TALLINN UNIVERSITY OF TECHNOLOGY
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WIND AND AVERAGE AIRFLOW AT DIFFERENT ESTONIAN COASTAL STATIONS DURING 1966-2005

Master's thesis

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Earth science

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I declare that this master's thesis, which is the result of my independent work, is presented in Tallinn University of Technology for the getting of the master's degree. The results of present master's thesis have been never used for the getting of the academic degrees.

All other authors' works and literature sources, which was used for the preparation of the present paper, are represented in references, out of the main text.

Viktoria Kudrjavtseva

CONTENTS

INTRODUCTION

Due to the wide interest in changing climate, the investigations of long-term trends in meteorological characteristics at the global and regional scales are on the agenda. A lot of different activities are made in this direction. Both observational data and climate models are investigated. The main attention is paid to air temperature, precipitation, cloudiness and snow cover. The wind characteristics are less studied [1]. Unquestionably, air temperature is the main indicator of climate change. All other indicators, in a varying degree, are connected to this meteorological parameter. Air temperature influences the decrease or increase of precipitation amount, the depth of snow cover and the number of days, when there is snow cover. Air temperature differences determine air pressure differences, which, in turn, play the most important role in winds formation.

Only air temperature investigations do not give the complete picture of climate change, especially in local scales. For better understanding of climate change in a certain region, it is necessary to investigate also wind regime variations. The changes in wind characteristics may influence the redistribution of heat and moisture and the variations of other climate characteristics [1]. Therefore the first aim of this paper is to analyse 1966-2005 time period wind characteristics and describe the connections between variations of the wind characteristics and other climate parameters in Estonia.

Wind characteristics, especially direction, affect also environment [2]. Estonia is surrounded by industrially developed countries: Sweden, Finland, Latvia, Lithuania, Russia. As the local industry has a strong impact on the regional ecology, it is necessary to know, what the probability is that the pollution, which is caused by industrial activities of neighbouring countries, reaches Estonia. That is why the motion of the air masses should be investigated. Therefore the second aim of this paper is analysis of the average airflow in 1966-2005 time period in Estonia.

Extensive analysis of long-term changes in meteorological parameters at several parts of Estonia has been carried out and related to the large-scale atmospheric circulation indices. An increase in the intensity of the zonal circulation during 1951-2000 is accompanied by an increase in the late winter and spring air temperature [3, 4], a decrease in the snow cover extent [4, 5], an increase in the amount of low clouds [4], a decrease in sea ice duration [5], and an increase in winter storminess [6, 7]. Although the territory of Estonia is small, significant differences exist in local trends of precipitation [3, 4] and changes in the water level near the Estonian coast [6].

The database of cyclones described in [8] offers several possibilities to characterize and count cyclones entering a certain area. It has been shown that the number of cyclones reaching Northern Europe has increased during the second half of the previous century and their trajectories have moved northward [9]. A closer look at the Baltic Sea region shows that the total number of cyclones did not change, but the percentage of deep cyclones increased [10]. In case the Arctic Basin is involved, the annual number of incoming cyclones increased significantly, as did the percentage of deep cyclones formed within the Arctic region, while the number and percentage of shallow cyclones decreased. These changes were most evident in winter. [11]

In the present paper, the analysis of wind direction, wind speed and average airflow in Estonia are based on the measurements at nine Estonian coastal stations during a period of 39 years from 1966 to 2005. Until the 1st of August 2003 the measurements of wind speed and direction at these stations were manual and gave information every three hours. Since the 1st of August 2003 the measurements are carried out by means of automatic weather stations that give information every hour. The measurements of every third hour were used in this paper.

This paper consists of 5 parts. In the first part the general concepts of wind are given: air masses, factors that affect wind formation, speed and direction, winds classification. In the second part wind characteristics and their measurement are described. The third part gives information about the data collection and its processing. Analysis of collected data is given in the fourth part and the conclusions are drawn in the fifth part.

1 WIND DEFINITION

Nowadays it is possible to find different scientific definitions of the wind. Only one dictionary can give two or even more definitions of the word „wind“.

> Wind is the perceptible natural movement of the air, especially in the form of a current of air blowing from a particular direction. Wind is breath as needed in physical exertion, speech, etc., or the power of breathing without difficulty in such situation: she hit the floor with a thud that knocked the wind out of her. [12]
>
> Wind is a natural movement of air of any velocity; especially: the earth's air or the gas surrounding a planet in natural motion horizontally. Wind is an artificially produced movement of air. Wind is a destructive force or influence. [13]
>
> Wind is the movement of air from areas of higher pressure to areas of lower pressure. The greater is the difference in pressure the stronger are the winds. Wind direction is defined by the direction it is coming from. [14]

Despite of the amount of wind definitions, the main meaning is constant. In meteorology wind is the horizontal flow of gases on a large scale. Near the surface of the Earth wind represents the movement of air masses. It is possible to classify winds by their speed, strength, direction, duration and the types of forces that influence atmospheric motion. Local winds may have special names (e.g., foehn, simoom, sirocco, mistral, bora), but more general publicly known wind types are breeze, gale, storm, hurricane. Short bursts of wind with high speed are called gusts and wind's bursts with intermediate duration (above 1 minute) are called squalls.

Difference in atmospheric pressure is the most important reason, which causes winds. When there is a difference in atmospheric pressure, air masses start to move from the higher to the lower pressure area. This movement is wind.

But many centuries ago winds had other names and people explained air motions differently. Wind was a mythological phenomenon (see Appendix 1).

1.1 Air masses [35]

Earth is separated in 7 climatic zones: 2 arctic, 2 polar, 2 tropic and 1 equatorial. According to the latitude Earth gets more or less solar radiation. In this case different air masses are formed in these climatic zones. The names of air masses are similar to the climatic zones, where they are formed. Arctic air masses are formed in arctic zones, polar air masses are formed in polar zones, tropic air masses are formed in tropic zones and equatorial air masses are formed in equatorial zone. According to the moisture air masses can be marine or continental. Marine air masses are more wet then continental air masses.

Continental arctic, marine arctic, continental polar, marine polar, continental tropic and marine tropic air masses can impact on Estonian climate and weather. Equatorial air masses can not achieve Estonia.

Continental arctic air masses are formed over arctic sea and islands, where is ice. These air masses bring cold, dry and cloudless weather. The moisture content of continental arctic air masses is very small. There are no precipitations in Estonia, when continental arctic air masses are dominant.

Marine arctic air masses are formed over Arctic Ocean, over its west part, where is no ice. These air masses are warmer and wetter than continental arctic air masses. Marine arctic air masses bring strong precipitation to Estonia.

Continental polar air masses are formed over Eurasian continent. Often continental and marine arctic air masses are transformed into continental polar airflow. In winter these air masses bring cold weather. Air temperature can decrease till -40 C°. In summer these air masses bring precipitation and thunderstorms.

Marine polar air masses are formed over Atlantic Ocean, over its northern part. In winter these air masses bring precipitation, in summer – thunderstorms.

In winter continental tropic air masses are formed over North-Africa, Malaysia, Iran, Afghanistan. In summer continental tropic air masses are formed over the northern part of Caucasus, Kazakhstan, near Caspian steppes. Continental tropic air masses bring dry and warm weather in Estonia.

Marine tropic air masses are formed near the Azores. These air masses bring wet and warm weather in Estonia. In summer they can cause thunderstorms.

1.2 Forces that affect wind

The most important reason for all airflow, including wind, is difference in pressure between different areas of the atmosphere. *The pressure gradient force* puts air to move from the region of higher pressure to the region, where atmospheric pressure is lower. The pressure gradient force by unit mass is expressed by equation (1).

$$G = \frac{-1}{\rho} * P_n \text{ , (1)}$$

where G is the pressure gradient force (N);

ρ is the air density (kg/m^3);

P_n is the air pressure gradient. [36]

Air pressure gradient increases from the low pressure value to the high pressure value. At the same time winds blow from the higher pressure area to the lower pressure area that is opposite to the air pressure gradient. That is why there is minus in equation (1).

Due to the Earth rotation air can not move directly from one point to another. The force putting air masses to change their direction is *the Coriolis force*. In the Northern Hemisphere the Coriolis force turns the blowing wind to the right and in the Southern Hemisphere to the left from its current direction. In the Northern Hemisphere the Coriolis force puts air to flow clockwise around high pressure areas and counterclockwise around low pressure areas. In the Southern Hemisphere the effect is opposite. The Coriolis force changes wind direction but not its speed. The Coriolis force depends on wind speed and the latitude of the region, where the wind blows. Therefore the Coriolis force is expressed by equation (2).

$$C = 2 * \omega * v * \sin(\varphi) \text{ , (2)}$$

where C is the Coriolis force (N);

ω is the angular velocity of the Earth rotation, which equals $7{,}292*10^{-5}$ (rad/s);

V is the wind speed (m/s);

φ is the latitude. [36]

The Coriolis force is the strongest on the Earth poles and zero on the Equator.

The frictional force impacts on winds movement too. Its direction is opposite to the wind direction and it is expressed by equation (3).

$$R=-k*V, (3)$$

where R is the frictional force (N);
V is the wind speed (m/s);
k is the drag coefficient, which depends on the surface roughness. [36]

The friction over the ocean is less than the friction over the mountains, because the ocean surface roughness is less than the mountains surface roughness. At the same time the frictional force in higher atmospheric layers is less than the frictional force in lower atmospheric layers, because this force depends on the Earth surface roughness. In the free atmosphere the frictional force practically disappears. Wind speed is important for the frictional force too. Greater wind speed produces greater friction.

An apparent force that seems to impact on air parcel moving along curved trajectory is *the centrifugal force* that is expressed by equation (4).

$$F=\frac{V^2}{R}, (4)$$

where F is the centrifugal force (N);
V is the wind speed (m/s);
R is the radius of the curvature of the trajectory (m).

The balance of all forces is shown in Figure 1.8.

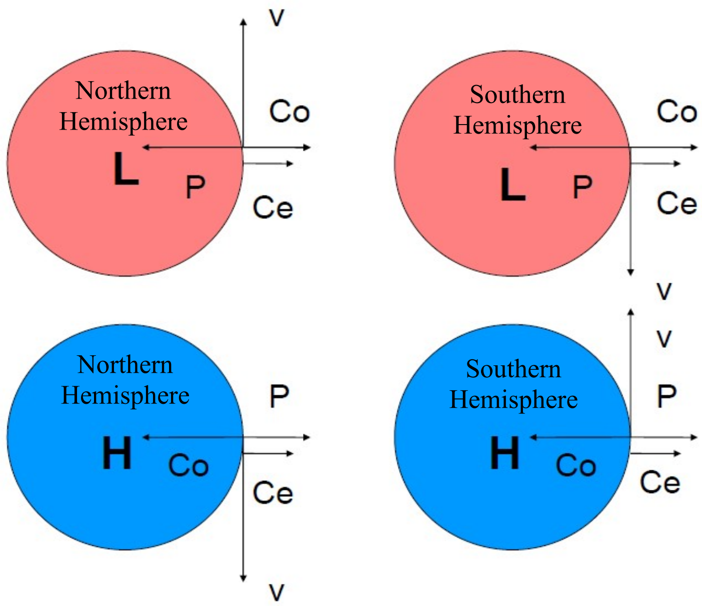

Figure 1.8 The balance of the forces, which impact on the winds; Co – the Coriolis force, Ce – the centrifugal force, P – the pressure gradient force, V – the wind speed

1.3 Wind types

Breeze is light or moderate current of air. A sea breeze is a wind, which blows from the sea to the land. Especially sea breeze blows in the late spring and in the summer, particularly in the afternoon, when air temperature differences and therefore pressure differences between sea and land are greater. Water is good solar energy absorber. It heats up and cools down much slower than land. During the day warm air over the land surface expands and forms the area of high pressure in the upper layers, where the air starts to move towards the sea forming high pressure area in the lower layers near the sea surface. The wind blows from the higher pressure area at the water surface to lower pressure at the land surface causing the sea breeze. The sea breeze strength depends on the temperature difference between land and sea. At night, the roles reverse. Land cools down faster than sea and in the lower layers of the atmosphere wind blows from land to sea, causing land breeze. [37]

Gale and *storm* are strong winds on land or on sea. Gale speed is approximately 24-28 m/s and storm speed is about 32 m/s. In Beaufort scale of storms (see Appendix 2) gale value is 8 or 9 points and storm value is 10 or 11 points. Gales and storms are formed when a centre of deep low pressure develops together with the high pressure surrounding it.

Hurricanes (tropical cyclone, which is formed in the Atlantic Ocean) or *typhoons* (tropical cyclone, which is formed in the Pacific Ocean) are huge weather systems characterised by very strong winds with destructive force. They are intense low pressure areas over the warm ocean. In Beaufort scale of storms hurricane / typhoon value is 12 points. Their source of energy is water, which evaporates from the warm ocean surface in late summer and early autumn and forms water vapour. Warm air from the ocean surface rises and cools, the water vapour condenses and a large amount of energy releases. The latent heat causes the air in the upper layers to warm and expand upward. This supports upper-level divergence, which promotes low pressure and convergence near the surface. Here the air moves towards the low pressure area, but is deflected by the Coriolis force and spirals inward towards the hurricane centre and up around the hurricane eye. [35]

2 WIND CHARACTERISTICS AND THEIR MEASUREMENT

2.1 Wind characteristics

The most important wind characteristics, which are used in modern science for the weather forecast, are the wind speed and direction. These parameters are used also for monitoring and predicting weather and global climate.

The wind speed is measured in knots or meters per second. One knot is equal to 0,514 m/s. When the wind speed is 1 knot or even less, it means that the weather is calm, wind speed 16...21 knots means fresh breeze, 48...55 knots means medium force storm and when wind speed is more than 64 knots, it means hurricane. [38] There is the scale of wind speed impact on sea and land (see Appendix 2).

Every wind speed has its own graphical image on the weather map (see Figure 2.1).

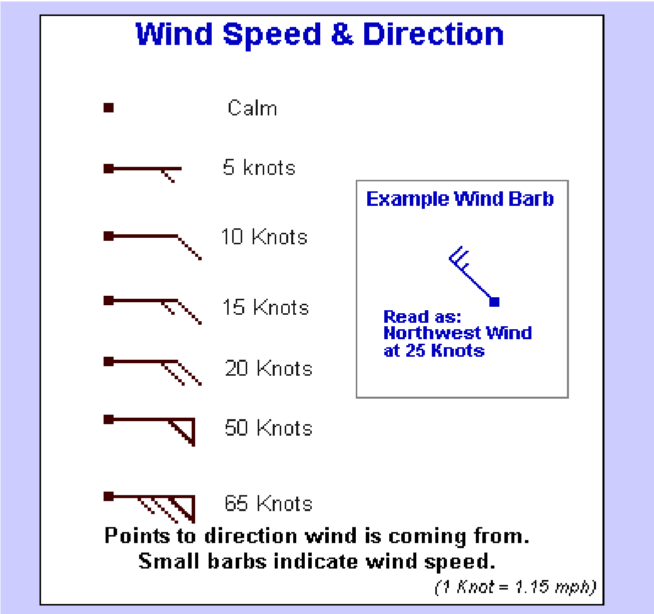

Figure 2.1 The wind speed and direction graphical image [39]

The wind direction is measured in degrees. Scientists use the winds rose to describe the wind directions. The winds rose shows the direction, where wind is blowing from and it consists of 36, 32, 16 or 8 rhumbs. 45 degrees corresponds to the North-East, 90 degrees is equal to the East, 135 degrees shows the South-East direction, 180 degrees corresponds to the South, 270 degrees is the same as the West on a compass and 360 degrees denotes North wind. 0 is reserved for calm situations. The table converting rhumbs to degrees is shown in Appendix 3.

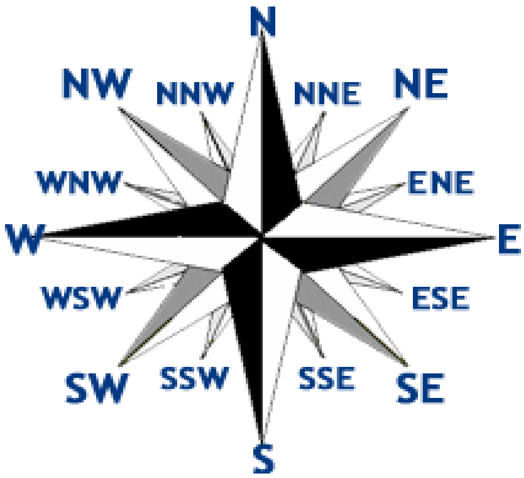

Figure 2.2 Wind rose with 16 rhumbs [40]

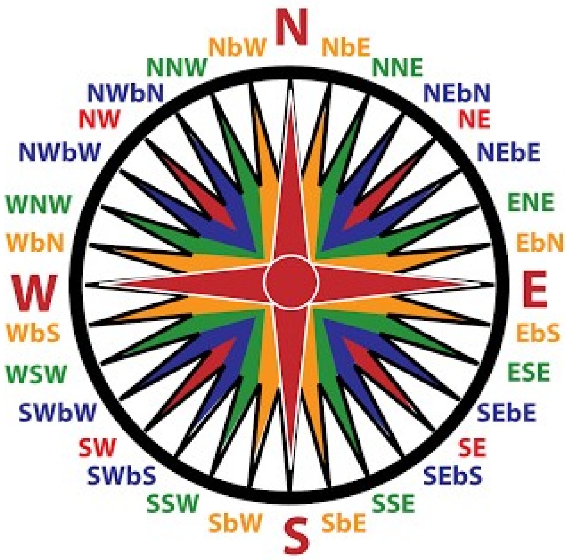

Figure 2.3 Wind rose with 32 rhumbs [41]

2.2 Wind characteristics measurement

An anemometer is used for wind speed measurement in almost all world meteorological stations.

A vane anemometer (see Figure 2.4) combines two instruments, a wind vane and an anemometer, into one unit. Because the vane and the anemometer are combined, it is possible to measure both, the wind direction and speed. For the vane anemometer calibration is necessary to measure the wind speed by the speed at which wind causes the propeller to spin. The typical vane anemometer may use mechanical or electronic means for data calculation. [42] When wind parameters are measured with the vane anemometer, the axis of rotation must be parallel to the direction of wind. Additional functions of the vane anemometer may be temperature, humidity and dew point measurements.

Figure 2.4 Vane anemometer Testo 417 [43]

A thermal anemometer (see Figure 2.5) is commonly used in meteorology for the wind speed measurement. Thermal anemometers use a wire, which is heated up to some temperature above the environment. When airflow passes over this wire, they cool it. As the electrical resistance of most metals depends on the temperature, it is possible to find a relationship between the resistance of the wire and the flow speed. [44] Than larger is the wind speed, that greater is the cooling effect.

Figure 2.5 Thermal anemometer Testo 425 [45]

A cup anemometer (see Figure 2.6) is the simplest instrument for the wind speed measurement. It consists of three or four hemispherical cups, which are mounted on the ends of horizontal arms. These arms are mounted at equal angles to each other on a vertical shaft. The amount of cups turns over a set time period gives us an average wind speed. [44]

Figure 2.6 Typical cup anemometer [46]

Another equipment, which can measure both, the wind speed and wind direction, is *an anemorhumbometer*. The anemorhumbometer combines into itself the vane and the anemometer functions. In different times there were used M-63, M-63-M, M-63-M1 anemorhumbometers in Estonia. M-63-M, M-63-M1 anemorhumbometers are much more sensitive, than M-63. The working principle of the anemorhumbometer is based on the connections between wind speed and frequency of propeller rotations and between wind direction and the anemorhumbometer position. The resolution of anemorhumbometer is 1 m/s for the wind speed measurement and 10 degrees for the wind direction measurement. The permissible error will be $\mp(0{,}5+0{,}03\,V)$ m/s, if the wind speed measurement is made in 1...40 m/s range. If the wind speed are measured in 1...60 m/s range, so the permissible error will be $\mp(1{,}0+0{,}05\,V)$ m/s. V is the wind speed. [47]

Figure 2.7 M-63-M1 anemorhumbometer [48]

A wind vane or a weather vane (see Figure 2.8) is mechanical device, which rotates freely and is used to show the direction of the wind. The wind vanes are used not only in all world meteorological stations but on the roof of some living houses, in airports or ships too. The wind vanes are used also for the weather forecasting. For example if wind is blowing from a warm ocean, so cloudy and wet weather can be expected. The wind vanes have very different design. [42] There are two different types of the vane: the vane with light plate and the vane with heavy plate. The first one is used, when regional wind speed does not exceed 20 m/s, the resolution of this vane is 1 m/s. The second type of the vane is used, when regional wind speed can reach 40 m/s. The resolution of the second type vane is 2 m/s. [47]

Figure 2.8 Typical wind vane [49]

Nowadays a lot of meteorological, hydrological and coastal stations are automatic. The Estonian Environment Agency uses in its work MILOS 520 automatic stations, which are connected to different sensors for meteorological characteristics measurement. For wind direction measurement the wind vane WAV151 (see Figure 2.9) is used.

> The WAV151 is a counterbalanced, low-threshold optoelectronic wind vane. Infrared LEDs and phototransistors are mounted on six orbits on each side of a 6-bit GRAY-coded disc. Turned by the vane, the disc creates changes in the code received by the phototransistors. The code is changed in steps of 5.6°, one bit at a time to eliminate any ambiguities in the coding. A heating element in the shaft tunnel keeps the bearings above freezing level in cold climates. Nominally it provides 10 W of heating power. A thermostat switch is included in the sensor crossarm WAC151, for switching power on below +4 °C. [50]

Figure 2.9 The wind vane WAV151 [50]

For wind speed measurement the anemometer WAA151 (see Figure 2.10) is used.

The WAA151 is a fast-response, low-threshold anemometer. It has three lightweight conical cups in the cup wheel, providing excellent linearity over the entire operating range, up to 75 m/s. A wind-rotated chopper disc, attached to the cup wheel's shaft, cuts an infrared light beam 14 times per revolution, generating a pulse output from a phototransistor. The output pulse rate can be regarded directly proportional to wind speed (e.g., 246 Hz = 24.6 m/s). For the best available accuracy, however, the characteristic transfer function should be used (see technical data), for compensating starting inertia and slight overspeeding. A heating element in the shaft tunnel keeps the bearings above freezing level in cold climates. Nominally it provides 10 W of heating power. A thermostat switch in the sensor cross arm WAC151 keeps heating on below +4 °C. [51]

Figure 2.10 The anemometer WAA151 [51]

3 WIND DATA

3.1 The measurement sites

For the present analysis nine Estonian coastal stations were chosen: Kihnu, Kunda, Pakri, Pärnu, Ristna, Ruhnu, Sõrve, Vilsandi, Virtsu.

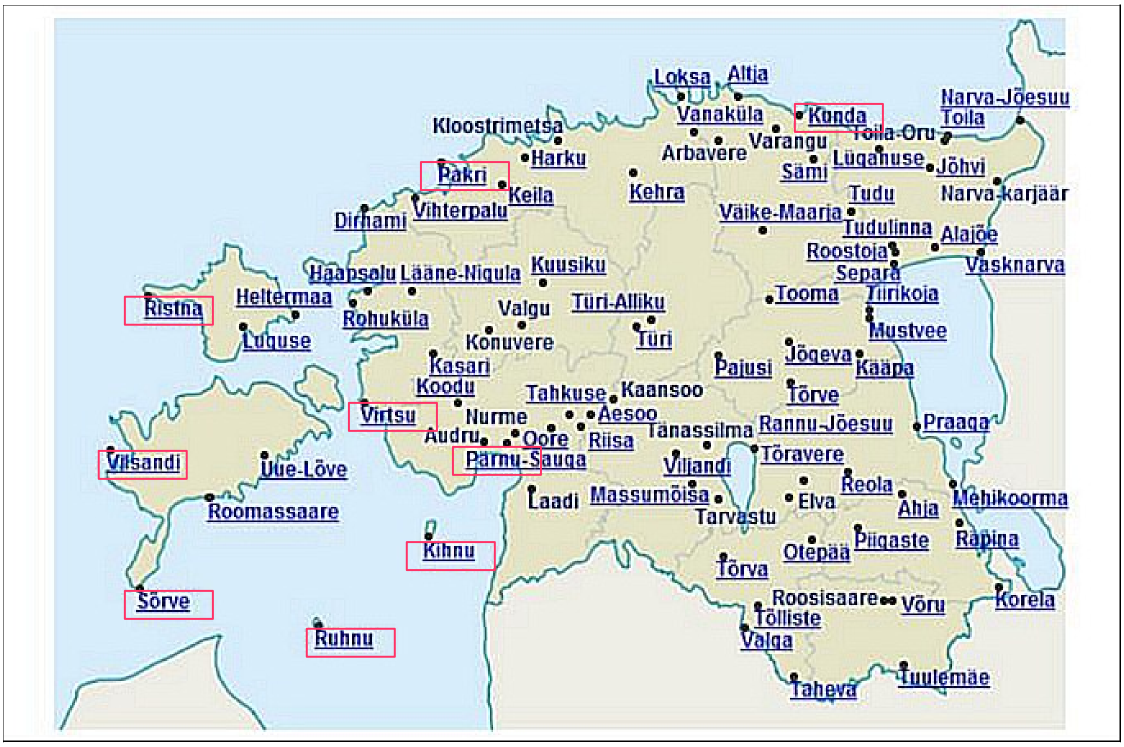

Figure 3.1 Estonian meteorological stations [52]

Almost all these stations, excluding Kunda, are situated on the West, North-West or South-West coast of the country. The choice of the stations is caused by the necessity to estimate, how probable is the ecological impact of neighbouring countries on Estonia. As Baltic Proper collects the pollution of most European countries and Estonia is situated in the immediate vicinity to Baltic Proper, it was necessary to choose those meteorological stations, which are nearer to Baltic Proper. Kunda is located on another side of Estonia. This station was chosen for the comparison of meteorological situations in the West and in the East.

Kihnu meteorological and hydrological station (N 58°05′55′′, E 23°58′13′′) is situated on the

Kihnu island. The altitude of the station is 3 m and the measurement site is open to the sea. The observations on the island are made from 1931 but the station with this location started operating in 1954. *Kunda meteorological and hydrological station* (N 59°31´04´´, E 26°32´43´´) is situated near Kunda town. The altitude of the station is 1 m and the measurement site is open to the sea. The observations are made from 1849. *Pakri meteorological station* (N 59°23´22´´, E 24°02´24´´) is situated on the Pakri peninsula, which separates the Gulf of Paldiski and the Gulf of Lahepere. The altitude of the station is 23 m and the measurement site is open to the sea. The observations on the peninsula are made from 1865. The station with this location started operating in 2003. Before 2003 the location of the station was changed several times (in 1969, in 1992), due to the instability of the soil, where the station was. In 1992 Pakri station was moved to a sheltered site and in 2003 to the seaside. *Pärnu meteorological and hydrological station* (N 58°25´11´´, E 24°28´11´´) is situated near Pärnu city. The altitude of the station is 12 m. The observations near Pärnu city are made from 1842. The station with this location started operating in 2004. Before 2004 the site of meteorological observations was changed also in 1990, it was moved from the beach into the town centre – the distance between old and new locations was 1,5 km. In 2004 station was moved to the airport. *Ristna meteorological and hydrological station* (N 58°55´15´´, E 22°03´59´´) is situated in Kalana village. The altitude of the station is 7 m. The station started operating in 1922. *Ruhnu meteorological and hydrological station* (N 57°47´00´´, E 23°15´32´´) is situated on the Ruhnu island. The altitude of the station is 2 m. The observations were started in 1906, but the station with this current location started work in 1964. *Sõrve meteorological and hydrological station* (N 57°54´49´´, E 22°03´29´´) is situated on the Saaremaa island, on the peninsula, which separates Baltic Proper and the Gulf of Riga. The altitude of the station is 3 m and the measurement site is open to the sea. The observations are made from 1865, but the location of the station was changed several times. In 1987 the station was moved by approximately 200 m to avoid the influence of the lighthouse. *Vilsandi meteorological and hydrological station* (N 58°22´58´´, E 21°48´51´´) is situated on the Vilsandi island. The altitude of the station is 6 m. The observations are carried out from 1865. *Virtsu meteorological and hydrological station* (N 58°34´22´´, E 23°30´49´´) is situated near Virtsu town. The altitude of the station is 2 m. The observations are made from 1903. [47, 53]

3.2 The measurement times

A 39-year period of 1966-2005 was chosen for the analysis. During the period of 1966-1991 measurements were carried out every three hours by Moscow time (in winter the difference between Moscow time and GMT is three hours). Since the 1st of January 1992 measurement are carried out by GMT (in summer the difference between East European time and GMT is three hours, in winter – two hours). [53]

Until the 1st of August 2003 the data of the wind speed and directions at these stations have not recorded automatically and have given information every three hours – at 00, 03, 06, 09, 12, 15, 18, 21 GMT. After the 1st of August 2003 stations forward information every hour. The wind speed was registered with a resolution of 1 m/s, earlier wind direction observations were made using the wind rose of 16 rhumbs and later wind direction observations were made with a resolution of 10 degrees [54]. For the equivalent data estimation, the measurements of every third hour were used in this analysis. The average monthly air temperature and the average monthly air pressure data were used in this paper for more informative analysis. Air temperature was registered with a resolution of 0,1 ^{o}C and air pressure was registered with a resolution of 1hPa.

For several reasons, there are shorter or longer gaps in the data. They are shown in Table 3.1.

Table 3.1. Missing wind data

Vilsandi	June 1990 – October 1991
Pakri	January 1967, February 1967, January 1981
Pärnu	September 1989 – April 1990
Ristna	January 2005, October 2005
Ruhnu	August 1984, April – June 1985, October 1987 – September 2003, March – April 2005, August 2005
Sõrve	June 1983, May 1993 – December 1994, January 2005
Virtsu	March – April 1973, November 1973 – March 1974, July 1974 – September 1975, December 1983 – February 1985

As the accuracy of mean values mainly depends on the number of measurements, it was decided to exclude from the analysis those months and years, when data information is not complete.

3.3 The equipment for measurements

In different times different equipments for wind speed and direction measurement were used. In *Kihnu meteorological and hydrological station* in 1961-1986 the wind direction was measured with both, the vane with light plate and the vane with heavy plate. M-63-M1 anemorhumbometer worked at station from 1975. In 1986 the vane with heavy plate was dismantled. In 1988 the vane with light plate was changed to the vane with heavy plate, which was used in this time, when anemorhumbometer did not work. In 2003 automatic station with WAV151 and WAA151 started work in Kihnu. At *Kunda meteorological and hydrological station* in 1961-1977 the wind direction was measured with the vane with light plate. In 1977 M-63-M1 anemorhumbometer started work. In 2003 automatic station with WAV151 and WAA151 started operating. At *Pakri meteorological station* in 1961-1981 the wind direction was measured with both, the vane with light plate and the vane with heavy plate. In 1981-1988 time period the vane with light plate, the vane with heavy plate and M-63-M1 anemorhumbometer worked at Pakri station. In 1988-2003 time period M-63-M1 anemorhumbometer was in use. Since 2003 WAV151 and WAA151 are used in Pakri. At *Pärnu meteorological and hydrological station* until 1974 the wind direction was measured with both, the vane with light plate and the vane with heavy plate. In 1974 the vane with heavy plate was changed to M-63 anemorhumbometer, which was changed to M-63-M1 anemorhumbometer in 1996. In 2004 automatic station with WAV151 and WAA151 started operating. At *Ristna meteorological and hydrological station* in 1961-1972 time period both, the vane with light plate and the vane with heavy plate, were used. In 1972 the vane with heavy plate was changed to M-63 anemorhumbometer. In 1977 the vane with light plate was dismantled. Since 1978 measurements were made with M-63-M anemorhumbometer and new vane with light plate. Since 2003 WAV151 and WAA151 are in use. At *Ruhnu meteorological and hydrological station* in 1961-1977 time period both the vane with light plate and the vane with heavy plate were used. The vane with heavy plate was changed to M-63-M anemorhumbometer in 1977. Since 2003 WAV151 and WAA151 are in use. At *Sõrve meteorological and hydrological station* in 1961-1967 time period both, the vane with light plate and the vane with heavy plate, were used. The vane with light plate was changed to M-63-M anemorhumbometer in 1973. M-63-M1 anemorhumbometer worked in station since 1987. Since 2003 WAV151 and WAA151 are in use. At *Vilsandi meteorological and hydrological station* in 1961-1984 time period both, the vane with light plate and the vane with heavy plate, were used. M-63-M anemorhumbometer started work in 1976. The vane with heavy plate was dismantled in 1984. Two M-63-M1 anemorhumbometer and the vane with light plate were used in 1984-1994 time period. In 1994-2000 time period the vane with heavy plate, the vane with light plate and two anemorhumbometers were in use at Vilsandi station. In 2000 automatic meteorological station started work and since 2003 WAV151 and WAA151 are in use. At *Virtsu meteorological and hydrological station* in 1961-1976 time period both, the vane with light plate and the vane with heavy plate, were used. In 1976-2003 M-63-M1 anemorhumbometer was used and since 2003 WAV151 and WAA151 are operating. [47]

3.4 Wind direction conversion

Before the introduction of anemorhumbometers, wind direction measurements were recorded as codes. When, the wind rose with 16 rhumbs was used, each of 16 wind directions had its own code. The correspondence between wind direction codes and degrees is shown in Table 4.1.

Table 3.2. The correspondence between wind direction codes and degrees

Codes	Abbreviation	Degrees interval	Degrees
0 0	Calm	-	
0 2	NNE	From 12 to 33	22,5
0 5	NE	From 34 to 56	45,0
0 7	ENE	From 57 to 78	67,5
0 9	E	From 79 to 101	90,0
1 1	ESE	From 102 to 123	112,5
1 4	SE	From 124 to 146	135,0
1 6	SSE	From 147 to 168	157,5
1 8	S	From 169 to 191	180,0
2 0	SSW	From 192 to 213	202,5
2 3	SW	From 214 to 236	225,0
2 5	WSW	From 237 to 258	247,5
2 7	W	From 259 to 281	270,0
2 9	WNW	From 282 to 303	292,5
3 2	NW	From 304 to 326	315,0
3 4	NNW	From 327 to 348	337,5
3 6	N	From 349 to 11	360,0
9 9	Wind of variable directions	-	

3.5 Wind data processing

For the present analysis necessary data was handled in Excel program. Using the definitions of the mean values (5) and Excel formulas, it was possible to find mean values of meteorological parameters (the wind speed, air temperature, air pressure) for every month, season and year. In this paper “season” means three spring months (March, April, May), three summer months (June, July, August), three autumn months (September, October, November) and three winter months (December, January, February). It is necessary to add, that at data averaging for winter, January and

February values were taken for one year and December values were taken for the previous year.

$$M=(\sum_{i=1}^{n} x_i)/n \text{ , (5)}$$

where x is meteorological variable,
i is the sequence number of the value of meteorological variable,
n is the amount of meteorological variables,
M is mean value of meteorological parameter.

To describe wind direction, 16-rhumb wind roses were composed by means of the Excel histogram tool.

Wind is a two-dimensional vector quantity. This vector may be specified by means of its components in the local Cartesian coordinates or by means of its direction and speed. In case the instantaneous wind values are in use, there is no difference between these two ways of wind description. On the other hand, several problems require averaged wind data. In these cases the average wind speed and average airflow, calculated from average wind velocity components, are completely different quantities. [37]

Traditionally, *u* is the zonal component of the wind vector (positive to the East) and *v* is the meridional component (positive to the North). These components are expressed by formulas (6).

$$u=-V*\sin q\,;v=-V*\cos q \text{ , (6)}$$

where V is the wind speed (m/s) ,
q is the wind direction (rad) .

The speed of the average airflow *U* is actually the modulus of the average wind vector during a certain time period. Therefore it can be calculated as follows:

$$U=\sqrt{(|u|)^2+(|v|)^2} \text{ , (7)}$$

where $|u|$ is the average zonal wind component and $|v|$ is the average meridional component.

Knowing thw wind speed and the wind vector modulus, it is possible to find the connection between the wind speed and average airflow by means of a stability factor that is calculated as a ratio of the average airflow to the average wind speed.

4 ANALYSIS OF LONG-TERM WIND SPEED, AIRFLOW AND WIND DIRECTION VARIATIONS

For better understanding of climate change in certain region, the knowledge on the wind regime variations is necessary. It is especially important to detect the wind speed trends and to establish the connection between average wind and average airflow. This can be done by means of stability factor that shows, how big is the stable part of winds blowing in one direction and forming the average airflow. In this paper such analysis is carried out for the 1966-2005 time period.

4.1 Analysis of long-term wind speed and airflow variations

In order to estimate the connections between the wind speed and climate change in a certain region, it is necessary to analyse long-term wind speed variations together with the variations in the air temperature and air pressure. Changes in temperature may indicate warming or cooling while the air pressure changes show, what kind of activity (cyclonic / anticyclonic) dominated in the region under investigations.

For this aim for each of nine coastal meteorological stations seasonal wind speed and airflow variations, annual wind speed and average airflow speed, annual air temperature and air pressure variations are shown and analysed in the present section. Statistical significance of all trends is estimates on the 0,05 level.

4.1.1 Kihnu station

In Figure 4.1 seasonal wind speed and airflow variations at Kihnu station are presented. As it is shown in Figure 4.1, in winter there is no trend in the wind speed time series: the decreases in one year were followed by equivalent increases in the next year. Decreasing trends in spring, summer and autumn are statistically significant: the decreases are much stronger than the increases. In Kihnu wind speed strongly decreased during 1985-1992. This period was followed by numerous storms and consequently wind speed increase [55]. Next strong decrease took place during 2000-2002. Average airflow shows practically no trends.

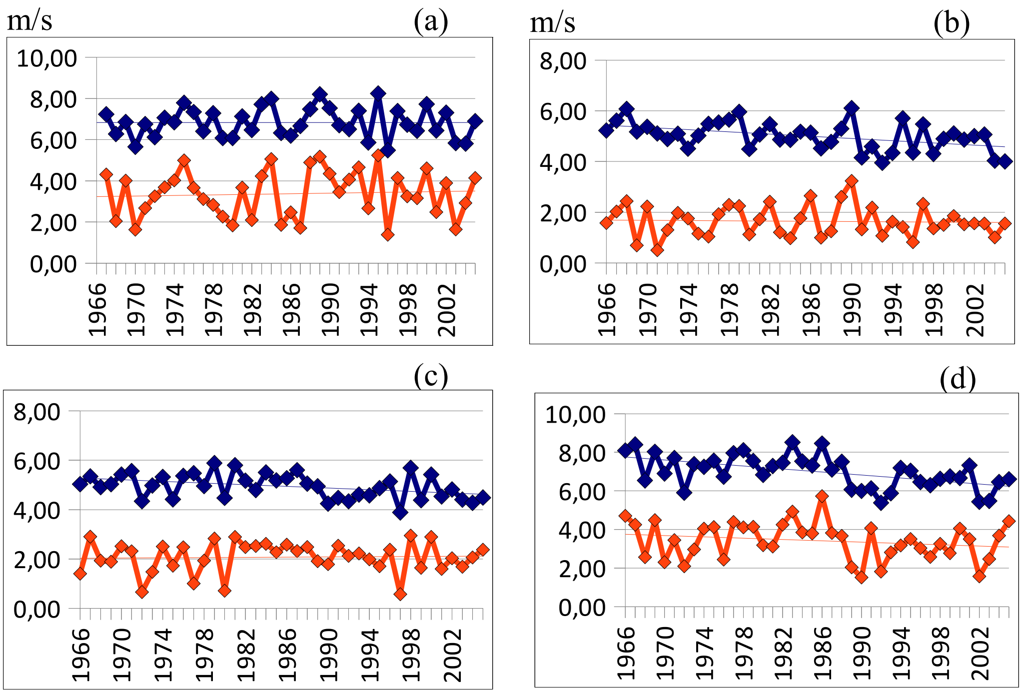

Figure 4.1 Seasonal wind speed (blue line) and airflow (red line) variations at Kihnu station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.2 annual wind speed and airflow variations at Kihnu station are presented. The decreasing trend in the wind speed is statistically significant and there is no trend in the average airflow. Figures 4.1 and 4.2 show that mostly the wind speed decreases and increases are accompanied by the decreases and increases of the airflow speed.

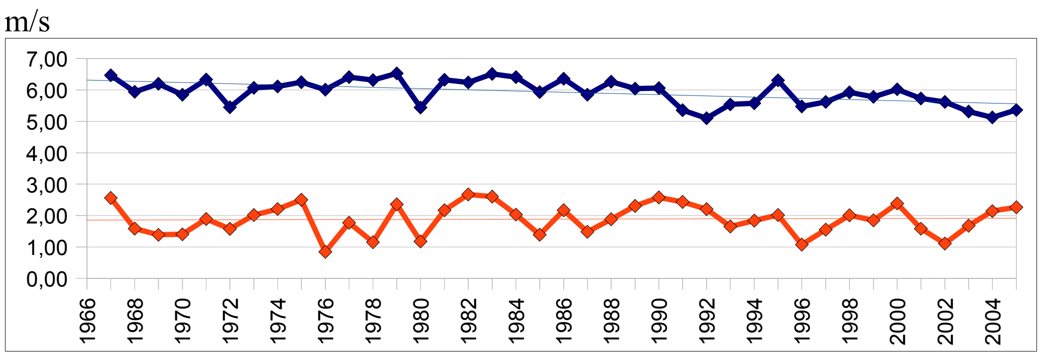

Figure 4.2 Annual wind speed (blue line) and airflow (red line) variations at Kihnu station. Straight line is linear trend

In Figure 4.3 annual air temperature and air pressure variations at Kihnu station are presented. The air temperature shows statistically significant positive trend. The negative trend in the air pressure is statistically insignificant. The strongest air temperature increase was in 1987-1990, which corresponds to the wind speed decrease period. As it is shown in Figures 4.2 and 4.3, every air pressure increase (anticyclonic activity) corresponds to the wind speed decrease and every air pressure decrease (cyclonic activity) corresponds to the wind speed increase. Also as it is shown in Figure 4.3, some air temperature decreases correspond to the air pressure increases. It can be explained by winter air temperature and air pressure influence on annual air temperature mean value. In winter, when continental polar masses prevail in Estonia, they bring dry and cold weather with high air pressure.

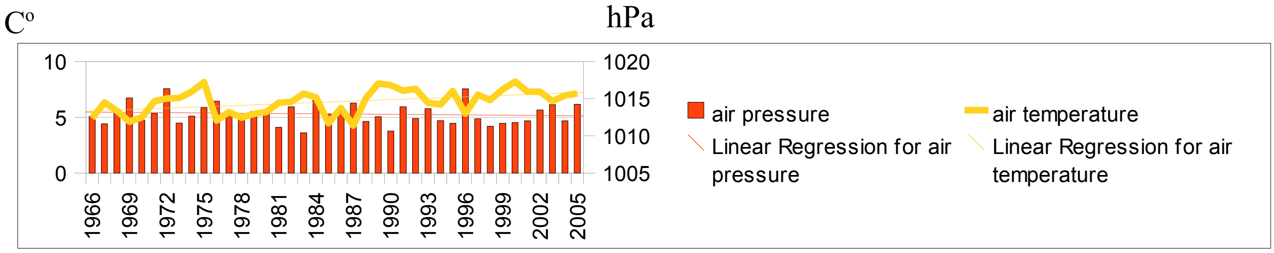

Figure 4.3 Annual air temperature and air pressure variations at Kihnu station

4.1.2 Kunda station

In Figure 4.4 seasonal wind speed and airflow variations at Kunda station are presented. All wind speed and airflow trends, except autumn, are statistically significant and negative. The strongest decrease of wind speed took place in summer and autumn, the strongest decrease in airflow is in winter. Spring and summer wind speed strongly decreased in 1997. This period was followed by the wind speed increase in 1997-1999.

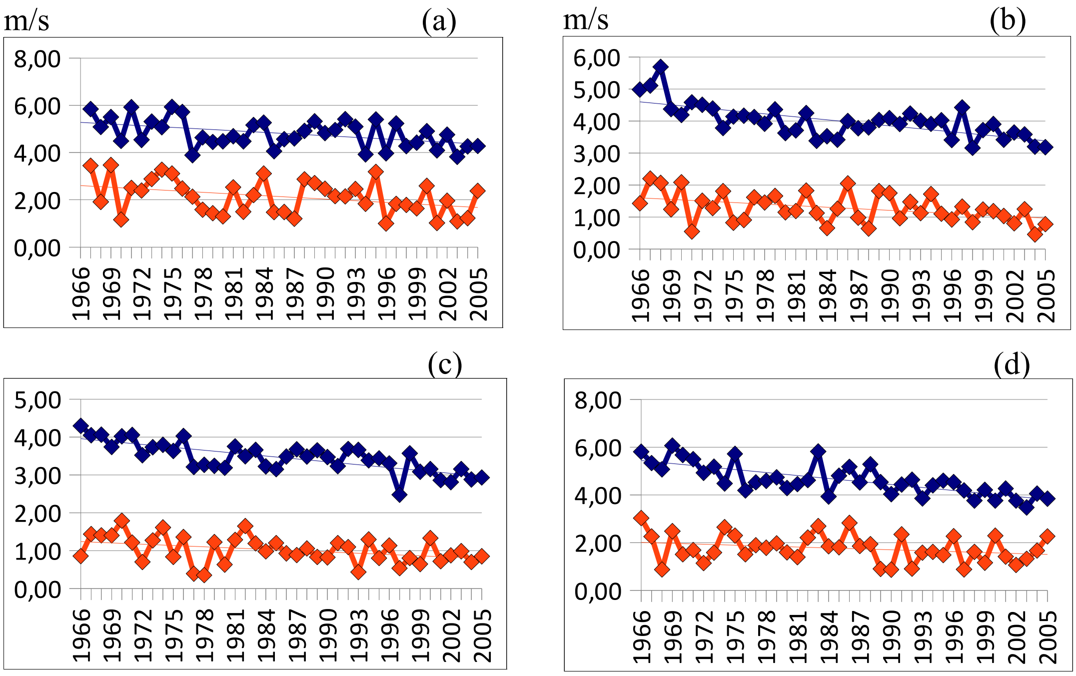

Figure 4.4 Seasonal wind speed (blue line) and airflow (red line) variations at Kunda station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.5 annual wind speed and airflow variations at Kunda station are presented. Both trends are negative and statistically significant. The strongest decrease in the airflow speed was in 1978. At the same time, the average wind speed increased slightly.

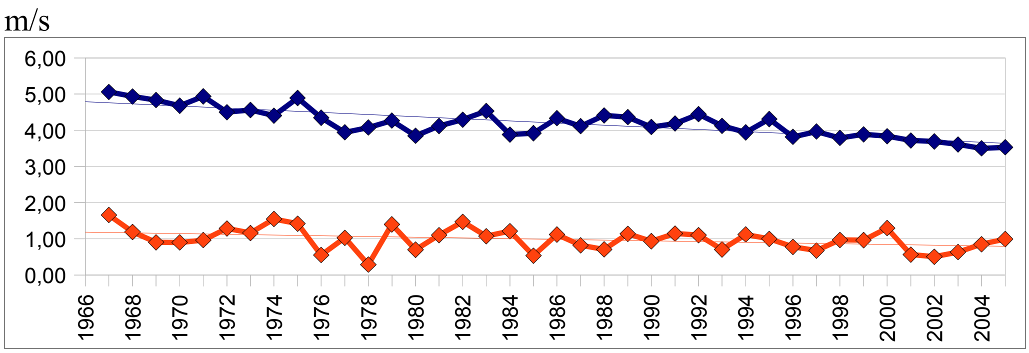

Figure 4.5 Annual wind speed (blue line) and airflow (red line) variations at Kunda station. Straight line is linear trend

In Figure 4.6 annual air temperature and air pressure variations at Kunda station are presented. The trend of the air temperature is increasing and statistically significant, the trend of the air pressure is decreasing and statistically insignificant. The strongest air temperature increase was in 1987-1990, at the same time wind speed was approximately without any changes. The strongest air pressure increase was in 1996 that corresponds to the wind speed desrease.

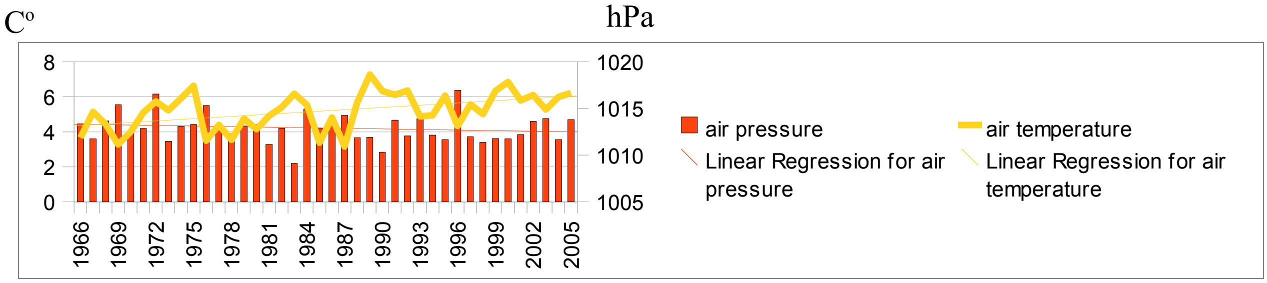

Figure 4.6 Annual air temperature and air pressure variations at Kunda station

4.1.3 Pakri station

In Figure 4.7 seasonal wind speed and airflow variations at Pakri station are presented with the gaps shown in Table 3.1. As it is shown in Figure 4.7, all trends are negative and statistically significant, while only the decreases of airflow speed in spring and summer are statistically insignificant. It should be kept in mind that in December of 1992 the station was moved to a more sheltered place and in August of 2003 to a cliff at the seaside. Therefore, the decrease in the wind speed does not necessarily show changes in the wind regime on the Pakri peninsula. It could be noticed that although the wind speed decreased, the average airflow speed remained practically the same.

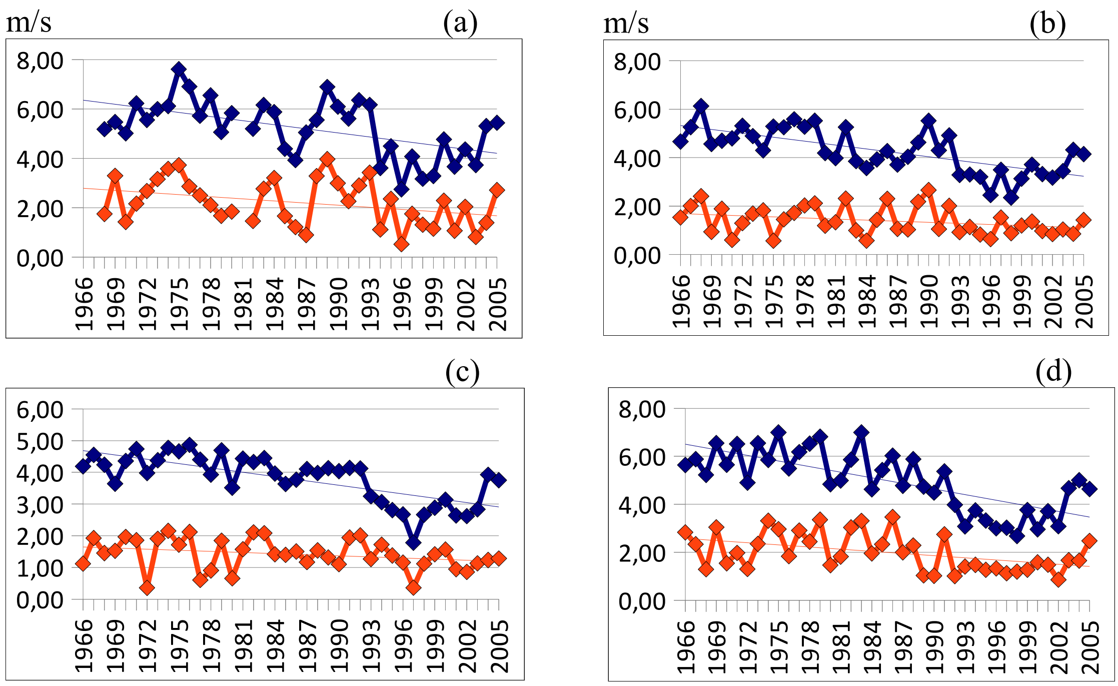

Figure 4.7 Seasonal wind speed (blue line) and airflow (red line) variations at Pakri station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.8 annual wind speed and airflow speed variations at Pakri station are presented. Although seasonal airflow speed trends in spring and summer were statistically insignificant, the annual decreasing trend is statistically significant. The strongest wind speed and airflow speed decreases were in 1996, to certain extent due to the bad location of the measurement field.

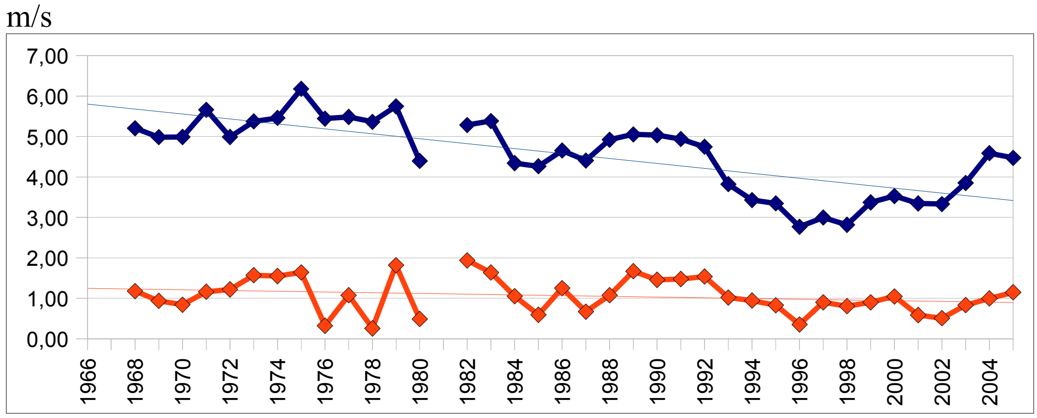

Figure 4.8 Annual wind speed (blue line) and airflow (red line) variations at Pakri station. Straight line is linear trend

In Figure 4.9 annual air temperature and air pressure variations at Pakri station are presented. Here the trend in the air temperature is positive and statistically significant. The air pressure trend is negligible. The warmest period was 1989-1992 that corresponds to the wind speed decrease.

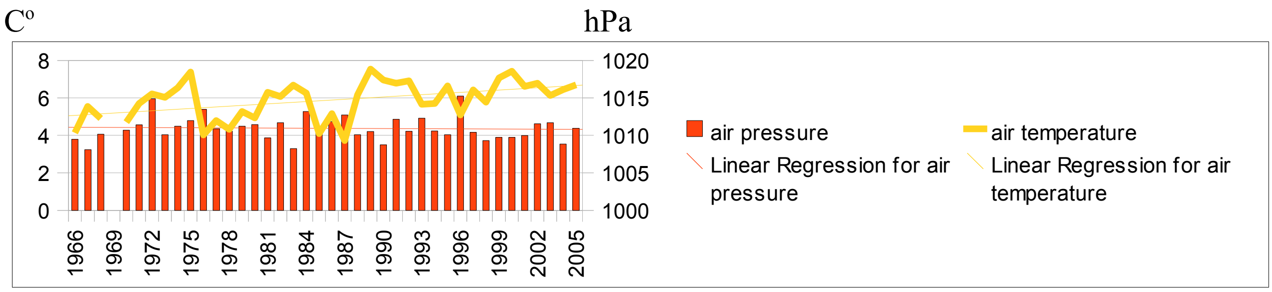

Figure 4.9 Annual air temperature and air pressure variations at Pakri station

4.1.4 Pärnu station

In Figure 4.10 seasonal wind speed and airflow variations at Pärnu station are presented with the gaps shown in Table 3.1. As it is shown in Figure 4.10, all seasonal trends are negative and statistically significant, except that of the airflow speed in winter that is statistically insignificant. The most rapid decreases are noted in autumn.

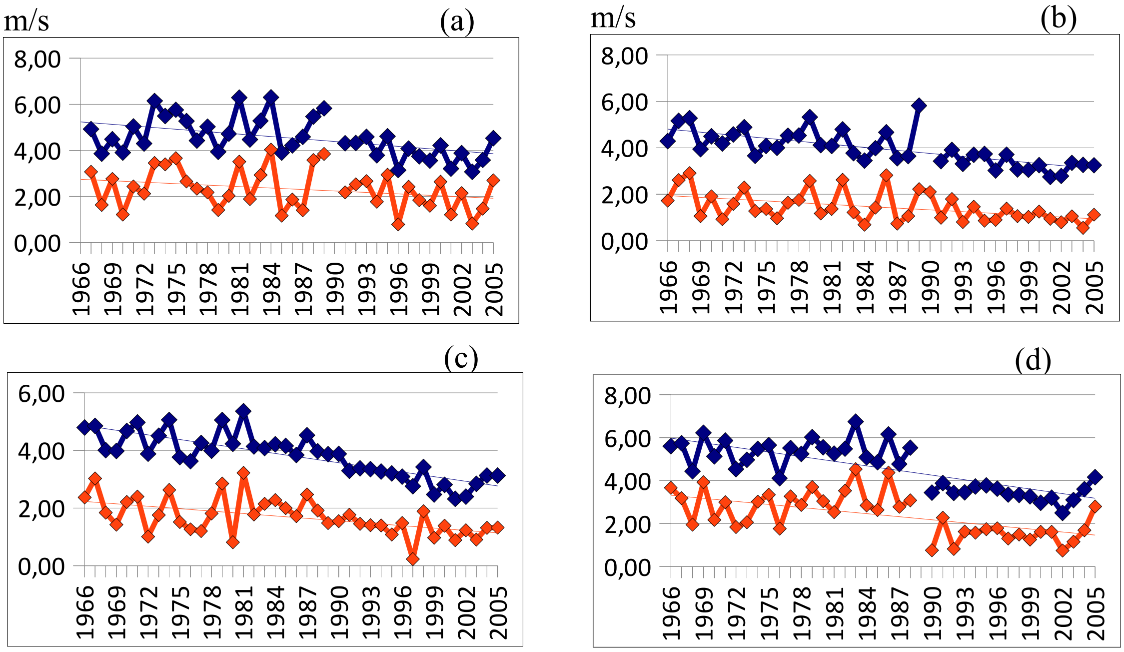

Figure 4.10 Seasonal wind speed (blue line) and airflow (red line) variations at Pärnu station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.11 annual wind speed and airflow variations at Pärnu station are presented. Both airflow speed and wind speed decreased and show statistically significant trends. At the analysis of Figures 4.10 and 4.11 it should be kept in mind that serious changes in the station location took place. In September 1990 the measurement site was moved from the beach to the town and in December 2004 to the airport. The time series of the wind speed and average airflow mirror these changes rather clearly.

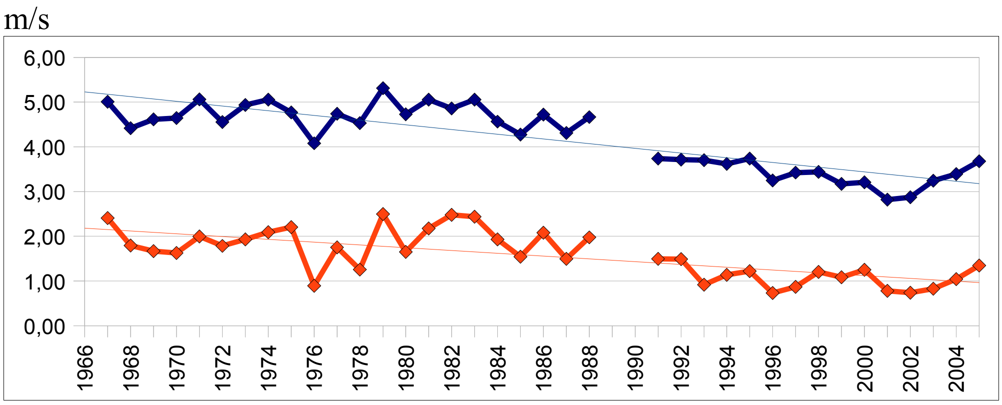

Figure 4.11 Annual wind speed (blue line) and airflow (red line) variations at Pärnu station. Straight line is linear trend

In Figure 4.12 annual air temperature and air pressure variations at Pärnu station are presented. The air temperature shows statistically significant positive trend, but there is no air pressure trend. The warmest year was 2000.

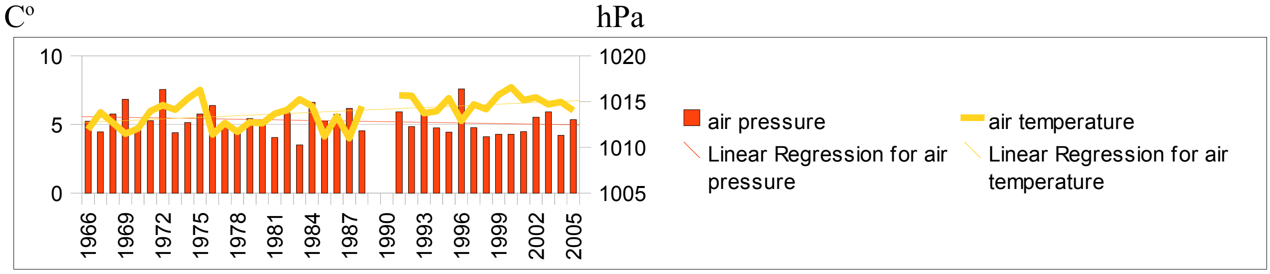

Figure 4.12 Annual air temperature and air pressure variations at Pärnu station

4.1.5 Ristna station

In Figure 4.13 seasonal wind speed and airflow variations at Ristna station are presented. There are no airflow speed trends in winter, spring and summer. All other trends are negative and statistically significant, except wind speed trend in winter. The wind speed decrease was the largest in autumn. In Ristna the wind speed notably decreased at the beginning of the 21st century.

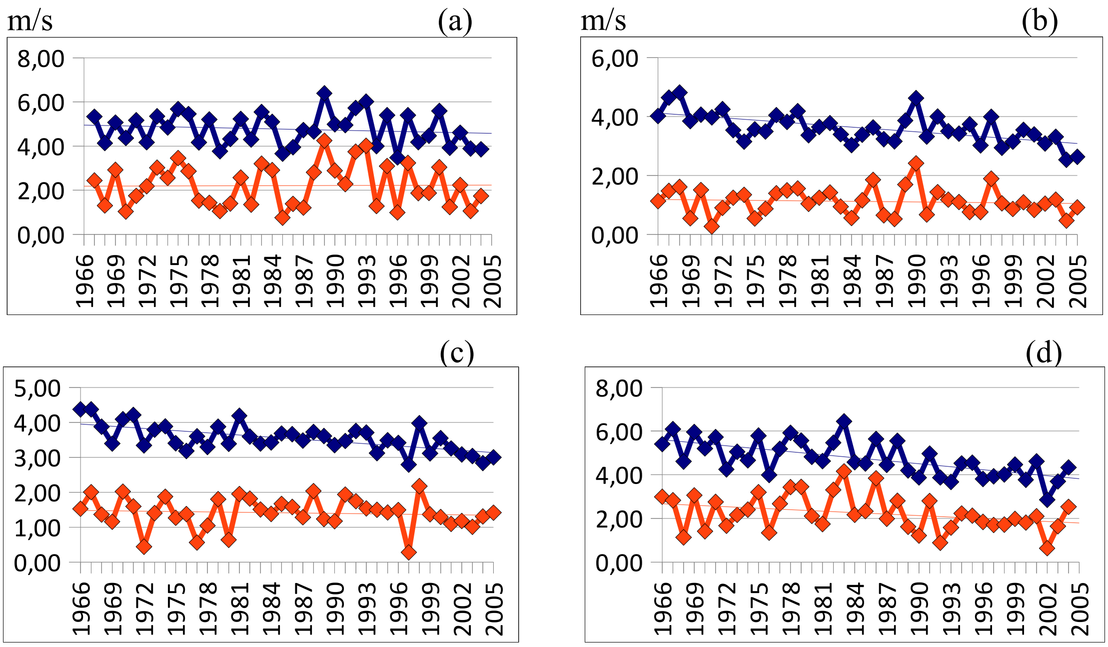

Figure 4.13 Seasonal wind speed (blue line) and airflow (red line) variations at Ristna station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.14 annual wind speed and airflow variations at Ristna station are presented. There is no airflow trend. At the same time the wind speed decreased and the trend is statistically significant. The strongest decrease was in 1976.

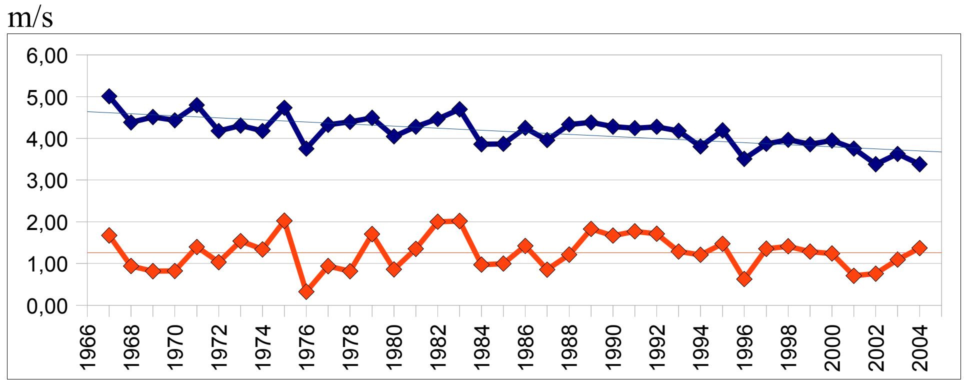

Figure 4.14 Annual wind speed (blue line) and airflow (red line) variations at Ristna station. Straight line is linear trend

In Figure 4.15 annual air temperature and air pressure variations at Ristna station are presented. The air temperature shows statistically significant increasing trend and annual air pressure is without any changes. The warmest years were 1975 and 1989. The same years were the calmest.

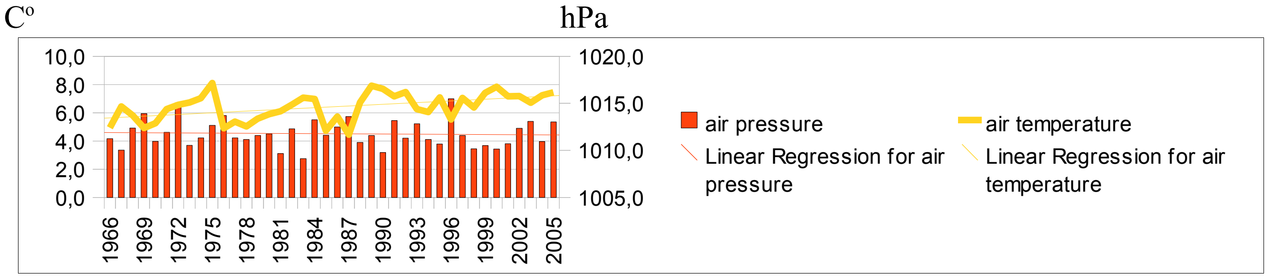

Figure 4.15 Annual air temperature and air pressure variations at Ristna station

4.1.6 Ruhnu station

In Figure 4.16 seasonal wind speed and airflow variations at Ruhnu station are presented. Unfortunately, the measurements were interrupted for a long period and therefore the calculated trends characterise only the first half of the period under investigation. As it is shown in Figure 4.16, the wind speed winter, spring, summer and autumn trends are negative. All wind speed trends, except winter trend, are statistically significant. The decrease of the wind speed is the largest in spring and summer. The trends in the airflow speed are statistically insignificant.

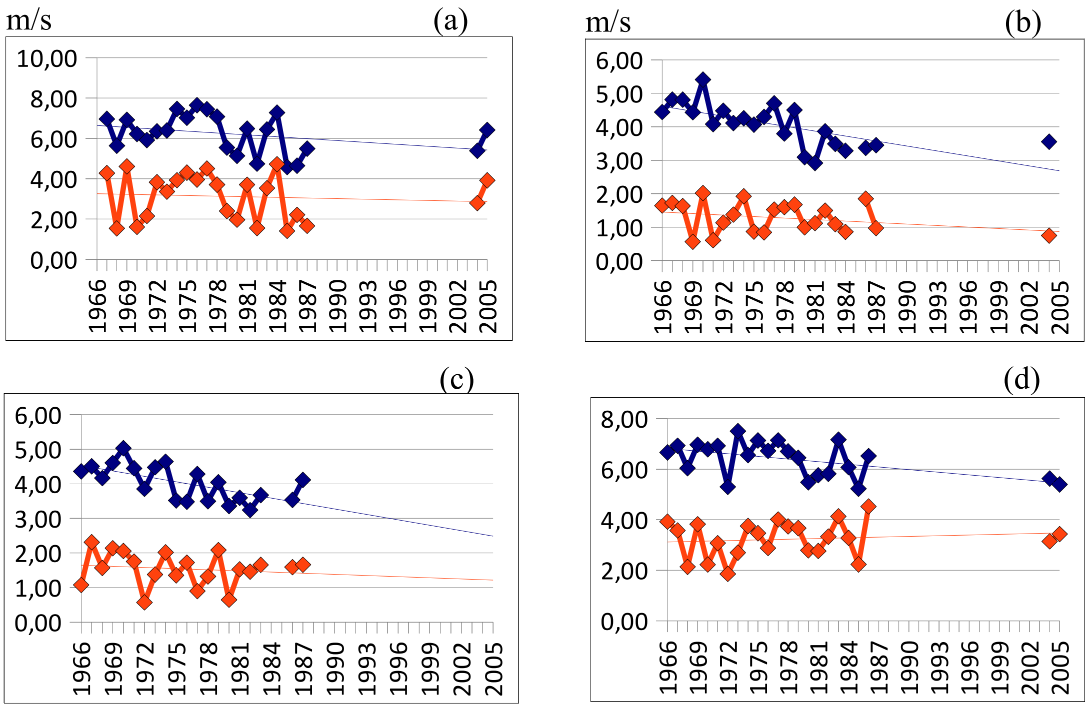

Figure 4.16 Seasonal wind speed (blue line) and airflow (red line) variations at Ruhnu station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.17 annual wind speed and airflow variations at Ruhnu station are presented. The trend in the airflow speed is positive, but statistically insignificant, while the trend in the wind speed is negative and statistically significant.

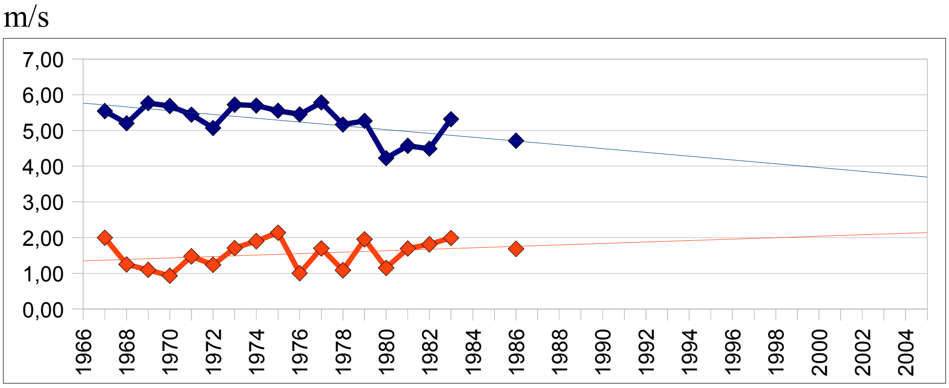

Figure 4.17 Annual wind speed (blue line) and airflow (red line) variations at Ruhnu station. Straight line is linear trend

In Figure 4.18 annual air temperature and air pressure variations at Ruhnu station are presented. The trend in the air temperature is positive and statistically significant, while the trend in the air pressure is negative and statistically insignificant. The strongest air temperature increase was in 1975. This period is connected with wind speed decrease.

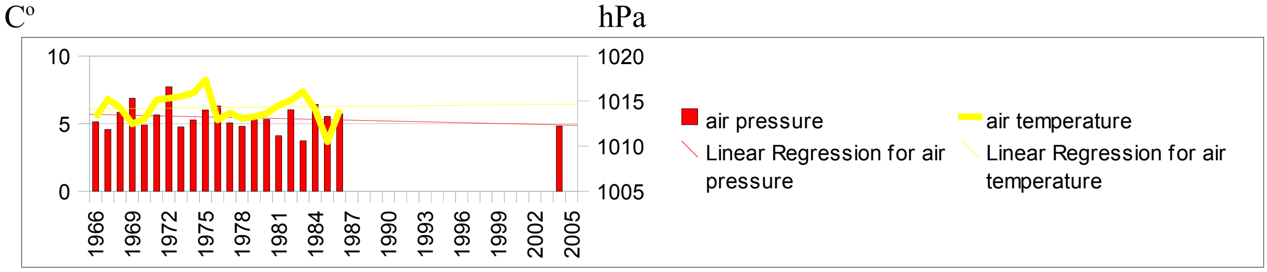

Figure 4.18 Annual air temperature and air pressure variations at Ruhnu station

4.1.7 Sõrve station

In Figure 4.19 seasonal wind speed and airflow variations at Sõrve station are presented. In winter the wind speed trend is positive. In spring, summer and autumn the trends are negative. All wind speed seasonal trends, excluding autumn trend are statistically insignificant. In autumn the decrease of the wind speed is the largest. In spring and autumn near Sõrve station the wind speed strongly decreased in 1989-1990. In winter strong decrease took place in 1983-1985. The trends in the average airflow are negligible or statistically insignificant.

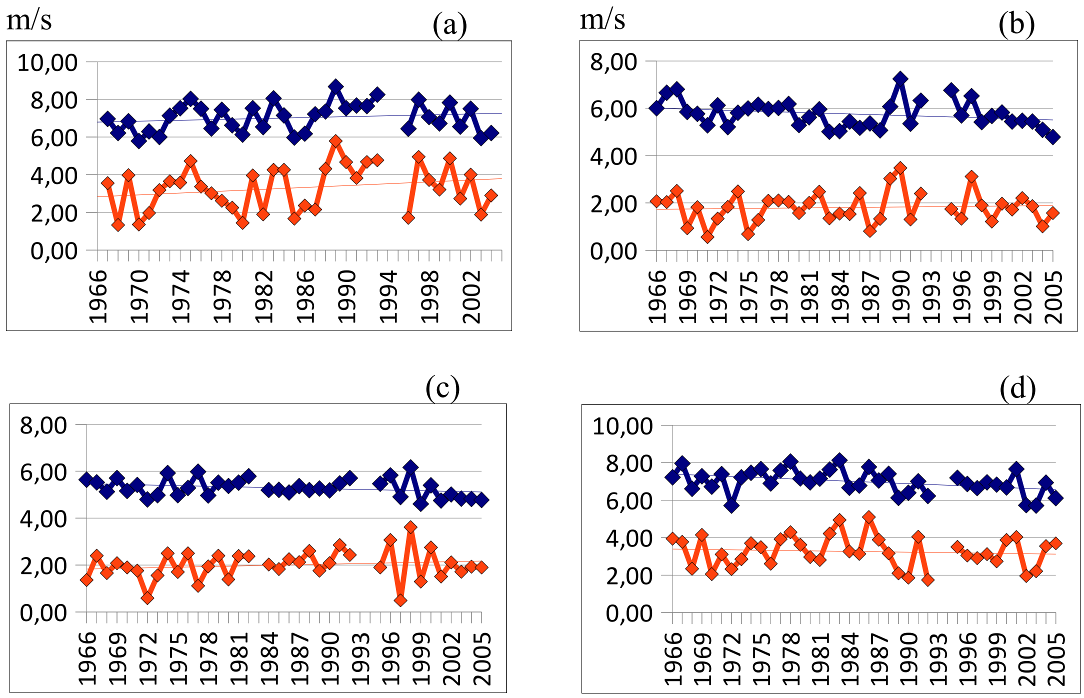

Figure 4.19 Seasonal wind speed (blue line) and airflow (red line) variations at Sõrve station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.20 annual wind speed and airflow variations at Sõrve station are presented. The trend in the average airflow is positive and that in the wind speed negative. Both trends are statistically insignificant.

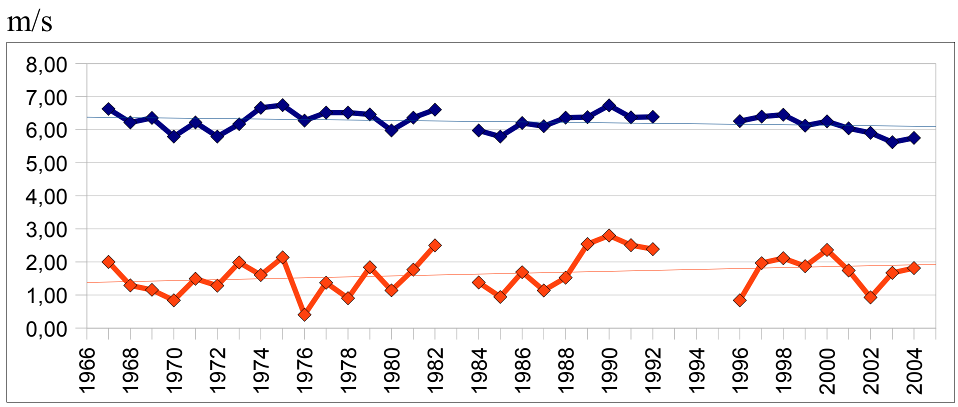

Figure 4.20 Annual wind speed (blue line) and airflow (red line) variations at Sõrve station. Straight line is linear trend

In Figure 4.21 annual air temperature and air pressure variations at Sõrve station are presented. The air temperature increases and the trend is statistically significant. The air pressure decreases, but the trend is statistically insignificant. The warmest and calmest year was 1989.

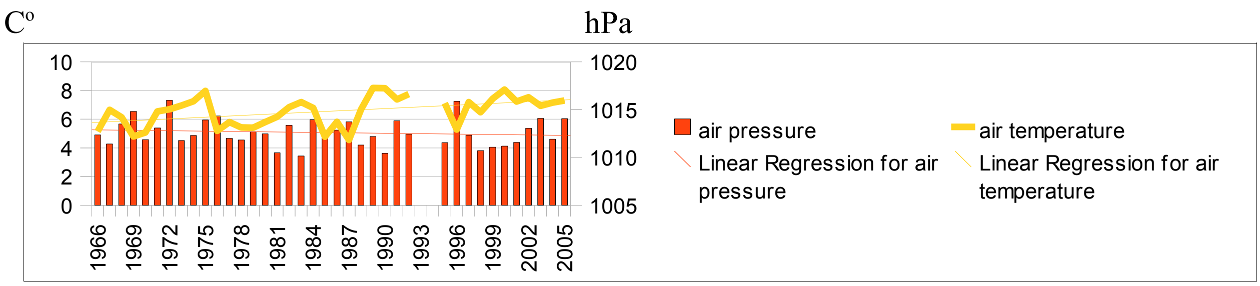

Figure 4.21 Annual air temperature and air pressure variations at Sõrve station

4.1.8 Vilsandi station

In Figure 4.22 seasonal wind speed and airflow variations at Vilsandi station are presented. There is no trend in the wind speed in winter, but in spring, summer and autumn the trends are negative and statistically significant. The strongest decrease in the wind speed took place in autumn. In summer and autumn near Vilsandi station the wind speed strongly decreased in 1974-1976. In spring the strongest decreas was in 1974-1979. There is no the airflow speed trend in winter, spring and summer. In autumn the airflow speed decreases, but the trend is statistically insignificant.

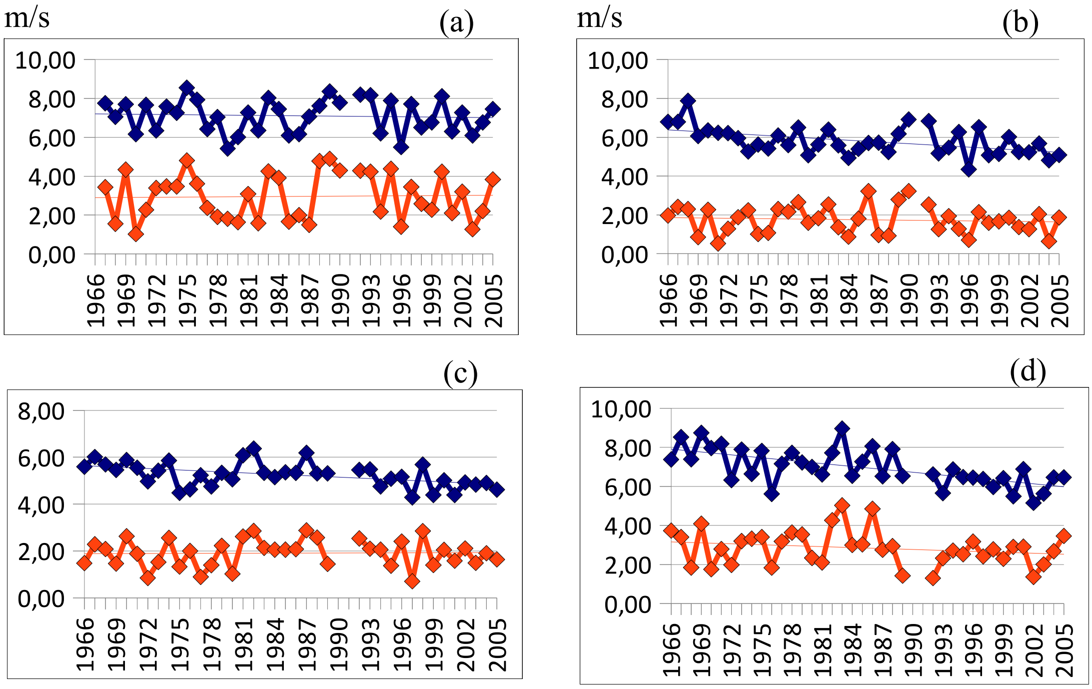

Figure 4.22 Seasonal wind speed (blue line) and airflow (red line) variations at Vilsandi station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.23 annual wind speed and airflow variations at Vilsandi station are presented. There is no trend in the annual airflow speed, but the decreasing trend in the wind speed is statistically significant.

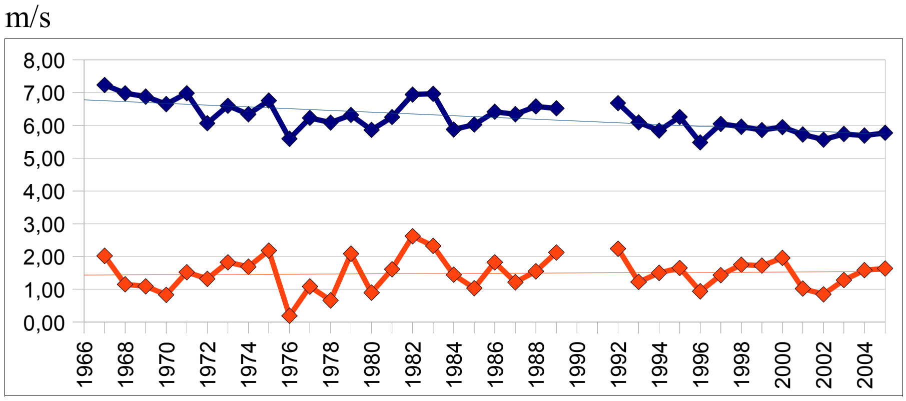

Figure 4.23 Annual wind speed (blue line) and airflow (red line) variations at Vilsandi station. Straight line is linear trend

In Figure 4.24 annual air temperature and air pressure variations at Vilsandi station are presented. The air temperature trend is positive and significant, but there is no air pressure trend.

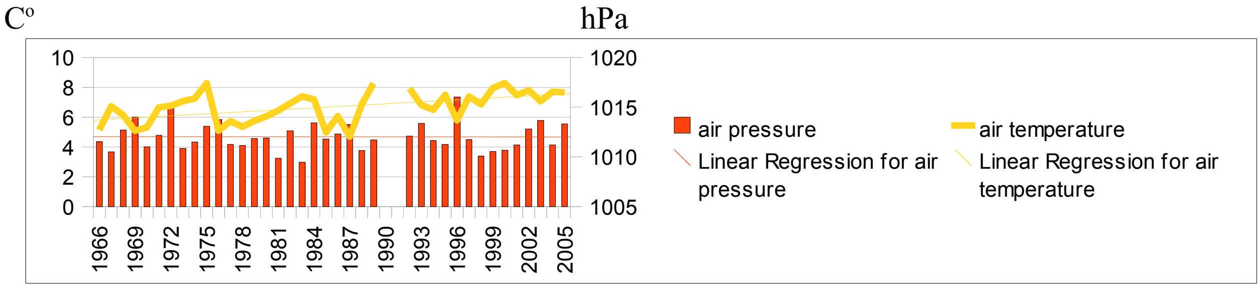

Figure 4.24 Annual air temperature and air pressure variations at Vilsandi station

4.1.9 Virtsu station

In Figure 4.25 seasonal wind speed and airflow variations at Virtsu station are presented. There are no wind speed trends in winter and spring. In summer and autumn the trends are negative and statistically significant. The strongest decrease in the wind speed took place in autumn. In winter, spring and summer near Virtsu station wind speed strongly decreased in 1995-1997. In autumn the strongest decrease took place during 1986-1990. There is only one trend in the average airflow – a decreasing one in autumn, but this is statistically insignificant.

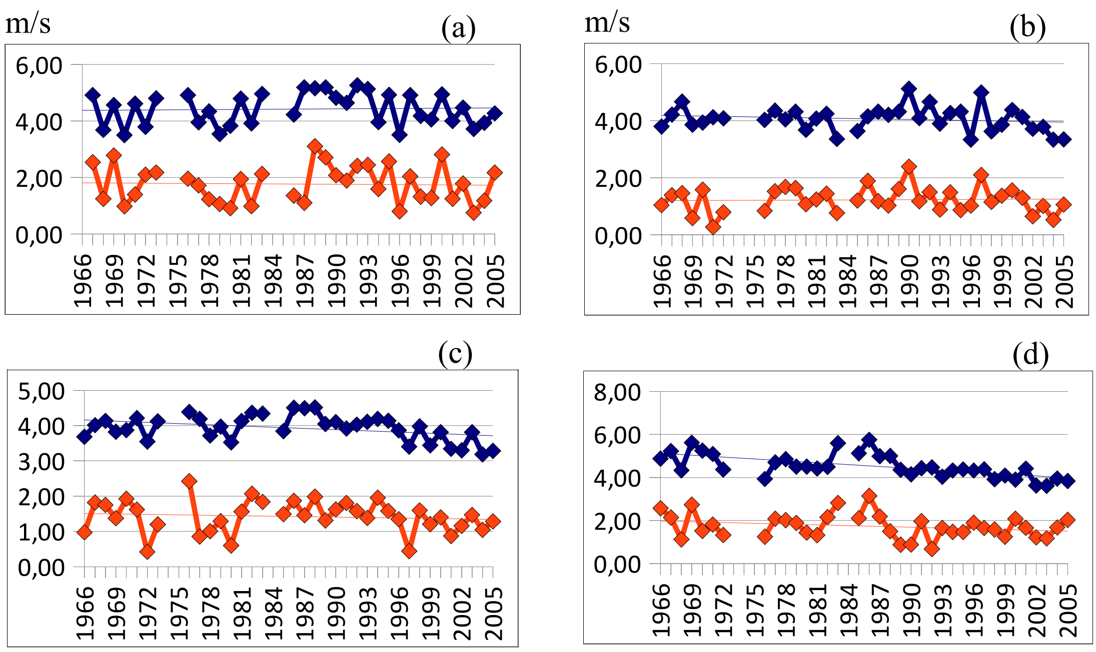

Figure 4.25 Seasonal wind speed (blue line) and airflow (red line) variations at Virtsu station. a – d are winter, spring, summer and autumn. Straight line shows linear trend

In Figure 4.26 annual wind speed and airflow variations at Virtsu station are presented. There is an insignificant trend in the wind speed, but no trend in the average airflow.

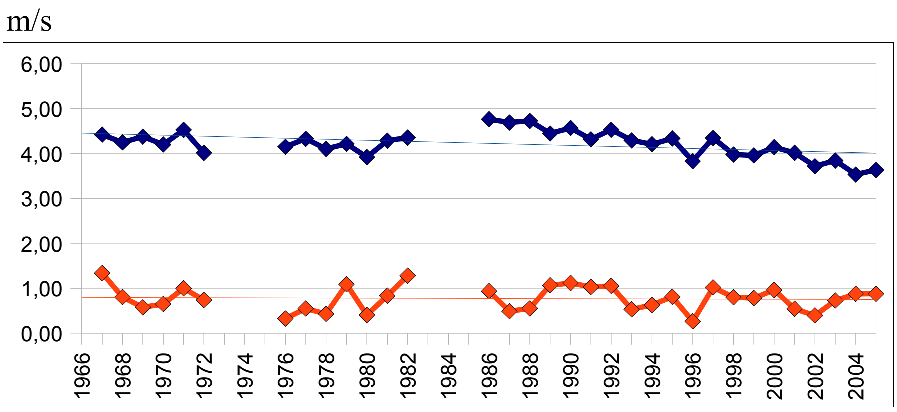

Figure 4.26 Annual wind speed (blue line) and airflow (red line) variations at Virtsu station. Straight line is linear trend

In Figure 4.27 annual air temperature and air pressure variations at Virtsu station are presented. The air temperature increases and the trend is statistically significant, while the air pressure decreases, but the trend is statistically insignificant. The air temperature was the highest in 1989 and 2000. The same period was calm too.

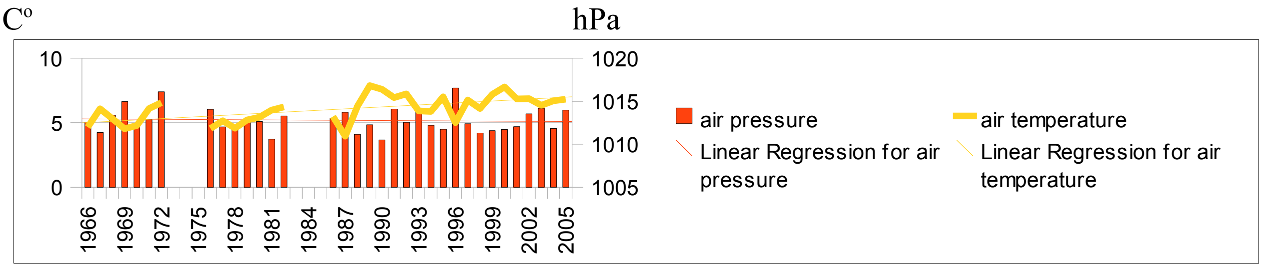

Figure 4.27 Annual air temperature and air pressure variations at Virtsu station

4.2 Analysis of long-term wind direction and airflow variations

Numerous wind measurements on ships show that southwest winds overwhelmingly dominate almost round the year at open Baltic Proper [56]. Only in March-April relatively weak North and North-East winds form a large part of all winds. Marine wind reconstruction based on coastal measurements mostly agree with this description, but demonstrate that wind roses for moderate (6-10 m/s) and strong winds (>10 m/s) as a rule differ from the wind roses for all winds showing in the northern Baltic Proper a secondary peak from the northern sector and a deep minimum for easterly winds [57]. This leads to an idea that the traditional wind rose is not the best tool to estimate the probable impact of neighbouring countries industrial activities on Estonian environment. For this purpose, the average airflow vector and stability factor are better indicators.

Stability factor shows the proportion of winds that contribute to the average airflow. Wind components blowing approximately equally strong and equally often from opposing directions are cancelled at averaging in time [58]. Therefore strong winds with large wind speed need not form a strong average airflow.

The average value of long-term stability factor is 0,31 at Kihnu, 0,22 at Kunda, Pakri and Vilsandi, 0,36 at Pärnu, 0,29 at Ristna, 0,27 at Ruhnu, 0,25 at Sõrve and 0,17 at Virtsu. It means that less than 36% of average wind speed takes part in the average airflow formation.

In Figure 4.28 stability factors for each of nine meteorological stations are shown.

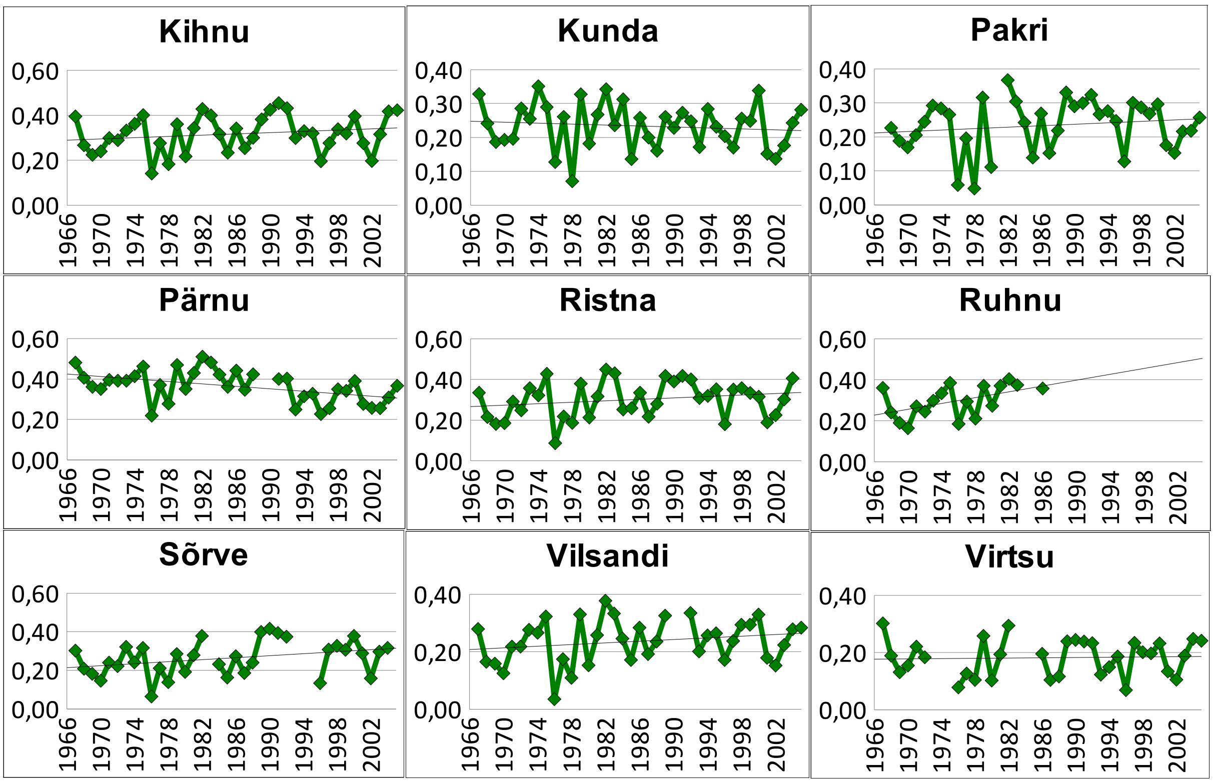

Figure 4.28 Annual stability factor variations at nine meteorological stations

Trends in the stability factor are mostly insignificant. Exceptions are Ruhnu and Sõrve, where stability factor increases during the period under investigation. The negative trend at Pärnu may not be caused by meteorological factors, as the location of the station changed twice during 1966-2005.

The stability factor values were the largest in Pärnu until 1992, when the station was situated on the beach and totally open to strong winds from the sea. When the station was moved to the town centre, stability factor shows similar values with those at Kihnu, the nearest measurement site to Pärnu. The stability factor was the lowest in 1976 and 1978 in all stations – less than 22%.

The comparison of annual wind speed, airflow and stability factor graphics shows, that when the wind speed and the airflow speed increase at the same time or the airflow speed increases and the wind speed decreases at the same time, then stability factor can decrease or increase. When the wind speed and the airflow speed decrease at the same time or the airflow speed decreases and the wind speed increases at the same time, then stability factor can increase or decrease. Both, the first case and the second case, can be explained not only by the wind speed, but also by the wind direction variations. The same value of stability factor can show different situations. First, strong winds blow from opposite direction and there is only a slight difference between the frequencies of winds from these directions, i.e. the wind rose is nearly spherical. Second, the winds are weak, but their frequency from one direction is much larger than from the opposite direction, i.e., the wind rose is notably asymmetric.

The average wind speed, airflow and stability factor should be studied together, as only their combination gives a comprehensive description of the wind field. At Pärnu and Sõrve values of the long-term airflow speed are similar – 1,52 m/s and 1,57 m/s, respectively. On the other hand, the wind speed at Pärnu is 4,2 m/s and at Sõrve 6,2 m/s. One can resume that at Pärnu relatively weak winds blow frequently from one sector and at Sõrve the angular distribution of strong winds is more variable. This feature is clearly described by means of the stability factor that is 0,36 at Pärnu and 0,25 at Sõrve. Another example: at Ristna the long-term average stability factor is 0,29 and at Ruhnu 0,27, but the average wind speed and airflow are larger at Ruhnu where the stability factor is smaller.

Long-term wind roses for the nine studied stations are shown in Figure 4.29. Wind roses show, that the most frequent wind directions are S, SSW, SW and W. In these stations, which are situated closer to the Baltic Proper, winds from W, WSW, SW, SSW prevail. These stations are Ristna, Ruhnu, Sõrve and Vilsandi. In Ruhnu the NW winds are also frequent. In those stations that are not situated so close to the Baltic Proper, dominant wind direction is S.

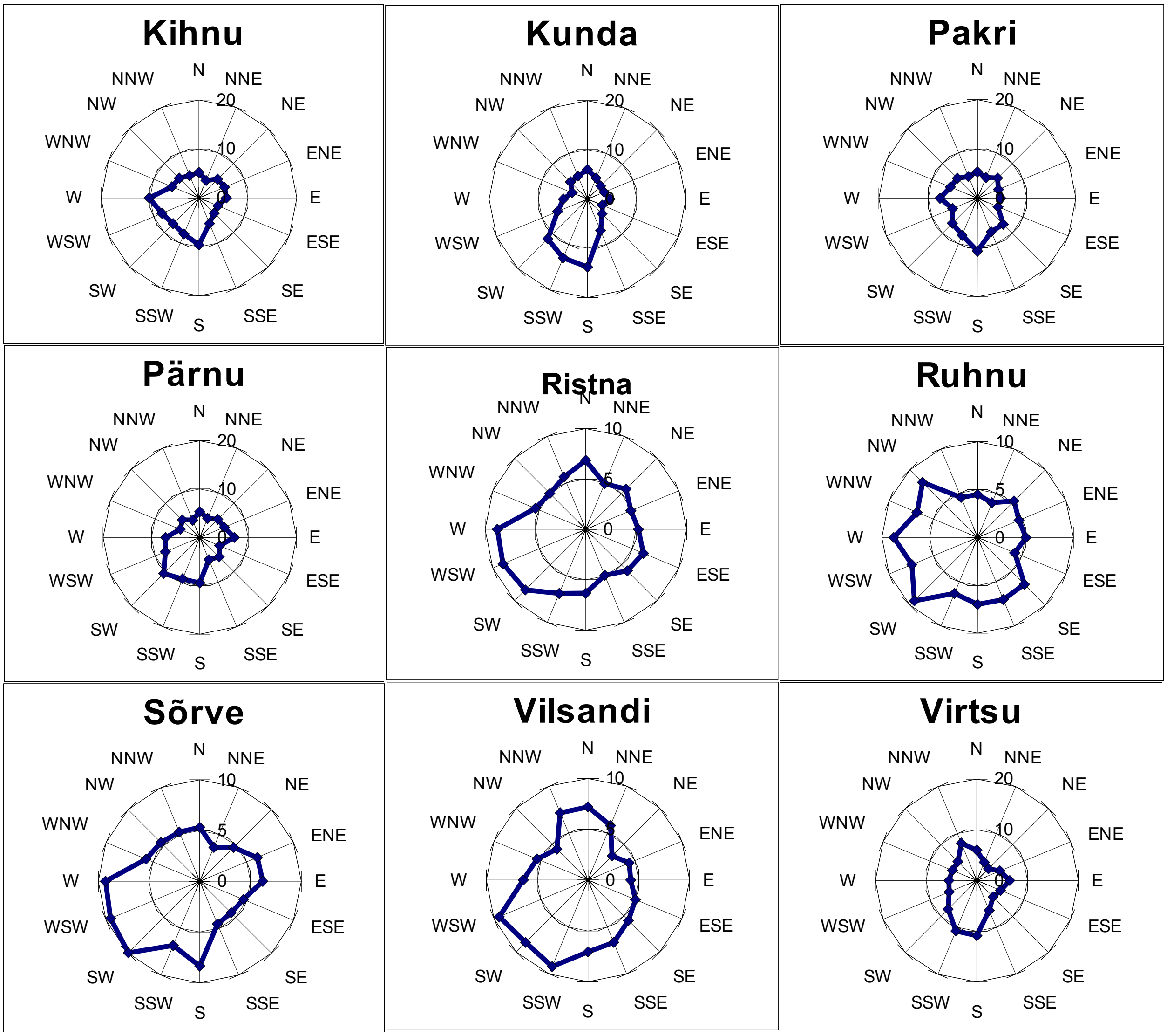

Figure 4.29 Annual wind direction variations at nine meteorological stations

Figure 4.30 presents long-term average airflow vectors for the nine stations under investigation.

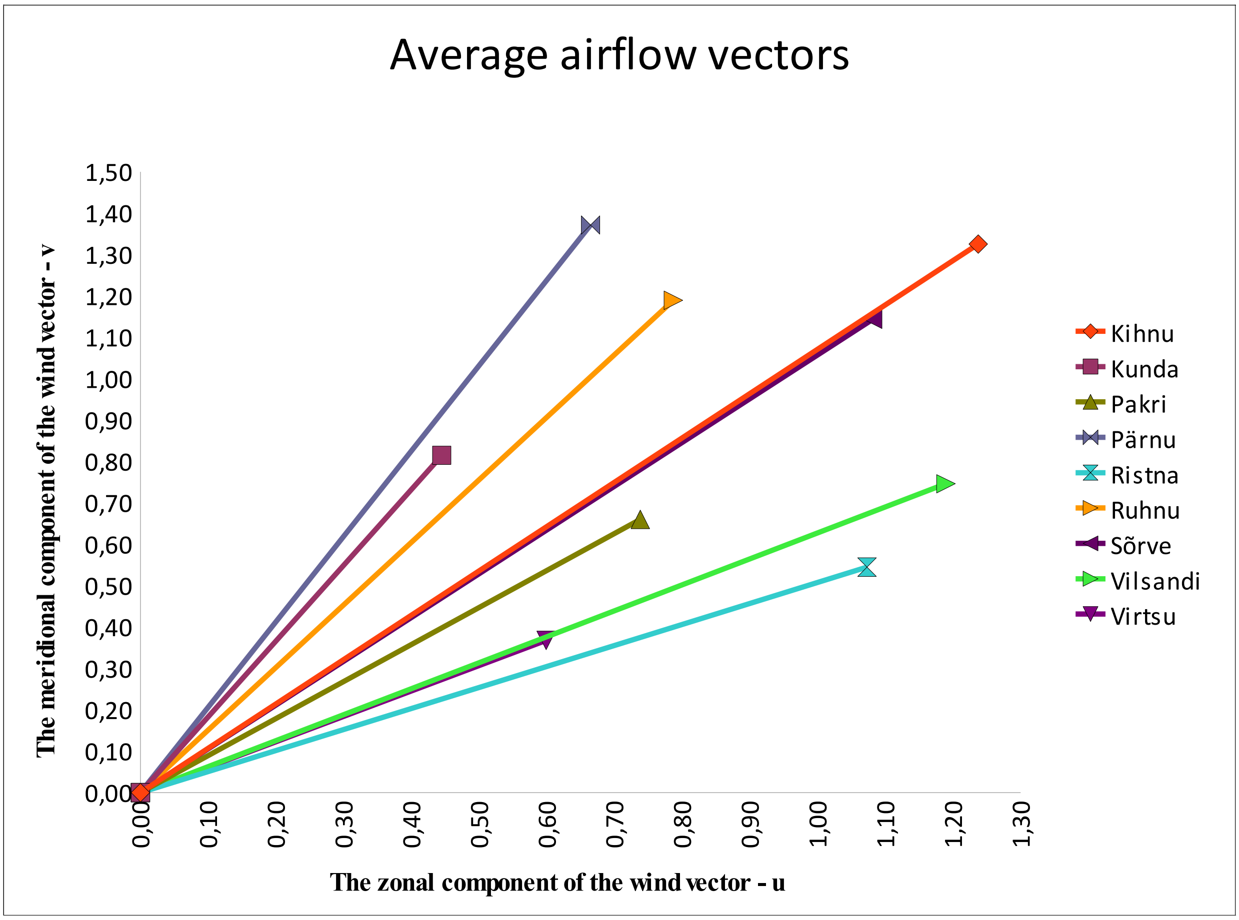

Figure 4.30 Average airflow vectors at nine meteorological stations

The vectors can be grouped by their modula (average airflow speed) and direction. The average airflow speed is large (more than 1,5 m/s) at Kihnu, Pärnu and Sõrve, average at Ristna, Ruhnu and Vilsandi and weak (less than 1,0 m/s) at Kunda, Pakri and Virtsu. Kihnu, Pärnu and Sõrve are situated around the Gulf of Riga and the shape of this water body seems to favour the free airflow. On the other hand, Kunda, Pakri and Virtsu are coastal stations on the continent where orography strongly influences the wind speed. The long-term average airflow vectors can be grouped also by direction. It is directed to the sector of 27°-32° (counted from the East counterclockwise) at Ristna, Vilsandi and Virtsu, to the sector of 42°-47° at Kihnu, Sõrve and Pakri and to the sector of 57°-64° at Ruhnu, Pärnu and Kunda. The comparison of Figures 4.29 and 4.30 reveals that the wind roses indicate partly the direction of the average airflow only at Ristna, Sõrve and Vilsandi. Therefore, the average airflow vector should be calculated to get information on the possible pollution advection from neighbouring areas.

5 CONCLUSIONS

Analysing wind and average airflow speed and direction at nine Estonian coastal stations, it is possible to make some conclusions about the behaviour of the wind speed, direction and average airflow.

The first set of conclusions demonstrates influence of the orography on the average wind and airflow speed. The smallest long-term average wind speed is traced at Pärnu (4,20 m/s), Ristna (4,17 m/s) and Virtsu (4,21 m/s) stations and the largest long-term average wind speed is traced at Kihnu (5,94 m/s), Vilsandi (6,25 m/s) and Sõrve (6,27 m/s). The most probable explanation of this is the openness of the measurement sites. Due to the facts that Pärnu station is situated in the town centre and Ristna and Virtsu stations are surrounded by trees, wind speed at these stations is lower than at Kihnu, Vilsandi and Sõrve stations, which are situated on the open site near the sea. At the same time the elevation of the coastal stations above the sea level does not play such important role like the openness of the place. The wind speed at Sõrve station is the largest, but the elevation of the station is one of the smallest – 3 m above the sea level. At the same time the smallest wind speed is recorded at Ristna station, which elevation is 7 m above the sea level. Long-term average airflow speed is also connected with orography. Long-term average airflow speed is within the boundaries from 0,77 m/s at Virtsu station to 1,88 m/s at Kihnu station. The explanation of this fact is the same as for the wind speed – the openness of the measurement site contributes to the large airflow speed. Like the connection between the wind speed and the elevation of the station, there is no connection between long-term average airflow speed and the measurement site elevation. Long-term average stability factor is within the boundaries from 0,18 at Virtsu station to 0,36 at Pärnu station. It means that approximately only 18%…36% of the average wind speed contributes to the formation of the average airflow. At the same time it can be seen that average stability factor, in contrast to the wind speed and the airflow speed, does not depend on the openness of the measurement site.

The second set of conclusions is connected with average wind speed, average airflow speed and stability factor trends. Both annual and seasonal average wind speed trends are mostly decreasing at all coastal stations, but the strongest decreases took place at Pakri and Pärnu stations. This can be explained by the change of the measurement site, from the open place near the sea these stations were moved inland, where wind speed is lower. At the same time trends in the average airflow speed are mostly negligible or statistically insignificant. It means that the average wind speed is not a good indicator to describe the average airflow speed. Trends in the stability factor are mostly insignificant showing statistically significant increase only at Sõrve and Ruhnu. On the other hand, it must be stressed that the observation period at Ruhnu was much shorter than that at the other stations. Comparison of the variations of the annual average airflow speed and stability factor in different stations shows that the year-to-year changes are correlated. E.g., the stability factor was the lowest in 1976 and 1978 in all stations – less than 22%.

The third conclusion is that the traditional wind roses show the direction of the average airflow only approximately. In the stations under consideration the long-term average airflow direction varies within 18° around NE. It is directed slightly more towards ENE at Ristna, Vilsandi and Virtsu, practically to NE at Kihnu, Sõrve and Pakri and slightly more towards NNE at Ruhnu, Pärnu and Kunda.

The fourth conclusion of this paper is connected with the comparison of the changes in several meteorological parameters. During the studied period the annual average temperature trend is increasing and statistically significant at all stations and the annual average air pressure trend is negligible or decreasing, but insignificant. As it was shown in the second set of conclusions, the wind speed showed mostly decreasing trends. Keeping in mind that there were no trends in the atmospheric pressure, it can be concluded that the decrease in the wind speed was caused by changes in local factors. Statistically significant temperature trend refers to the generally accepted warming in the Baltic Proper region.

SUMMARY

The first aim of the present Master's Thesis was to analyse wind characteristics in Estonia during 1966-2005 and describe the relationships between variations of wind and other climate parameters. The second aim of this paper was analysis of the average airflow during the same time period in order to estimate the possibilities of pollution transfer to Estonia from the neighbouring countries.

The analysis is based on the measurements at nine Estonian coastal stations during the period of 39 years. Wind is described by speed and direction while long-term averages for these parameters are average wind speed and wind rose. Average airflow is calculated by means of the zonal and meridional wind components that after averaging permit one to compose average wind vector. The latter is characterised by modulus or average airflow speed and direction. The stable part of winds blowing in one direction and forming the average airflow can be described by means of the stability factor: the ratio of the average airflow speed to the average wind speed.

The results demonstrate the influence of the orography on the average wind and airflow speed. The smallest values of the long-term averages were measured at these stations, which are not open to the sea and are surrounded by trees or buildings. The elevation of the coastal stations above the sea level has no influence on the long-term average wind speed and airflow speed. On the other hand, average stability factor does not depend on the openness of the measurement site and it shows that only 18%…36% of the long-term average wind speed contributes to the formation of the average airflow.

The wind speed trends are mostly decreasing and the trends of the average airflow are negligible or statistically insignificant. Therefore the average wind speed is not a good indicator to describe the average airflow speed. The comparison of traditional wind roses and average airflow direction shows that wind roses only approximately describe the average airflow direction. This means that for pollution tracking the kowledge of the average airflow vector with its modulus (speed) and direction is essential. The present analysis shows that the long-term average airflow speed is within the boundaries from 0,77 m/s to 1,88 m/s and its direction varies within 18° around NE.

The annual average temperature trend during the same time period was increasing and statistically

significant at all stations that confirms the general knowledge on the climate warming in the Baltic Sea region. The annual average air pressure trend was negligible or decreasing, but statistically insignificant. Keeping in mind that the average wind speed trends are mostly decreasing, it is possible to suppose that the decrease in the wind speed was caused by changes in local factors.

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RESÜMEE

Tuul ja keskmine õhuvool erinevates Eesti rannikujaamades ajavahemikul 1966-2005.

Antud töö koosneb viiest peatükist. Esimeses osas on kirjeldatud üldised mõisted, mis puudutavad tuult: õhumassid, tuule tekkimist ja arenemist mõjutavad jõud, tuule kiirus ning suund, tuule klassifikatsioon. Teises osas on toodud tuule karakteristikud ning nende mõõtmised. Kolmas peatükk on pühendatud antud töös kasutatud andmetele ning nende töötlemisele. Andmete analüüs on kirjeldatud neljandas osas ning tulemused on toodud viiendas osas.

Seoses sellega, et viimasel ajal pööratakse suurt tähelepanu kliima muutumisele, on meteoroloogiliste parameetrite pikaajaliste trendide uuringud väga olulised ja laialt kasutatavad. Kõige suurem tähelepanu on pööratud õhutemperatuuri, sademete hulga, pilvisuse ja lumikate uurimisele. Tuule parameetrite analüüs ei ole nii laialt levinud. Seetõttu oli antud töö esimene eesmärk analüüsida tuule parameetrite muutust ajavahemikul 1966-2005 ja kirjeldada seoseid tuule parameetrite ning teiste kliima näitajate vahel. Töö teine eesmärk seisnes keskmise õhuvoolu analüüsis ajavahemikul 1966-2005 selleks, et hinnata, kui tõenäoline on naaberriikide poolt tuleva õhusaaste mõju Eesti keskkonnale.

Käesoleva töö analüüs põhineb tuule kiiruse ja suuna mõõtmistele, mis olid tehtud üheksas Eesti rannikujaamas 39 aasta jooksul. Tuule kirjeldamiseks oli leitud kuu, sesooni ja aasta keskmine tuule kiirus ning oli koostatud tuuleroos iga jaama jaoks. Keskmise õhuvoolu arvutamiseks ning selle suuna leidmiseks olid kasutatud tsonaalsed ja meridionaalsed tuule komponendid. Keskmise õhuvoolu kirjeldamiseks kasutati keskmise õhuvoolu absoluutväärtust ja suunda. Selleks, et hinnata, kui suure osa moodustavad ühes suunas puhuvad tuuled keskmise õhuvoolu kujunemises, arvutati stabilsusfaktor, mis on keskmise õhuvoolu kiiruse ja keskmise tuule kiiruse suhe.

Käesoleva töö käigus olid tehtud mõned tähtsad järeldused. Kõigepealt on vaja öelda, et mõõtmiskoha orograafia mõjub tugevasti tuule kiirusele ja keskmisele õhuvoolule. Kõige väiksemad näitajad olid seal, kus mõõtmiskoht on ümbritsetud puude või ehitistega. Samal ajal mõõtmisväljaku kõrgus merepinnast ei mõju tuule kiirusele ega keskmisele õhuvoolule.

Stabiilsusfaktor ei sõltu koha orograafiast ega kõrgusest, vaid näitab, et ainult 18%...36% tuule kiirusest võtab osa keskmise õhuvoolu kujundamisest.

Teine antud töö tulemus seisneb selles, et kuna tuule kiiruse trendid on enamasti negatiivsed, aga keskmise õhuvoolu trendid on praktiliselt olematud või statistiliselt ebaolulised, siis tuule kiirus ei ole hea indikaator keskmise õhuvoolu hindamiseks. Sama järeldus oli tehtud tuuleroosi ja keskmise õhuvoolu suuna jaoks.

Õhutemperatuuri trendid on positiivsed ja statistiliselt olulised kõigis vaadeldud jaamades, mis kinnitab üldtuntud tõsiasja, et Läänemere regioonis toimub kliima soojenemine. Uudseks tulemuseks on enamasti langevad tuule kiiruse trendid. Samal ajal olematud või statistiliselt ebaolulised õhurõhu trendid näitavad seda, et tuule kiiruse langemise põhjuseks ei ole muutused suuremõõtmelises tsirkulatsioonis.

Käesoleva töö tulemused näitavad, et kliimamuutuste hindamiseks peavad olema arvesse võetud mitte ainult õhu temperatuur, pilvisus, sademete hulk ja lumikate, vaid ka tuule parameetrid. Teiselt poolt antud töö tõendab mõõtmiskoha olulisust tuule parameetrite mõõtmisel. Lisaks kõigele väivad töö tulemused olla kasulikud Eesti keskkonna seisundi hindamisel.

APPENDICES

Appendix 1.

Wind in world mythology

In the ancient word every civilization had its own description of different nature phenomenon. People believed in many gods and have explained every event of their life by gods' happiness, sadness, anger or wish. Every civilization had the god of the Life or the god of the Sun, the god of the Death and Underworld, the god of the Sea, Earth, Medicine and another things, which is possible to meet in everyday life and nature. It has been natural for civilizations to have one or even more gods of the Wind.

There were a lot of the Wind gods in *the Greek mythology*:

- Boreas was the god of the North Wind and of Winter;
- Eurus was the god of the East Wind;
- Notus was the god of the South Wind;
- Zephyrus was the god of the West Wind;
- Caicias was the god of the North-East Wind;
- Skeiron was the god of the North-West Wind;
- Euronotus was the god of the South-East Wind;
- Lips was the god of the South-West Wind.

In *the Egyptian mythology* Amun was the god of Creation and the Wind and Shu was the god of the Wind and Air.

The Aztec civilization, like the Greeks, had more than two gods of the Wind:

- Ehecatl was the main god of Winds;
- Cihuatecayotl was the god of the West Wind;
- Tlalocayotl was the god of the East Wind;
- Vitztlampaehecatl was the god of the South Wind;
- Mictlanpachecatl was the god of the North Wind;
- Ehecatotontli were the gods of the Breezes.

In *the Japanese Shinto*[1] *religion* the god of Wind was called Fujin. Enlil was *the Mesopotamian / Sumerian* god of the Air, Wind, Breadth. In *the Norse mythology* Njord was the god of Wind. There were also four dwarves of Wind: Norðri, Suðri, Austri and Vestri – and four stags, which personified four winds. Pazuzu was the demon of the South-West Wind and son of the god Hanbi in *the Assyrian and the Babylonian mythology.* Stribog was *the Slavic god* of Winds, Sky and Air. He was also the grandfather of the winds of eight directions. Vate was the god of the Air and Wind in *the Iranian mythology*, he could make a cloud for a useful rain or for a destroyer flood. *The ancient Romans* called the main god of Winds Venti.

The Greek mythology

The first gods of Winds appeared between the natural gods and goddess already in the Mycenaean Greece. The Priestess of Winds was named on the Tablet from Mycenaean Knossos, which was written in Linear Script B. [16] Linear Script B is the oldest surviving record of the Greek dialect, which is known as Mycenaean dialect. The scientists think, that Greeks used this script in time period between approximately 1500 BCE and 1200 BCE. [17] This historical evidence, like mention about the gods of Winds in the Knossos palace can convince us, that the cult of winds was very important for ancient Greeks and that the deities of Winds existed in ancient Greece.

Hesiodos, one of the earliest Greek poets, who is often called the "father of Greek didactic poetry", is the author of nowadays existed epic "Theogony", which describes about the Greek myths of the gods [18]. He has mentioned only three of Wind gods. Hesiodos wrote about Boreas (the god of the North Wind), Zephyrus (the god of the West Wind) and Notus (the god of the South Wind). The interesting fact is that by Hesiodos Wind gods had surname – Argestus, which is possible to translate as "brightness". But also is necessary to add that the Greeks had the fourth Wind god, the god of the East Wind – Eurus. The Greeks worshipped to these four Wind gods, which composed the Anemoi (main Wind gods group). [16]

1 Shinto - "the way of the gods"; basic religion in Japan which celebrates life [15].

Figure 1.1 Boreas – the god of the North Wind in the Greek mythology [19]

The Greeks described Boreas (see Figure 1.1) as the purple-winged or amber-winged, extremely strong, with a beard god of the North Wind, who normally was clad in a short pleated tunic [19, 20]. He was the son of the goddess of the Dawn – Eos – and the Titan – Astraeus [21]. In Hesiodos "Theogony" is possible to find lines about Boreas birth:

Eos bore to Astraios the strong spirited winds and
the cleanser Zephyr and swiftly speeding Boreas, and
Notos, a goddess bedded with a god in philotes [22].

Boreas lived in Thrace[2] – a fertile and northern region of Greece, beside the river Strymon or in a caves on Mount Haemus. Boreas was the strongest and speediest of all winds. He brought snow and hail, he was called the bringer of winter, but, at the same time, he could prove to be nice and calm and help sailors by providing them with a friendly breeze. [24] Boreas moved the clouds, return the clear weather and froze the water [25].

When in 480 BC (the middle time of the war between Persia and Athens) the fleet of the Persian King Xerxes threatened the city of Athens, the oracle told the Athenians ask Boreas to help them and destroy the Persian fleet. Strong and angry Boreas blew at the Persians and 400 Persian ships sank immediately. [16] The proof of the north wind's participation in the battle between the Persians and the Athenians is possible to find in the historical description of this battle. From the history is known, that the Athenians won because of the good geographical place of the battle, the Greek military commander tricks, knowledges and useful for the Greeks weather conditions.

2 Thrace - ancient and modern region of the south-eastern Balkans [23].

Figure 1.2 Zephyrus – the god of the West Wind in the Greek mythology [19]

The Greeks described Zephyrus (see Figure 1.2) as gentle, handsome, young man with a lovely face and long grooved hair, who normally was clad in a light wrapper. Zephyrus was very fine and pleasant wind, which blew from the West and brought spring and humidity. In this case the ancient Greeks called him the protector of the plants [16].

He was the son of the goddess Eos and the Titan Astraeus and the brother of Boreas. In Hesiodos "Theogony" Zephyrus birth is described in the same lines as Boreas birth. Zephyrus lived in the caves of Thrace. The god of the West Wind also was the father of the immortal horses Xanthus and Balius, who were the Trojan War hero Achilles immortal horses. [19]

The most famous and sad myth described, Zephyrus love to the young man Hyacinthus. Not only Zephyrus loved Hyacinthus, the god of Light – Apollo – was in love in Hyacinthus too. Once Zephyrus saw, how Apollo was teaching Hyacinthus, how to throw the discus. Jealous Zephyrus was enraged, he caught Hyacintus in mid-air, beat him on the head and killed. From Hyacintus blood sprang the hyacinth flower. [19]

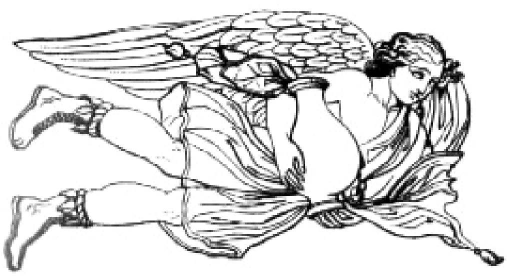

Figure 1.3 Notus – the god of the South Wind in the Greek mythology [19]

The Greeks described Notus (see Figure 1.3) as winged, handsome, young, beardless man with a lovely face and long grooved hair, who normally was clad in a short mantle with one open arm. He kept a vessel in his hands, from which the god took rains and sprinkled dew in early morning. [16] Notus was warm, wet and refreshing wind, which blew from the South in late summer and early autumn and brought storms, fogs, mists and rain-clouds. This wind was very dangerous to shepherds on the mountaintops and to mariners at sea, because he limited visibility. That is why people have feared Notus.[19]

Notus was the son of the goddess Eos and the Titan Astraeus and the brother of Boreas and Zephyrus. In Hesiodos "Theogony" Notus birth is described in the same lines as Boreas and Zephyrus birth. Notus lived in the caves of Aithiopia[3] [26].

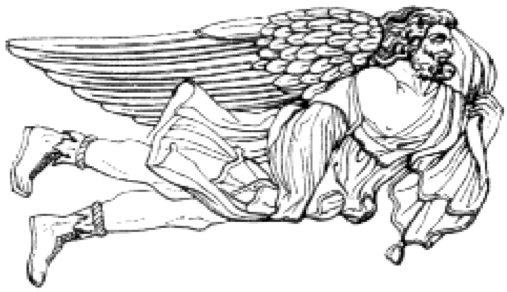

Figure 1.4 Eurus – the god of the East Wind in the Greek mythology [19]

The last of the main gods of the Winds is Eurus, the god if the East Wind (see Figure 1.4). The Greeks described Eurus as winged, handsome, man with long bread and long grooved hair, with some sadness on his face. This god normally was clad in a short mantle. Eurus was strong wind, which blew from the East and brought warmth and rains in autumn.

Eurus was the son of the goddess Eos and the Titan Astraeus and the brother of Boreas, Notus and Zephyrus. He lived near the palace of the god of the Sun – Helios.

During ancient time mythology was developed, divine family of Winds gods grew. There were eight members. Besides Boreas, Zephyrus, Eurus and Notus there were Caicias (the god of the North-East Wind), Skeiron (the god of the North-West Wind), Euronotus (the god of the South-East Wind) and Lips (the god of the South-West Wind).

3 Aithiopia – the Greek name for Nubia.

The Egyptian mythology

The Egyptians did not have a lot of Wind gods like the Greeks. The Egyptians did not have a big fleet like the Greeks, which depended on wind and its direction. And the sailing and fishing was not the main method of the food producing, like it was in Greece. But because of geographical location the Egyptians life depended on the moisture, rains / rainclouds and therefore on wind that brought these clouds. In this case the Egyptians had only one god of the Wind, but he was very important for them.

The god of Creation / the Sun – Amun – had a lot of others names: Amen, Amun, Ammon, Amoun, Amun Ra. He was one of the most important gods in the ancient Egypt. The Egyptians worshipped to him and believed, that he was the God of Kings and the King of Gods [27]. Amun was the creator of all things even self-creator. He could assume any another form. That is why he could assume the form of the Wind deity too. But the function of the Wind god was not foreground for him.

Figure 1.5 Shu – the god of Air and Wind in the Egyptian mythology [28]

The most close to wind was the god of the Air – Shu (see Figure 1.5). Shu was also considered as the god of the Atmosphere and the god of Wind. He was the son of Amun Ra, husband of Tefnut – the goddess of the Moisture, the father of Nut – the goddess of the Sky – and of Geb – the god of the Earth.

Shu was the second divine ruler after Amun Ra. The Egyptians believed, that before life creation the sky and the earth were not separated. The myth told, that at the start of world creation the goddess of the Sky – Nut – and the god of the Earth – Geb – very loved each other, they were always together and finally Nut became the wife of Geb. Every night Nut bore stars and every morning she ate them. Geb was very angry that his wife ate their children. Amun Ra did not like, that Nut and

Geb quarrelled and ordered Shu to separate them. From that time the sky and the earth are separated by the atmosphere. Shu was holding Nut on his hands and sometimes Tefnut helped her husband, but when she was tired, she started to cry. In that time in Egypt was rain. [29]
When Shu separated the sky and the earth, he created the area for the life of all things, which was around the Egyptians. Shu also brought good wind from the north and helped sailors. In this case the Egyptians worshipped to Shu.

Usually Shu was shown as a man in headdress with feathers and with sceptre in his hand. Another existed images show us a man, who raises hands up, holds his daughter Nut on the hands and stands over his son Geb. [30]

The Slavic mythology

The geographic location of the place, where lived ancient Slavs, was not very suitable and good for living. The weather characteristics were very hard, especially in winter time. Strong winds, heavy rains and snowfalls made the Slavs life harder then it was in ancient Greece or Egypt. The Slavs have understood the winds power and impact on their life, work and food producing, that is why they very strongly glorified the Winds divine family. The Slavs had a lot of different Winds gods. Their description, importance and functions depended on the time, when they blew, on the side, from where they blew, on the power and the weather conditions, which they brought.

Figure 1.6 Stribog – the god of the Wind in the Slavic mythology [31]

The main god of the Wind was Stribog (see Figure 1.6). From the god name is possible to understand, how important he was both for people and another winds gods. The word “strega” in Russian means “big” or “senior”, and the word “bog” means “god”.

Stribog was the grandfather of another Winds gods. All this divine family lived in the middle of the Earth, in the Okiyan-Sea, on the amazing island Buyan, in the castle from white stone. When all divine brothers, sons and parents started to talk, the strong howl was on the island. [32]

Stribog was the strongest and speediest wind, he could help the people by sending or stopping some of his children or grandchildren such as Whistling (the god of the Storm), Podaga (the god of Hot and Dry Wind from the South), Siverko (the god of Cold Wind form the North).[21]

Usually Stribog was shown as an old man with long grey hair and long grey beard. Sometimes he was shown with magic bird Stratim, which sat on the god shoulder. [31]

Stribog was the protector of the Spring goddess – Vesna. Every year he brought spring on the wings of spring breeze. In this way Vesna and Sviborg brought spring's warmth and better living conditions for the Slavs. [33]

There were a lot of Sviborg idols on the coasts of Dnepr river, especially near Kiev city [31]. Day, when the Slavs celebrated and worshipped Stribog, was August 21 [34].

Appendix 2.

Wind speed table for Conversion of Knots, Beaufort, m/s and km/h [38]

Knots	Beaufort	m/s	km/h	mph	Label	Effect on sea	Effects on land
< 1	0	0 - 0.2	<1	<1	Calm	Sea like a mirror.	Calm. Smoke rises vertically.
1-3	1	0.3-1.5	1-5	1-3	Light Air	Ripples with the appearance of scales are formed, but without foam crests.	Wind motion visible in smoke.
4-6	2	1.6-3.3	6-11	4-7	Light Breeze	Small wavelets, still short, but more pronounced. Crests have a glassy appearance and do not break.	Wind felt on exposed skin. Leaves rustle.
7-10	3	3.4-5.4	12-19	8-12	Gentle Breeze	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	Leaves and smaller twigs in constant motion.
1.11.1 5	4	5.5-7.9	20-28	13-17	Moderate Breeze	Small waves, becoming larger; fairly frequent white horses .	Dust and loose paper raised. Small branches begin to move.
16-21	5	8.0-10.7	29-	18-24	Fresh Breeze	Moderate waves, taking a more pronounced long form; many white horses are formed. Chance of some spray.	Branches of a moderate size move. Small trees begin to sway.
22-27	6	10.8-13.8	39-49	25-30	Strong breeze	Large waves begin to form; the white foam crests are more extensive everywhere. Probably some spray.	Large branches in motion. Whistling heard in overhead wires. Umbrella use becomes difficult. Empty plastic garbage cans tip over.
28-33	7	13.9-17.1	50-61	31-	High wind, near gale	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.	Whole trees in motion. Effort needed to walk against the wind. Swaying of skyscrapers may be felt, especially by

							people on upper floors.
34-40	8	17.2-20.7	62-74	39-46	Gale	Moderately high waves of greater length; edges of crests begin to break into spindrift. The foam is blown in well-marked streaks along the direction of the wind.	Twigs broken from trees. Cars veer on road.
41-47	9	20.8-24.4	75-88	47-54	Severe Gale	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility.	Larger branches break off trees, and some small trees blow over. Construction/temporary signs and barricades blow over.
48-55	10	24.5-28.4	89-102	55-63	Storm	Very high waves with long over-hanging crests. The resulting foam, in great patches, is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes on a white appearance. The 'tumbling' of the sea becomes heavy and shock-like. Visibility affected.	Trees are broken off or uprooted, saplings bent and deformed, poorly attached asphalt shingles and shingles in poor condition peel off roofs.
56-63	11	28.5-32.6	103-117	64-73	Violent Storm	Exceptionally high waves (small and medium-size ships might disappear behind the waves). The sea is completely covered with long white patches of foam flying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	Widespread vegetation damage. More damage to most roofing surfaces, asphalt tiles that have curled up and/or fractured due to age may break away completely.

64-71	12	>32.7	>118	>74	Hurricane	The air is filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	Considerable and widespread damage to vegetation, a few windows broken, structural damage to mobile homes and poorly constructed sheds and barns. Debris may be hurled about.

Appendix 3.

Wind directions [38]

Abbreviation	Wind direction	Degrees
N	North	0
NNE	North-northeast	22,5
NE	North-East	45
ENE	East-northeast	67,5
E	East	90
ESE	East-southeast	112,5
SE	South-East	135
SSE	South-southeast	157,5
S	South	180
SSW	South-southwest	202,5
SW	South-West	225
WSW	West-southwest	247,5
W	West	270
WNW	West-northwest	292,5
NW	North-West	315
NNW	North-northwest	337,5