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Meteorological observations in tall masts for mapping of atmospheric flow in Norwegian fjords

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Abstract. Since 2014, 11 tall meteorological masts have been erected in coastal areas of mid-Norway in order to provide observational data for a detailed description of the wind climate at several potential fjord crossing sites. The planned fjord crossings are part of the Norwegian Public Roads Administration (NPRA) Coastal Highway E39-project. The meteorological masts are 50 - 100 m high and located in complex terrain near the shoreline in Halsafjorden, Julsundet and Storfjorden in the Møre og Romsdal county of Norway. Observations of the three-dimensional wind vector are done at 2-4 levels in each mast, with a temporal frequency of 10 Hz. The dataset is corroborated with observed profiles of temperature at two masts, as well as precipitation, atmospheric pressure, relative humidity and dew point at one site. The first masts were erected in 2014 and the measurement campaign will continue to at least 2024. The current paper describes the observational setup and observations of key atmospheric parameters are presented and put in context with observations and climatological normals from a nearby reference weather station. The quality-controlled 10-minute and 10 Hz data as well as other meteorological parameters is publicly available through Arctic Data Centre (https://adc.met.no/datasets/10.21343/z9n1-qw63; Furevik et al., 2019).

1 Introduction

In 2014, the Norwegian Public Roads Administration (NPRA) started an evaluation of the environmental conditions, i.e. wind, atmospheric turbulence, waves and currents, pertaining to making the E39 road 'ferry-free' between Kristiansand and Trondheim on the western coast of Norway. If realised, the project will include new crossings of eight of the largest fjords in Norway. The fjords are typically surrounded by steep mountains going up to 500 m. Fjord widths are 2-7.5 km, and water depths 200-1300 m. This requires a detailed understanding of the wind, wave and ocean current climate at the proposed crossings which is achieved partly through a large atmospheric and oceanographic measurement programme.

In mid-Norway new fjord crossings are planned in Vartdalsfjorden, Sulafjorden and Halsafjorden, as well as in Julsundet. The observational campaign started here in 2014, with a considerable increase in measurement effort in October 2016. The observational programme will continue for at least 8 years, but may be extended to 12 years or more. The program includes tall meteorological masts erected and operated by Kjeller Vindteknikk (KVT) equipped with sonic anemometers observing with a temporal resolution of 10 Hz, at several elevations. The most recent masts are 70-100 m high while the masts erected first have an elevation of ~50 m. A number of wave buoys with meteorological and oceanographic measurements are also installed. The fjord measurement programme is unique in Norway, both in terms of measurement density, parameters measured and the time frame. To the authors knowledge, there has been no other dedicated measurement campaign, providing simultaneous and detailed measurements of both the ocean and the lower atmospheric boundary layer in the complex coastal terrain of western Norway. Oceanographic and atmospheric measurements have typically been carried out independently and during shorter periods, related to e.g. research programmes or industry projects. Ongoing large observation programmes include the LoVE, Lofoten–Vesterålen Cabled Observatory of the shelf marine ecosystem (Godø et al., 2014), the Integrated Carbon Observation System (ICOS)-Norway and Ocean Thematic Centre (OTC) which is an international observation programme of greenhouse gasses (Steinhoff et al. 2019), and the Nansen Legacy, a national

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research programme which includes extensive observations in the northern Barents Sea and Arctic Ocean (Reigstad et al., 2019). The Norwegian Meteorological Institute (MET Norway) operates a national network of meteorological stations (observational data typically freely available) in the region of the E39 campaign. The NPRA and the National Coastal Administration (NCA) operate meteorological stations in connection with infrastructure and road safety/operations, but wind measurements from these stations may be strongly affected by obstacles and local terrain features. The Frøya meteorological mast recorded ocean wind conditions to form the basis for the NORSOK standard (Andersen and Løvseth, 1995, 2006; Standard Norge, 2017).

From a scientific standpoint, the measurement campaign provides an excellent platform to study the multi-scale variability in boundary-layer flow in complex terrain, and the variation of local flow with regard to the synoptic flow aloft, as previously studied by Jonassen et al. (2011) for southern Norway. The current campaign has already provided unique observations of extreme winds and storms in complex terrain, but here the relevant topographic forcing is typically at a smaller scale than has been studied in many large field campaigns in and near the North Atlantic (e.g. the Norwegian IPY-Thorpex (Kristjánsson et al., 2011) and the Greenland Flow Distortion Experiment (Renfrew et al., 2008)). The boundary layer flow in this part of Norway is to a first order governed by a large scale orographic forcing on the mesoscale and synoptic flow, i.e. due to the high mountains of southern and western Norway. The boundary layer flow may decouple from the flow aloft while the local variability near the surface occurs on scales on the order of a few kilometres, as the flow is for example accelerated along steep mountain slopes and narrow fjords, or stagnates in blocked flow in deep valleys, i.e. in terrain typical for the locations of the masts in the campaign. From a more pragmatic and engineering point of view, the observational data set provides invaluable data describing the atmospheric forcing, both climatic and short-term, pertaining to the technical design of large structures in complex terrain. The wind and turbulence data has already highlighted that for such large structures as are planned, the spatial variability in the flow must be properly accounted for and described.

The objective of the present paper is to provide documentation of the atmospheric part of the E39 dataset and the data handling process. The measurement programme is ongoing and the description given here is valid at the time of publication. The paper is structured as follows. Section 2 describes the setup of the observation system, including mast details, the data quality control and an overview of data availability. Access to the data is open, and handled through a new procedure at MET Norway, which is described in section 3. Section 4 presents observations of selected variables to illustrate available parameters and the data quality, and puts the data in context with the regional climate. A summary is given in section 5.

2 Setup of the observation system

As of December 2019, the observational dataset includes observations from 11 tall masts in three main regions of interest in Møre and Romsdal county in western Norway (Fig. 1). All the masts are operational except one which has been dismantled. Most masts are expected to be operational for at least 8 years, with more details on their setup given below. The masts are located in a region characterized with a relatively complex orography, e.g. narrow and deep fjords, surrounded by steep and high mountains. The conditions are more challenging in the Storfjorden region (region S in Fig. 1), where the brunt of the campaign is focussed, than in the Julsundet and Halsafjorden regions (J and H in Fig. 1). Further details on the setup and conditions at individual masts is given below. Long-term reference surface weather stations, operated by MET Norway, are found within approx. 20 km of each of the main region of interests. Two of these are located in flat terrain at airports, with upper-air observations while the third is a located on the small island of Ona. The nearest upper air observations are made ~240 km to the northeast, at Ørlandet (not shown).

The main focus of the measurement campaign is to collect climatic data on the atmospheric and oceanic conditions at possible fjord crossings, pertaining to the dimensioning and design of very long connections (bridge or other). In this aspect, wind is the most important atmospheric variable. The main parameters of relevance can be split into two sets: a) mean quantities which can be described by e.g. the 10-minute mean wind, i.e. the wind speed and direction distribution, return levels of extreme winds and the vertical wind profile. b) turbulence quantities which must be described using observations with a high temporal frequency, e.g. turbulence intensities, the spectral energy density and coherent variations of the turbulence at two locations separated by short distance. Furthermore, the measurement campaign is corroborated by observations from buoys and LIDARs (not yet documented), as well long datasets with high-resolution simulations of weather with mesoscale numerical weather prediction and CFD models (not presented here).

2.1 Masts and instrumentation

A summary of the key parameters for the masts are presented in Table 1, including geographical position, measurement period, base level height and measurement heights. The masts are built and operated by Kjeller Vindteknikk (KVT) for NPRA. Observations of wind are made at 2 - 4 levels in each of the masts, while several other atmospheric variables are observed at three sites. Observations are ongoing at all masts, except at Midsund which was dismantled in March 2019. The masts are guyed lattice towers (Storfjorden) and tubular masts (Julsundet and Halsafjorden), except at Kårsteinen, Langeneset and Nautneset which are self-supporting lattice masts. Nautneset has previously been instrumented with an accelerometer to verify that the swinging motion of the self-supporting masts has a negligible impact on the intended use of the wind measurements (Tallhaug, 2017).

The three wind components are recorded using three-axial ultrasonic anemometers (Gill WindMaster Pro) which is logging at 20 Hz. The data is subsequently averaged to a temporal resolution of 10 Hz to minimise aliasing. The anemometers are located on 2 - 6 m long horizontal booms, with the boom directions approximately perpendicular to the prevailing wind directions (derived a-priori from mesoscale simulations of wind). The true boom direction, as seen from the mast, is presented in Table 1 (average for all levels). The lowermost sensors at the masts at Julbø, Halsaneset and Midsund are located at ~13 m above ground level and have been found to be too strongly affected by their vicinity to the tree top level. This is to some degree also the case for the lowermost sensor at Åkvik (17 magl). In July 2018 it was known that a software bug was affecting the vertical wind component of instrument produced before October 2015 (Gill Instruments, 2016). This error has been accounted for and only corrected data are made available as a part of the current dataset.

10-minute mean wind data is produced from the 10 Hz wind recordings. Since there is no minimum on the amount of 10 Hz samples used in producing the 10-minute averages, the availability of 10 Hz wind data is slightly lower than of the 10-minute mean wind data. The amount of 10 Hz data used to produce 10-minute data can be deduced by inspection of the available 10 Hz data, showing that more than 99.95 % of the 10-minute samples are based on a 50 % or better 10 Hz availability. A 90 % availability of 10 Hz data is found in 99 - 100 % of the 10-minute samples, depending on station. If a 99 % availability is required then the numbers are 96 - 99 %.

The total uptime for 10-minute mean wind for all sensors and all masts is 98.9%. Data losses are related to sporadic meteorological disturbances (e.g. precipitation), and times of equipment fault. Instrument failures are fixed at the earliest convenience, with highest priority given to having operational sensors at the top of the masts.

The stations Kvitneset_Temp and KvitnesetKlima are located in the same masts as Kvitneset. Kvitneset_Temp has inter-calibrated temperature sensors (PT100 from Campbell Scientific) at the same levels as the wind sensors, with a sampling rate of 0.2 Hz. KvitnesetKlima has measurements (1 Hz sampling rate) of temperature, dew point temperature, relative humidity and air pressure at 9 m above ground level (not corrected to mean sea level). Temperature measurements at 0.2 Hz (similar as at Kvitneset_Temp) are also done at four levels in the Trælbodneset mast, i.e. at the three levels with wind sensors as well as at 3 m above ground level (here named as Trælbodneset_temp). A Geonor T-200B precipitation gauge is installed at Brandal (cf. Fig. 2).

Storfjorden

Storfjorden is the name of the fjord system, which is divided into Sulafjorden, Hjørundfjorden and Vartdalsfjorden in addition to several other extensions further inland (Fig. 2). Sulafjorden is located approximately 10 km southwest from Ålesund between the islands Hareidlandet in the west and Sula in the east. The fjord is aligned along a south-southeast north-

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northwest axis, and it is ~12 km long from the mainland to the island Godøy and 3-6 km wide. Hareidlandet and Sula have steep mountains and their upper levels have an elevation of 500 – 700 m asl. In the south, Sulafjorden connects to Vartdalsfjorden, a long narrow fjord, which runs perpendicular to Sulafjorden, southwest to northeast. South of Vartdalsfjorden is Ørsta municipality with Sunnmørsalpene, a high and steep mountain region reaching more than 1200 masl. In the northeast, the narrow Hjørundfjorden connects to Storfjorden, running in a southeast - northwest direction. Figure 3 provides terrain profiles at all of the masts while Fig. 4 shows a photograph of Sulafjorden at the location of Kvitneset and Trælbodneset. The largest effort in the measurement campaign of Coastal Highway E39 project in mid-Norway can be found here. An overview of the specific conditions at each mast is given below while details were presented in Haslerud (2019) and references therein.

Sulafjorden

A precipitation station and four tall meteorological masts are located in Sulafjorden. The masts are located near both ends of two possible fjord crossing locations. Kvitneset and Langeneset on the western side and Trælbodneset and Kårsteinen on the eastern side.

The mast at Kvitneset is located on the headland Kvitneset on the northeast corner of Hareidlandet. The headland is a 300 m wide and 200 m long relatively flat area just below steep mountains reaching up more than 500 m over a distance of 1 km in the southwest. Figure 3 shows the terrain profile along a section through the locations at Kvitneset and Trælbodneset, and serves to highlight the steepness and height of the surrounding mountains. The masts are located at 6 m asl, open to the Norwegian Sea in the sector west-northwest to north-northwest. The 10-minute wind data availability is near 100 % for all sensors. There was sporadic loss of 10 Hz data before July 2017 and in March 2019 due to technical issues. The data availability for the other atmospheric variables is near 100% until December 2018 when it is 0.1-0.9% lower.

A precipitation station was put in operation in March 2018, in the village Brandal between Kvitneset and Langeneset. Due to a fault, precipitation was not registered the last 10 days of August 2018.

The Langeneset mast is located to the south in Sulafjorden (i.e. inward) from the mast at Kvitneset. It is mounted in a 100 m wide industrial area, with a very steep mountain side (cf. Fig. 3). The slope is partly covered with an open forest and there are low buildings in the industrial area. Due to sporadic losses and mast downtime in the summer of 2017 data acquisition over the first year was 94.6%. For 2018 and onwards the data availability is good (100 %).

The mast at Trælbodneset is located at 12 m asl, on a small headland on the western side of the island Sula, with view to the open sea towards the westnorthwest. Towards the east, a mountain rises 450 m over a distance of 1 km (Fig. 3). The vegetation is relatively sparse at the mast and along the coast, while the mountainside has open forest. The 10-minute availability is 99-100% but the top sensor had a slightly later start than the other sensors (16 January 2018). The overall availability of 10 Hz data is good, with a somewhat reduced availability during some winter months. The 10-minute availability of the temperature sensors in the masts is near 100 % the first two years, then 92.1 and 97.2% in 2019 and 2020.

The mast at Kårsteinen is also located on a small headland with a steep mountain rising to 660 m in the northeastern quadrant (Fig. 2). The mast is located near the opening of Sulafjorden into Vartdalsfjorden. Due to defect hardware, the availability was poor during the first few months of operation, but it is near 100% after February 2018. The availability of 10 hz data is generally good, but relatively low in September 2018.

Vartdalsfjorden

The mast at Rjåneset is located at the tip of a small peninsula, just west of the settlement at Grøvika, on the southeastern shore of Vartdalsfjorden. There is a mountain rising to 1035 m a few kilometers to the east (Fig. 3), with steep mountainsides in the sector from north - northeast to east. The headland has some trees and the mountainside is forested. There are some low islands a couple of kilometres to the south and southeast. There are steep mountains across the fjord to the north and west, while the fjord is more open to the southwest where it meets Rovdefjorden and Voldsfjorden. The availability of 10-

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minute data from the top-most sensor is close to 100 % for the whole measurement period, while due to hardware issues, some data were lost for all sensors during September - November 2018, and after April 2019. The availability of the 10 Hz raw data is generally good, with sporadic losses during summer and slightly increase in the losses during late autumn for both years (2018 and 2019).

Hjørundfjorden

The mast at Gjeveneset is relatively low compared to the other masts, and is located at a potential building site for floating bridge components. Gjeveneset mast is situated at the inlet of Hjørundfjorden at 3 m asl just by the sea, southwest of Hundeidvik, where the fjord opens up towards the north before meeting Storfjorden (Fig. 2). The mast is facing the fjord in the sector south-southeast over west to north, and the land is fairly open towards northeast with spread buildings within a few hundred metres. In the east, open terrain slopes gently up to 20 m over a distance of 200 m and then more steeply up to above 600 m over a distance of 600 m. On both sides of the fjord, steep mountains raise up to more than 1000 m asl. The headland has areas of trees and the mountain side is covered by forest. Data availability from the mast was just over 90% in 2019 due to a hardware failure in the spring. In 2018 and 2020 the availability was good (100%).

Julsundet

Julsundet is the sound that connects Molde and Fræna municipality on the southeast side and the island municipalities Midsund and Aukra on the northwest side. Julsundet is approximately 17 km long and runs in a north-south direction. On the south side, the sound opens into Moldefjorden, and on the north side into Harøyfjorden. A bridge is planned in the narrowmost part of the sound, where the width is 2.5 km and mountains reach up to 500 – 600 m on both sides, as seen in Fig. 5 and Fig. 6. Two masts, Midsund (dismantled in spring 2019) and Nautneset, are placed on the western side and one, Julbø, on the eastern side of Julsundet (Fig. 5). The masts at Midsund and Nautneset are only separated by a horizontal distance of ~100 m and have sensors at the same height over mean sea level as well as the same height over ground level. More details are given in Eriksen (2019), and references therein.

Julbø mast is placed on a low headland reaching fairly far into the sound. The topography on the headland goes up to 8m while the mast is located at 4 masl. There are a few trees and a small cliff down to the sea on the southwest side. The monthly 10-minute data availability is near 100% except during periods associated with technical failures in May, July, November and December 2014, March and July 2017. The 10 hz data availability is generally good, with greater loss during the previously mentioned months.

The Midsund mast was mounted on the west side of the sound, on the Nautneset headland. The headland is forest covered and reaches roughly 300 m into the sound. The topography at the headland reaches up to 50 m with steep cliffs up from the sea. To the west of the headland the terrain rises steeply to 600 m. The mast was mounted 100 m from the outer headland at 24 m asl. The monthly 10-minute data availability is 99 - 100% and the 10 Hz availability typically high, except during periods associated with technical failures in March and August 2014, May and July 2017, as well as June 2018. The Nautneset mast is placed on the harbour about 100 m east of the location of the Midsund mast. The mast has free sight from north (360°) over east to south (180°). In the west the topography rises steeply to Midsund mast and further towards the mountains. In November 2016 - January 2017 the two topmost sensors were out due to a lightning strike, but the lowermost sensor operated normally, and in March 2019 a technical failure caused loss of data. Apart from this, the data availability has been close to 100%.

Halsafjorden

The Halsafjorden fjord runs in a southeast - northwest direction from Todalen in the south, towards the island Tustna (Fig. 7). The fjord is roughly 2.5 km wide at the planned bridge location. The terrain reaches up to 200 – 500 m asl on both sides and the sides are covered by forest (Fig. 7 and Fig. 8). A mast is placed at Halsaneset on the western side and another, Åkvik, is placed on the eastern side of the fjord. More details are given in Eriksen (2019), and references therein.

Halsaneset mast is mounted 10 masl, at tip of the headland Halsaneset which reaches 500 m out into Halsafjorden. There are two small, forested hills (15 and 40 m) on the headland, while the tip of the headland is more sparsely vegetated.

The Åkvik mast is mounted at 6 masl on the tip of a 200 m wide and 500 m long and forest covered headland, Orneset, on the eastern side of Halsafjorden. The headland is about 80 m high at the farm Haugen and slopes gradually towards the tip while the southern side of the headland is steep. Both masts have a high annual data-availability of 99.8-100% for 2016-2020.

3 Data handling and Quality

Monthly data files are available from Arctic Data Centre (ADC) (adc.met.no) https://doi.org/10.21343/z9n1-qw63. They are registered as a data collection, as it is a dynamic data set which is growing in time.

Data from the sites is handled as follows. Observational data is transmitted in near-realtime to KVT, with a temporary backup locally in the mast loggers. Data is processed and quality checked on an hourly basis at KVT. The operational filtering of the 10 Hz wind data includes identifying and removing noise and data spikes in the dataset, as well as locked values, i.e. repeated and identical measurement values for the three wind components. As the mast measurements are ongoing and instruments may need replacing, the filtering process is monitored and improved when the need arises. During the filtering, the observed wind direction is rotated towards correct north, and 10-minute means are produced from the 10 Hz wind data.

The resulting files for both 10 Hz and 10-minute sampling are sent to a virtual server belonging to MET Norway via sftp as soon as they are ready. MET Norway performs an additional quality control on the data and to track any delays in the data stream. Data from the masts are published as open access on http://thredds.met.no. THREDDS (Thematic Real-time Environmental Distributed Data Services) is a web server that provides metadata and data access for scientific datasets, using a variety of remote data access protocols such as OPeNDAP (Open-source Project for a Network Data Access Protocol). Due to the high data amount for the 10 Hz data, the 10-minute data are stored in separate netCDF-files. Both type of files include wind speed, wind direction and vertical wind speed. Wind speed is the average of the 10-minute of 10 Hz data previous to the time stamp.

Precipitation data from Brandal station is available on the API (Application Programming Interface) frost.met.no with station number 59570.

The long term automatic weather station Ona II (an island station just of the coast, Fig. 1) is used as a reference station for the wind and temperature measurements. Ona II is operated by MET Norway and data are available from the open data API frost.met.no. Wind speed and direction from an 18 years climatological period from 2001.04.01 to 2019.03.31 are presented here. The meteorological station Ålesund (Nørve, no. 60945) has been operational since 2009 and is used as a reference for precipitation.

4 Wind climate and data overview during observation period

Climatologically at Ona, the median wind speed varies from 8-9 ms^{-1} with the highest recorded wind speeds of in December and January down to 5-6 ms^{-1} during July and August (Fig. 9). Winds above 30 ms^{-1} are recorded in September to December. Since the fjord crossings are separate projects with different timelines and since permits for mounting the masts are granted separately, all the masts were erected at different times from 11 February 2014 in Julsundet to 14 March 2018 in Hjørundfjord. Using a 3-year period from Ona II, 1 April 2016 to 31 March 2019, to represent the period with fjord measurements the wind climate during measurement period has been slightly calmer during the measurement period than usual (fig. 10 top left). The median and 75th percentiles of February, July and November is lower than normal and there has been no recordings of wind speed above 30 ms^{-1}.

At the 11 stations (Table 2), the lowest median wind speed is found in the inner part of Sulafjorden at Langeneset (2.95 ms^{-1}) and Kårsteinen (2.39 ms^{-1}) while median wind speed above 5 ms^{-1} are recorded in Julbø (5.15 ms^{-1}), Kvitneset (5.03 ms^{-1}), and Rjåneset (5.04 ms^{-1}). The highest 99th percentile data are found in the inner part of the fjords (Gjeveneset and Rjåneset) in spite of their lower measurement heights. The 99th percentile data for the, separately, upwards and downwards, oriented vertical winds, indicates that the strong vertical gusts are often found at the stations in Sulafjorden as well as at Nautneset, compared to at the other stations, especially at the stations in Halsafjorden.

The wind speed shows a clear seasonal variation at the Ona reference station and most of the masts, except Trælbodneset, Kårsteinen, Gjeveneset and Rjåneset (Fig. 9 and Fig. 10). Here, the time series are short, and the statistics more unreliable. From these plots, the stronger wind climate is found in Julsundet and at Kvitneset in Sulafjorden, but episodically the winds in the fjords are stronger, as seen in Table 2.

The wind roses from Ona (Fig. 9 and top left in Fig. 10) for the climatological period of 18 years as well as for a 3 year period overlapping with the mast observations, shows that winds are most frequent and strongest from the southwest and the northeast, following the general orientation of the coast. The wind roses (Figure 11) for the 11 stations indicate flow which is strongly affected by the local terrain. Southerly winds (winds blowing towards the sea) are frequent at all stations, and dominant at Julsundet, Halsafjord, Trælbodneset, Gjeveneset and Rjåneset. The strongest winds are also typically associated with southerly flow.

The monthly temperature, observed at the top most sensor in the Kvitneset mast is shown in Fig. 12, in addition to temperature observations from the Ona II reference station. There are on average small differences between the monthly temperature at both sites, with most notable difference being that the maximum temperature is typically 1-3°C higher at Kvitneset than at Ona. The observed mean monthly temperatures are also quite similar to the climatological mean from the 18 years climatological period at Ona II. The most notable differences are that April, July and November 2018, as well as 2019 were 1-2°C warmer than average, while March 2019 was ~2°C colder.

Brandal station located in Sulafjorden reveals much higher precipitation than what is recorded at Nørve, both when comparing to the climatology based on 10 years but also within the same year (Fig. 13). This may be related to the proximity to the steep and high mountains at Brandal, stronger forced uplift during northerly flow and more spillover during southerly flow.

Masts on both sides of the fjords allow for investigation of the simultaneous differences in the wind field on each side of the fjord. An example is given in the wind variation across Halsafjorden is shown in Fig. 14. The mean wind speed is stronger at Åkvik than at Halsaneset for all wind directions except for winds from the south. The strongest winds observed at the masts are observed at Halsaneset during southerly winds, while winds are strongest at Åkvik during northwesterly flow.

As the full 3-dimensional wind vector is observed with a temporal frequency of 10 Hz, the turbulence spectra can be estimated. An example is given in Fig. 15, based on 20-minute period preceding 14 UTC on 1 January 2019 during a northerly storm at the Julbø mast, and shows the power spectral density for the along flow component of the turbulence. The horizontal wind vector has previously been rotated along the mean wind direction and the linearly detrended to ensure the stationarity of the wind data. The spectral density is calculated using a fast Fourier transformation, implemented in periodogram-method in a standard signal processing package in python. The analyzed spectra has a similar slope as indicated by the -5/3 power law for turbulence spectra.

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5 Data availability

The data are available on the MET Norway API frost.met.no (precipitation measurements at Brandal II with station number 59570) and from ADC at https://adc.met.no/datasets/10.21343/z9n1-qw63 (Furevik et al., 2019).

The data on ADC are posted as a file for the raw data (10 Hz) and a file for the 10-minute mean wind speed for each mast every month. Each file contain data from the different heights at the specific mast, including self-describing metadata, such as geographical location and sensor heights. Temperature at different heights is also posted for each month for each mast (Kvitneset and Trælbodneset) where it is available (files of type temp_0p2hz). Additional meteorological data from the weather mast at Kvitneset,i.e. tMetpack_1hz (temperature), prsMetpack_1hz (air pressure), dewpointMetpack_1hz (dew point temperature), RHMetpack_1hz (relative humidity) are posted in files with KvitnesetKlima in the file name.

6 Summary

A unique and large atmospheric and oceanic dataset is presently being built, in connection with several planned fjord crossings in the Coastal Highway E39 - project of the NPRA. The atmospheric part of this measurement programme includes wind observations in 11 tall masts in the three different fjord systems of Mid-Norway started in 2014 and is presently ongoing. The overall data return is 98.9 %. The data collection is described, including a short summary of the geography at the sites. Examples of observed parameters are presented and put in context with observations and climatology from reference weather stations. The examples illustrate the quality, but also a strong influence of the steep terrain on the wind measurements from these land-based masts. In addition to local design and planning of infrastructure, the data collection is useful for investigation of flow in complex terrain, and for verification of numerical modelling in that respect. In combination with remote sensing and oceanographic data from the buoys, it offers a solid basis for the study of a fjord system over at least a decade. The data collection may furthermore be useful for the industry or in other fields of research, where wind climate is of importance.

Author contributions. B. R. Furevik is responsible for publication of the data set and writing of the manuscript together with H. Ágústson. H. Ágústson is responsible for quality control and processing of files into netCDF-format and transfer to MET Norway. A. L. Borg is responsible for futher quality control of files, aggregation into monthly files and posting to the repository. B.R. Furevik, H. Ágústson and Z. Midjiyawa made the analyses. F. Nyhammer is responsible for deployment and maintainance of the masts and instrumentation. M. Gausen is in charge of the measurement campaign for the Coastal Highway E39 project in Mid-Norway.

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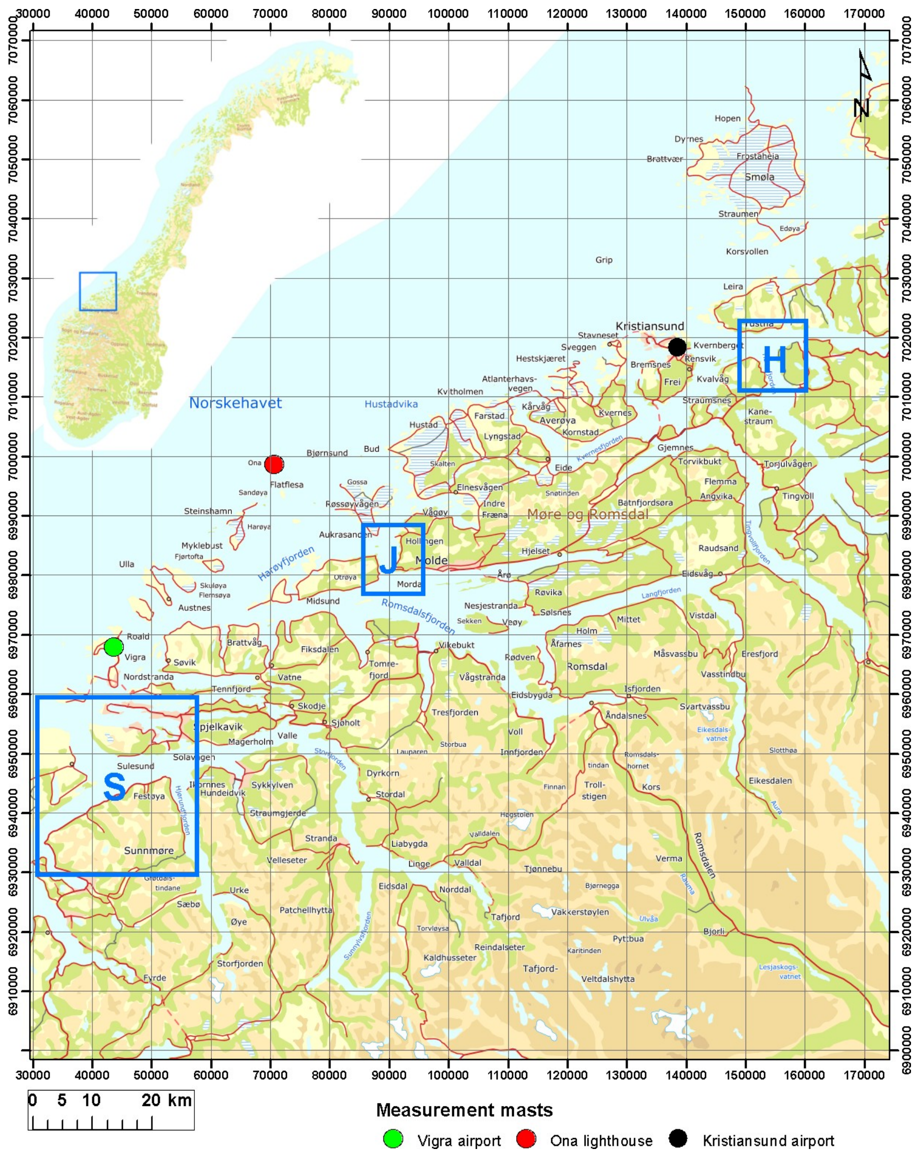

Figure 1. Overview of a part of the Møre and Romsdal region (approximate location shown in the inset) and the location of the three areas where the meteorological masts are located (S, J and H). The locations of three national weather stations with long-term data available, are indicated with coloured circles. Map layers are © Kartverket and licensed under Creative commons version 4.

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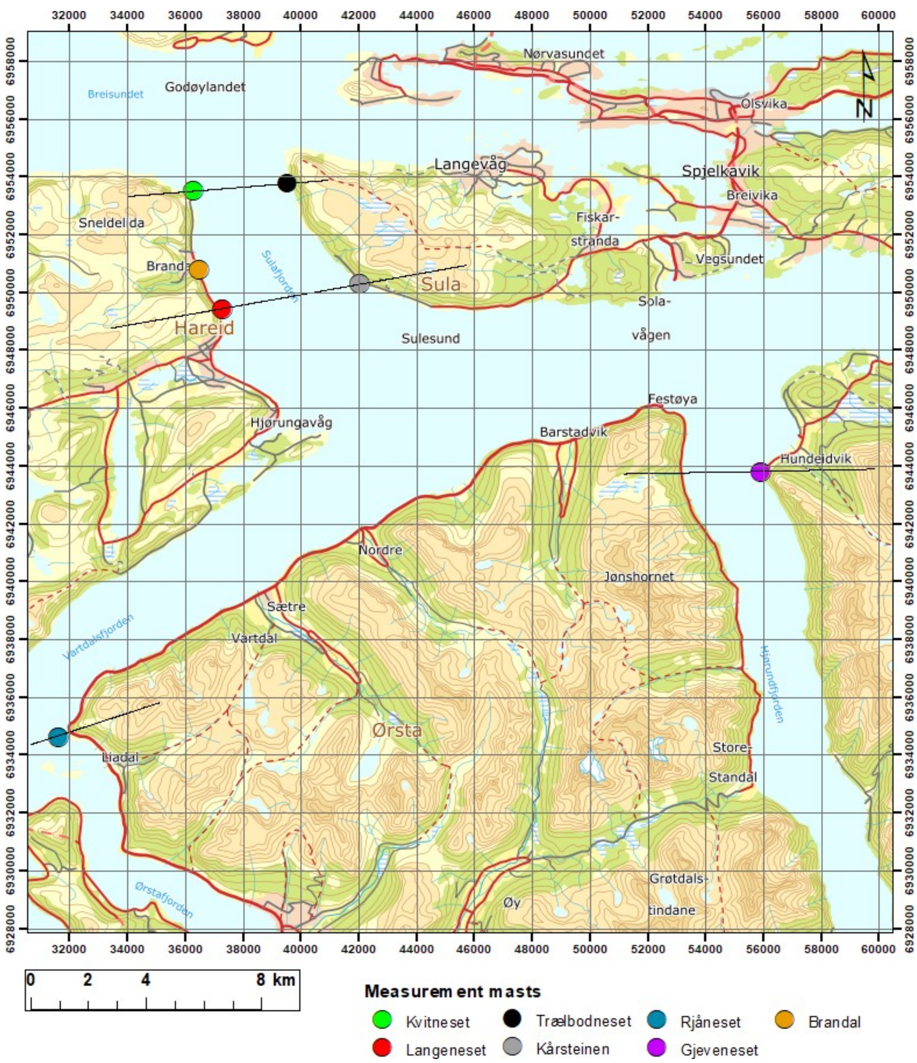

Figure 2. Map of Storfjorden fjord system with location of the seven observational sites and height profiles shown in Fig. 3. Map layers are © Kartverket and licensed under Creative commons version 4.

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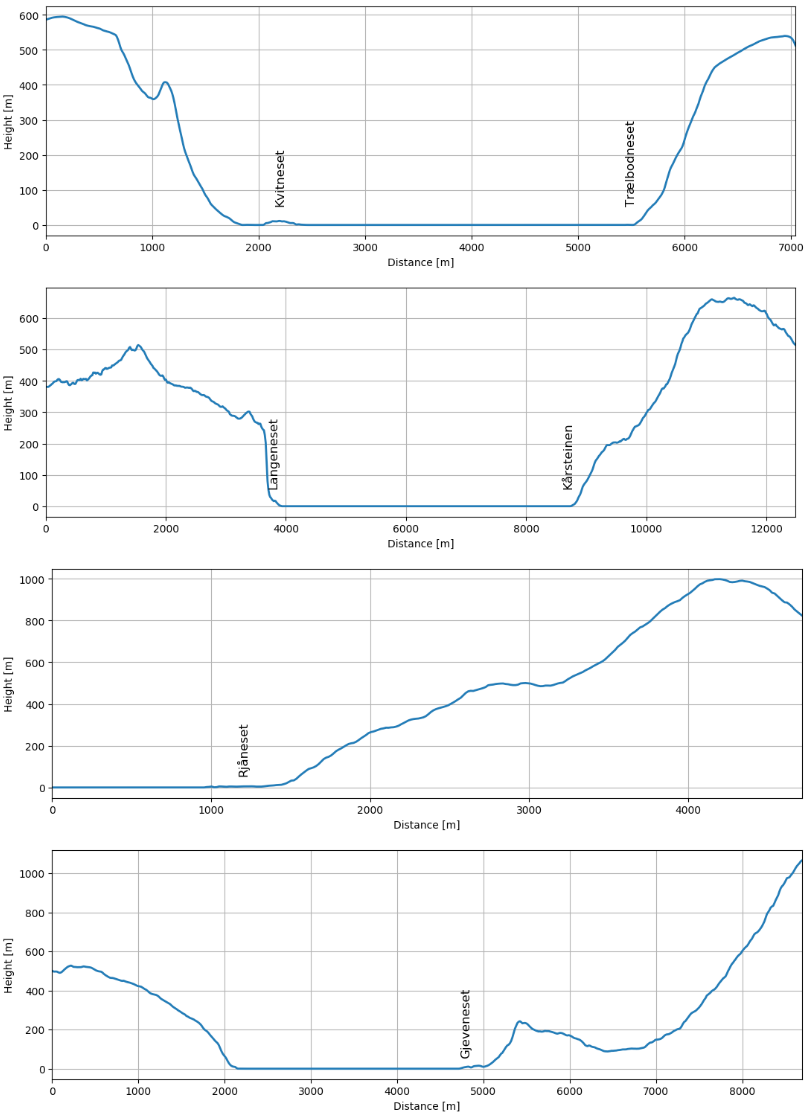

Figure 3. Terrain profiles along the sections indicated in Fig. 2, with the locations of the masts indicated. Terrain data are © Kartverket and licensed under Creative commons version 4.

375 **Figure 4. Sulafjorden with the islands Hareidlandet, Godøy and Sula from left to right. Between Hareidlandet and**
376 **Godøy is Breisundet, which is the main opening of the fjord system to the Norwegian Sea. Photograph taken on 13**
377 **October 2016.**

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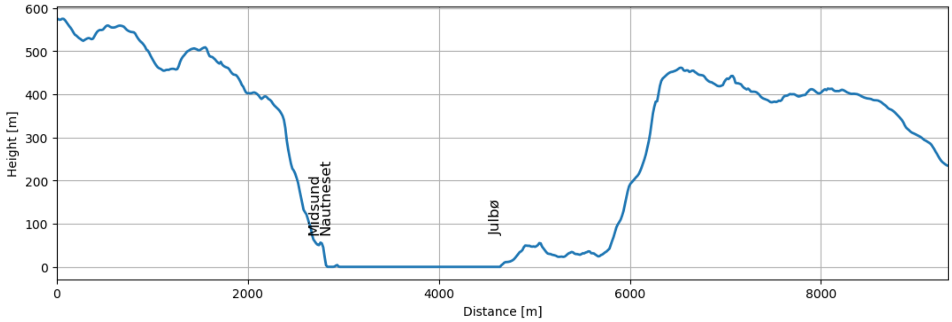
Figure 5. Map of Julsundet with location of meteorological masts and the height profile shown in Fig. 6. Map layers are © Kartverket and licensed under Creative commons version 4.



380 **Figure 6 Terrain profiles along the sections indicated in Fig. 5, with the locations of the masts indicated. Terrain data**
381 **are © Kartverket and licensed under Creative commons version 4.**

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Figure 7. Map of Halsafjorden with location of the meteorological masts, and the height profile shown in Fig. 8. Map layers are © Kartverket and licensed under Creative commons version 4.

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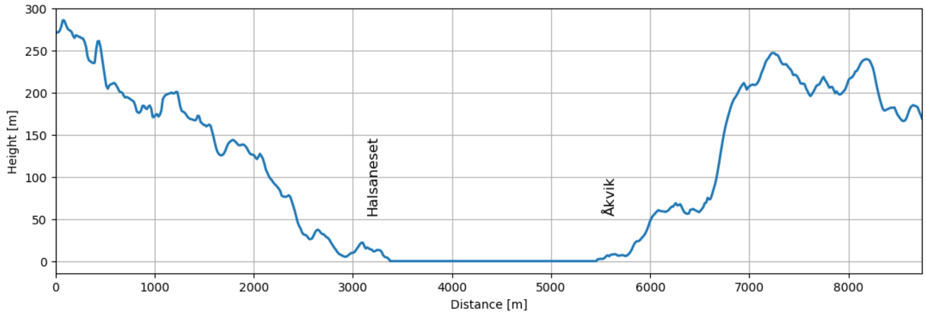

Figure 8 Terrain profiles along the sections indicated in Fig. 7, with the locations of the masts indicated. Terrain data are © Kartverket and licensed under Creative commons version 4.

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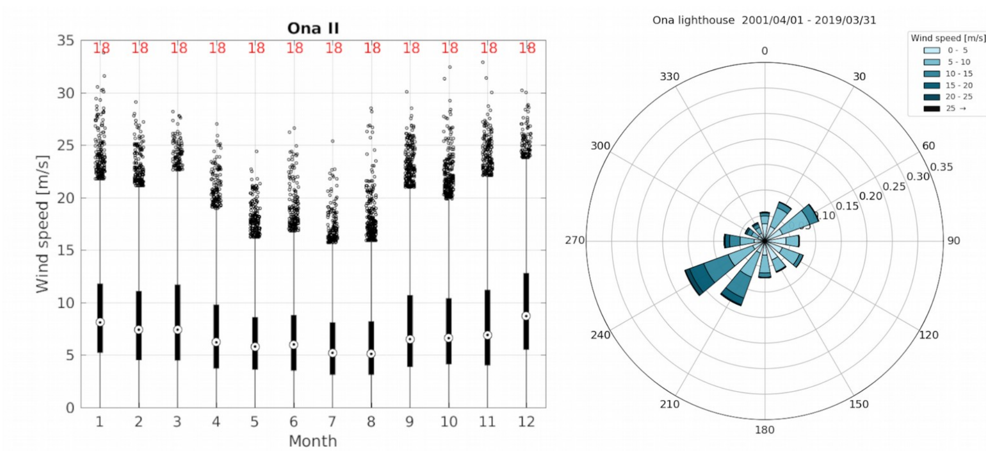

Figure 9. Wind statistics for the 18 year climatological period at Ona II. Left: Box plot of wind speed per month of the year. The boxes in the plots shows the 25/75 percentiles with the median value as a circle inside. The lines above and below (the whiskers) represent 1.5 interquartile range from the box. Values beyond this are plotted as dots above each line. The red numbers above each month, show the number of full months used to produce each box. Right: Wind rose showing the wind speed and direction distribution. The length and direction of the bar shows the directional distribution of the wind speed while the colour scale shows the wind speed distribution.

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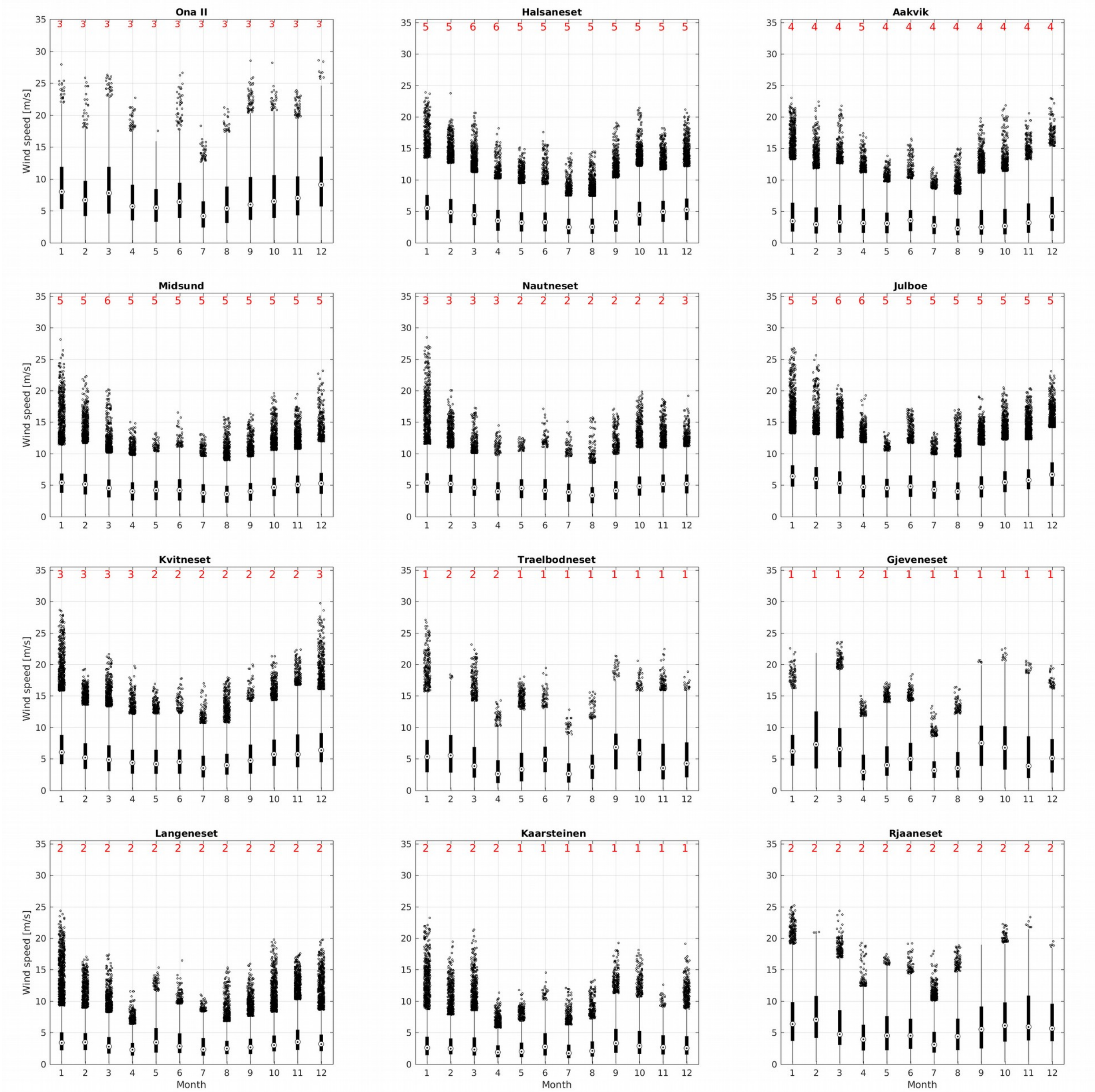

Figure 10. Box plots of wind speed per month of the year over three years from Ona II (reference station) and all available data the uppermost sensor on the 11 masts. The time periods for each panel are found in the corresponding panel in Fig. 11.

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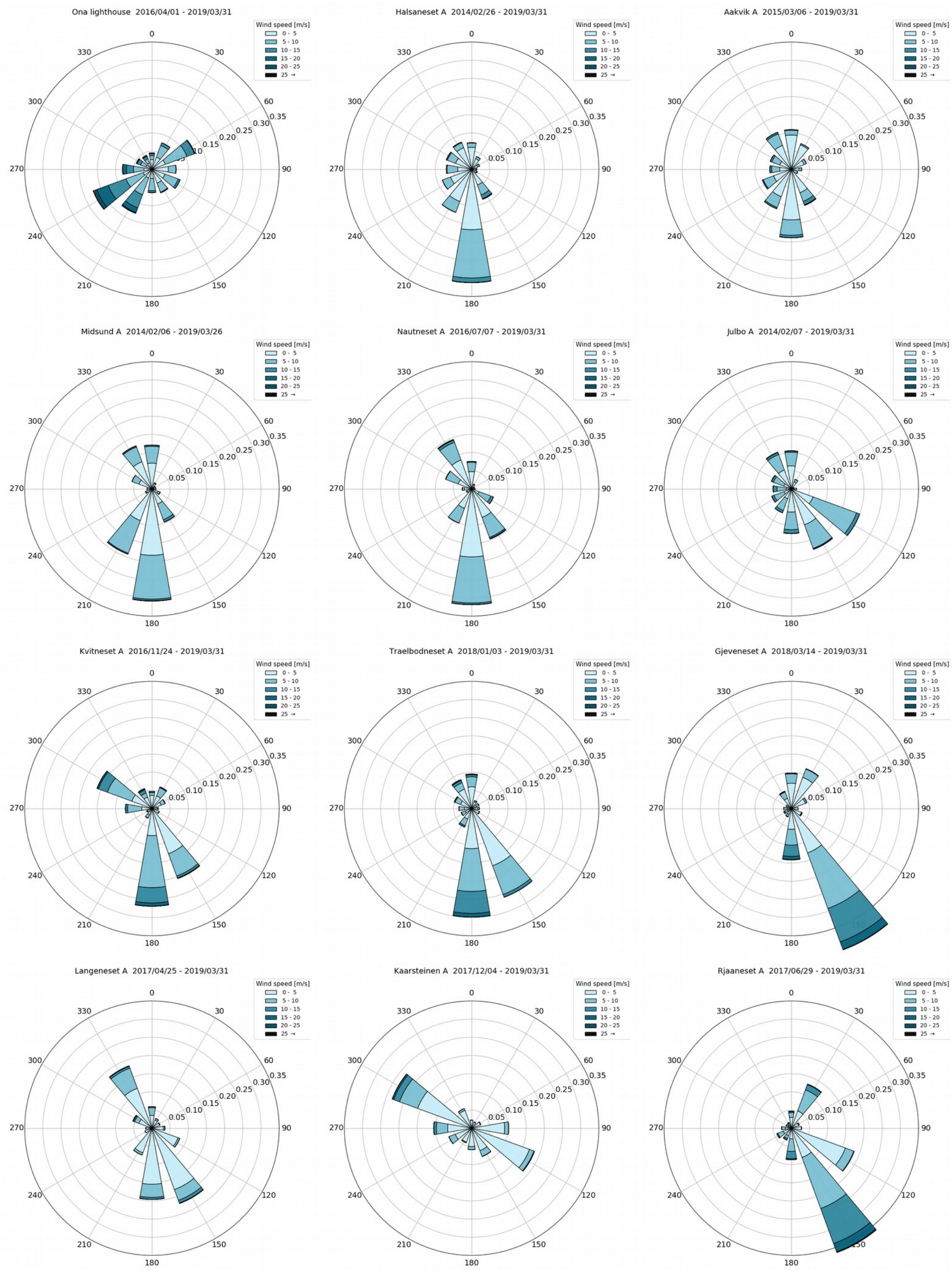

Figure 11. Wind roses showing the wind speed and direction distribution over three years from Ona II (reference station) and all available data from the uppermost sensor on the 11 masts.

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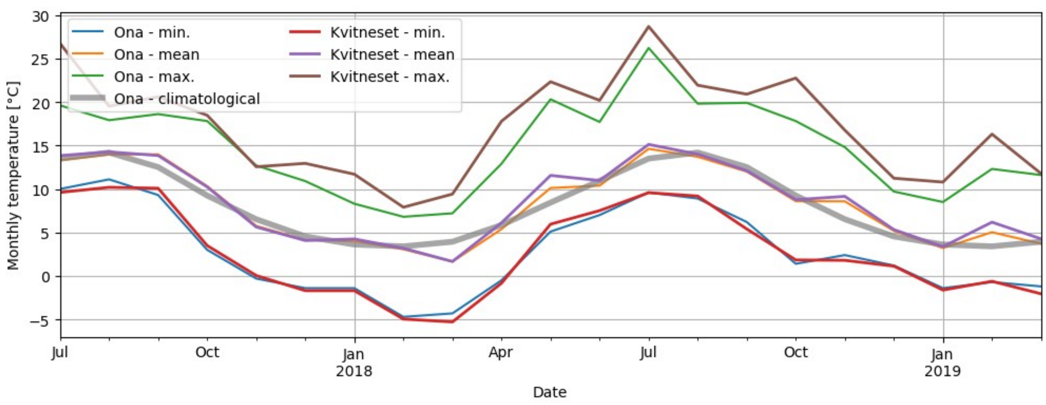

397 **Figure 12. Monthly mean, maximum and minimum temperature at top of Kvitneset mast and at the Ona reference**
398 **meteorological station. Also shown is the climatological temperature (thick gray line) at Ona, for the 18 year period.**

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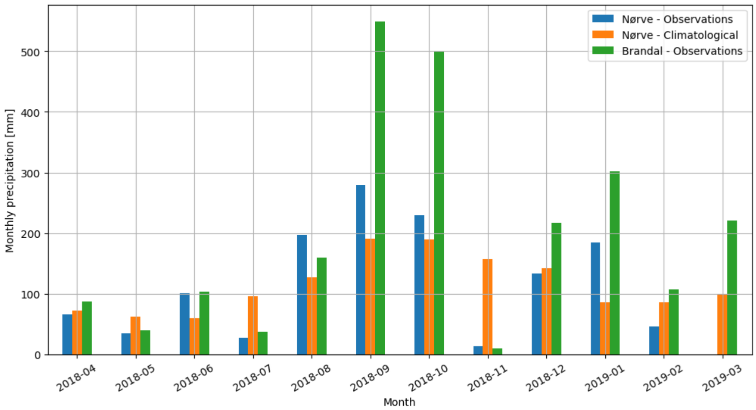

Figure 13. Monthly measured precipitation at Brandal (green), compared to the same period (blue) and climatology for 2009 - 2019 (orange) at the reference station Nørve in Ålesund.

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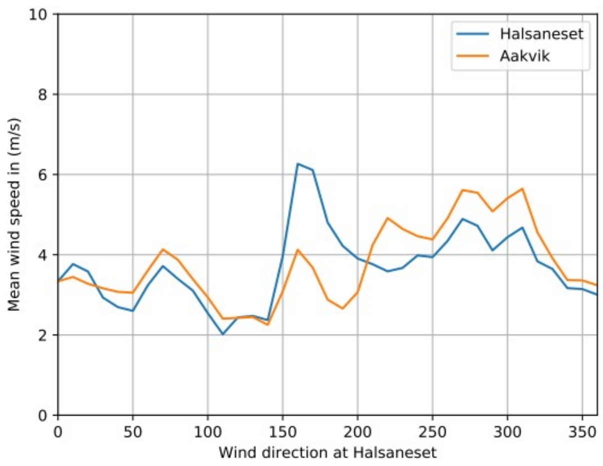

401 **Figure 14. Wind speed variation at Halsaneset and Åkvik in Halsafjorden, as a function of wind direction at**
402 **Halsaneset on the western side of the fjord. Based on 4 years of data (2016 - 2019).**

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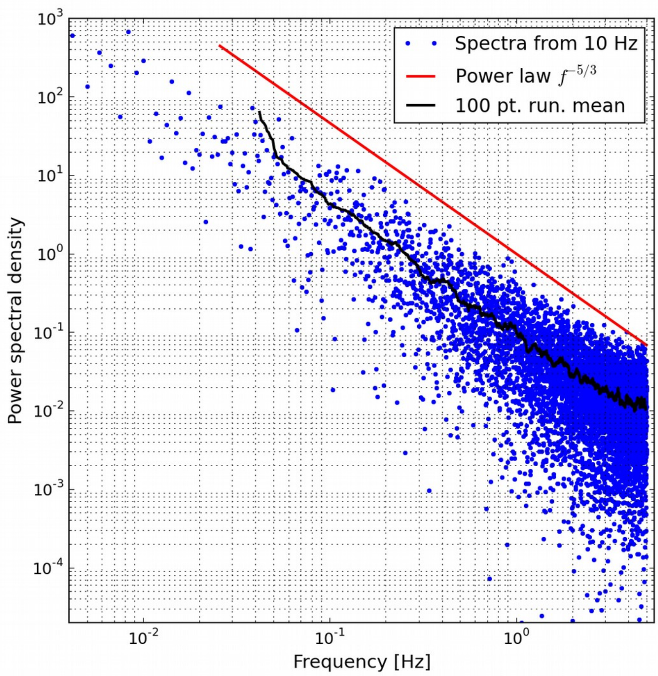

Figure 15. Example of turbulence spectra for the along wind component during a northerly storm with ~25 m/s mean wind at the top sensor of the Julbø mast. The spectra are analysed from the 20-minute period before 14:00 UTC on 1 January 2019.

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Table 1: Overview of key parameters regarding the meteorological measurement sites, grouped by location. Boom direction is given as the true direction as seen from the mast, and can be used for all levels. An empty end date for the observation period implies that the observations are ongoing. Observed variables are wind speed (f) and direction (d), vertical wind speed (w), temperature (t), dew point (td), relative humidity (rh) and atmospheric pressure (prs).

Fjord	Mast	Mast height	Ground level	Coordinates (UTM 32 / WGS84 geographical)	Observation period	Sensor heights [m]	Boom dir.	Var.
Sula-fjorden	Kvitneset	100.5 m	6 m	6924741 N, 345142 E 62.421595° N, 6.00112° E	2016-11-24 -	92.5, 44.5, 71.5	72°	f, d, w
	Kvitneset temperature		6 m	6924741 N, 345142 E 62.421595° N, 6.00112° E		21.0. 44.0, 71.0, 92.0		t
	Kvitneset Klima		6 m	6924741 N, 345142 E 62.421595° N, 6.00112° E	2017-06-27 -	9.0		t, td, rh, prs
	Langeneset	97.0 m	6 m	6920740 N, 346520 E 62.386301° N, 6.031318° E	2017-04-26 -	27.0, 50.0, 75.0, 94.8	80°	f, d, w
	Trælbodneset	78.0 m	14 m	6925267 N, 348347 E 62.42763° N, 6.062626° E	2018-01-03 -	27.3, 48.3, 76.8	289°	f, d, w
	Trælbodneset temperature	78.0 m	14 m	62.42763° N, 6.062626° E		3.0, 30.0, 50.0, 78.0		t
	Kårsteinen	63 m	12 m	6922074 N, 351140 E 62.400201° N, 6.119176° E	2017-12-04 -	13.4, 40.0, 62.8	222°	f, d, w
	Brandal precipitation		27 m	6922033 N, 345589 E	2018-03-15 -	1.5		r
Hjørund-fjorden	Gjeveneset	30 m	3 m	6916898 N, 365563 E 62.359209° N, 6.402158° E	2018-03-14 -	18.5, 29.0	267°	f, d, w
Vartdals-fjorden	Rjåneset	72.0 m	8 m	6905511N, 342274 E 62.248022° N, 5.963142° E	2017-04-28 -	28.8, 51.4, 71.5	278°	f, d, w
Julsundet	Midsund	50m	24m	6957381 N, 394530 E 62.731663° N, 6.936432° E	2014-02-11 - 2019-03-26	31.9, 12.7, 50.3	73°	f, d, w
	Julbø	50 m	4 m	6957730 N, 396210 E 62.735273° N, 6.969062° E	2014-02-14 -	12.7, 31.9, 50.3	233°	f, d, w
	Nautneset	68 m	2 m	6957381 N, 394634 E 62.731693° N, 6.938466° E	2016-11-10 -	32.7, 52.3, 68.3	238°	f, d, w
Halsa-fjorden	Halsaneset	50 m	4 m	6995095 N, 456472 E 63.082697° N, 8.138198° E	2014-02-26 -	12.7, 31.9, 50.3	104°	f, d, w

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	Åkvik	50 m	6 m	6995697 N, 458519 E 63.08834° N, 8.178568° E	2015-03-06 -	17.0, 31.9, 48.3	225°	f, d, w

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Table 2: Main statistics of wind data set at top sensor, including mean, median, maximum wind speed and 99th percentile of wind speed, the maximum gust (3 s), as well as the 99th percentile of the up/down vertical wind gust [ms^{-1}].

Fjord	Mast	Height [m]	Mean wind speed	Median wind speed	Maximum wind speed	99th perc. of wind speed	Max. gust	99th perc. vert. gust
Sulafjorden	Kvitneset	92.5	5.64	5.03	29.70	16.52	37.0	-13.4 / 8.6
	Langeneset	94.8	3.59	2.95	24.34	13.26	37.3	-13.6 / 7.4
	Trælbodneset	76.8	5.01	4.24	27.04	15.97	46.1	-9.2 / 7.1
	Kårsteinen	62.8	3.17	2.39	23.21	12.97	32.1	-8.6 / 6.3
Hjørundfjorden	Gjeveneset	29.0	5.85	4.83	23.55	17.82	43.6	-6.3 / 5.7
Vartdalsfjorden	Rjåneset	71.5	6.04	5.04	25.18	17.34	41.2	-6.8 / 6.3
Julsundet	Midsund	50.3	4.61	4.45	28.15	11.75	40.0	-7.4 / 6.2
	Julbø	50.3	5.47	5.15	26.74	14.14	39.6	-4.8 / 5.0
	Nautneset	68.3	4.80	4.59	28.46	12.83	41.9	-9.0 / 6.1
Halsafjorden	Halsaneset	50.3	4.30	3.91	23.87	12.62	35.1	-5.0 / 4.3
	Åkvik	48.3	3.80	3.03	23.00	12.94	34.4	-3.5 / 4.8