Concawe
Environmental Science for European Refining

Report

Report no. 12/19

A study of wind flow around a refinery

ISBN 978-2-87567-110-3

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A study of wind flow around a refinery

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ABSTRACT

Assessment of diffuse emissions using remote sensing needs appropriate information on vertical profiles of wind speed and wind direction. This information has then to be combined with concentration, or path-integrated concentration, in order to estimate the mass flux of hydrocarbons through the measurement plane.

The presence of plant units, buildings, tanks, process areas, etc. modifies the wind as it passes across the refinery. It is not practical to make wind measurements at alongside concentration measurements in order to determine flux explicitly. Assumptions about the wind spatial and temporal resolution are therefore necessary and contribute to overall uncertainty in flux determinations.

To provide information on variability in wind parameters, Concawe carried out a programme of wind measurements on a refinery site using a combination of traditional meteorological instruments mounted on fixed masts and a wind LIDAR which was made mobile by mounting it on a pick-up truck. The study was carried out during a 9-day period. The purpose of the exercise is to investigate whether there are significant differences in wind data gathered at various locations.

This report is confined to an inter-comparison of the fixed mast data. Review of the LIDAR data revealed obvious errors in some of the LIDAR measurements (see Appendix B) and so these were not used in the analysis.

It was found that the wind vector (speed, direction) is modified as the wind interacts with the refinery. Measurements at one reference station are not always representative of measurements elsewhere. The difference in wind vector between stations varies with time denying the development of a correction factor. The difference is greater for measurements made at 3.7 m height compared to those made at 10 m height.

Recommendations have been made for the placement of wind masts to provide data to support remote sensing campaigns.

Recommendations are also made for both the evaluation of wind data and exclusion of time periods for meaningful interpretation of data. The need for sensitivity calculations to account for uncertainty in wind parameters in the derivation of emission flux is identified.

Although there were problems in this wind campaign with the use of a truck-mounted wind LIDAR, pre-campaign experience with a static mounted LIDAR was positive and the technique has advantages for measuring vertical profiles.

KEYWORDS

Wind LIDAR, Wind mast, Vector Wind Speed, Vector Wind Direction, Measurement

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1. INTRODUCTION

Assessment of diffuse emissions using remote sensing needs appropriate information on vertical profiles of wind speed and wind direction. This information has then to be combined with concentration, or path-integrated concentration, in order to estimate the mass flux of hydrocarbons through the measurement plane.

The presence of plant units, buildings, tanks, process areas, etc. modifies the wind as it passes across the refinery. It is not practical to make wind measurements that are equivalent to the concentration measurements in terms of location or spatial and temporal resolution in order to determine flux explicitly. Assumptions about the wind at concentration measurement locations are therefore necessary and contribute to overall uncertainty in flux assessment.

To provide information on variability in wind parameters, Concawe carried out a programme of wind measurements on a refinery site using a combination of traditional meteorological instruments mounted on fixed masts and a wind LIDAR which was mounted on a pick-up truck for rapid deployment.

Meteorological masts (2 heights at each location) were fixed in three reference sites (stations) located to the West (W), North West (NW) and East (E) on the refinery boundary. Data from masts at a fourth location (in the South East (SE) of the refinery near the process area) were limited to low level measurements due to collection errors. The partial higher level data in the SE have not been analysed here.

A wind LIDAR provides vertical profiles of both horizontal and vertical wind components. An evaluation of the LIDAR before it was used in this study showed that it gave credible wind profiles that were consistent with measurements from anemometers mounted at different heights on a meteorological mast. The evaluation is given in a companion report [1]. Unfortunately, in this trial, there were some problems of unknown cause with the LIDAR mounted upon a pick-up truck. Although the LIDAR appeared to function effectively during the study, subsequent data-analysis revealed obvious errors in some of the data, especially relating to wind-direction (see Appendix B). Unfortunately, no objective test was found to indicate an error-free measurement. To keep the results data-led it was decided to not make a subjective judgement of which LIDAR data to report and which to exclude. This is disappointing as we believe that wind LIDAR has a useful role to play in profiling refinery wind.

This report describes the study and the main features of the wind field as observed between the fixed meteorological masts between the 18th and 26th of October 2016. Learning points for the use of the wind LIDAR in the field and data-processing needed to use wind speed and direction data for emission monitoring purposes are developed.

2. REFINERY STUDY OVERVIEW

A map of the refinery is shown below with the four locations for fixed wind measurements marked out with red crosses. The refinery was chosen because it was in a location with a relatively homogeneous incident wind field. It is surrounded on three sides by level farmland. To the North is another industrial plant. The ground covered by the refinery itself is approximately 1 km square.

Two meteorological masts were placed at each of the numbered stations 1 (W), 2 (NW) and 3 (E). The masts were instrumented to measure wind speed and direction at heights of 10 m and 3.7 m of the ground respectively. These stations are situated to measure incident wind on the refinery and are relatively free from local obstructions although Station 1 is downwind of a large tank for a North wind.

At station 4 (SE) there were 4 instruments. A weather station, a 10 m mast and two masts measuring at 3.7 m height. Station 4 is close to the main process area and obstructed on all sides. Unfortunately, there was data loss from both the weather station and the 10 m mast and complete information is limited to the low-level instruments.

The wind LIDAR, recording wind speed and direction between 12 m and 100 m height, was mounted on a pick-up truck and driven to several locations on the refinery as shown by the pin symbols on the map below. Some locations were revisited several times. A total of 60 measurement periods were taken ranging from 30 minutes to more than 24 hours in duration. A portable meteorological station equipped with a sonic anemometer was used to measure wind at 3 m height at the wind LIDAR location.

As previously stated, the LIDAR data are not presented here because analysis showed that some of the results were clearly incorrect even though the instrument had appeared to function normally in use. With no objective means of identifying sound data it was decided there was a risk of drawing incomplete conclusions if analysis proceeded on a subjective basis. The data-processing procedures applied to the LIDAR output are generic and are included below.

The data acquisition system for the reference masts was a packaged system which output 1-minute averages of scalar wind speed and of wind direction. This was post-processed to give 10-minute interval and 10-minute moving averages. The latter smooths out the short-term variations while indicating how representative a single 10-minute average data value might be.

Time-delay correlations, using the 1-minute wind speed data, were made between stations to test the need to incorporate an advection time delay when comparing station data. This was found not to be necessary. The correlations are not reported.

The LIDAR profile data were obtained at approximately 0.05 Hz which is the operational rate of the instrument. The duration of the measurement at each of the 20 height bands was 1 s. The interval between data profiles is not constant and is dependent on the signal to noise ratio. These data were averaged into 10-minute interval periods.

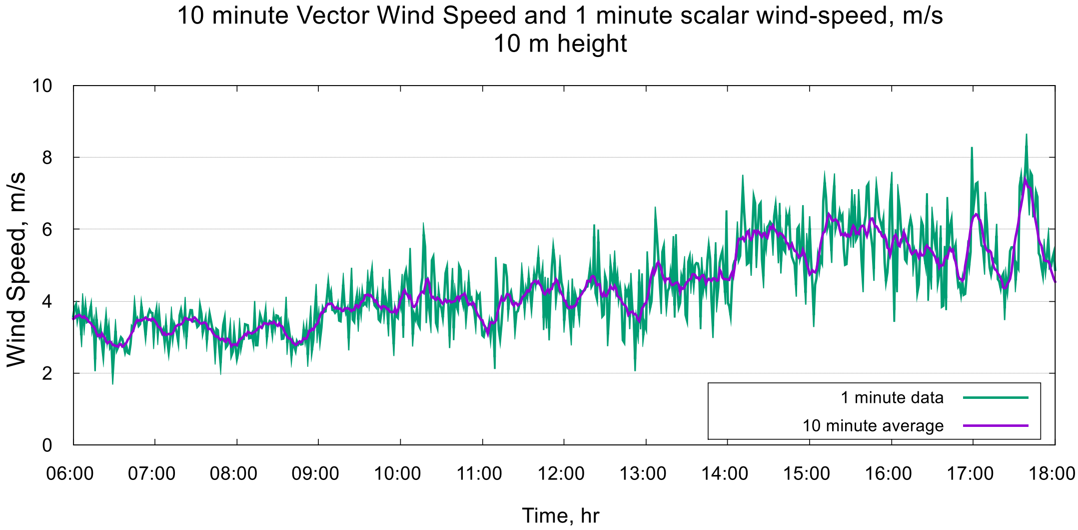
All data results were post-processed. This contributed to the lack of awareness of problems with the LIDAR data quality. It would have been better to use real-time processing and enable data visualisation during the course of measurement.

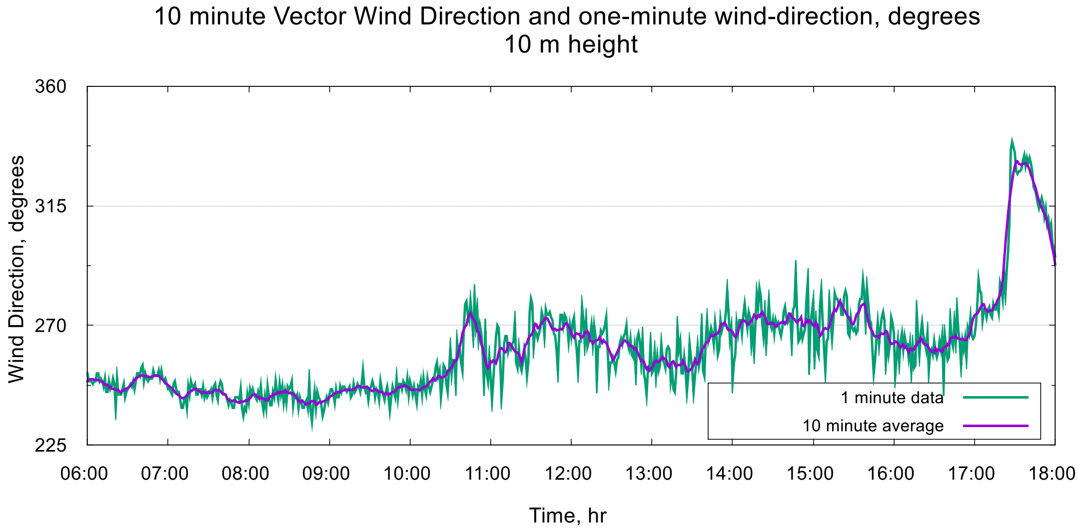
The averaged data provide wind vector (speed, direction), scalar wind speed, and, for the LIDAR, vertical wind speed. The wind vector is calculated in the following way:

- An anemometer gives a measure (U, θ) where U is the wind speed and θ the wind direction. This can be written as (u, v) where u and v are the Cartesian components of the wind speed. These components are averaged over the desired time period to give the average wind vector $(\bar{u}, \bar{v})$. This can be recast in the form (V, Φ) where V is the average wind speed in the direction Φ. The scalar wind speed is the arithmetic average of the recorded wind speed, $\bar{U}$.

The ratio, $\frac{V}{\bar{U}}$, of vector to scalar wind speed is called the persistence. A value of 1 indicates a constant wind direction over the averaging period and a value of 0 indicates the wind came equally from all directions over the averaging period.

A comparison of 10-minute smoothed data and 1-minute data-logger output for the 19th October is shown below. A considerable amount of variation in the wind speed and direction is removed by the data-logging package supplied with the anemometers. Even so, it can be seen that there is a high variability in wind speed and direction on a 1-minute period compared to the ten-minute average. In this case, the wind is from the WSW to W between 06:00 and 17:00 and represents relatively undisturbed flow at Station 1.





It would have been preferable to access the higher frequency data processed by the data logger. A data record at a higher frequency, e.g. 4 Hz would allow better account to be taken of building induced turbulence and of atmospheric turbulence at the building scale.

2.1. REFERENCE STATION MEASUREMENTS

The standard reference height for near ground meteorological measurements is 10 m. Wind speeds at other heights can be obtained by scaling using standard profiles for flow over flat ground as discussed in the companion report [1]. Under steady conditions these profiles develop over distances of several hundred metres to several kilometres. Therefore, they are appropriate for winds measured at the upwind side of an industrial site if the upwind terrain is flat. It is preferred to take measurements at more than one height. In this study the heights were 3.7m and 10m.

Due to turbulence wind speed and wind direction can vary greatly with time. It is important to perform some averaging to reduce short term fluctuations. A time-scale of ~10 minutes is sufficient to average atmospheric turbulence generated by friction at the ground and is also commensurate with the time taken for the wind to cross a refinery. If wind speed and direction change significantly on a 10-minute time scale, then unsteady conditions prevail and interpretation of plume trajectories in an emission survey will not be possible.

Because fixed mast measurements were made at only two heights at each station a vertical profile extending upward to, say, 200 m cannot be accurately being derived from mast data alone, although consistency with an expected profile can be demonstrated. The wind LIDAR data suggested that the incident wind was typical of a neutrally stratified boundary layer but results were not complete enough to establish accurate profiles. The following discussion will address the relative characteristics of the mast measurements expressed as time series presented for the 10 m and 3.7 m height instruments.

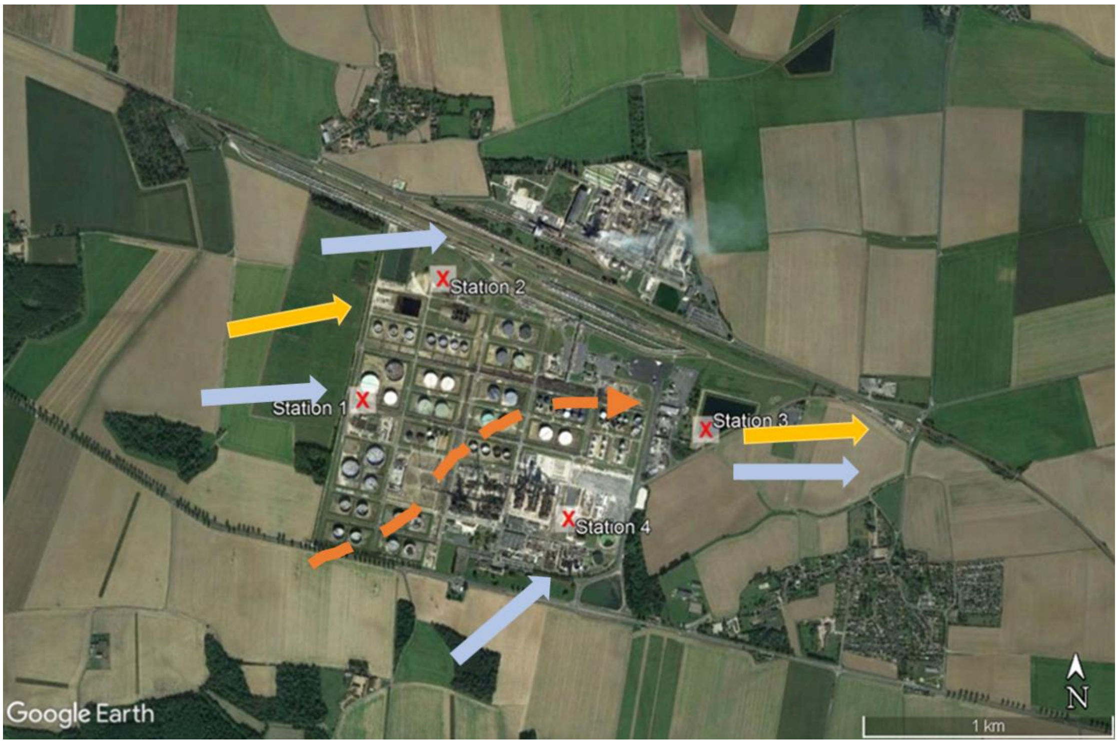
There are a lot of data to present and for ease of reading the first 24-hour period is described in the main text and the data for the other days has been moved to Appendix A. The day has been split into two 12-hour periods chosen to be 06:00-18:00 and 18:00–06:00. We note that remote sensing would ordinarily be done in day-time but this is not a technical constraint on the DIAL (Differential Absorption Lidar) method. Sunshine is necessary for the SOF (Solar Occultation Flux) technique. During the campaign period sunrise at the test location was at ~8:20 and sunset at ~18:50 so the first two hours of the day-time sequence are under night-time conditions.

2.1.1. October 18th (evening/night-time)

Data recording started at 18:30. After 19:30 the wind measured at 10 m height at each station was fairly steady with respect to wind speed and wind direction. The wind direction was from between WSW[1] and W, as measured by the two upwind stations 1 (W) and 2 (NW). Station 3, which is downwind of the refinery, recorded a more westerly wind. The wind speed varied mainly between 2 and 4 m/s overall with consistent but small differences between stations. Station 1 showed the lowest and Station 3 the greatest wind speed. This is possibly due to blocking of flow by the main process area with subsequent diversion and acceleration as indicated in the Figure below.

[1] The abbreviation WSW will be used for west-south-west indicating a point between SW (225 degrees) and W (270) degrees. Similar abbreviations will be used for the other sectors.

Approximate directions of wind at 10 m (yellow) and 3.7 m (blue) with possible direction of flow around the process area. Schematic only.

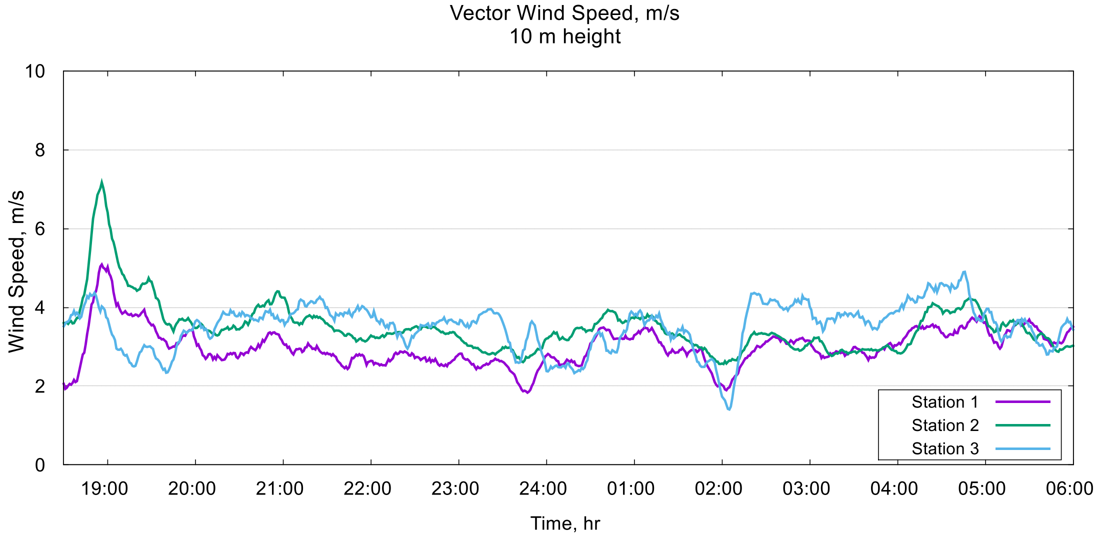


The differences between the stations averaged over the period are summarised below. These average values are calculated in the following way:

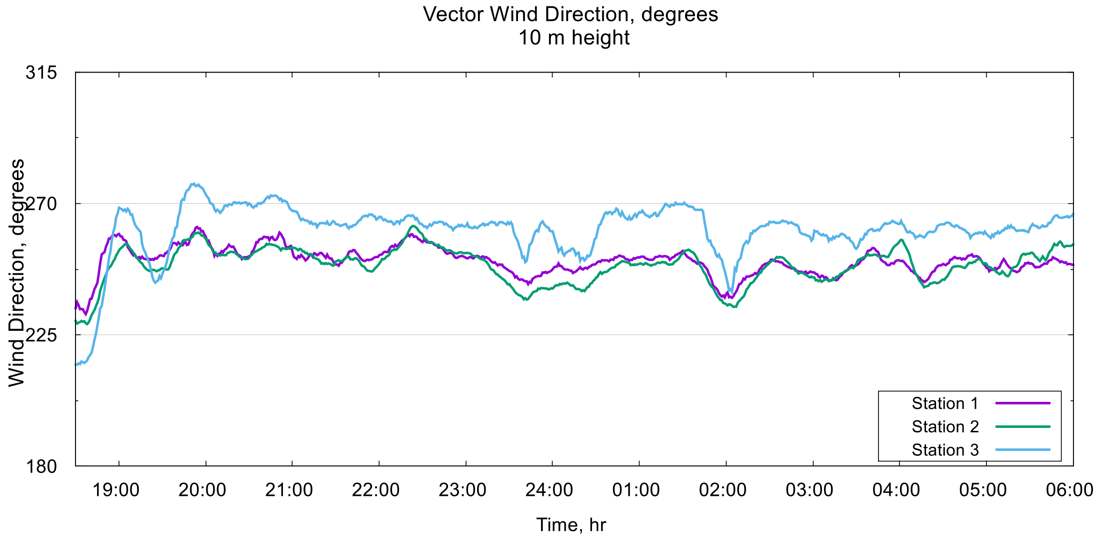
- Consider the difference between station 1 and station 3 at 10 m height. For each minute in the time-series plotted below, the 10-minute smoothed wind vector **U** = (u, v) was obtained at each station. The velocity difference is calculated as $|\mathbf{U_1} - \mathbf{U_2}|$ which is the length of the resultant vector. If there is no difference in wind direction this is the absolute difference in wind speed. The difference in wind direction is calculated from the scalar product $\mathbf{U_1} \bullet \mathbf{U_2} = |\mathbf{U_1}|.|\mathbf{U_2}|\cos(\theta)$. These differences are then averaged over the interval.

Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	1.06	12.1
Station 1 and Station 2	10	0.58	2.7
Station 2 and Station 3	10	1.08	12.95
Station 1 and Station 3	3.7	1.1	12.4
Station 1 and Station 2	3.7	0.63	12.9
Station 2 and Station 3	3.7	1.34	22.8
Station 1 at 10 m and Station 1 at 3.7 m		0.88	4.6
Station 2 at 10 m and Station 2 at 3.7 m		0.96	8.1
Station 3 at 10 m and Station 3 at 3.7 m		1.84	8.4

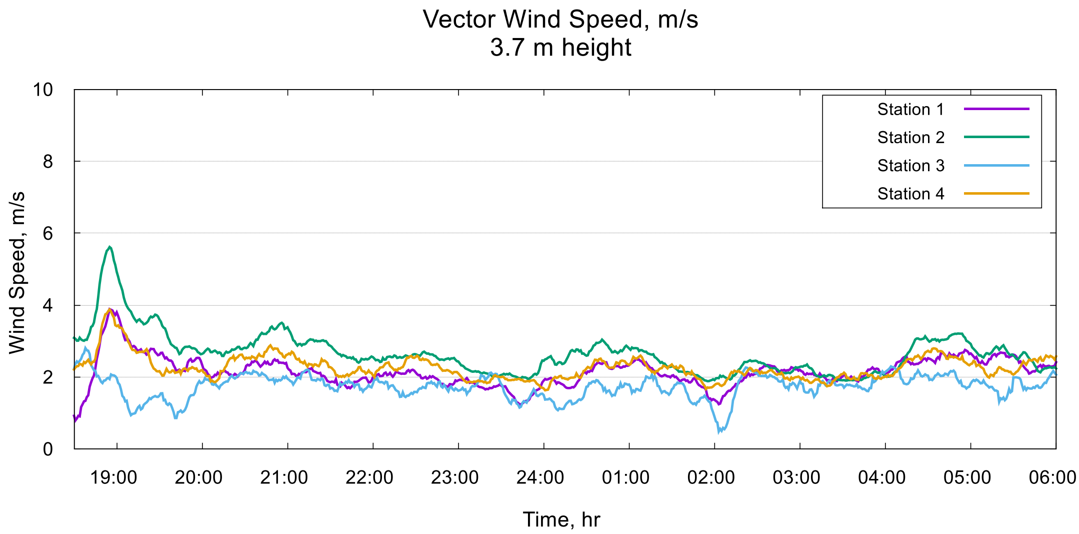
Time series of the wind vector speed **|U|** and direction are shown below in the order upper measuring station (10 m) and lower measuring station (3.7 m); the latter also includes results for the SE station 4.



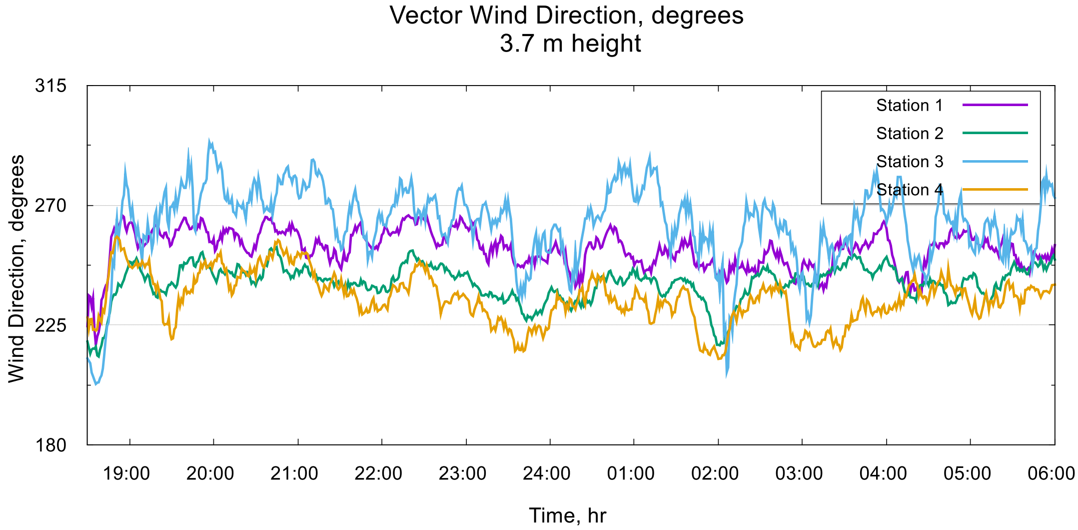
Vector Wind Speed, m/s
10 m height
Wind Speed, m/s
Time, hr
0
2
4
6
8
10
19:00
20:00
21:00
22:00
23:00
24:00
01:00
02:00
03:00
04:00
05:00
06:00
Station 1
Station 2
Station 3



Vector Wind Direction, degrees
10 m height
Wind Direction, degrees
Time, hr
180
225
270
315
19:00
20:00
21:00
22:00
23:00
24:00
01:00
02:00
03:00
04:00
05:00
06:00
Station 1
Station 2
Station 3



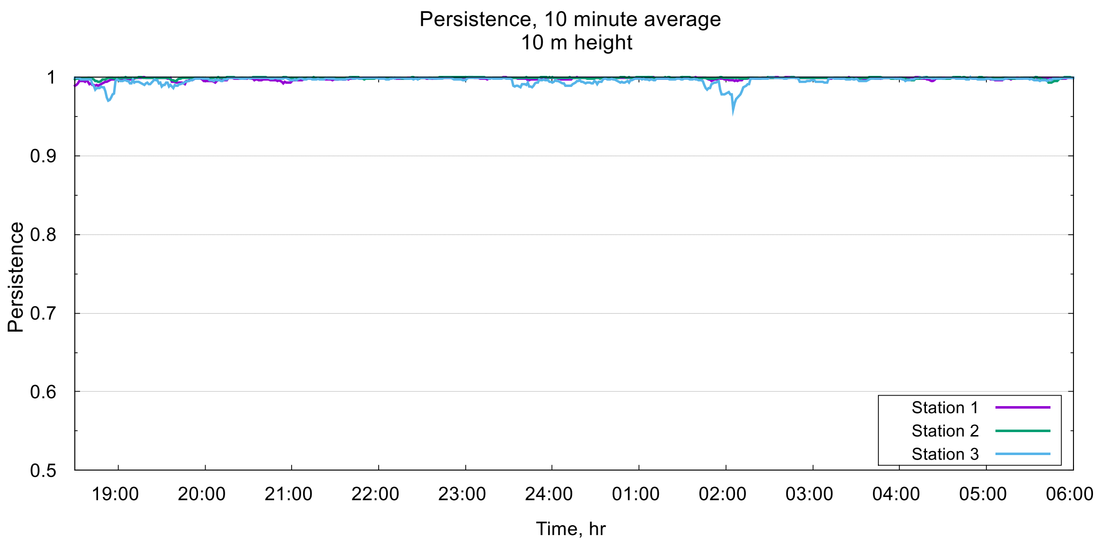
Vector Wind Speed, m/s
3.7 m height
Wind Speed, m/s
Time, hr
0
2
4
6
8
10
19:00
20:00
21:00
22:00
23:00
24:00
01:00
02:00
03:00
04:00
05:00
06:00
Station 1
Station 2
Station 3
Station 4

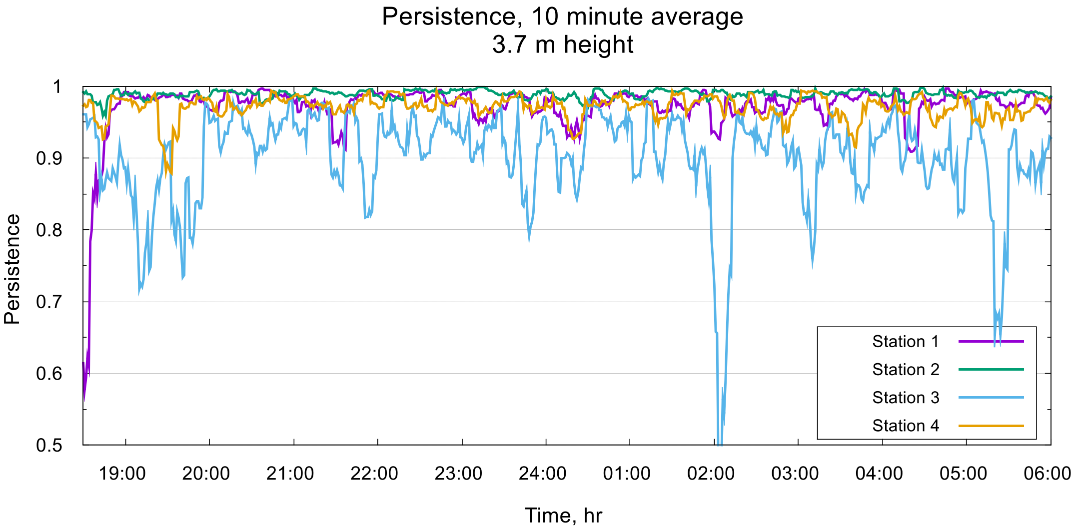


Visually it can be seen from the time-series that, as well as recording lower wind speeds the wind directions at a height of 3.7 m are also more variable over the period. The persistence informs on how significant the short-term variability in wind conditions is by comparing the magnitude of the wind vector with the magnitude of the scalar wind speed.

A value of persistence close to 1 indicates that wind conditions are constant over the averaging period. Where the wind conditions are constant then it is reasonable to assume emissions can be transported over a distance of up to $|\mathbf{V}|.\tau$ in the wind direction, where τ is the averaging time.

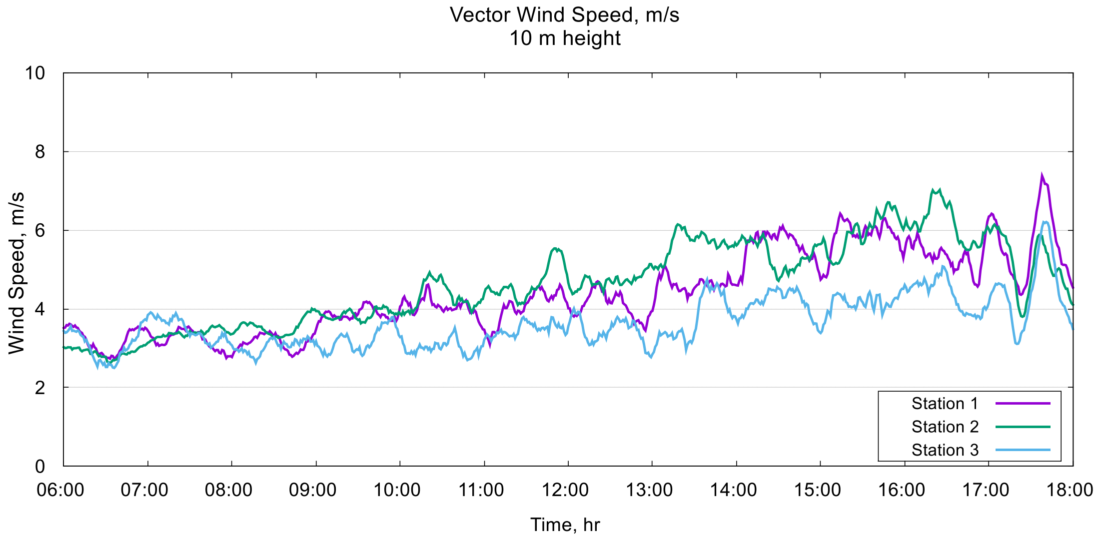
For this period the persistence of measurements at 10 m height is close to 1 and at 3.7 m height it is less, indicating more variability at this height. This is particularly so at station 3. The reason for the large difference in steadiness between measures at 10 m and 3.7 m for this wind direction is not clear. Station 3 is free of immediate obstructions to the flow so it would be expected that large scale turbulence due to flow over the refinery would affect measurements at both heights.

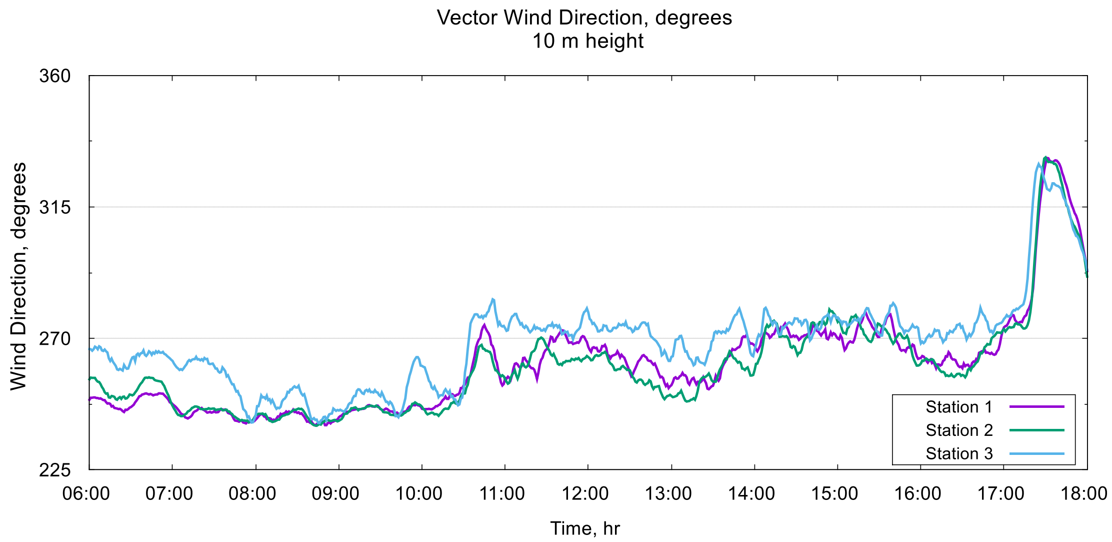




2.1.2. October 19th (daytime)

During the day of the 19th the wind measured at 10 m built steadily during the day with an increasing separation between the stations with station 3 (E), which was down-wind of the refinery for the majority of the period, recording the lower wind speed, stations 1 (W) and 2 (NW) being more comparable. Wind speed variability also increased.

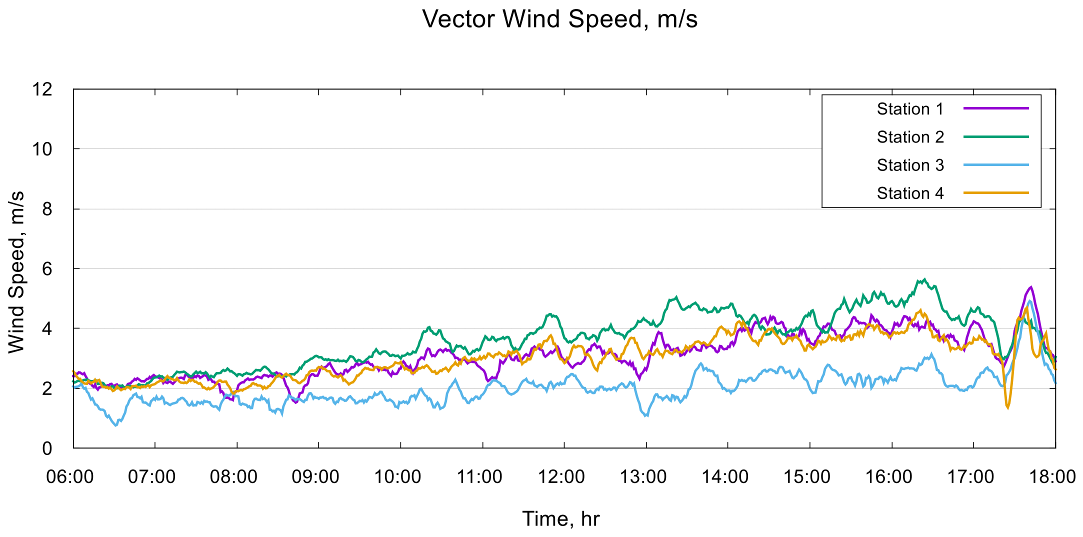


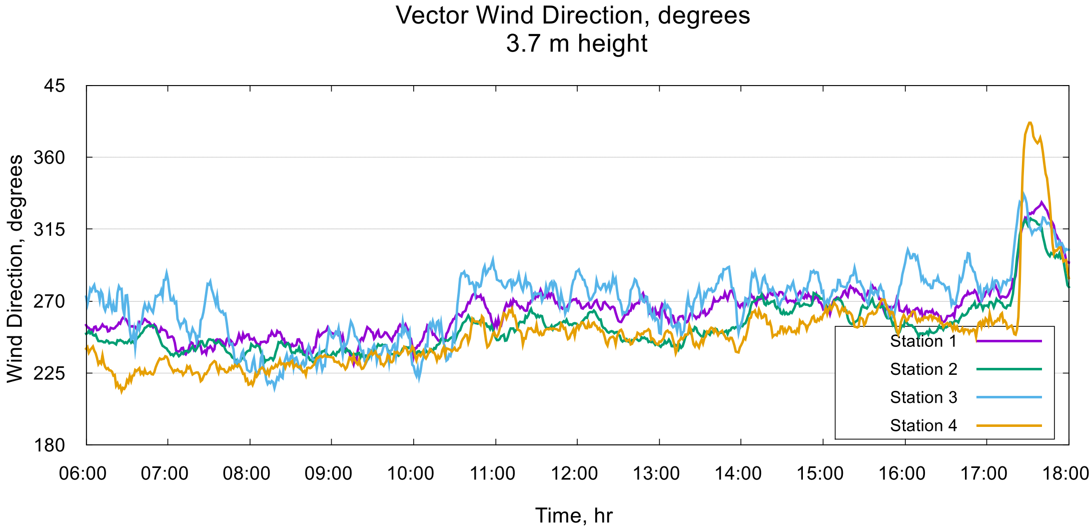


Wind direction remained fairly steady throughout the day at WSW turning more W after 10:00. All stations observed a large change in wind direction at 17:30.

The wind direction measured at 3.7 m was broadly consistent with that measured at 10 m and the wind speed was less as expected. There is no consistent record at 10 m height for the SE station (4) for comparison. The 3.7 m wind speed was similar to the lower mast at Station 1 (W) and during the day the direction there was more southwest than the others. At 17:30 the wind turned through North when the others were NW.

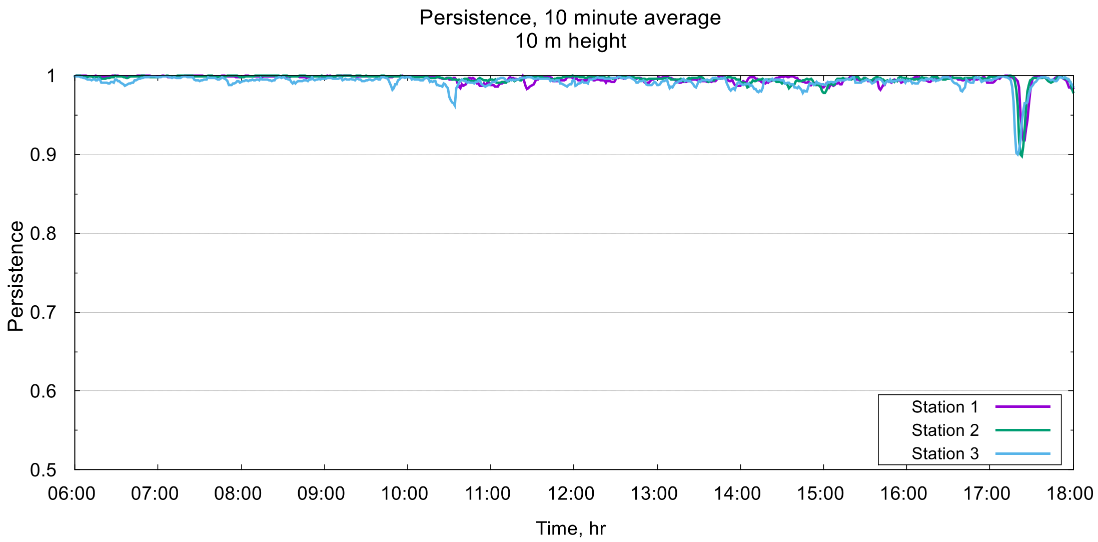
Overall, station 3 (E) recorded the lowest wind speed of the stations and there was a greater difference between the 10 m and the 3.7 m measurements at this location.

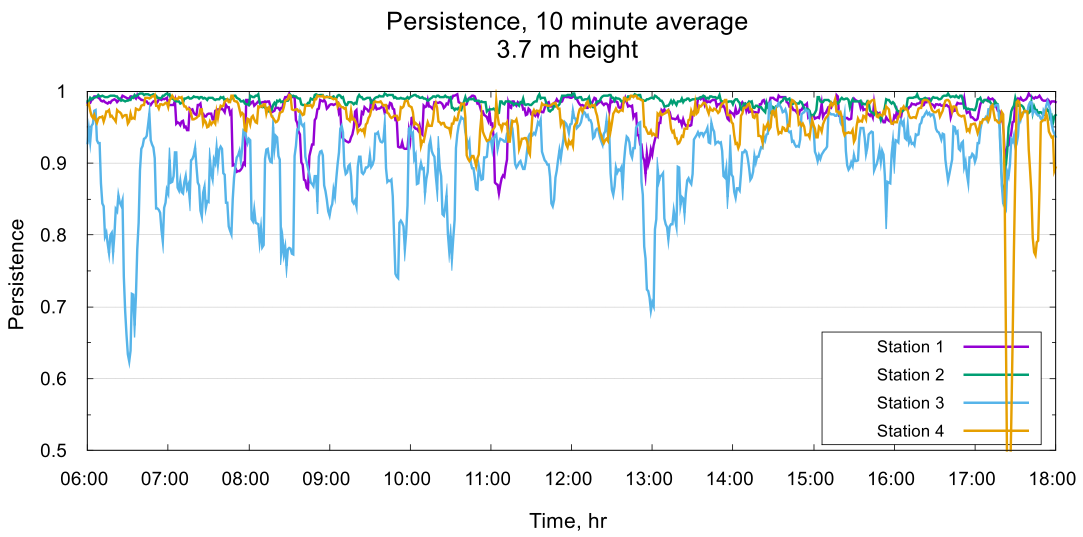




The summary differences between stations, tabulated below, shows that the average difference in wind direction is slightly reduced compared to the previous evening. The height variation in wind velocity at station 3 remains greater than for the other stations and there remain directional differences between heights at each station. The persistence graphs show that there is very considerable variability at low level on station 3 and, at this low level, all stations show intermittent short periods of unsteady behaviour. At 10 m only the period around 17:30, when there was a large change in wind direction, shows as unsteady in the persistence graph.

Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	1.1	8.5
Station 1 and Station 2	10	0.63	3.1
Station 2 and Station 3	10	1.34	9.1
Station 1 and Station 3	3.7	1.26	11.8
Station 1 and Station 2	3.7	0.88	9.7
Station 2 and Station 3	3.7	1.88	17
Station 1 at 10 m and Station 1 at 3.7 m		1.31	3.6
Station 2 at 10 m and Station 2 at 3.7 m		1.13	6.4
Station 3 at 10 m and Station 3 at 3.7 m		1.68	8.4





The data record continues in Appendix A.

3. SUMMARY OF RESULTS

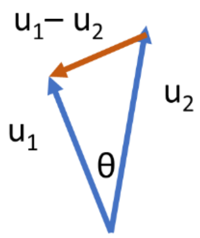
A campaign of measurements has been carried out to investigate the spatial variability in wind measurements on a refinery, supported by the use of a wind LIDAR to inform on the vertical wind profile at heights between 12 and 100 m. The purpose of the project was to assess whether measurements taken at a single location can be considered representative of wind conditions elsewhere. This is relevant to the exercise of remote sensing methods for emissions assessment which rely on reference meteorological data. Specifically, wind direction and the profile of wind speed with height are key inputs to these calculations.

To our knowledge this was the first attempted use of a mobile wind LIDAR for this purpose. Static wind LIDARs have been used in remote sensing audits to provide information away from actual sites. Concawe's experience with the wind LIDAR before the experiments was limited to a comparison of LIDAR results with those from a co-located wind mast in a flat-field setting. That data comparison is described in an accompanying report [1] and indicated that the LIDAR returned credible wind profiles, consistent with the meteorological mast measurements. A small offset in wind-direction was attributed to the calibration of North.

Unfortunately, on analysis of this campaign data, problems were found with the consistent determination of wind direction using the mobile LIDAR, including the potential for measured wind direction to drift in time in a way not supported by other measurements. Although much of the LIDAR data appeared plausible given the understandings that exist from aerodynamic considerations, wind tunnel and computational fluid mechanical studies, it was decided not to make a subjective judgement of which LIDAR data to report and which to exclude. This is disappointing as we believe that wind LIDAR has a useful role to play in profiling refinery wind.

The data from the fixed reference stations showed real differences in time in wind speed and wind direction when processed using ten-minute moving averages to smooth the data. This time scale is relevant to remote sensing and to the time of flight across a refinery. Both wind direction and wind speed show variability from one ten-minute period to another. These have been illustrated using time-series across consecutive 12-hour periods that separate day and night. Average differences in wind speed and wind direction have been tabulated for these periods.

Wind speed differences can be described in two ways: as the difference in magnitude of the wind vector at each of two locations $|\mathbf{u_2}| - |\mathbf{u_1}|$ or as the magnitude of the vector difference $|\mathbf{u_2} - \mathbf{u_1}|$. As shown below, the two are the same if the vectors are parallel but the magnitude of the vector difference is larger if there is difference in wind direction, θ.



The average differences in wind speed on these criteria are listed below. The convention used is that the subscript 1 refers to the first named station and subscript 2 the second. The tabulated data comprises:

- The time period – either 12 hours overnight (18:00 – 06:00) or 12 hours during the day (06:00 – 18:00).
- The reference height. If the height is not given, then the difference is between two mast heights at a single location.
- The modulus of the wind vector difference between the locations averaged over the period.
- The average difference in wind direction averaged over the period.
- The average of the ratio of the wind speeds at each location (different to the ratio of the average wind speeds).
- The average wind speed at position 1.
- The average wind speed at position 2.
- The ratio of the modulus of the wind vector difference to the average of the wind speeds at the two locations as a %.
- The ratio of the difference in wind speeds at the locations to the average of the wind speeds at the two locations.

The latter two columns give a sense of the proportion of change in wind speed defined by both methods.

To begin with, consider the difference between Station 1 (W) and Station 3 (NE) measurements made at 10 m height. The stations are 1.4 km apart and, on a line of sight basis, separated by tanks. Station 3 is almost due East of Station 1 (heading 95^{o}).

Over the campaign there were consistent differences in the wind speed and wind direction measured at the two stations. For days where the average wind at station 1 was > 2 m/s the difference in average wind direction ranged between 5.2º and 21.8º and the difference in average wind speed between -16% and 21.9%. The joint effect of wind speed and direction difference is reflected in a variation of between 19.7% and 55.18% in the size of the resultant wind vector.

Table 1 Summary of Differences between Station 1 (u_1) and Station 3 (u_2) at 10 m.

Period	Height	$\overline{\|u_1 - u_2\|}$	θ	$\frac{\overline{\|u_2\|}}{\overline{\|u_1\|}}$	$\overline{\|u_1\|}$	$\overline{\|u_2\|}$	$2\frac{\overline{\|u_1 - u_2\|}}{\overline{\|u_1\|} + \overline{\|u_2\|}}$	$2\frac{\overline{\|u_1\|} - \overline{\|u_2\|}}{\overline{\|u_1\|} + \overline{\|u_2\|}}$
	m	m/s	deg.	-	m/s	m/s		
Oct 18 - 19	10	1.06	12.1	1.19	3.00	3.52	32.53%	-16.02%
Oct 19	10	1.10	8.5	0.85	4.38	3.63	27.46%	18.67%
Oct 19 - 20	10	0.80	13.9	0.96	3.10	2.90	26.80%	6.67%
Oct 20	10	0.94	6.3	0.81	4.03	3.23	25.88%	21.92%
Oct 20 - 21	10	0.55	5.2	0.90	2.96	2.62	19.70%	12.28%
Oct 21	10	0.82	9.7	1.03	2.63	2.45	32.32%	7.02%
Oct 22 - 23	10	1.26	21.8	1.12	2.30	2.27	55.18%	1.45%
Oct 23	10	0.97	11.0	1.05	3.71	3.88	25.56%	-4.30%
Oct 23-24	10	0.84	14.2	0.90	2.80	2.55	31.40%	9.35%
Oct 24	10	0.81	21.9	1.20	1.69	1.67	48.19%	1.19%
Oct 24-25	10	0.93	46.0	1.69	0.90	1.28	85.32%	-34.86%
Oct 25 – 26	10	0.86	21.1	1.42	1.53	1.92	49.90%	-22.80%

The comparison for measurements made at 3.7 m height shows a general increase in the difference between the two stations with the spread in average wind direction differences becoming 7.2 – 34^0 for periods where the average wind speed at 10 m exceeds 2 m/s.

Table 2 Summary of Differences between Station 1 (u_1) and Station 3 (u_2) at 3.7 m.

Period	Height	$\overline{\|u_1 - u_2\|}$	θ	$\frac{\overline{\|u_2\|}}{\overline{\|u_1\|}}$	$\overline{\|u_1\|}$	$\overline{\|u_2\|}$	$2\frac{\overline{\|u_1 - u_2\|}}{\overline{\|u_1\|} + \overline{\|u_2\|}}$	$2\frac{\overline{\|u_1\|} - \overline{\|u_2\|}}{\overline{\|u_1\|} + \overline{\|u_2\|}}$
	m	m/s	deg.	-	m/s	m/s		
Oct 18 - 19	3.7	1.1	12.4	0.834	2.149	1.735	56.64%	21.32%
Oct 19	3.7	1.26	11.8	0.656	3.102	2.017	49.23%	42.39%
Oct 19 - 20	3.7	0.967	19.03	0.714	2.218	1.554	51.27%	35.21%
Oct 20	3.7	0.98	10	0.693	2.804	1.943	41.29%	36.28%
Oct 20 - 21	3.7	0.39	7.2	0.925	0.925	1.486	32.35%	-46.54%
Oct 21	3.7	0.54	11.85	0.956	1.711	1.509	33.54%	12.55%
Oct 22 - 23	3.7	1.35	34	0.94	1.847	1.447	81.97%	24.29%
Oct 23	3.7	0.82	13.7	0.978	3.032	2.958	27.38%	2.47%
Oct 23-24	3.7	0.8	21.9	0.816	2.294	1.906	38.10%	18.48%
Oct 24	3.7	0.78	27	1.282	1.305	1.082	65.35%	18.68%
Oct 24-25	3.7	0.62	47.5	1.79	0.683	0.866	80.05%	-23.63%
Oct 25 – 26	3.7	0.55	28.4	0.981	1.203	1.085	48.08%	10.31%

Stations 2 (NW) and 4 (SE) are at opposite corners of the refinery. Station 4 is only downwind of Station 2 when the wind is in the NW which occurs infrequently. There are no 10 m data at Station 4 which is to the east of the main process area.

The differences between the two stations are systematically large. The average wind direction difference between them ranges from 8.4 to 52.6 degrees. The short-term variations are larger as visualised in the time-series plots. The wind speed difference is proportionately not that large for most periods, the direction contributing most to the vector difference range of 24 to 86%.

Table 3 Differences between Station 2 (u_1) and Station 4 (u_2) at 3.7 m height.

Period	Height	$\overline{\lvert u_1 - u_2 \rvert}$	θ	$\frac{\overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert}}$	$\overline{\lvert u_1 \rvert}$	$\overline{\lvert u_2 \rvert}$	$2\frac{\overline{\lvert u_1 - u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$	$2\frac{\overline{\lvert u_1 \rvert} - \overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$
	m	m/s	deg.	-	m/s	m/s		
Oct 18 - 19	3.7	0.59	8.41	0.87	2.65	2.26	24.21%	15.81%
Oct 19	3.7	0.93	9.76	0.85	3.62	3.02	27.98%	18.16%
Oct 19 - 20	3.7	0.85	18.33	1.18	2.20	2.51	36.04%	-13.12%
Oct 20	3.7	1.14	20.87	0.89	2.89	2.54	41.96%	12.93%
Oct 20 - 21	3.7	1.13	30.10	1.20	1.73	2.00	60.59%	-14.91%
Oct 21	3.7	1.67	49.80	1.35	1.68	2.01	90.54%	-18.38%
Oct 22 - 23	3.7	1.38	38.00	1.19	1.97	2.01	69.33%	-2.16%
Oct 23	3.7	1.05	14.20	1.01	2.85	2.80	37.19%	1.84%
Oct 23-24	3.7	1.64	52.60	0.79	2.14	1.67	86.09%	24.67%
Oct 24	3.7	0.87	32.10	1.00	1.63	1.50	55.50%	8.10%
Oct 24-25	3.7	0.73	42.50	1.54	0.89	1.12	72.60%	-22.38%
Oct 25 – 26	3.7	1.32	36.60	1.65	1.30	2.13	77.06%	-48.34%

Stations 3 (NE) and 4 (SE) are both on the downwind side of the refinery for October 18th through October 21st and for short intervals thereafter. They are upwind on October 23rd which shows the smallest difference in wind direction of 9.1^{o} between them. Otherwise the difference is the greatest between stations. Station 4 generally shows higher average wind speeds.

Table 4 Differences between Station 3 (u_1) and Station 4 (u_2) at 3.7 m height.

Period	Height	$\overline{\lvert u_1 - u_2 \rvert}$	θ	$\frac{\overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert}}$	$\overline{\lvert u_1 \rvert}$	$\overline{\lvert u_2 \rvert}$	$2\frac{\overline{\lvert u_1 - u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$	$2\frac{\overline{\lvert u_1 \rvert} - \overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$
	m	m/s	deg.	-	m/s	m/s		
Oct 18 - 19	3.7	1.20	29.07	1.35	1.74	2.26	60.08%	-26.28%
Oct 19	3.7	1.53	22.89	1.54	2.02	3.02	60.72%	-39.79%
Oct 19 - 20	3.7	1.70	40.47	1.63	1.55	2.51	83.66%	-47.05%
Oct 20	3.7	1.30	26.30	1.37	1.94	2.54	58.01%	-26.60%
Oct 20 - 21	3.7	1.18	30.86	1.34	1.49	2.00	67.62%	-29.68%
Oct 21	3.7	1.53	43.23	1.44	1.51	2.01	87.03%	-28.67%
Oct 22 - 23	3.7	0.89	20.99	1.89	1.45	2.01	51.58%	-32.67%
Oct 23	3.7	1.05	9.10	1.01	2.96	2.80	36.49%	5.60%
Oct 23-24	3.7	1.23	41.80	1.11	1.91	1.67	68.79%	13.20%
Oct 24	3.7	1.16	44.70	1.71	1.08	1.50	89.71%	-32.64%
Oct 24-25	3.7	0.94	56.50	1.84	0.87	1.12	94.76%	-25.40%
Oct 25 – 26	3.7	1.30	25.50	2.57	1.09	2.13	80.95%	-64.88%

Station 1 (W) and Station 4 (SE) show consistently different wind directions with the difference ranging from 16.4 to 43.8º.

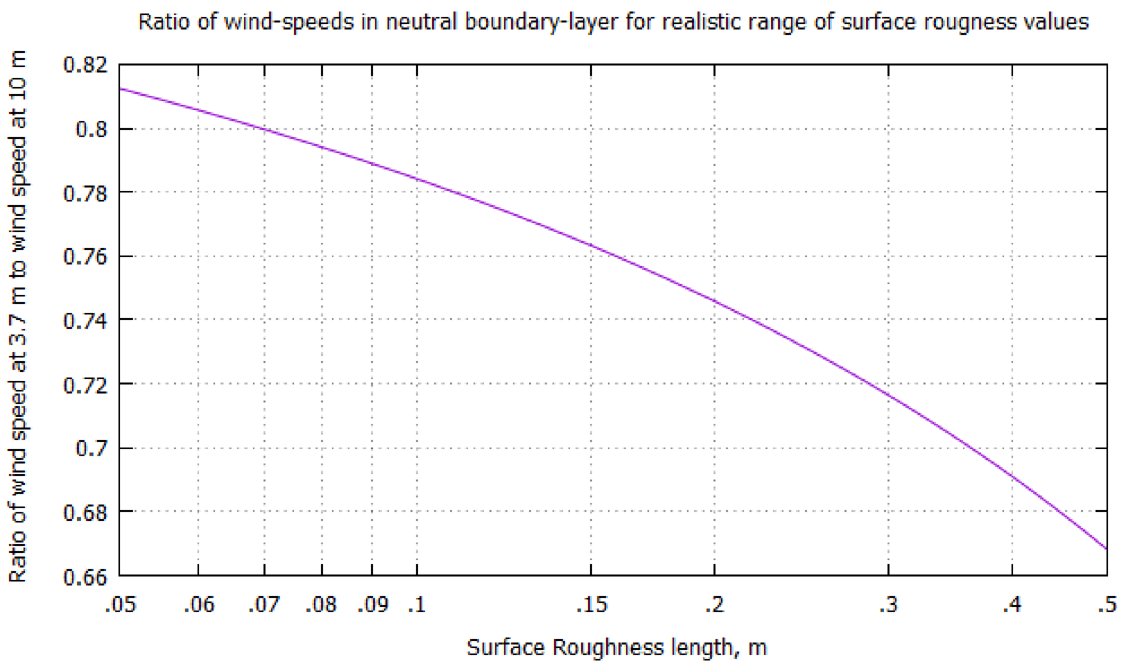
Table 5 Difference between Station 1 (u_1) and Station 4 (u_2) at 3.7 m height.

Period	Height	$\overline{\lvert u_1 - u_2 \rvert}$	θ	$\frac{\overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert}}$	$\overline{\lvert u_1 \rvert}$	$\overline{\lvert u_2 \rvert}$	$2\frac{\overline{\lvert u_1 - u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$	$2\frac{\overline{\lvert u_1 \rvert} - \overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$
	m	m/s	deg.	-	m/s	m/s		
Oct 18 - 19	3.7	0.77	18.72	1.07	2.15	2.26	34.84%	-5.04%
Oct 19	3.7	0.94	16.42	0.98	3.10	3.02	30.84%	2.71%
Oct 19 - 20	3.7	0.97	21.74	1.15	2.22	2.51	41.07%	-12.35%
Oct 20	3.7	1.10	20.70	0.92	2.80	2.54	41.18%	9.92%
Oct 20 - 21	3.7	1.14	28.80	1.24	0.93	2.00	77.84%	-73.68%
Oct 21	3.7	1.55	43.80	1.36	1.71	2.01	83.22%	-16.27%
Oct 22 - 23	3.7	1.58	37.70	1.38	1.85	2.01	81.89%	-8.55%
Oct 23	3.7	1.35	19.30	0.97	3.03	2.80	46.32%	8.06%
Oct 23-24	3.7	1.33	28.80	0.80	2.29	1.67	67.10%	31.48%
Oct 24	3.7	0.86	32.70	1.59	1.31	1.50	61.23%	-14.17%
Oct 24-25	3.7	0.81	40.40	2.19	0.68	1.12	89.95%	-48.31%
Oct 25 – 26	3.7	1.48	43.40	2.07	1.20	2.13	88.89%	-55.50%

The average difference in wind conditions with height at stations 1 (W), 2 (NW), and 3 (NE) are shown in Table 6 to Table 8. At each of the three stations the average wind speed at 3.7 m was less than at 10 m as would be expected. A difference in wind direction was noted of up to 8.3º for station 1, 9.2º for station 2, and 10.8º for station 3 for periods where the average 10 m wind speed exceeded 2 m/s.

The difference in wind speed between the two heights was greatest for Station 3. The ratio $\frac{|u_2|}{|u_1|}$ for station 3 was also significantly smaller than would be expected for an undisturbed boundary layer (range 0.66 – 0.8) on days where the station was downwind of the refinery.

Figure 1 Ratio of wind speed at 3.7 m to 10 m as a function of surface roughness. An indicative value of 0.2 is appropriate for refineries.



At Station 2 (NW), which was the most often unobstructed station, the ratio most often fell into the expected range.

Table 6 Change of wind with height at Station 1 (u_1 = 10 m, u_2 = 3.7 m).

Period	Height	$\overline{\lvert u_1 - u_2 \rvert}$	θ	$\frac{\overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert}}$	$\overline{\lvert u_1 \rvert}$	$\overline{\lvert u_2 \rvert}$	$2\frac{\overline{\lvert u_1 - u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$	$2\frac{\overline{\lvert u_1 \rvert} - \overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$
	m	m/s	deg.	-	m/s	m/s		
Oct 18 - 19		0.88	4.64	0.88	3.00	2.15	34.19%	32.99%
Oct 19		1.31	3.60	0.71	4.38	3.10	35.03%	34.22%
Oct 19 - 20		0.90	4.50	0.72	3.08	2.22	33.89%	32.45%
Oct 20		1.25	3.23	0.70	4.03	2.80	36.58%	35.88%
Oct 20 - 21		1.31	3.10	0.56	2.96	0.93	67.37%	104.86%
Oct 21		0.95	5.55	0.66	2.63	1.71	43.81%	42.20%
Oct 22 - 23		0.53	8.30	0.81	2.30	1.85	25.56%	21.85%
Oct 23		0.74	3.80	0.81	3.71	3.03	21.94%	20.19%
Oct 23-24		0.57	5.20	0.82	2.80	2.29	22.38%	19.87%
Oct 24		0.43	8.12	0.75	1.69	1.31	28.70%	25.77%
Oct 24-25		0.34	14.80	0.79	0.90	0.68	42.96%	27.42%
Oct 25 – 26		0.40	10.90	0.77	1.53	1.20	29.30%	23.74%

Table 7 Change of wind with height at Station 2 (u_1 = 10 m, u_2 = 3.7 m).

Period	Height	$\overline{\lvert u_1 - u_2 \rvert}$	θ	$\frac{\overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert}}$	$\overline{\lvert u_1 \rvert}$	$\overline{\lvert u_2 \rvert}$	$2\frac{\overline{\lvert u_1 - u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$	$2\frac{\overline{\lvert u_1 \rvert} - \overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$
	m	m/s	deg.	-	m/s	m/s		
Oct 18 - 19		0.96	8.10	0.75	3.49	2.65	31.28%	27.46%
Oct 19		1.13	6.40	0.78	4.63	3.62	27.40%	24.37%
Oct 19 - 20		0.92	6.60	0.71	3.05	2.20	34.97%	32.38%
Oct 20		0.99	7.49	0.77	3.76	2.89	29.73%	26.09%
Oct 20 - 21		0.94	9.20	0.66	2.60	1.73	43.51%	40.22%
Oct 21		0.62	8.96	0.75	2.20	1.68	31.98%	27.19%
Oct 22 - 23		0.83	9.32	0.78	2.68	1.97	35.75%	30.40%
Oct 23		1.38	7.70	0.70	4.12	2.85	39.61%	36.45%
Oct 23-24		0.95	5.00	0.74	3.04	2.14	36.69%	34.69%
Oct 24		0.44	7.53	0.82	1.98	1.63	24.34%	19.53%
Oct 24-25		0.36	12.10	0.78	1.16	0.89	35.16%	25.59%
Oct 25 – 26		0.64	10.60	0.70	1.87	1.30	40.46%	35.78%

Table 8 Change of wind with height at Station 3 (u_1 = 10 m, u_2 = 3.7 m).

Period	Height	$\overline{\lvert u_1 - u_2 \rvert}$	θ	$\frac{\overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert}}$	$\overline{\lvert u_1 \rvert}$	$\overline{\lvert u_2 \rvert}$	$2\frac{\overline{\lvert u_1 - u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$	$2\frac{\overline{\lvert u_1 \rvert} - \overline{\lvert u_2 \rvert}}{\overline{\lvert u_1 \rvert} + \overline{\lvert u_2 \rvert}}$
	m	m/s	deg.	-	m/s	m/s		
Oct 18 - 19		1.84	8.40	0.49	3.52	1.74	70.03%	67.94%
Oct 19		1.68	8.40	0.55	3.62	2.02	59.57%	56.95%
Oct 19 - 20		1.45	9.35	0.51	2.94	1.55	64.59%	61.92%
Oct 20		1.33	6.05	0.60	3.23	1.94	51.38%	49.87%
Oct 20 - 21		1.16	5.90	0.57	2.62	1.49	56.49%	55.27%
Oct 21		0.97	6.30	0.62	2.45	1.51	49.03%	47.46%
Oct 22 - 23		0.90	10.80	0.59	2.27	1.45	48.47%	44.16%
Oct 23		0.94	2.60	0.76	3.88	2.96	27.51%	26.87%
Oct 23-24		0.68	6.80	0.74	2.55	1.91	30.52%	28.90%
Oct 24		0.63	8.62	0.65	1.67	1.08	45.77%	42.79%
Oct 24-25		0.52	15.40	0.72	1.28	0.87	48.46%	38.58%
Oct 25 – 26		0.89	10.70	0.58	1.92	1.09	59.23%	55.57%

See Appendix A and B for a complete summary of results.

4. CONCLUSIONS AND RECOMMENDATIONS

These conclusions are based on wind measurement data averaged for 10 minutes (smoothed data) to diminish the influence of small-scale turbulence on the results.

This study has shown that the use of a single meteorological reference point is insufficient to characterise the wind field across a refinery site. The wind speed and wind direction at reference masts placed in relatively clear areas at the boundary sides of the refinery are different. Both wind direction and wind speed differences are important, and both are needed to quantify the change in wind vector.

The differences in wind vector between the fixed masts vary with time and incident wind direction. There are no fixed offsets between locations that could be used as a simple correction factor to predict wind conditions at one location from measurements at another.

Greater differences in wind vector were found between measurements at 3.7 m height compared to measurements at 10 m height. This likely reflects the growing importance of locally generated turbulence closer to the ground. It suggests that care should be taken with the interpretation of portable anemometer results typically used at heights of 2 to 3 m.

Only limited information on reference station wind profiles was gathered. Measurements at two heights is insufficient to define a profile, but a predefined profile may be fitted. When wind was incident on a measuring station, the vertical wind speed profile was well represented by a logarithmic increase in wind speed with height. This is characteristic of a neutral boundary layer. When a station was downwind of the refinery (e.g. at Station 3, which was most often downwind of the refinery), measurements tended to show lower wind speed at 3.7 m height than would be obtained from a standard profile (i.e., wind speed nearer the ground was reduced).

Only limited observations on the effect of the refinery on wind pattern can be inferred from the fixed mast measurements. These observations are influenced in this campaign by Station 4 which was closest to the process area. The process area in a typical refinery comprises large, tall vessels surrounded by tightly packed pipework and supports. This blocks the wind flow so that wind approaching the process area is slowed, diverted around the main elements, with some small increase in wind speed, and then closes behind.

Detailed information on wind patterns within the refinery at the scale of individual units was not reported because of lack of confidence in the wind direction reported by the pick-up truck mounted wind LIDAR (Appendix B). Some LIDAR data was clearly wrong. Much of the remaining LIDAR data could be taken to show the flow diversion around and between tank arrays and modification of the vertical wind profile expected on aerodynamic principles. However, with no methodological basis for rejecting data that does not fit expectation, or accepting data that does, it was decided not to report selected results. LIDAR data seemed especially unreliable near to heat sources such as air coolers. This is possibly due to a combination of air density fluctuations and strong localised vertical flow. In contrast a pre-campaign evaluation of the LIDAR instrument in a non-refinery setting [1] showed credible results.

Reference wind measurements

The following recommendations for wind measurements and their interpretation can be made:

Reference wind measurements should be made using two or more masts instrumented for wind speed and wind direction at 10 m height.

To derive a vertical wind profile at least one mast should also be instrumented at both 2 m and 10 m height and a functional form (logarithmic or power law) for the wind profile assumed. If possible, the wind profile should be verified by measurements at a third height. A taller mast enabling measurement at 30 m height would be ideal.

Although the experience here with a wind LIDAR mounted on a truck was inconclusive we believe that a wind LIDAR able to resolve wind speed and direction at heights up to, say, 100 m with a vertical resolution of ~10 m, can be used to establish a reference wind profile.

Reference wind measurements should reflect the wind incident upon the refinery. As wind direction changes in time this will generally require more than one mast. Climatic analysis using refinery wind data, or data from the nearest World Meteorological Organization (WMO) accredited station, can be used to determine the most frequent wind-directions.

The wind mast(s) and wind LIDAR should be located in an open area as free from upwind obstructions as possible. Ideally this requires a fetch of several hundred metres of flat ground.

The setting of North for all instruments should be verified and a common time-base for data-recording established.

In practical terms it is almost impossible to place a meteorological mast free from interference in all wind directions. The WMO guidance is that an anemometer should be at least 10 obstacle heights away [2]. This translates to a minimum separation of 100 m from typical plant structures or buildings. The German standard VDI 3786 [3] gives specific guidance, based on wind tunnel experiments. For buildings of height (H) and width (B) they specify:

a) Separation should be at least 0.5 H + 10 B if $1 < \frac{H}{B} < 10$ and at least 15 B if $\frac{H}{B} > 10$.

b) Separation should be at least 5(H+B) if $\frac{H}{B} = 1$

c) Separation should be at least 0.5 B + 10 H if $1 < \frac{B}{H} < 10$ or at least 15 H if $\frac{B}{H} > 10$

If these separations cannot be achieved for all wind directions then the angle, θ_s, subtended by the upwind obstacles should be determined, and in later analysis, data from these wind directions should be assessed for wake effects.

These separations apply also for the placement of a wind-LIDAR. The angle subtended by any upwind source of heat that could be a source of convection should be determined. In later analysis data from these wind directions should be assessed for the effects of convection.

It is to be expected that data from two (or more) reference wind stations will show different wind-speed (10 m) and wind-direction. These differences can be used to infer the effect of the refinery on the incident wind and to set the uncertainty to be used in deriving information reliant on wind data.

Wind instruments should be calibrated on a regular basis and carry an in-date manufacturer's certificate.

For data processing, anemometer data should be output at a frequency of 1 Hz and processed to generate a 10-minute running average of the wind vector, wind speed and persistence. The running averages should be output at one minute intervals.

Wind LIDAR data should be output at the native rate of the instrument – typically 0.5 Hz, processed to generate a 10-minute running average of the horizontal wind vector and wind speed, the vertical wind speed and persistence at each LIDAR height interval. The running averages should be output at one minute intervals.

LIDAR orientation and verification data should be provided using an anemometer mounted at 10 m height. For inspection purposes, the running averages should be output at minute intervals. The wind LIDAR and anemometer wind vector data should be compared over a period of several hours to evaluate consistency. If the wind LIDAR is relocated, e.g. to provide additional information, then the consistency check should be repeated.

Supporting wind measurements

Reference wind measurements can only be made at a few select locations, whereas for the purpose of emissions assessment, the wind within the site is needed and will generally be affected by the presence of process structures, buildings, storage tanks etc. Supporting wind measurements are therefore needed to assess the representativeness of the reference measurements. Supporting measurements can make use of a mobile mast and/or a portable anemometer. It is important to record each location, verify each north orientation and ensure the time of measurement for comparison with the reference wind data. Measurement data should be processed in the same way as the reference mast data, with the following objectives:

- To check for locations where building effects are dominant, e.g. to avoid calm zones or recirculation zones when making concentration measurements.

- To identify wind-direction differences as might arise from diversion of wind along site roadways between in built areas

- To identify areas of wind speed increase as might arise from channelling of wind between built areas.

Data interpretation

When analysing data to guide assessment of emissions impacts or interpret air concentrations in terms of emission sources, it is important to identify periods of steady conditions and exclude periods of unsteady conditions:

Interpretation of wind data requires a degree of expertise and judgement. The above-specified averaging time of ten-minutes should smooth out variability due to small scale turbulence generated at the ground and by flow through an industrial site. At moderate wind-speed it also reduces considerations of whether measurements at different locations need to be time-corrected to account for time delay/advance as the wind passes the locations.

The 10-minute persistence value indicates how much variability due to larger scale turbulence is present. This can be a product of flow around large structures or changes in overall wind-direction. Persistence approximates the standard deviation of wind-direction [4] for standard deviation values < 30°. It is not straightforward to calculate standard deviation directly because crossings of North have to be accounted for to distinguish, for example, a 10 degree from a 350-degree direction change.

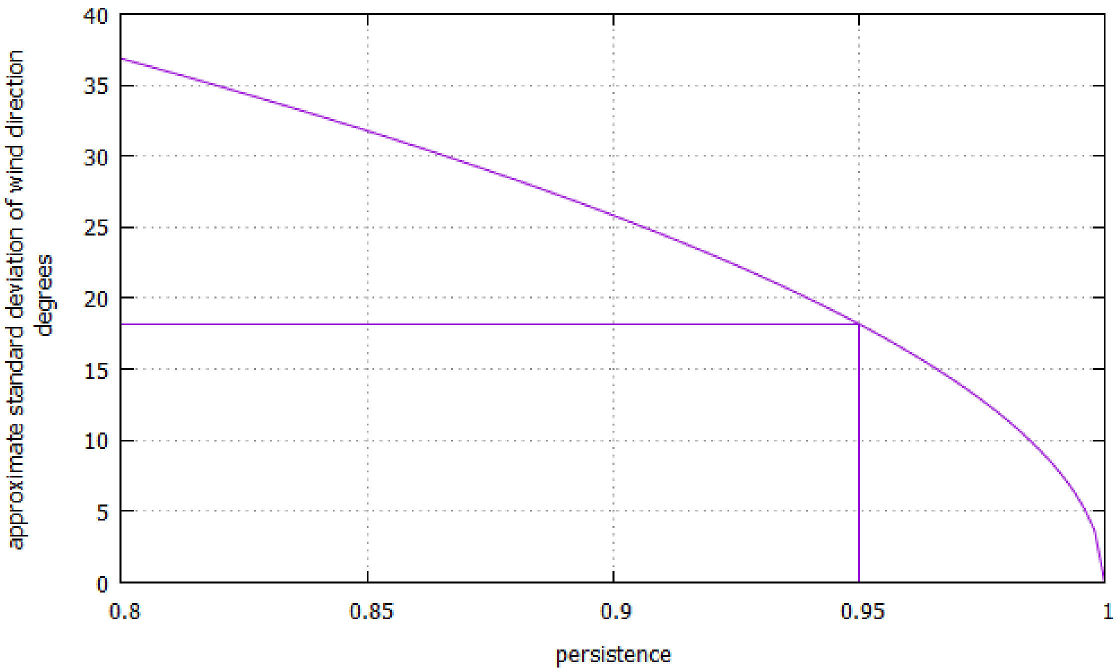


Figure 1 Approximate relation between persistence and the standard deviation of wind-direction illustrating choice of 0.95 as an indicator of unsteady conditions

To take one marker, a persistence value of 0.95 is roughly equivalent to a wind-direction standard deviation of ~18 degrees, which represents a highly variable condition. Appraisal of wind-data should therefore assess and reject unsteady conditions where it would be difficult to assess plume trajectories or determine emission flux estimates from remote sensing measurements.

Periods of low wind speed, e.g. where the 10 m wind speed is less than 2 m/s should be captured by a persistence criterion. However, the lower the wind speed the less likely it is that reference measurements will reflect conditions far from the measurement location. Time of flight become a consideration when comparing data from separated stations. Therefore, exclusion criteria should include a low-wind speed condition.

Sensitivity analysis

Because wind measurements at any two positions, reference or supporting, will be different and no program of wind measurement will ever be complete on an industrial site, any use of wind data will have to include appropriate sensitivity analysis.

A qualitative view of the overall wind pattern across the industrial site should be developed for the principal wind directions. This will identify where interior winds are likely to differ consistently from reference winds in terms of direction and speed. This will be guided by the supporting measurements.

A selection of times for data analysis should be made on the basis of persistence and wind speed. When looking at emissions or emissions impacts, times where concentration measurements are made closer to buildings by the separation criteria above should be deselected, unless supporting wind data shows wake effects to be small.

Flux calculations are linear in wind-speed and the main uncertainties in wind-speed are the reference speed and the wind-profile. Concentrations are distributed vertically so the effect of wind-profile is attenuated by averaging over the concentration extent. Wind speeds sensitivity can be taken from the spread of 10 minute values across measuring stations.

Flux calculations are non-linear in wind-direction with error increasing if the wind is increasingly not normal to the sampled concentration plane. The effect of varying wind direction should therefore be an important part of the sensitivity analysis. Wind-direction should be perturbed by whichever is the greatest of: twice the standard deviation implied by the persistence recorded at the most relevant station, or the largest difference between measurement stations.

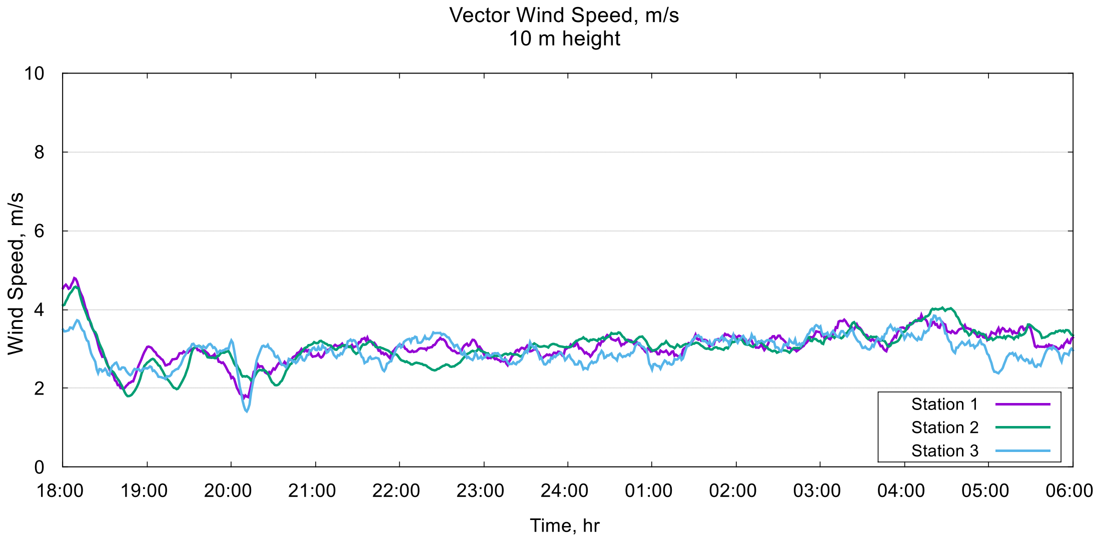
5. REFERENCES

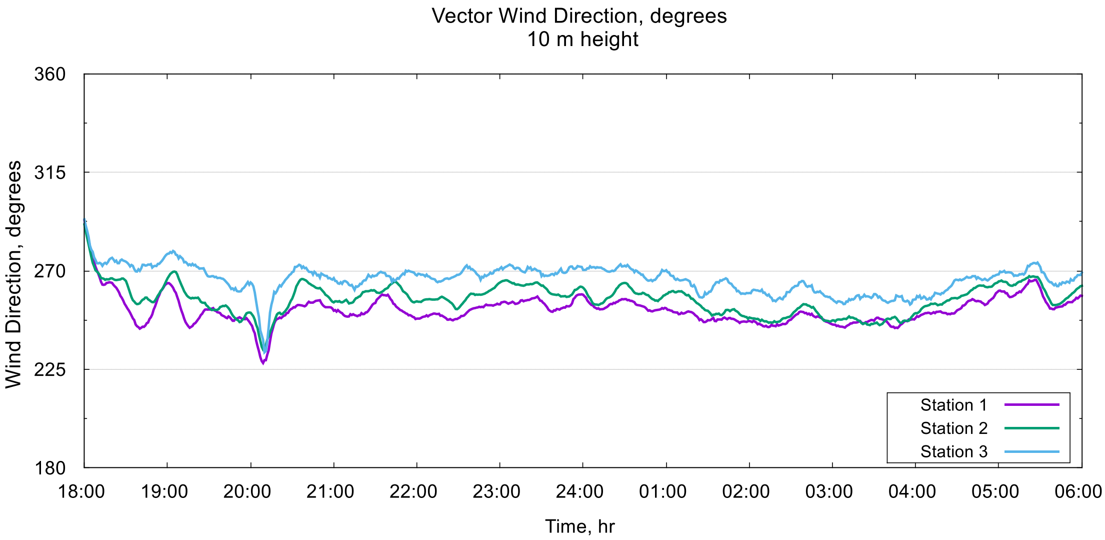
1. Concawe (2019): A comparison exercise between a wind LIDAR and anemometers mounted on a 30 m mast. Report No. 13/19. Brussels: Concawe.
2. World Meteorological Organization (2012): Guide to Meteorological Instruments and Methods of Observation. WMO-No.8, 2008 edition. Updated in 2010.
3. The Association of German Engineers – VDI (2013): Environmental meteorology. Meteorological measurements. Fundamentals. VDI-Standard: VDI 3786 Blatt 1.
4. Yamartino R, J. (1984) A comparison of several “single-pass” estimators of the standard deviation of wind direction. Journal of Climate and Applied Meteorology 23, pp1362-1366.

APPENDIX A: TIME SERIES DETAILS

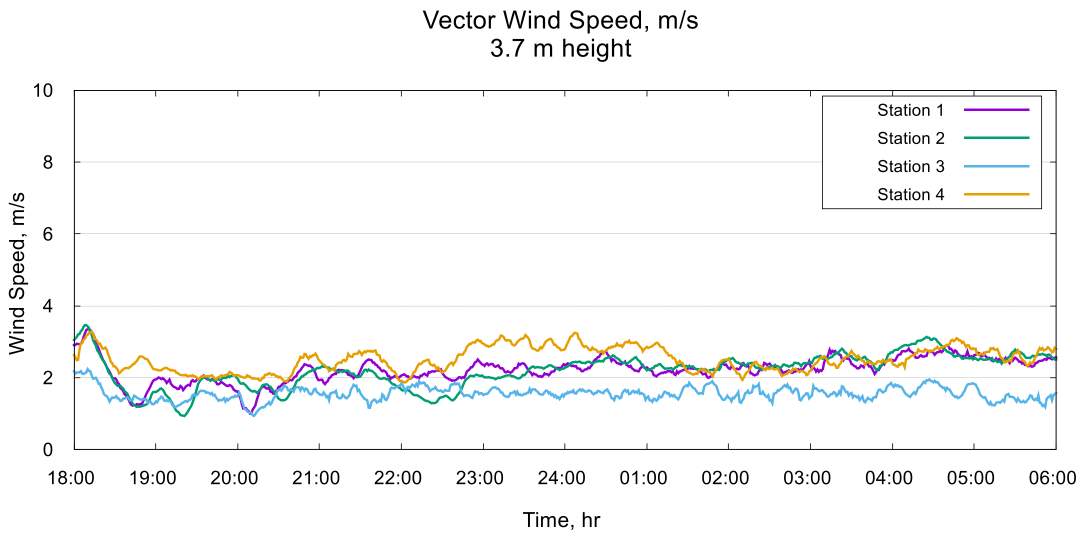
A.1 October 19th (evening/night time)

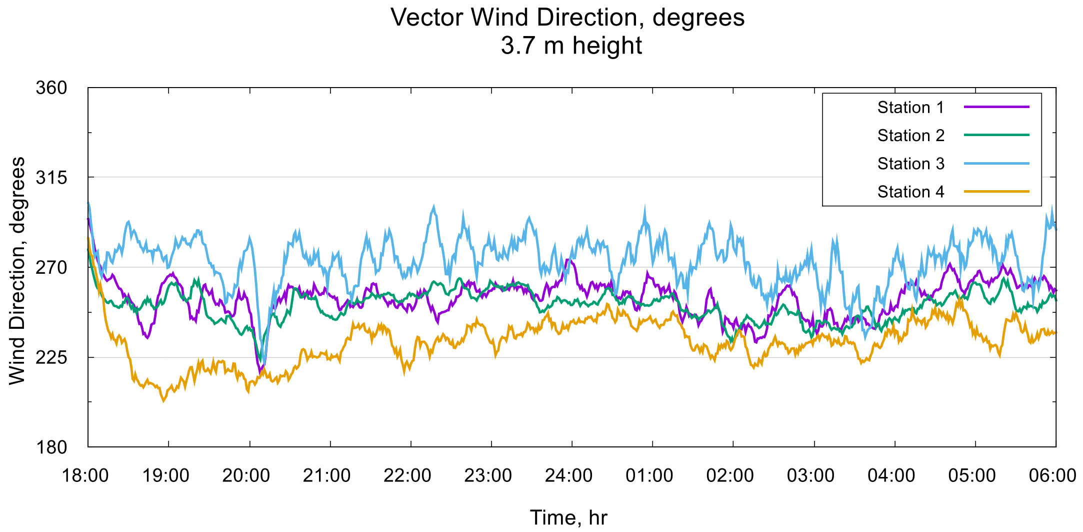
During the evening/night of the 19th the wind dropped after 18:00 and remained steady. Remarkably similar wind speed values were recorded at 10 m height on the three stations. From a low value of 2 m/s at 19:00 there was a steady increase to 4 m/s at 04:30 before dropping to 3 m/s. The wind direction was fairly steady. Station 1 (W) registered WSW for most of the night, similar to station 2 (NW) and station 3 (E) was more often W. The span of wind directions on average was 13.9 degrees.





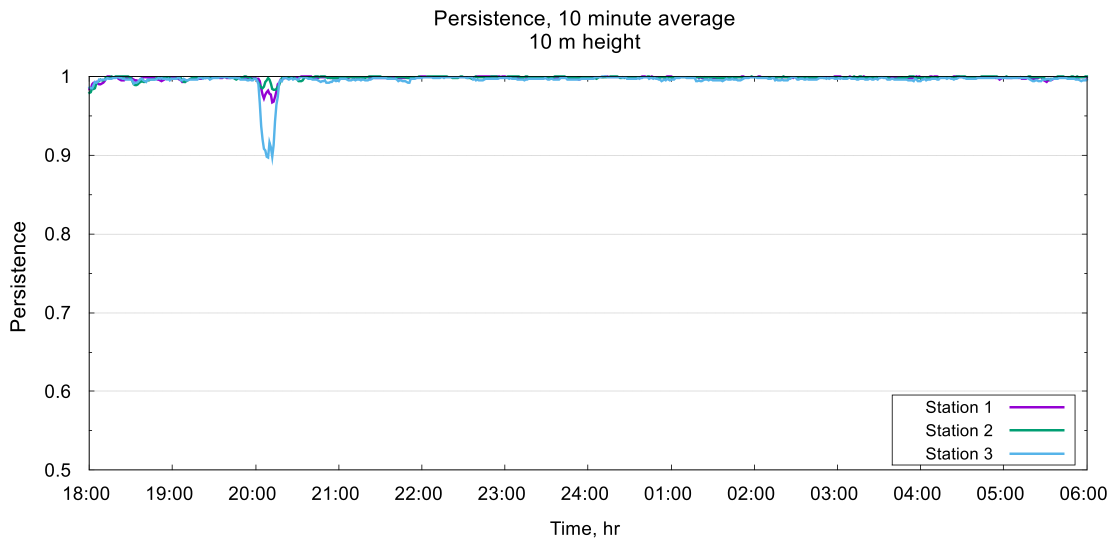
On the lower masts there was a greater difference between locations and the wind speed at station 3 (E) was consistently below 2 m/s and the direction more variable. At station 4 in the SE a slightly higher wind speed and south-westerly direction was recorded. This is consistent with its location downwind from and sheltered by the process-area. The average difference in wind direction between station 4 (SE) and station 3 (E) was 40.5 degrees

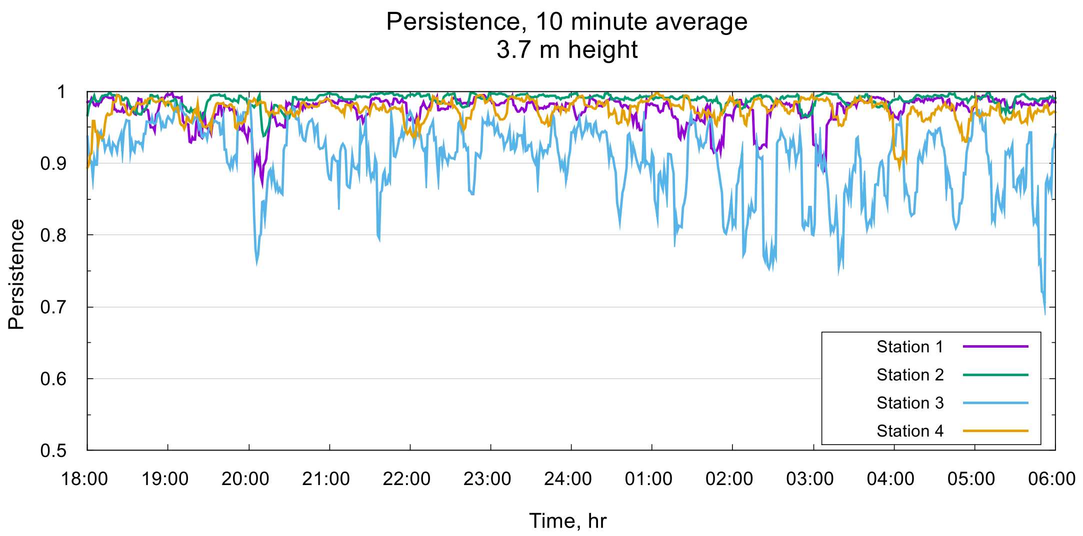




Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.804	13.9
Station 1 and Station 2	10	0.353	4.9
Station 2 and Station 3	10	0.62	9.1
Station 1 and Station 3	3.7	0.967	19.03
Station 1 and Station 2	3.7	0.371	6.5
Station 2 and Station 3	3.7	1.05	22.59
Station 1 and Station 4	3.7	0.971	21.74
Station 3 and Station 4	3.7	1.7	40.47
Station 1 at 10 m and Station 1 at 3.7 m		.898	4.5
Station 2 at 10 m and Station 2 at 3.7 m		.918	6.6
Station 3 at 10 m and Station 3 at 3.7 m		1.45	9.35

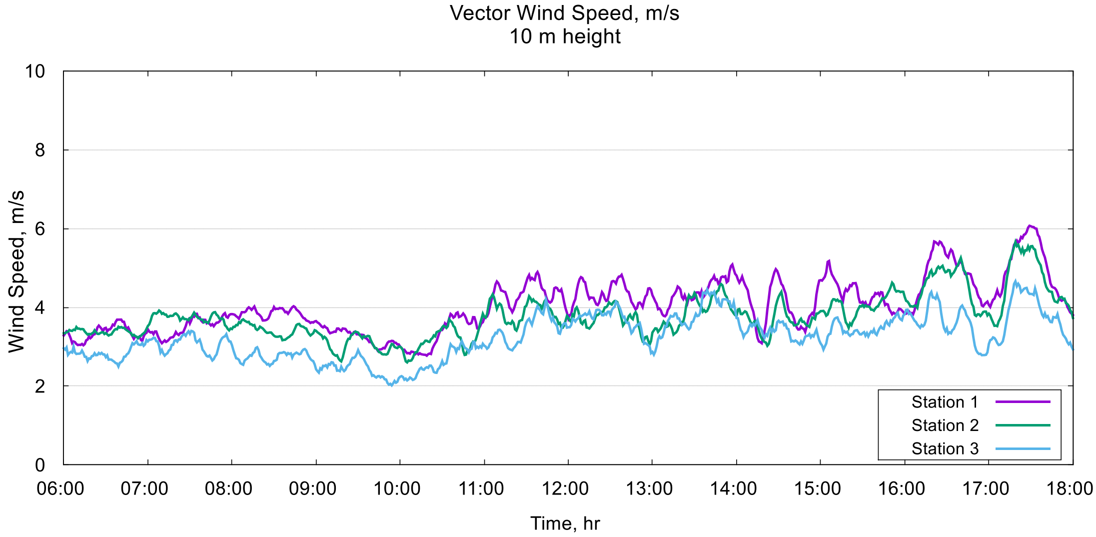
Despite the low wind speeds, the persistence was quite high, even at station 4 (SE). Station 3 (E) again showed the most variability.

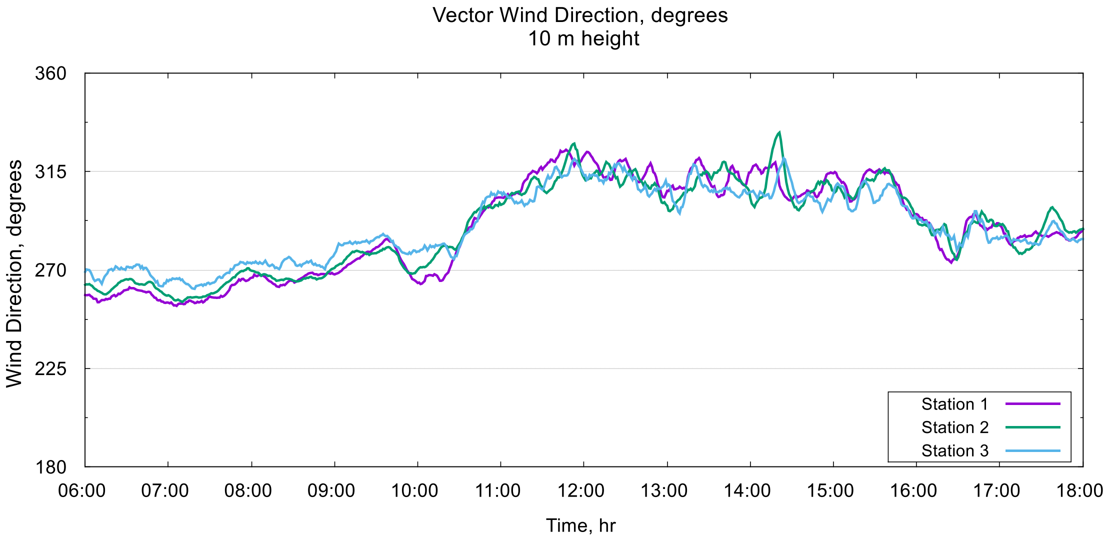




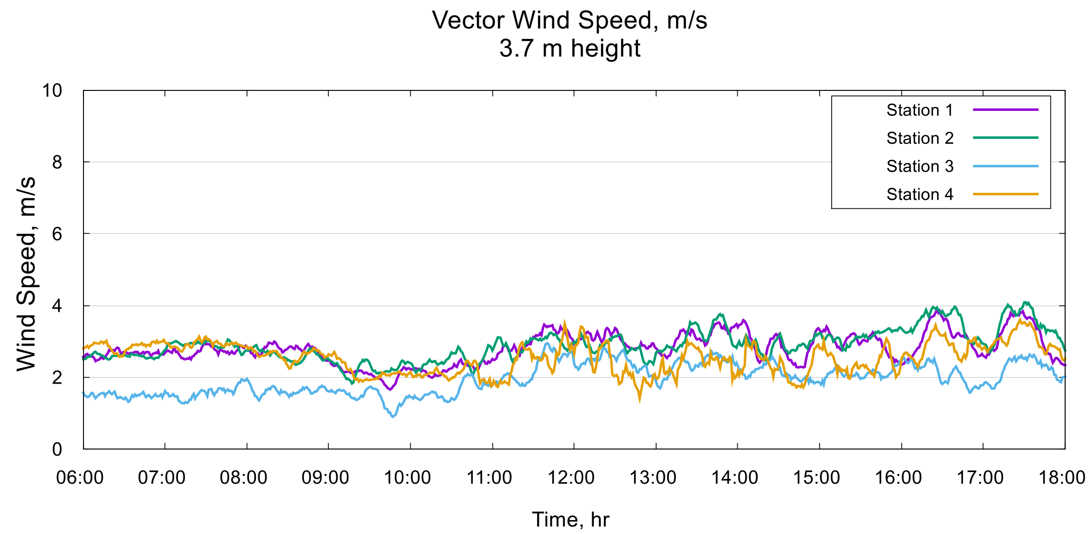
A.2 October 20th (daytime)

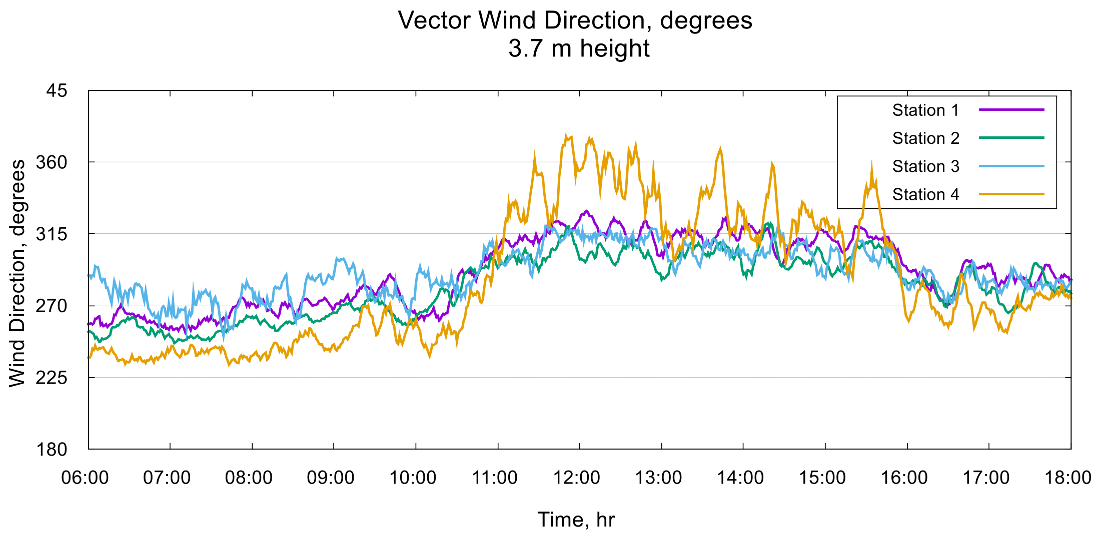
During the day of the 20th there was a change in the wind at about 10:00 picked up by all stations. The wind direction shifted from just south of W to NW, changing back to just north of W again at 16:00. The change was preceded by a small drop in wind speed which then picked up again. At height 10 m and before the change, station 3 (E) measured lower wind speed (3 m/s) and stations 1 (W) and 2 (NW) were similar (4 m/s). After the change the measurements at all stations became more variable and this was most marked at Station 1 (W). The amplitude of the variation was about 2 m/s and the frequency about 1/60 $mins^{-1}$. Wind direction measurements showed less variability and the persistence close to 1 except for a brief period about 14:30 at station 2.





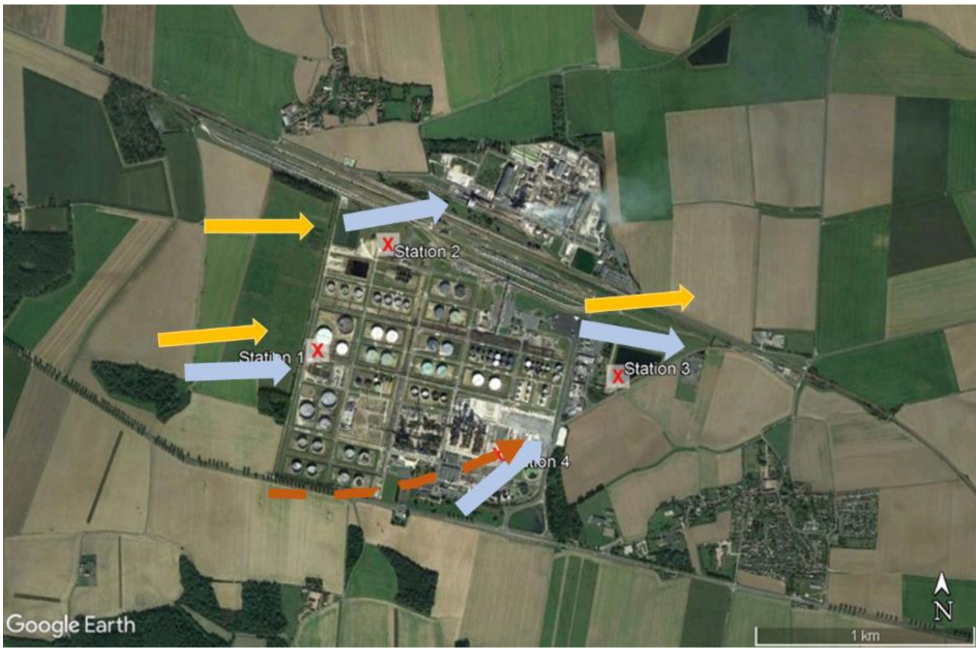
Similar behaviour was seen on the lower stations where the low value seen at Station 3 (E) persisted until 11:00. The wind at station 4 (SE) turned through north at mid-day while the other low-level stations tracked their 10 m partners. The greatest difference in wind direction was between station 4 (SE) and the others. The average difference over the period with station 1 (W) was 21 degrees and with station 3 (NE) 26 degrees.





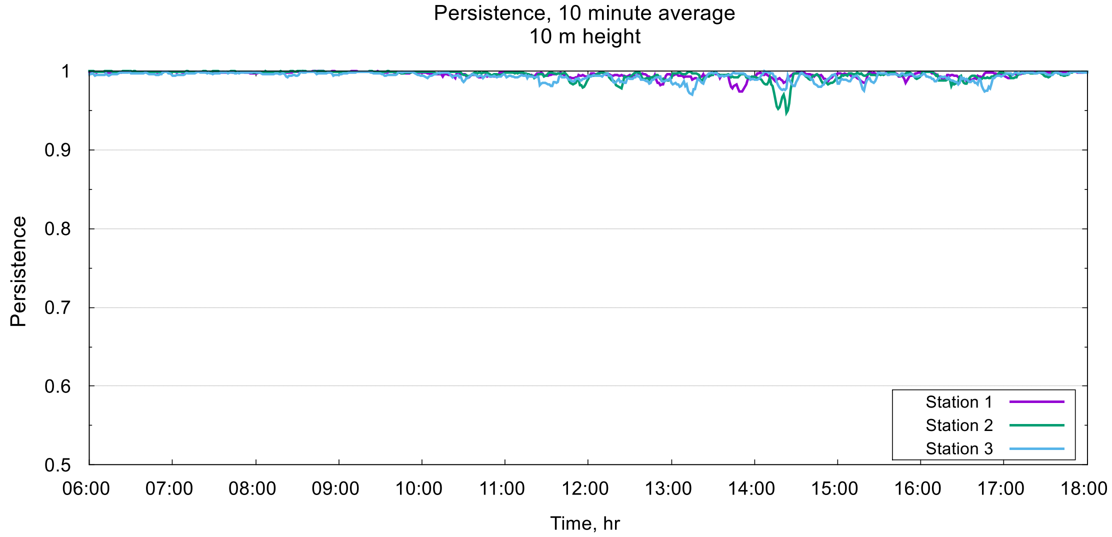
Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.94	6.3
Station 1 and Station 2	10	0.54	4.4
Station 2 and Station 3	10	0.68	5.3
Station 1 and Station 3	3.7	0.98	10.0
Station 1 and Station 2	3.7	0.59	9.9
Station 2 and Station 3	3.7	1.1	11.5
Station 1 and Station 4	3.7	1.1	20.7
Station 3 and Station 4	3.7	1.3	26.3
Station 1 at 10 m and Station 1 at 3.7 m		1.25	3.23
Station 2 at 10 m and Station 2 at 3.7 m		.988	7.49
Station 3 at 10 m and Station 3 at 3.7 m		1.33	6.05

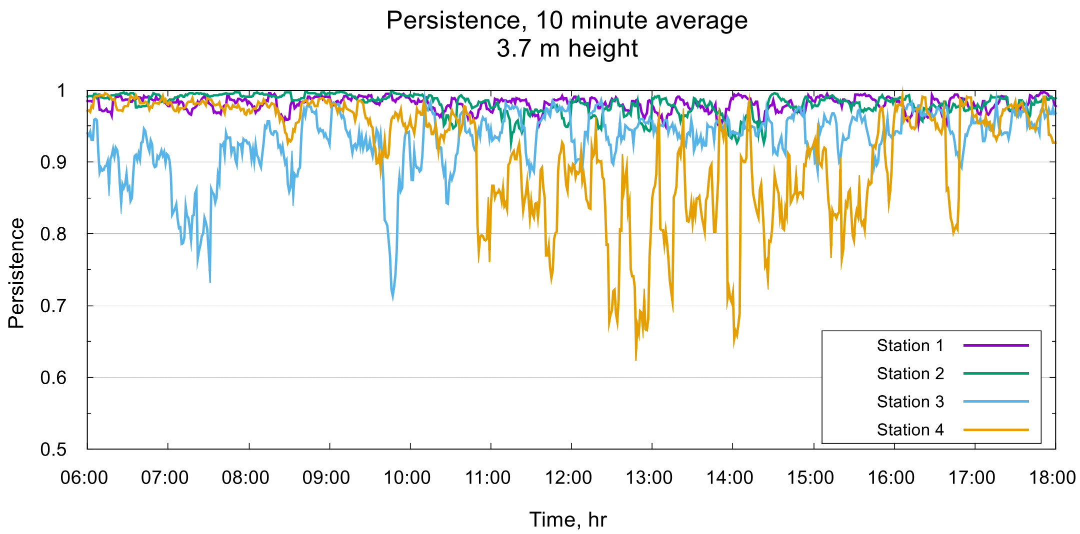
The persistence graphs show that variability at station 3 (NW) decreased when the wind direction shifted from W to NW whereas the variability at station 4 (SE) increased. This is consistent with the fetch over the refinery at each station.



Indicated flow pattern before wind shift toward the NW

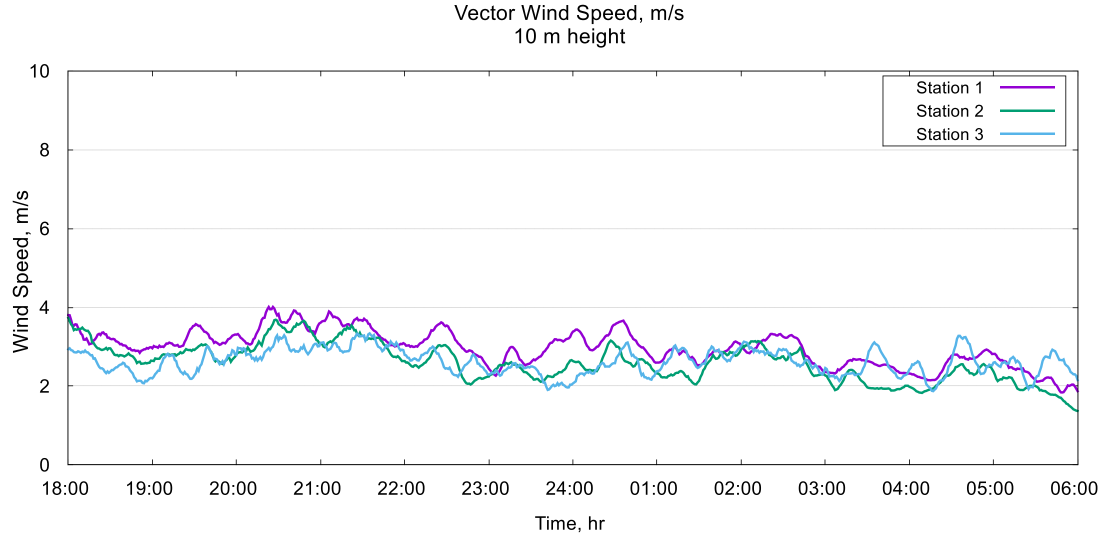
Indicated flow pattern after wind shift toward the NW

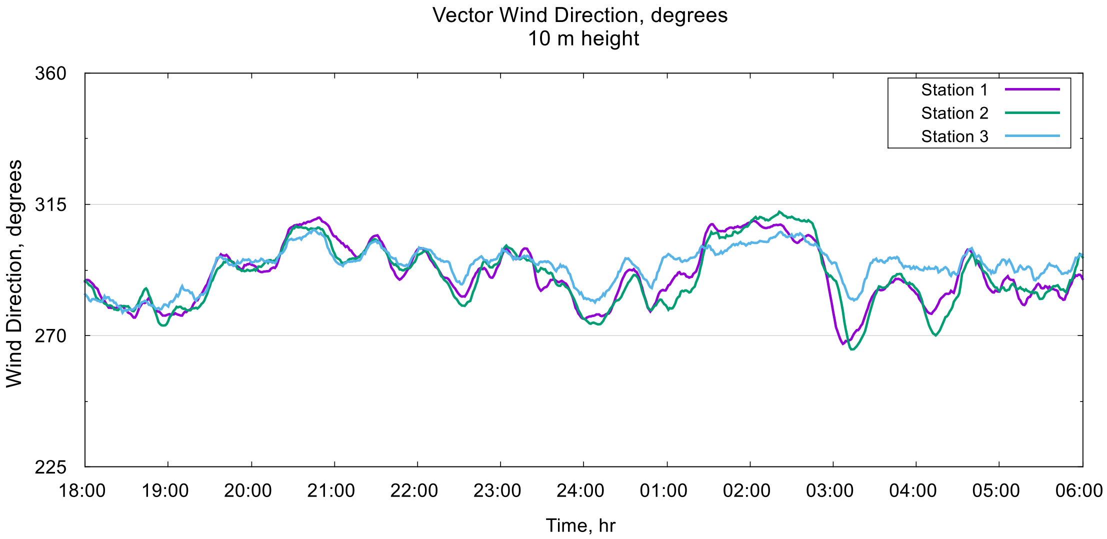




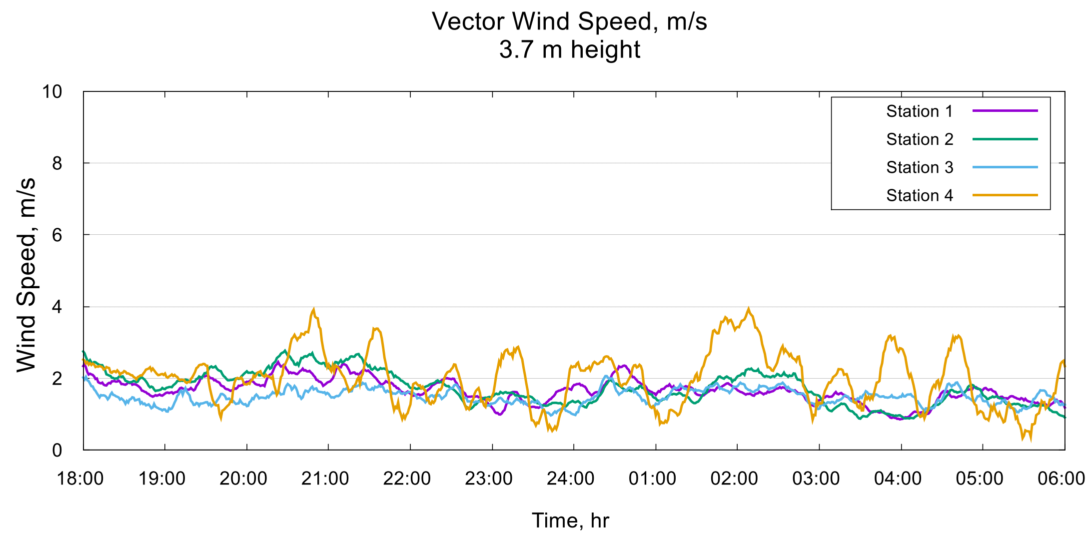
A.3 October 20th (evening/night-time)

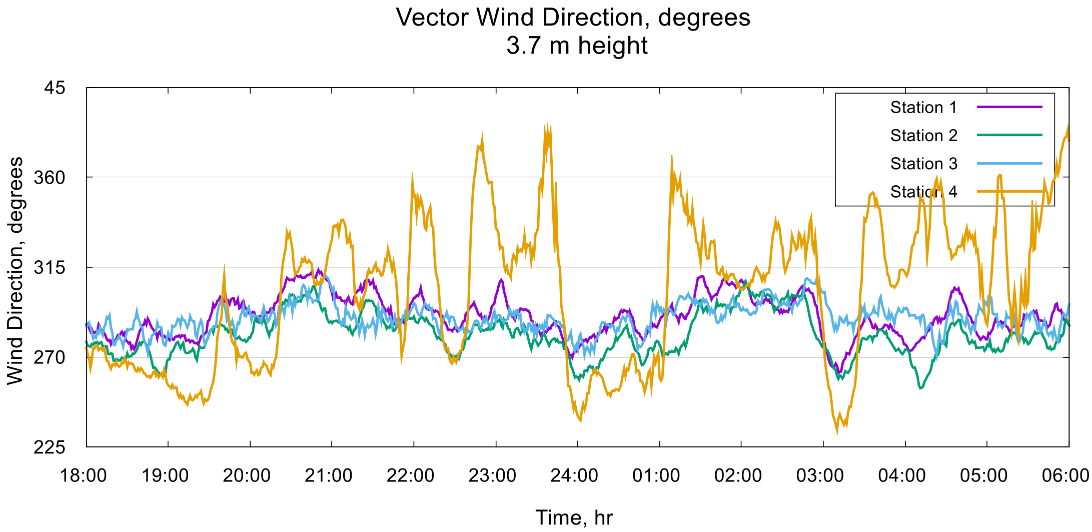
During the night of the 20th the wind speed dropped steadily at all stations from about 3 m/s to 2 m/s. Wind direction measured at 10 m height remained between W and NW but was slowly varying across the octant throughout the period. All the 10 m masts were in agreement with only small differences in averaged velocity and direction between them. Despite the low wind speed the persistence was nearly 1 indicating very steady conditions.



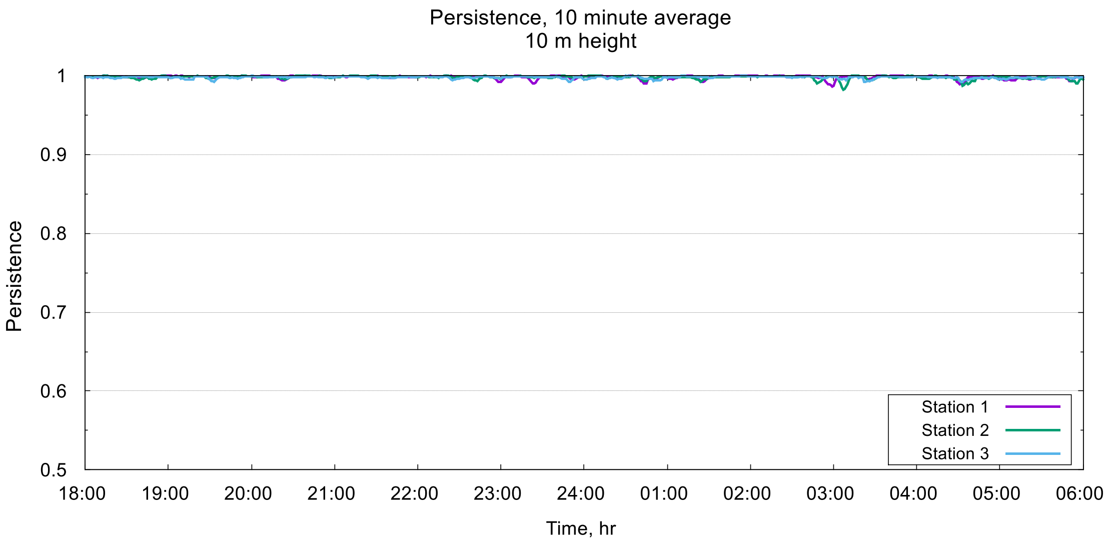


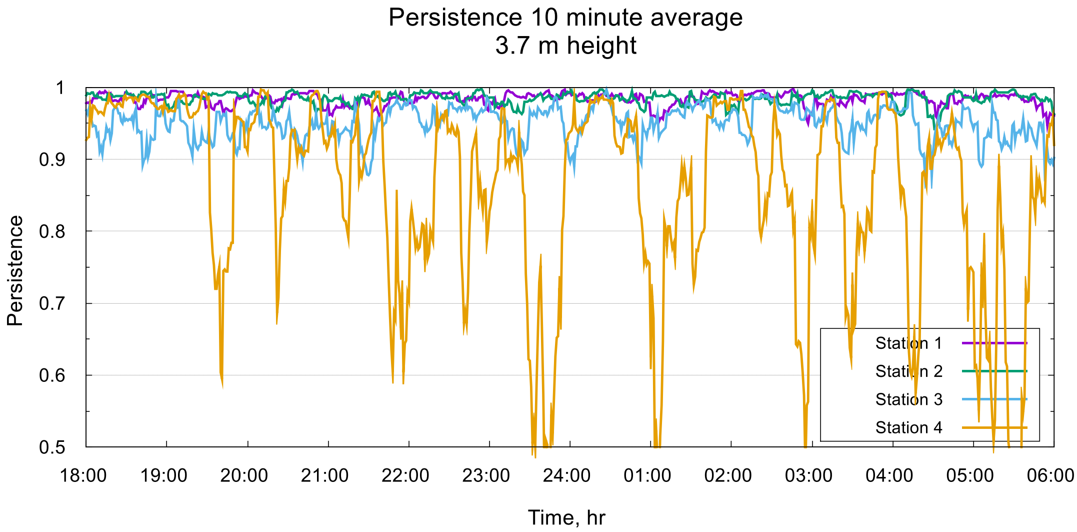
The wind speed recorded at 3.7 m height was less than at 10 m and the wind direction more variable. The fourth station (SE) was the most volatile with direction crossing North several time and low values of the persistence marked these crossings. This suggests that the flow field seen in the previous day was being expressed again with flow diverted around the process area filling from either the north or south side according to the incident wind.





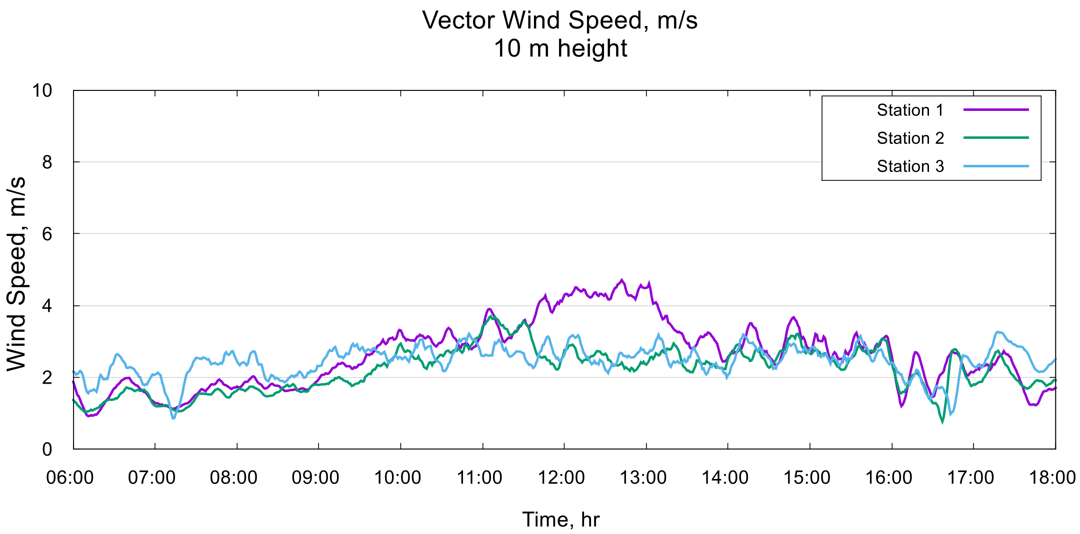
Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.55	5.2
Station 1 and Station 2	10	0.42	2.7
Station 2 and Station 3	10	0.45	5.47
Station 1 and Station 3	3.7	0.39	7.2
Station 1 and Station 2	3.7	0.4	9.8
Station 2 and Station 3	3.7	0.51	9.95
Station 1 and Station 4	3.7	1.14	28.8
Station 2 and Station 4	3.7	1.13	30.1
Station 1 at 10 m and Station 1 at 3.7 m		1.31	3.1
Station 2 at 10 m and Station 2 at 3.7 m		0,94	9.2
Station 3 at 10 m and Station 3 at 3.7 m		1.16	5.9

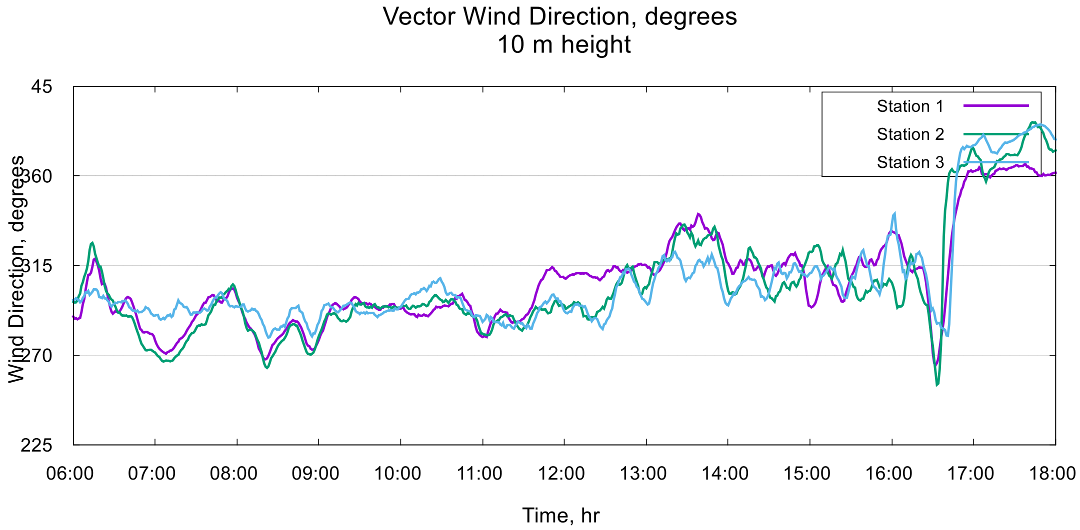




A.4 October 21st (daytime)

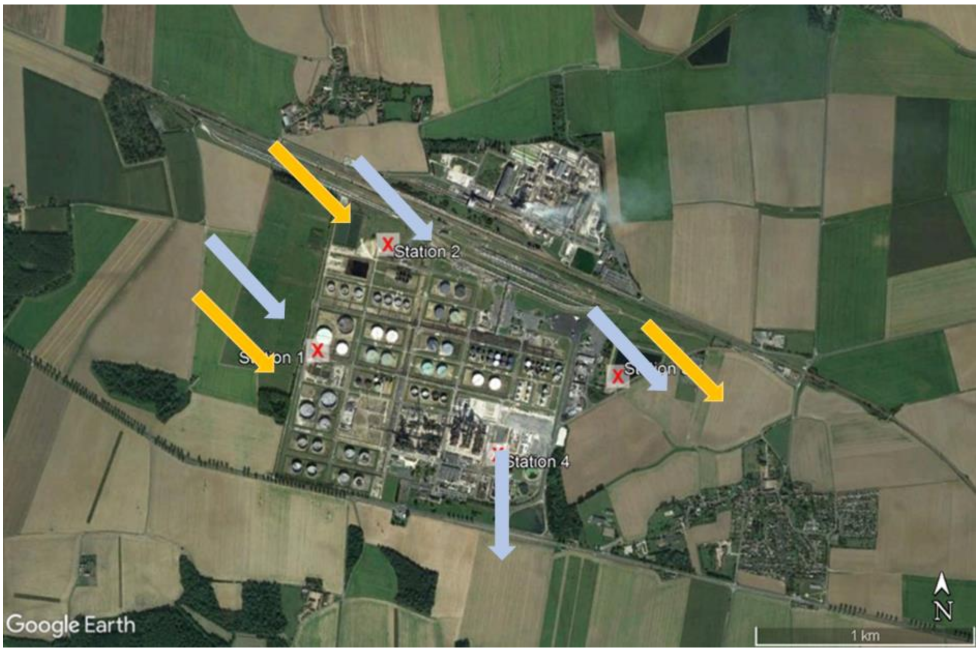
On the day of the 21st the wind speed started low at 06:00 picking up particularly at station 1 (W) to reach 4 m/s at midday before settling to 3 m/s. The other stations registered a more modest increase and station 3 (E) changed little during the day but started higher than the other two. The wind direction was W to WNW until 13:00 for stations 2 (NW) and 3 (E) before turning NW. Station 1 (W) changed earlier at ~11:00. At 16:00 the wind turned N touching NNE after 17:00. The wind speed also dropped in this period and stations 2 (NW) and 3 (E) measurements became extremely variable at ~16:45.

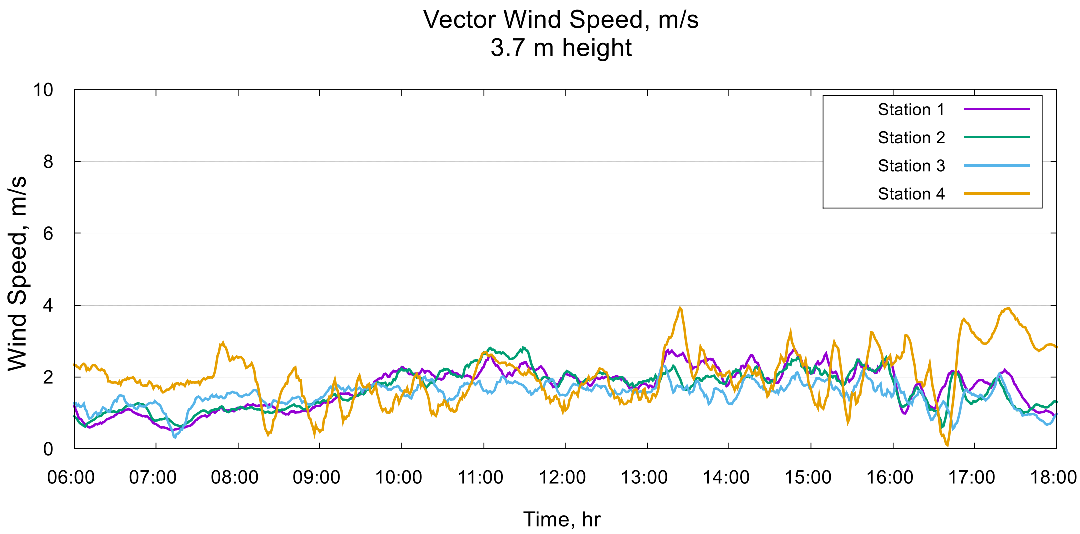


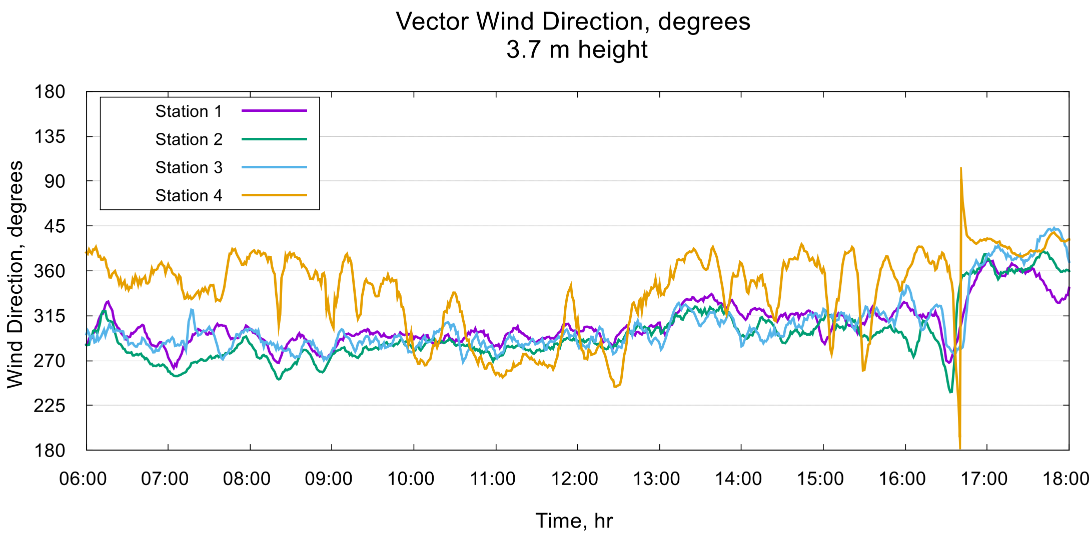


As expected the lower level stations mirrored this behaviour. Outside the very changeable period around 17:00 the wind data were quite consistent. Again station 4 (SE) downwind of the main process area showed the greatest variability with the wind turning through North several times and only loosely following the (broadly) NW direction at the other locations.

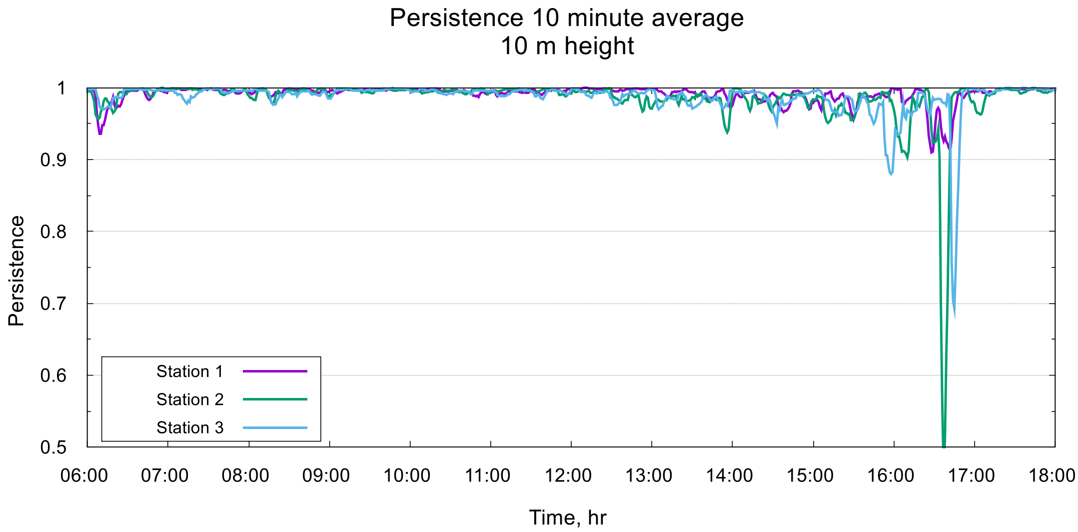
The flow in the afternoon, after 13:00, appears similar to the previous day when blocking by the process area causes the wind to flow around it as shown schematically below. Over the whole period the difference in average wind direction between station 2 (NW) and station 4 (SE) was 50 degrees.

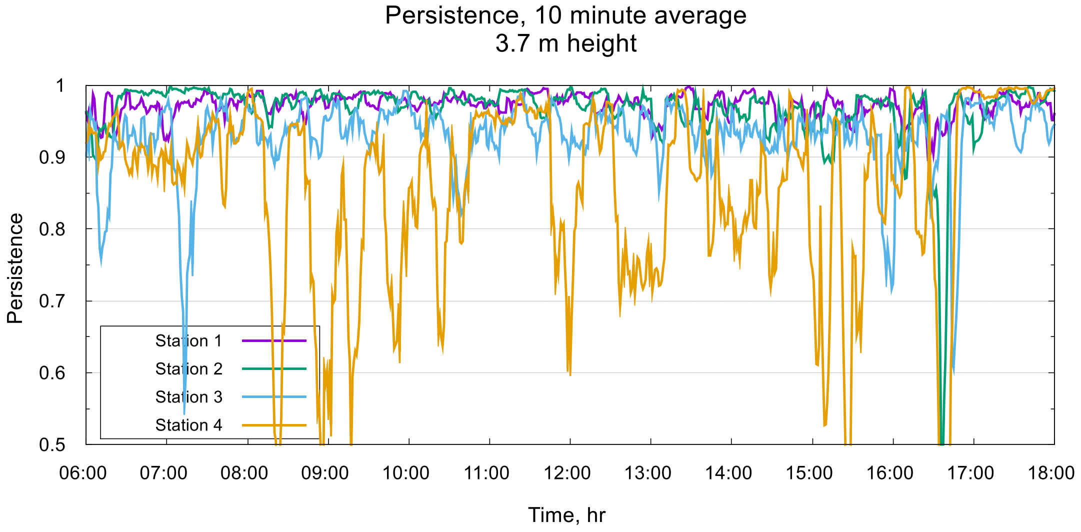

Station 2
Station 4
Google Earth
N
1 km


Vector Wind Speed, m/s
3.7 m height
Station 1
Station 2
Station 3
Station 4
Wind Speed, m/s
Time, hr
0
2
4
6
8
10
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00



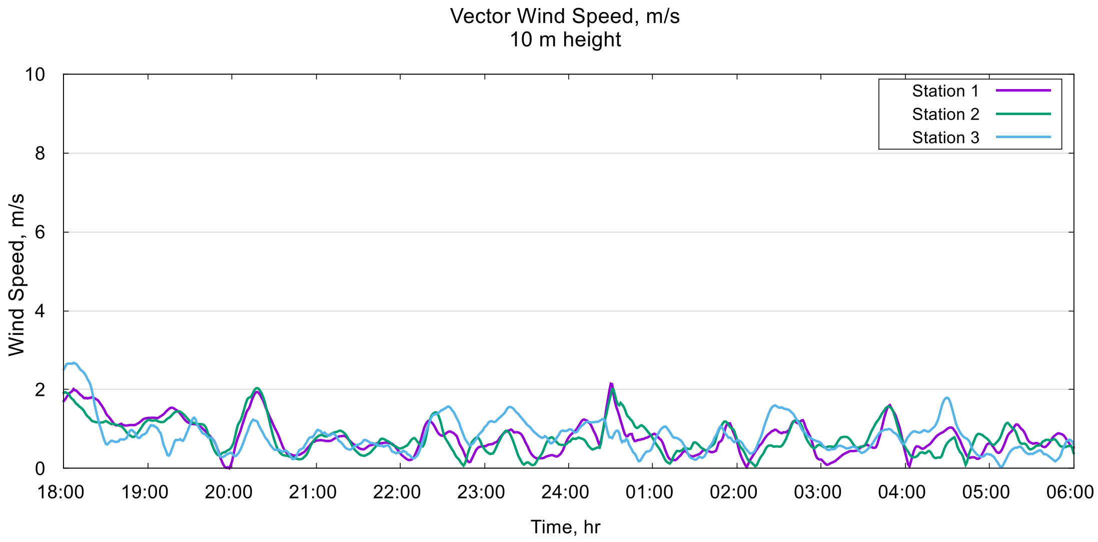
Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.82	9.74
Station 1 and Station 2	10	0.66	8.23
Station 2 and Station 3	10	0.62	8.78
Station 1 and Station 3	3.7	0.54	11.85
Station 1 and Station 2	3.7	0.475	14.2
Station 2 and Station 3	3.7	0.52	13.2
Station 1 and Station 4	3.7	1.55	43.8
Station 2 and Station 4	3.7	1.67	49.8
Station 1 at 10 m and Station 1 at 3.7 m		0.95	5.55
Station 2 at 10 m and Station 2 at 3.7 m		0.62	8.96
Station 3 at 10 m and Station 3 at 3.7 m		0.97	6.30

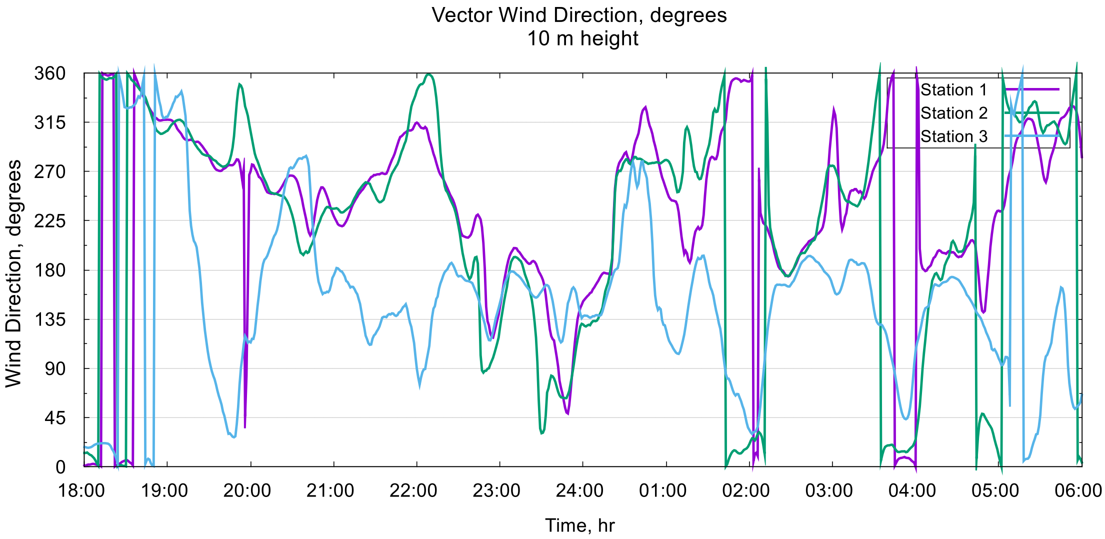


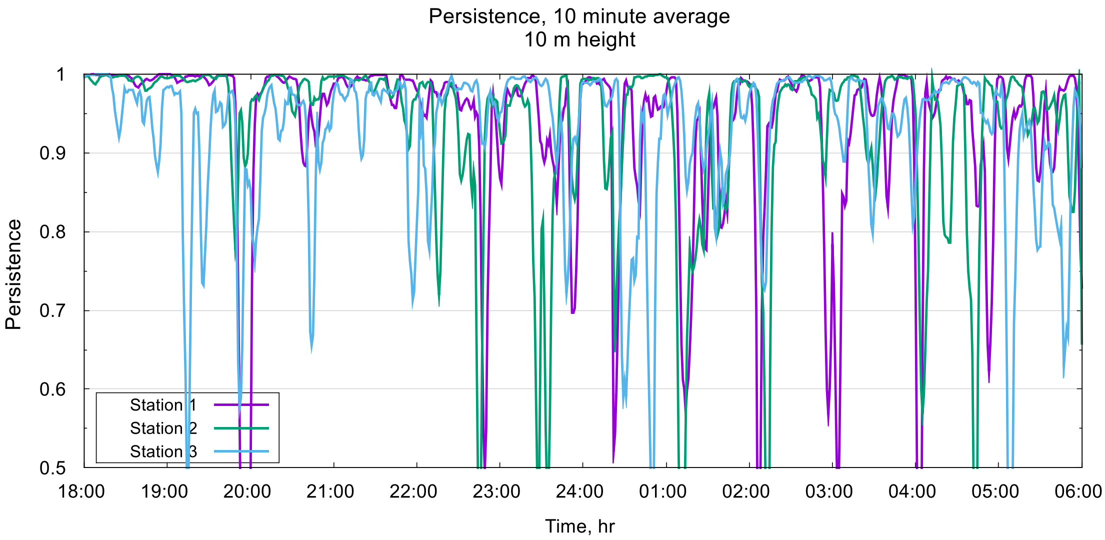


A.5 October 21st (evening/night-time)

During the night of the 21st the wind speed fell very low, below 1 m/s for all stations for much of the night. Wind information is not useable for emissions estimation because wind direction is very variable, and its measurement may be unreliable. Time series results are shown for illustrative purposes at the 10 m height only. Data from 3.7 m height, where wind speed is lower, are not shown.







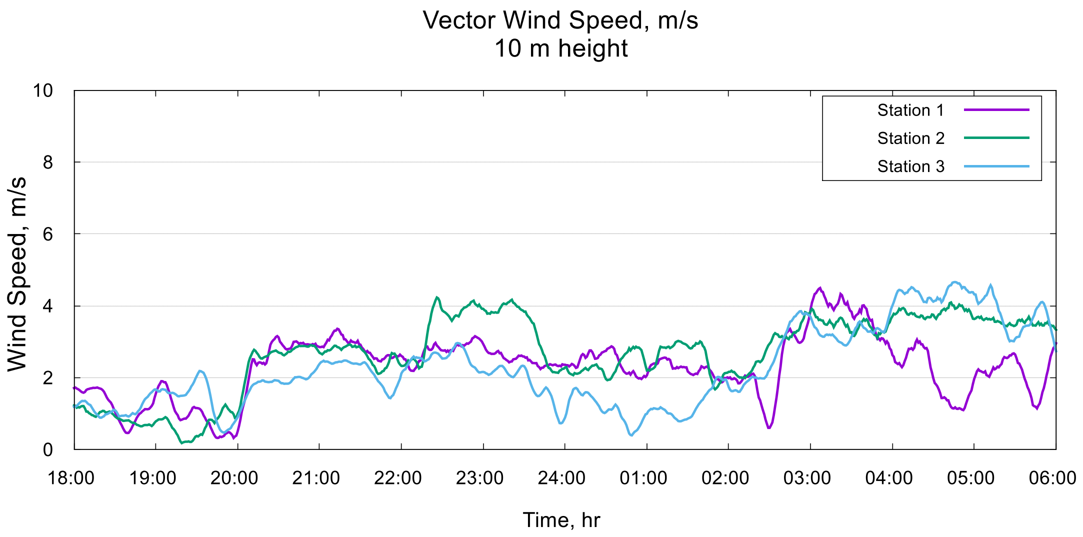
A.6 October 22nd (daytime)

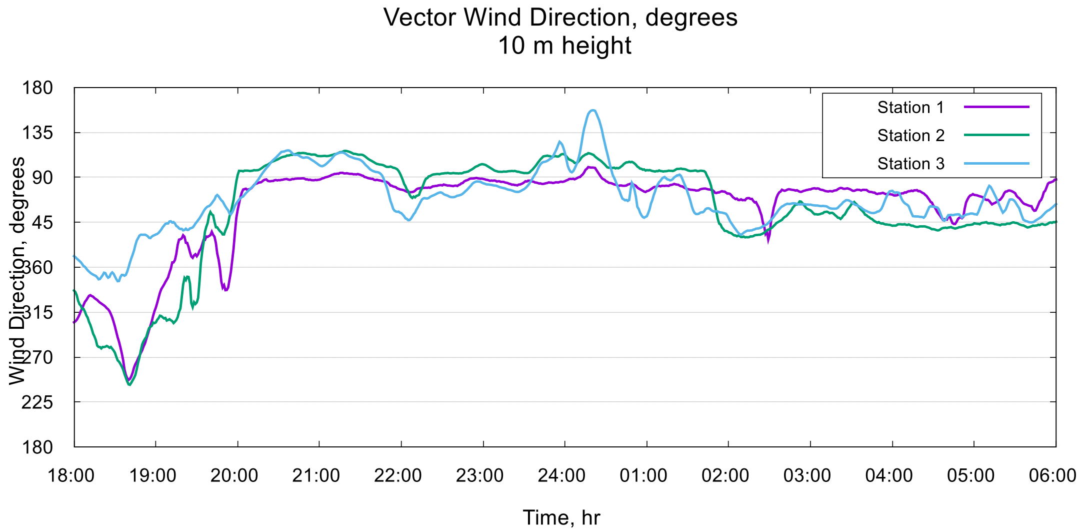
During the day of the 22nd wind speed remains low, ~ 1 m/s and wind direction is not well defined. Results are not shown.

A.7 October 22nd (evening/night-time)

During the night of the 22nd the wind picks up at 20:00 and stays above 2 m/s for most of the night although there are quite some differences between stations. Station 3 (E) sees a period of calm between 24:00 and 02:00.

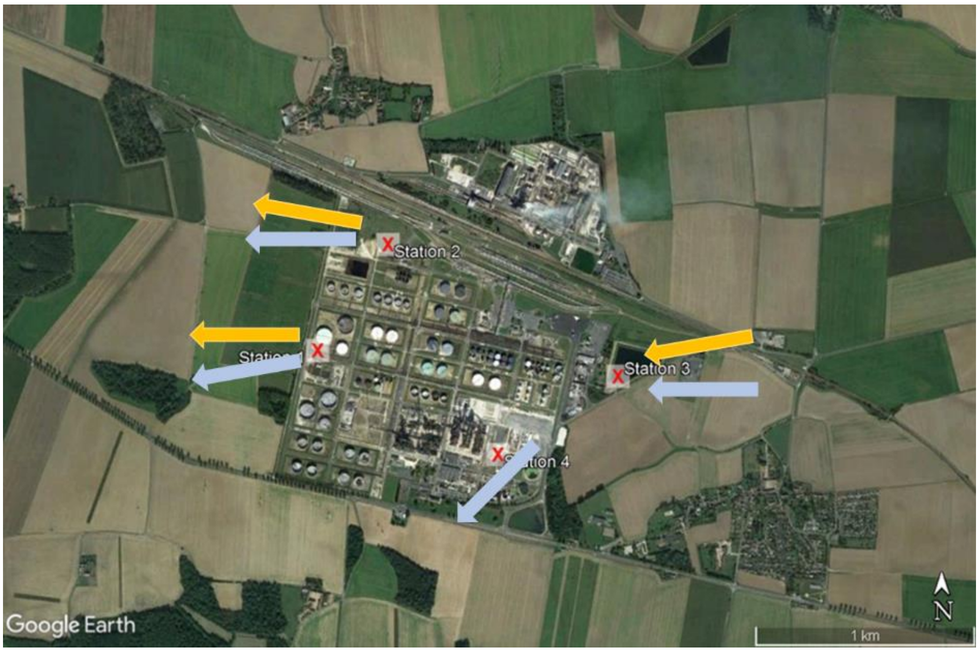
Wind direction has turned from N to the East between 20:00 and 02:00 with quite some variation during the night with stations 2 and 3 moving between ESE and NNE. Station 1 (W) follows more closely to E varying between E and NE during the early hours.

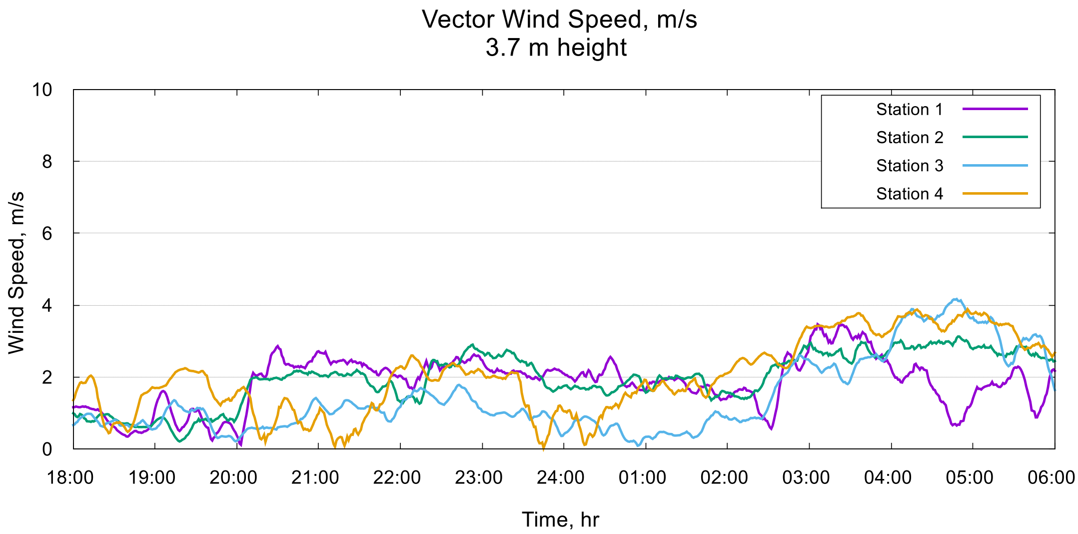


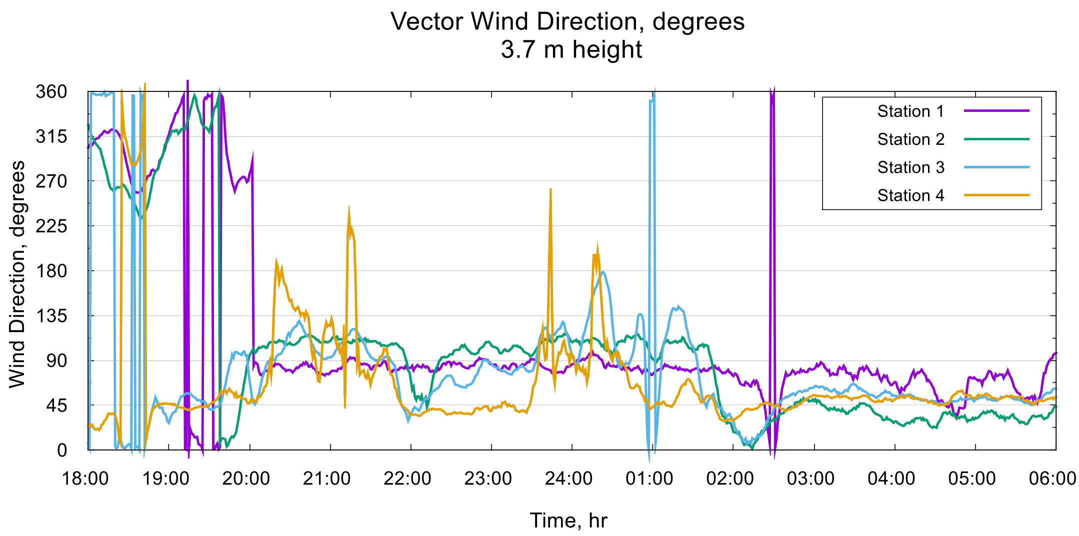


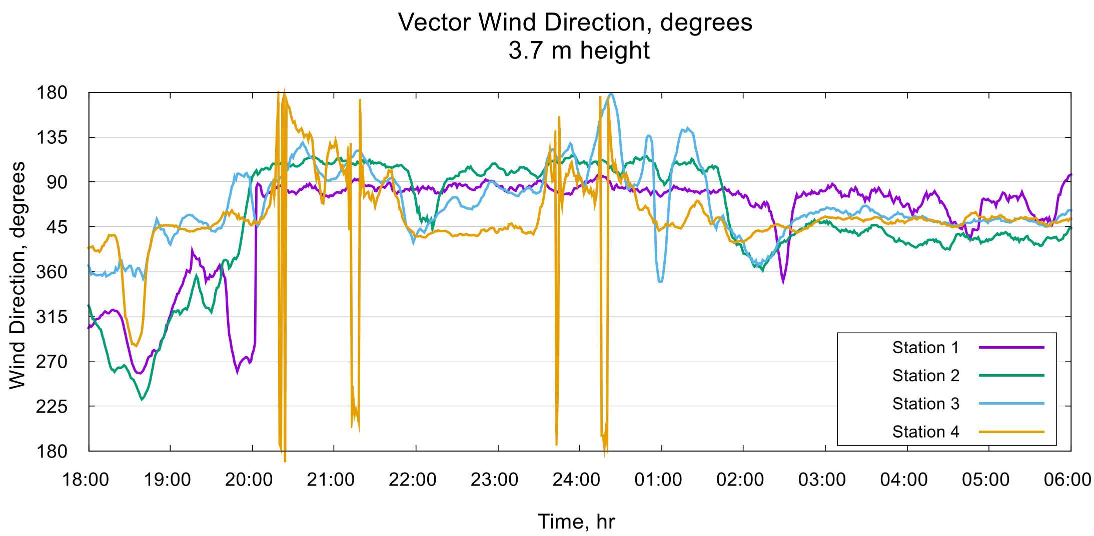
Outside of the periods of direction change before 20:00 conditions are fairly stable with persistence near to 1 in value for long periods.

Of the lower stations only Stations 1 (W) and 2 (NW) record wind speeds above 2 m/s between 20:00 and 02:00 hours with wind direction broadly east. Outside this period the recorded conditions are very variable. Wind direction is plotted twice, on scales of 0-360 and 180 to 180, to clarify the crossings of N that take place. Although there are periods of low wind speed that give variable direction measurements the overall picture is of the wind again being blocked by the process area as shown in the schematic below: Yellow arrows indicate measurement at 10 m height and blue those at 3.7 m.

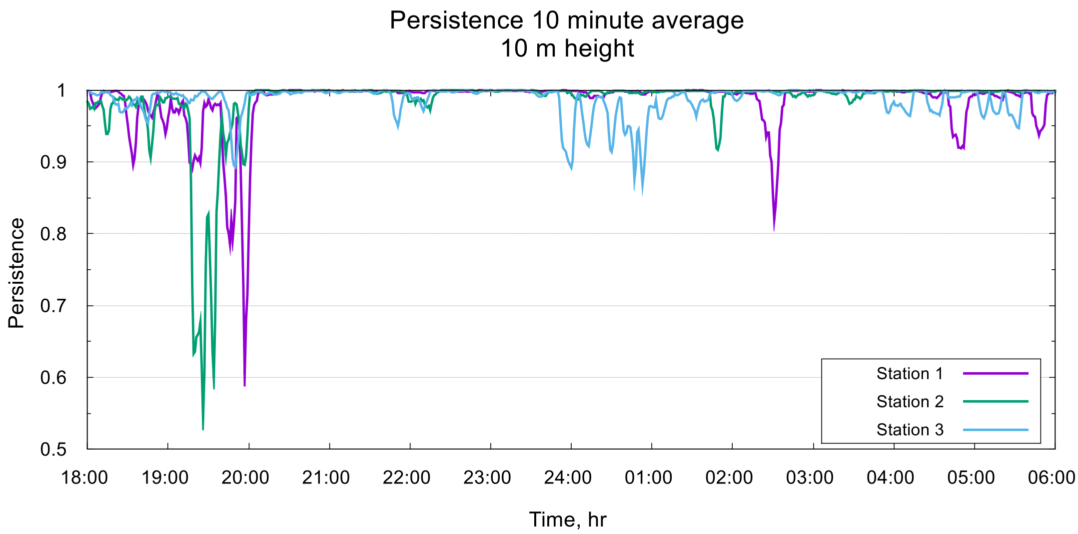

Station 2
Station 3
Google Earth
1 km
N

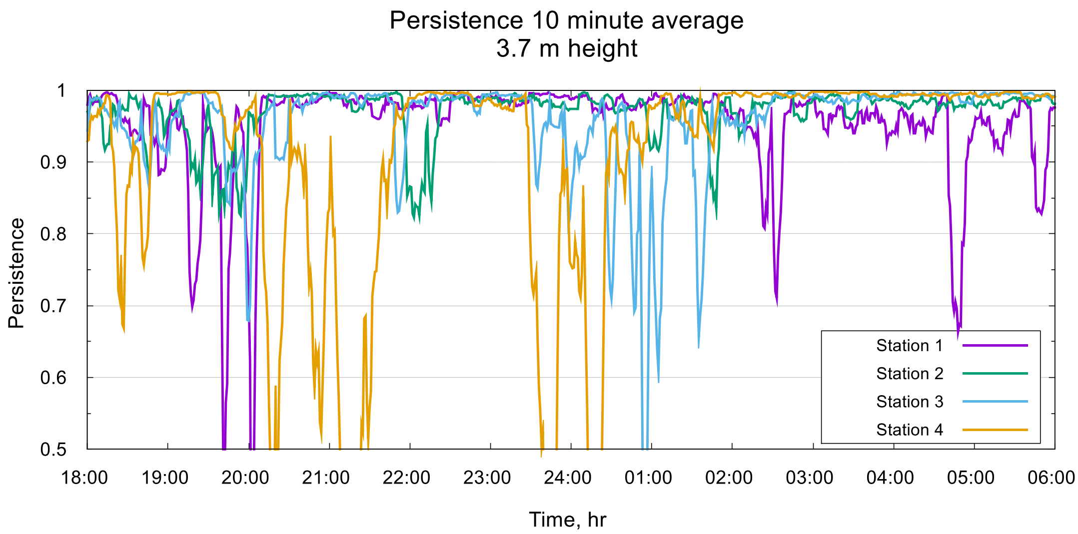

Vector Wind Speed, m/s
3.7 m height
Wind Speed, m/s
Time, hr
Station 1
Station 2
Station 3
Station 4
0
2
4
6
8
10
18:00
19:00
20:00
21:00
22:00
23:00
24:00
01:00
02:00
03:00
04:00
05:00
06:00





Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	1.26	21.8
Station 1 and Station 2	10	1.23	21.7
Station 2 and Station 3	10	1.15	23.43
Station 1 and Station 3	3.7	1.35	34.0
Station 1 and Station 2	3.7	1.12	29.7
Station 2 and Station 3	3.7	1.14	30.2
Station 1 and Station 4	3.7	1.58	37.7
Station 2 and Station 4	3.7	1.38	38
Station 1 at 10 m and Station 1 at 3.7 m		0.53	8.3
Station 2 at 10 m and Station 2 at 3.7 m		0.83	9.32
Station 3 at 10 m and Station 3 at 3.7 m		0.9	10.8





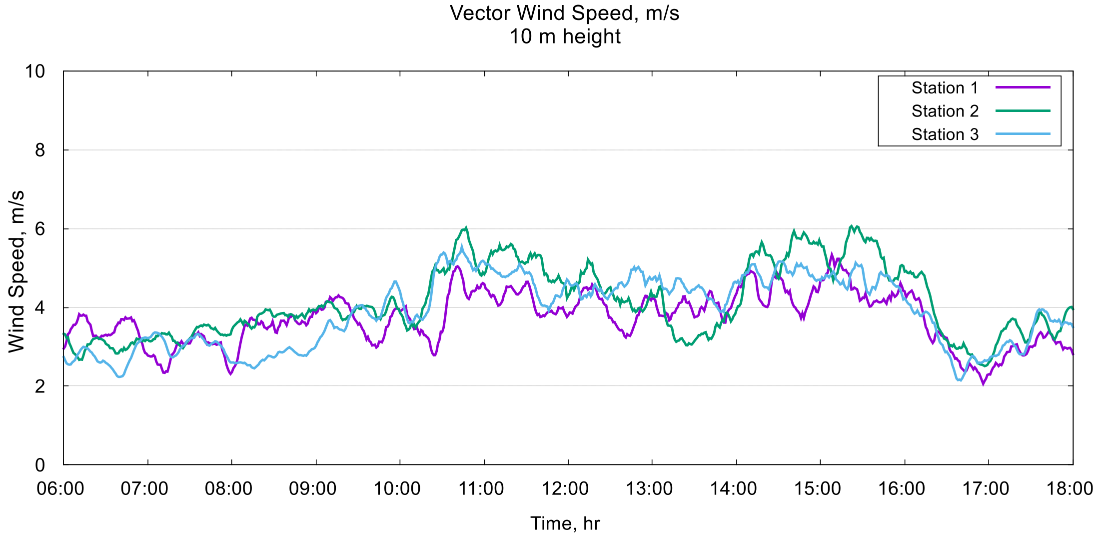
A.8 October 23rd (daytime)

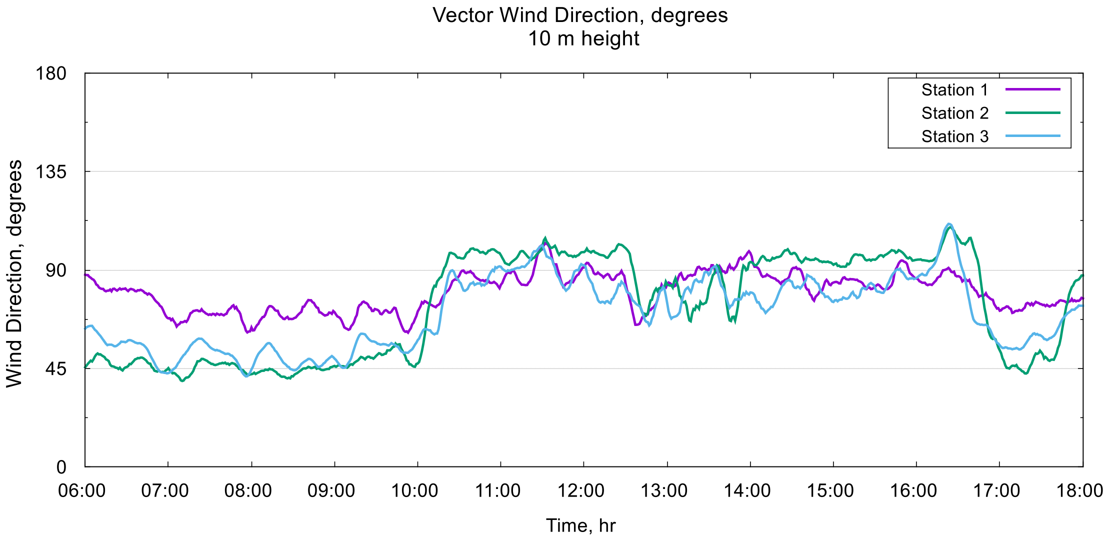
During the 23rd conditions are steadier and wind speed increases from ~3 m/s at the start of the day to 5 m/s before reducing again after 16:00. The difference between stations at specific times can be quite large.

The wind direction is quite stable at each station. It starts NE for stations 2 (NW) and 3 (E) and E for station 1 (W) and then slowly turns there toward ENE before a change in directions at all stations at 10:00 to E until 16:00 when it turns back to NE.

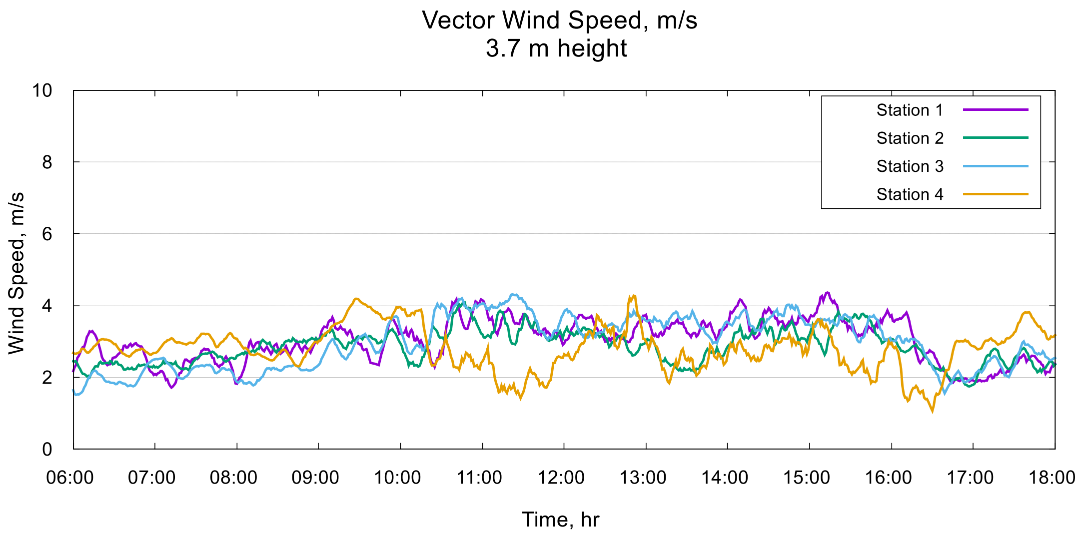
For NE winds station 1 (W) is sheltered by a large tank and an array of smaller tanks which possibly accounts for the distinct difference in wind direction between 06:00 and 10:00 at both 10 and 3.7 m heights.

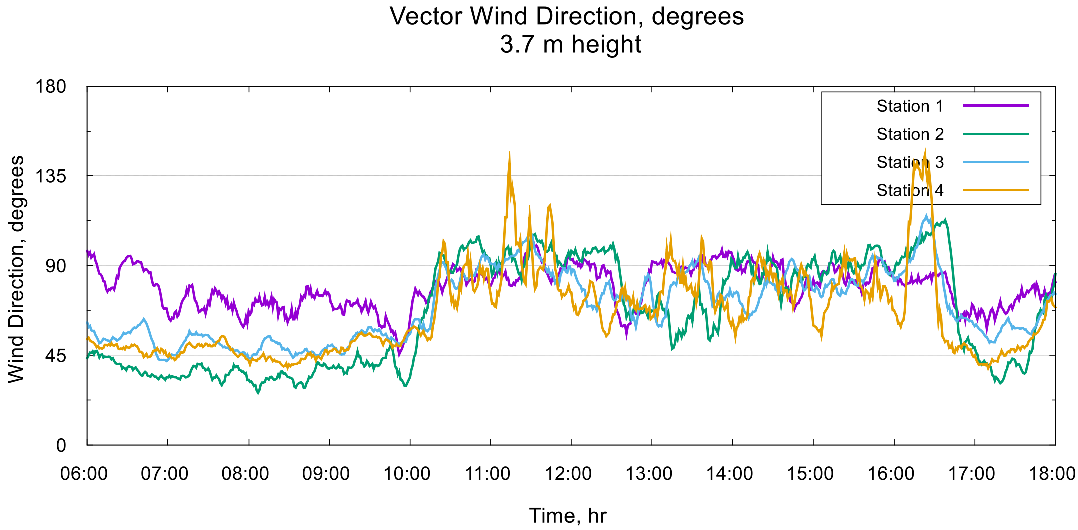
Wind speeds at the different stations are consistently different and varying out of phase. The spread is up to 2 m/s at any one time. The average differences are summarised in the table below.



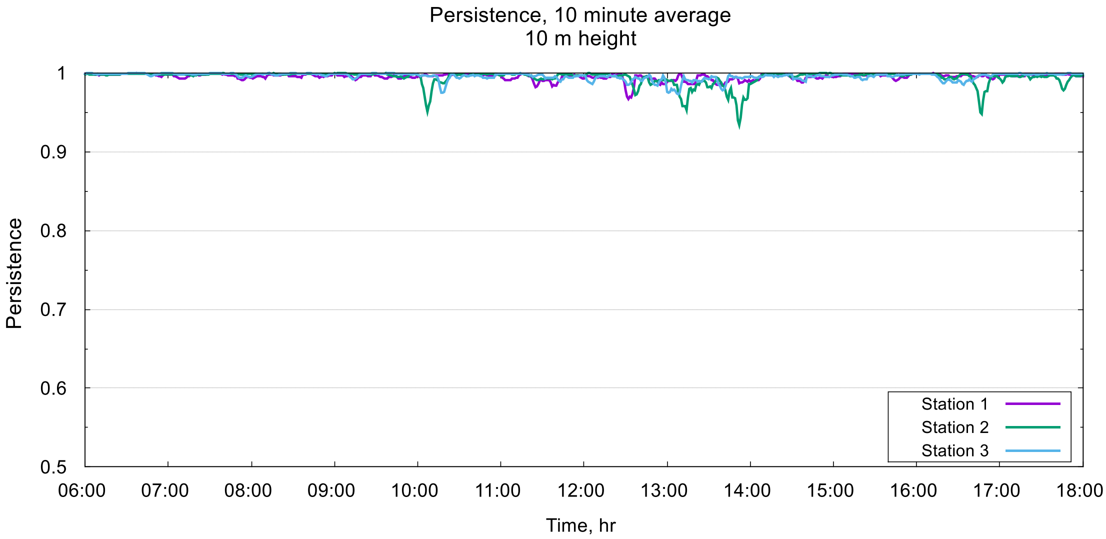


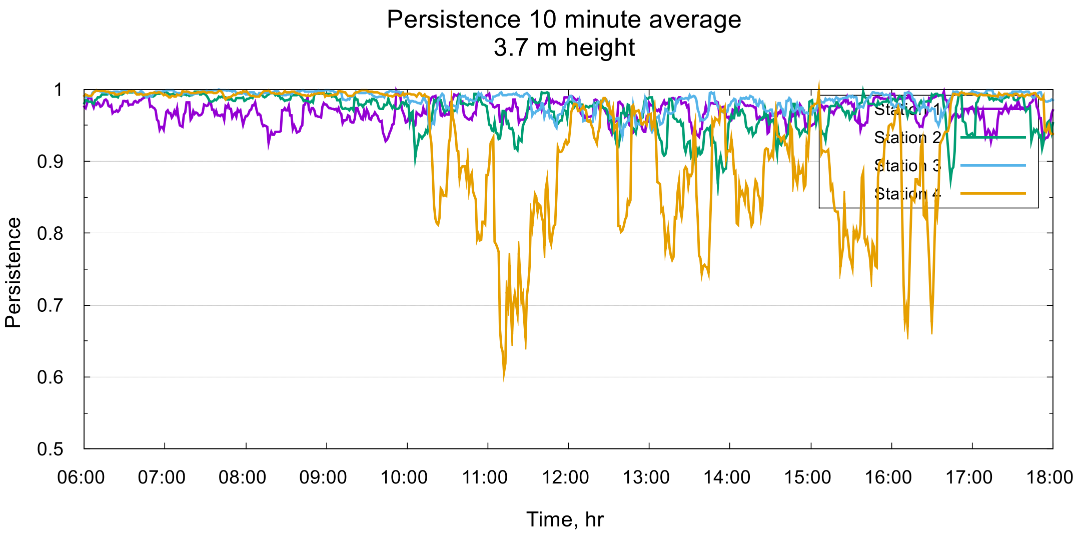
The lower level stations show similar behaviour with more variability on Station 4 (SE) which is upstream of the process-units for an E wind.





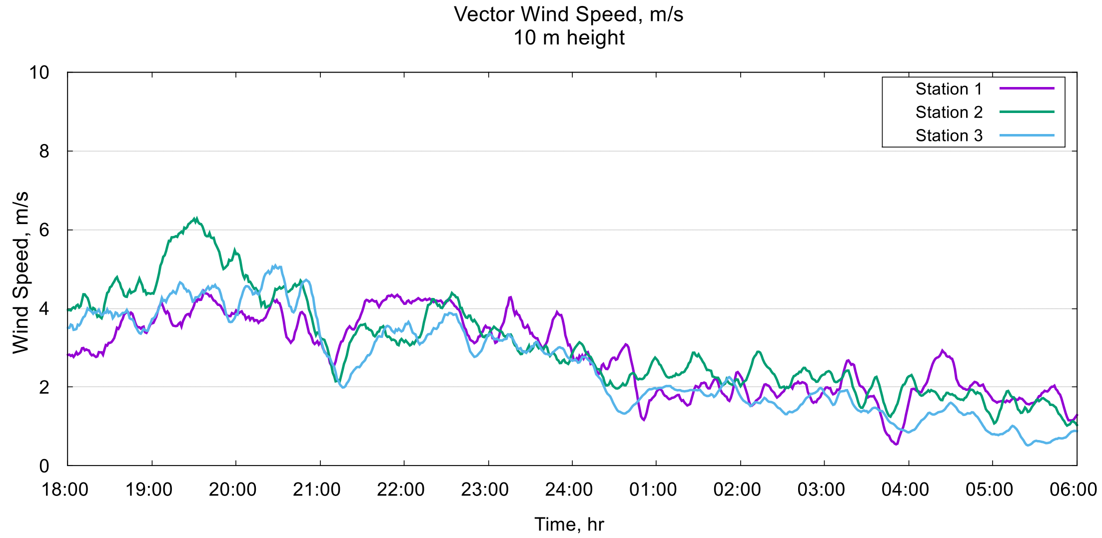
Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.97	11.0
Station 1 and Station 2	10	1.3	16.3
Station 2 and Station 3	10	0.93	9.3
Station 1 and Station 3	3.7	0.82	13.7
Station 1 and Station 2	3.7	1.14	20.95
Station 2 and Station 3	3.7	0.81	12.7
Station 1 and Station 4	3.7	1.35	19.3
Station 2 and Station 4	3.7	1.05	14.2
Station 3 and Station 4	3.7	1.05	9.1
Station 1 at 10 m and Station 1 at 3.7 m		0.74	3.8
Station 2 at 10 m and Station 2 at 3.7 m		1.38	7.7
Station 3 at 10 m and Station 3 at 3.7 m		0.94	2.6



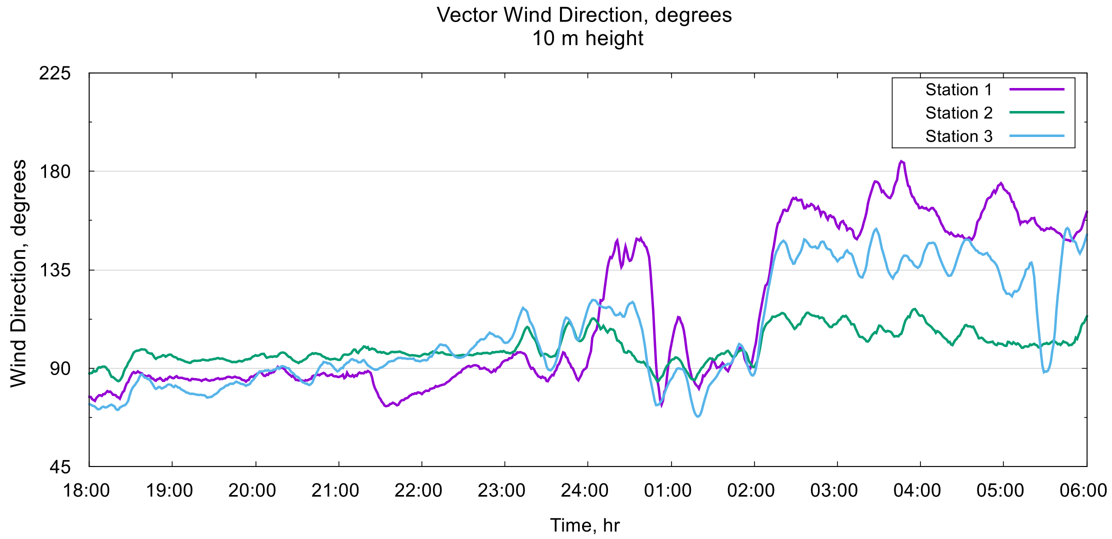


A.9 October 23rd (evening/night-time)

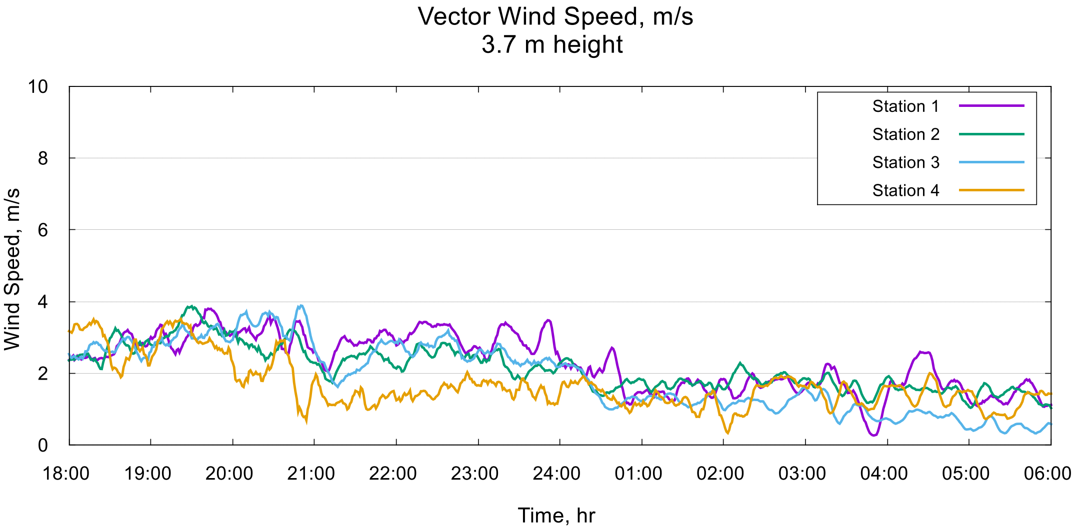
During the night of the 23rd the 10 m wind speed is quite variable (2 - 6 m/s) between stations about a central value of ~ 4 m/s until 23:00 after which the wind falls to ~ 2 m/s at about 01:00 and then remains at this value with less variation than before.

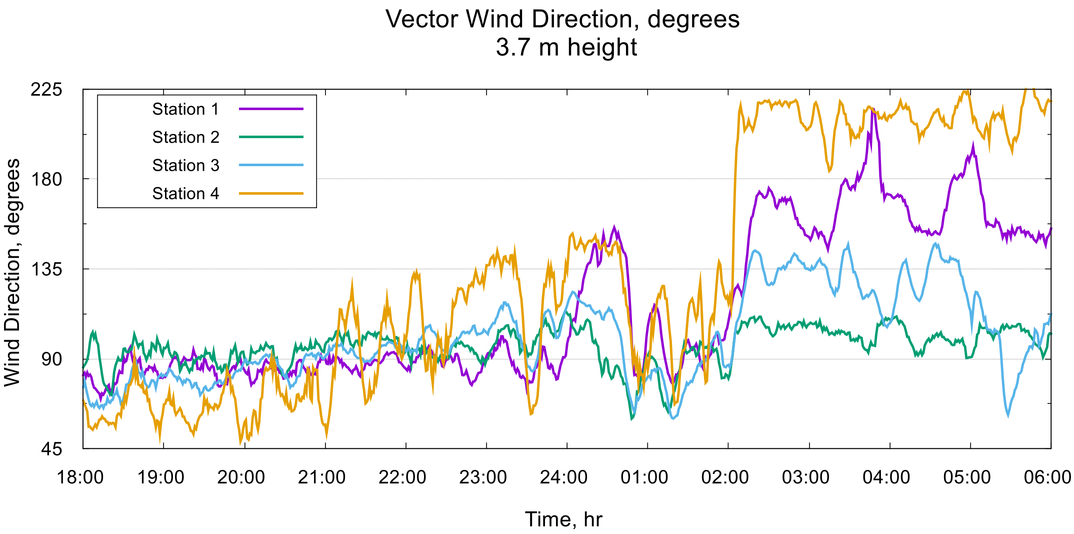


The wind direction is E up to 02:00 when there is a significant but different change seen at each station. Station 1 (W), also sees an earlier shift toward SE between 24:00 and 01:00. Despite the low wind speeds in the last part of the night the direction conditions are quite steady in the short term as shown by the persistence.

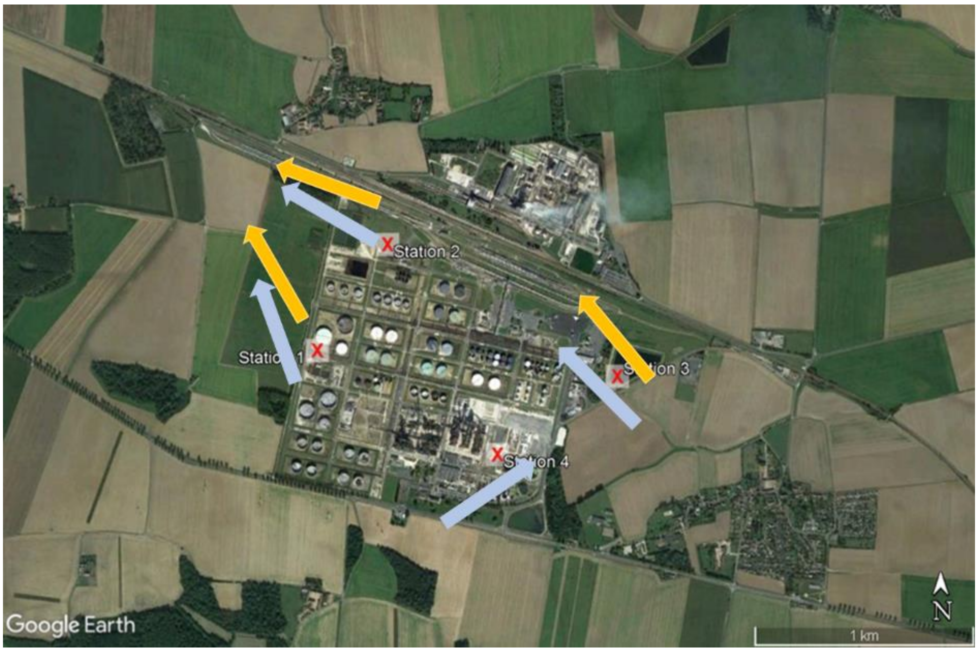


Although the wind speed measured at 3.7 m height was mainly below 2 m/s after 01:00 the record on the lower masts show a good degree of agreement with the 10 m data with respect to the station to station difference. The most variation and the greatest turning of wind direction is shown by Station 4 (SE) indicating further the influence of the process area.





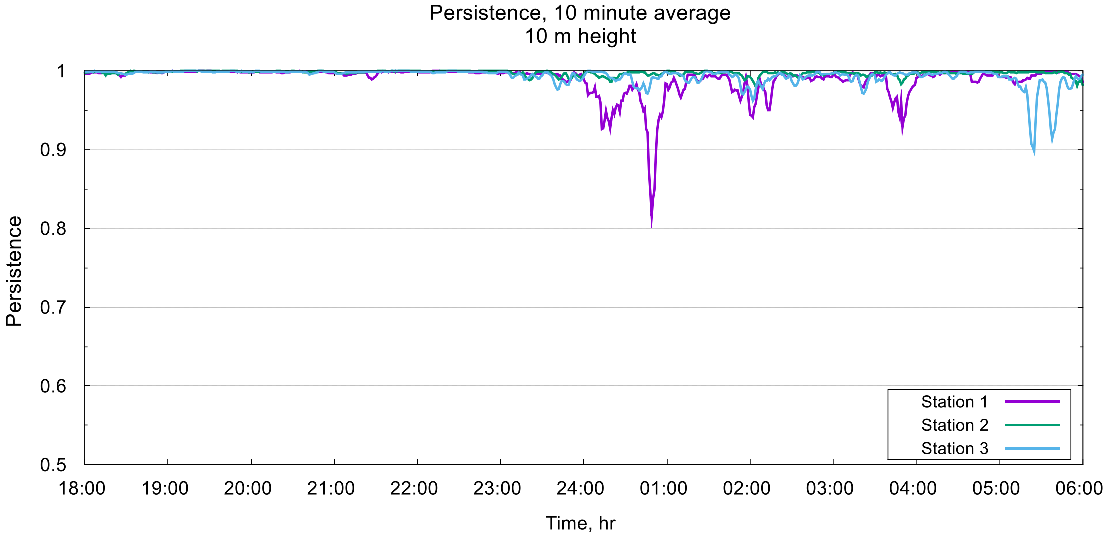
The whole suggest that from 02:00 a SE wind is blocked by the refinery and diverted around the process area as shown schematically below.

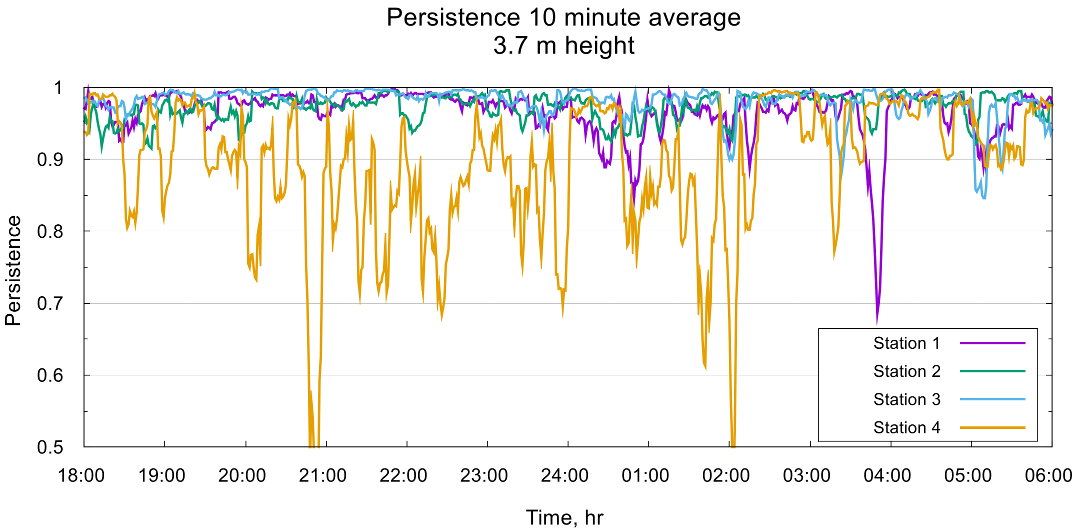


Earlier, with the wind centred on the east, measurements at station 4 (SE), immediately upwind of the process area are extremely unsteady and suggests that the incident flow splits in the neighbourhood of station 4 in order to go around the process area. This shows in the persistence calculation.

Period average differences are given in the table below but are affected by the flow regime change.

Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.84	14.2
Station 1 and Station 2	10	1.29	25.5
Station 2 and Station 3	10	0.88	15.7
Station 1 and Station 3	3.7	0.8	21.9
Station 1 and Station 2	3.7	1.02	28.9
Station 2 and Station 3	3.7	0.71	14.4
Station 1 and Station 4	3.7	1.33	28.8
Station 2 and Station 4	3.7	1.64	52.6
Station 3 and Station 4	3.7	1.23	41.8
Station 1 at 10 m and Station 1 at 3.7 m		0.57	5.2
Station 2 at 10 m and Station 2 at 3.7 m		0.95	5.0
Station 3 at 10 m and Station 3 at 3.7 m		0.68	6.8



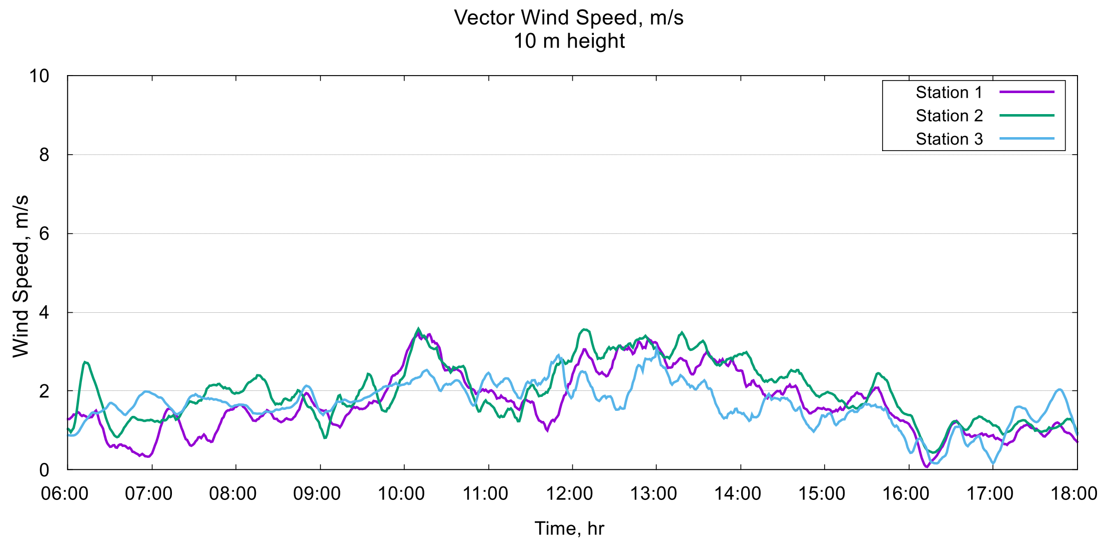


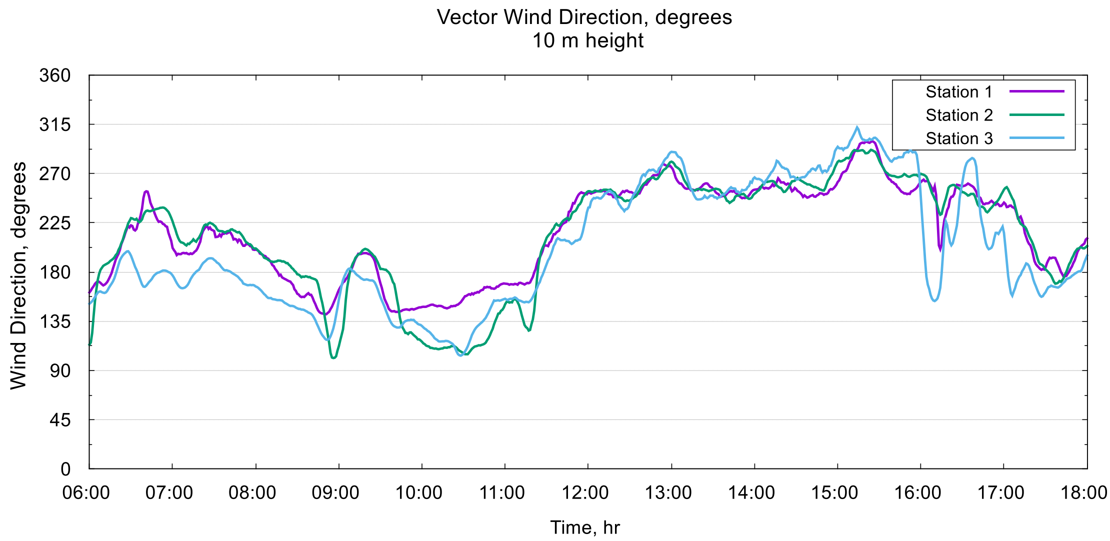
A.10 October 24th (daytime)

On the 24th the 10 m wind speed stays low except for an hour period after 10:00 and again between 12:00 and 15:00 when it reaches ~3 m/s.

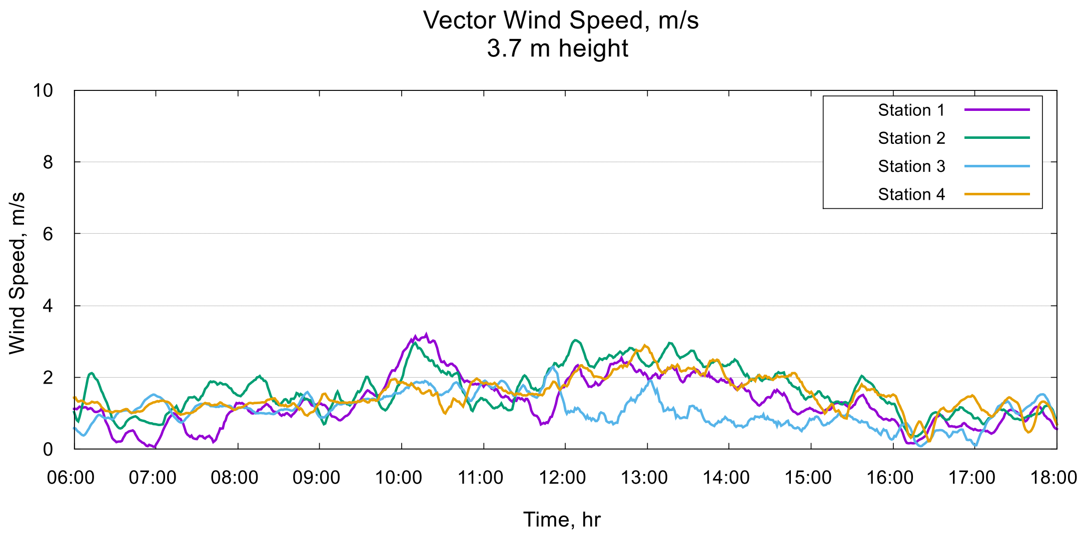
The wind direction is very variable through the morning between ESE and WSW before settling W after 13:00. After 16:00 it backs S.

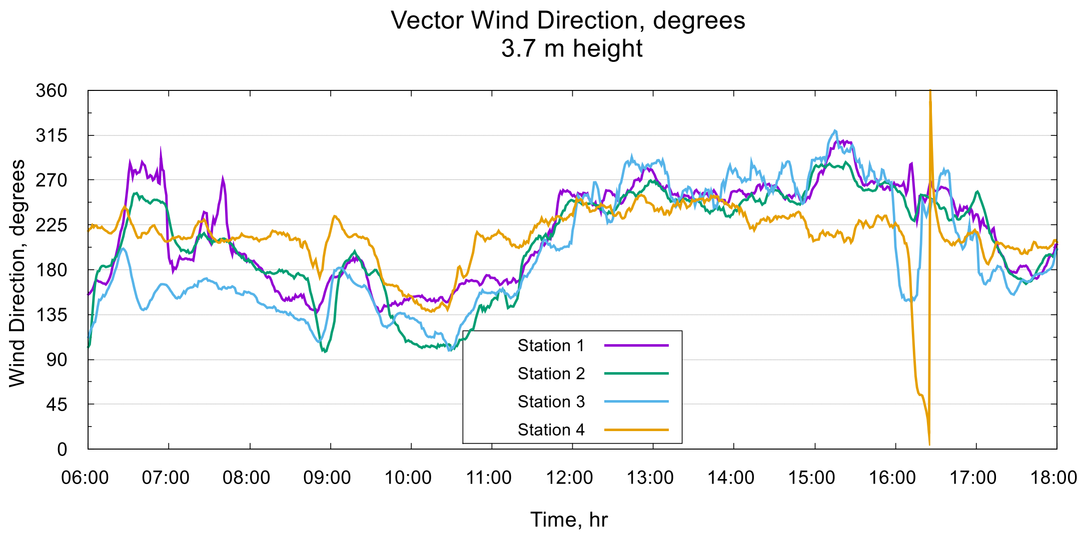
Short term variability is greatest between 16:00 and 17:00 on Stations 1 (W) and 3 (E).



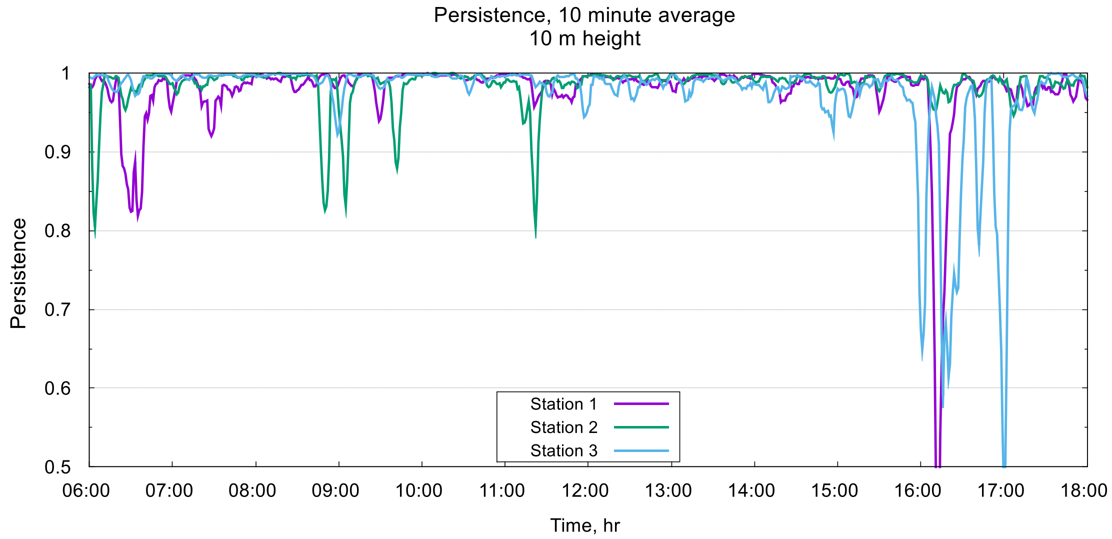


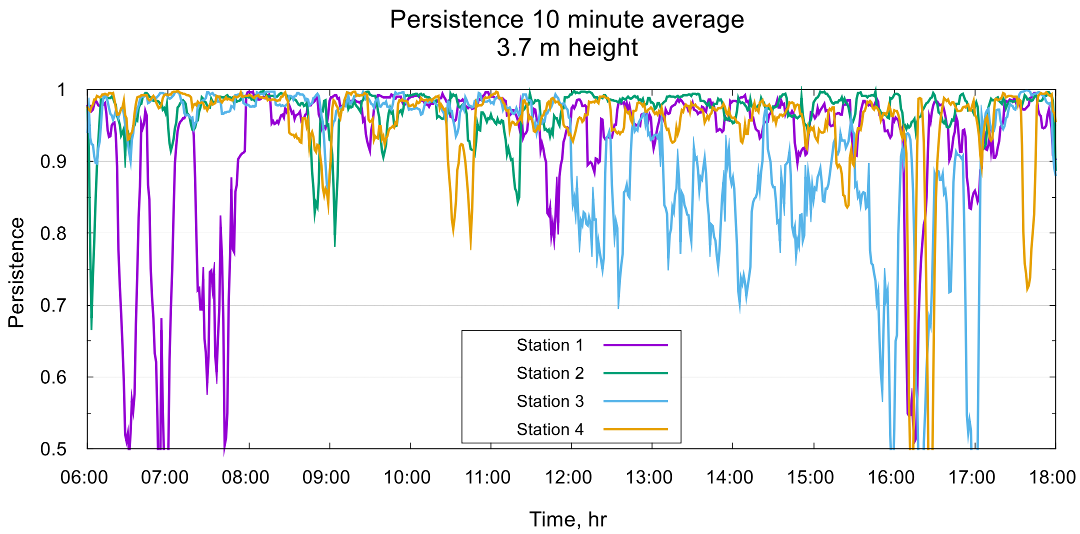
This behaviour is mirrored at 3.7 m height, where the wind speed is less and direction more variable.





Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.81	21.9
Station 1 and Station 2	10	0.65	12.1
Station 2 and Station 3	10	0.93	22.4
Station 1 and Station 3	3.7	0.78	27.0
Station 1 and Station 2	3.7	0.71	16.3
Station 2 and Station 3	3.7	0.97	26.4
Station 1 and Station 4	3.7	0.86	32.7
Station 2 and Station 4	3.7	.87	32.1
Station 3 and Station 4	3.7	1.16	44.7
Station 1 at 10 m and Station 1 at 3.7 m		0.43	8.1
Station 2 at 10 m and Station 2 at 3.7 m		0.44	7.5
Station 3 at 10 m and Station 3 at 3.7 m		0.63	8.6

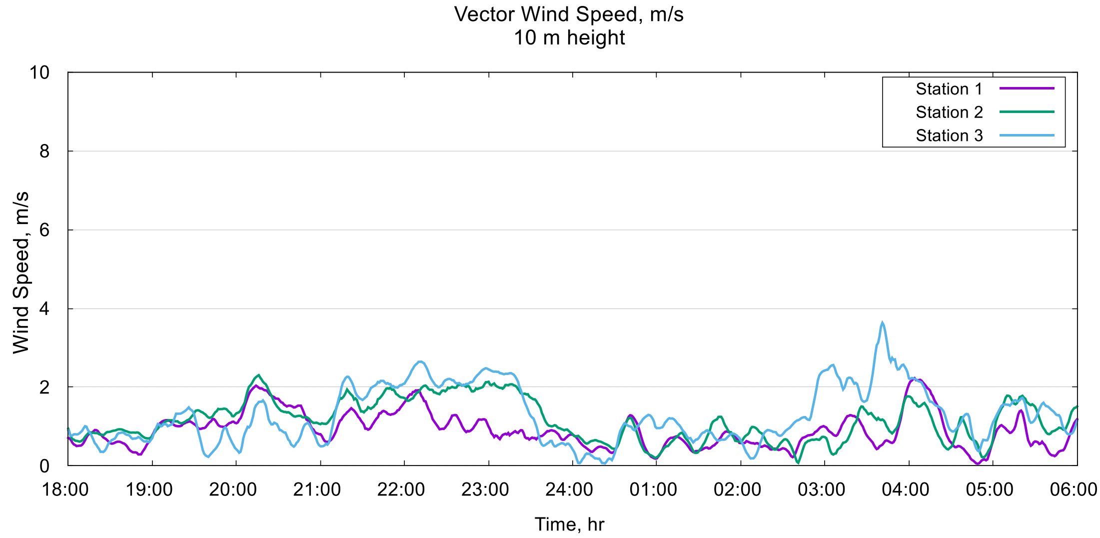




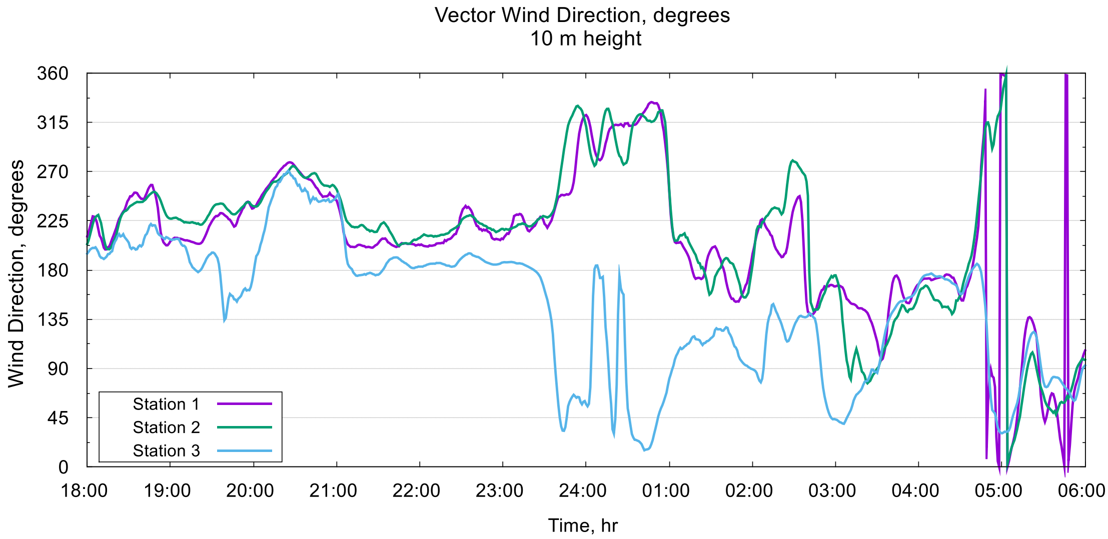
A.11 October 24th (evening/night-time)

During the evening of the 24th the wind speed is consistently below 2 m/s, the wind directions very variable and persistence low.

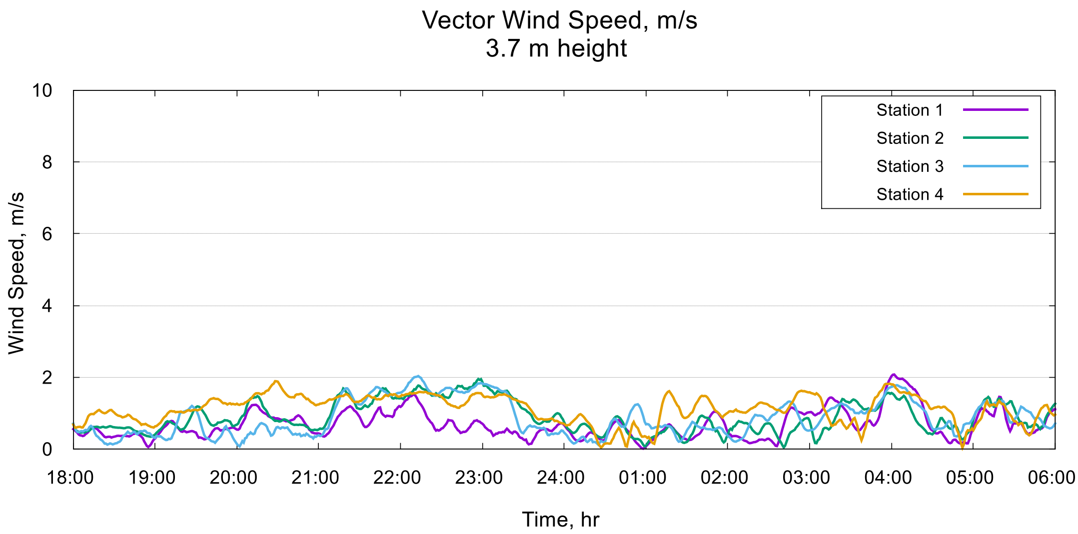
During the lowest wind speed period between 23:30 and 03:00 the smoothed wind directions appear to show the wind turning NW for Stations 1 (W) and 2 (NW) and turning NE for Station 3 (E). Although there is a degree of consistency with the low level stations the short term variability in wind direction is extremely large as evidenced by the persistence.

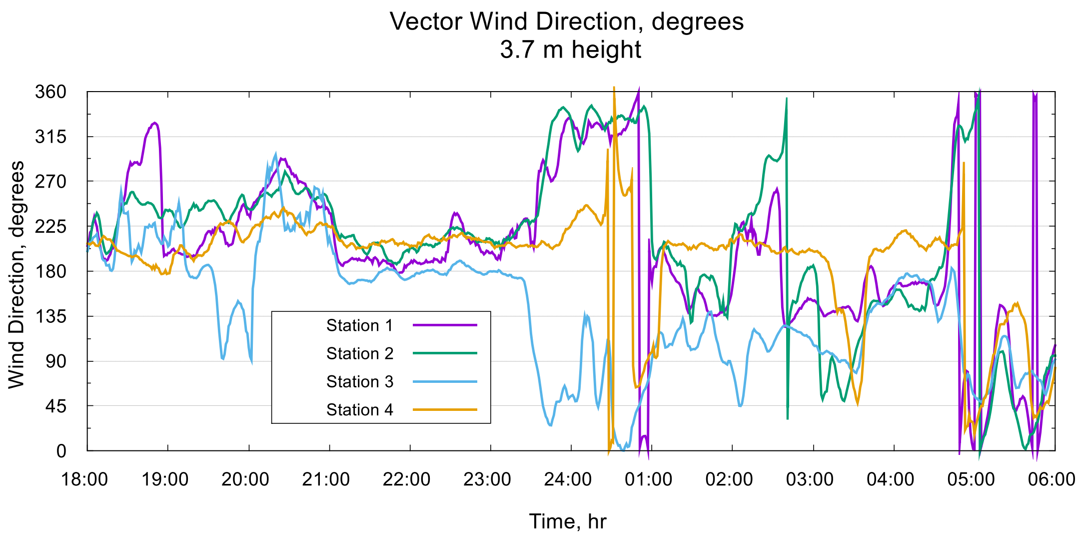


Vector Wind Speed, m/s
10 m height
Wind Speed, m/s
Time, hr
Station 1
Station 2
Station 3
0
2
4
6
8
10
18:00
19:00
20:00
21:00
22:00
23:00
24:00
01:00
02:00
03:00
04:00
05:00
06:00

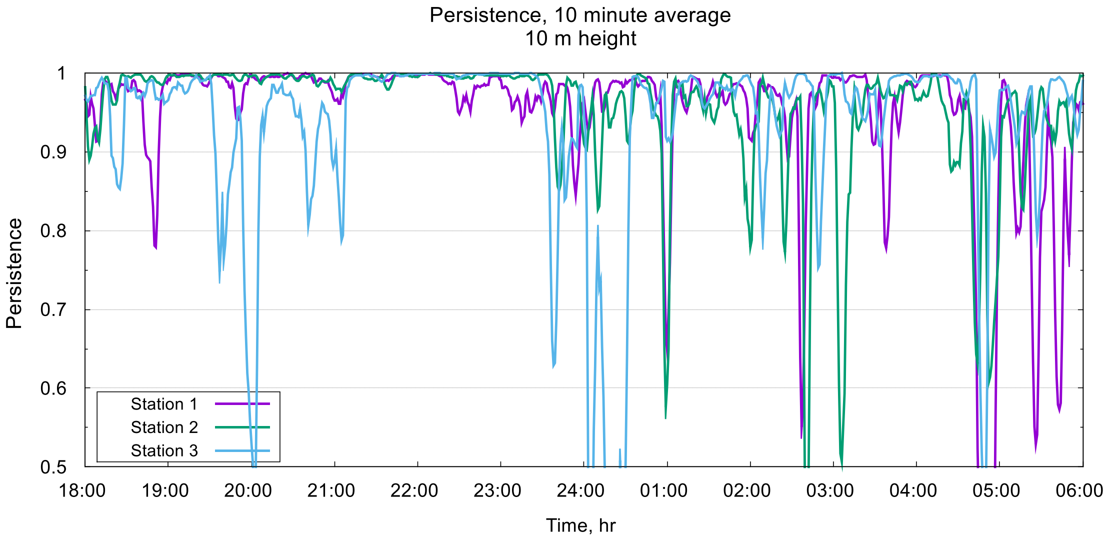


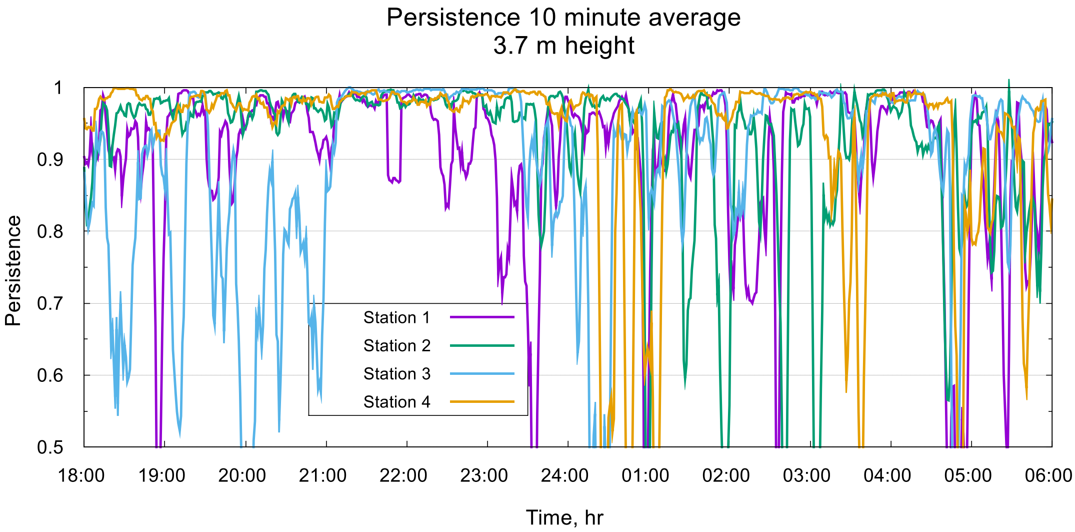
Vector Wind Direction, degrees
10 m height
Wind Direction, degrees
Time, hr
Station 1
Station 2
Station 3
0
45
90
135
180
225
270
315
360
18:00
19:00
20:00
21:00
22:00
23:00
24:00
01:00
02:00
03:00
04:00
05:00
06:00





Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.93	46.0
Station 1 and Station 2	10	0.48	16.6
Station 2 and Station 3	10	0.97	50.2
Station 1 and Station 3	3.7	0.62	47.5
Station 1 and Station 2	3.7	0.50	23.8
Station 2 and Station 3	3.7	0.70	54.2
Station 1 and Station 4	3.7	0.81	40.4
Station 2 and Station 4	3.7	0.73	42.5
Station 3 and Station 4	3.7	0.94	56.5
Station 1 at 10 m and Station 1 at 3.7 m		0.34	14.8
Station 2 at 10 m and Station 2 at 3.7 m		0.36	12.1
Station 3 at 10 m and Station 3 at 3.7 m		0.52	15.4



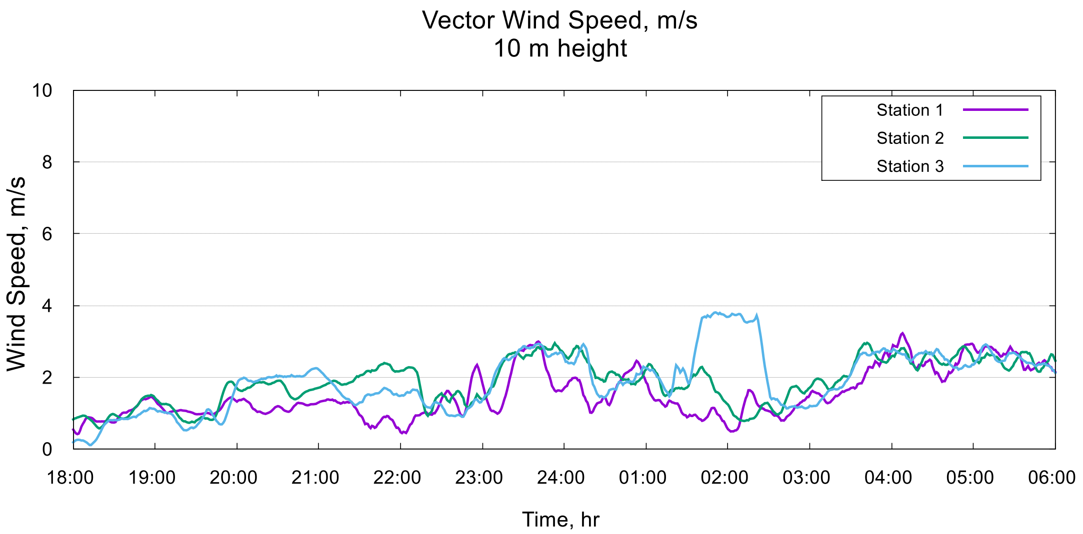


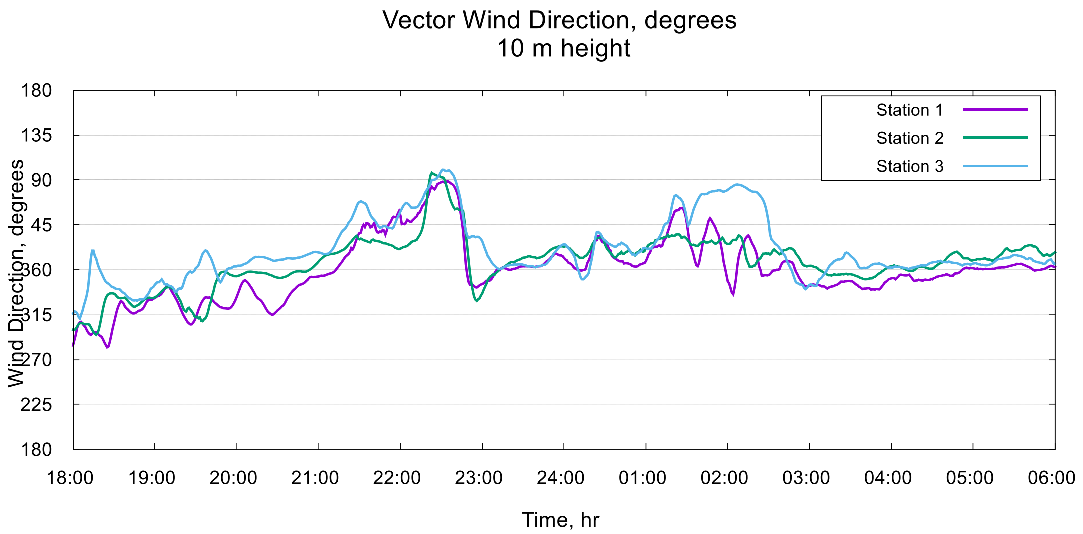
A.12 October 25th (daytime)

The low wind speed conditions continue through the day of the 25th and the results are not shown. Interpretation of data is not possible.

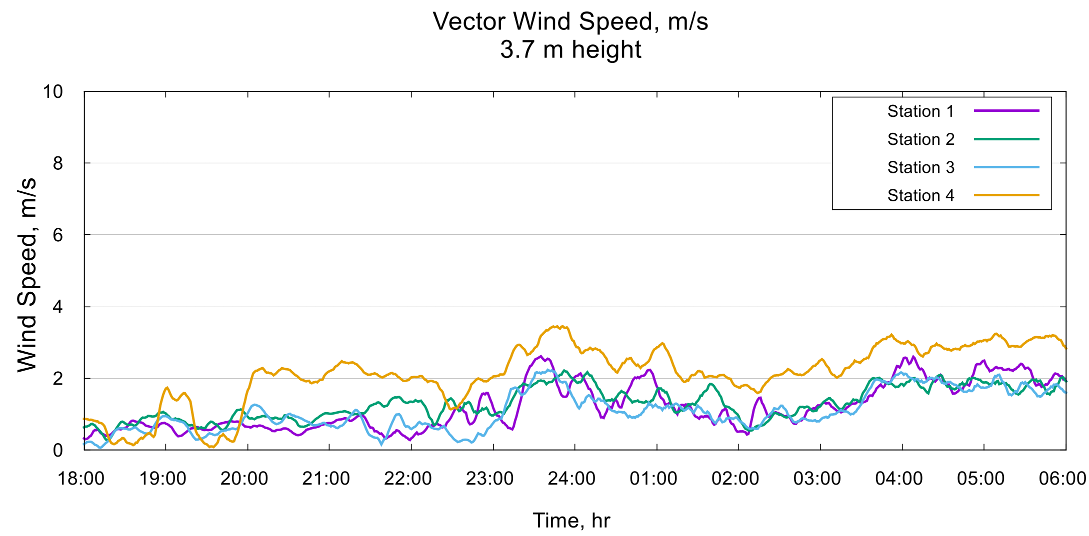
A.13 October 25th (evening/night-time)

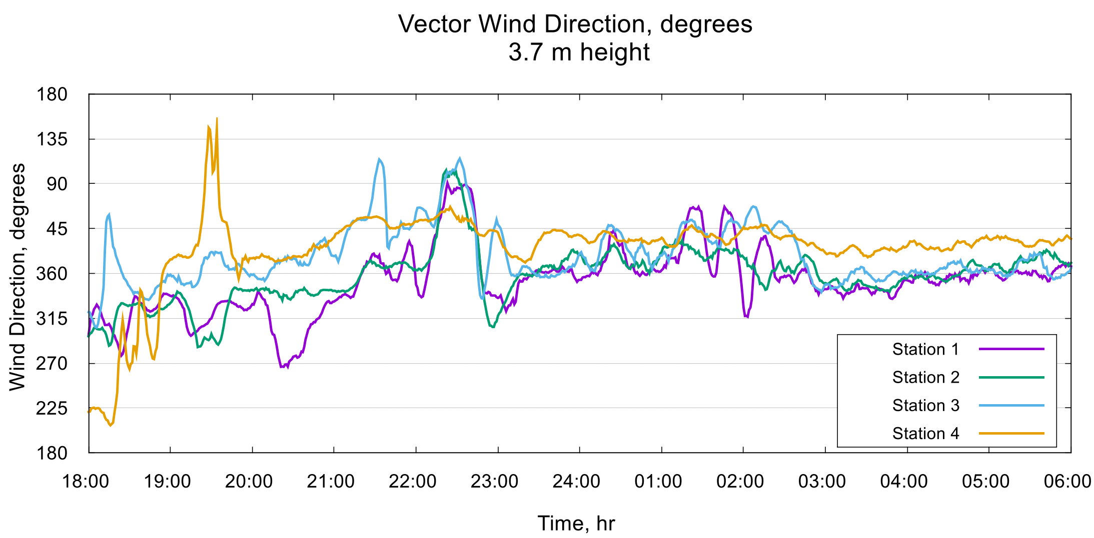
The low wind speed conditions persist into the night of the 25th although there are short periods where individual 10 m stations record wind speeds of 2 m/s. Conditions become more steady after 03:00 when the wind settles in the N. During the night the wind changes from NW through N to E and then back to N. The persistence plot shows that the movement in wind direction between 19:00 and 22:00 from NW to E is fairly steady. Periods of change in wind direction are between 22:00 and 23:00, when it suddenly reverts to N, and between 01:00 and 03:00 when wind speed is low.



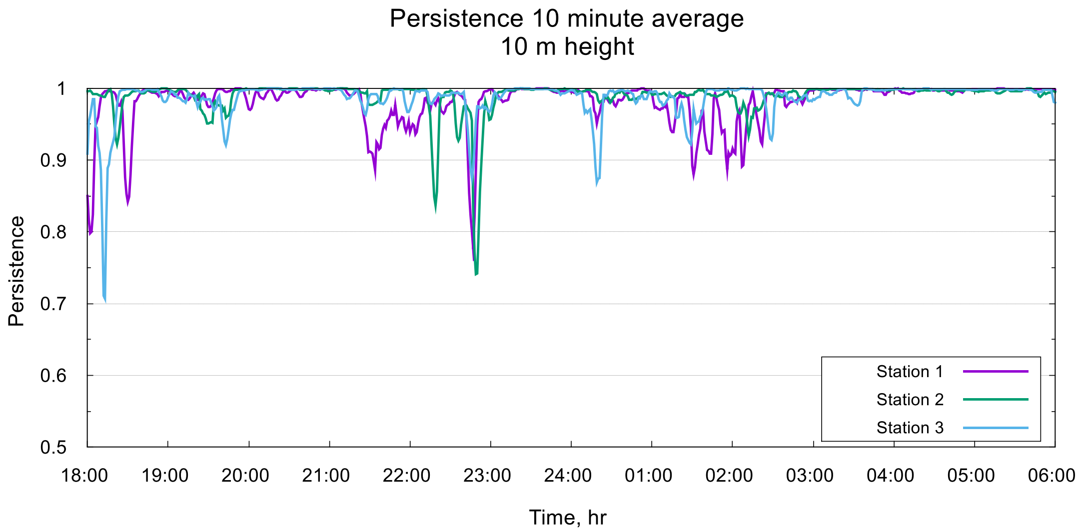


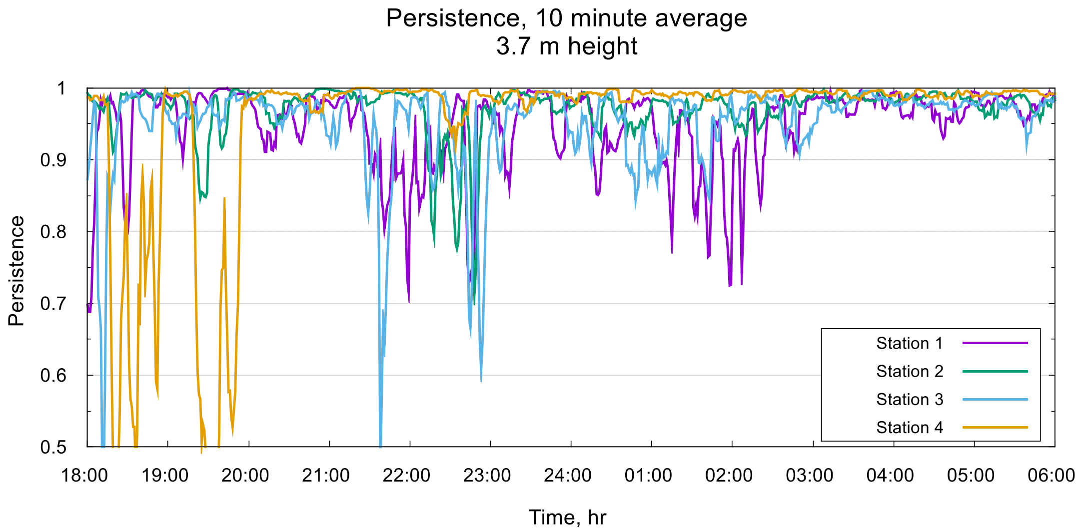
The measurements at 3.7 m mirror the 10 m mast data. The wind speed measured at Station 4 (SE) is higher than at the other stations and, although the direction varies between N and NE through the night, after 20:00 the persistence is high, suggesting steady conditions. The change in wind direction between 22:00 and 23:00 seen by the other stations is not as clearly marked as at 10 m height and is not seen at station 4.


Vector Wind Speed, m/s
3.7 m height
Wind Speed, m/s
10
8
6
4
2
0
18:00
19:00
20:00
21:00
22:00
23:00
24:00
01:00
02:00
03:00
04:00
05:00
06:00
Time, hr
Station 1
Station 2
Station 3
Station 4


Vector Wind Direction, degrees
3.7 m height
Wind Direction, degrees
180
135
90
45
360
315
270
225
180
18:00
19:00
20:00
21:00
22:00
23:00
24:00
01:00
02:00
03:00
04:00
05:00
06:00
Time, hr
Station 1
Station 2
Station 3
Station 4

Difference Between	Height m	Velocity m/s	Direction degrees
Station 1 and Station 3	10	0.86	21.1
Station 1 and Station 2	10	0.67	13.7
Station 2 and Station 3	10	0.70	17.4
Station 1 and Station 3	3.7	0.55	28.4
Station 1 and Station 2	3.7	0.47	14.7
Station 2 and Station 3	3.7	0.53	24.8
Station 1 and Station 4	3.7	1.48	43.4
Station 2 and Station 4	3.7	1.32	36.6
Station 3 and Station 4	3.7	1.3	25.5
Station 1 at 10 m and Station 1 at 3.7 m		0.4	10.9
Station 2 at 10 m and Station 2 at 3.7 m		0.64	10.6
Station 3 at 10 m and Station 3 at 3.7 m		0.89	10.7



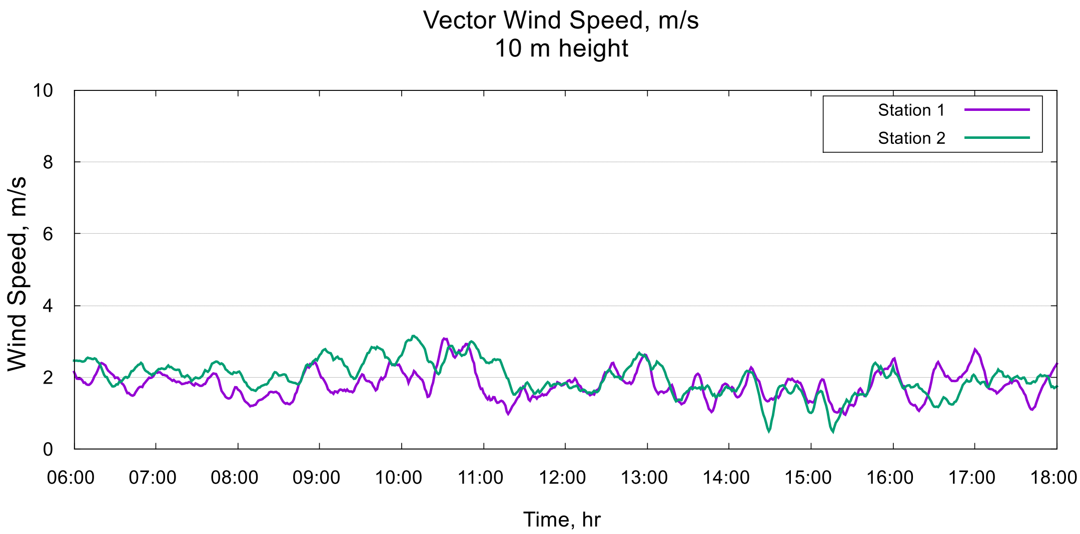


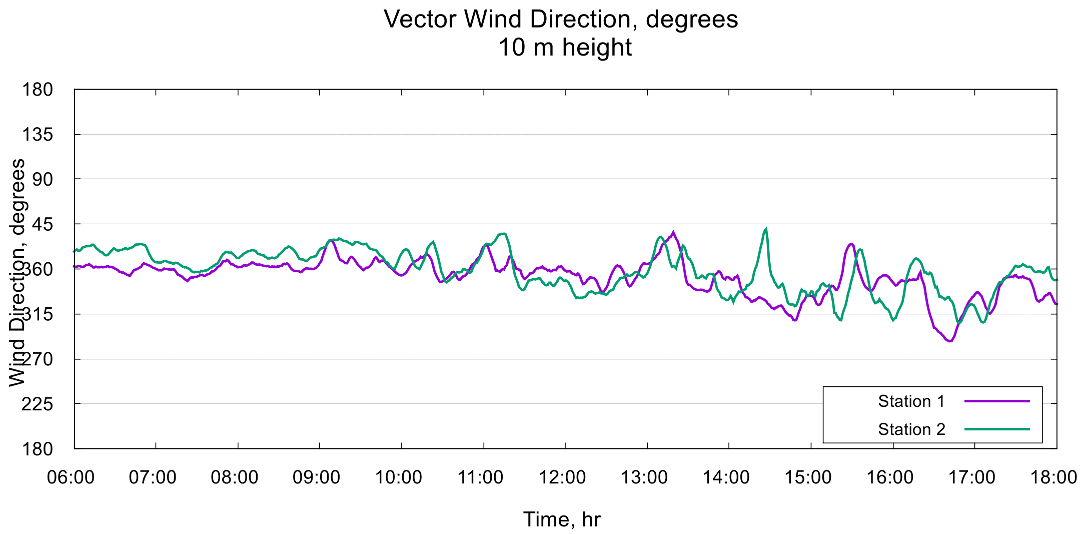
A.14 October 26th (daytime)

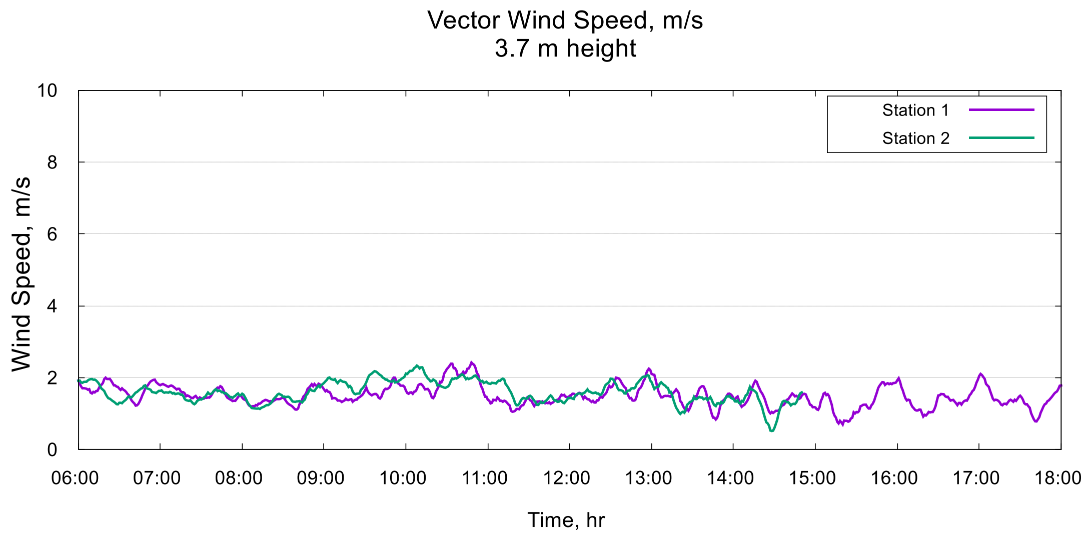
There are only partial data from station 1 (W) and station 2 (NW) on the 26th which do not inform on changes in flow across the site. The wind speed at 10 m height is also low with values generally below 2 m/s.

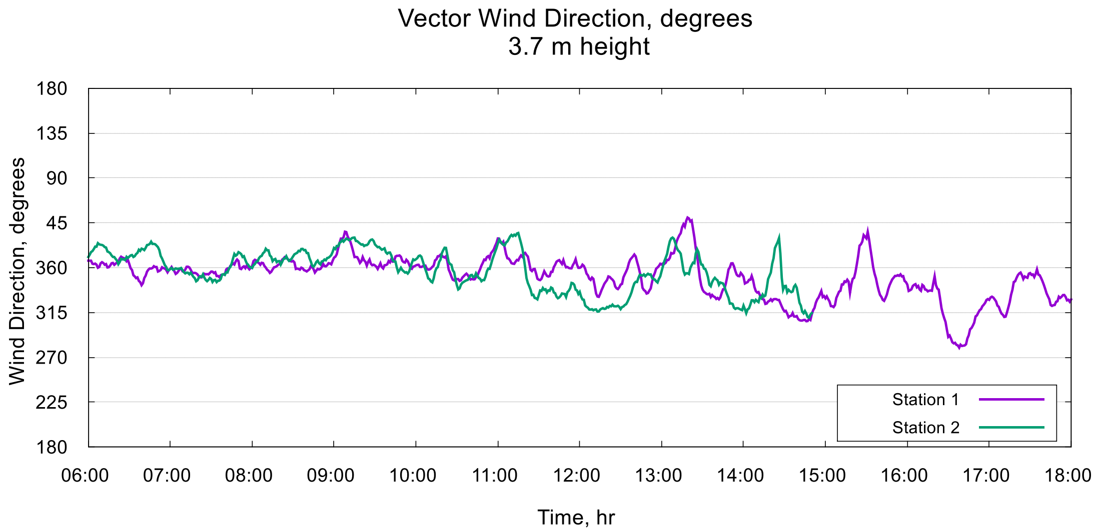
The wind remains in the N, varying between NNE and NNW and becomes increasingly unsteady after 10:00 as shown by steadily decreasing persistence. The data at 3.7 m follow the same trend with increased variability after 09:00. Some periods of invalid data on station 2 (NW) are marked by significant changes on the persistence graph.

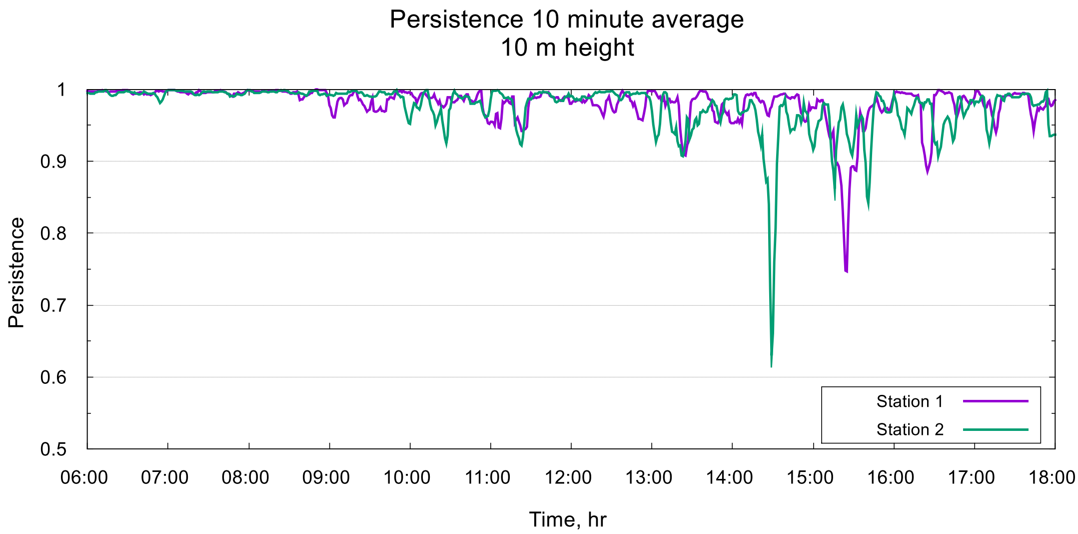
Summary data have not been calculated as there is not enough information to infer the flow across the site.

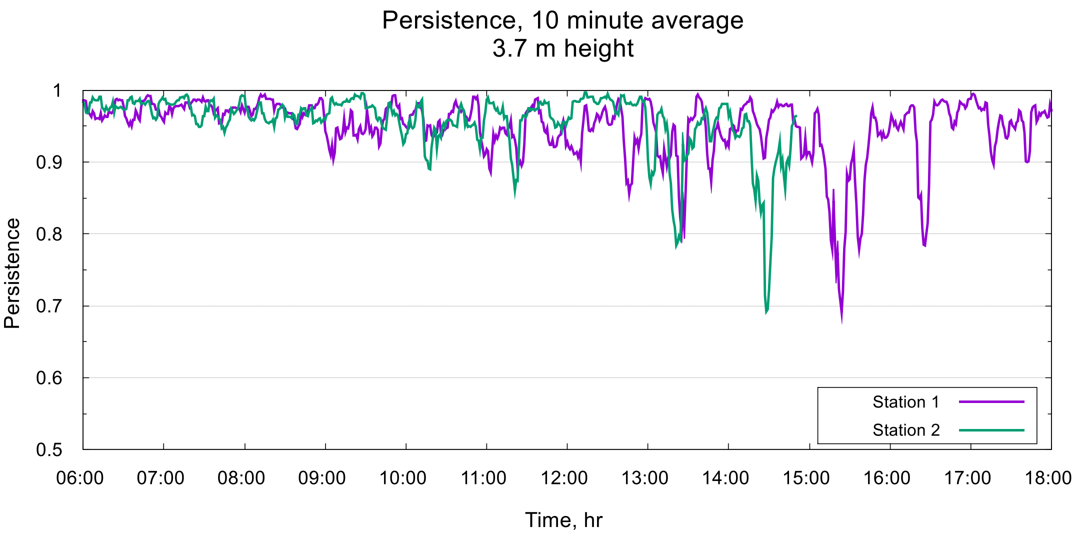





Vector Wind Speed, m/s
3.7 m height
Wind Speed, m/s
Time, hr
Station 1
Station 2
0
2
4
6
8
10
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00


Vector Wind Direction, degrees
3.7 m height
Wind Direction, degrees
Time, hr
Station 1
Station 2
180
225
270
315
360
45
90
135
180
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00


Persistence 10 minute average
10 m height
Persistence
Time, hr
Station 1
Station 2
0.5
0.6
0.7
0.8
0.9
1
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00


Persistence, 10 minute average
3.7 m height
Persistence
1
0.9
0.8
0.7
0.6
0.5
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time, hr
Station 1
Station 2

APPENDIX B: A NOTE ON WIND LIDAR MEASUREMENTS

The reasons for not reporting wind LIDAR results are discussed in this section.

LIDAR vertical profiles of wind speed and direction are measured at a frequency of ~0.05 Hz. The interval between data points varies according to the signal to noise ratio of the individual measurement.

At each output height between 10 m and 98 m from baseline the LIDAR returns a horizontal and vertical velocity and a wind direction measurement. The LIDAR itself cannot reconcile the absolute direction of flow and requires steering from an independent portable anemometer. Both LIDAR and anemometer were mounted on a pick-up truck. The effective height range of the LIDAR was 12-100 m (after allowing for the height of the pickup truck on which it was mounted) with the portable anemometer measuring at 2 m + 1 m because in the truck = 3 m.

In normal use the LIDAR would be in a fixed location, free from obstructions and steered from a reference mast using data from 10 m height. Before using the LIDAR in this study CONCAWE conducted an evaluation of the LIDAR against a reference mast and a credible performance was observed [1]. There was a small mismatch in wind-directions attributed to North calibration.

Output from the portable anemometer was collected through the LIDAR data system and averaged before being output at ~0.05 Hz.

Output from the LIDAR data system was time-averaged into 10-minute periods for graphical display using vector averaging. The wind speed shown is therefore the average wind speed in the average wind direction over the period.

The wind vector speed is plotted as a function of height using a logarithmic scale and for comparison purposes a neutrally stable theoretical boundary layer profile has been superposed. A surface roughness of 0.2 m has been used to calculate the profile; this choice is arbitrary but typical of values used to estimate boundary-layer profiles above built areas and industrial sites which would range from 0.1 m upwind to 0.3-0.5 m downwind until the effect of the refinery has dissipated.

The theoretical profile is not a fit but it has been forced to go through the 20 m value of the LIDAR profile.

Also plotted are the 10 m and 3.7 m wind values from the fixed masts at the reference stations 1 (W), 2 (NW) and 3 (E). Where available a 3.7 m value from Station 4 (SE) is included.

The variation of wind direction with height is plotted on a polar chart to avoid the complicated crossings of North that confuse the time-series plots of wind direction when drawn on a linear scale. The distance from the centre represents height, also using a logarithmic scale.

The reading from the portable anemometer has been plotted at height 3 m for presentation reasons.

The LIDAR system was placed alongside the reference stations for several periods during the campaign to allow verification of the measurements. However, the data were not available for inspection at those times during the measurement period.

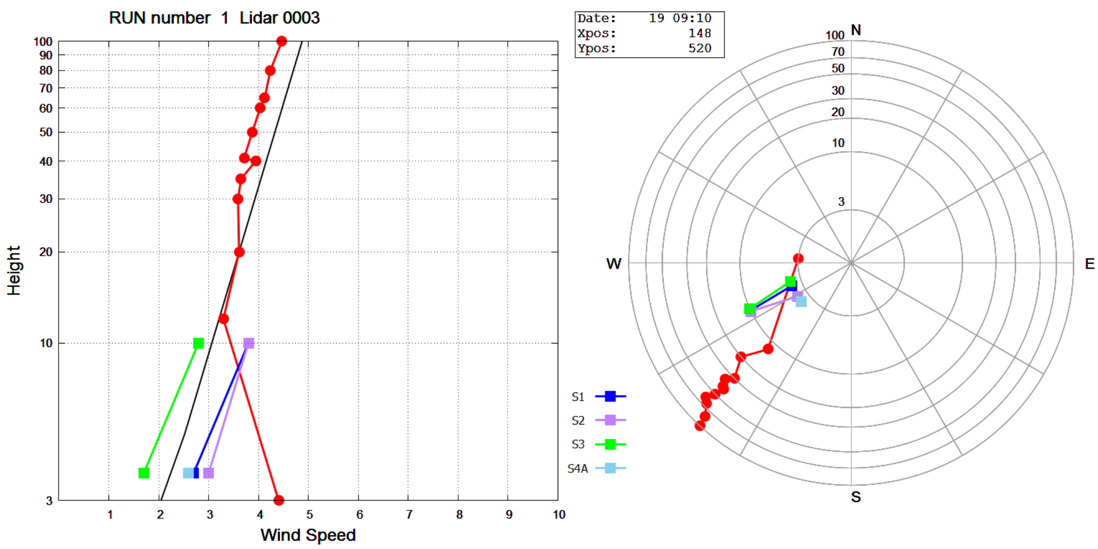
The below graphs show the LIDAR (red, data above 12 m) co-located with station 1 (blue, height 3.7 and 10 m) together with the measurements at fixed stations 2 and 3 (heights 3.7 and 10 m) and station 4 (height 3.7 m). Averages over three consecutive 10-minute periods are shown.

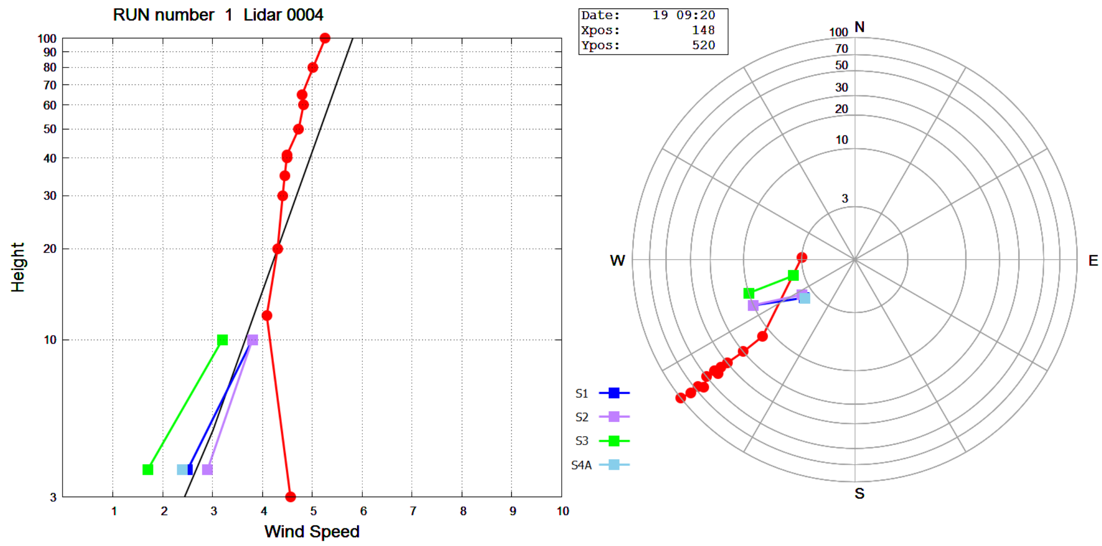
The approach wind direction is from open ground and so should approximate an undisturbed boundary layer profile, drawn in black.

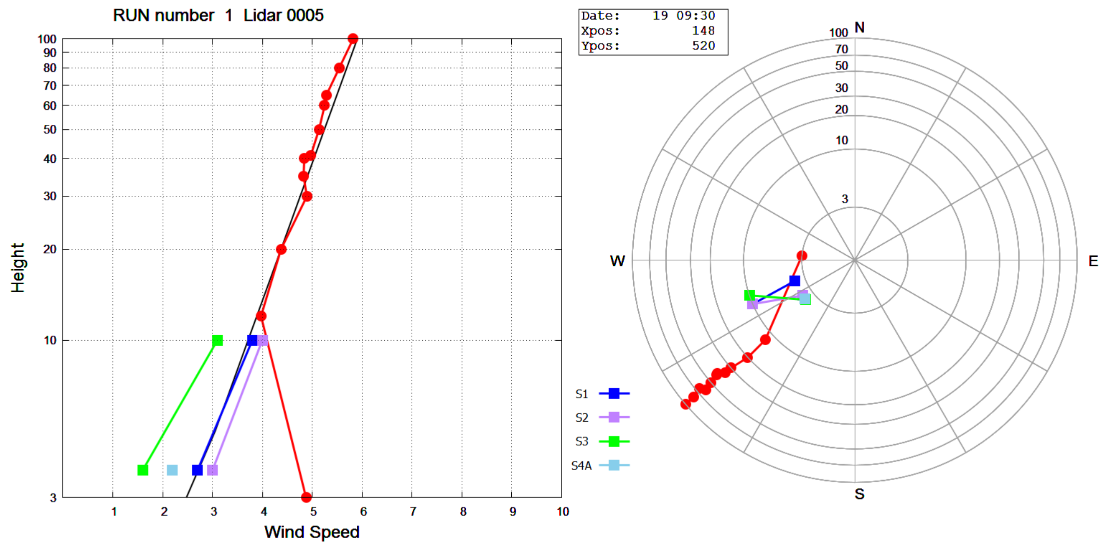
The portable anemometer (height 2 m) installed with the LIDAR is plotted at 3 m height on the same profile as the LIDAR (the values for which start at 12 m). This is showing an anomalously high wind speed, possibly a local effect due to flow around the pick-up truck or an operational problem with the meteorological station.

In terms of the variation in wind speed with height all three stations show a credible slope compared to the example wind profile, as does the LIDAR data. In the third time period the coincidence of the LIDAR, the monitors at station 1 and the example profile is close to what would be obtained by curve fitting.

In terms of wind direction, the LIDAR shows wind direction invariant with height and coming from the SW. There is a consistent difference in wind direction between the LIDAR at height 12 m and the fixed mast 10 m result at station 1 of about 15 degrees. This is larger than the differences between wind direction measured at the different fixed stations and between the wind direction at 10 m and at 3.7 m height at those stations.

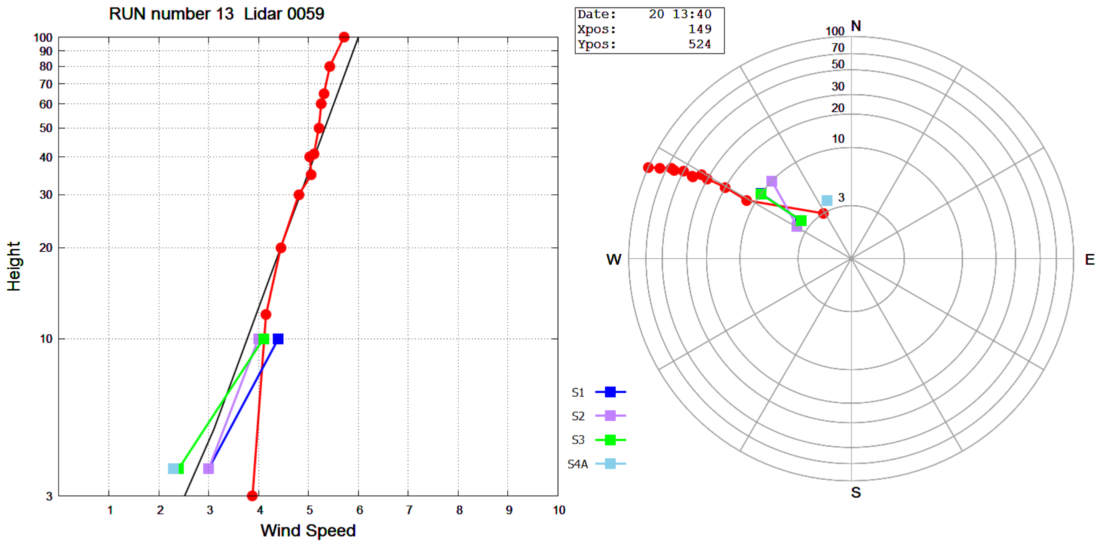


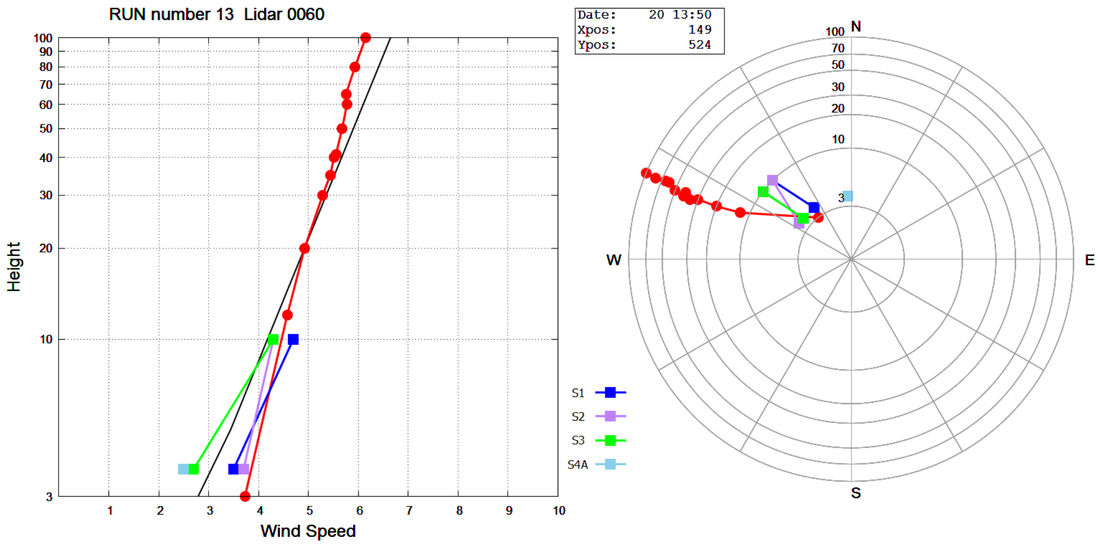


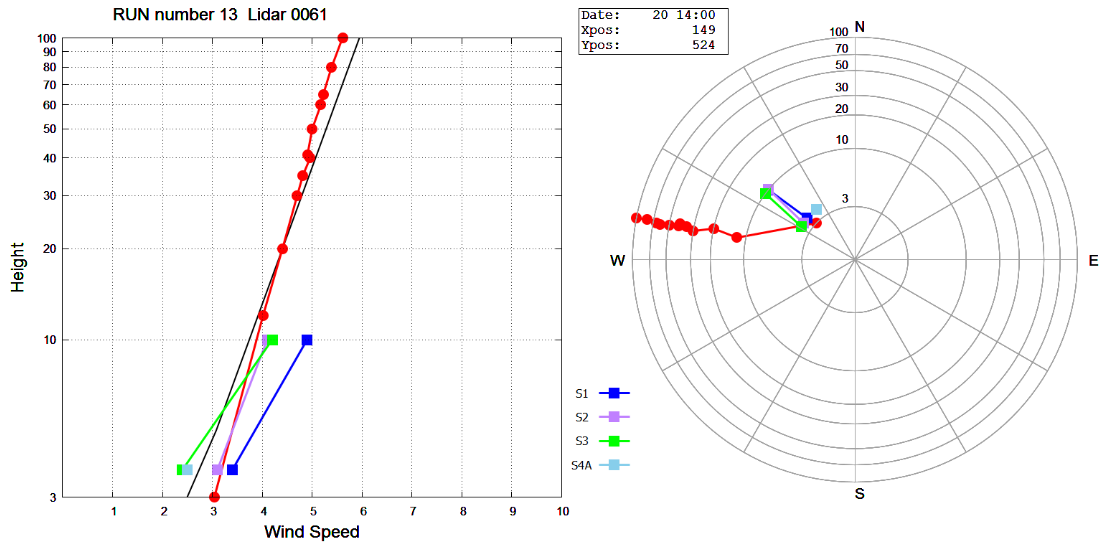


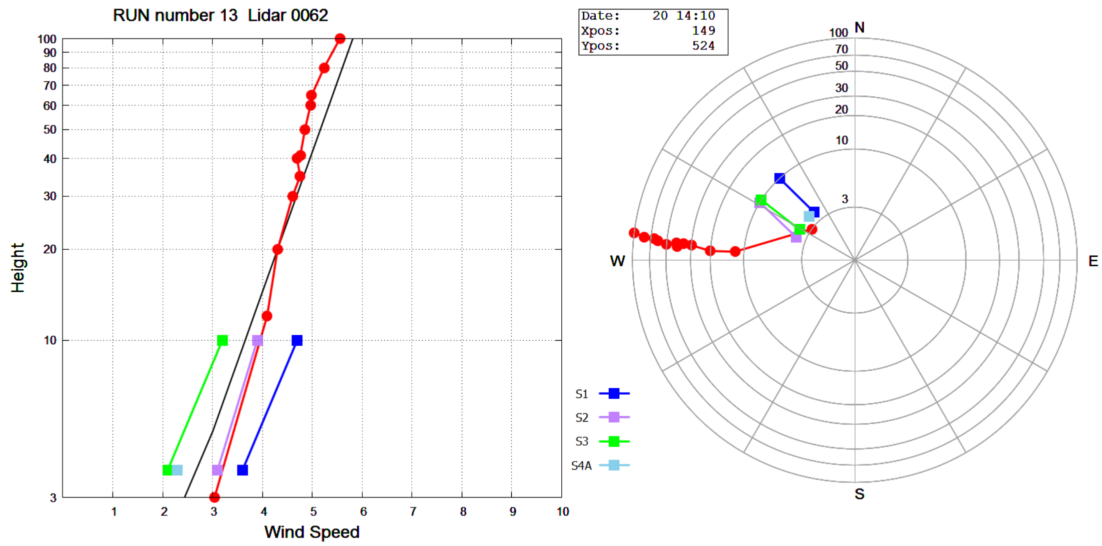
A second set of co-located results at station 1, taken on the next day, is shown below. The wind is from north of West so is unobstructed upwind of station 1. Again the wind speed profile closely resembles that of an undisturbed neutrally-stratified boundary layer. The wind speed at 10 m height at station 1 is a little greater than indicated by the LIDAR and similar those at the other fixed stations. The wind direction at 10 m height at station 1 is the same as at station 3 (hidden behind the green) and just a few degrees different to that at the LIDAR which shows that wind direction is almost invariant with height. As in the previous case the low-level portable anemometer records an anomalously large wind speed and a significantly different (30 degree) direction which may be due to flow around the pick-up.

The sequence of 4 consecutive ten-minute time periods shows that the wind direction determined by the LIDAR moves in a southerly direction, continuously increasing the difference with station 1 to 45 degrees. The other fixed stations do not indicate a large change in wind direction at 10 m height although station1 is about 15 degrees more northerly than stations 2 and 3.


RUN number 13 Lidar 0059
Date: 20 13:40
Xpos: 149
Ypos: 524
Height
Wind Speed
N
E
S
W
S1
S2
S3
S4A


RUN number 13 Lidar 0060
Date: 20 13:50
Xpos: 149
Ypos: 524
Height
Wind Speed
N
E
S
W
S1
S2
S3
S4A





These two examples show two problems with the LIDAR measurements as made. The consistent difference in wind direction in the first set might be explained by an error setting the North alignment of the instrument. Practically this could occur if there was interference with the determination of magnetic north. Correcting the LIDAR measurements by the addition of ~15 degrees would also make worse the comparison of the portable anemometer with station 1 at 3.7 m but in this case the anemometer is clearly out of line with the fixed mast measurements.

In the second set the gradual change in LIDAR wind direction cannot be due to a simple incorrect calibration. The direction signal is drifting. As the sequence progresses, and the drift increases, it is not shown in the portable anemometer results. Both wind speed and wind direction for this instrument come into line with the reference station 1 measurements at 3.7 m height.

Interpretation of the LIDAR measurements made at the many locations internal to the site requires that the wind direction information be compared with that recorded at the reference masts. Without confidence in the LIDAR wind direction it is not possible to attribute if the direction of flow is affected by the presence of refinery structures. In many cases the profiles obtained do appear credible and to be plausibly explained in terms of flow modification however, without certainty on the measurements, evidence for this behaviour is lacking. For this reason, it has been decided not to report results.

When measurements were made next to strong convective sources such as air-coolers the wind LIDAR indicated large erratic wind direction changes with height. However, a confounding factor is that LIDAR measurements may be unreliable near to such sources due to air density fluctuations.

Environmental Science for European Refining

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ISBN 978-2-87567-110-3