Video monitoring of meso-scale aeolian activity on a narrow beach

P.M. Hage

3471799

Supervisor: prof. dr. B.G. Ruessink

MSc Earth Surface and Water

Faculty of Geosciences

Utrecht University

September 2013 - April 2014

Universiteit Utrecht

Summary

Dune erosion takes place during high storm surges, which is a process that takes place on a short time scale (hours to days). They can recover from these storm events, but this process takes much longer (months to years). Dunes need sediment to grow back and recover which comes from the beach and is transported towards the dunes by the wind. It is therefore important to understand the process of aeolian transport. High aeolian transport rates and strong dune growth are expected to happen with high wind velocities with a wind direction that is orthogonal to the dune row, but this is not always the case for narrow beaches (with a width of a few tens of meters). Weather conditions that seem quite favourable for aeolian transport do not always result in actual transport on those kinds of beaches, so there is something that limits the aeolian transport rate. This MSc research focuses on aeolian transport on a narrow beach at Egmond aan Zee, the Netherlands, to figure out what limits aeolian transport here and what kind of conditions are needed to create aeolian transport towards the dunes. Data from the KNMI was used to calculate potential transport rates for this beach. This data was later compared to Argus images from the Coast3D tower, which monitors the coastline with 5 cameras since 1995. Two of these cameras have a good view on the beach, which are used to search for traces of aeolian transport in the form of sand strips or streamers. These images are visually classified based on these traces to indicate how strong the actual aeolian transport rate is. An event has a limited transport if it has a high potential transport rate, but a much lower transport rate in reality. It turned out that the other way was also possible: events that have a low potential transport rate can still cause a strong aeolian transport. The width of the beach and the wind direction play a very important role in this; every wind that is strong enough to transport sediment can cause a high aeolian transport rate on a narrow beach, as long as the wind direction comes from an alongshore direction. All events that produce strong aeolian transport on the Argus images have a wind direction like this. However, this is not favourable for dune growth, because only a small part of this transported sediment ends up in the dunes. A lower wind velocity with a south-westerly wind direction will probably contribute the most to aeolian transport towards the dunes. High wind velocities are rare and occur often during storms. It is not uncommon that the dunes erode, due to the storm surge. This happens often here, which is quite a good wind direction for dune growth because quite a large part of the transported sediment still ends up in the dunes. Other limiting factors are moisture, the location of the bar and snow/ice, but they seem to be more important for events with a low wind velocity. The location of the bar, with a moist area between the bar and the beach, seems to be a larger problem for winds that have a seaward direction. These wind directions cause aeolian transport close to the shoreline, while the other wind directions cause transport close to the dunes. This area of transport can spread out along the entire beach width if the wind is strong enough for it.

Contents

List of figures

List of tables

1. Introduction

Processes involving dune growth or destruction happen on various time scales. Dunes are usually damaged during storms; short, but severe events where water levels are so high that the water can reach the dunes and cause erosion. The time it takes for dunes to recover from events like this is much longer. It can take months to years until a dune grows back to its original strength. The sand needed for dune recovery comes from the beach and is transported towards the dune foot by the wind. Not every wind velocity is strong enough to transport sand grains; it has to surpass a certain threshold velocity to bring a sand particle in motion. A lot of research is done about aeolian transport, which shows that the highest amount of aeolian sediment transport is reached during the strongest winds that blow over a large area of sand. The aeolian transport is assumed to be transport limited and to be in equilibrium with the wind conditions under those circumstances. There is one remark on this; this research was usually done in desert areas, which is a very different area than coastal environments; there is a large area is covered with sand, no sea and the weather is different. Aeolian transport rates are therefore different on beaches than in deserts. This is especially the case when the beach is narrow (a few tens of meters). Narrow beaches tend to be supply limited, which means that they will not always show large aeolian transport even if wind conditions are good. This is not good for dune growth. Narrow beaches also tend to be a weak spot when it comes to flood protection, so it must be understood which wind conditions are good for aeolian transport on narrow beaches in reality. The first aim of this research is to figure out what these weather conditions are. Even if this is figured out, it is still not known what is causing the difference between the predicted and the actual aeolian transport. These limiting factors form the second subject of this research; the aim here is to determine what limiting factors are most important and under what circumstances they usually occur.

1.1 General approach

This research needs two types of data; predicted and actual aeolian transport rates of a narrow, sandy beach. The site that will be studied for this research is Egmond aan Zee in the Netherlands. The Egmond beach is quite narrow (30 to 100 m), which makes it fit for this research. A large set of data is available from this site as well, which will be used to investigate the amount of actual aeolian transport. The predicted aeolian transport rate will not be determined with data from this site; it will be calculated with data from a weather station that is located 40 km away from there.

The first step is to find out when significant aeolian transport was possible. These moments are called ‘wind events’ and they can be determined with weather data. The wind events are divided into a number of classes according to their potential aeolian transport rate. This was done to make the next step easier: comparing the wind events with actual data from the Egmond site. This data consists of images from the beach, which can show traces of aeolian transport. These images are also classified according to their aeolian transport rate, but this time it is based on how strong the transport rate appears on the images. The classified wind and transport events are compared to each other. This gives an indication when aeolian transport was limited, which is the case when a high aeolian transport rate was predicted, but did not result in actual high transport rates. The wind event class is higher than the transport class. These situations are studied further to figure out what kind of factors that limit aeolian transport play a role here.

This thesis starts with some basics about aeolian transport and used equations in chapter 1, ‘Aeolian transport basics’. It is followed by the chapter ‘Description of site and used data’. This chapter gives information about the Egmond site and the weather and image data. Chapter 4 shows the characteristics of the wind derived from this weather data. The wind events derived in chapter 4 and the images are classified in chapter 5. Chapter 6 compares the wind and transport events to find out what the limiting factors are. This thesis ends with a discussion and a conclusion.

2. Aeolian transport basics

Aeolian sediment transport involves the entrainment, transport and deposition of sediment by wind. Particle motion was classified in three categories by Bagnold (1941): creep, saltation and suspension, which can be seen in figure 2.1. Sediment that rolls over the surface without losing contact to it is called creep. These particles are relatively large and have a size often larger than 500 µm, which means that they are too heavy for the wind to pick up. Saltation involves particles that are transported through the air for a short distance and bounce over the surface. The particles create an impact when they hit the ground which can push other particles in the air. This mode of transport is mostly responsible for the birth and growth of aeolian bedforms. Most of the sediment (up to 95%) is transported this way and they have a size of 70 to 500 µm. There is a smooth transition between saltation and suspension, which is the mode where sediment travels through the air over relatively long distances. This happens for very fine sediment. Long term suspension can last for several days, which involves particles with a size of 20 µm and smaller, which is often called dust. Short term suspension lasts for a few minutes to hours and particles here have a size of about 20 to 70 µm (Nickling and McKenna-Neuman, 2009).

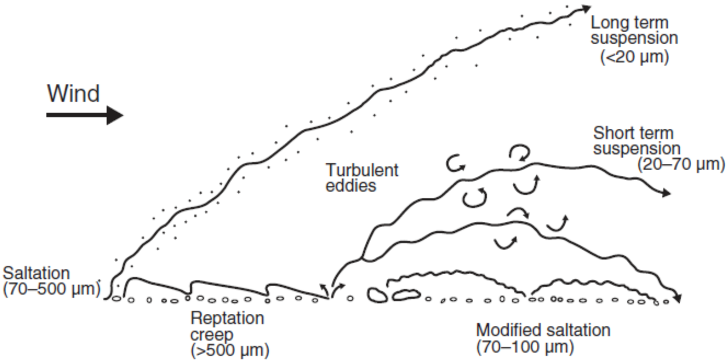


Figure 2.1: Different modes of aeolian transport. Source: Nickling and McKenna-Neuman (2009).

2.1 Entrainment of sediment

The wind speed is the driving force of aeolian sediment transport. It needs to be higher than a certain threshold velocity to entrain the grains into the air and to transport them on the beach. A stronger wind can move more sediment, but also larger grains. A sediment grain will be picked up from the surface when the force exerted by the wind is larger than the gravitational force and cohesion effects of the particle. The air flows around and over the sediment particle creating drag and lift forces and the resultant moment. The lift force is created by the decreased static pressure at the top of the grain and by the steep velocity gradient near the surface of the grain. A schematic drawing about this can be found in figure 2.2. There is a critical value for the shear velocity u_* when grain movement starts; this is the threshold shear velocity u_{*t}. It can be calculated by the following equation (Nickling and McKenna-Neuman, 2009);

$$u_{*t} = A(\left(\frac{\rho_p-\rho}{\rho}\right)gd)^{1/2} \tag{1}$$

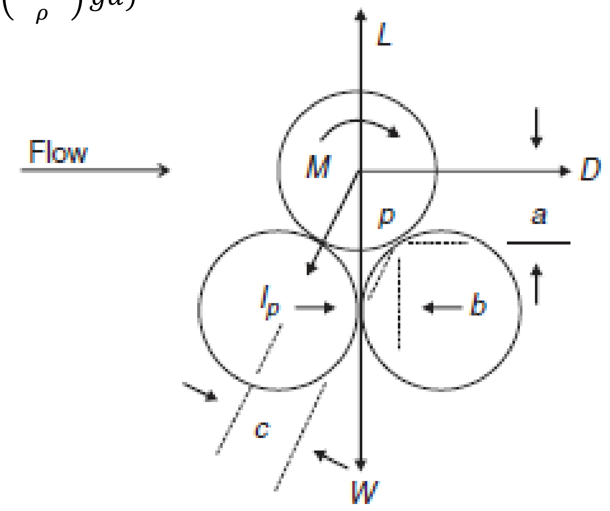


Figure 2.2: A schematic drawing of the forces acting on particles. L is the lift force, M is the moment, D is the aerodynamic drag, Ip is the interparticle force and W is the weight. a, b and c are moment arms about the point p. Source: Nickling and McKenna (2009).

A is an empirical coefficient (~0.1 for a rough particle, so the particle friction Reynold number Re_p is larger than 3.5), ρ_p is the density of the sediment (~2650 kg/m^3), ρ is the air density (~1.225 kg/m^3 at sea level at 15 ^{o}C), g is the gravitational acceleration (~9,81 m/s^2) and d is the grain size (~2.5*10^{-4} m for the Dutch coast) (Nickling and McKenna-Neuman, 2009; Sherman and Bauer, 1993). A typical value for u_{*t} for the Netherlands is around 0.2 m/s. The shear stress can be derived from:

$$u_* = (u - u_t) * \kappa \,/ln(z/z_0) \tag{2}$$

Where u_t is the threshold velocity (m/s, see the discussion for more information), κ the von Karman constant (0.4), z the height at which the wind velocity is measured (m), z_0 aerodynamic roughness length (m).

The shear velocity and threshold shear velocity are calculated with the mean wind velocity for every hour of data. This can become a potential transport moment: a moment in the data of 1 hour where the wind velocity exceeds its threshold value, so the shear velocity is larger than the threshold shear velocity.

The velocity and momentum of the grains increase when they fall back to the surface. They can bounce off the surface or bring other particles in the air as a result of their impact on the ground. Momentum is transferred to the surface by disturbing stationary grains. This means that grains that were hit after the impact of another grain will eject into the air at lower shear velocities than required to move a grain that is stationary. The movement of particles due to the impact of another particle is known as splash (Nickling and McKenna-Neuman, 2009; Iversen and Rasmussen, 1999). The aeolian transport increases from zero to a certain maximum upwind due to these impacts between grains. This is known as the fetch effect. It occurs when the wind is blows over an area with no transport (the sea) to a zone with transport (the beach). Sediment transport increases when the wind blows over a large stretch of sand. However, at a certain distance the maximum sediment transport capacity will be reached and the aeolian sediment transport rate will be constant as it is in equilibrium with the wind forcing. This distance is called the critical fetch distance. If the critical fetch

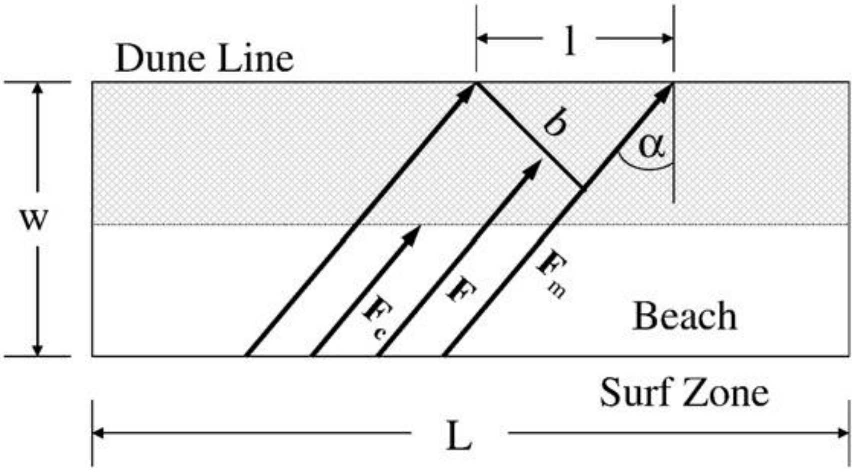


Figure 2.3: A schematic view of a beach with the maximum fetch length F_m, the critical fetch length F_c and the actual fetch length F. α is the angle of the wind, W is the width of the beach and L the length of the beach. The sand is transported in the direction of the arrows. The grey area indicates the zone where the maximum aeolian transport rate is reached. l is the stretch of land where the sediment ends up if it is blown towards the dune line. This sand was first transported under a nominal width of beach, here indicated with b. Source: Bauer and Davidson-Arnott, 2002.

distance is reached depends on the maximum available fetch distance. The maximum fetch distance depends on e.g. the wind direction and the width of the beach, which can be seen in figure 2.3.

If and how a particle is going to lift off due to this impact depends on the velocity and the angle of the impacting particle. An impacting particle usually has an angle between 10° and 15°, which is quite constant and low compared to the rebounding particles which have an angle between 23° and 40°. These angles can be much larger when the particles collide in mid-air. A transport regime is known as a steady-state or successive when the energy lost during impact is small, which results in almost continuing rebounds of the sediment downwind. The opposite happens during low wind velocities, when the particles are only move for a few millimetres and do bring other particles into saltation (Nickling and McKenna-Neuman, 2009).

The grain size influences the threshold wind velocity. A large, heavy particle is more difficult to move for the wind than small ones. Very small particles are also hard to move, because they are kept together by interparticle forces. Not only grain size matters for aeolian transport, the shape and density of the sediment grain also have an impact on the threshold of motion. Grains with large densities are more difficult to pick up for the wind. A large sphericity of a grain will bring more particles into the air when it hits the surface, but a grain that has a lower sphericity has a lower threshold of movement (Rice, 1991).

2.2 Transport rate

The potential sediment transport can be calculated by using the following equation (adapted from Hsu, 1974):

$$Q = 1.16 * 10^{-5} * u^3 * 3600 \qquad (3)$$

Where Q is the transport rate (kg/m/hour) and u is the wind velocity (m/s). There are more equations which can be used to calculate the potential transport rate from the wind velocity (Sherman and Li, 2012), but this one is often used for its simplicity.

The highest potential transport rate will be reached under the highest wind velocities. The wind direction determines how much of this transported sediment ends up in the dunes. Only a small amount of sediment ends up there when the wind is blowing almost alongshore, but cross-shore winds favour transport towards the dunes. This is known as the cosine effect. This amount is the highest with westerly winds, as long as the fetch length is long enough as well. The equation by Hsu looks like this if the transport rate towards the dunes (Q_d) is calculated;

$$Q_d = Q * \cos a \tag{4}$$

Where α is the wind direction. The cross-shore direction is 0^{O}. These potential transport rates are only reached on an actual beach if the critical fetch distance can be reached. The direction of the wind and the width of the beach are both factors that have an effect on the fetch length. If the wind is blowing in the cross-shore direction, the maximum fetch length will be the shortest, but a long maximum fetch is achieved when the wind is blowing in the alongshore direction (Ruz and Meur-Ferec, 2004). The values of critical fetch can range from 10 to 40 m (Davidson-Arnott and Law, 1990) up to over 200 m, but sometimes no significant fetch effects are measured at all (Lynch et al., 2008).

The critical fetch is highly variable and depends on wind velocity, the amount of lag deposits present on the beach and moisture content (De Vries et al., 2012). The fetch distance is long under parallel winds and high transport rates are reached (Arens, 1996; Ruz and Meur-Ferec, 2004). However, transport is mainly limited to the bare upper beach and there is low accumulation on the foredunes (Bauer and Davidson-Arnott, 2002; Ruz and Meur-Ferec, 2004).

There are other factors that can prevent the actual transport rate from reaching the potential transport rate. One transport limiting factor can be agents that cause the particles to stick together. The threshold of motion becomes higher, so stronger winds are required to pick up sand and transport them. Bonding agents can be moisture, the presence of clay and silt, precipitated salt and organic matter (Nickling and McKenna-Neuman, 2009). Something that is related to moisture is the beach profile. Ground water makes the beach moister if it has a low elevation. The low-lying area between the bar and beach remains quite moist due to this and can form a barrier for sand transport (Houser, 2009), even during low tide. The airflow can be disrupted by objects on the beach and lower the transport rate as well (Nickling and McKenna-Neuman, 2009). A literature study during the course preparation MSc Research (GEO4-4407) done in advance of this research showed that the most important limiting factors are probably an high moisture content, short fetch lengths and the location of the sand bars. These factors might play only an important role during certain weather conditions. It is best for dune recovery that these factors are not present and that aeolian transport to the dunes is optimal. It is not known what kind of condition is needed for the recovery of dunes, which leads to the first main question:

1: Which events determine meso-scale (years) sand transport to the dunes?

The first main question will not explain why there is less transport than predicted during moments with strong winds. Therefore, a second main question was needed:

2: What are the most important limiting factors for a narrow beach?

3. Description of site and used data

3.1 Study site

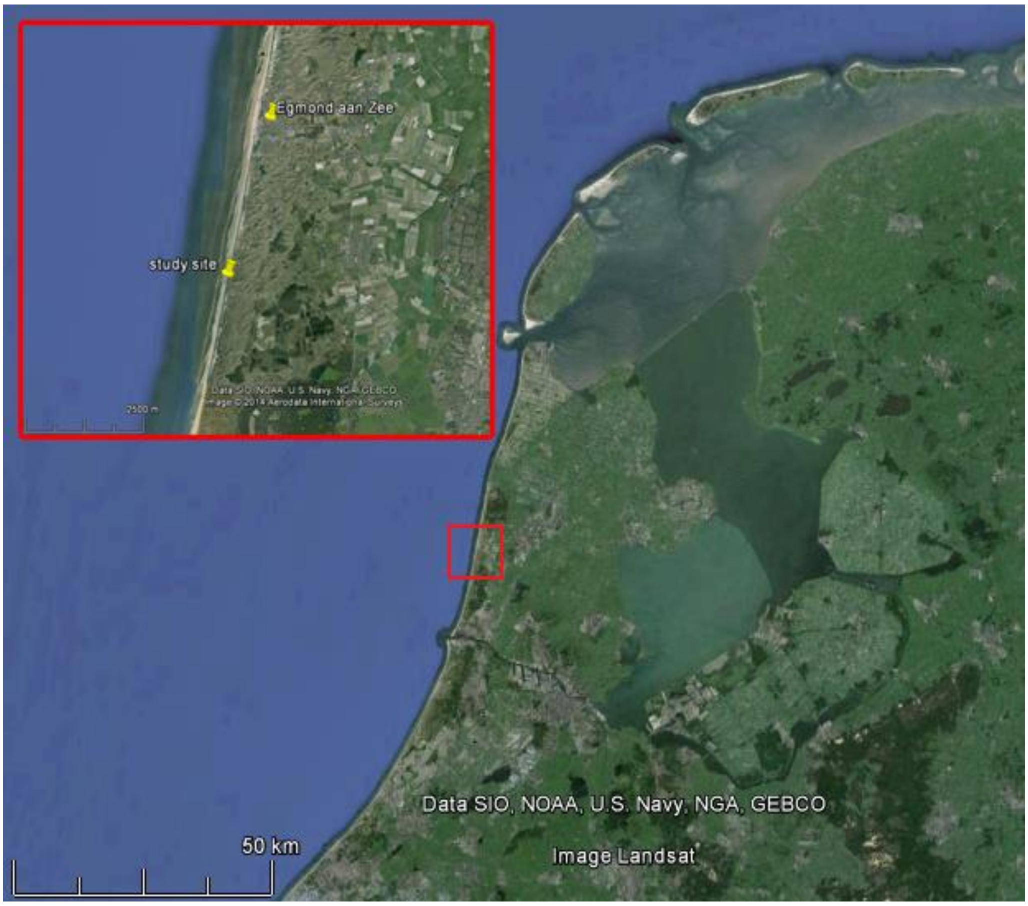


Figure 3.1: The location of the study site, close to Egmond aan Zee, the Netherlands.

The beach studied here lies south of Egmond aan Zee, which is located in the central part of the Dutch coast (see figure 3.1). This coast is uniform and has an almost continuous row of dunes that protect a large part of the Netherlands from flooding. The dunes have an height between 15 and 20 m (AHN) and are covered with marram grass to prevent erosion. The beach itself is quite narrow and has a varying width between 30 and 100 m. The beach has a median grain size of approximately 240 µm (VTV). This coast is characterized by a semidiurnal micro-tide and is wave dominated. There are 1 or 2 slipface intertidal bars present as well at this location.

Factors that probably have a large effect on the aeolian transport rate at Egmond are i.a. the fetch length. The chances of reaching the critical fetch distance are small when the beach is narrow, because that reduces the maximum fetch length (Bauer et al., 2009). This is often the case for the Egmond site, which is characterized by a narrow beach. The critical fetch length will only be reached when the wind comes in under a very oblique angle. This makes the fetch length an important factor. The fetch length is affected by the water level as well. The water levels at the Egmond beach are often higher in winter than summer due to the more stormy weather. This will not only affect beach width, but also moisture content of the sand.

The beach at Egmond has a moderate gradient (approximately 1:30) and does not vary much through the year. However, the elevation of the beach profile itself does change, which influences aeolian transport. The elevation of the intertidal banks have a different moisture content that varies with the elevation of the banks, which can create different amounts of aeolian transport for a situation with otherwise equal width, weather conditions, etc. Water can still be standing in the low areas between intertidal banks, which can act like a barrier for aeolian transported sediment. The sand cannot travel from sandbar to the shore due to this water, even under wind conditions that otherwise would create good conditions for aeolian transport (Houser, 2009).

3.2 KNMI weather data

The weather data used in this research comes from a weather station in de Kooy, close to Den Helder and is operated by the Royal Netherlands Meteorological Institute (KNMI). Figure 3.2 shows a photo and the location of this weather station. It makes hourly measurements at this location since 1906. It measures wind velocity in three different ways: the hourly mean, strongest wind during that hour and mean velocity for the last 10 minutes. It also measures wind direction, temperature (during measurement, minimum during last 6 hours at 10 cm height and dew point temperature), amount of rainfall and rainfall duration, air pressure, atmospheric humidity, visibility, cloud cover, presence of fog, rain, snow or ice, etc. The hourly mean wind velocity and direction are the most important measurements for this study and are used in calculating the potential sediment transport. The wind velocity has an resolution of 1 m/s and the wind direction has a resolution of 10^{O}. The anemometer is placed at a height of 10 meters above ground level. It is an automatic weather station (AWS) since 1993. The site is approximately 40 km away from Egmond aan Zee, which makes this one of the closest weather stations. There are stations closer to Egmond, but they do not measure as many weather variables as the one in de Kooy (KNMI Handboek Waarnemingen, KNMI de Kooy).

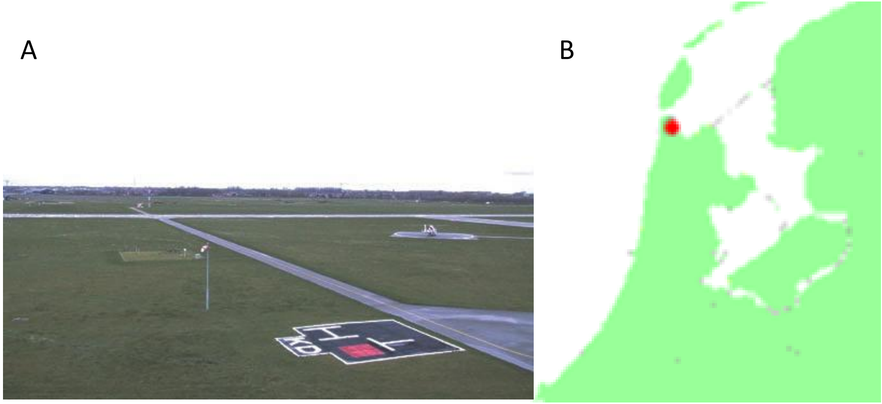


Figure 3.2; Weather station at the Kooy, close to Den Helder (A). The location is indicated on the map (B). Source: KNMI de Kooy.

3.3 Argus images

Argus is an optical remote sensing system which monitors the beach with a number of video cameras. The video cameras are located on a tower or a high building, so that they can cover the entire beach. Beach monitoring like this is done for approximately 30 years and over 50 camera systems are now installed worldwide. Argus was developed by the Coastal Imaging Lab at Oregon

State University. Argus is used for many different applications, like monitoring the morphodynamic changes around hard structures, like groynes, to determine the effect of beach nourishment in front of the coast, to monitor long-term shoreline changes or to assess dune erosion after storm events, but also for scientific research. It is mainly used for understanding the morphodynamics of the nearshore. The bathymetry and sediment transport are part of the nearshore system, which can change due to the presence of waves and currents. The flooding risk of the beach and dune system depends on the nearshore characteristics as well, which makes it important to do sufficient research on this topic. Wave observation is one of the most used aspects of the Argus Program. The cameras can easily see the period, wavelength and the direction of the wave. Waves start to break and create white foam when the water depth becomes too shallow, which gives an indication of where sand bars are located. Drifting flocks of foam can be used to determine the strength of the currents in the water. This makes Argus a useful tool for investigating many different aspects of the nearshore (Holman and Stanley, 2007).

The Argus system makes use of multiple cameras: the 5 cameras at Egmond are mounted on top of the Coast3D tower, where each camera is looking in a different direction to cover the entire beach. The tower stands on the beach itself, which gives the cameras a good view of it. Argus gives at this location a single snapshot for each camera every 30 minutes (Argus coast3D Tower). It also makes a time-exposure image, which is the time mean image over a certain period. This period is 10 minutes, where images were made with a frequency of 2 Hz. These time-exposure images will smooth out moving objects. The beach will therefore look the same as in the snapshot image, but the sea shows white bands at the locations of breaking waves, which indicate the location of sand bars. Another image product produced by the Argus system is the variance image. This image shows the variety of the images collected in the 10 minute time span. 'Variance image' is a misleading name, because the image actually shows the standard deviation. A variance image shows a bright colour when the variety is high. This means that the beach often has dark colours, while the sea is bright. Variance images are usually used to delineate the zone of wave breaking and the surf zone (Holman and Stanley, 2007). An example of each of these three images can be found in figure 3.3. The tower itself can be seen in figure 3.4. Making use of a remote sensing system is cheaper than measuring aeolian transport during a field campaign and it can monitor the beach over a longer time scale as well. A down side is that a system like this can be affected by bad weather and does not work overnight, unless enhanced cameras are installed. The pixel resolution of the images becomes smaller for the beach close to the horizon, which makes small details there hard or impossible to see.

The Argus cameras at Egmond have been monitoring the beach since 1998, but only a part of this time span will be used during this research. The images from 2005 to 2012 will be used. This time span was chosen because of the type of camera that was used during these years for the Argus system; the cameras used before had a much lower resolution and the dunes were less visible, which makes it hard to compare these images with the images from the more modern camera. The images used during this thesis are the snapshot images and the time-exposure images from the two cameras (c1 and c5) that are able to monitor the beach, because these images can show traces of aeolian transport. Aeolian transport is visible as streamers or sand strips. Streamers are fast-moving, ‘snakelike’ clouds of sand. They move too fast for the time-exposure images to be picked up and can therefore only be seen on the snapshot images. The streamers are picked up the best when the corresponding time-exposure and the snapshot images are compared to each other. It is sometimes hard to see the difference between an active streamer and one that recently stopped. Sand strips, on the other hand, move much slower. They appear on the images as stripes of light coloured sand on dark sand and create zebra-like patterns on the beach. The sand strips are visible in both the snapshot and the time-exposure images. However, it is possible that the sand strips are inactive. There are multiple images needed which are taken a few hours after each other to see the movement of the sand strips.

Figure 3.3: A Snapshot (A), time-exposure (B) and a variance image (C) from one of the cameras on top of the Coast3D tower at Egmond aan Zee. The red area indicates a zone with sand strips, the green circle an area with (hardly visible) streamers. Source: Argus Coast3D Tower.

Figure 3.4: The Coast3D Tower on the beach at Egmond. Source: Flickr

4. Wind characteristics

The KNMI data consist of hourly measurements of various weather characteristics. This chapter sometimes uses the data from every hour, which contain moments with and without aeolian transport, but at other times only the moments with transport are studied. That can happen in the form of wind events as well. A wind event is a certain time span where the wind velocity is high enough to potentially bring sediment in movement. These moments must also have a minimal duration to transport a significant amount of sediment. The characteristics of the wind event therefore only show the conditions which are good enough for aeolian transport. That takes place when the actual wind velocity surpasses the threshold wind velocity. How this can be calculated is explained in chapter 2.1. This results in a threshold shear velocity (u_{*t}) of 0.2256 m/s at the Egmond site, so there should be aeolian transport when the shear velocity surpasses this (this corresponds to a wind velocity of 7.9 m/s that must be surpassed by wind measurements of the KNMI to create aeolian transport).

The minimal duration of a wind event on the other hand must be chosen by the observer. This duration influences the number of events that occur between 2005 and 2008. Delgado-Fernandez and Davidson-Arnott (2011) did a similar research and used a minimal duration of 2 hours for an event. This time span can be determined by visual inspection of the Argus images. The sand must show some movement within that time to be significant as transport towards the dunes. This can be seen the best when there are sand strips present on the beach; streamers move all the time, are often small and appear temporarily. 2 hours felt slightly short for the Egmond beach, so the minimum duration of the wind event was varied to see how this affected the number of events and the potential transport rate. A minimal duration of 2, 4 and 6 hours was used here and the number of wind events for each year was calculated for 2005 to 2012. The resulting graph can be seen in figure 4.1. The number of events varies between 205 and 139 for a minimum event duration of 2 hours, 146 and 102 for 4 hours and 122 and 80 for 6 hours. The difference in the number of events is larger between a minimal duration of 2 hours and 4 hours than between 2 and 6 hours. Figure 4.2 shows the potential volume of the transported sediment. The difference in potential transported sediment volume here is larger between the individual years than between the minimum duration of each event. The duration of an event only has a small influence on the total potential sediment transport, so it does not matter that much which duration is chosen.

Most events on the Argus images showed a significant amount of transport during 4 hours, but there also was quite some transport visible between two hours or even one hour if the wind velocity was high. The movement of sand was hard to see when transport rates were low, which happened often during conditions with low wind velocities. This makes it more difficult to choose a good minimal duration of the events. A minimum duration of 4 hours was chosen, which includes some of these minor transport events. This duration only has a minor impact on the potential sediment volume, but the number of events is affected strongly.

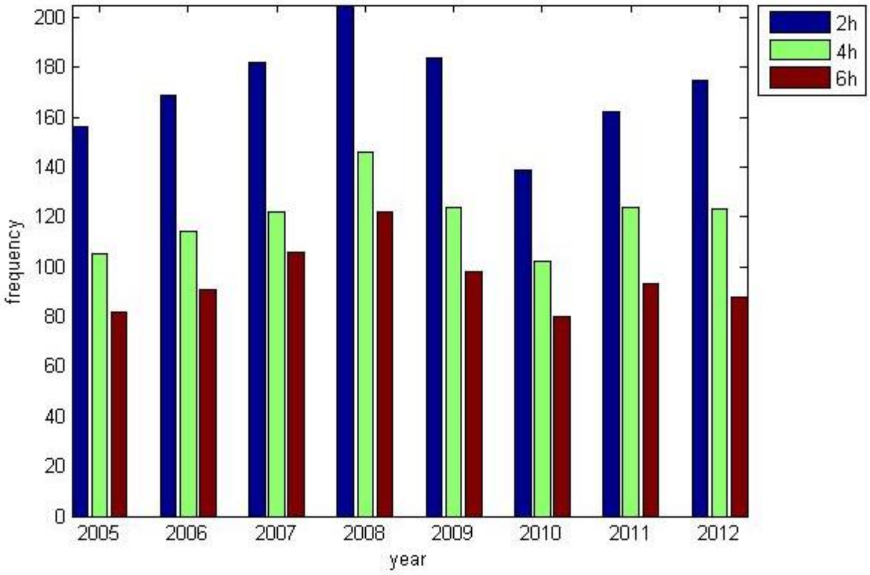


Figure 4.1: The number of events with different minimal durations for 2005 to 2012.

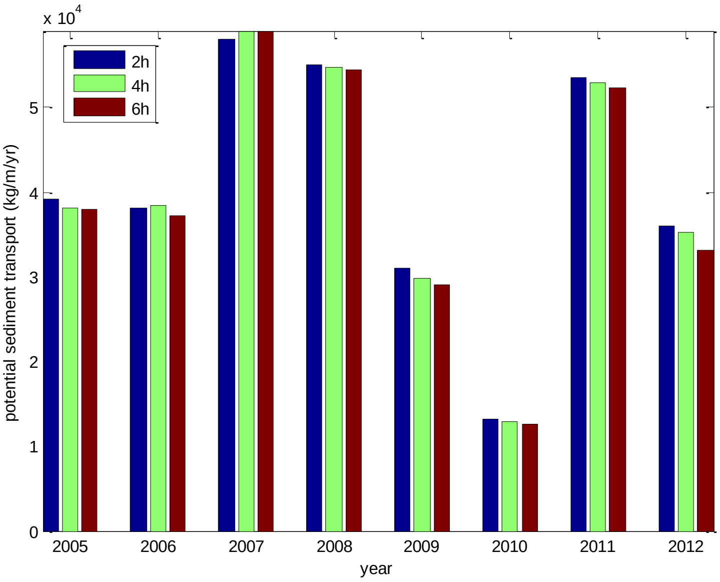


Figure 4.2: The potential sediment transport for 2005 to 2012. The cosine effect is included here. The potential sediment transport was calculated with the hourly mean wind velocity for every hour that was part of a wind event.

4.1 Distribution of wind events over time

There were 960 wind events in total with these definitions of a wind event over the 8-year long period from 2005 to 2012. The number of events for each year can be found in table A1 in the appendix and in figure 4.1. The year with the most wind events is 2008, while the year with the least amount of events is 2010. The number of events that occur each month is visible in figure 4.3. There is a small, monthly trend visible for the number of events through the year. There are generally more events during the autumn and winter period for the 8 years of data, of which November is the month with the largest number of events. However, the number of events per month varies considerably and individual years can show a different pattern. Figure 4.3 shows how the number of each month can very every year. More years of data must be added to this figure to see if there is a clearer pattern visible.

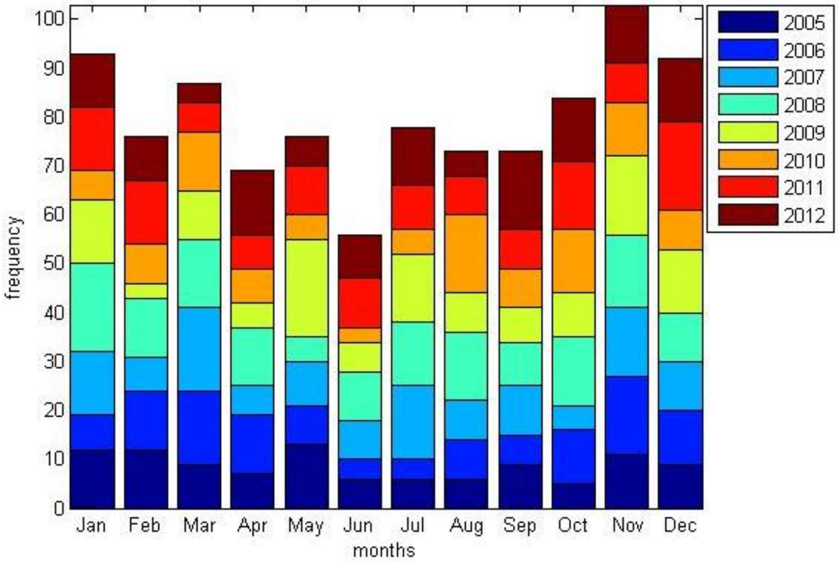


Figure 4.3: the number of events for each month.

4.2 Potential transport rate

The potential transport rate of each event is calculated with equation 3 and 4 in chapter 2.2. The potential sediment transport can be calculated with the wind velocity. This was done here for every hour that was part of the wind events. These potential transport rates for every hour were summed up to determine the yearly and monthly potential sediment transport rates.

The yearly variability of the potential sediment transport without the cosine effect is large, ranging from 1.12*10^5 kg/m/year in 2008 to 5.29*10^4 kg/m/year in 2010, which can be seen in figure 4.2. The transport rate depends on the wind velocity to the power of 3, so a slightly larger wind velocity can cause much more aeolian transport. 2008 had not only more events than 2010, but they were also stronger, which caused most of the difference between the transport rate of these two years. An event from 2008 will have an average potential transport rate of 769 kg/m per event, while this is 518 kg/m per event for one from 2010. 2007 is the year with the highest potential transport per event (847 kg/m). These mean transport rates per event can be found in table A2 in the appendix.

The amount of sediment that ends up in the dunes is less. The potential aeolian transport rate with the cosine effect is 2.5*10^4 kg/m/year (2010) to 6.6*10^4 kg/m/year (2007). The difference between the total transport rate and the potential aeolian transport rate that is directed towards the dunes can be very large. The potential transport rate is halved when the cosine effect is taken into account, but this tends to be even more when the potential transport rate was low in the first case. This is for example well visible for 2010, where the potential transport rate without cosine effect is approximately four times as large as the transport rate with cosine effect.

The potential transport rate with and without cosine effect can be seen in figure 4.4. January has the largest potential transport if all the data is combined in both figures, while the spring and summer months show the potential transport rate. However, there is a large variability for the monthly transport rate, which can cause a completely different pattern for the transport rate each year. This is visible in figure 4.5 and 4.6. The transport rate was quite low in January 2006 and 2010 for example, while this is otherwise a month with high transport. There is hardly any transport left in January 2006 and 2010 when the cosine effect is considered.

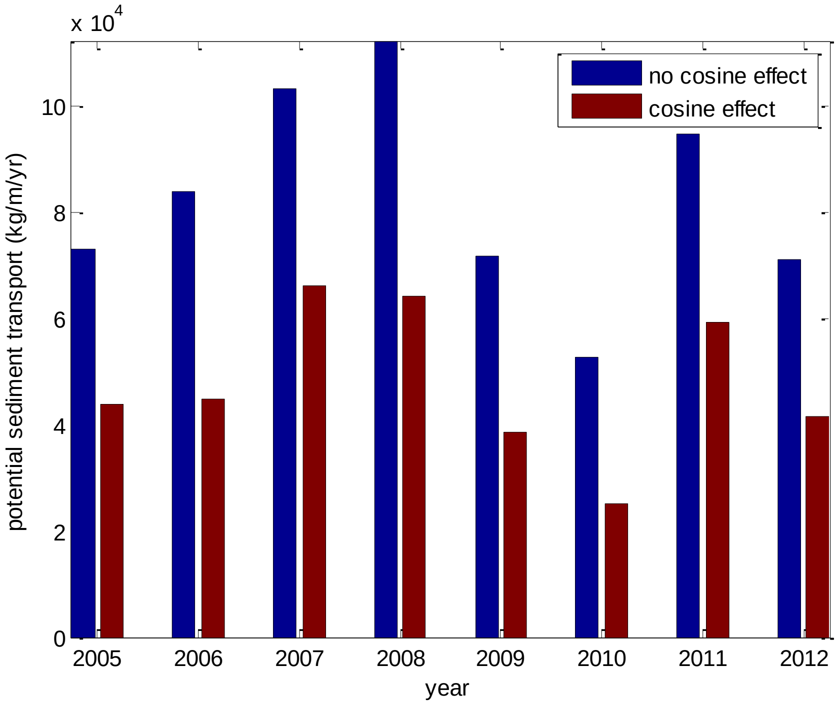


Figure 4.4: yearly potential sediment transport rate, with and without the cosine effect. The potential sediment transport was calculated with the hourly mean wind velocity for every hour that was part of a wind event.

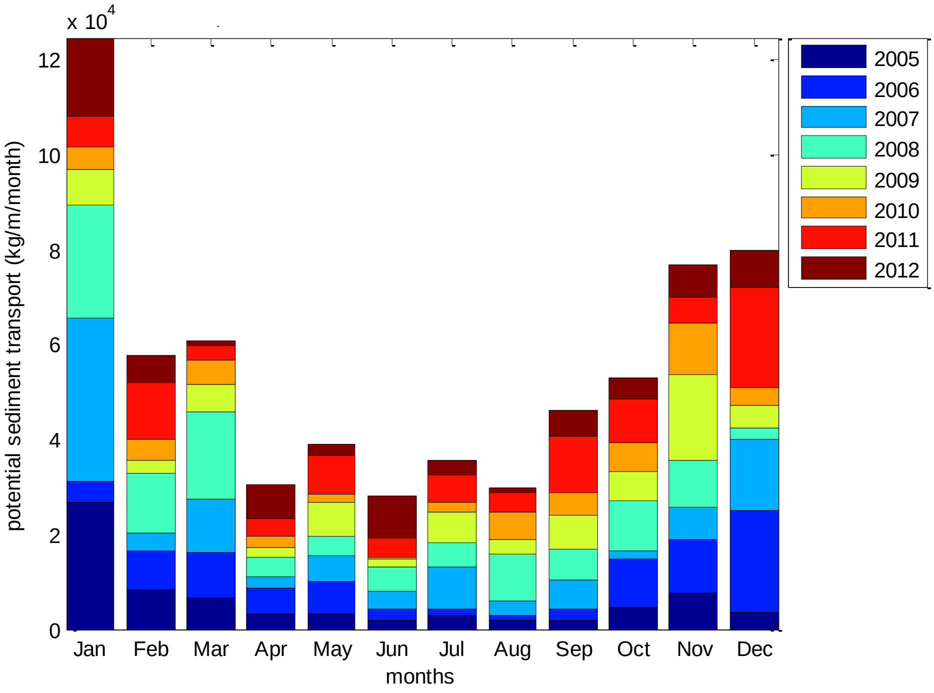


Figure 4.5: monthly potential sediment transport. The potential sediment transport was calculated with the hourly mean wind velocity for every hour that was part of a wind event. The cosine effect is not included here.

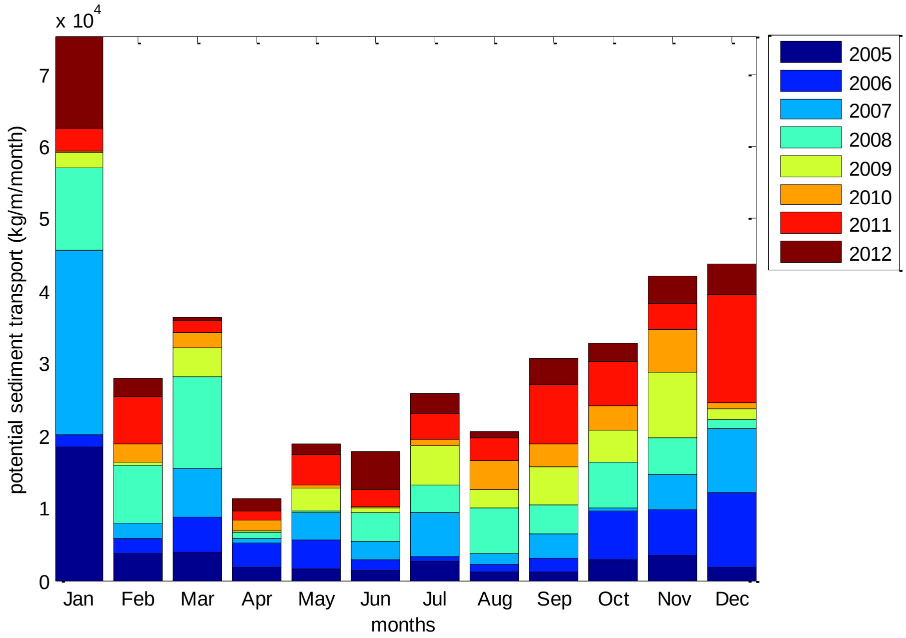


Figure 4.6: monthly potential sediment transport with the cosine effect. The potential sediment transport was calculated with the hourly mean wind velocity for every hour that was part of a wind event.

4.3 Wind direction

Figure 4.7a shows the wind events sorted by their mean wind direction and figure 4.7b shows the potential total volume of sediment that gets transported in each wind direction from 2005 to 2012. These figures show a similar pattern: there are two peaks visible and the biggest one is southwest by south. The other, small peak is located around the north east. The wind directions that are the least common are approximately southeast and north. Southwest to west are common wind directions here and are not that much affected by the cosine effect. Sand will therefore still end up in the dunes. There wind directions will probably cause most of the aeolian transport to the dunes.

The wind direction distribution of the potential transport moments is different from the moments without transport, which can be seen in figure 4.8. This figure does not show the wind direction of wind events, but that of each hour from the entire dataset. The pattern described earlier for the transport events can be found here as well for all the hours of data. This is not the case for the wind direction during moments with no potential transport. The number of these hours with no transport seems to be more or less the same in each direction, especially compared to the number of hours that potentially can cause aeolian transport. There are generally more moments that show no potential transport than the ones that do, except when the wind is blowing from the south to southwest, where the number of potential transport hours is high.

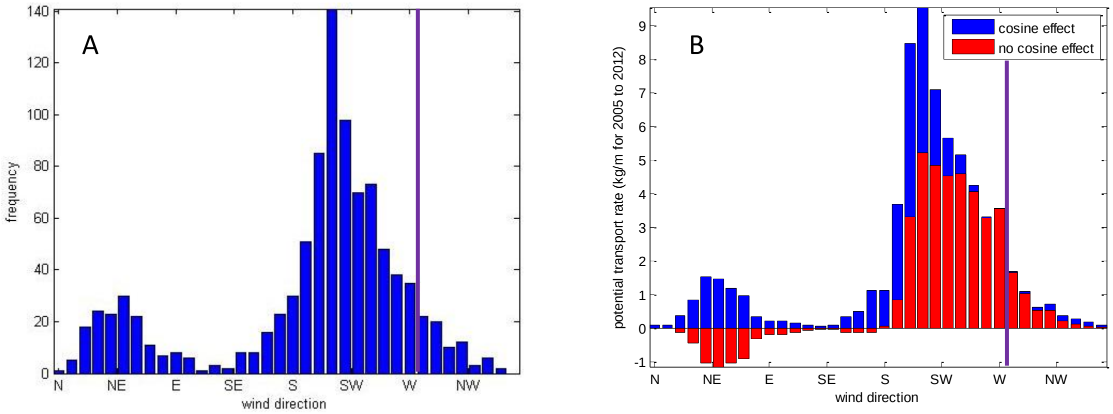


Figure 4.7: The wind events sorted by their wind direction. Figure A shows the frequency of the wind events and B the total amount of transported sediment transported by them in 8 years (2005-2012). Shore-normal is indicated with the purple line. The potential sediment transport was calculated with the hourly mean wind velocity for every hour that was part of a wind event. Hours with negative potential sediment transport are further ignored.

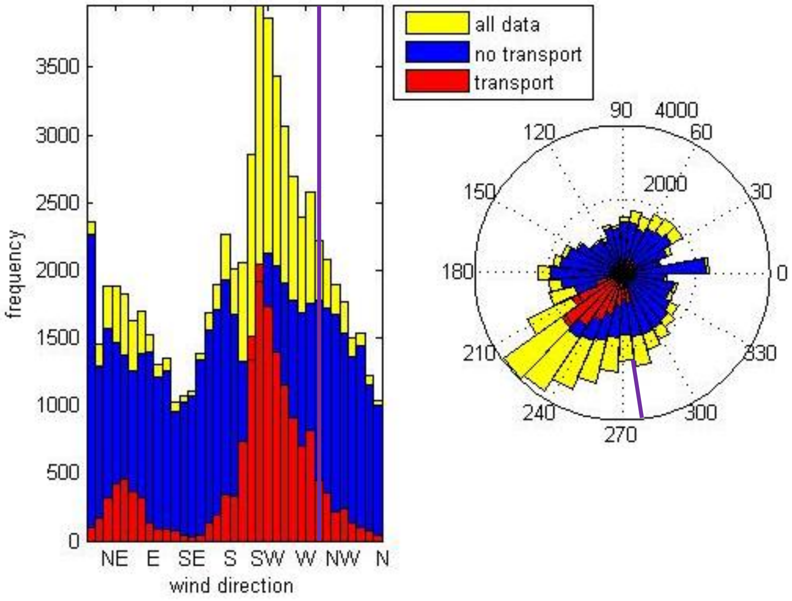


Figure 4.8: The mean wind direction of every hour of data between 2005 and 2012, shown as a bar graph and a rose. It shows the distribution for all data, no transport moments and potential transport moments. Moments with no transport are not grouped as wind events, so therefore every hour of data is used here. The purple line indicates shore-normal.

4.4 Wind velocity

Figure 4.9 shows the mean wind velocity of each hour from 2005 to 2012. The number of hourly moments with a very low wind velocity (1 m/s) is not very high. This number increases strongly when the wind velocity increases, until the most common wind velocity of 5 m/s is reached. The number of moment decreases strongly first when the wind velocity increases even more, but this decrease becomes more gentle later. A similar graph was made for the wind events (figure 4.10), which gave a slightly different result. The wind velocity represented in this graph is the highest hourly mean wind velocity that takes place during a wind event, called the maximum hourly mean wind velocity, or $\bar{u}_{he}$. This is higher than the mean wind velocity of an event used to calculate the potential transport in chapter 4.2. This wind velocity was here to make this graph more comparable with figures in later chapters, where also this maximum hourly mean wind velocity is used. There are no events with an $\bar{u}_{he}$ below 8 m/s, which is below the threshold of movement. The most common $\bar{u}_{he}$ here is 9 m/s. This might be strange looking back to figure 4.9, where there is a decrease in frequency from 5 m/s to larger wind velocities. An hourly mean wind velocity of 8 m/s is there more common than 9 m/s. A reason for this can be that there are many hourly moments that have a mean wind velocity of 8 m/s, but that they are often part of an event that contains hours with wind velocities that are higher than that. The highest $\bar{u}_{he}$ of an event ends up in figure 4.10, so a lot of low, hourly mean wind velocities are not represented there.

The mean $\bar{u}_{he}$ per month does not vary much through the year; there is only a slight decrease in the summer months. This wind velocity does not vary much through the years either. A table with these wind velocities for each month and each year can be found in figure A3 in the appendix. The mean $\bar{u}_{he}$ of all events is 10.22 m/s.

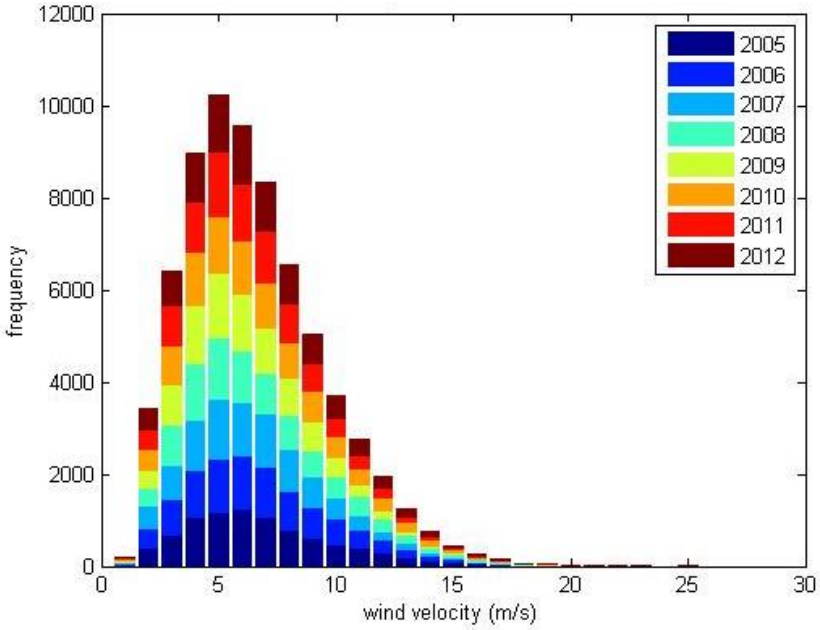


Figure 4.9: A histogram of the wind velocity of all hourly moments.

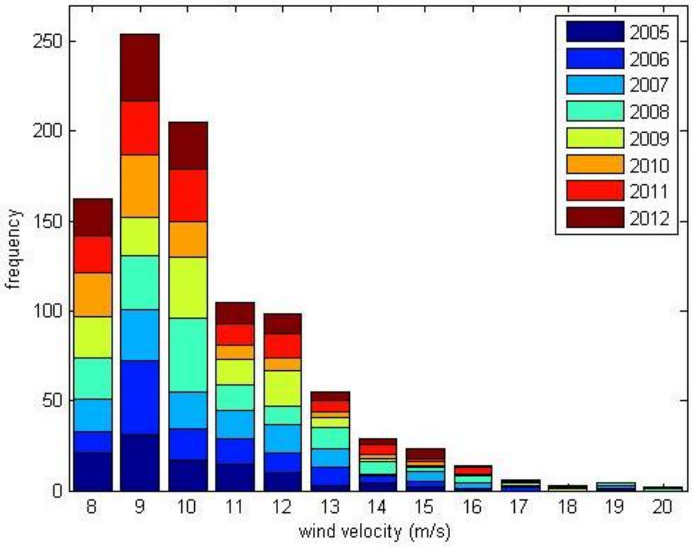


Figure 4.10: A histogram of the wind velocity of all wind events. The wind velocity here is the mean velocity of the hour of an event with the largest wind speed. Wind velocities below 8 m/s do not show up here, because these winds do not cause aeolian transport and are therefore not included in the wind events.

4.5 Duration

The duration of a wind event tends to increase with its wind velocity. There is however, a large variation here; it occurs quite often that an event with a high wind velocity has a shorter duration than an event with an average wind just above the threshold of movement. Figure 4.11 shows the mean duration of an event versus its mean $\bar{u}_{he}$, including the standard deviation. It shows that the mean duration increases with the wind velocity, but that there is also a very large standard deviation. Some of the standard deviation bars overlap each other, so there is no significant difference between the data points in those cases.

Figure 4.12 shows the distribution of the mean duration for each month, which all years of data stacked atop of each other. It shows that January is the month where the events are on average the longest. This might form an explanation for the large peak in figure 4.5 and 4.6 in chapter 4.2, which showed the transport rate for each month, without and with cosine effect. January showed a very high potential aeolian transport rate there.

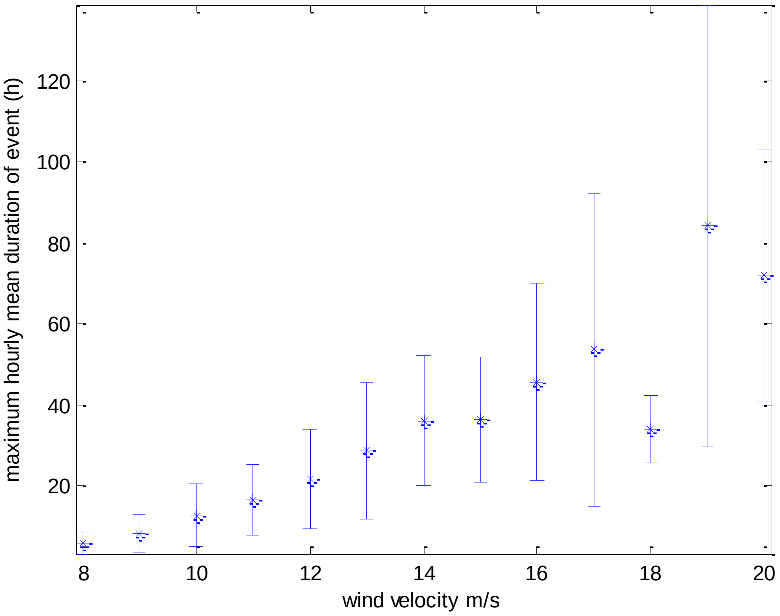


Figure 4.11: the mean maximum hourly mean wind velocity $\bar{u}_{he}$ *against its mean duration, including the standard deviation.*

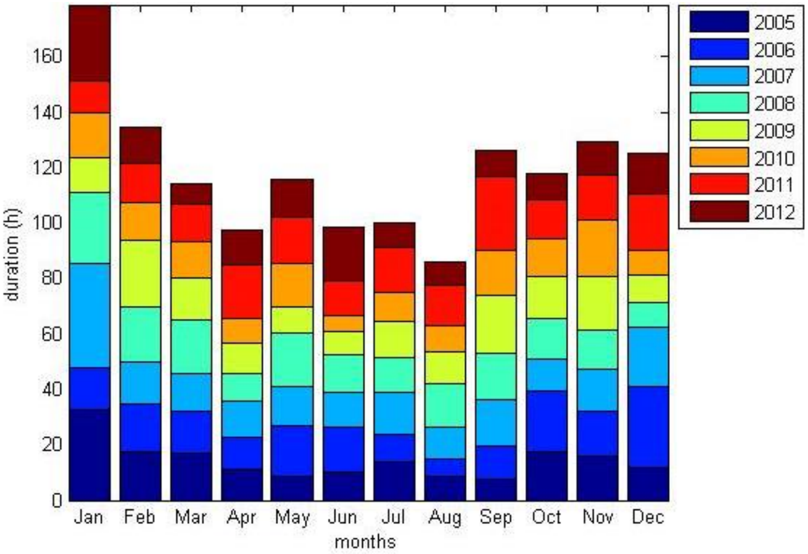


Figure 4.12: Monthly main duration of events stacked for the years 2005 to 2012.

4.6 Best wind conditions for aeolian transport

The distribution of the wind events must be known, to see what wind event class is the most common one. The wind velocity is actually studied here, because the classification is based on that. The potential transport increases with wind velocity, but those very strong winds are rare. A wind velocity that is lower, but with a higher occurrence will contribute more to the total amount of aeolian transport. The optimal wind velocity must therefore be the sum of the potential transport and the number of occurrences. The duration of an event is important as well, because more sediment gets transported if wind conditions remain favourable for this for a long time. It is hard to say how strong the relation is between the wind velocity and the length of an event, because figure

4.11 in chapter 4.5 showed that a duration of an event can be highly variable at the same wind velocities.

Figure 4.13 shows multiple graphs with an increasing wind velocity on the x-axis, without and with the cosine effect. This wind velocity is the $\bar{u}_{he}$ of an event. Figure 4.13a shows the potential sediment transport rate, which increases when the wind velocity increases (no cosine effect). This is only for the most part the case with the cosine effect. It still shows the same pattern, until a velocity of 19 m/s or higher is reached. The potential transport rate is however lower. The number of hours with very high wind speeds is low, so it is hard to say much about them statistically. This also explains why the potential transport rate does not have a clear pattern for wind velocities of 19 m/s and higher. For example: the high potential transport rate at a wind velocity of 22 m/s looks quite good for dune growth, but this point consists of only two hours of data. They both had a shore-normal wind direction, so the result could have been very different if this was not the case. The graph will probably look different if more data was added. There is a gap at a wind velocity of 21 m/s, because there were no hours with that wind velocity.

Figure 4.13b shows how often a certain wind velocity occurs, where the frequency becomes lower when the wind velocity increases. It shows a decreasing trend, because events with high wind velocities are rarer. Figure 4.13b does not depend on the cosine effect.

Figure 4.13c shows the product of the previous two graphs, which shows a peak at a wind velocity of 9 m/s when the cosine effect is ignored. This wind velocity will potentially be responsible for most of the aeolian transport. This graph with the cosine effect shows a similar trend, but only with a lower product of potential transport rate and frequency. However, the peak here is located at 11 m/s. The potential transport rate is lower with the cosine effect than without, but this has a relative larger impact on low wind velocities than high velocities. That makes the product of the potential transport rate and the frequency with the cosine effect lower as the one without the cosine effect as well, but with a larger difference between them for low wind velocities. This makes the peak shift from 9 to 11 m/s.

In theory, the best wind direction for transport to the dunes is the west for the Egmond beach. Southwest, however, is a more common wind direction, which might contribute more to the total volume of transported sediment. There is more potential transport during the winter than summer, with and without the cosine effect, so this is in theory the most important season for dune growth.

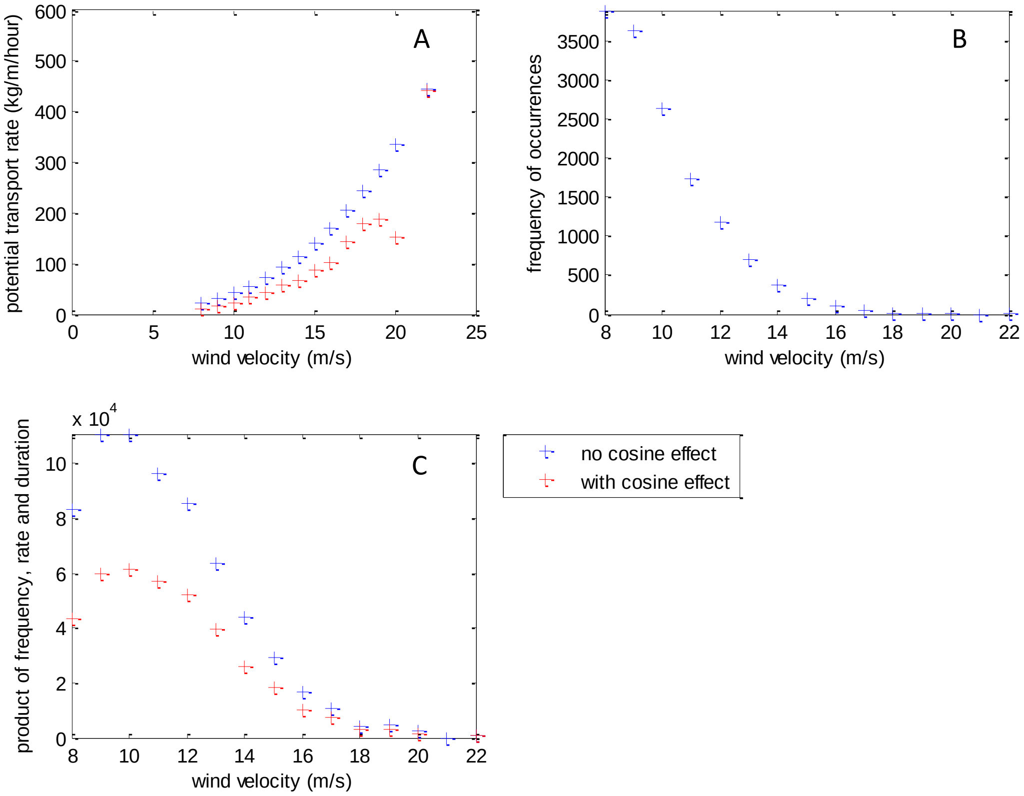


Figure 4.13: This figure shows the mean wind velocity on the x –axis and on the y-axis the potential transport rate (A), the number of occurrences (all hours that potentially can cause transport (B) and the product of A and B (C).These graphs do include potential transport with (red) and without (blue) the cosine effect. Figure b remains the same, with or without this effect. The wind velocity of every hour of each event is used to calculate the potential transport rate and the frequency.

5. Classification of events

5.1 Wind events classification

The wind events were classified according to a scale from 1 to 5, to make it easier to compare these wind events with actual transport later during this research. The potential transport of an event was classified according to table 5.1, which is based on the potential transport rate for the hour with the highest wind event ($\bar{u}_{he}$). Equations 3 and 4 were used for this. The same kind of method is applied for the classification of the Argus images; one hour is used to represent the entire event. That is the main reason why that was done here as well; it makes the two datasets more comparable.

The boundaries of the wind event classes are also visible in figure 5.1 and in figure 5.2 for the potential transport rate towards the dunes. This classification was done by using the potential transport rate with and without the cosine effect. The event was ignored when its transport rate was negative (transport of sand towards the sea) when the cosine effect was used. The potential transport rate was calculated with the wind velocity ($\bar{u}_{he}$), but there is no transport when the wind velocity is not high enough (when the threshold shear wind velocity is larger than shear wind velocity). This is shown in figure 5.1, where the potential sediment rate does not drop below a transport rate of 21.4 kg/m/hour. The wind velocity used to calculate this transport rate is just strong enough to surpass the threshold of motion, so lower wind velocities are ignored and smaller transports are not created. This is not the case for figure 5.2, where the cosine effect can create very small transport rates when the wind is blowing alongshore.

Table 5.1: Classification of the wind events.

Wind class	**description**	**aeolian transport rate (kg/m/hour)**
1	very small potential transport rate	< 30
2	small potential transport rate	30 – 60
3	medium potential transport rate	60 – 90
4	large potential transport rate	90 – 120
5	very large potential transport rate	> 120

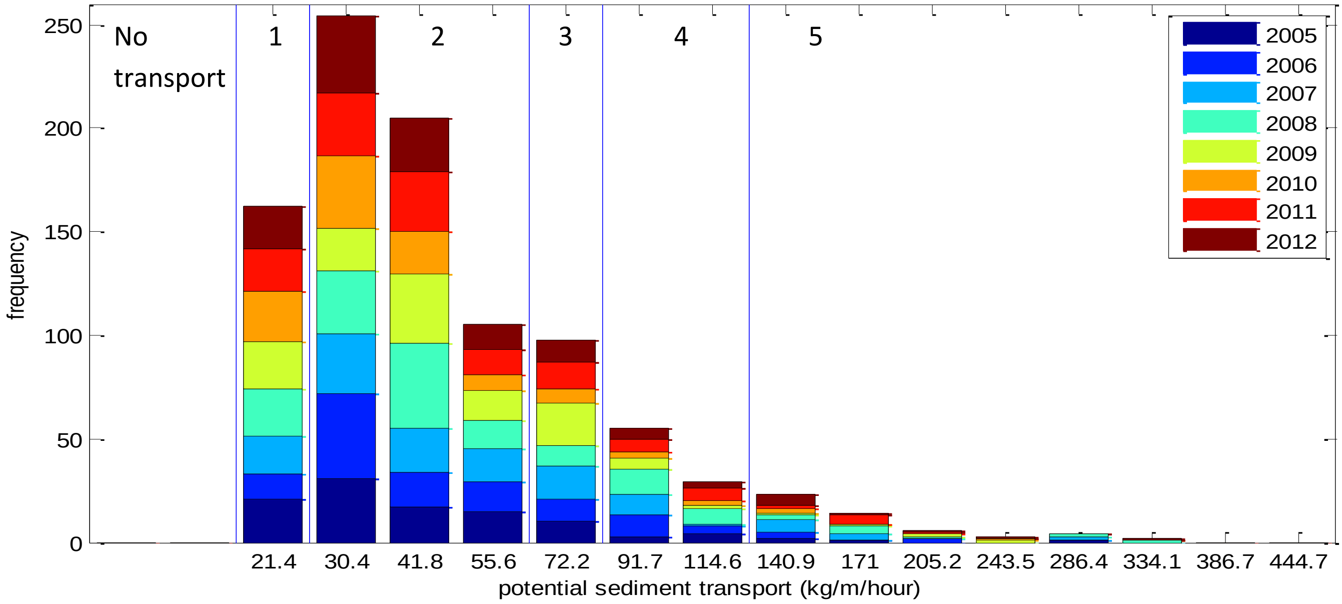


Figure 5.1: Potential transport frequency, which was calculated with the maximum wind velocity of each wind event ($\bar{u}_{he}$). The numbers indicate the wind class.

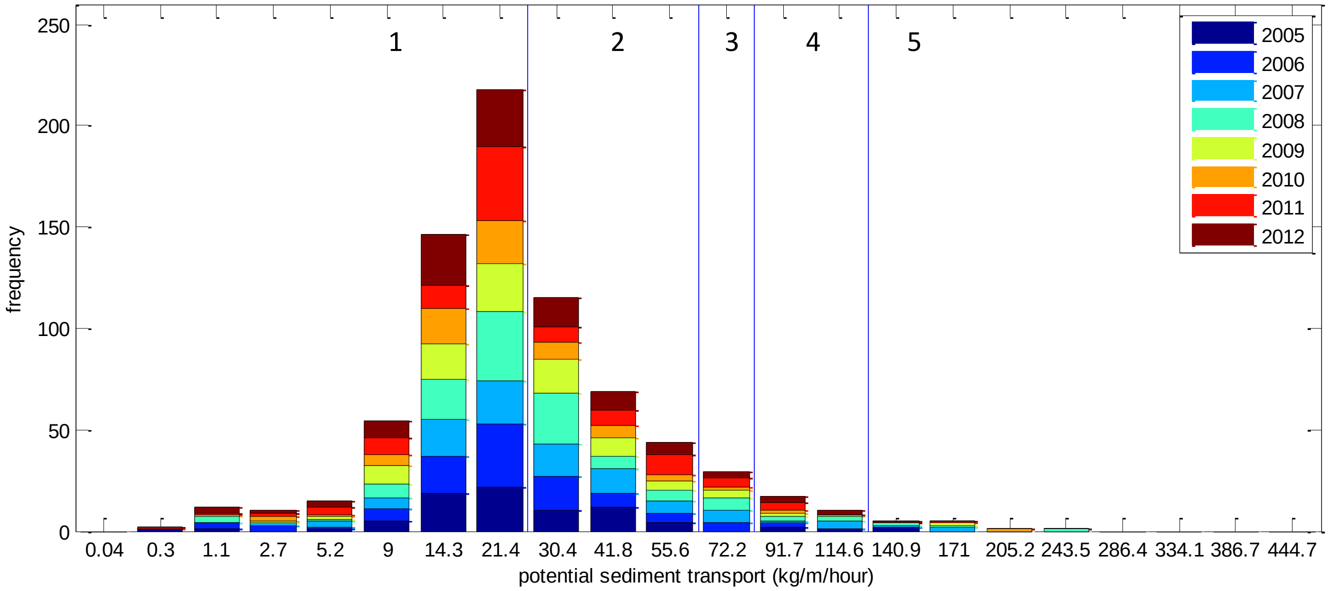


Figure 5.2: Potential transport frequency (with the cosine effect), which was calculated with the maximum wind velocity of each wind event ($\bar{u}_{he}$) and its wind direction. The numbers indicate the wind class.

5.1.1 Occurrence of wind events

Figure 5.3 shows a pie chart with the wind classes, with and without the cosine effect. For the classification without concerning about the cosine effect, the class with small wind events is the largest and contains 59% of all wind events. The amount of events that is classified as a very small wind event is smaller, only 17%. The medium potential transport class contains 10% of all wind events and the large wind event class is only slightly smaller and contains 9%. The smallest class

contains the very large wind events, which has only 5% of all wind events. The highest potential transport rate that was reached is 577 kg/m per hour.
These ratios change when only the amount of sediment that ends up in the dune field is considered. This can make the potential sediment transport to the dunes very small for winds that have an almost shore parallel direction, even though the total amount of sediment transport is relatively high. It is negative when the wind blows from the east, which is when sediment is blown away from the dunes towards the sea. The wind events with a wind blowing in the offshore direction are therefore ignored, which are 207 of the 959 events. The number of wind events which are classified as 'very small' becomes larger due to the cosine effect (55% of all wind events), at the cost of the other classes. The class with small wind events becomes much smaller (26% while it was 59% without the cosine effect). The remaining classes became much smaller as well, with 7%, 3% and 3% for the medium, large and very large wind events. This shows that the wind at Egmond aan Zee often has an oblique angle compared to the cross shore direction. Less sand is therefore transported towards the dunes, which diminishes dune growth. On the other hand, the fetch length is also larger when the wind is blowing at an angle, which can enhance sand transport if the beach is narrow.

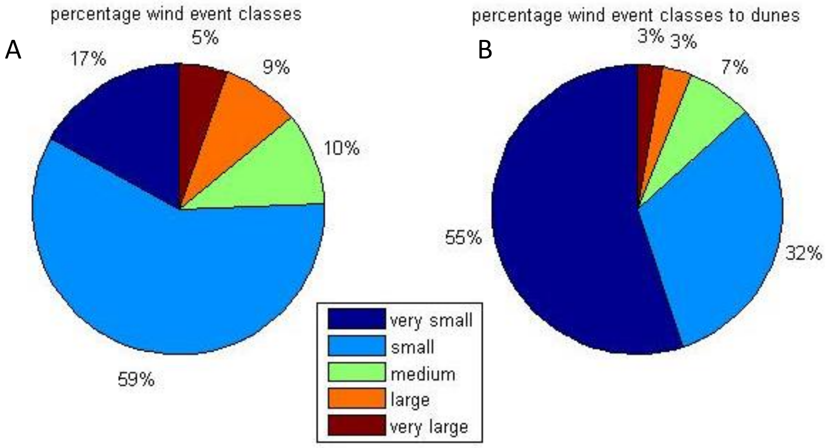


Figure 5.3: The percentages of wind event classes, without (A) and with (B) the cosine effect.

5.1.2 Monthly number of wind events

Figure 5.4 shows the monthly event distribution of the wind event classes, with and without considering the cosine effect. The amount of events occurring each month shows only a small seasonal pattern, which was already found in chapter 4.1. The number of events is only slightly lower during the summer months when all data is combined, but this is not always the case for each individual year. The months with the highest (or lowest) number of events changes every year, which is visible in figure A4 and A5 in the appendix. There is, however, a pattern visible for the distribution of the classes of the wind events. The amount of small and very small events remain quite the same for each month in figure 5.3, but strong and very strong wind events are more common in the winter months, especially December and January. January has a smaller number of strong and very strong wind events if the cosine effect is included. Almost all classes diminish in size compared to the situation without the cosine effect, except the class for very small wind events. This was already shown in chapter 5.1.1. The number of events in a certain wind class occurring each month varies strongly each year, but it is also visible here that very strong wind events tend to occur more often during winter. This is not as clearly visible when the cosine effect is taken into account, because the amount of events that are classified as a very strong wind event is much lower.

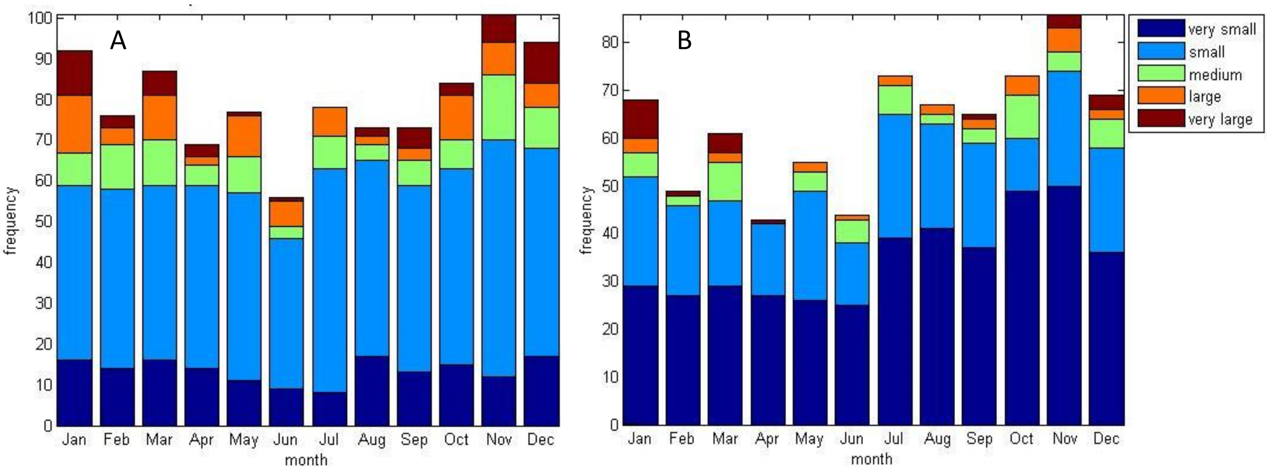


Figure 5.4: The monthly number of classified events, excluding (A) and including (B) the cosine effect.

5.2 Classification of transport events

Each wind event will be represented by one Argus image, which than can be classified visually. These events are now called 'transport events' (a wind event that causes no actual transport is often referred to as a ‘no transport event’). This was done by Delgado-Fernandez and Davidson-Arnott (2011) in approximately the same way.

The image taken at the moment of maximum, hourly mean wind velocity of each event, $\bar{u}_{he}$, was used for classification, as long as it happened during daylight hours. Table A6 in the appendix shows the hours at which photos can be taken for each month. It happened quite often that there were multiple moments during one event with the same highest hourly mean wind velocity. A second distinction was made based on the highest wind velocity in the last 10 minutes of that hour if that occurred. If this still resulted in more than one moment, a third distinction was made based on highest wind gust measured that hour. If this still did not result in one image for each event, which was very rare, the moment closest to 12.00h was chosen. Sand transport is best visible during the middle of the day when there is plenty of sunlight.

Aeolian transport can be recognized by sand strips or streamers that move across the beach. Their movement can be seen with multiple subsequent Argus images. Argus images were visually classified according to the scale in table 5.2. Figure 5.4 shows photos of events from every transport class. This classification was done without taking the cosine effect into consideration, because it is not possible to know how much sand ends up in the dunes by just inspecting the images visually.

Delgado-Fernandez and Davidson-Arnott had a total of 184 wind events, which turned out to be too little to properly describe very large wind events. Therefore, this study will use 8 years of data, with a total of 960 wind events. Another reason to pick a dataset of 8 years is the quality of the cameras used over the years. The cameras used from 1995 to 2004 created images with a low resolution compared to later images by better cameras, which make it hard to see small traces of aeolian transport, especially when weather conditions are bad. They also are less focused on the dunes, so a part of the beach close to the dunes is not included in the images. These images are therefore not used.

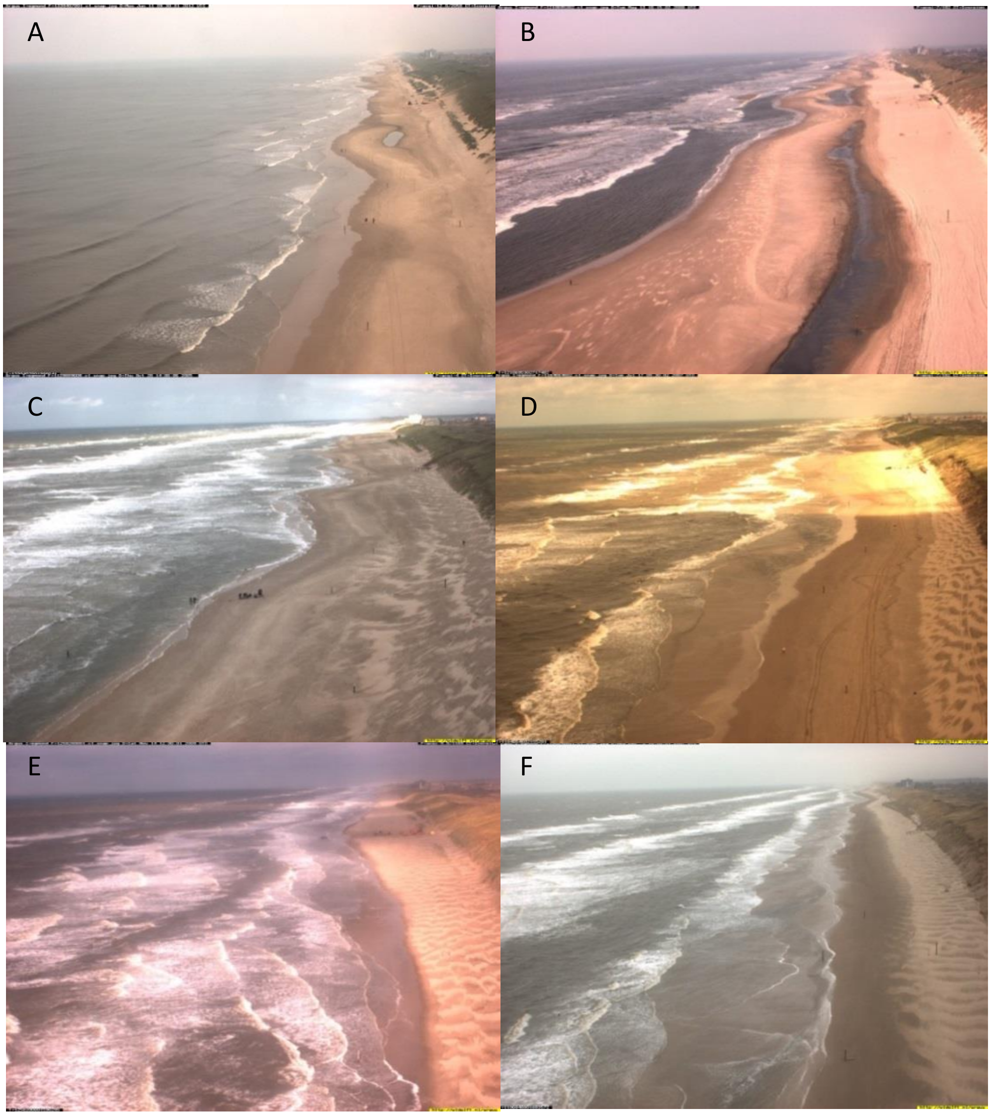


Figure 5.5: Photos taken by one of the Argus cameras, with the different transport classes. Photo a shows no transport, b shows a very small transport rate, c a small rate, d a medium rate, e a large and f a very large transport rate.

Table 5.2: Classification of the transport events.

Transport class	Description
0	No aeolian transport.
1	Very small – the wind is just strong enough to transport sand. There are sometimes sand strips visible, but there are usually only some streamers visible. They appear at various places on the beach.
2	Small – the sand strips appear more often, but the sand strips and streamers do not occur along the entire beach
3	Medium - sand strips are visible along the beach, but the sand strips are relatively small and/or are not completely developed and they move slowly.
4	Large - sand strips and streamers are visible along the entire beach, but the sand strips do not move that fast.
5	Very large – there are many sand strips and streamers. The sand strips move very fast.

5.2.1 Occurrence of transport events

The years 2005 to 2012 were used for the event transport classification. Unfortunately, 2005 was a year with data missing from February to July. The other years on the other hand missed only a few days of data.

Figure 5.6 shows a pie chart with the different transport classes. Most transport events are a class 1, showing only small traces of aeolian transport. These events form 26% of all transport events. The second largest group contains no data (21%). This means that some of these events did not take place during daylight hours, that the camera was broken or that bad weather blocked the view. A large part of the events (17%) were classified as class 0 as well, meaning that there is no aeolian transport. This forms an interesting group, because the wind is strong enough to cause aeolian transport. There must be something that prohibits aeolian transport during these events.

The transport classes 2, 3, and 4 have approximately the same size if the data from 2005 to 2012 is combined, which can be seen in the circle diagram (figure 5.6). Class 5 is slightly smaller. The distribution of the classes for each year separately is visible in figure A7 in the appendix. This figure shows that the sizes of the classes can vary quite strongly.

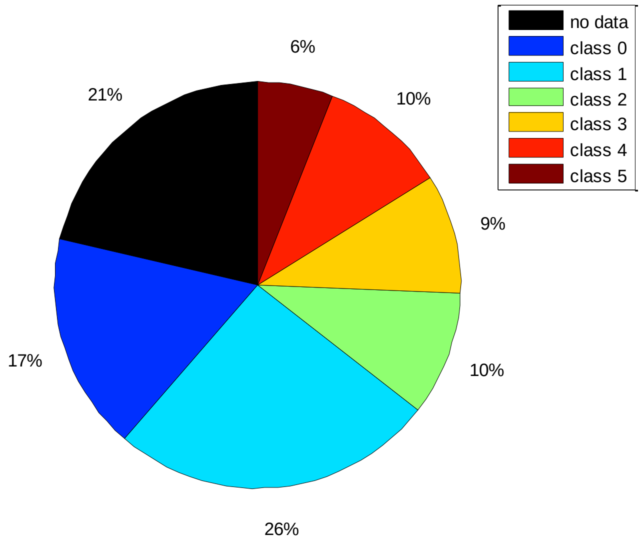


Figure 5.6: Pie chart with the transport classes.

5.2.2 Monthly number of transport events

Figure 5.7 shows the number of transport events for each month. There is not a seasonal pattern visible in the number of transport events in this figure; there is only a very small dip during the spring and early summer, but that is too small to say something about it. The distribution of the classes themselves does show a pattern. The large and very large transport events do occur more often during the winter months, which was also visible for the wind events in figure 5.3. There are also fewer events that are classified as a no transport event during the summer months, but very small events occur more often during this time. The other classes on the other hand do not show seasonal patterns like this. The number of events that contain no data shows a seasonal pattern as well; there are more wind events that do not have a useful Argus image during the winter than during the summer. It therefore looks like that the events with the highest transport tends to occur most often during winter and the smaller events during summer, but that these smaller events are less often affected by limiting factors as the events during winter. That might explain why there are more events with no transport during the winter. The winter also has less daylight and worse weather than the summer, which can explain why there are more wind events with no Argus data.

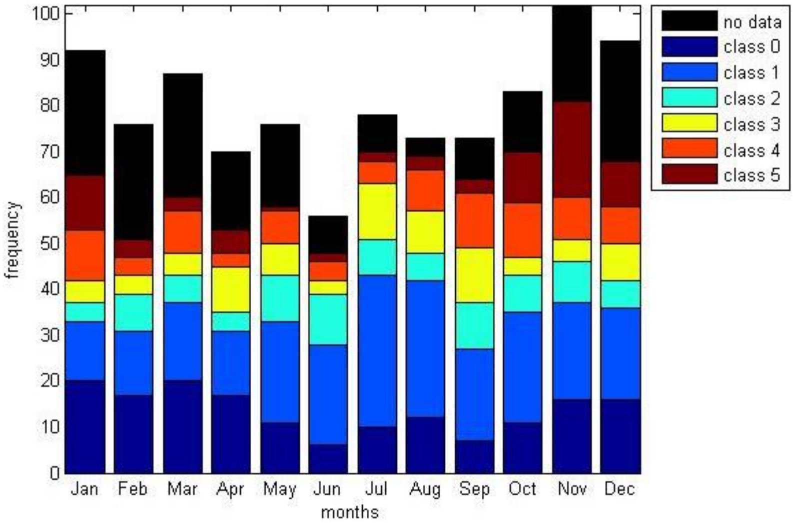


Figure 5.7: The monthly distribution of the transport classes.

6. Comparing wind events with transport events

The wind classes and the transport classes are compared to each other to see what the differences are between the two classifications. The classification methods might be completely different from each other, but the distribution of their classes can reveal something about possible limiting factors. Table 6.1 and 6.2 show how the events were classified. Figure A8 and A9 show this as well, which can be found in the appendix.

When there is no cosine effect taken into account, the number of transport events with no data is 205. These events have no data because there was no (useful) Argus image available at that moment. The number of no data transport events goes up to 352 when the cosine effect is considered. This is not because there were no Argus images available, but because the wind events with a seaward wind direction were ignored here. A high number of events ended up as no data transport events as a result of this. Most transport events that do not contain data have a wind event class of 1 when the cosine effect is considered (239 events), but this number is 44 without the cosine effect. This indicates that many events with wind class 1 have a seaward wind direction. This difference is much smaller for the other wind classes; medium and large wind events hardly show a difference between the results including and excluding the cosine effect.

A better look at both the tables shows that an event that has a very high potential sediment transport rate (class 5) will not always result in large volumes of aeolian transport. The actual aeolian transport rate can be very low or even nothing. There seems to be only a handful of very large wind event that have a transport class that is small (class 2) or medium sized (class 3). It looks like that these very strong wind events are separated into two groups: or they strongly affected by limiting factors and therefore have (almost) no transport or they are not affected at all and have a high transport rate.

The opposite can happen as well, which is slightly unexpected: Events with a low wind class can still create a large or a very large transport. This has to do with the wind direction, which tend to come only from an alongshore direction in these cases. This is visible in figure 6.1, which shows the wind direction for all transport classes (no cosine effect). This figure shows that the large and very large transport events more often have an alongshore wind direction.

Table 6.1: number of events for each wind and transport class without cosine effect.

		transport class							
		no data	*0*	*1*	*2*	*3*	*4*	*5*	*sum*
wind class	***1***	44	44	43	16	9	4	3	163
	2	128	97	151	47	67	58	16	564
	3	11	8	26	16	12	13	10	96
	4	9	10	16	17	4	14	15	85
	5	13	7	10	2	0	6	14	52
	Sum	205	166	246	97	92	96	58	960

Table 6.2: number of events for each wind and transport class with cosine effect.

		transport class							
		no data	*0*	*1*	*2*	*3*	*4*	*5*	*sum*
wind class	*1*	239	59	95	37	44	61	29	564
	2	88	37	74	23	30	18	19	289
	3	9	7	13	14	4	5	6	58
	4	9	6	9	3	0	1	0	28
	5	7	8	4	0	0	0	2	21
	sum	352	117	195	77	78	85	56	960

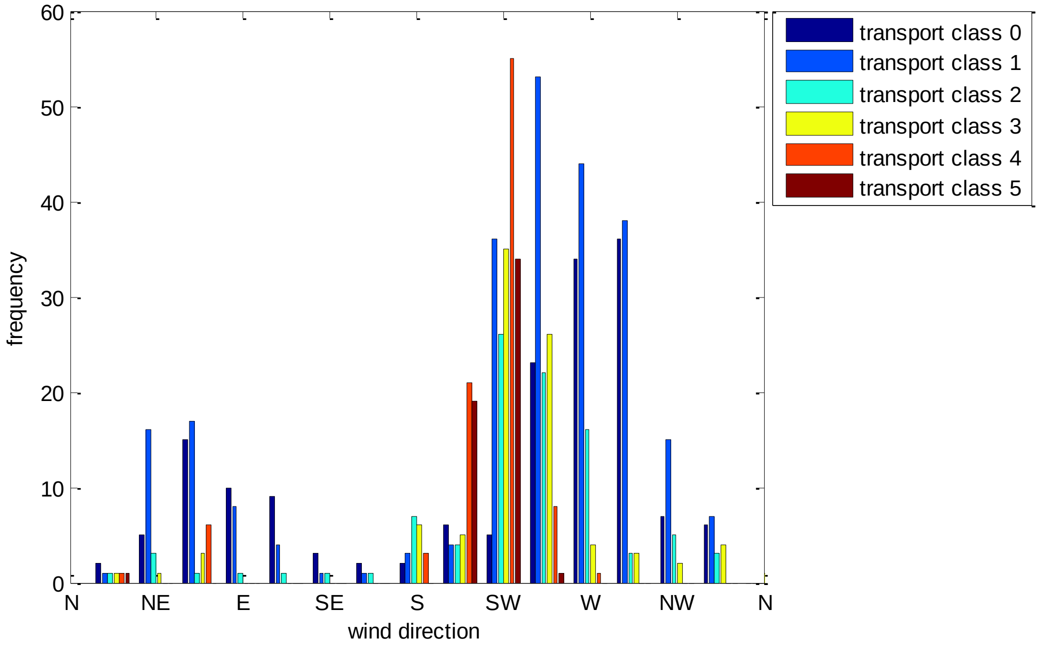


Figure 6.1: This figure shows the wind direction of the events from the 6 different transport classes. The transport classes with no or very little transport (class 0 and 1) tend to have two peaks; one for westerly winds and one for north or north north-easterly winds. The small and medium transport classes (class 2 and 3) can have winds coming from almost every direction, but most of the time these winds come from the southwest. Strong and very strong transport events (class 4 and 5) come almost always from this direction. There are only a handful of these events that have winds coming from a different direction.

6.1 Limited and unlimited events

The research done with table 6.1 and 6.2 already gave some indication for which events the aeolian transport rate was probably limited and which ones not. The events were checked individually to see if there were more events that showed a limited aeolian transport rate. This was done by looking at multiple images taken a couple of hours before and after the potential peak of the event took place (i.e., the moment with the highest wind velocity). If the image showed a higher actual transport during this time than at the moment of highest wind velocity, then the actual transport was probably hindered by a limiting factor. The tide is for example an important factor to keep in mind. The aeolian transport rate is the highest during low tide, when the beach is wide, so it can be expected that the aeolian transport rate will drop during high tide a few hours later.

It turned out quite soon during this check that almost every transport event could be limited by a short fetch. It is possible for a weak wind event with a low wind speed to get classified as very strong transport event, because the wind has a parallel direction compared to the shoreline. So, as long as the fetch is long enough, each wind event can be a very large transport event. This will make it hard to figure out when limiting factors are most important, so only the events that are very likely to have limited transport were used. Table 6.3 was used to figure out which transport events had a limited aeolian transport and which ones had not. This table shows the transport class and wind event class distribution of all events, just like 6.1, but it indicates which combination of transport and wind classes have limited or unlimited transport.

Comparing the wind and transport classes doesn’t mean that a wind class and a transport class with the same number represent the same value for aeolian transport, because the classification was derived in two completely different ways. Comparing them however is still possible and shows that there is probably something going on with an event that has a large difference between its wind class and its transport class. For example: an event with a very large potential aeolian transport rate (wind class 5) also has a very small actual transport rate (transport class 1). An event like this is probably affected by a limiting factor. The events that are classified as a transport event with no aeolian transport are always limited, because the wind velocity of all wind events should be large enough to transport sediment. Events that are not or rarely limited on the other hand often have approximately the same wind and transport class. It is also possible for these events to have a higher transport class than wind class, which indicates that aeolian transport conditions were particularly good. It is still possible that there are still some limited events in a certain wind and transport class that is defined as unlimited, but that number is low compared to the number unlimited events there (less than 10%). This can also be the case the other way around. There are only a few combinations of transport and wind class that contain almost an even number of limited and unlimited events. They are treated as limited events in that case.

The cosine effect was not included in the wind event classes, because this was also not done during the classification of the transport event classes. The classification of the transport event classes is based on visual observations of the aeolian transport. It is not very difficult to visually estimate the total aeolian transport rate (in other words, to divide the events in very low, low, medium, high and very high transport events), but it is very hard to see how much of this sand ends up in the dunes. A dataset about transport classes with the cosine effect would be possible if sand transport data was collected. A few problems would show up when the current transport classes were compared to the wind classes with the cosine effect. For example; an event with a very high wind class (class 5, no cosine effect) has a small transport class (class 2). This large wind class becomes low when the cosine effect is considered, due to an alongshore wind (class 2, with cosine effect). An event with a very large potential aeolian transport rate and a small actual transport rate is probably affected by a limiting factor and stands out amongst the entire dataset due to this difference in classes. This however, is no longer visible when the cosine effect is used; it doesn’t look odd when the wind and transport class are both low. This event will look like it was a weak event, so it will be ignored. That is the reason why the cosine effect is ignored here. The number of small and very small wind events would have increased strongly if the cosine effect for the wind events was included.

Table 6.3: Combination of wind classes (no cosine effect) and transport classes. The green areas contain events with mainly unlimited events; the red ones contain mainly events limited aeolian sediment transport. The total sum, sum of the limited and sum of the unlimited events of the wind and transport classes are displayed as well.

		Transport class									
		no data	0	1	2	3	4	5	Total sum	Sum unlimited	Sum limited
Wind class	1	44	44	43	16	9	4	3	163	75	44
	2	128	97	151	47	67	58	16	564	339	97
	3	11	8	26	16	12	13	10	96	35	50
	4	9	10	17	16	4	14	15	85	29	47
	5	13	7	10	2	0	6	14	52	20	19
	Total sum	205	166	246	97	92	96	58	Total 960		
	Sum unlimited	unknown	0	194	62	88	96	58			
	Sum limited	unknown	166	52	35	4	0	0			

6.1.1 Characteristics unlimited events

It is possible to figure out the best circumstances for aeolian transport by defining the characteristics of unlimited events. There are 498 unlimited events out of the 960. Transport classes are called tc and wind classes wc. Events that have for example a wind class of 2 and a transport class of 3 are therefore called wc2-tc3 events.

Unlimited events are mainly classified as a small wind class event. This group is much larger than the other wind classes. This is mainly because the wc2-tc1 group is very large to start with. This is visible in table 6.3, in the green column of the sum of the unlimited transport events. The distribution of the transport classes of the unlimited events is shown in the green row with the name ‘sum unlimited’. This row shows that most of the unlimited events only cause little aeolian transport. There are many small transport events, which might explain why there are many events that do not seem to be limited. The second largest class on the other hand is transport class 4, for strong transport events. Strong and very strong events are not limited at all, which causes the relative high number of strong events here.

Figure 6.2 shows the wind velocity distribution and the transport classes of the unlimited transport events. This figure shows a peak around the southwest for almost every transport class. Quite a large part of the aeolian transported sediment ends up in the dune area with this wind direction, even with the cosine effect. That makes this wind direction probably the most important one for dune growth. The events that have a very low aeolian transport are the most spread over the various wind directions. There are only a few wind directions where their numbers are low, but these wind directions are not very common in the first place. These are for example the wind directions between northeast and southeast and the northwest. The transport class becomes more focused on the southwest when the transport class increases. This makes southwest the best wind direction for aeolian transport.

The wind velocity distribution looks similar to the one in figure 6.1. The most common wind direction is between 9 to 10 m/s. It is also here not possible to say if this is also the wind velocity that is responsible for most of the aeolian transport, because the actual aeolian transport rate must be known here as well. A figure about the wind velocity of unlimited events can be found in figure A10 in the appendix.

The wind direction and velocity also influence where on the beach aeolian transport takes place. Aeolian transport takes place over the entire width of the beach if the wind is strong (except often on bars). This can happen with medium sized transport events. The sand strips often start to develop close to the dune, but streamers are less bound to this area. The zone with sand strips start to expand from there towards the shoreline, if the wind conditions allow it. This is not the case for offshore winds, where aeolian transport starts to develop close to the shoreline.

Figure 6.3 shows the distribution of the unlimited events for each month. A clear pattern is visible for the occurrence of the classes of these events. Very small events are the most common class during the summer period. They are less common in the winter, but still occur quite often. Small and medium events are more or less evenly spread over the year, but large and very large transport events are more dominant during the winter. That is a comparable to the result that was predicted with the KNMI data. Figure A11 in the appendix shows that this distribution can vary strongly each year for the events that are unlimited.

The total number of the events for each month can be found in table 6.4. It shows that the months between February to July have a relative small amount of events compared to the other months. These are the months that also do not have any transport events in 2005, due to a problem with the cameras. However, this problem is probably not enough to cause this difference. The other months are not necessarily the months with the highest transport, because that is also determined by the wind strength of an event. This will probably be one of the winter months as well, because that is when the most strong and very strong events take place. There are however no actual transport measurements to confirm this.

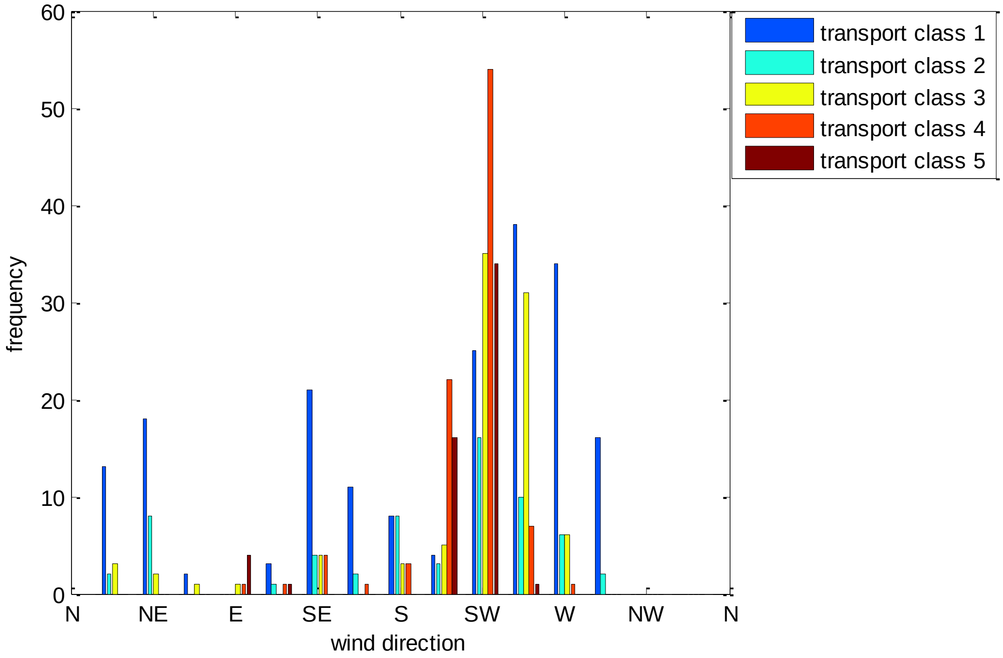


Figure 6.2: The wind directions of unlimited transport events.

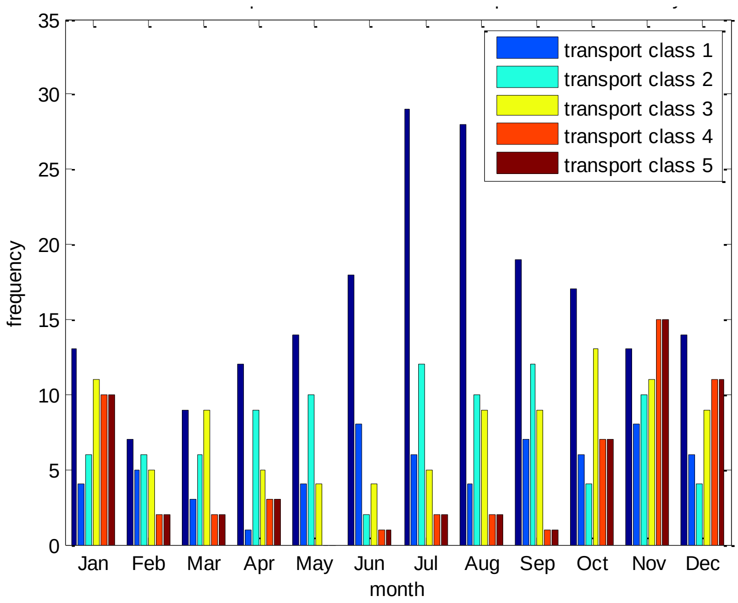


Figure 6.3: The monthly occurrence of unlimited transport events.

Table 6.4: The number of unlimited transport events occurring each month.

Month	Number of events
January	54
February	27
March	31
April	33
May	32
June	34
July	56
August	55
September	49
October	54
November	72
December	55

6.1.2 Characteristics limited events

There are 257 limited events. These events can be classified as a wind event of various sizes, although the largest wind class here is the one for small wind events. There are many events classified as a small wind event and that peak is visible here as well. Limited events cannot reach a large actual aeolian transport rate, so their transport classes are quite low. The number of wind classes of the limited events is visible in the red column with the name ‘sum limited’ in table 6.3. The number of transport classes of the limited events is shown in the red row with the same name.

Figure 6.4 shows the wind velocity distribution and the transport classes of the limited transport events. There is a large peak for events with no transport at a wind direction approximately from the west. It also shows a peak for winds from the southeast and the north-northeast. Very small and small transport events have often a west to southwest wind direction. Very small wind events show a smaller peak for winds from the southeast as well. There are also a few medium sized transport events. There are however only four of those events, which is not enough to say something about their wind direction.

The wind velocity distribution looks different from that in figure 6.1 and figure 6.2 for unlimited events. A figure of this graph can be found in appendix A12. There is a peak for wind velocities ($\bar{u}_{he}$) around 9 m/s and one for 12 m/s with a dip at 11 m/s between them. Events with these wind velocities were probably seen as an unlimited event. The class for small wind events includes wind events with a maximum hourly mean wind velocity of 9, 10 and 11 m/s. The events from this class that have a limited transport might be the ones that have the lowest velocity, while the events with a velocity of 11 m/s are just strong enough to be not affected by limiting factors. These wind events might have ended up in a higher transport class and are therefore not included in this graph.

The characteristics of limited events are different from unlimited ones or even the complete dataset. The difference between these characteristics is caused by the presence of various factors that limit aeolian transport. It is for example possible to see traces of fetch limited events in graph 6.4, where the wind direction is shown. The wind directions that are most common for limited events are not always suitable for large amounts of aeolian transport and can make the event fetch-limited.

Figure 6.5 shows the distribution of the limited events over a year. The events without aeolian transport show a dip during the summer month and a peak around March. The number of events with a very small aeolian transport varies each month. These events occur less often during the summer months and looks like there is a seasonal pattern in it, but a high peak in May and July disrupts this. The small transport events do almost not occur during winter and the medium sized transport classes are not numerous enough to say anything about it. There is not a very clear seasonal pattern visible in this figure, unlike this graph for unlimited events. There seems to be a large seasonal variability visible here, but there are not enough limited events to say more about that. A figure about this can be found in appendix A12. The total number of the events for each month can be found in table 6.5. It shows that the months between February to July have a relative small amount of events compared to the other months. These are not necessarily the months with the highest transport, because that is also determined by the wind strength of an event. This will probably be one of the winter months as well, because that is when the most strong and very strong events take place. There are however no actual transport measurements to confirm this.

Table 6.5: The number of limited transport events occurring each month.

Month	Number of events
January	21
February	27
March	32
April	21
May	26
June	13
July	18
August	16
September	14
October	22
November	22
December	25

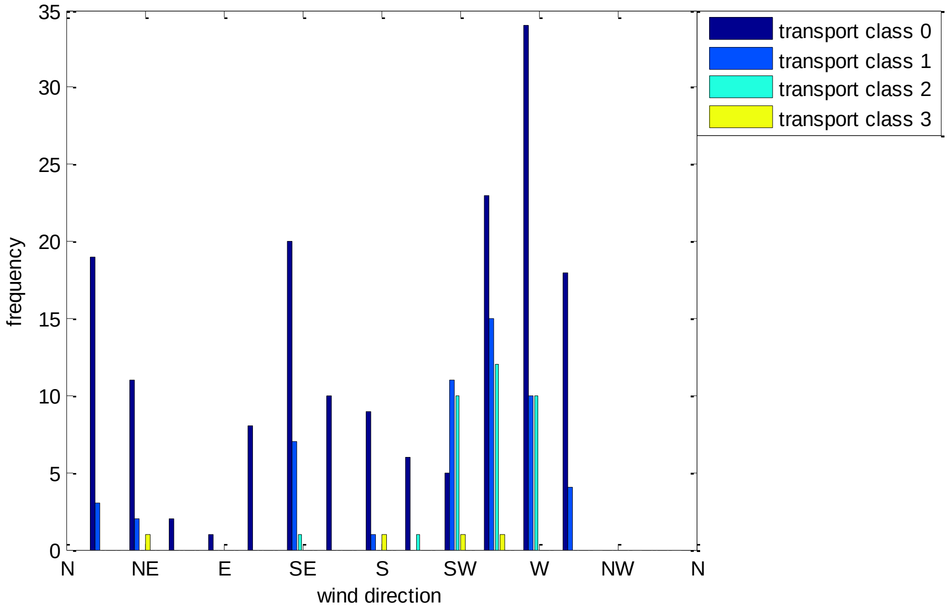


Figure 6.4: The wind directions of limited transport events.

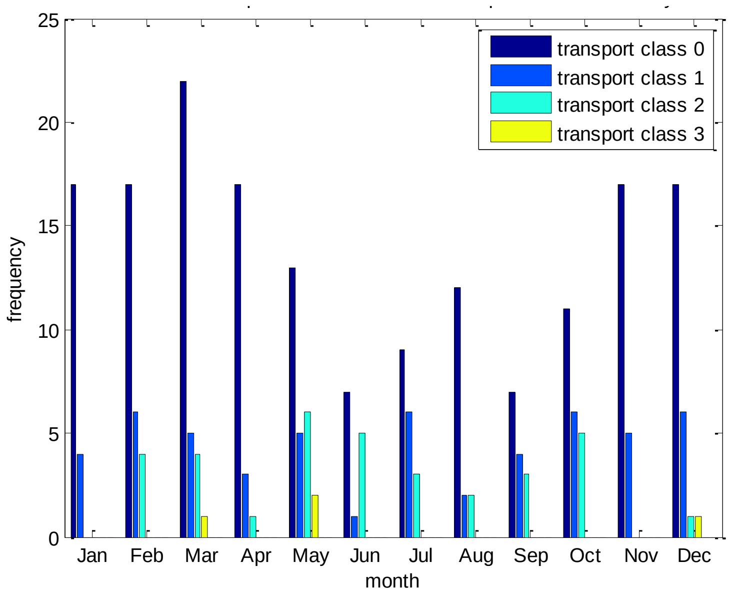


Figure 6.5: The monthly occurrence of limited transport events.

6.2 Limiting factors

A number of limiting factors were found when the Argus images were inspected by the method explained in the previous chapter. The limiting factors are: a short fetch length, a high moisture content, an unfavourable location of the intertidal bars, and the presence of snow and/or ice. Which limiting factor affects aeolian transport can be figured out by inspecting Argus images even further. Multiple Argus images of the same event are needed to see if an event suffers from a short fetch. The beach gets wider during low tide and shorter and high tide, which means that an event that takes place during high tide might be limited due to a short fetch. The Argus images taken after or before the maximum wind velocity of an event show an increase in aeolian transport if this is the case.

The moisture content of the beach can be seen on Argus images as well. Dark sand has an higher moisture content than light sand. A quantification of the moisture content is not possible, but a visual inspection can give an indication. Moisture due to rain is even better visible, due to raindrops that get stuck on the camera's housing. A situation without a moist beach must be compared to a situation with a moist beach to see if moisture is affecting the aeolian transport rate. That means that there are multiple Argus images needed here from the same event.

The location of the bars forms a limiting factor when the water between the bar and the beach becomes an obstacle for the sand that travels from the bar to the beach (or the other way round). This means that a broad beach can still be transport limited if it has bars that are not connected to the beach. There can still be limited aeolian transport when the bars and the beach are connected, because the area between the bar and the beach has a low elevation and is often quite moist. The bar itself can also be too moist for aeolian transport if the bar has a low elevation. Multiple images of the same event are needed here as well to see if the location of the bars affects aeolian transport. The location of the bar may change during an event and the Argus images can show how the bar changes and if aeolian transport will improve due to this or not.

The presence of snow and frost can be determined from one Argus image. A blanket of snow protects the sand particles from getting lifted up into the air. The snow itself can get transported by the wind, which results in snow drifts. The downside is that snow can stick on the housing of the cameras, making the Argus image useless. It is not possible to see if the ground is frozen, but frozen water can give an indication.

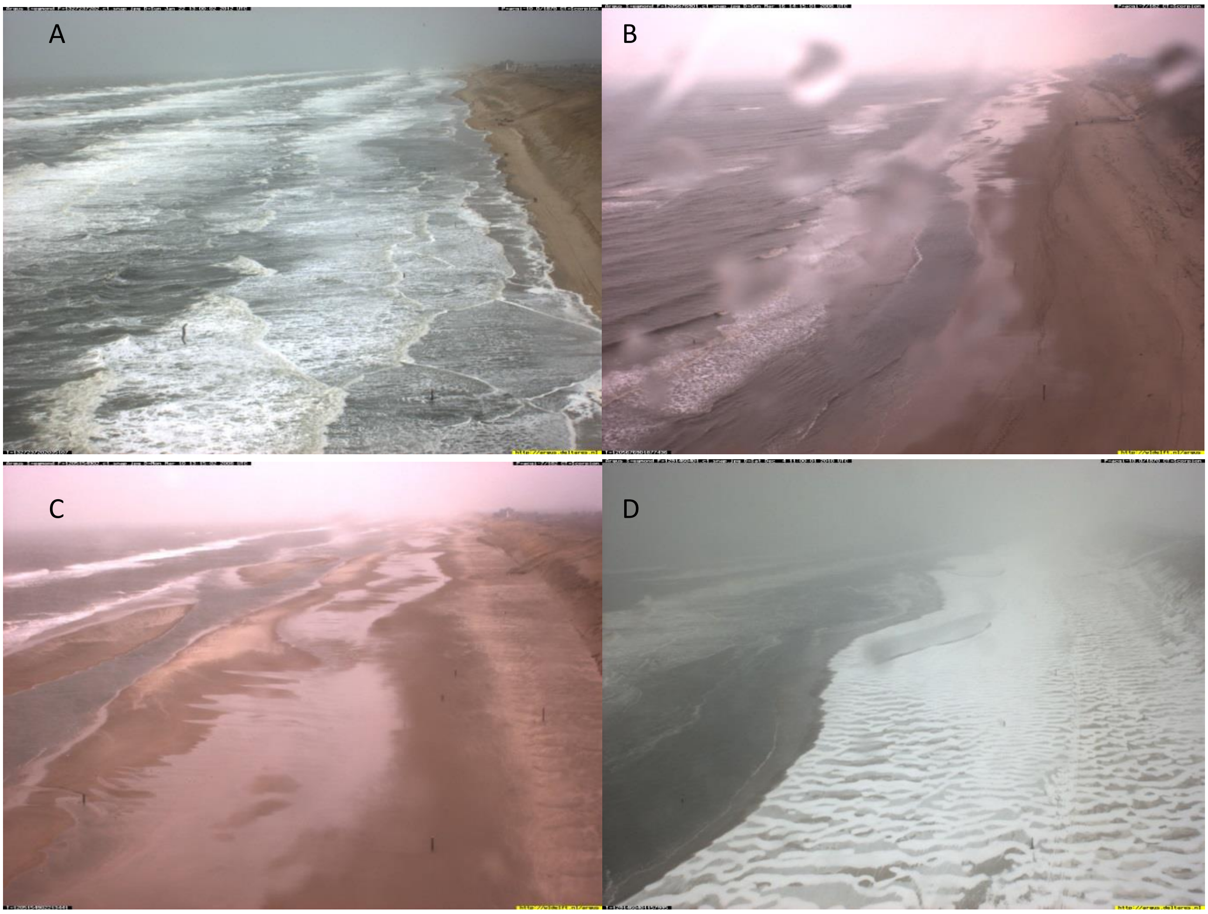


Figure 6.6: examples of events that are limited. A = fetch limited, B = limited by moisture, C = limited by the location of the bar, D = limited by snow/ice.

6.2.1 Checking events for limiting factors

Each combination of wind class and transport class was checked to see which limiting factors played a role. These limiting factors showed a pattern, which depended on the wind velocity.

Limiting factors for events with a low wind class

Overall, these events do not share the same characteristics. Their wind direction, beach shape and their limiting factors vary. Their wind velocity is just above the threshold velocity, so a limiting factor that would otherwise cause a small decrease in actual aeolian transport rate can be enough here to stop all aeolian transport. Even though there is a strong variation, there is still clearly a limiting factor that shows up more often than the other ones. This is a short fetch. This is not because the beach was very narrow; the beach in this category tends to be quite broad. However, the wind direction varies strongly and usually comes from the west of north-east in these cases, which are directions that do not favour aeolian transport. The beach must be extremely broad to create actual aeolian transport, especially when the wind velocity is not that high either. The fetch tends to be too short for aeolian transport when the wind is blowing from the west or east, but the circumstances should be better for winds coming from the northeast. There seems to be a different problem though, because the aeolian transport rate is low or zero here as well. It can be possible that local topography (dunes) disrupt the airflow, which makes aeolian transport only possible at the most seaward side of the beach. There are a few other events where the wind direction is quite favourable for large aeolian transport rates, but then there is another limiting factor that plays a role in that situation. Moisture is quite often a limiting factor, especially during rainy seasons. A snowy or frozen surface can limit aeolian transport too, but that is a rare situation.

The beach shape here can range from broad to narrow, with and without intertidal bars. Extremely narrow beaches, where there is almost no beach present anymore, are however rare for these low wind and low transport classes. The location of the bar often forms a limiting factor when the wind is blowing from the northeast or southeast to east. Aeolian transport seems only to take place with such winds when the beach is very broad. It stops here because the moist zone between bar and beach stops sediment from being picked up by the wind. The beach has various shapes for the events of this category; only extremely narrow beaches with possible dune erosion are rare.

In case there is aeolian transport; that can happen along entire beach width, but does not cover it completely. It usually happens in small, separated areas. Aeolian transport close to sea is possible when there are north-easterly winds. It happens more often close to dunes when wind velocity increases.

Limiting factors for events with a high wind class

The variation in weather type and limiting factor tends to become less when the wind velocity picks up. Beaches become narrower as well and a short fetch becomes very important as a limiting factor.

An high moisture content is more often a limiting factor here, but it is always present in combination with another limiting factor. The wind comes from different angles, except for the alongshore directions. This is probably the reason why fetch is quite important here, because the width of the beach is not long enough with these wind angles, especially when the beach is narrow to start with. Westerly winds become more dominant when the wind velocity increases and the weather turns stormier. The water level is very high due to the stormy weather, which sometimes creates dune erosion. Many of the events occurred during high tide, which also contributed to the high water level. This is especially the case for events with an high wind class. However, some events did show traces of aeolian transport when the beach was broader during low tide. The events here tend to happen most often during winter.

Aeolian transport tends to be small, if it even occurs. It can cover the entire beach sometimes, but tends to stay close at dunes. The beach is short here, so ‘entire beach’ and ‘close to dune’ are relatively similar. It almost never happens only at the shoreline.

Figure 6.7: Storm surge.

6.2.2 Occurrence of limiting factors

Table 6.6 shows how often a certain limiting factor plays a role. It shows that a short fetch is the main problem that prohibits sand transport. It is followed by moisture and the location of the bar. Snow, ice and frost are rare at the Egmond beach, so they will hardly form a problem for aeolian transport. Each limiting factor is studied to determine when they are likely to play a role. A table similar to table 6.6 can be found in the appendix (A14), which shows the occurrence of the limiting factors for each combination of wind and transport classes (these are the ones marked in red in figure 6.3).

Table 6.6: Occurrence of limiting factors. Note that these numbers about limiting factors were derived from the events with wind and transport classes that are marked red in table 6.3. This means that a few limited events can be missed. More than 1 limiting factor can take place at the same event, which is why the sum of the percentages can be higher than 100%.

Limiting factor	Fetch	Moisture	Bar location	Snow/ice
Number of events	177	103	38	15
Percentage of all events (%)	18,44	10,73	3,96	1,56
Percentage of limited events (%)	68,87	40,08	14,79	5,84

Fetch

Fetch is probably the most important factor that limits aeolian transport. The most ideal wind direction for dune growth is in theory west, but the beach at Egmond is so small that winds from this direction hardly cause any aeolian transport. It was found out during the classification that even small wind velocities are capable of transporting large amounts of sediment. This only occurred with shore-parallel wind directions. It is therefore possible to say that probably every event that is not a class 5 transport event is supply limited.

The very strong wind events show a very peculiar pattern when they are classified in transport classes; they are classified as a very large transport event (which means that they are not limited) or they are classified as relatively small transport event (which means that they are limited). These events are mostly limited by their short fetch length, which stops every form of aeolian transport or slows it down strongly. A closer look at these events shows that the tide plays a large role in this. The events that have a large wind class and a large transport class took place during low tide (or better: the Argus image used for classification was taken at low tide). The events that have a large wind class and a low transport class took often place during high tide. These events have strong winds from the west and can even cause dune erosion. There are very short to no beaches in these cases, which make the aeolian transport fetch limited. There are only a few transport events that were classified this way, compared to the number of events in total.

Moisture

Moisture seems only to be an effective limiting factor for events with relatively small wind velocities. The sediment transport rate seems not to be effected by moisture as soon as the wind picks up speed. The fetch length is often the only limiting factor at those wind velocities. This is nicely illustrated by short showers that occur during events. A small aeolian transport rate can be present at the first part of an event, but this stops as soon as a shower passes over. Aeolian transport might take place again when the sand has dried enough, but this might take a while or it will not happen at all. The aeolian transport rate can remain very high for events with strong winds on the other hand, even if the surface is very wet. The transport rate might become temporarily lower when a shower passes over, but the transport rate usually becomes as high as it was before as soon as the rain stops.

Location bar

The location of the bar forms a limiting factor when the wind is blowing from landward directions, especially the northeast. There is also a large peak for winds from the southwest, but is probably because there are many events from the southwest to start with. The water or moist area between the bar and the beach forms a barrier for aeolian transport.

Seaward winds which cause aeolian transport do that at the shoreline. These are often north-easterly winds, but they have a very low transport class, even though other limiting factors seem not to be present. A close look at the images of events with these winds revealed that traces of sediment transport occur close to the shoreline, which happens only at relatively wide beaches. An explanation for this can be that the airflow gets disturbed by the local topography. The dunes can distort the airflow and create a zone of no wind at their lee side, where aeolian transport is not possible.

The location of the bars seems to be most important for seaward winds. These winds need broad beaches to create any aeolian transport at all. Their wind velocity tends to be small as well, so transport will therefore not happen when there is water or moisture present between the bar and the beach.

Snow, ice and frost

Snow, ice and a frozen surface are rare as a limiting factor, because it is often not cold enough at Egmond for this. There can be snow drift during these events, which looks quite the same as sand strips or streamers, but with snow instead of sand.

7. Discussion

The distinction between potential transport events and no potential transport events is based on the threshold wind velocity. The wind velocity measured by the KNMI must surpass a certain threshold velocity to bring sediment in motion. This was here the shear velocity u_* which had to surpass the threshold velocity u_{*t}. They were calculated according to equation 1 and 2. However, equation 2 requires a value for the threshold velocity (u_t) which is unknown for the Egmond site. There are several methods to determine this parameter. The value used here, 6 m/s, comes from Delgado-Fernandez and Davidson-Arnott (2011). They used this number for a similar research at Greenwich Dunes in Canada. They have derived this number from their own field measurements and by research done by Belly (1964) and by using Bagnold's equation (1941):

$$u_t = 5.75 * u_{*t} * log\left(\frac{z}{z'}\right) + u'_t = 6.1\ m/s \qquad (5)$$

z' is the roughness surface factor and u'_t the threshold wind velocity at a height of z'. z is the height where wind velocity measurements were done. The values for them are:

$$\mathrm{z} = 3.05 * 10^{-3}\ \mathrm{m}$$
$$\mathrm{u'_t} = 2.74\ \mathrm{m/s}$$
$$\mathrm{u_{*t}} = 0.16\ \mathrm{m/s}$$

Which result in an u_t of 6 m/s.
u_t can also be calculated from Bagnolds equation:

$$u_t = 5.75 * A * \sqrt{(\rho_s - \rho_a)/\rho_a * g * d} * log(z/k) \qquad (6)$$

Where A is 0.1, ρ_s is the density of the sand (2650 kg/m^3), ρ_a the density of the air (1.225 kg/m^3), g the gravitational acceleration (9.81 m/s), d the grain size (0.00024 m), which results in u_t = 4.75 m/s. This is however too low according to Delgado-Fernandez and Davidson-Arnott (2011). 6 m/s as the value for u_t is used here, like Delgado-Fernandez and Davidson-Arnott did. This was chosen because Davidson-Arnott and Delgado-Fernandez did their research at Greenwich Dunes, Canada, which has quite similar characteristics as the Egmond beach.
The classification of the wind events is based on their transport rate. There are several equations which can be used to calculate potential aeolian transport rates. There can be quite a difference between the transport rates of these equations. Two of these are the equations by Kawamura (1951) and Hsu (1974), which are compared to each other to illustrate their difference. The equation by Hsu is equation 3 in chapter 2.2. The adapted equation by Kawamura is:

$$Q = C_k * \frac{\rho}{9} * (u_* - u_{*t}) * (u_* + u_{*t})^2 * \frac{3600}{\rho_p} * (1 - p) * cos\,\alpha \qquad (7)$$

Where Ck is the Kawamura constant (2.78).
The potential aeolian transport calculated by the equation Hsu was much lower compared to that of Kawamura, which is visible for the yearly amount of potential sediment transport in figure 7.1. According to Sherman and Li (2012), the Kawamura equation over predicts the amount of aeolian

transport. The Hsu equation was used in further calculations during this research, due to its relative simplicity and quite good results. Still, these results were used relatively to see when the largest aeolian transport could be expected. It can be seen in the figure below that both the Kawamura and the Hsu equation agree on the relative amount of aeolian transport. That is more important in this research, because the events get classified and numerical values about aeolian transport are not used after that classification. De Vries et al. (2012) calculated the dune growth rate, which was found to be between 0 to $6.4*10^4$ kg/m/year. The volumes calculated with the equation by Hsu match these values, which was another reason to use this equation.

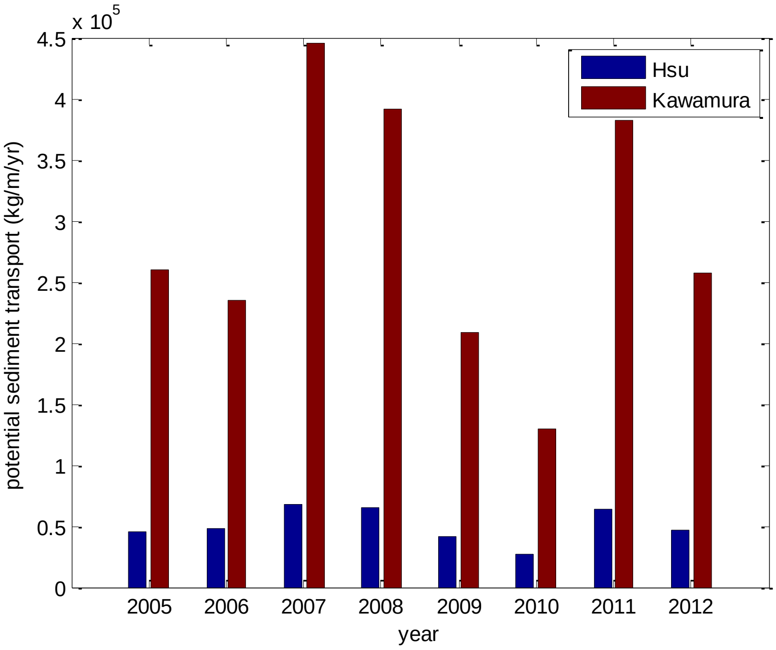


Figure 7.1: The potential sediment transport rats for each year, calculated with the equations by Hsu and Kawamura. These volumes include the cosine effect.

The minimal duration of an event must be 4 hours to transport a significant amount of sediment. This however depends largely on the wind strength of an event; a strong event can transport a high amount of sand in a shorter amount of time. Some wind events are missed due to this. It can be a good idea to make the minimal duration of an event dependable on its wind velocity, where an event with a high wind velocity has a shorter minimal duration than an event with a low wind velocity.

Picking only one moment to represent an entire event creates some problems: sometimes an event first creates a high transport rate, but later causes severe dune erosion when it is high tide. This moment of erosion is however not included in the classification. Some wind events had such a long duration that they covered multiple days, but there is only one Argus image chosen to represent that event. How this moment is chosen is explained in chapter 5.2. It is possible more than one moment gets defined as the strongest moment of the wind event, as long as these moments happen on different days. Only one of these moments was chosen to represent the entire event, which was the one that occurred first. It is therefore possible that an event could have had a different transport classification if the other moment was chosen to be used for classification.

There are some remarks on the classification process. Visual classification was here done by one person. This classification will improve if the dataset was checked by a second observer. The dataset was checked multiple times, but that still makes it possible that how events are classified slightly changes over time.

Not all events were checked for limited transport, which would otherwise take too much time. This happened for events that have a combination of a wind and transport class that is very common, which is for example the case for events with a wind class of 2 and a transport class of 1. Table 6.3 in chapter 6.1 gives an overview of the occurrence of these wind and transport classes. A few (approximately 20) events of each transport and wind class combination were checked. No other events were checked if most of them (90%) were unlimited. This means that there are a few limited events in the dataset that were not studied properly.

The direction of the sand strips can give an indication about the amount of sand that gets transported to the dunes. Figure 7.2 shows the sand strip/streamer direction compared with the wind direction. 0 degrees is in the cross-shore direction, 90 is in the northern alongshore direction and -90 the southern one. It shows that sand strips often travel parallel to the shoreline from south to north. The wind direction on the other hand is more oriented around -50 degrees (southwest). Sand strips do have more alongshore orientation than wind direction; the dunes can disturb the wind pattern and create different wind conditions very locally at the dune's foot. This illustrates that the wind direction measured at a weather station can be quite different from the local wind direction. The amount of sediment that ends up in the dunes becomes less due to this change in direction of the sand strips.

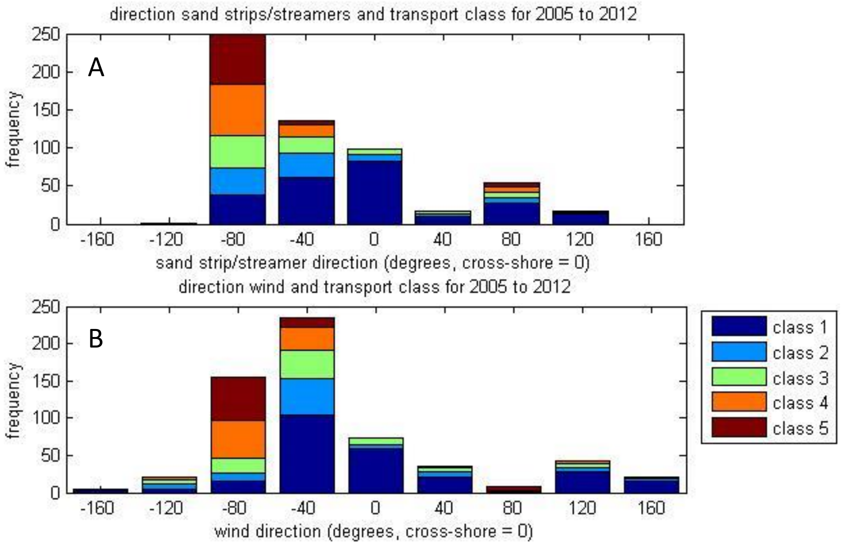


Figure 7.2: The direction of the sand strips (A) and the direction of the wind (B).

The Argus images can be hard to study. Remnant sand strips make classification difficult, because they make it look like there is aeolian transport at first glance, while this is not the case in reality. They also make it difficult to see in what direction the sand gets transported, because the remnant strips tend to steer the transported sand in a certain direction. This sand usually ends up in the troughs between remnant strips.

Aeolian transport can be hard to classify, especially with cross-shore wind directions. The beach is often too narrow to form decent sand strips. The sand here blows over the beach, but it does not look like streamers. This type of transport gets often classified as a low transport class. It is however hard to estimate how much sand gets transported this way and therefore what class it should get.

A disadvantage of this type of study is the lack of other measurements to quantify these results. It is now not known what the volume of the sediment is that ended up in the dunes over this period of 8 years. It makes it hard to say what kind of transport event is more important for transport towards the dunes: one with a medium strength with winds from the west or a very strong event with winds that travel almost cross-shore. The duration of a transport event will be known as well if there were other measuring methods. That is now not possible, because many of the wind events take place during the night. The Argus cameras are useless during those moments. The duration of an event can be used to calculate how much sediment gets transported during a single event. Aeolian transport is sometimes hard to see as well. This is possible when there is a thick fog or rain/snow on the housing of the camera, but also during nice weather. There must be a colour difference between the sand strips and the surface, otherwise the movement of sand will not be visible. The beach can look very bright when the sun is shining on it, which makes it harder to see traces of aeolian transport, especially when there is just a small amount of transport. Using two cameras can sometimes solve this problem; there might be a useful photo left if only one of the cameras fails.

The wind data was not derived from the same location as where the beach images were made. The weather station in de Kooy is approximately 40 km north from the Coast3D tower at the Egmond beach. Local wind condition might be different at the weather station than on the beach. The wind velocity might be higher at the Egmond beach than at the weather station in de Kooy, which is located more inland where wind velocities tend to be lower. The dunes might disrupt the airflow as well, creating a different, local wind direction. A weather station at the same position as the tower would be ideal, but was not possible here. But the KNMI data was still good and useful, even though there is quite some distance between the Argus tower and the weather station.

8. Conclusion

The dunes in the Netherlands protect the low lying area behind them from flooding and it is therefore important that these dunes are high and strong. Aeolian transport is the mechanism that makes dunes grow and must therefore be studied properly. The studied area in this research, the beach south of Egmond aan Zee, is very narrow and does not always show aeolian transport when that is expected. It is important to understand why this is happening, and under what conditions one can expect large aeolian transport rates. This is even more important for a narrow beach, where the dunes are more easily damaged by storm surges. This brings us to the first main question of this research:

1: Which events determine meso-scale sand transport to the dunes?

A long fetch, a strong wind and a westerly wind direction are needed in theory to create the largest potential aeolian transport rate to the dunes for the Egmond coast. KNMI weather data was studied to find out what weather conditions are common at Egmond and which of those conditions are potentially responsible for most of the aeolian transport.
The most ideal situation in theory would be a very strong wind event with a long duration and a westerly wind, as long as the fetch is long enough as well. The wind at Egmond aan Zee is blowing often from the west, but the KNMI data shows that the southwest is a more common wind direction. This is quite a good direction regarding aeolian transport, because a large part of the sediment that potentially gets transported can end up in the dunes, despite the cosine effect. Winds from the south and north sometimes create much aeolian transport, but not much of it ends up in the dunes, due to this effect.
The wind velocity determines the aeolian transport rate; strong winds are favourable here, because they potentially cause the strongest aeolian transport. Strong winds are however less common than weak ones. The most common hourly mean wind velocity ($\bar{u}_{he}$) is 5 m/s for example, which is not even strong enough to bring particles in motion. The wind velocity that is responsible for most of the aeolian transport will therefore not be the largest velocity or the most common one, but the product of the potential transport rate and the number of events. The duration of an event can be part of this product too, because the wind velocity tends to increase when the duration of an event increases. However, the variance of this is very large for the Egmond beach. The wind events for which one would expect the highest aeolian transport are therefore events with a wind velocity ($\bar{u}_{he}$) of approximately 9 m/s. That is for a situation where the cosine effect is not taken into consideration; 11 m/s is more favourable for a situation with the cosine effect, because this effect leads to a stronger decrease in transport rates on low wind velocities. The highest potential transport rate occurs in February. This is mainly because the strongest wind events occur in that month, so the winter months will potentially cause more aeolian transport than the summer months.
The Argus images must be investigated to see if these weather conditions do indeed cause the most aeolian transport. Good weather conditions for aeolian transport were determined by looking at what kind of circumstances the unlimited transport events took place. The transport events that are not affected by a limiting factor also tend to come from the southwest, just like it was predicted. How stronger the unlimited transport event was, the more likely it came from this direction. However, it is important to note that the wind direction and the direction of the streamers and sand strips are not always the same. The sand strip direction tends to change direction when they come

close to the dunes, which can be caused by local wind conditions. The sand strips turn often to a more alongshore direction, which does not enhance dune growth. This occurs often for wind directions with and angle of (-)60^{O} to (-)80^{O} from the cross-shore direction. The local topography probably changes the wind direction in front of the dunes, which alters the direction of the sand strips. A wind direction of about 45^{O} will be responsible for a large part of the sediment that is transported towards the dunes. It is however partly based on visual inspection and no actual transport rates towards the dune are known. It is therefore hard to say what kind of event is more important for dune growth: a large event with a wind direction that is almost shore parallel will a strong aeolian transport, with a relative small part of that transported sand ending up in the dunes or a medium-sized event with a wind direction that is almost cross-shore, where much of the transported sand ends up in the dunes.

The most common hourly mean wind velocity for the hour with the highest mean wind velocity ($\bar{u}_{he}$) for unlimited transport events is 9 to 10 m/s. This is comparable with the same wind velocity ($\bar{u}_{he}$) of all events, which is 9 m/s or 11 m/s (without and with cosine effect). What wind velocity causes the most aeolian transport in realty is unknown, because the actual transport rate must be known for this as well.

In theory, most potential transport happens in January, but this is not necessarily the month with most events. Strong and very strong wind events tend to happen during the winter months, which will probably make the aeolian transport rate larger during winter.

The actual conditions that cause the most of the aeolian transport are therefore quite the same as the ones that were predicted. However, there are quite some events left that were predicted to have aeolian transport and did not have it or had it in a lesser amount. This is more common for strong wind events than weak ones. They must therefore suffer from limiting factors, which brings us to the next main question:

2: What are the most important limiting factors for a narrow beach?

Different limiting factors can occur at the same time during an event, which is why the sum of the percentages can become larger than 100%. Fetch is probably the most important factor that limits aeolian transport. It was found out during the classification that even small wind velocities are capable of transporting large amounts of sediment. This only occurred with shore-parallel wind directions. It is therefore possible to say that probably every event that is not a class 5 transport event is supply limited. There are not that many events with a very large wind class. These very strong wind events show a very peculiar pattern too when they are classified in transport classes; they are or classified as a very large transport event (which means that they are not limited) or they are classified as relatively small transport event or as a no transport event (which means that they are limited). These events are mostly limited by their short fetch length, which stops every form of aeolian transport or slows it down strongly. A closer look at these events shows that the tide plays a large role in this. The events that have a large wind class and a large transport class took place during low tide (or better: the Argus image used for classification was taken at low tide). The events that have a large wind class and a low transport class took often place during high tide. These events have strong winds that have a western direction. The events that cause dune erosion have westerly winds as well. There are only a few transport events that were classified this way compared to the number of events in total.

Seaward winds which cause aeolian transport do that at the shoreline. These are often north-easterly winds with often a very low transport class, even though other limiting factors seem not to be present. A close look at the images of events with these winds revealed that traces of sediment transport occur close to the shoreline, which happens only at relatively wide beaches. An explanation for this can be the disturbed airflow by the local topography. The dunes can distort the airflow and create a zone of no wind at their lee side, where aeolian transport is not possible. The location of the bars seems to be most important for these seaward winds. These winds need broad beaches to create any aeolian transport at all. These are often events with weak winds, but with a broad beach. Transport will therefore often not happen when there is water or moisture present between the bar and the beach.

Moisture seems only to be an effective limiting factor for small wind events. The sediment transport rate seems not to be effected by moisture as soon as the wind picks up speed. The fetch length is often the only limiting factor at those wind speeds. This is nicely illustrated by short showers that occur during events. A small aeolian transport rate can be present at the first part of an event, but this stops as soon as a shower passes over. Aeolian transport might take place again when the sand has dried enough, but this might take a while or it will not happen at all. The aeolian transport rate can remain very high for events with strong winds on the other hand, even if the surface is very wet. The transport rate might become lower when a shower passes over, but the transport rate often becomes as high as it was before as soon as the rain stops.

Snow, ice and a frozen surface are rare as a limiting factor, because it is often not cold enough at Egmond for this. There can be snow drift during these events, which looks quite the same as sand strips or streamers, but with snow instead of sand.

References

Literature

Arens, S.M. (1996) *Rates of aeolian transport on a beach in a temperate humid climate.* Geomorphology, volume 17, pp. 3 - 18

Bagnold, R.A. (1941) *The physics of blown sand and desert dune*s, London: Chapman & Hall

Bauer, B.O., Davidson-Arnott R.G.D. (2002) *A general framework for modeling sediment supply to coastal dunes including wind angle, beach geometry, and fetch effects,* Geomorphology, volume 49, issue 1–2, pp. 89–108

Davidson-Arnott, R.G.D., Law, M.N., 1990. *Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie.* In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.), Coastal Dunes: Form and Process. John Wiley & Sons Ltd, pp. 177–200

Delgado-Fernandez, I. and Davidson-Arnott, R.G.A. (2011) *Meso-scale aeolian sediment input to coastal dunes: The nature of aeolian transport events.* Geomorphology, volume 126, issue 1-2, pp. 217-232

De Vries, S., Southgate, H.N., Kanning, W. and Ranasinghe, R. (2012) *Dune behavior and aeolian transport on decadal timescales.* Coastal Engineering, volume 67, pp. 41–53

Holman, R.A. and Stanley, J. (2007) *The history and technical capabilities of Argus.* Coastal Engineering, volume 54, pp. 477–491

Houser, C. (2009) *Synchronization of transport and supply in beach-dune interaction.* Progress In Physical Geography, volume 33, no. 6, pp. 733-746

Iversen, J.D. and Rasmussen, K.R. (1999) *The effect of wind speed and bed slope on sand transport.* Sedimentology, volume 46, pp. 723-731

Hsu, S.A. (1974) *Computing aeolian sand transport from routine weather data,* Proc. 14th Coastal Engineering Conf., ASCE, New York, pp. 1619‑1626

Lynch, K., Jackson, D.W.T. and Cooper, J.A.G. (2008) *Aeolian fetch distance and secondary airflow effects: the influence of micro-scale variables on meso-scale foredune development.* Earth Surface Processes and Landforms, volume 33, issue 7, pp. 991–1005.

Nickling, W.G. and McKenna-Neuman, C. (2009) *Aeolian sediment transport.* A.J. Parsons, A.D. Abrahams (eds.), Geomorphology of Desert Environments, 2nd ed., 517 pp., Springer Science+Business Media B.V. 2009

Rice, M.A. (1991) *Grain shape effects on aeolian sediment transport*. Aeolian Grain Transport 1, Acta Mechanica Supplementum, volume 1, pp. 159-166

Ruz, M.H. and Meur-Ferec, C. (2004) *Influence of high water levels on aeolian sand transport: upper beach/dune evolution on a macrotidal coast, Wissant Bay, northern France.* Geomorphology, volume 60, pp. 73–87

Sherman and Bauer, B.O. (1993) *Dynamics of beach-dune systems,* Progress in Physical Geography volume 17, pp. 413-417

Sherman, D.J. and Li, B. (2012) *Predicting aeolian sand transport rates: A re-evaluation of models,* Aeolian Research, volume 3, pp. 371–378

Digital sources

AHN: *Algemeen Hoogte bestand Nederland, an interactive map which shows the elevation of the Netherlands.*
Available at: http://ahn.geodan.nl/ahn/ (20-01-2014)

Argus coast3D Tower: *Argus data, with Argus images from several years and locations. The data from the coast3D Tower is used here.*
Available at: http://argus-data.wldelft.nl/argus/index.html (20-01-2014)

Flickr: *Photo of the Coast 3D tower at Egmond.*
Available at: http://farm6.staticflickr.com/5215/5465789668_a922b571f1_z.jpg (20-01-2014)

KNMI de Kooy: *Information about the weather station at de Kooy.*
Available at: http://www.knmi.nl/klimatologie/metadata/dekooy.html (20-01-2014)

KNMI Handboek Waarnemingen; *Information about measurements at weather stations.*
Available at: http://www.knmi.nl/samenw/hawa/pdf/Handboek_H01.pdf (20-01-2014)

VTV: *Voorschrift toetsen op Veiligheid Primaire Waterkeringen (VTV2006) Open Earth tool with grain size data from Rijkswaterstaat.*
Data can be downloaded at: http://kml.deltares.nl/kml/rijkswaterstaat/ (20-01-2014)

Appendix

A1 Table with the number of events for each year.

A2 Table with the mean potential transport rate per event per year, with and without the cosine effect.

A3 Table with the mean wind velocity of an event for each month, every year.

A4 figure with the monthly distribution of the wind events for each year, without the cosine effect.

A5 figure with the monthly distribution of the wind events for each year, with the cosine effect.

A6 Table with the start and end of daylight for each month.

A7 Figure with the occurrence of the transport classes for every year.

A8 Table with the wind classes versus the transport classes, no cosine effect.

A9 Figure with the wind classes versus the transport classes, with cosine effect.

A10 Figure with the wind velocity distribution of unlimited events.

A11 Figure with the monthly distribution of transport classes of unlimited events.

A12 Figure with the wind velocity distribution of unlimited events.

A13 Figure with the monthly distribution of transport classes of unlimited events.

A14 Table with the occurrence of limiting factors for different combinations of wind and transport classes.

A1

Table A1: The number of events for each year. The total number of events is 960.

Year	Number of events
2005	105
2006	114
2007	122
2008	146
2009	124
2010	102
2011	124
2012	123

A2

Table A2: The mean potential transport rate per event per year, with and without the cosine effect.

Year	Mean potential transport rate per event (kg/m)	Mean potential transport rate per event with cosine effect (kg/m)
2005	695.4	363.8
2006	734.6	337.1
2007	847.5	484.1
2008	769.1	375.2
2009	577.5	241.2
2010	518.2	127.0
2011	763.3	426.6
2012	577.7	286.5

A3

Table A3: The mean wind velocity of an event for each month, every year. The maximum, mean hourly wind velocity is used here to calculate this.

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Jan	11,08	9,71	13,23	11,72	10,38	10,00	10,23	11,30
Feb	10,33	10,42	10,43	10,73	10,33	9,88	9,46	9,80
Mar	10,78	9,93	10,41	12,13	10,70	9,83	10,67	9,50
Apr	10,57	10,31	9,33	9,83	9,20	9,43	9,33	10,38
May	9,62	11,25	11,22	9,60	9,90	8,80	11,18	9,50
Jun	9,33	9,75	9,75	10,50	9,83	8,33	9,60	11,33
Jul	10,67	9,75	10,67	9,77	10,21	10,40	10,78	9,42
Aug	9,33	9,13	9,63	10,29	9,75	9,44	10,00	9,60
Sep	8,89	9,83	10,60	10,00	10,43	10,38	11,25	10,19
Oct	10,80	10,73	9,40	10,71	10,00	9,77	10,07	10,31
Nov	10,36	10,81	10,15	10,60	12,00	10,20	10,25	10,83
Dec	9,44	11,73	11,27	9,00	9,77	9,67	11,33	10,69
Yearly mean	10,10	10,28	10,51	10,41	10,21	9,68	10,35	10,24

A4

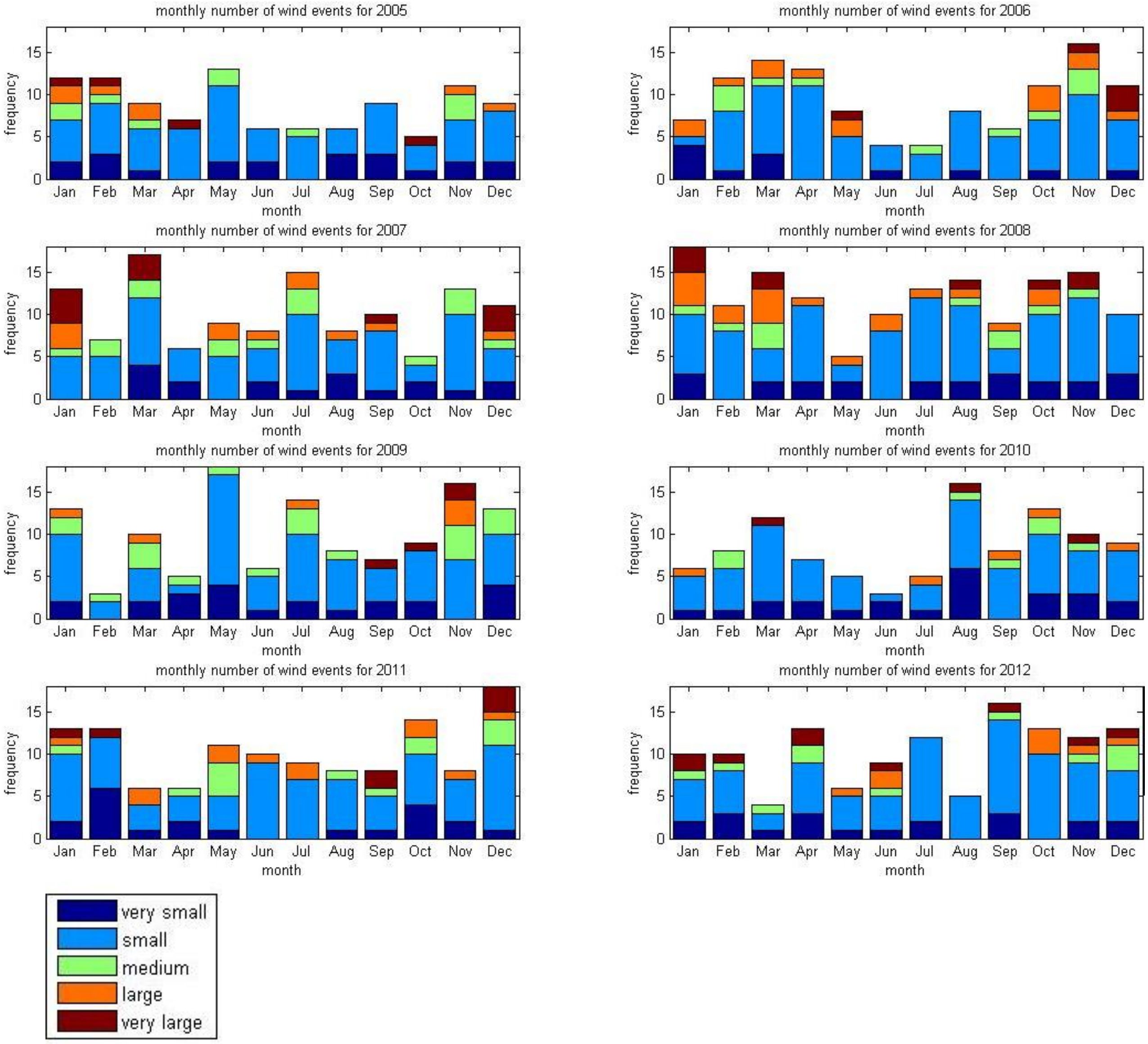


Figure A4: The monthly distribution of the wind events for each year, without the cosine effect.

A5

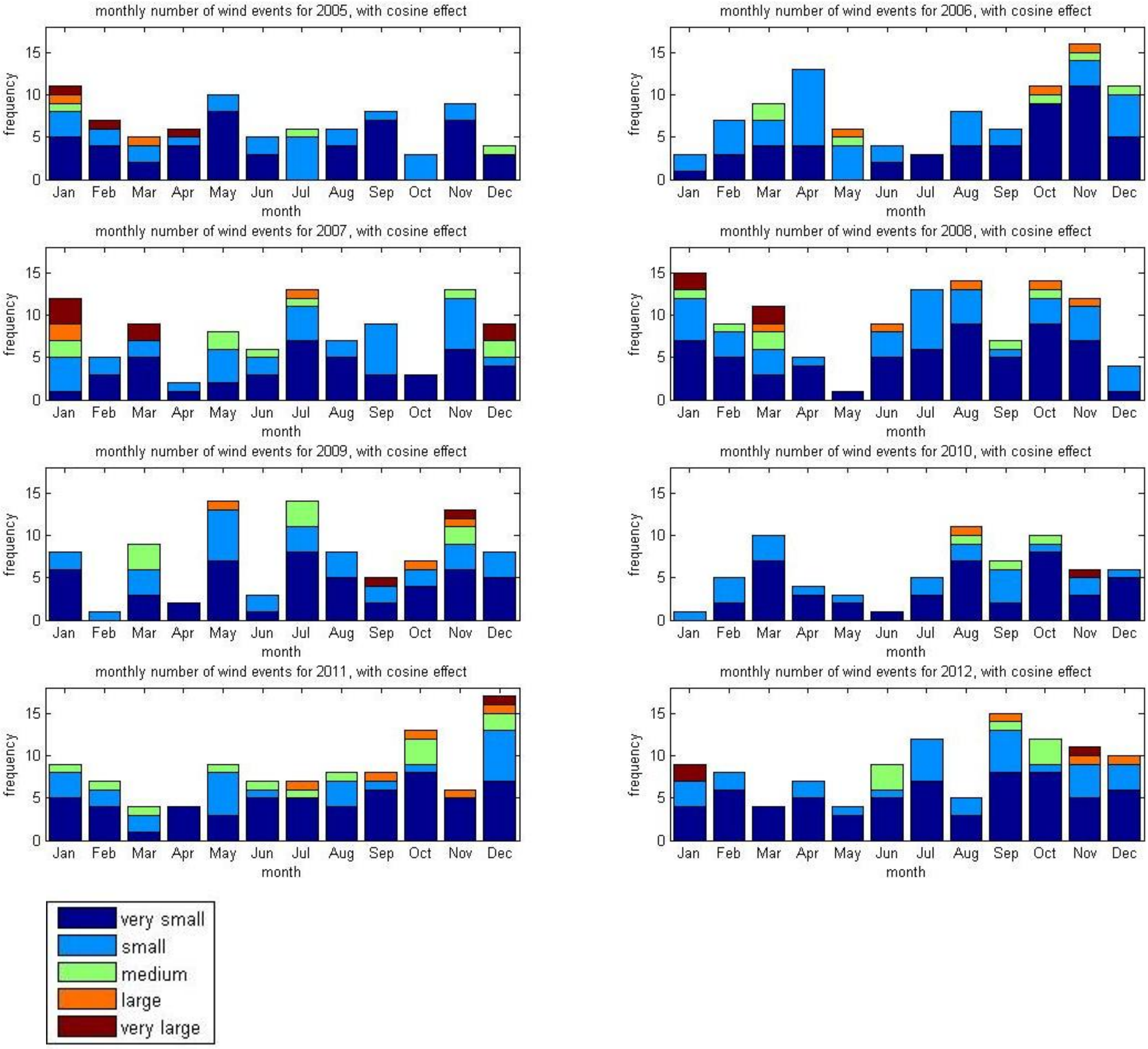


Figure A5: The monthly distribution of the wind events for each year, with the cosine effect.

A6

Table A6: The start and end of daylight for each month.

month	start daylight (h)	end daylight (h)
January	8	16
February	7	17
March	6	17
April	5	18
May	4	19
June	4	20
July	4	20
August	5	19
September	6	18
October	6	17
November	7	16
December	8	15

A7

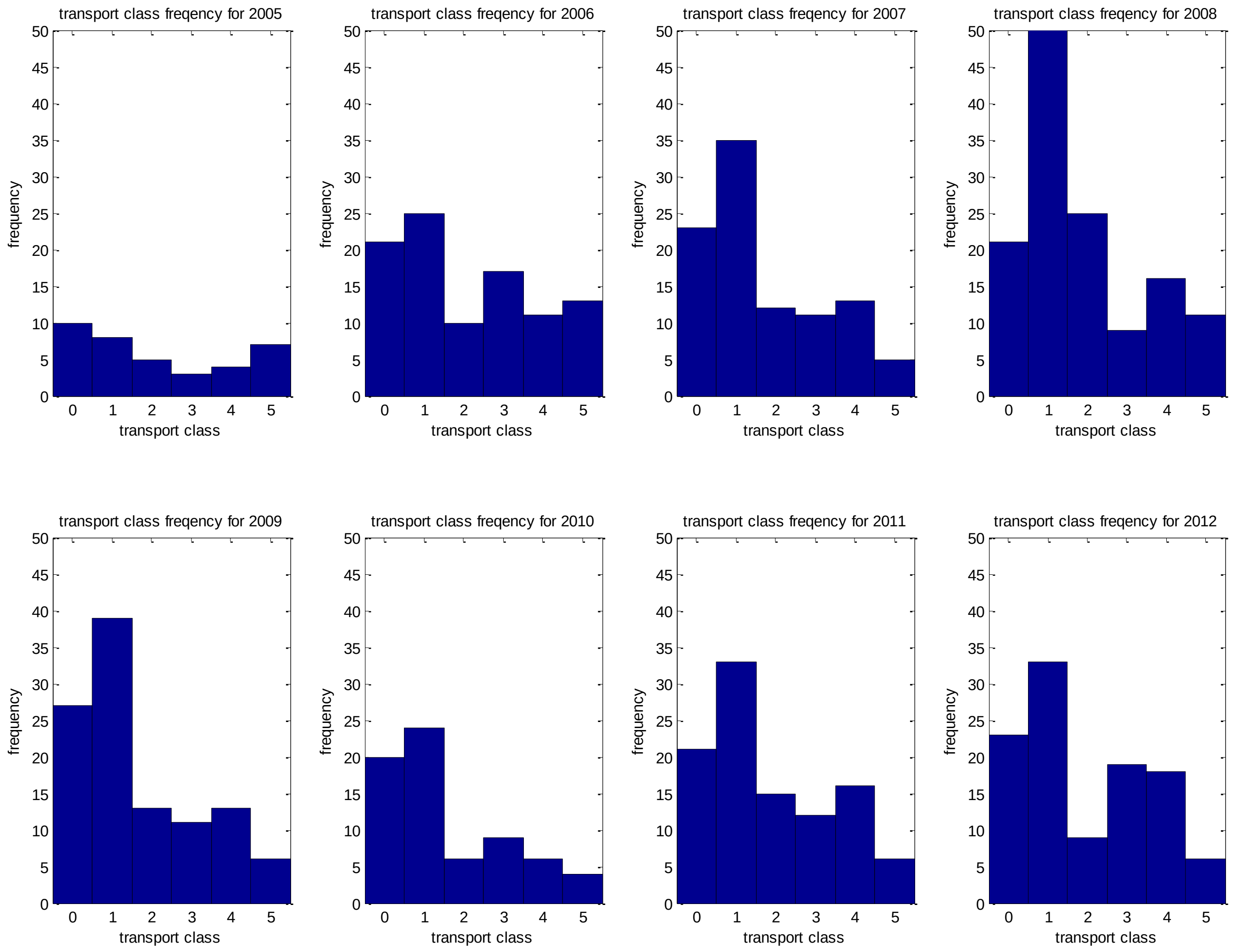


Figure A7: The occurrence of the transport classes for every year from 2005 to 2012.

A8

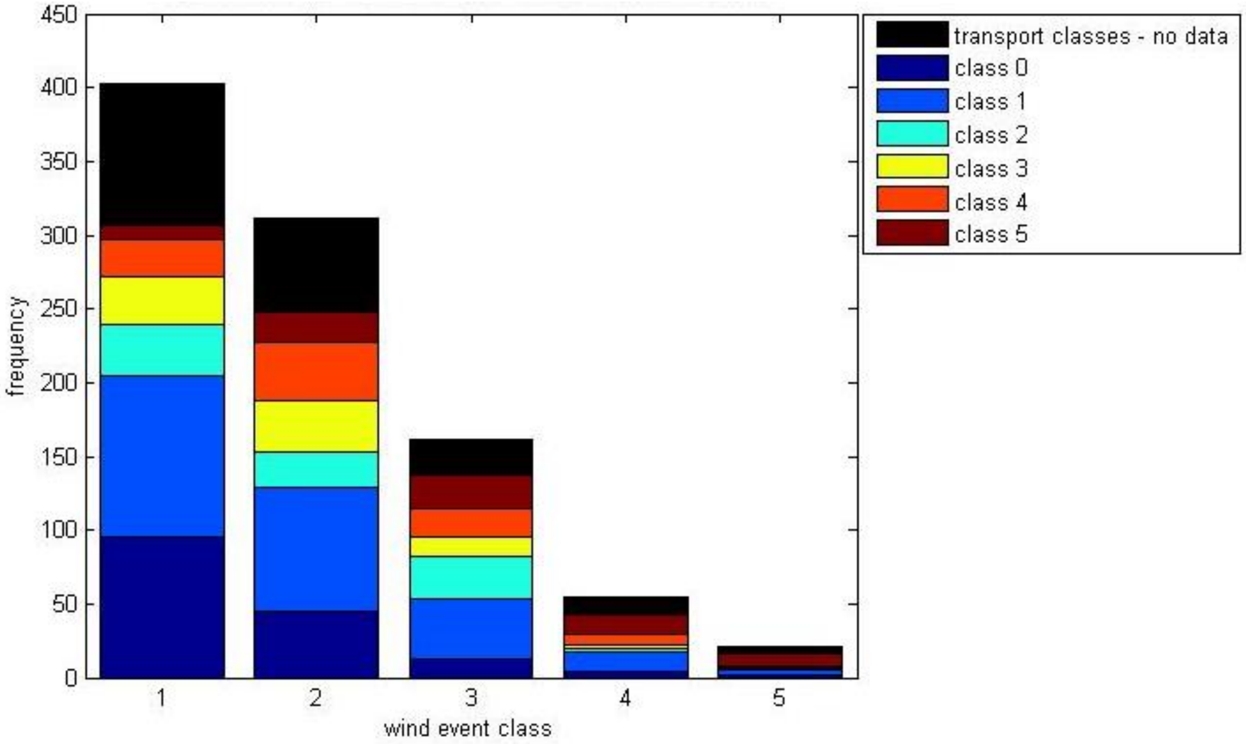


Figure A8: Wind classes versus transport classes, no cosine effect.

A9

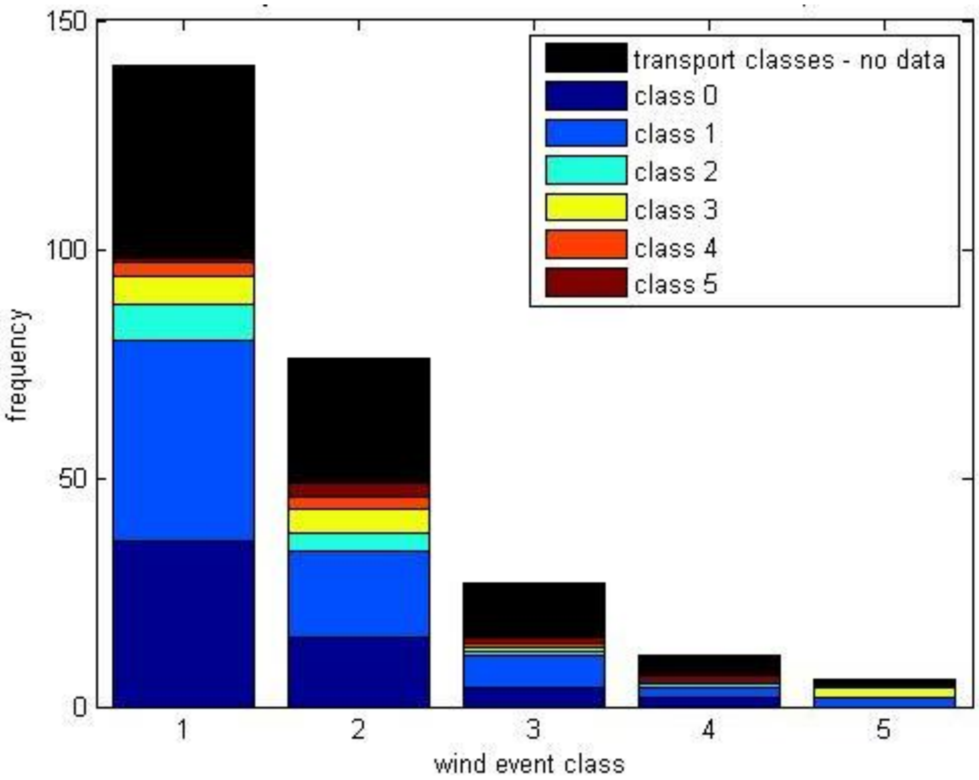


Figure A9: Wind classes versus transport classes, with cosine effect.

A10

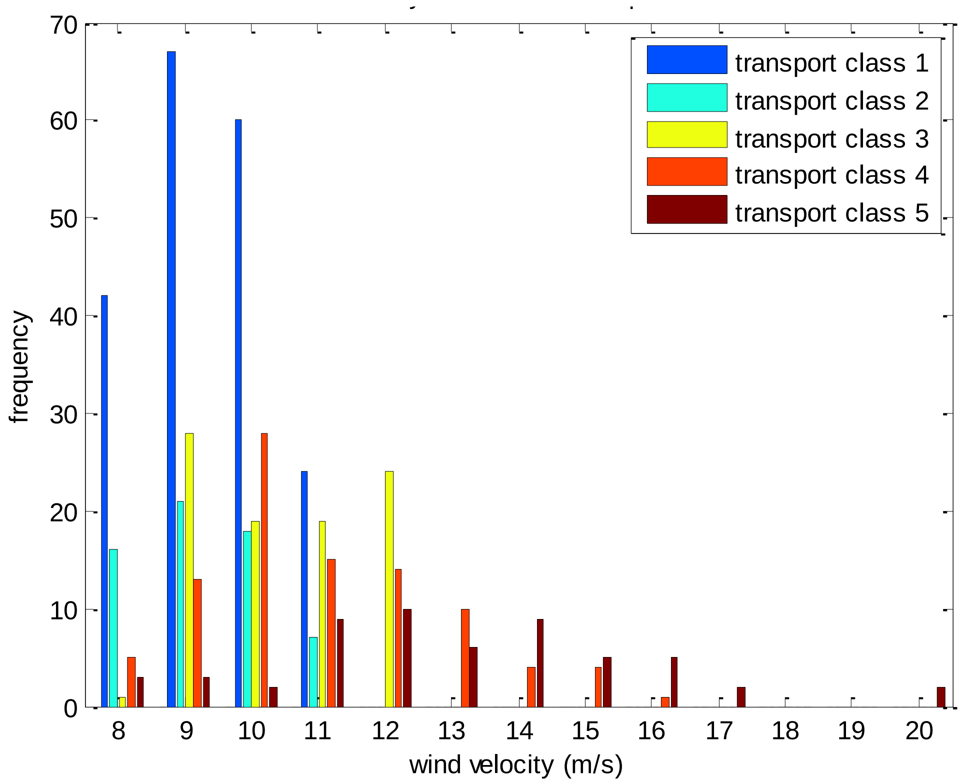


Figure A10: Wind velocity distribution of unlimited events.

A11

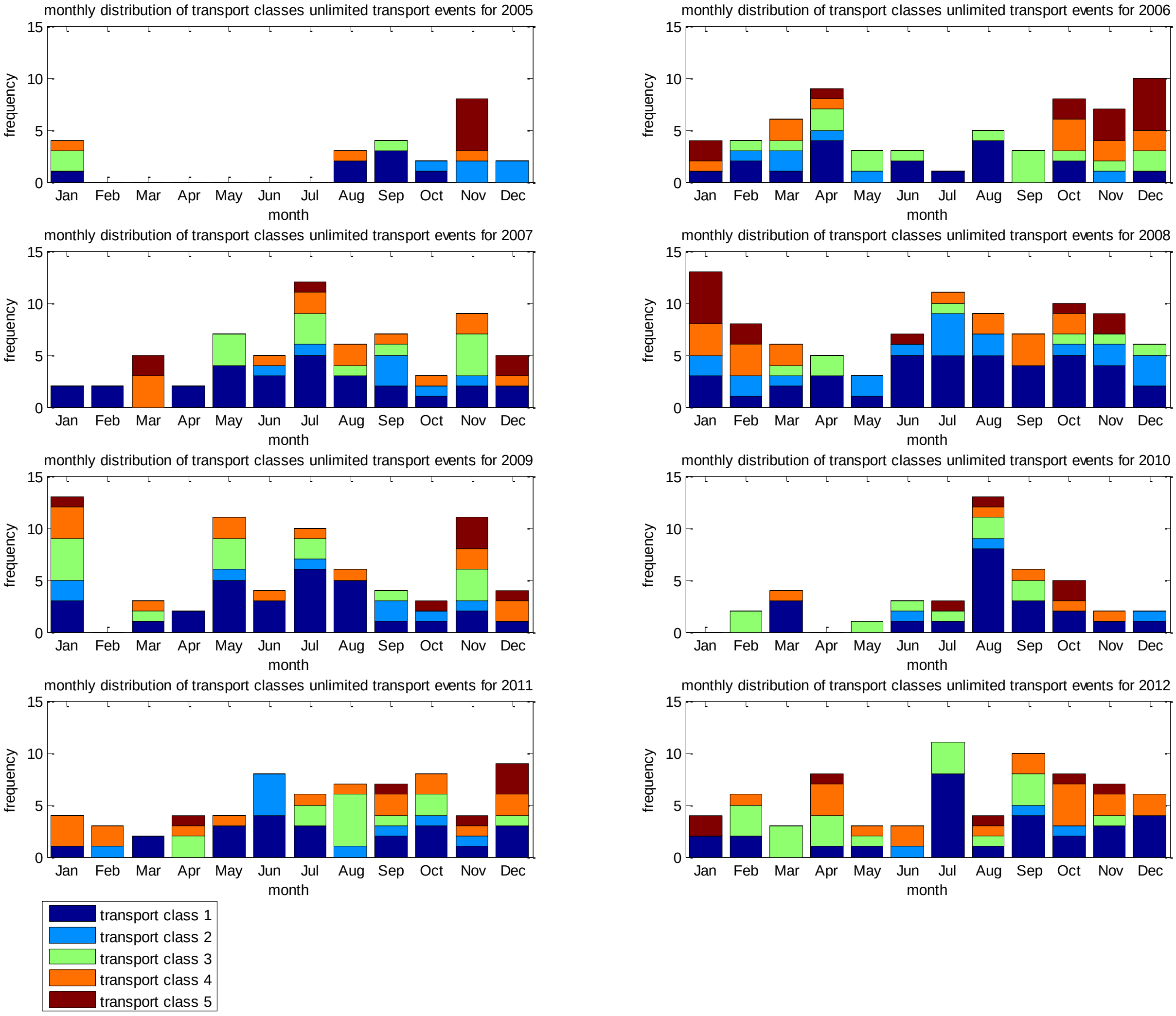


Figure A11: The monthly distribution of transport classes of unlimited events.

A12

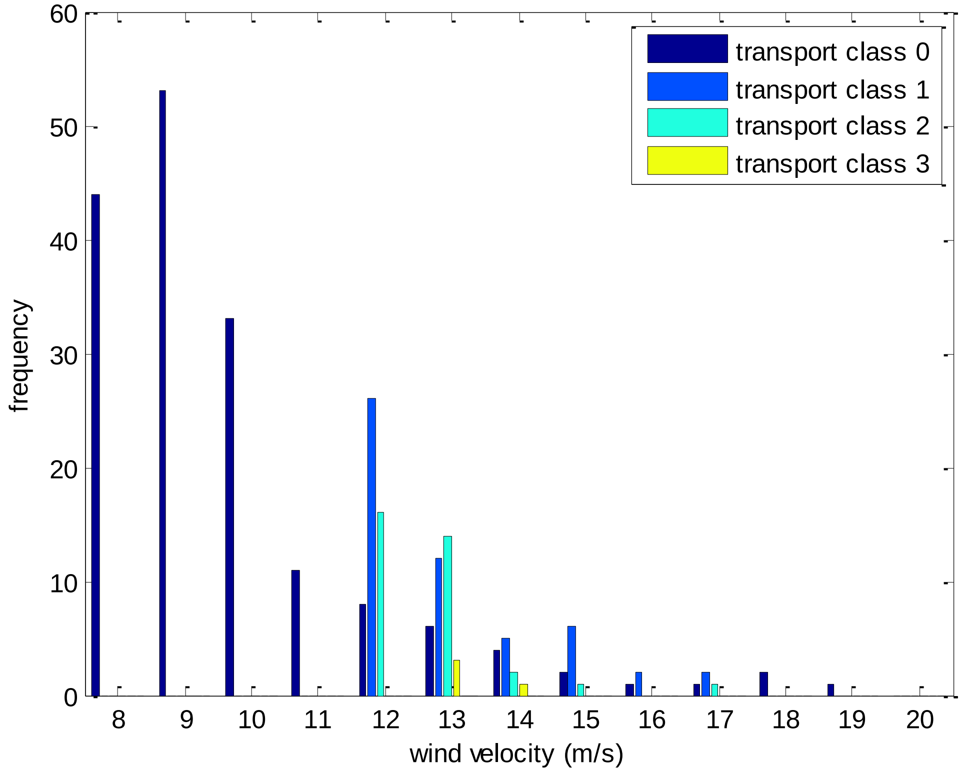
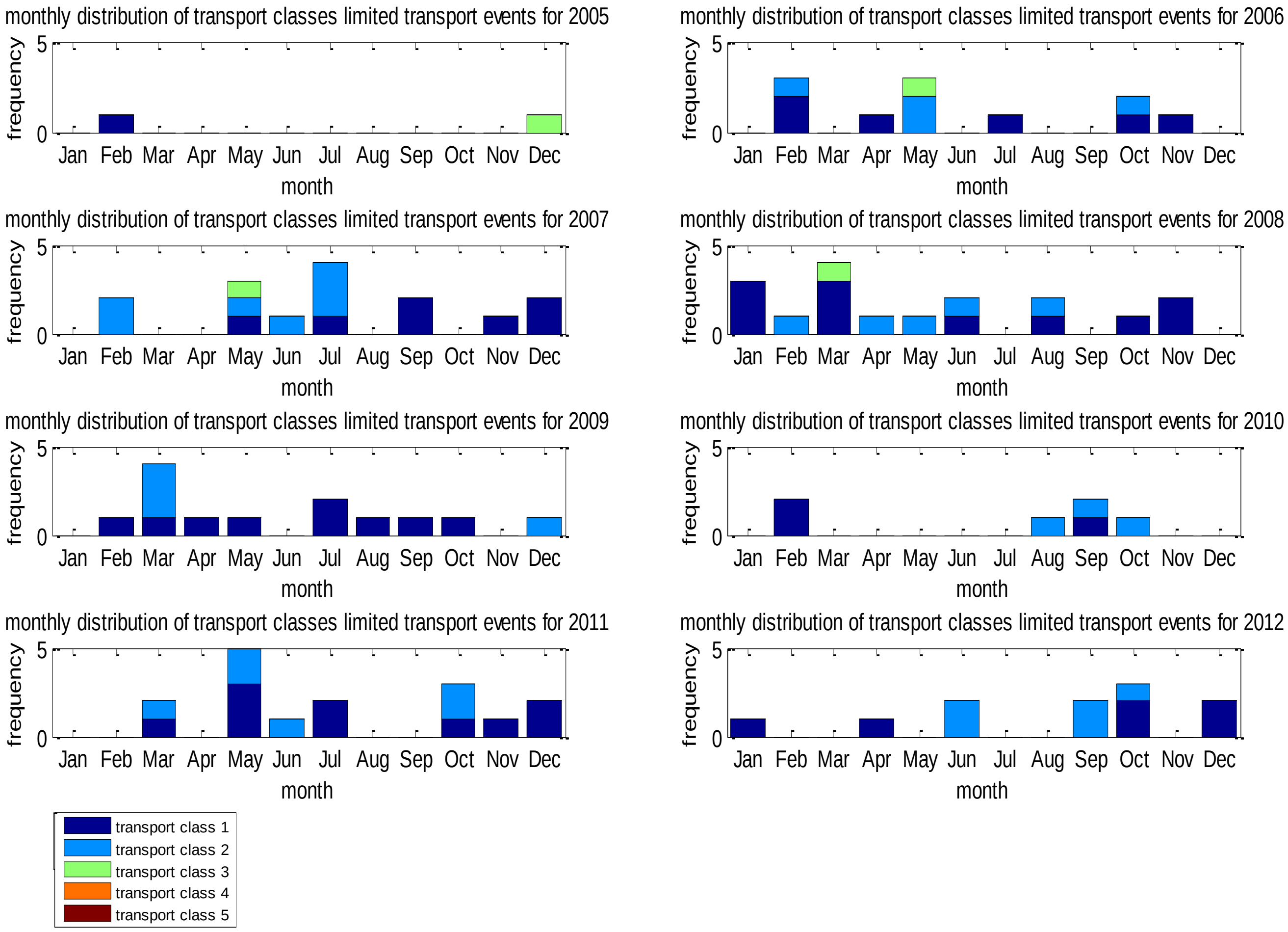


Figure A12: Wind velocity distribution of unlimited events.

A13


monthly distribution of transport classes limited transport events for 2005

monthly distribution of transport classes limited transport events for 2006

monthly distribution of transport classes limited transport events for 2007

monthly distribution of transport classes limited transport events for 2008

monthly distribution of transport classes limited transport events for 2009

monthly distribution of transport classes limited transport events for 2010

monthly distribution of transport classes limited transport events for 2011

monthly distribution of transport classes limited transport events for 2012

Figure A13: The monthly distribution of transport classes of unlimited events.

A14

Table A14; The occurrence of limiting factors for different combinations of wind and transport classes.

	short fetch	moisture	location bar	Snow/ice
tc0-wc1	29	18	14	2
tc0-wc2	63	32	21	11
tc0-wc3	6	3	1	2
tc0-wc4	9	7	0	1
tc0-wc5	7	2	0	0
tc1-wc3	20	13	0	1
tc1-wc4	12	10	0	0
tc1-wc5	10	2	0	0
tc2-wc3	9	5	0	0
tc2-wc4	9	8	1	0
tc2-wc5	2	2	0	0
tc3-wc4	1	1	1	0