0.08°1	-0.01°1	-0.01°1	0.6**°3
SCUOL	0.04°1	0.01°1	0.04^1	0.13**°1	0.03^1	0.11*^1	-0.04^1	-0.01°1	-0.14**°1	-0.07°1
SION	0.12***°1	0.23***°1	-0.3***°2	0.17***°1	-0.05*^1	-0.04^1	-0.02^1	-0.12**^2	0.13**^2	-0.06**^1
ST.GALLEN	0.13***°1	0.12***°1	-0.11*°2	0.1***°1	-0.01°1	-0.1***°1	-0.26**°3	0.04°1	-0.15**°2	0.02°1
ULRICHEN	0.02°1	-0.39*°3	0.2***°1	0.09°1	0.07^1	-0.07^1	0.49**°3	-0.01°1	-0.42*°3	0.07°1
VISP	-0.01°1	0.03°1	0.17***°1	0.12*°1	-0.03^1	0.03°1	-0.02^1	0.14**°1	-0.04^1	0.03^1
WADENSWIL	0.06°1	-0.02°1	0.23***°1	0.1°1	0.05°1	0.45*°3	0.24**^2	0°1	0.49**°3	-0.03°1
WEISSFLUHJOCH	0°1	-0.18***°1	0.38***°2	-0.02°1	0.06^1	0.17***^1	-0.1°1	0.21*°2	0.04^1	-0.02°1
WYNAU	0.21***°1	0.19***°1	0.06*°1	0.22***°1	-0.17***^2	-0.08**^1	-0.2*°3	-0.2*^3	-0.01^1	-0.03°1
ZERMATT	0.02°1	0.01°1	0.05°1	0.06°1	0.44*°3	-0.32***^1	-0.05^1	-0.04°1	-0.23***°1	-0.06°1
ZUERICH-AFFOLTER	0.07°1	-0.03°1	0.17***°1	0.08°1	-0.24**°2	0.01^1	-0.06^1	-0.12**°1	-0.37***°2	-0.08°1
ZUERICH-FLUNTER	0.18***°1	0.17***°1	-0.06*°1	0.17***°1	0.08**^1	0.08**^1	-0.03°1	0.05°1	0.08**^1	0.01°1
ZURICH-KLOTEN	0.16***°1	0.14***°1	-0.02^1	0.06**°1	0.05*^1	0.06*^1	-0.02^1	0.01^1	0.03^1	-0.01^1

T: temperature, RH: relative humidity, DewP: dew point, V: wind speed in synoptic times, Vt: wind speed in all records, NEW: number of erosive winds, WPD: wind power density, EWPD: erosive wind power density.
°: Homogenous data ^: Adjusted data to remove inhomogeneity, ***: The trend statistically significant at 99% level
**: The trend statistically significant at 95% level, *: The trend statistically significant at 90% level.
1: Calculations based on monthly data 2: Calculations based on seasonal data 3: Calculations based on annual data

Note: As an exemplary monthly trend of mean wind speed has been presented here. The trend of other parameters enclosed to the thesis in a digital appendix.

Table B-3: Monthly trend of mean wind speed in Switzerland based on conventional approach (all-times)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AADORF-TAENIKO	-0.2°	-0.45*°	-0.24°	-0.45*°	0.27ˆ	-0.27°	-0.45**°	-0.48**°	0.13ˆ	0.08°	0.33ˆ	-0.5**ˆ
ACQUAROSSA-COMPROVA	0.27*°	-0.04°	0.03°	-0.07ˆ	0.21°	0.03°	-0.14°	-0.02°	-0.02°	-0.03°	-0.08°	0.25°
ADELBODEN	-0.49**°	-0.2°	-0.3°	-0.36°	-0.24ˆ	0°	-0.36°	-0.64***°	-0.24°	0.14°	-0.09°	0.12°
AIGLE	-0.13°	0.06°	0.01°	-0.05°	0.18°	0.02ˆ	0.05ˆ	-0.06ˆ	0.14°	0.08°	0.04°	0.02ˆ
ALTDORF	-0.2*°	0.08°	-0.09°	-0.09°	0.03ˆ	-0.15°	-0.02ˆ	0.03ˆ	0.03ˆ	-0.12°	-0.03°	0.15°
BASELBINNINGEN	-0.42*°	-0.31°	-0.2°	-0.31°	0.27ˆ	0.27ˆ	0.27ˆ	-0.49**°	0.09ˆ	0.38ˆ	-0.02°	0.21°
BERN-ZOLLIKOFE	-0.27°	0.09°	0.16°	0.24°	0.21°	0.3°	0.38°	0.24ˆ	-0.49**ˆ	-0.21°	0.16°	0.15°
BUCHS-SUHR	-0.38°	-0.06°	-0.21°	-0.53**°	0.05°	-0.3°	0.03ˆ	-0.67***°	-0.38°	-0.05°	0.35ˆ	-0.15°
BULLET-LA-FRETAZ	-0.53**°	-0.06°	-0.31°	-0.27°	-0.17°	-0.3°	0.18ˆ	0.09ˆ	-0.02°	0.18ˆ	0.05°	0.24°
CHASSERAL	-0.53**°	0.06°	-0.31°	-0.18°	-0.24°	-0.18°	-0.36°	-0.48**°	-0.27°	0.09ˆ	0.42*ˆ	0.21°
CHUR-EMS	0.04ˆ	0.04ˆ	0.03ˆ	-0.21*ˆ	0.12ˆ	0.12ˆ	-0.01ˆ	0.15ˆ	-0.02ˆ	0.08ˆ	-0.23*°	0.02ˆ
CIMETTA	-0.06°	-0.1°	-0.13°	-0.18°	-0.12°	-0.22*°	-0.14°	-0.16°	-0.21°	0.05ˆ	0.15ˆ	-0.06ˆ
DAVOS	-0.06°	-0.03°	0.02°	-0.64***°	-0.21°	-0.24°	-0.42*°	-0.33°	-0.06ˆ	-0.38°	-0.3°	0.32°
ENGELBERG	0.03°	-0.03°	0.48**°	-0.08°	0.35°	0.71***°	0.27ˆ	0.05ˆ	0.12ˆ	0.45*°	0.03°	0.42*°
GENEVE-COINTRIN	-0.03ˆ	0.01ˆ	0.01ˆ	-0.08ˆ	0.02ˆ	0.15ˆ	0.02ˆ	-0.07ˆ	0ˆ	-0.14ˆ	0.07ˆ	-0.04ˆ
GLARUS	-0.27°	-0.03°	0.18°	-0.3°	-0.21°	-0.3°	0.2°	0.27ˆ	-0.13°	0.16°	-0.33°	0.33°
GRIMSEL-HOSPIZ	0.13°	-0.13°	0.05°	0°	-0.13°	-0.21°	-0.16°	-0.45*°	-0.13°	0.03°	0.15°	0.27°
GUETSCHOBANDERMAT	-0.06°	0.08°	0.05°	0.12°	0.05°	0.12°	0.22**°	0.18*°	-0.04°	0.08°	0.17*°	0.12°
GUTTINGEN	-0.3°	-0.06°	-0.05°	-0.27°	0.09°	0.29°	-0.15°	-0.15°	-0.24°	-0.11°	-0.06°	-0.09°
INTERLAKEN	-0.11°	-0.08°	-0.2°	-0.3**°	-0.32**°	-0.36***°	0.09ˆ	-0.17°	-0.18°	-0.09°	-0.18°	0.03°
LACHAUX-DE-FONDS	0.02ˆ	-0.1°	-0.3**°	0.02ˆ	0.12ˆ	0.09ˆ	-0.11°	0.04ˆ	-0.2°	-0.07ˆ	-0.12°	-0.17°
LEMOLESO	-0.53**°	0.27ˆ	-0.09°	-0.24°	-0.03°	0°	-0.3°	0.03°	-0.05°	0.09ˆ	0.24°	-0.42*ˆ
LOCARNO-MAGADINO	0.14ˆ	0.11ˆ	-0.11°	-0.01ˆ	-0.19*ˆ	0.04ˆ	-0.02ˆ	-0.12ˆ	-0.19*°	-0.05ˆ	0.04ˆ	-0.23**ˆ
LOCARNO-MONTI	0.05ˆ	0.06ˆ	-0.08°	0.1ˆ	0.25**ˆ	0.16ˆ	-0.16°	-0.02ˆ	-0.15°	-0.04°	0.1ˆ	-0.22*°
LUGANO	-0.2*°	0.19°	0.15°	-0.07°	-0.03ˆ	0.05ˆ	0.04ˆ	0.01ˆ	0.01°	-0.21*°	0.07ˆ	-0.2*°
LUZERN	-0.39*°	-0.13°	-0.16°	-0.24°	0.12°	-0.2°	-0.12°	0.05°	-0.2°	0.03ˆ	0.02°	-0.21ˆ
MONTANA	-0.03ˆ	-0.13°	0.03°	-0.13°	-0.06°	-0.08ˆ	-0.41***°	-0.11ˆ	0.09ˆ	-0.11°	0.12°	-0.07°
NAPF	-0.01°	0.05°	0.03°	-0.01°	0.17°	0.08ˆ	0.03°	0.02°	-0.13°	0.01°	0.05°	0.15°
NEUCHATEL	-0.12°	-0.02°	-0.14°	-0.13°	0.02°	-0.08°	0.05°	-0.13°	-0.06°	-0.26**°	-0.12°	0.01°
NYON.CHANGINS	-0.55**°	0.12°	-0.12°	-0.02°	-0.03°	-0.3°	0.06°	-0.42*°	-0.06°	0.13°	-0.02°	0.15°
PAYERNE	-0.05°	-0.05°	-0.11°	-0.05ˆ	-0.07°	-0.1ˆ	-0.07°	-0.05ˆ	-0.14°	-0.11°	-0.01ˆ	-0.18*°
PILATUSMTN	-0.18°	-0.27°	-0.18°	-0.53**°	0.33ˆ	-0.31°	0.18ˆ	-0.09ˆ	0ˆ	0.18ˆ	-0.31°	-0.09°
PIOTTA	0.04ˆ	-0.01°	-0.08°	-0.14ˆ	0.06ˆ	-0.06ˆ	-0.12ˆ	0.12ˆ	-0.17°	-0.22*°	-0.05°	-0.28**°
PIZCORVATSCH	0.12°	0.14°	0.14°	-0.03°	0.19°	0.14°	0.14°	0.18°	0.04°	0.03°	0.04°	0.05°
PLAFFEIEN-OBERSCHRO	-0.04°	-0.08°	-0.01°	0.04°	0.19°	0.08°	0.01°	-0.08°	-0.02°	-0.04°	-0.03°	-0.11°
POSCHIAVO-ROBBIA	0.02°	0.28**°	0.04°	-0.2*°	0.28**°	-0.01°	-0.07°	0.01°	0.01°	-0.05°	-0.04°	-0.06°
ROBIEI	0.18ˆ	0.03°	-0.33°	-0.27°	0.24°	-0.11°	-0.15°	-0.16°	-0.06°	0.24°	-0.36°	0.27°
RUENENBERG	-0.3°	0°	0.03°	-0.18°	-0.02°	0.06°	0.03°	0.06°	0.02°	0.17°	0.21ˆ	0.29°
SAENTIS	-0.04°	-0.11°	-0.07ˆ	-0.07ˆ	-0.13°	0.03ˆ	0.09ˆ	-0.14ˆ	0.08ˆ	0.02ˆ	0.07ˆ	-0.32**°
SAMEDAM	0.09ˆ	-0.11°	-0.12°	-0.19°	0.12ˆ	0.05ˆ	0.05ˆ	-0.16°	0.08ˆ	0.01ˆ	0.08ˆ	-0.09ˆ
SBERNARDINO	0.1ˆ	-0.12°	-0.04°	-0.13°	-0.09°	0.17°	-0.24*°	-0.06°	-0.09°	-0.11°	0.03°	-0.1°
SCHAFFHAUSEN	-0.27°	0.21°	0.05°	-0.05°	0.21°	0.67***°	0.2°	0.12°	-0.12°	0.05°	0.18°	-0.27ˆ
SCUOL	-0.12°	-0.38°	-0.33°	-0.09°	0°	-0.2°	-0.03°	-0.02°	-0.27°	-0.18°	-0.15°	-0.18°
SION	-0.07ˆ	0.06ˆ	-0.02ˆ	-0.16ˆ	0.08ˆ	0.21**ˆ	0.07ˆ	0ˆ	-0.06°	-0.14°	-0.2*ˆ	-0.08ˆ
ST.GALLEN	-0.04°	-0.08°	-0.05°	-0.25*°	0.22*ˆ	0ˆ	-0.06°	-0.19°	0.02ˆ	-0.17°	-0.04°	0°
ULRICHEN	0.24ˆ	0.05°	-0.02°	-0.38°	-0.15°	-0.14°	-0.45*°	-0.15°	-0.33°	0.24°	-0.16°	0.05°
VISP	-0.09°	-0.08°	0.42*°	-0.09°	0°	0.71***°	-0.45**ˆ	-0.09°	-0.05°	0.05°	-0.09°	0.21°
WADENSWIL	-0.36°	-0.55**ˆ	-0.13°	-0.18°	0.15°	0.21°	0.09°	0.09°	0.27ˆ	0.02°	0.03°	0.12°
WEISSFLUHJOCH	0.2°	-0.24°	-0.02°	-0.53**°	-0.27°	-0.12°	-0.2°	0.35ˆ	-0.13°	-0.02°	0ˆ	0.12°
WYNAU	-0.1°	-0.03°	-0.04°	0.21*ˆ	-0.15°	-0.14ˆ	-0.1°	-0.21*°	0.04°	-0.17°	-0.22*°	-0.21*°
ZERMATT	0.15ˆ	-0.67***°	-0.3°	-0.36°	-0.33°	-0.18°	-0.35°	-0.39*°	-0.27°	-0.09°	-0.45*°	-0.56**°
ZUERICH-AFFOLTER	-0.3°	-0.27°	-0.2°	-0.45*°	-0.02°	-0.03°	-0.16°	-0.42*°	-0.38°	-0.11°	-0.03°	-0.17°
ZUERICH-FLUNTER	-0.1°	-0.01°	-0.06°	0.3**ˆ	0.16ˆ	-0.09°	-0.07°	-0.03°	-0.03°	-0.17°	-0.01°	-0.13°
ZURICH-KLOTEN	-0.11°	0.07ˆ	-0.06ˆ	0ˆ	0.04ˆ	0.08ˆ	0.21**ˆ	0.17ˆ	0.08ˆ	-0.07°	0.04ˆ	-0.04ˆ

°: Homogenous data ˆ: Adjusted data to remove inhomogeneity
***: The trend statistically significant at 99% level **: The trend statistically significant at 95% level
*: The trend statistically significant at 90% level.

Table B-4: The magnitude of monthly trends of mean wind speed estimated by the Sen's slope method in Switzerland (all-times)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AADORF-TAENIKO	-0.15	-0.11**	-0.06	-0.12**	0.04	-0.04	-0.06**	-0.05**	0.01	0.01	0.07	-0.1**
ACQUAROSSA-COMPROVA	0.05**	-0.01	0	-0.01	0.04	0.01	-0.01	0	0	0	-0.01	0.02
ADELBODEN	-0.2**	-0.06	-0.18	-0.05	-0.06	0	-0.03	-0.06**	-0.02	0	0	0.08
AIGLE	-0.02	0.01	0	-0.01	0.01	0	0	0	0.01	0.01	0	0
ALTDORF	-0.04**	0.02	-0.02	-0.03	0.01	-0.01	0	0	0	-0.02	0	0.02
BASELBINNINGEN	-0.17**	-0.07	-0.2	-0.07	0.05	0.03	0.03	-0.12**	0.01	0.07	-0.01	0.06
BERN-ZOLLIKOFE	-0.09	0.04	0.07	0.06	0.02	0.01	0.06	0.02	-0.03**	-0.02	0.06	0.03
BUCHS-SUHR	-0.08	-0.02	-0.07	-0.1**	0.01	-0.03	0.01	-0.07**	-0.07	0	0.08	-0.03
BULLET-LA-FRETAZ	-0.16**	-0.03	-0.03	-0.05	-0.01	-0.06	0.02	0.02	-0.01	0.02	0	0.02
CHASSERAL	-0.8**	0.06	-0.18	-0.22	-0.09	-0.07	-0.2	-0.24**	-0.15	0.07	0.45**	0.08
CHUR-EMS	0	0.01	0	-0.02**	0.01	0.01	0	0.01	0	0.01	-0.03**	0.01
CIMETTA	-0.02	-0.01	-0.02	-0.02	-0.02	-0.02**	-0.01	-0.02	-0.03	0.01	0.02	-0.01
DAVOS	-0.02	-0.01	0.01	-0.13**	-0.06	-0.08	-0.07**	-0.05	-0.01	-0.09	-0.06	0.02
ENGELBERG	0	-0.01	0.14**	-0.02	0.12	0.07**	0.04	0	0.01	0.08**	0.01	0.12**
GENEVE-COINTRIN	0	0	0	-0.01	0	0.01	0	0	0	-0.01	0.01	0
GLARUS	-0.14	-0.01	0.07	-0.1	-0.04	-0.05	0.06	0.13	-0.05	0.1	-0.1	0.13
GRIMSEL-HOSPIZ	0.01	-0.08	0.03	-0.02	-0.17	-0.21	-0.12	-0.29**	-0.11	0.02	0.05	0.05
GUETSCHOBANDERMAT	-0.01	0.03	0.01	0.05	0.02	0.03	0.03**	0.03**	-0.01	0.02	0.04**	0.03
GUTTINGEN	-0.18	-0.01	-0.03	-0.05	0.03	0.03	-0.01	-0.03	-0.04	-0.01	-0.03	-0.02
INTERLAKEN	-0.01	-0.01	-0.01	-0.02**	-0.02**	-0.02**	0.01	-0.01	-0.01	-0.01	-0.02	0
LACHAUX-DE-FONDS	0	-0.03	-0.04**	0	0.02	0.01	-0.01	0	-0.02	0	-0.02	-0.03
LEMOLESO	-0.56**	0.35	-0.14	-0.21	-0.01	0.01	-0.12	0.04	-0.02	0.11	0.12	-0.24**
LOCARNO-MAGADINO	0.01	0.01	-0.01	0	-0.01**	0	0	-0.01	-0.01**	0	0	-0.02**
LOCARNO-MONTI	0	0	-0.01	0.01	0.01**	0.01	-0.01	0	-0.01	0	0.01	-0.01**
LUGANO	-0.02**	0.02	0.02	-0.01	0	0	0	0	0	-0.01**	0.01	-0.02**
LUZERN	-0.13**	-0.02	-0.03	-0.02	0.02	-0.01	-0.01	0.01	-0.02	0	0	-0.03
MONTANA	0	-0.01	0	-0.01	-0.01	0	-0.02**	-0.01	0	-0.01	0.01	-0.01
NAPF	0	0.02	0.01	0	0.03	0.01	0	0	-0.02	0	0.02	0.03
NEUCHATEL	-0.02	0	-0.02	-0.02	0	-0.01	0	-0.01	-0.01	-0.03**	-0.03	0
NYON.CHANGINS	-0.15**	0.06	-0.11	0	-0.02	-0.09	0.01	-0.02**	-0.04	0.04	-0.03	0.03
PAYERNE	-0.01	-0.01	-0.02	0	0	0	0	0	-0.01	-0.01	0	-0.02**
PILATUSMTN	-0.13	-0.3	-0.12	-0.54**	0.22	-0.55	0.11	-0.05	-0.01	0.08	-0.38	-0.06
PIOTTA	0.01	0	-0.01	-0.01	0	0	-0.01	0.01	-0.01	-0.03**	-0.01	-0.03**
PIZCORVATSCH	0.05	0.06	0.03	-0.01	0.04	0.04	0.02	0.03	0.01	0.01	0.01	0.03
PLAFFEIEN-OBERSCHRO	-0.02	-0.02	-0.01	0.01	0.03	0.01	0	-0.01	0	0	-0.01	-0.02
POSCHIAVO-ROBBIA	0.01	0.05**	0.01	-0.04**	0.04**	0	-0.01	0	0	0	-0.01	-0.01
ROBIEI	0.04	0.05	-0.16	-0.07	0.06	-0.02	-0.03	-0.05	-0.01	0.08	-0.08	0.04
RUENENBERG	-0.07	0	0.01	-0.04	-0.01	0.01	0	0	0	0.02	0.05	0.04
SAENTIS	-0.01	-0.05	-0.01	-0.02	-0.02	0	0.01	-0.02	0.02	0	0.01	-0.08**
SAMEDAM	0.05	-0.05	-0.05	-0.09	0.03	0.01	0.01	-0.08	0.04	0	0.03	-0.02
SBERNARDINO	0.01	-0.01	0	-0.01	-0.01	0.01	-0.02**	-0.01	0	-0.01	0	-0.01
SCHAFFHAUSEN	-0.17	0.05	0.02	-0.01	0.07	0.1**	0.08	0.01	-0.03	0.11	0.1	-0.1
SCUOL	-0.01	-0.07	-0.02	-0.02	0	-0.04	0	0	-0.04	-0.02	-0.02	-0.05
SION	0	0	0	-0.01	0	0.01**	0.01	0	-0.01	-0.01	-0.01**	0
ST.GALLEN	-0.01	-0.01	-0.01	-0.03**	0.01**	0	0	-0.01	0	-0.01	0	0
ULRICHEN	0.03	0.03	-0.01	-0.19	-0.08	-0.01	-0.03**	-0.02	-0.09	0.03	-0.04	0.01
VISP	-0.06	-0.01	0.32**	-0.07	0	0.27**	-0.1**	-0.04	-0.02	0.01	-0.16	0.19
WADENSWIL	-0.15	-0.06**	-0.09	-0.03	0.02	0.03	0.01	0	0.01	0.01	0	0.04
WEISSFLUHJOCH	0.21	-0.28	-0.01	-0.38**	-0.11	-0.08	-0.07	0.1	-0.05	-0.01	-0.01	0.08
WYNAU	-0.01	-0.01	-0.01	0.02**	-0.01	-0.01	-0.01	-0.01**	0	-0.03	-0.03**	-0.02**
ZERMATT	0.01	-0.06**	-0.04	-0.08	-0.06	-0.03	-0.08	-0.05**	-0.04	-0.02	-0.05**	-0.06**
ZUERICH-AFFOLTER	-0.21	-0.06	-0.07	-0.08**	-0.01	-0.01	-0.02	-0.07**	-0.06	-0.01	0	-0.01
ZUERICH-FLUNTER	-0.02	0	-0.01	0.02**	0.01	-0.01	0	0	0	-0.02	0	-0.02
ZURICH-KLOTEN	-0.01	0.01	-0.01	0	0	0	0.01**	0.01	0	-0.01	0	0

***: The trend statistically significant at 99% level **: The trend statistically significant at 95% level
*: The trend statistically significant at 90% level.

2. Extreme wind analysis

Table B-5: Basic descriptive statistics of POT wind velocities for desired weather stations in Switzerland

Station Name	nobs	Min	Max	1st Qu.	3rd Qu.	Mean	Median	Var.	Stdev	Skew.	Kurtosis
AADORF-TAENIKO	197	13.19	33.32	14.41	17.74	16.93	15.68	15.67	3.96	2.08	4.36
ACQUAROSSA-COMPROVA	703	13.50	36.95	14.33	17.08	16.13	15.43	6.89	2.62	2.61	11.22
ADELBODEN	255	13.14	44.41	14.52	17.73	17.03	15.67	20.01	4.47	3.02	11.48
AIGLE	755	13.39	34.84	14.56	18.44	17.00	15.98	10.97	3.31	1.63	3.02
ALTDORF	2390	13.31	49.06	15.02	22.47	19.41	17.29	32.37	5.69	1.30	1.41
BASELBINNINGEN	356	13.17	46.94	14.55	19.05	17.78	16.17	25.31	5.03	2.65	9.31
BERN-ZOLLIKOFE	243	13.11	44.52	14.19	18.71	17.27	15.51	24.04	4.90	2.71	8.80
BUCHS-SUHR	132	13.11	32.97	14.13	17.95	16.96	15.54	16.96	4.12	2.02	4.18
BULLET-LA-FRETAZ	332	13.15	38.66	14.34	17.73	16.79	15.60	14.93	3.86	2.62	8.60
CHASSERAL	1593	13.51	118.22	17.86	33.26	26.75	23.70	135.91	11.66	1.74	5.70
CHUR-EMS	2305	13.20	98.81	14.24	16.52	15.83	15.16	8.85	2.98	12.26	297.86
CIMETTA	1729	13.35	44.68	14.62	19.26	17.49	16.27	15.58	3.95	1.85	4.82
DAVOS	695	13.16	38.81	14.30	17.64	16.66	15.44	13.79	3.71	2.49	7.83
ENGELBERG	231	13.11	43.02	14.90	21.10	18.44	17.17	22.58	4.75	1.64	3.97
GENEVE-COINTRIN	3926	13.51	73.04	14.80	19.28	17.54	16.33	16.15	4.02	3.13	23.31
GLARUS	1564	13.17	58.37	14.70	19.16	17.89	16.25	23.98	4.90	2.43	8.40
GRIMSEL-HOSPIZ	1528	13.50	66.91	15.04	20.15	18.56	16.80	32.31	5.68	3.17	15.79
GUETSCHOBANDERMAT	5651	13.32	79.86	16.07	26.40	22.88	20.12	86.75	9.31	1.85	4.37
GUTTINGEN	342	13.19	39.26	14.42	18.13	17.21	15.72	19.28	4.39	2.48	7.44
INTERLAKEN	532	13.53	40.26	14.34	17.13	16.20	15.43	7.99	2.83	3.16	17.25
LACHAUX-DE-FONDS	1169	13.12	64.67	14.43	17.61	16.52	15.62	10.63	3.26	4.76	50.41
LEMOLESO	1509	13.50	77.45	15.73	25.42	21.54	19.53	56.32	7.50	1.86	6.27
LOCARNO-MAGADINO	983	13.23	40.24	14.66	18.19	16.82	15.69	11.01	3.32	2.35	9.03
LOCARNO-MONTI	94	13.21	23.88	14.02	16.67	15.67	15.05	4.50	2.12	1.45	2.21
LUGANO	1217	13.50	50.28	14.83	18.70	17.13	16.27	10.11	3.18	2.13	11.39
LUZERN	302	13.22	35.24	14.64	19.26	17.54	16.22	16.98	4.12	1.65	2.97
MONTANA	231	13.11	23.71	14.01	16.52	15.53	14.97	3.89	1.97	1.40	2.03
NAPF	2603	13.50	98.58	14.96	21.03	18.73	16.95	28.20	5.31	2.70	21.63
NEUCHATEL	1438	13.10	35.25	14.50	18.05	16.62	15.81	8.03	2.83	1.82	5.41
NYON.CHANGINS	737	13.12	47.18	14.77	19.29	17.89	16.47	20.42	4.52	2.00	5.41
PAYERNE	1222	13.21	34.64	14.50	18.24	16.62	15.69	7.90	2.81	1.48	2.97
PILATUSMTN	1295	13.50	56.18	15.64	22.32	19.84	18.30	33.18	5.76	1.81	5.00
PIOTTA	1175	13.14	28.19	14.09	16.09	15.43	14.94	3.62	1.90	2.15	6.70
PIZCORVATSCH	3608	13.22	98.42	15.24	21.27	19.00	17.15	32.98	5.74	3.65	30.54
PLAFFEIEN-OBERSCHRO	1273	13.51	51.12	15.70	23.17	20.23	18.55	34.67	5.89	1.25	1.48
POSCHIAVO-ROBBIA	1700	13.31	44.18	15.93	21.95	19.44	18.59	20.47	4.52	1.22	2.17
ROBIEI	521	13.21	42.61	14.84	18.70	17.51	16.11	17.71	4.21	2.22	6.56
RUENENBERG	408	13.12	52.62	14.99	21.12	19.03	16.93	37.03	6.09	2.11	5.84
SAENTIS	4735	13.19	101.13	16.45	27.08	22.87	20.68	68.33	8.27	1.48	3.76
SAMEDAM	2610	13.11	32.60	14.38	16.70	15.78	15.42	3.57	1.89	1.80	6.36
SBERNARDINO	1898	13.26	37.19	14.85	18.63	17.15	16.33	9.90	3.15	1.59	3.68
SCHAFFHAUSEN	890	13.13	52.86	15.07	20.21	18.66	16.79	32.91	5.74	2.58	9.24
SCUOL	173	13.13	27.02	13.91	16.22	15.84	15.33	7.27	2.70	2.00	4.32
SION	3659	13.11	45.01	14.57	17.84	16.50	15.66	7.62	2.76	2.25	10.33
ST.GALLEN	523	13.34	37.04	14.49	18.07	16.58	15.82	7.86	2.80	1.81	6.18
ULRICHEN	855	13.17	44.81	14.49	18.40	17.17	15.90	15.27	3.91	2.25	7.06
VISP	1707	13.18	48.73	15.41	20.67	18.63	17.20	22.81	4.78	2.07	6.17
WADENSWIL	375	13.15	40.53	14.83	18.93	17.35	16.02	16.90	4.11	2.43	8.22
WEISSFLUHJOCH	1801	13.22	98.46	15.48	23.61	20.66	18.30	55.99	7.48	2.56	12.68
WYNAU	690	13.24	27.20	14.42	17.18	16.16	15.46	5.53	2.35	1.53	2.79
ZERMATT	780	13.12	36.96	14.24	18.11	16.90	15.40	15.35	3.92	1.99	4.34
ZUERICH-AFFOLTER	326	13.16	52.40	14.34	19.57	17.87	16.02	31.15	5.58	2.77	9.92
ZUERICH-FLUNTER	827	13.28	46.77	14.98	19.83	17.87	16.84	15.27	3.91	1.65	4.64
ZURICH-KLOTEN	3268	13.50	43.47	14.68	18.59	17.26	15.92	14.25	3.77	1.94	4.86

Table B-6: Estimated parameters of fitting GPD over POTs for desired weather stations in Switzerland

Station Name	Estimated parameters		Standard errors	
	Scale	Shape	Scale	Shape
AADORF-TAENIKO	3.9107	0.0046	0.3896	0.0697
ACQUAROSSA-COMPROVA	3.3896	-0.0891	0.1465	0.0214
ADELBODEN	3.7564	0.0678	0.3141	0.0556
AIGLE	4.6461	-0.1635	0.2054	0.0257
ALTDORF	7.3758	-0.1495	0.2026	0.0186
BASELBINNINGEN	4.5970	0.0377	0.3293	0.0482
BERN-ZOLLIKOFE	3.7987	0.1105	0.3460	0.0650
BUCHS-SUHR	3.8250	0.0352	0.4804	0.0906
BULLET-LA-FRETAZ	3.7480	0.0121	0.2716	0.0473
CHASSERAL	15.2000	-0.1100	0.4343	0.0140
CHUR-EMS	2.8077	0.0070	0.0629	0.0083
CIMETTA	4.9475	-0.1031	0.1463	0.0174
DAVOS	3.6169	0.0112	0.1836	0.0337
ENGELBERG	6.0738	-0.1188	0.4989	0.0498
GENEVE-COINTRIN	4.7520	-0.0479	0.0841	0.0077
GLARUS	4.8874	0.0007	0.1648	0.0223
GRIMSEL-HOSPIZ	5.4903	0.0126	0.1784	0.0200
GUETSCHOBANDERMAT	10.4441	-0.0570	0.1878	0.0121
GUTTINGEN	4.0738	0.0323	0.2999	0.0500
INTERLAKEN	3.3763	-0.0566	0.1688	0.0250
LACHAUX-DE-FONDS	3.5925	-0.0224	0.1166	0.0141
LEMOLESO	9.3129	-0.0930	0.2863	0.0170
LOCARNO-MAGADINO	4.1317	-0.0842	0.1560	0.0204
LOCARNO-MONTI	3.2260	-0.2152	0.4121	0.0786
LUGANO	4.4960	-0.0993	0.1356	0.0098
LUZERN	5.0069	-0.1022	0.3882	0.0523
MONTANA	3.0920	-0.2285	0.2461	0.0472
NAPF	5.9273	-0.0353	0.1316	0.0104
NEUCHATEL	4.1218	-0.1491	0.1217	0.0139
NYON.CHANGINS	5.2109	-0.0662	0.2482	0.0303
PAYERNE	4.2083	-0.1735	0.1309	0.0132
PILATUSMTN	7.6619	-0.1244	0.2521	0.0180
PIOTTA	2.7446	-0.1410	0.0910	0.0163
PIZCORVATSCH	6.1071	-0.0183	0.1184	0.0099
PLAFFEIEN-OBERSCHRO	8.6238	-0.1978	0.2797	0.0172
POSCHIAVO-ROBBIA	7.7612	-0.2311	0.2006	0.0106
ROBIEI	4.7561	-0.0542	0.2677	0.0354
RUENENBERG	5.9937	0.0068	0.4152	0.0485
SAENTIS	10.9065	-0.1112	0.1682	0.0054
SAMEDAM	3.1377	-0.1518	0.0627	0.0051
SBERNARDINO	4.8341	-0.1790	0.1213	0.0110
SCHAFFHAUSEN	5.6144	0.0088	0.2491	0.0291
SCUOL	2.9871	-0.0507	0.3071	0.0693
SION	3.8207	-0.0997	0.0670	0.0061
ST.GALLEN	4.0203	-0.1331	0.1921	0.0201
ULRICHEN	4.3714	-0.0489	0.1915	0.0274
VISP	6.2543	-0.1139	0.1826	0.0166
WADENSWIL	4.5255	-0.0405	0.2974	0.0407
WEISSFLUHJOCH	7.7799	-0.0159	0.2334	0.0186
WYNAU	3.8327	-0.2262	0.1687	0.0237
ZERMATT	3.8919	0.0031	0.1980	0.0361
ZUERICH-AFFOLTER	4.3240	0.1113	0.3430	0.0571
ZUERICH-FLUNTER	5.4776	-0.1336	0.2083	0.0161
ZURICH-KLOTEN	4.6687	-0.0970	0.1022	0.0133

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