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Analysis of vertical wind direction and speed gradients for data from the met. mast at Høvsøre

Risø-R-Report

Nicolas Cariou, Rozenn Wagner, Julia Gottschall
Risø-R-1733(EN)
May 2010



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Title: Analysis of vertical wind direction and speed gradients for data from the met. mast at Høvsøre
Division: VEA

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May 2010

Abstract (max. 2000 char.):

The task of this project has been to study the vertical gradient of the wind direction from experimental data obtained with different measurement instruments at the Høvsøre test site, located at the west coast of Denmark. The major part of the study was based on data measured by wind vanes mounted at a meteorological (met.) mast. These measurements enabled us to make an analysis of the variation of the direction with altitude, i.e. the wind direction shear. For this purpose, four years of wind direction measurements at two heights (60 m and 100 m) were analysed with special respect to the diurnal and seasonal variations of the direction gradient. The location of the test site close to the sea allowed for an investigation of specific trends for offshore and onshore winds, dependent on the considered wind direction sector.

Furthermore, a comparison to lidar measurements showed the existence of an offset between the two vanes used for the analysis, which has to be considered for evaluating the significance and uncertainty of the results.

Finally, the direction shear was analysed as function of wind speed and compared to the corresponding relation for the wind speed shear. Our observation from this is that the direction shear does not necessarily increase with the speed shear.

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Preface

This report presents the results obtained by Nicolas Cariou, engineering student at EFP, France, during his internship at Risø DTU (Denmark) from the 19th of August to the 24th of December 2009. He was supervised by Rozenn Wagner and Julia Gottschall, from VEA-TEM. The original report, with the title “Etude du gradient vertical de la direction et de la vitesse du vent”, was translated by the supervisors from French to English.

1 Introduction

The influence of the wind speed shear on the performance of large wind turbines has been shown and is nowadays an acknowledged fact (Wagner 2009, Antoniou 2009). The possible influence of the variation of the direction with altitude (the direction shear) was raised up more recently (Walter 2009). Unlike the speed shear, the direction shear has rarely been studied and is poorly documented.

For the study presented in this report, four years of wind direction measurements at two heights, 60 m and 100 m, were analysed in order to investigate the variation of the vertical gradient in wind direction with season, time of the day and wind sector. The measurements were obtained from the highly instrumented meteorological (met.) mast at the test site for large wind turbines at Høvsøre, Western Denmark. Lidar measurements were also available for short periods of time and were used for comparison purposes.

As a pre-analysis, we checked the vanes as it is described in section 2. Section 3 presents some basic mathematical tools that were used for the analysis of wind direction differences. The various results are shown and discussed in detail in section 4. The report ends with the conclusion in section 5.

References:

- (Wagner 2009) R. Wagner, I. Antoniou, S. M. Pedersen, M. S. Courtney and H. E. Jørgensen, *Wind Energ.* (2008) DOI: 10.1002/we.297
- (Antoniou 2009) I. Antoniou, S.M. Pedersen, and P.B. Enevoldsen. Wind shear and uncertainties in power curve measurement and wind resources. In *Proceedings of WindPower 2007*, Chicago, Il., USA, 2009.
- (Walter 2009) K. Walter, C.C. Weiss, A.H.P. Swift, J. Chapman, and N.D. Kelley. Speed and direction shear in the stable nocturnal boundary layer. *Journal of Solar Energy Engineering*, 131(011013), 2009.

2 Comparison of the directions measured by a LIDAR and a vane

As a pre-analysis, we checked if the wind vanes were working properly by comparing measurements from each vane to lidar measurements at the same height. Figure 2.1 and Figure 2.2 show the linear regression between the wind direction measured by the wind vane at 100 m and 60 m, respectively, and the direction measured simultaneously by the LIDAR (WindCube™ WLS7-0044) at the same height. The following filters were applied in order to remove non-reliable data:

- NULL Value: This filter removes all the data without assigned value.
- Available = 100: This filter only takes the data with a lidar availability of 100% for the considered 10-min period. We can see in Figure 2.1 that a group of dots around a value of 50° at the abscissa disappeared after filtering with respect to the lidar availability. More detailed investigations showed that the lidar indeed gives a default value of 47° when the availability is zero.
- Wind Speed > 5m/s: Wind speeds below 5m/s were rejected as the vanes are not trusted to be reliable enough in low wind speeds.

In Figure 2.1, the application of the filters described above resulted in a good comparison between lidar and vane measurements at 100 m. The dots remaining (plot on the right side of the figure) describe a straight line with a gain (regression slope) close to one and a high R^2 (coefficient of determination).

Figure 2.2 was obtained in exactly the same way as Figure 2.1 but for the measurements at 60 m. However, we can clearly see that even after filtering we do not obtain a linear relationship between lidar and vane measurements. From this we can conclude that one of the instruments compared here was not working properly.

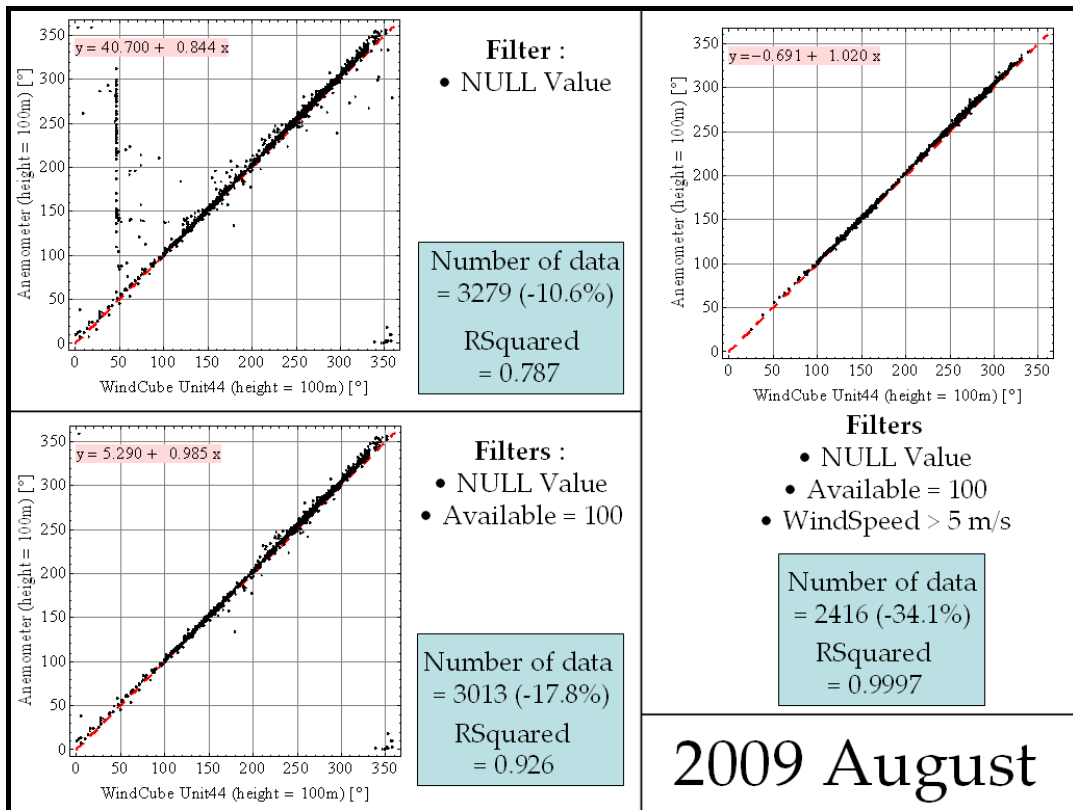


Figure 2.1 Linear regression between the wind directions measured by the lidar and by the vane at 100 m applying different filters. The red dashed line represents the relation $y = x$. The results of the linear regression, the number of data points and the R^2 are shown in each graphic.

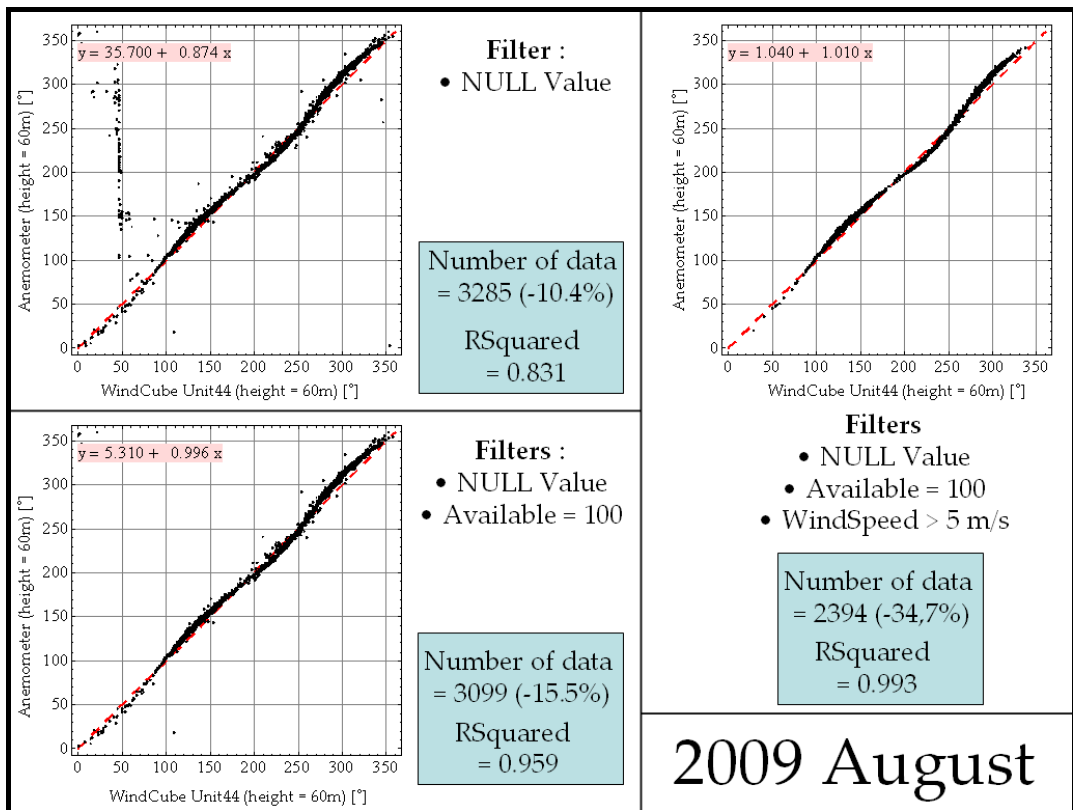


Figure 2.2 Linear regression between the directions measured by the lidar and by the vane at 60 m. The dashed red line represents the relation $y = x$.

Figure 2.3 shows the difference between the directions measured by the vanes and the lidar as a function of wind direction measured by the lidar for the months between May and August 2009, both for 60 m and 100 m measurement height. Again we can see that there is an acceptable (i.e. small enough) difference between the two instruments at 100 m but not at 60 m. Moreover the problem started before August 2009 and seemed to have been growing since.

The problem is strongly suspected to come from the vane at 60 m since if the problem was coming from the lidar, we would expect to see a problem at 100 m as well, which was not the case.

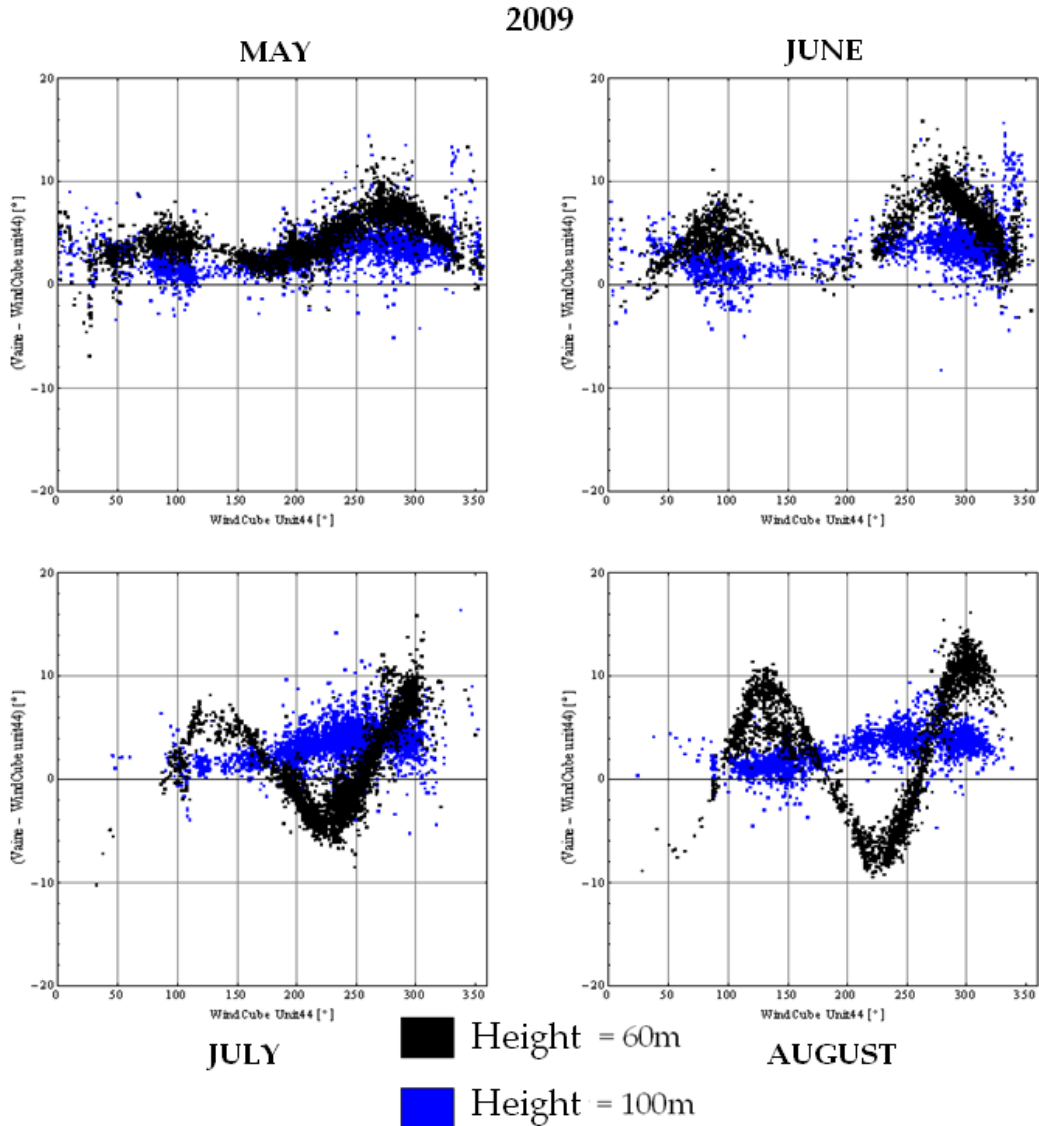


Figure 2.3 Difference between the 10 min mean directions measured simultaneously by the vane and the lidar as function of the wind direction (from the lidar) at 60 m and 100 m for May, June, July and August.

In order to check this wind vane over a longer period, we derived the quantity $\cos^2 \Phi + \sin^2 \Phi$, see Figure 2.4. When the vane works properly, this quantity is equal to 1. The advantage of using this method is that the data collected by the wind

vane are first expressed as cosine and sine of the direction angle in the database. Therefore, these data could be used directly to check the wind vane.

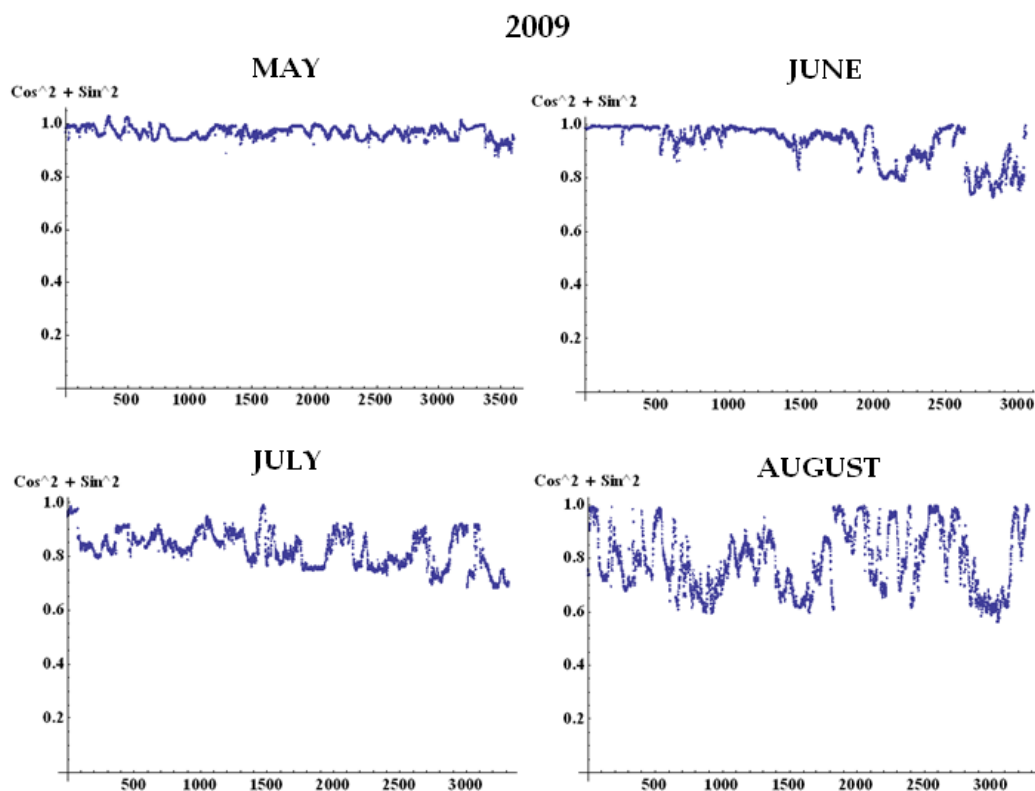


Figure 2.4 $\cos^2 \Phi + \sin^2 \Phi$ as function of time obtained with the vane at 60 m for each month between May and June 2009.

This figure confirms that the vane at 60 m was not working properly at that time. It was actually hit by a lightning during a thunderstorm in November 2008. The instrument was replaced in June 2009, but this did not solve completely the problem, the transmitter box was finally replaced in September, after that the vane has been measuring consistently again, see Annex A. The functioning of both vanes was checked for the complete time period considered with the last method, and the instruments were found to work properly for the complete years 2006, 2007 and 2008. Therefore data from these years were used to analyse the wind direction gradient.

3 Mathematical tools used for the analysis of the direction gradient

3.1 Averaging of direction difference

3.1.1 Problem of discontinuity

In order to analyse the behaviour of the vertical wind direction gradient, we had to average direction differences between 100 m and 60 m. However, this averaging is not straightforward. By convention, wind vane measurements give values between 0° and 360° , with $0^\circ=360^\circ$ corresponding to the North and the direction increasing clockwise, see Figure 3.1.

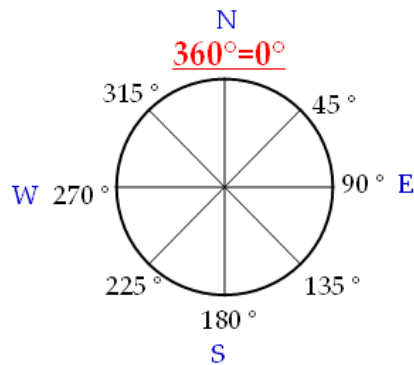


Figure 3.1 Definition of wind direction values from 0° to 360° .

Difference of directions

The direction difference between 135° and 45° is straightforward, the simple difference: $135^\circ - 45^\circ = 90$ gives directly the expected value. However, if we want the direction difference between 45° and 315° ; a simple difference gives -270° whereas we would like as a result $+90^\circ$, see Figure 3.2.

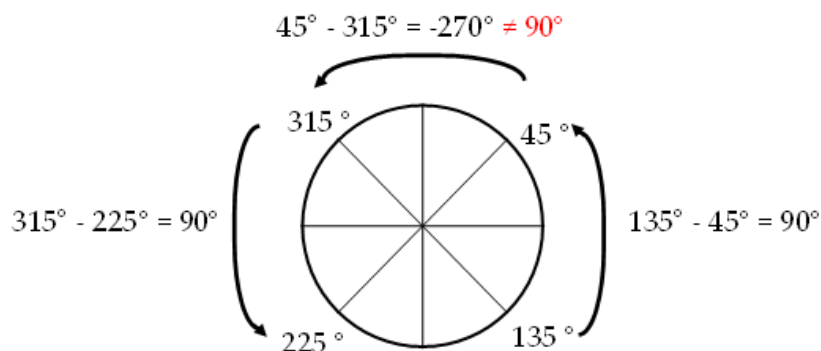


Figure 3.2 Illustration of discontinuity problem.

Direction averaging

The second problem is about direction averaging and is the same problem as encountered every time direction averages are needed. The problem occurs when the direction fluctuates around the North. For example, if we want to make the average direction between 350° and 10° . According to the usual definition of average (i.e. addition of the two values divided by 2 – as definition of (linear) arithmetic mean),

we would obtain 180° (South) which is obviously a wrong result since the expected value is 0° (North). That is why it is important to use a method which takes these problems into consideration.

For the present analysis we chose to have the wind direction differences between -180° and 180° -- which shifts the discontinuity to -180°=180° but does not change the basic problem.

3.1.2 Solution: Atan2 function

Based on trigonometry, one could think of defining the direction average by using the arc tangent function:

$$\langle \theta \rangle = \text{atan}(\langle \sin(\theta) \rangle / \langle \cos(\theta) \rangle)$$

However this would give only values between $-\pi/2$ and $\pi/2$. The usual way to cope with this problem is to use the so called atan2 function that gives a value in $[-\pi; \pi]$. This function can be defined in two ways:

$$\text{atan2}(y, x) = 2 \text{atan}(y / [(x^2 + y^2)^{1/2} + x])$$

or

$\text{atan}(y/x)$	$x > 0$
$\pi + \text{atan}(y/x)$	$y \geq 0, x < 0$
$-\pi + \text{atan}(y/x)$	$y < 0, x < 0$
$\pi/2$	$y > 0, x = 0$
$-\pi/2$	$y < 0, x = 0$
undefined	$y = 0, x = 0$

The average of the direction differences was then defined as:

$$\langle \Delta \Phi \rangle = \text{atan2}(y, x)$$

where

$\Delta \Phi = \Phi_1 - \Phi_2$ with Φ_1 the wind direction at 100 m and Φ_2 the wind direction at 60m and

$$x = \langle \cos(\Phi_1 - \Phi_2) \rangle$$

$$y = \langle \sin(\Phi_1 - \Phi_2) \rangle$$

This solves both problems outlined above.

3.1.3 Uncertainty

Because the amount of data varies from one dataset to another (for different wind sectors for example), it is important to estimate an uncertainty of the calculated mean value. The uncertainty was here defined as the standard uncertainty ε defined as:

$$\varepsilon = \frac{\sigma}{\sqrt{N}}$$

where σ is the standard deviation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (X_i - \bar{X})^2}{N-1}}$$

* N : number of data
 * X_i : i^{th} data in the dataset
 * \bar{X} : mean value

(Note, in this case, the mean of the data is calculated with the atan2 method.)

Thus, the more data there are, the smaller the standard error. However, this formula is only true for independent data. In this study, we assumed that the dependence of the data does not affect the results very much. An analysis about the impact of the dependence should be made in order to know if we can trust the standard uncertainties we obtained or if the degrees of freedom for our considerations have to be reduced.

The considered uncertainty only reflects the statistical uncertainty for the derived mean gradient. A basic uncertainty of the reference data is not considered here.

4 Results

4.1 Diurnal variations of the wind direction difference between 100 m and 60 m for the four seasons in 2007

The data were first grouped by season where the season was defined according to the solstices and equinoxes as follows:

- Spring: from the 21st of March to the 22nd of June
- Summer: from 22nd of June to 23rd of September
- Autumn: from 23rd of September to 21st of December
- Winter: from 21st of December to 21st of March

Secondly the data were grouped by time (hour) of the day. The histograms in Figure 4.1 to Figure 4.5 show for each season the diurnal variation of the wind direction difference between 100 m and 60 m. The figures are made of 4 histograms, one per season, and each bar of each histogram represents the average difference of the wind direction for 1 hour in a day, for all the days of one season.

Example : This table shows the mean value of the wind direction difference for each hour in the spring season.

	March			April - May	June		
Day	21	22	23	...	20	21	22
00h -> 01h	3,4	2,5	1,4	...	5,3	0,3	2,7
01h -> 02h	2,1	1,5	0,6	...	0,7	3,5	2,6
...
22h -> 23h	2,6	3,1	5,4	...	2,3	0,3	0,5
23h -> 24h	1,2	1,4	0,6	...	6,4	3,4	2,5

So, for each hour of a day (00h->01h for example), an average is made for the whole season, i.e. we average each line of the table above to obtain 24 mean values, each one corresponding to one hour of the day.

4.1.1 All directions

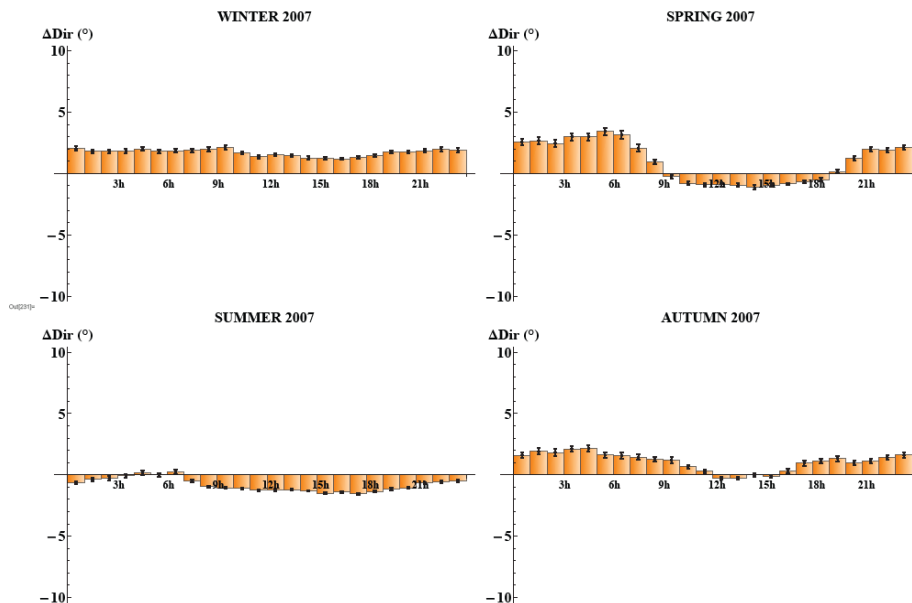


Figure 4.1 Diurnal variation of ΔDir per season in 2007

In the histograms in Figure 4.1, all directions are taken into account. However this figure does not show much since the results mix measurements from all sectors whereas the test site of Høvsøre has flat farm land on the east side, the North sea on the west side and a small fjord on the south side and a row of wind turbines on the north side. Those different conditions create different roughnesses and accordingly different stability conditions. Furthermore, measurements from the north have a high uncertainty (or are even biased) as the instruments are mounted to the south of the mast and are therefore in the wake of the mast and the turbines when the wind blows from the north. Thus, it is necessary to make an analysis on different sectors. The following four sectors were defined:

- East : $45^\circ \rightarrow 135^\circ$
- South : $135^\circ \rightarrow 225^\circ$
- West : $225^\circ \rightarrow 315^\circ$
- North : $315^\circ \rightarrow 45^\circ$

4.1.2 Direction between 225° and 315° (West)

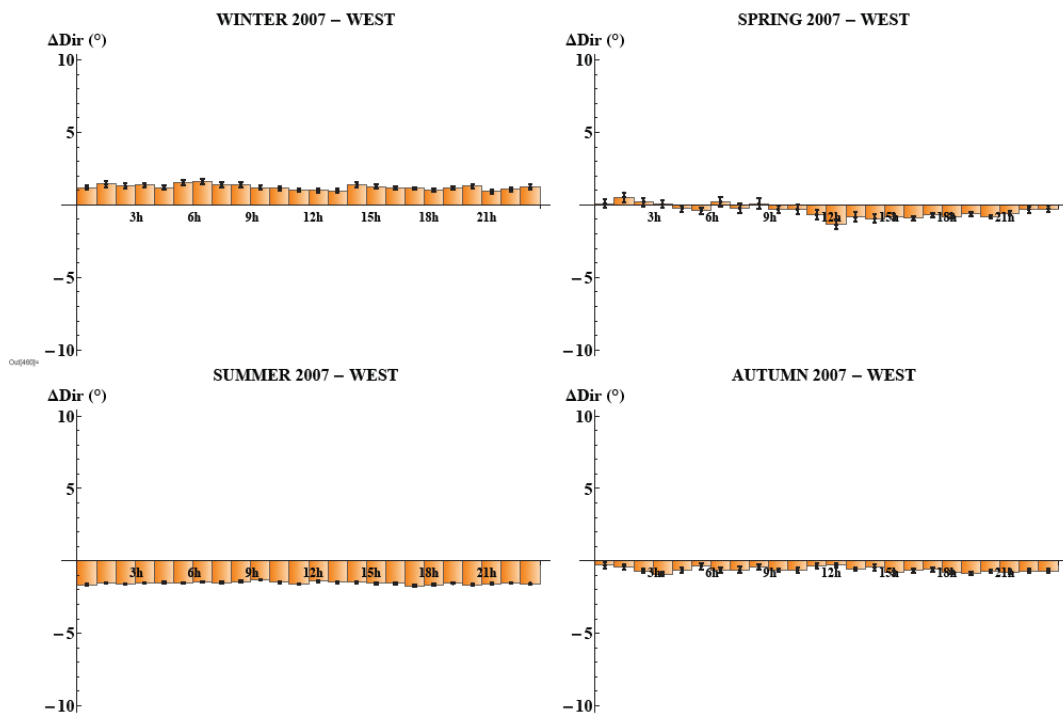


Figure 4.2 Diurnal variation of ΔDir per season in 2007 for the western sector.

In Figure 4.2, only directions from the west sector are considered. Therefore the wind is only coming from the sea. Each histogram is quite constant meaning that there is no variation of the direction difference with time of the day. This can be explained by the large heat capacity of the sea. Indeed the sea temperature changes too slowly to follow the diurnal pattern of the sun radiation. Therefore we do not expect any large change of stability over the sea during the day.

However, we can see some differences between seasons. There is generally a large direction difference in winter and a small one in summer. In winter, the sea roughness is probably higher than in summer resulting in a larger direction shear.

The negative average value obtained for any time in the day in spring, summer and fall is quite surprising. We will come back to this point later in the report.

4.1.3 Direction between 45° and 135° (East)

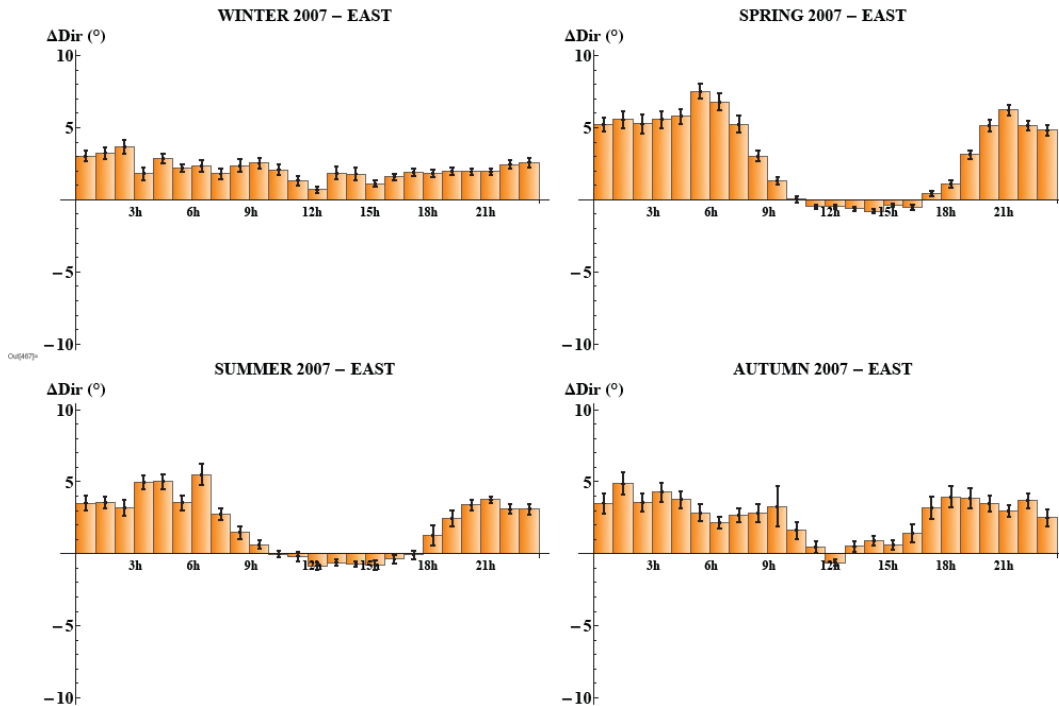


Figure 4.3 Diurnal variation of ΔDir per season in 2007 for the eastern sector.

In Figure 4.3, only directions coming from the east sector are considered. Therefore the wind is only coming from the land. Results obtained in that case present much more variations than the results from westerly winds. We can see larger differences between seasons as spring and summer present clear diurnal variations whereas it is more even in winter and autumn. When the wind blows from east, it blows over farmland which has a larger roughness than the sea. Consequently, the direction shear (due to the Coriolis force, which directly depends on the friction force) is larger for the easterly wind than for the westerly winds. Furthermore, as the land warms up faster than the sea when it is exposed to solar radiations, a clear distinction can be made during day and night. During the day, the ground is warmed up by the sun, the air next to the ground gets warmer than the air above, creating convection that mixes up the surface layer. Therefore within the surface layer, the wind speed and direction is quite uniform and there is almost no shear. During the night, the ground is cold letting the surface layer being stable and stratified. This favours the shear.

The extrema are observed in spring, during the night, especially just before the sunrise and just after the sunset. It might be due to local effects caused with the difference of temperature between the cold sea and the land which getting warmer.

4.1.4 Direction between 135° and 225° (South)

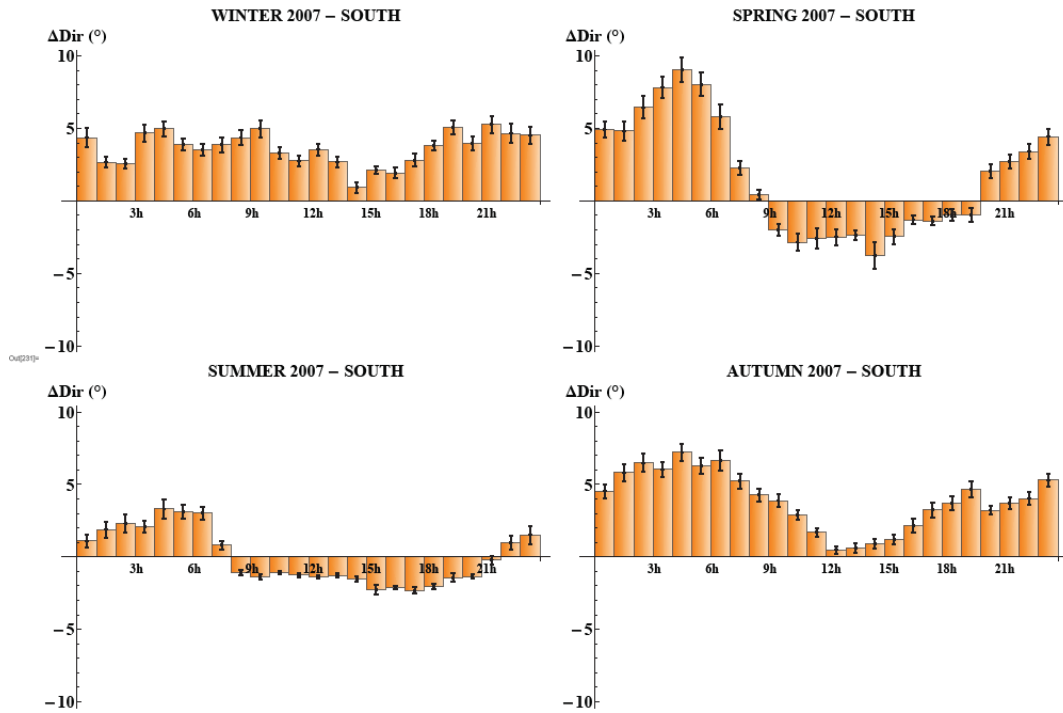


Figure 4.4 Diurnal variation of ΔDir per season in 2007 for the southern sector.

Figure 4.4 shows the direction shear for southerly wind. Although the wind comes from the small fjord 2 km away, the histograms show a pattern similar to those for the east site corresponding to a land pattern with clear seasonal and diurnal variations.

4.1.5 Direction between 315° and 45° (North)

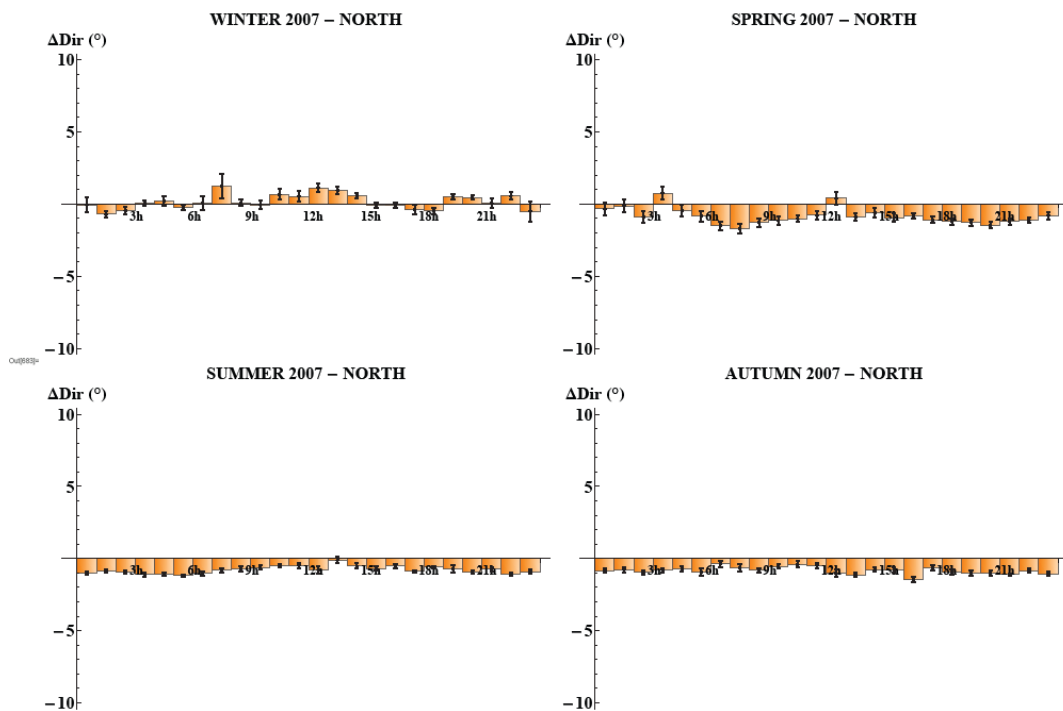


Figure 4.5 Diurnal variation of ΔDir per season in 2007 for the northern sector.

Results from northern wind shown in Figure 4.5 are not relevant as the vanes are then in the wakes of the mast and the turbines and the measurements should not be considered due to distortion effects.

4.1.6 Conclusion

The analysis of the difference between the directions measured at 100 m and at 60 m during 2007 showed that the direction gradient is different from one sector to another and that it varies with the season and the time of the day. It complies quite well with the variation of the vertical speed gradient, see annex B. The same analysis was made for 2006 and 2008; the results are presented in Annex C. A negative direction gradient on average for three quarter of the year is surprising. This issue is further investigated in section 4.2.

4.2 Analysis and comparison of the distributions of direction differences for LIDAR and vane data

As the Coriolis force deflects the flow towards the right in the north hemisphere, we were expecting a positive direction difference between 100 m and 60 m. Some local thermal effects might generate negative gradients; however they take place too rarely to be observed on average values.

An offset between two vanes mounted on a mast at two different heights, however, is quite probable. Indeed the alignment of the vane references depends on the boom installation and on the vane mounting itself which can be done only within a few degrees of precision. Concerning this difficulty, a lidar presents the great advantage of having the same reference for all measurement heights. Therefore we can be completely sure there is no offset between the directions measured at two different heights with a lidar. We used this lidar property to check the vanes.

Figure 4.6 shows the distribution of the direction difference measured by a lidar (Windcube) on one hand and by pair of vanes on the other hand for a period of four month (between June to September) in 2008.

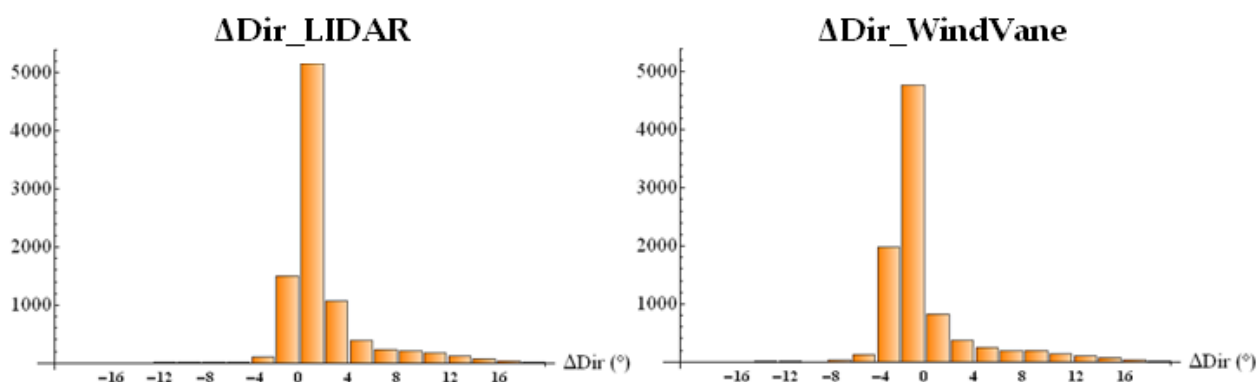


Figure 4.6 Distribution of the direction difference simultaneously measured by the lidar (left) and the pair of vanes (right) for 4 months (from June to September) in 2008.

We can see that the two distributions have a very similar shape but that the distribution obtained with the vanes is shifted to the left (towards negative values) compared to that obtained with the lidar. Figure 4.7 shows the difference between the two distributions. It then can be seen clearly that the vane measurements

generally underestimate the direction difference with a shift of 1.5° on average. It means that we should add 1.5° to all the bars of each histogram presented previously in section 4.1. Most of the negative values seen in Figure 4.1 to Figure 4.5 would then be around zero.

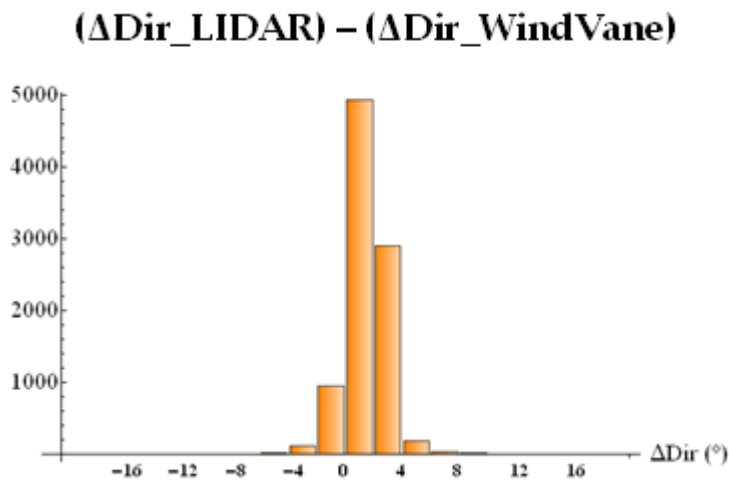


Figure 4.7 Distribution of the difference between the direction difference simultaneously measured by the lidar and the couple of vanes.

Note: This study was made with LIDAR measurements from 2008. This could not be checked for 2007 because there was no lidar available next to the mast at that time. However it is very probable that similar results would have been obtained.

4.3 Relation between Δwsp and 80 m wind speed

Figure 4.8 shows the wind speed difference between 100m and 60m as a function of the 80m wind speed, for the four seasons of 2007. In these plots, all directions were considered together.

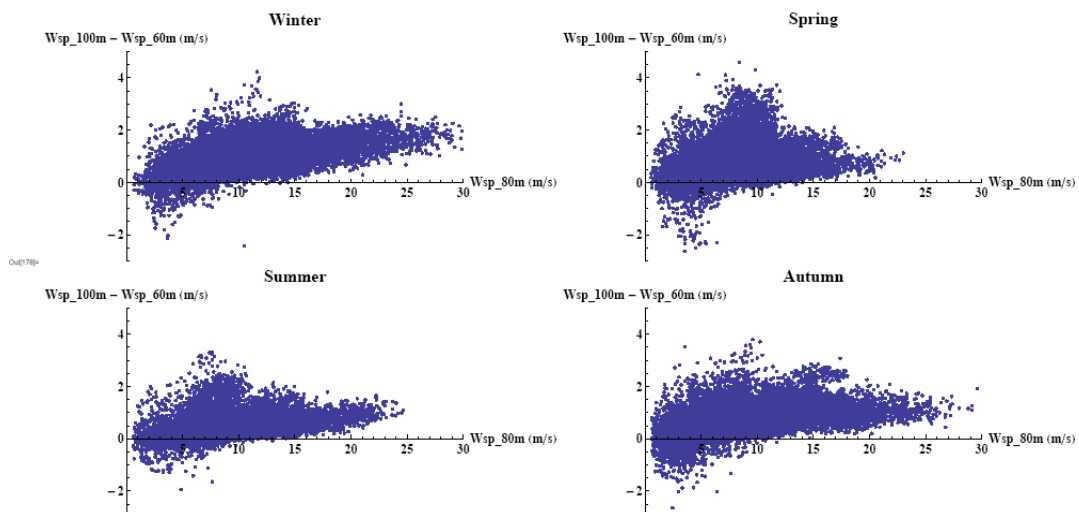


Figure 4.8 Difference of wind speed measured by a pair of cup anemometers at 100 m and 60 m for the four seasons of 2007. All wind directions together.

In a general manner, the vertical wind speed gradient increases when the wind speed increases. However, this increase is different depending on the season. We notice for the winter and autumn a quasi-linear increase, whereas for spring and summer this increase seems to take two different trends. In order to understand this, it is necessary to analyse these graphics for each direction sector separately.

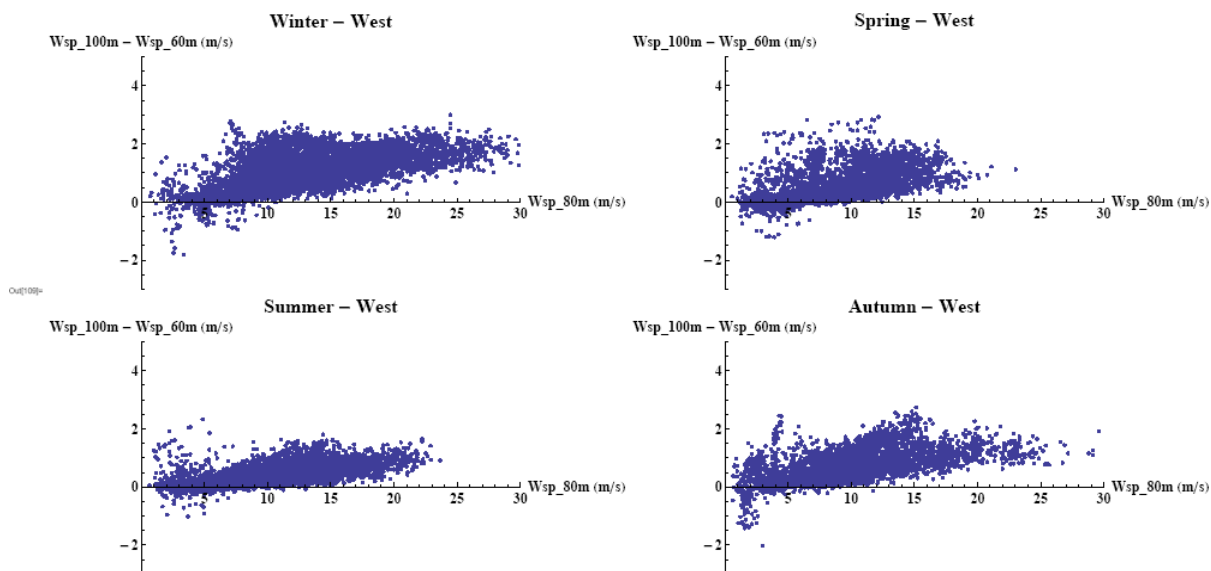


Figure 4.9 Difference of wind speed measured by a pair of cup anemometers at 100 m and 60 m for the four seasons of 2007 (West sector).

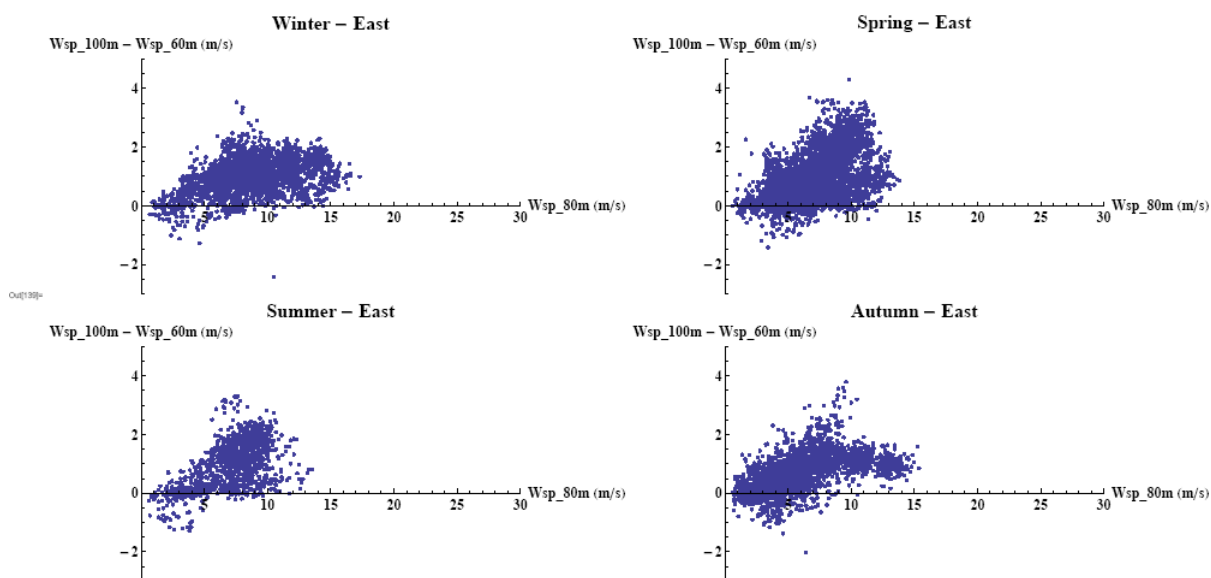


Figure 4.10 Difference of wind speed measured by a pair of cup anemometers at 100 m and 60 m for the four seasons of 2007 (East sector).

Figures 4.9 and 4.10 show two main results:
 The wind speed reaches higher values over sea than over land;

for the same wind speed, the speed shear is larger for easterly wind than for westerly winds. The two trends seen in 8 appear clearly to be coming from those two different sectors.

Both tendencies result from the fact that the friction over land is higher than that over the sea.

4.4 Relation between Δ Direction and the wind speed at 80 m

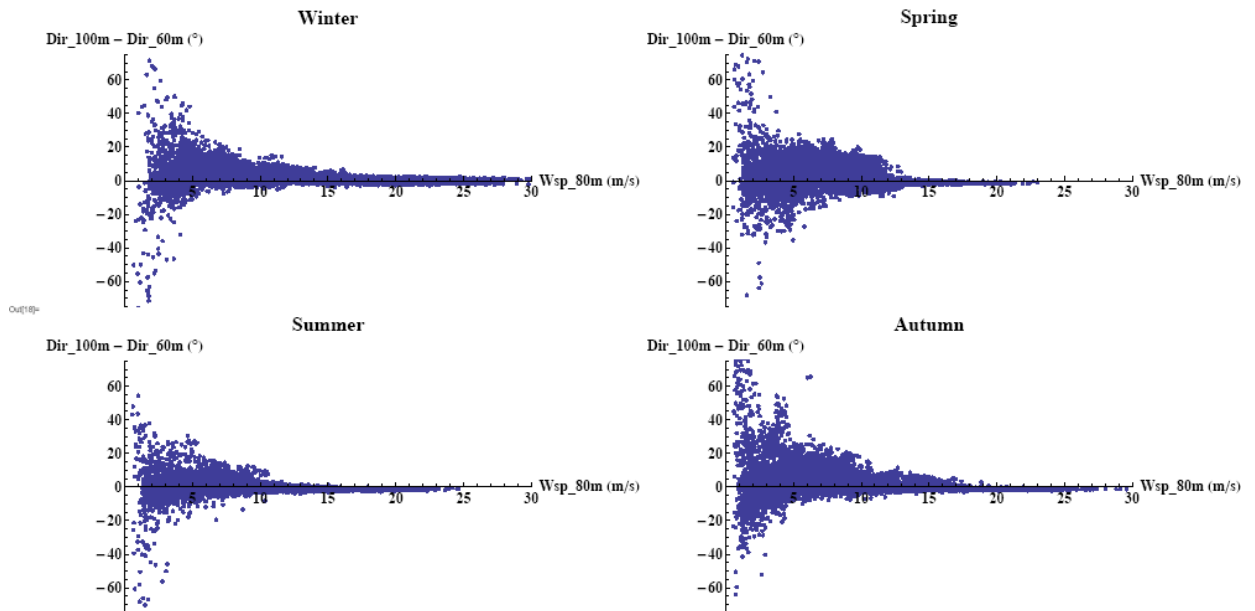


Figure 4.11 Difference of wind directions measured by a pair of vanes at 100 m and 60 m for the four seasons of 2007. All wind directions together.

Figure 4.11 shows the difference of direction between 100 m and 60 m versus the wind speed measured at 80 m. In these plots, all directions were considered together. Contrary to the speed gradient, the (absolute) direction gradient decreases as the wind speed increases and it becomes almost null for wind speeds over 15 m/s. This is directly related to the increasing speed shear as for high speed shear (generally occurring for high wind speeds), the friction force due to the ground decreases rapidly with height. Therefore the direction is then constant with height.

It would be interesting to do the same analysis for easterly and westerly winds separately (– which is however beyond the scope of this study). As the friction of the sea is smaller than that for the land, we expect the direction shear to get very small for smaller speed over sea than over land.

4.5 Relation between Δ Direction and Δ Speed

The previous two small analyses showed that the direction shear does not simply increase with the speed shear. The direction shear depends on the friction force due to the ground. Thus wind blowing over land can result in the combination of speed shear and direction shear whereas wind blowing over sea can present large speed shear with no direction shear.

5 Conclusion

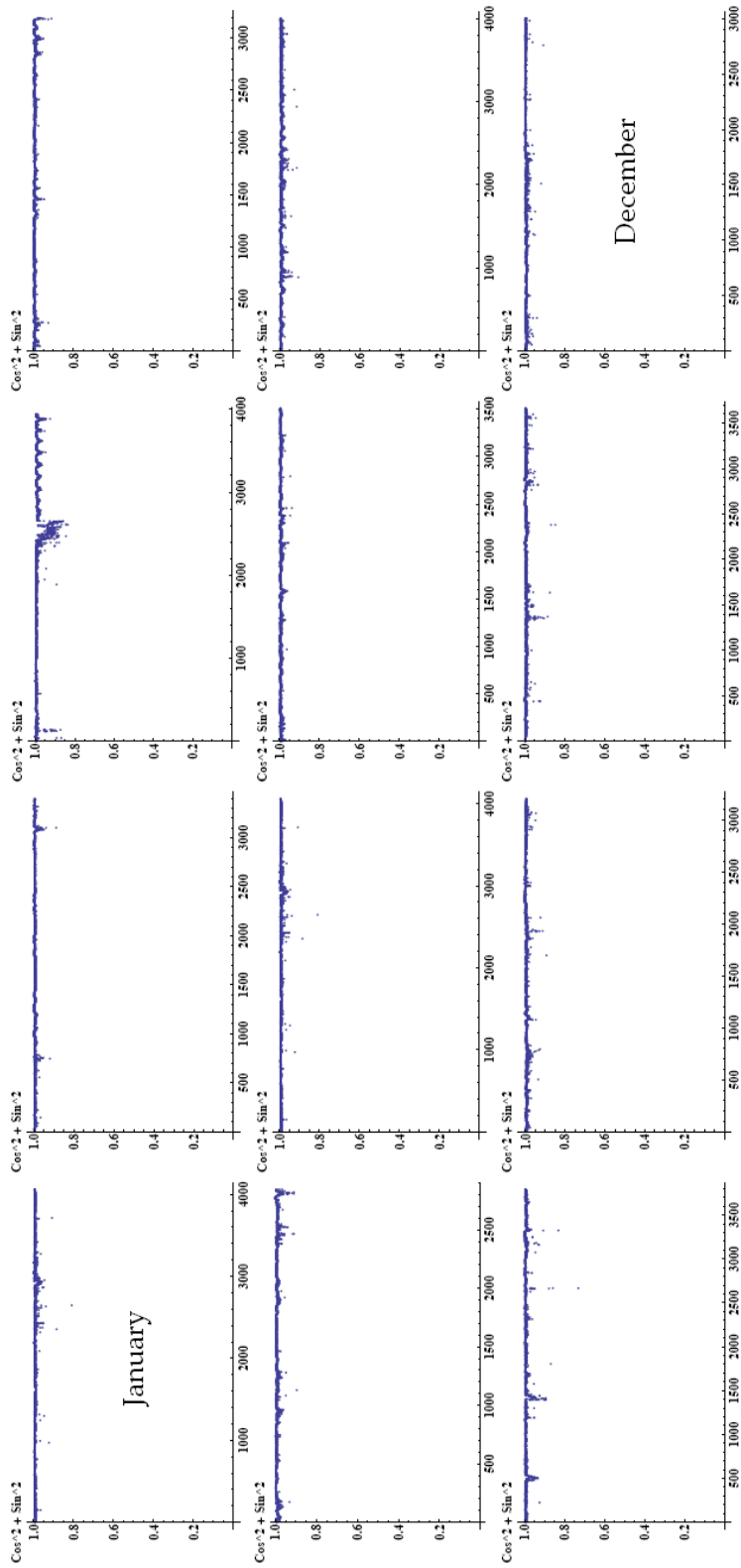
The difference of direction measured by two vanes at 60m and 100m during the year 2007 was analysed. A comparison to the same type of measurement with a lidar showed an offset between the two vanes causing a bias of all the measurements obtained with the pair of vanes.

The wind direction gradient showed dependence on the wind sector, the season and the time of the day. This shows a dependence on the friction force due to the ground and the stability of the surface layer. Although the direction gradient shows dependence to stability similar to the speed shear, the direction shear is not linearly correlated to the speed shear. Indeed, as the wind speed increases, the speed shear increases whereas the direction shear decreases as the friction force decreases faster with the altitude.

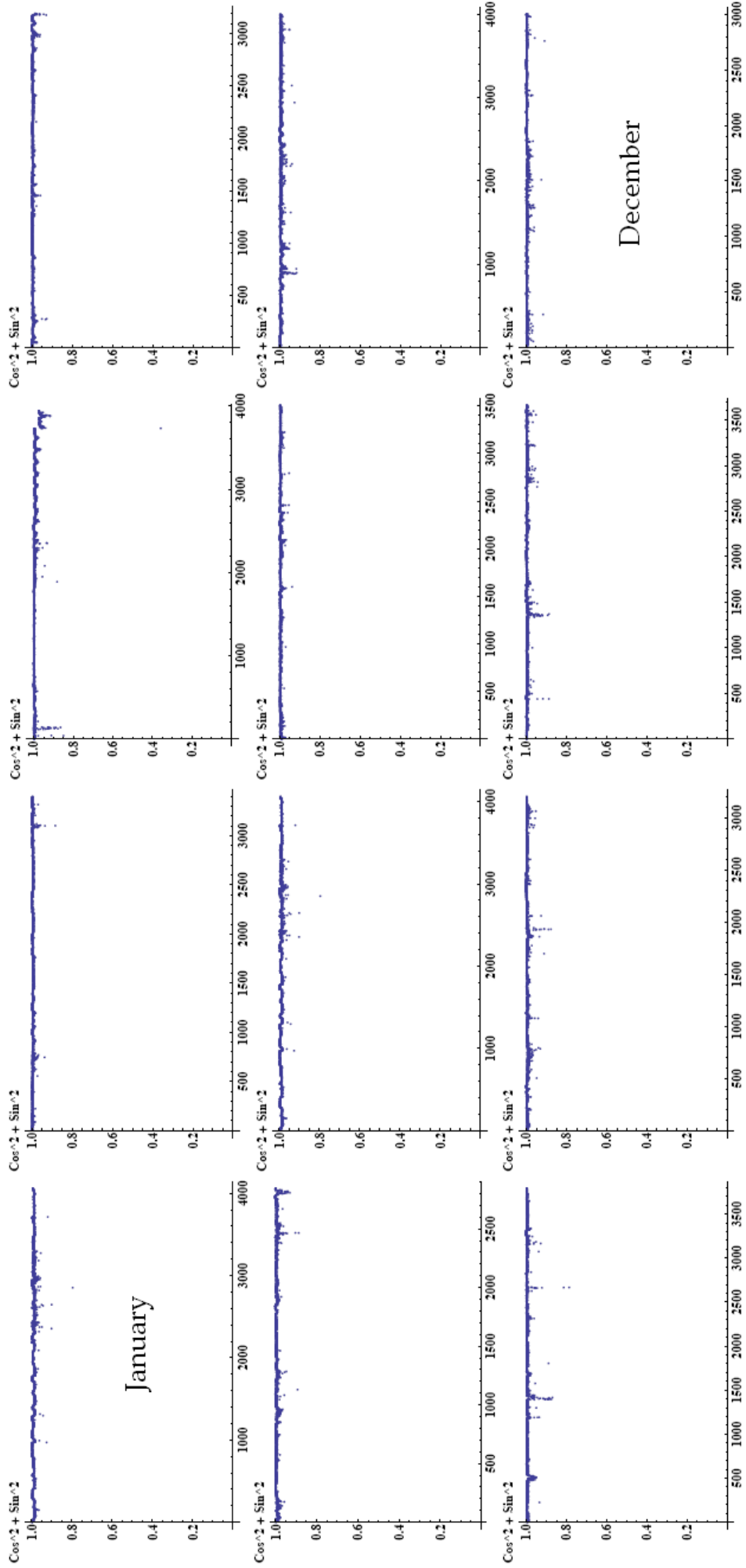
6 Annexes

Annex A: Høvsøre wind vane check

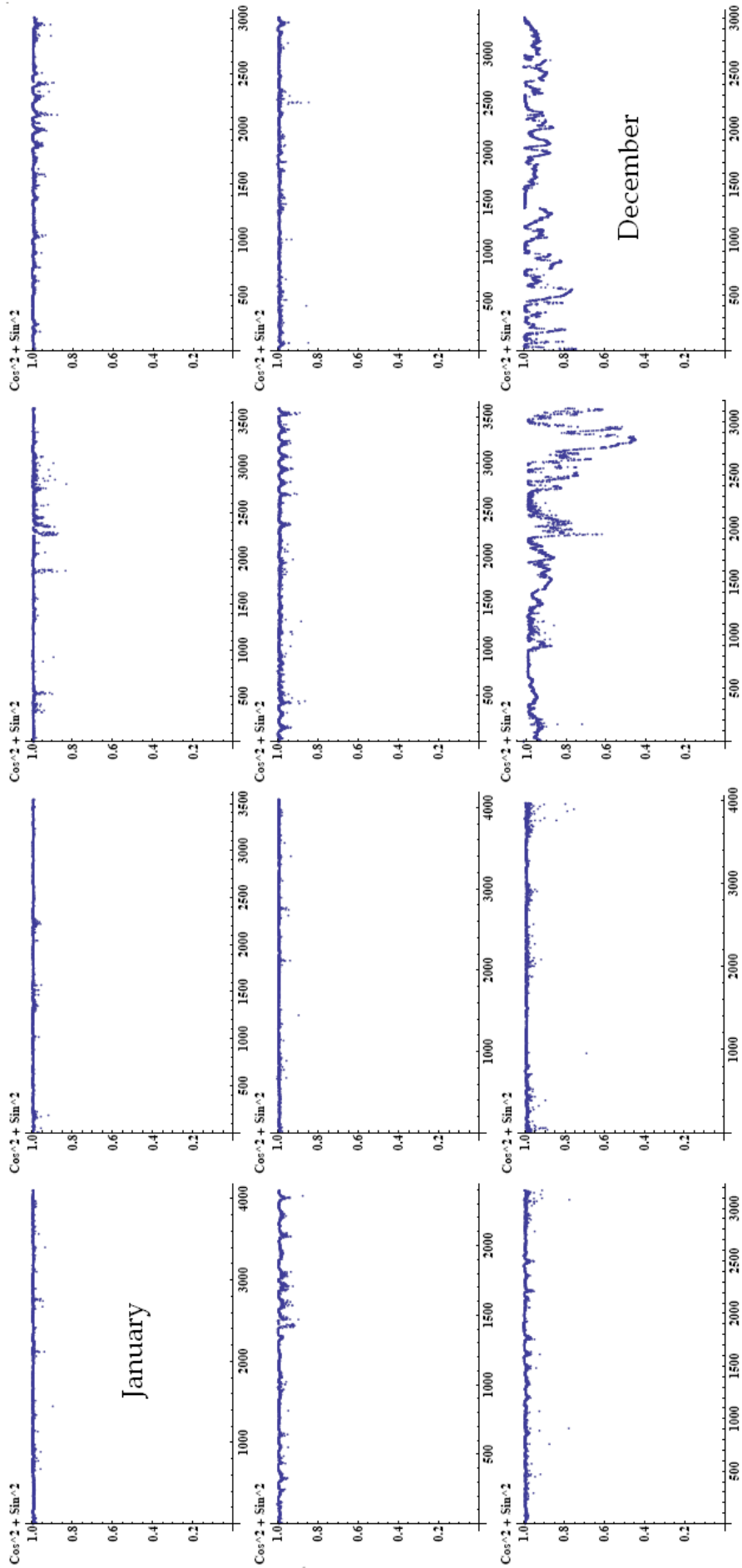
2007 - 60m



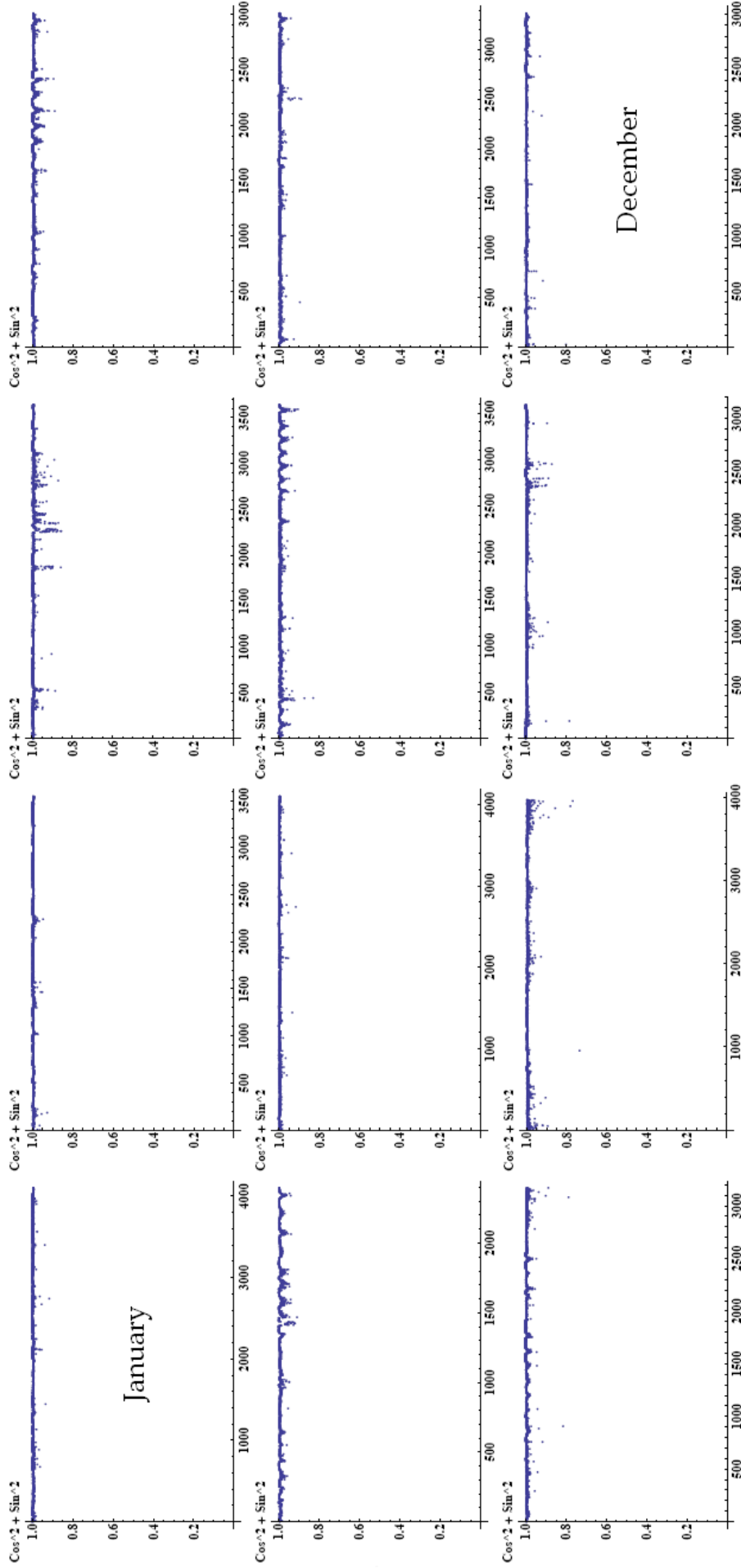
2007 - 100m



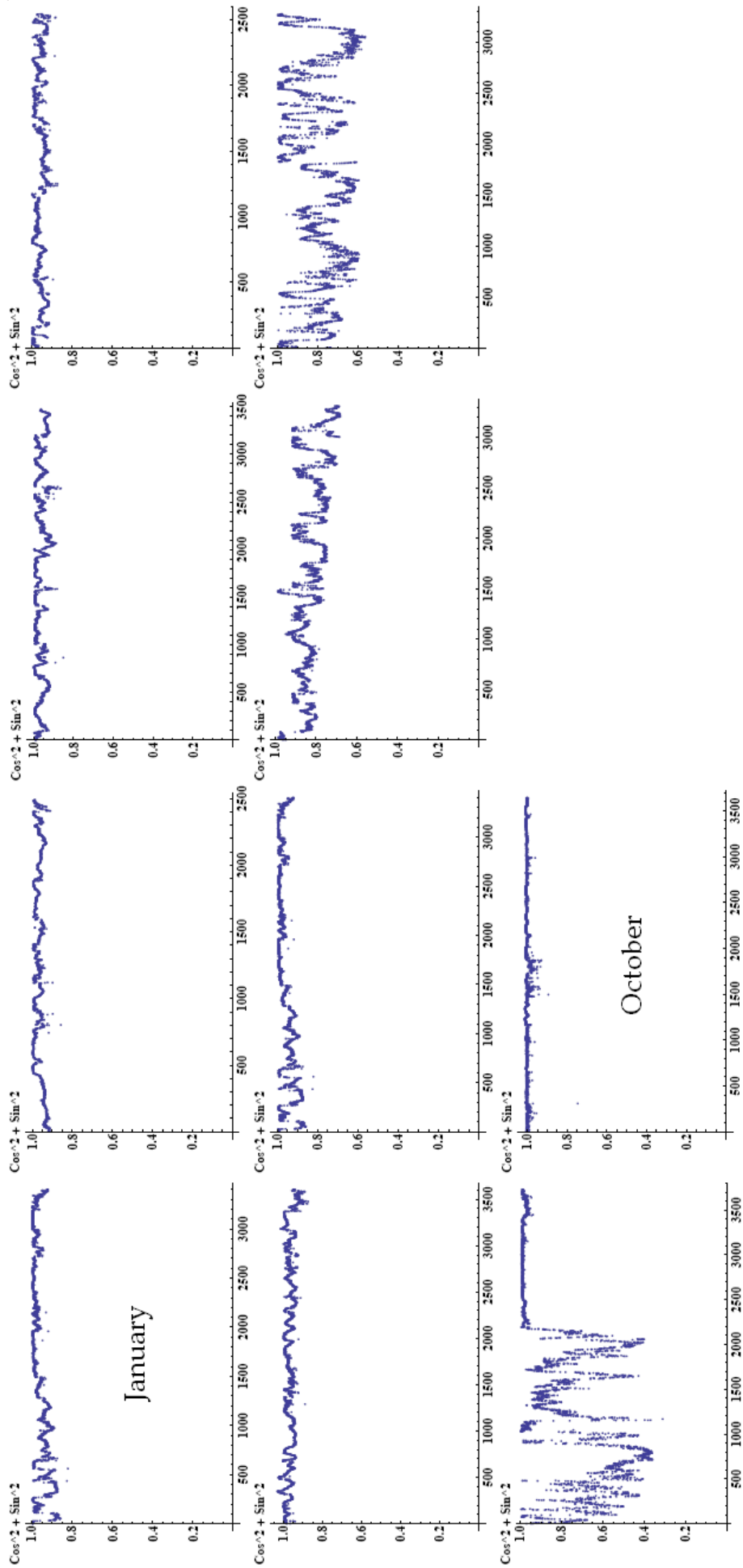
2008 - 60m



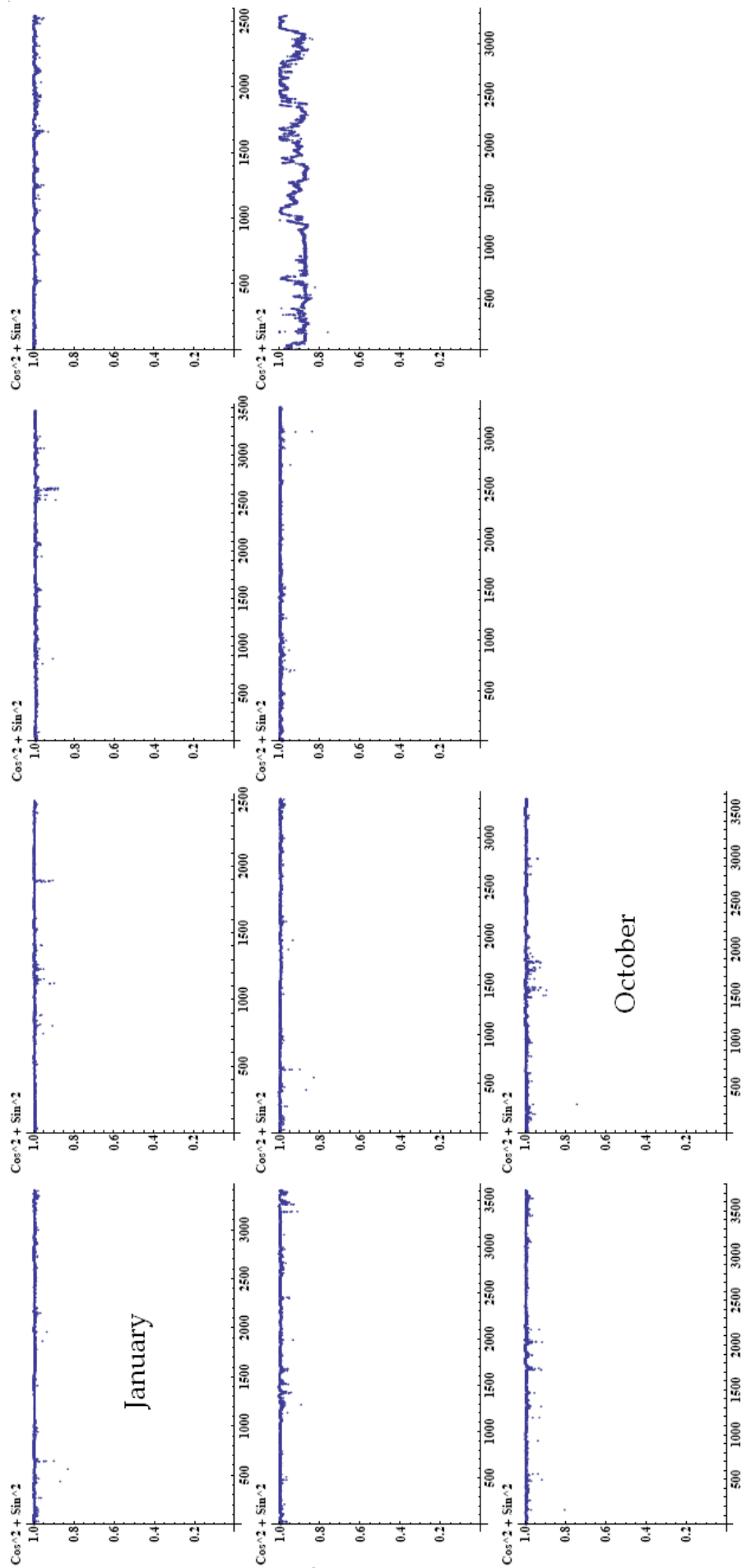
2008 - 100m



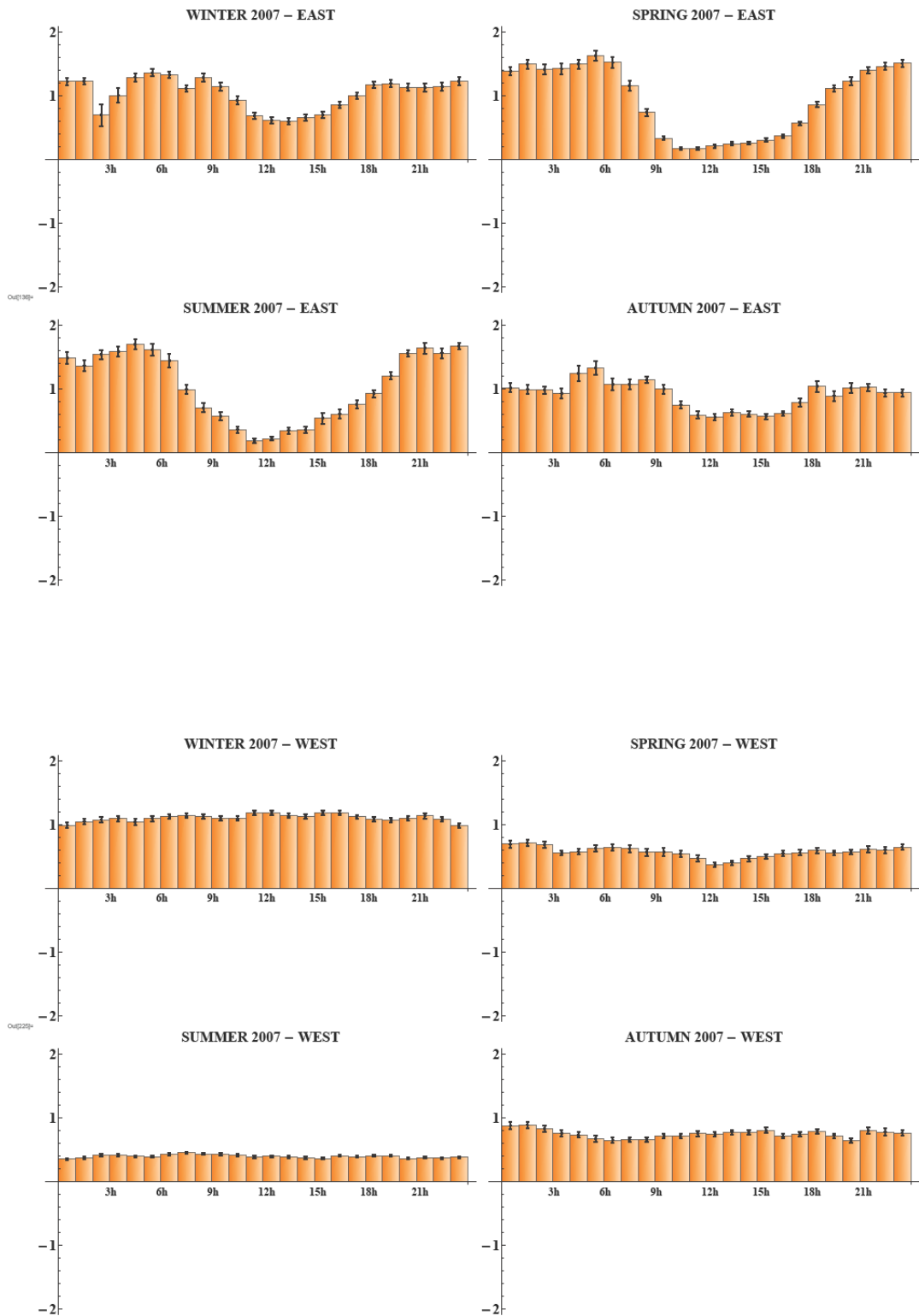
2009 - 60m

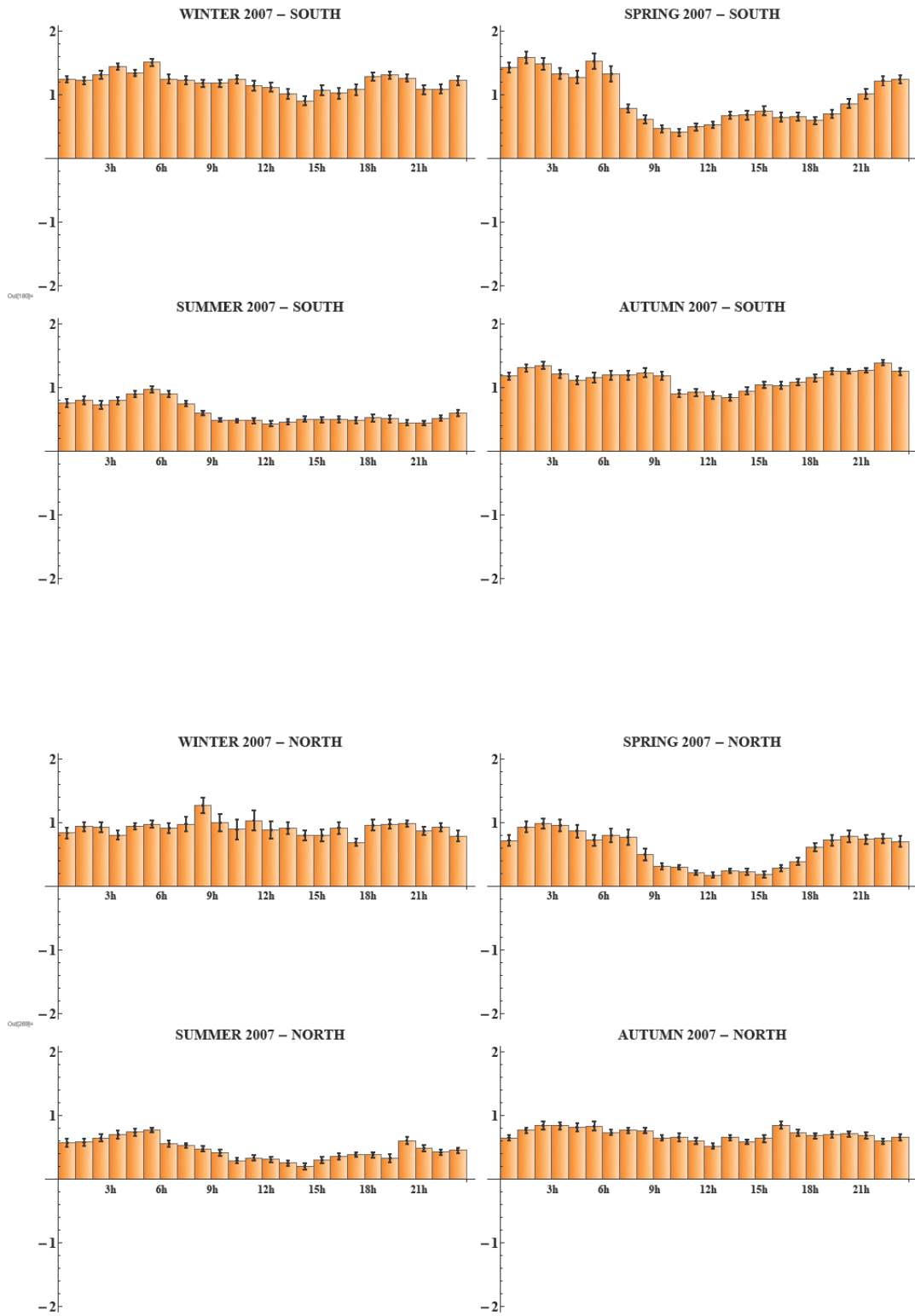


2009 - 100m



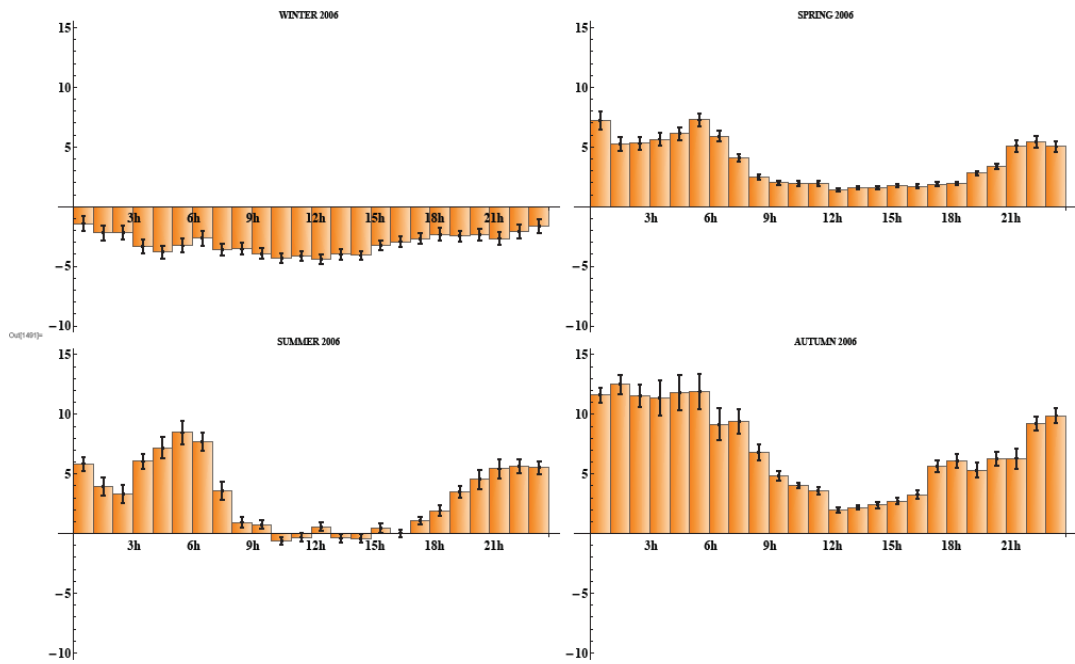
Annex B: Wind speed difference (100 m – 60 m) for the four seasons in 2007 and for the four different wind sectors



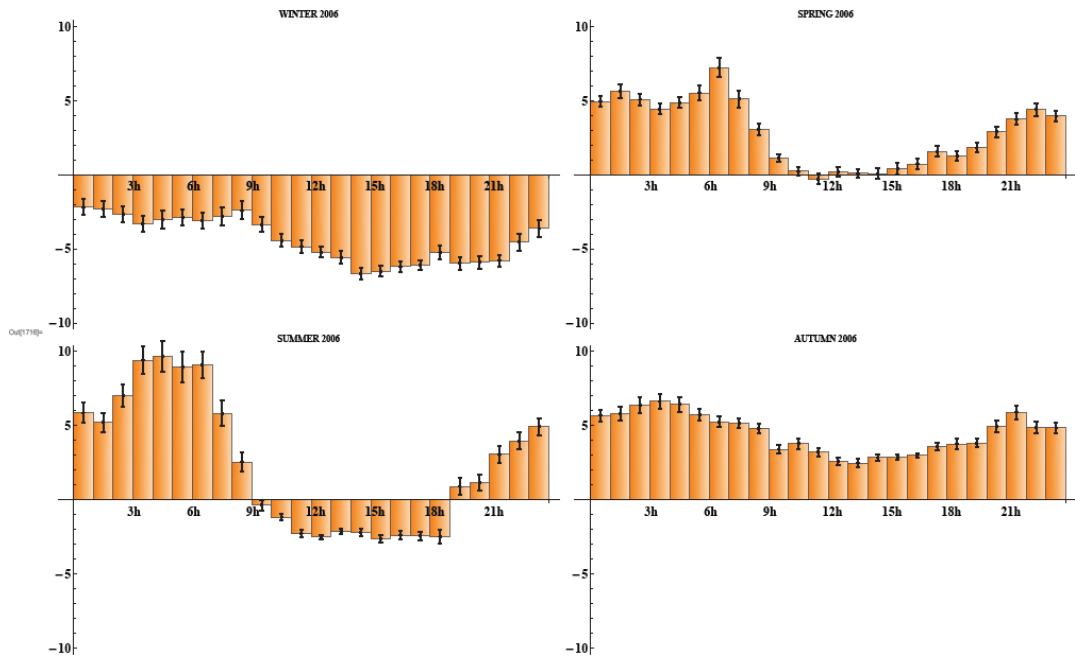


Annex C: Direction difference between 100 m and 60 m for 2006

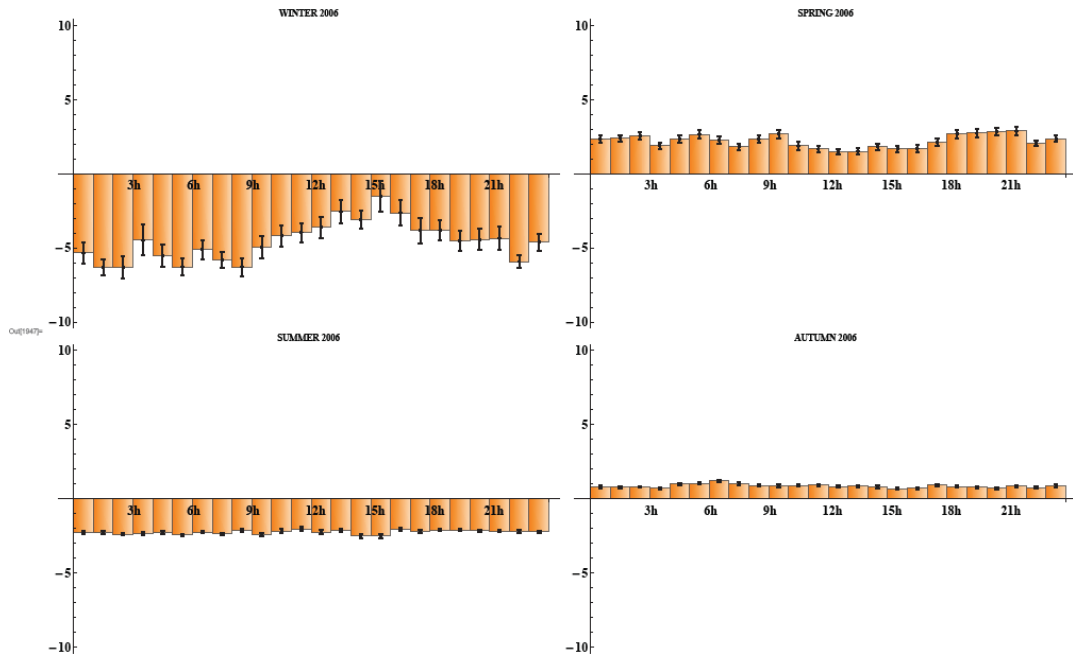
East



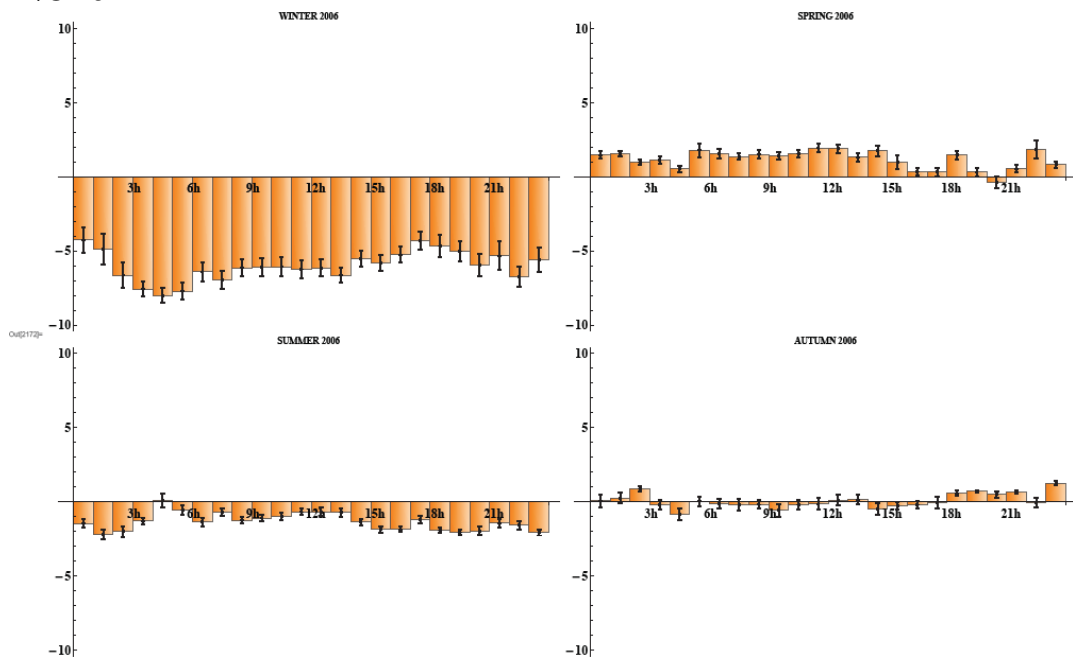
South



West

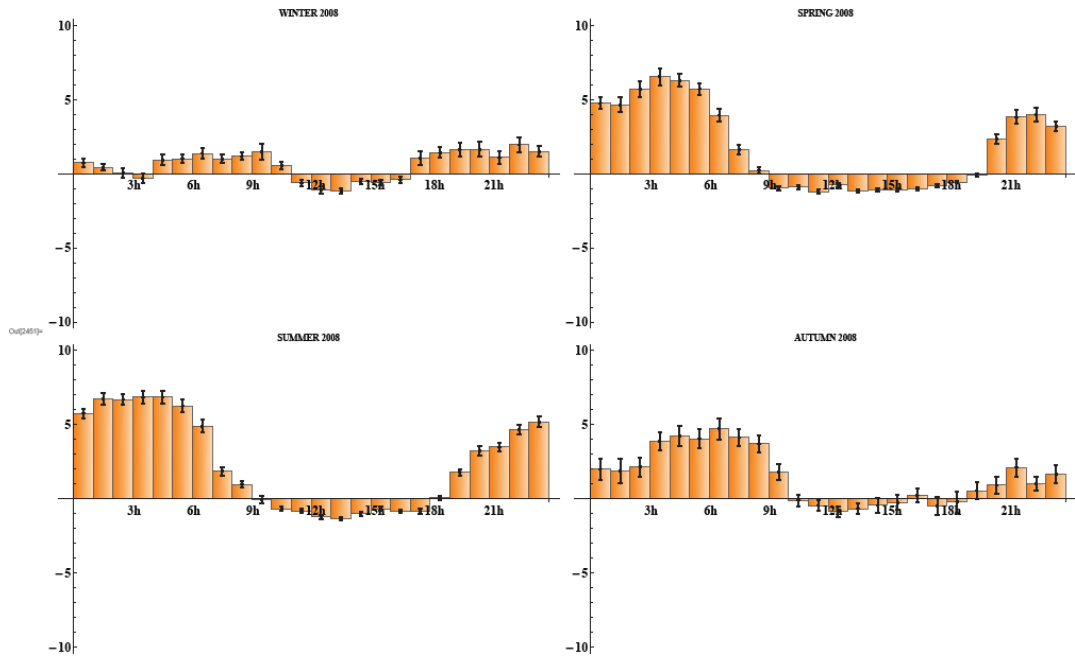


North

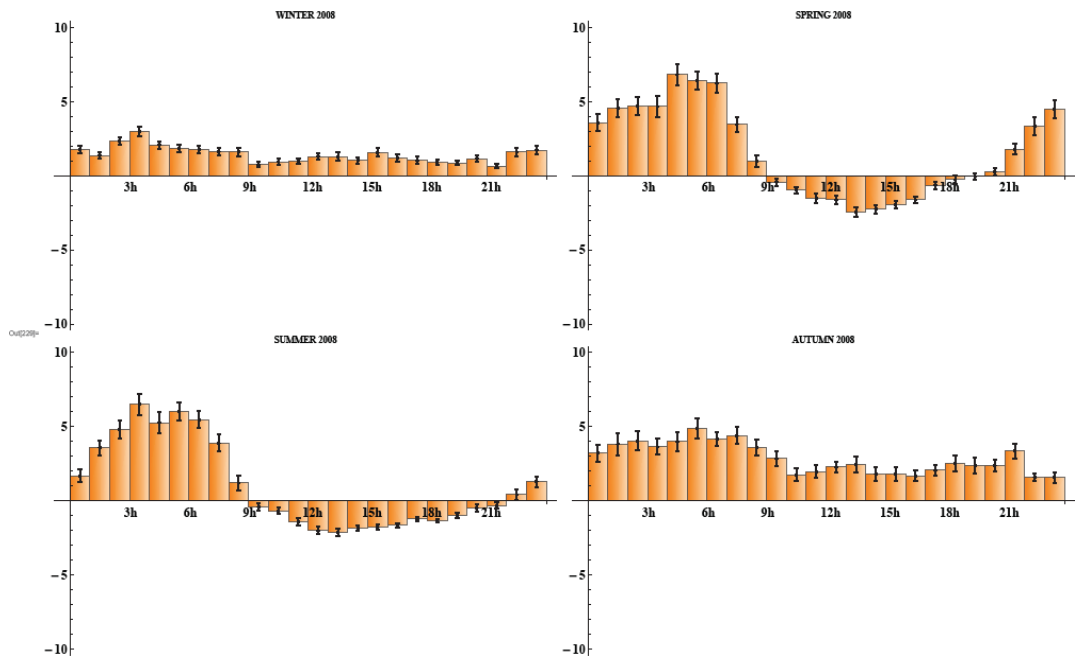


Annex D: Direction difference between 100 m and 60 m for 2008

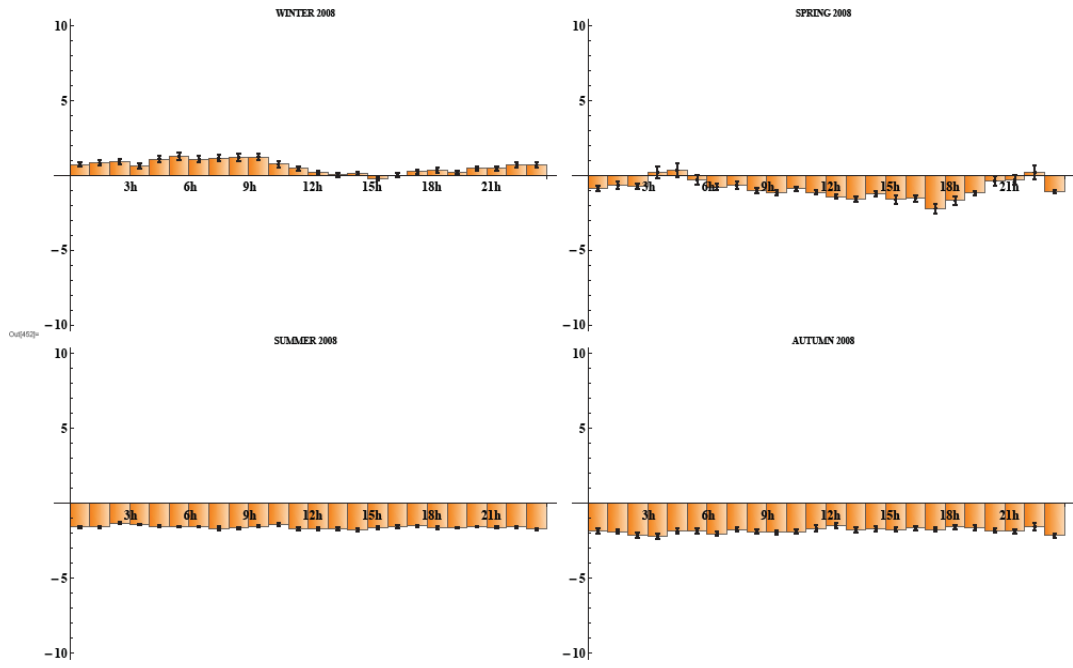
East



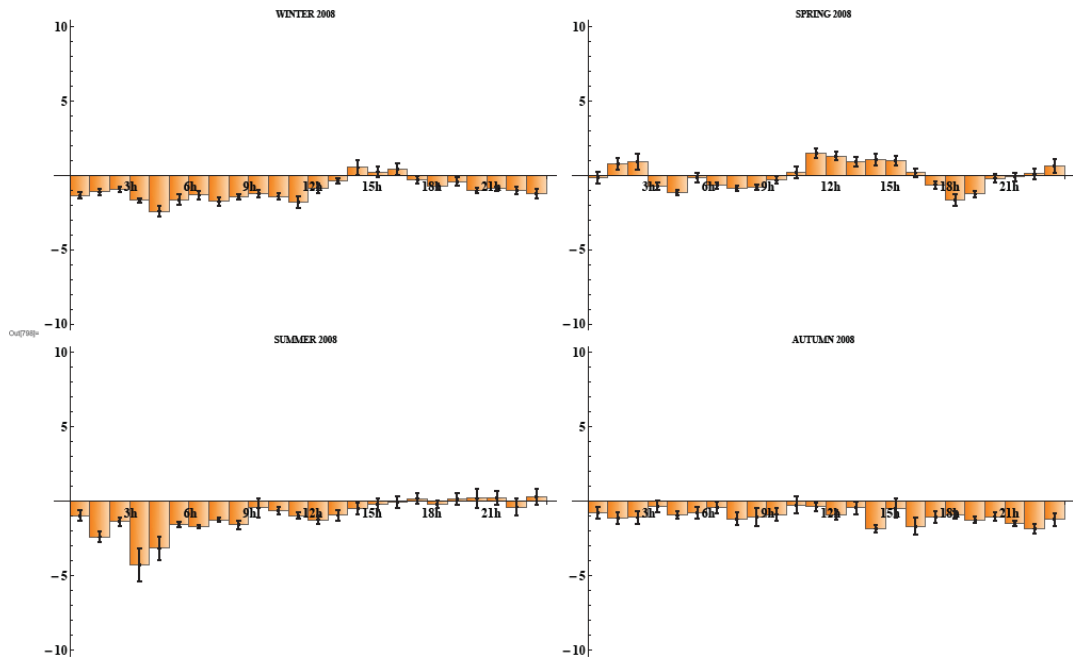
South



West



North



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