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Analysis of a Low-level Coastal Jet off the Western Coast of Norway

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Abstract

Offshore wind installations depend strongly on an improved knowledge of the atmospheric and ocean conditions affecting the marine atmospheric boundary layer (MABL). In particular the better understanding of atmospheric phenomena that are related to extreme atmospheric and sea state conditions e.g. high levels of wind speed, wind shear, waves and turbulence, is crucially important for offshore applications. This study investigates a low level coastal jet off the Western coast of Norway on 20 March 2011, using both in situ data and model results. The analysis is focused on parameters that are relevant to wind energy such as wind speed, turbulence intensity and wind shear. The jet is characterized by high wind speeds, moderate turbulence intensity and significant high wind shear. Furthermore, the structure and the dynamical characteristics of the low level coastal flow are investigated from the model results. The results show a maximum wind speed, greater than 30 m/s, between 500 to 800 m height above the sea level and at 15-20 km distance from the coast.

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1. Introduction

Due to the high frequency of low pressure systems over Western Norway and the correspondingly high average wind speed, the offshore and coastal waters in this area are in general considered viable for wind energy applications. The complex topography of the region causes however local and regional scale phenomena, such as low level coastal jets (LLCJ) [1], [2], gap winds [3], or land and sea breeze circulations [4] that can affect the harvestable wind potential and load and fatigue of the installations in these areas. The future development of offshore wind applications will strongly benefit from a detailed characterization of such phenomena.

The present study is focused on LLCJ and investigates a corresponding event off the Western coast of Norway on 20 March 2011. The analysis is focused on parameters that are relevant to wind energy, such as wind speed, turbulence intensity and wind shear. Furthermore, the dynamical characteristics and the structure of the LLCJ are investigated using a non-hydrostatic model.

The LLCJs are induced by blocking of winds by coastal mountains. In theory, a well-mixed, moist and cool marine atmospheric boundary layer (MABL) which is capped by an inversion is an essential atmospheric condition that can develop a LLCJ [2], [5], [6]. The maximum peak of wind speed is usually observed between 300 and 700 m above sea level (ASL) [7], [8]. The width of the jet has a typical range of 20 to 40 km and the observed surface winds can exceed the 18 m/s [6]. In addition, the low level jets are also related to intense wind shear which can induce damaging wind-load on offshore structures [9]. Numerical simulations of these mesoscale phenomena over southern Norway have also been studied by Barstad and Gornas [10], presenting ideally constructed southwesterly flows with strong winds along the coast.

2. Atmospheric Parameters

The atmospheric parameters related to wind energy such as turbulence intensity (I in %) and wind shear exponent (α) were calculated for the investigation of the event.

2.1 Turbulence Intensity (I)

The turbulence intensity is a measure of turbulence fluctuation of the wind field. It is strongly connected to the atmospheric stability [11], the shear of wind profiles [12] and has an impact on the wind power generation [13], [14]. It is defined as the standard deviation of horizontal wind speed (σ) divided by the mean horizontal wind speed (U):

$$I = \frac{\sigma}{U} \tag{1}$$

2.2 Wind shear exponent (α)

The wind shear exponent is an important parameter for the design and operation of wind turbines. Studies have shown that the wind power generation is influenced by wind shear [14], [15]. High wind shear is connected to higher power production compare to low wind shear conditions [16]. On the other hand, extreme wind shear has a negative impact on load control and rotor fatigue [17]. The wind power exponent (α) for this study was calculated from wind speeds at 60 and 120 m using the power law [18]:

$$\frac{U_{60}}{U_{120}} = \left(\frac{Z_{60}}{Z_{120}}\right)^{\alpha} \tag{2}$$

where U is horizontal wind speed (m/s) at height Z (m).

3. Case study

3.1 Study area

The area of this LLCJ event is located in the Havsul region off the coast of Western Norway as illustrated in Figure 1. The topography of the area is dominated by high coastal mountains with elevation more than 1000 m over sea level and long, narrow fjords.

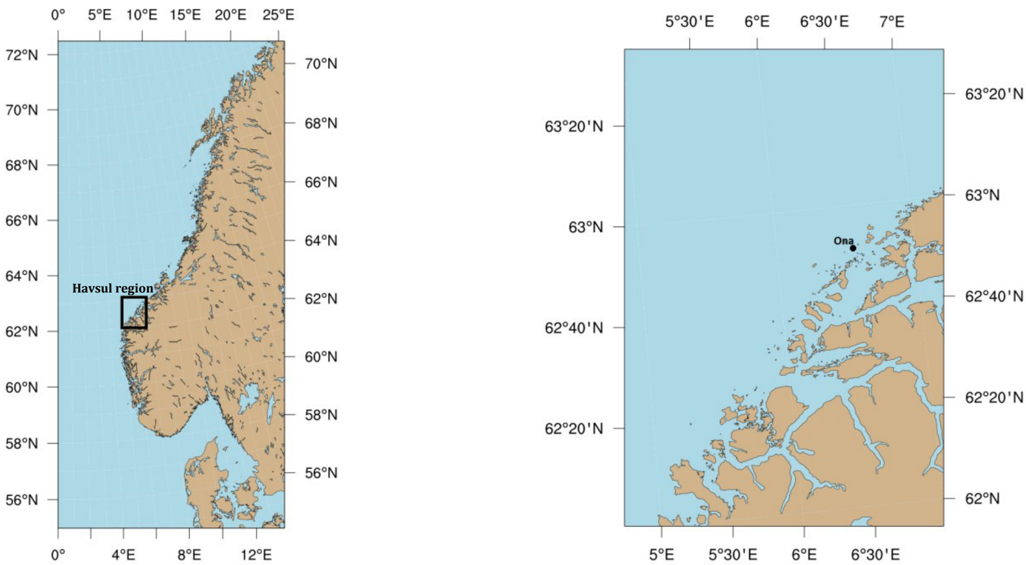
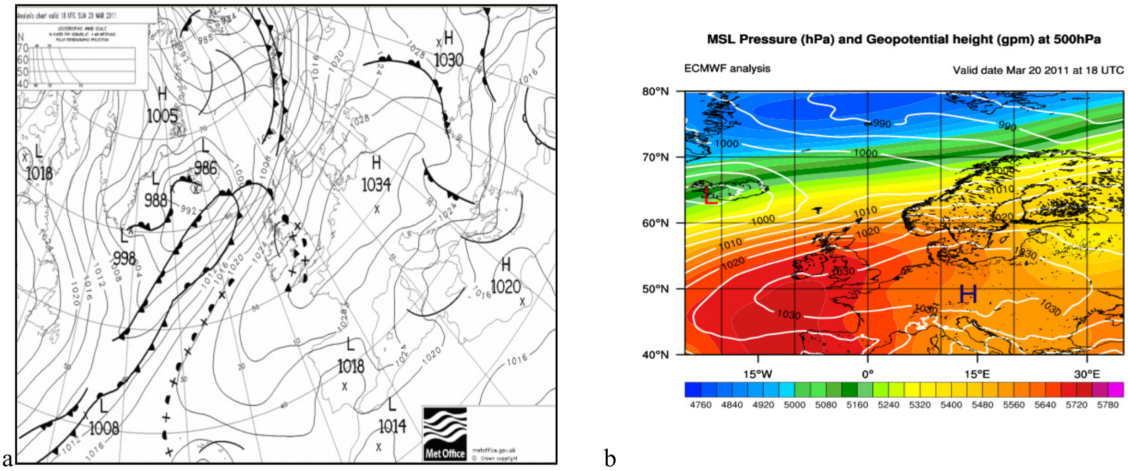


Figure 1. Left: Havsul region (black square) at Western Norway. Right: Location of Ona in the Havsul region.

3.2 Synoptic conditions

The first step of the analysis of LLCJ is the investigation of the synoptic meteorological conditions at the time of LLCJ event. Figure 2 (a) presents the synoptic situation (surface pressure analysis map) on 20 March 2011 at 18:00 UTC. A cold front approached the Norwegian coastline and advected cool and dense air into the area. It was mainly triggered by a widespread upper-level ridge extended from the Western Europe to the Scandinavian region (Figure 2, b). Close to the coast, the distance between the isobars is relatively low, indicating a strong gradient of the sea level pressure which leads to high wind speeds. In addition to the atmospheric conditions, the coastal mountains play an important role for the development of the jet since they channel the air flow parallel to the coastline.



a b

Figure 2. (a) Surface pressure analysis map (mb) on March 20 at 18:00 UTC. The map derived from UK Met office surface analysis archive. (b) Mean Sea Level Pressure (contours in hPa) and geopotential height at 500 hPa (colored shaded in gpm) on March 20 at 18:00 UTC. Data are based on ECMWF operational analysis.

3.3 Data Overview

3.3.1 Satellite Observation

The SAR (Synthetic Aperture Radar) image at 21:00 UTC, 20.03.2011 from the central west Norwegian coast is analyzed in Figure 3 to estimate the surface wind speed using the CMOD4 algorithm [20] and wind direction from High-Resolution Limited Area Model (HIRLAM). The analysis shows clearly the presence of LLCJ with high wind speeds from 14 to 20 m/s close to the coast and a width of the jet of about 30 to 40 km. The analysis also indicates a sharp, only a few kilometers wide, boundary zone which separates the high (14-20 m/s) and low (8-10 m/s) wind speed areas.

3.3.2 Observations at Ona.

Wind data from a meteorological mast were collected during the day of the LLCJ event from March 20 at 00:00 UTC to March 21 at 00:00 UTC at Ona island which is located in the Havsul region (Figure 1, b). The met mast measured wind speed, wind direction and the corresponding standard deviation in 40 m, 50 m and 60 m with cup anemometers. The results of high surface wind speed from SAR analysis are in good agreement with the wind measurements at Ona presented in Figure 4 (a). They show a steady increase in wind speed from 12 m/s to a maximum of 22 m/s at 60 m ASL with a sudden drop to 14 m/s at around 21.30 UTC. Figure 4 (b) illustrates the turbulence intensity (%) during the event of LLCJ, ranging between 5% and 12%, with a mean value of around 7%. These results indicate that the air flow is steady with high wind speeds and moderate fluctuations. During the LLCJ event, the turbulence intensity follows in general the curve of the wind speed with a maximum of both around 18 UTC.

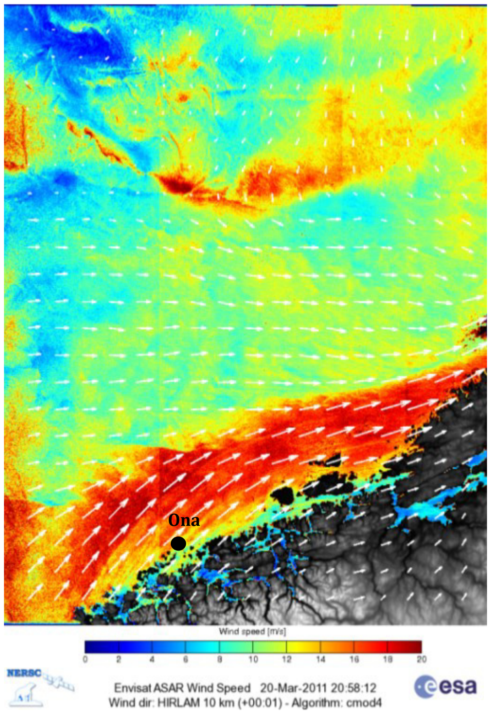


Figure 3. Analysis of the SAR image (ENVISAT ASAR Wideswath) of the coast of Norway obtained on 20 March 2011 [19].

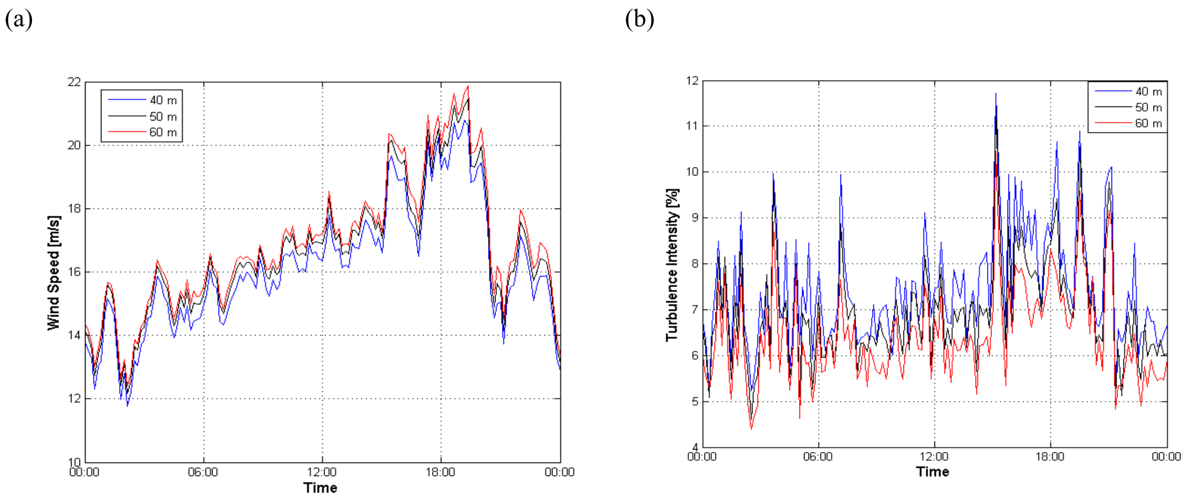


Figure 4. (a) Time series of wind speed (a) and turbulence intensity (b) from March 20 at 00:00 UTC to March 21 at 00:00 UTC at Ona island, [19].

4. Model set up

The Weather Research and Forecast Model (WRF) ARW version 3.5 [21] was used to simulate the LLCJ. In this case study four domains (Figure 5) were used with two way nesting. The parent domain (D1) is covering the Norwegian and North Sea with a horizontal resolution of 9 km. The second domain (D2) has a resolution of 3 km and covers the southwest part of Norway and part of Norwegian and North Sea. The third domain (D3) with 1 km horizontal resolution covers the coastal mountains and the area off the coast of Ålesund. The inner most domain (D4) covering the Havsul region has a resolution of 1/3 km. The data for the initialization was provided by the reanalysis product ERA-Interim from the European Centre for Medium-Range Weather Forecast (ECMWF). The model simulation time was 30 hours, from March 20, 2011 at 00:00 UTC to March 21, 2011 at 06:00 UTC. The basic parameterization schemes used in this simulation are listed in Table 1.

Table 1. Parameterization schemes in WRF used for the LLCJ simulations.

Sub-grid physics	**Parameterization Scheme**
Microphysics	WRF Single-Moment 3-class [22]
Planetary Boundary layer	Yonsei University (YSU) [23]
Surface Layer	MM5 Monin-Obukhov [24]
Land Surface	Unified Noah land-surface model [25]

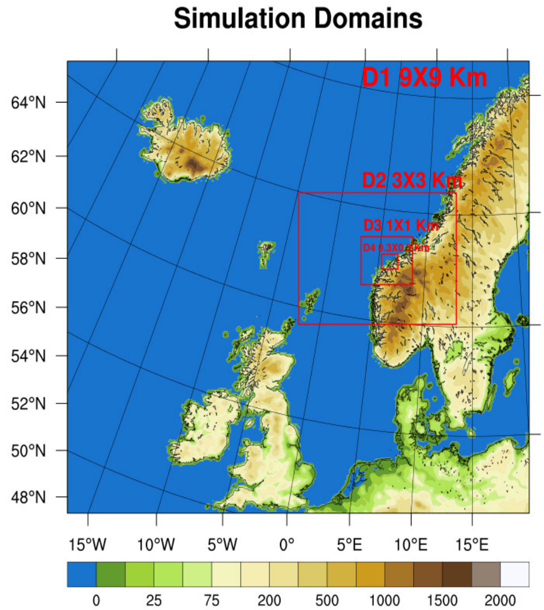


Figure 5. Location of the four model domains with 9km, 3km 1km and 1/3km resolution.

5. Model results

The result of the model simulation for the 10 m wind speed at 21:00 UTC 20.03.2011 is presented in Figure 6 for the four model domains. It illustrates the fully developed LLCJ with wind speeds above 18 m/s close to the coast. The width of the high speed flow is in the range of 30 to 40 km. A sharp transition zone of a few kilometers in width separates the jet from the lower wind speeds in the surrounding. Both the magnitude of the wind speed and the extension of the jet agree well with the SAR analysis presented in Figure 3. Zooming into the Havsul area also shows the existence of band-like structures of higher and lower wind speeds oriented parallel to the coast that seem to be directly connected to the complex topography of the region and creating additional horizontal wind shear in the area.

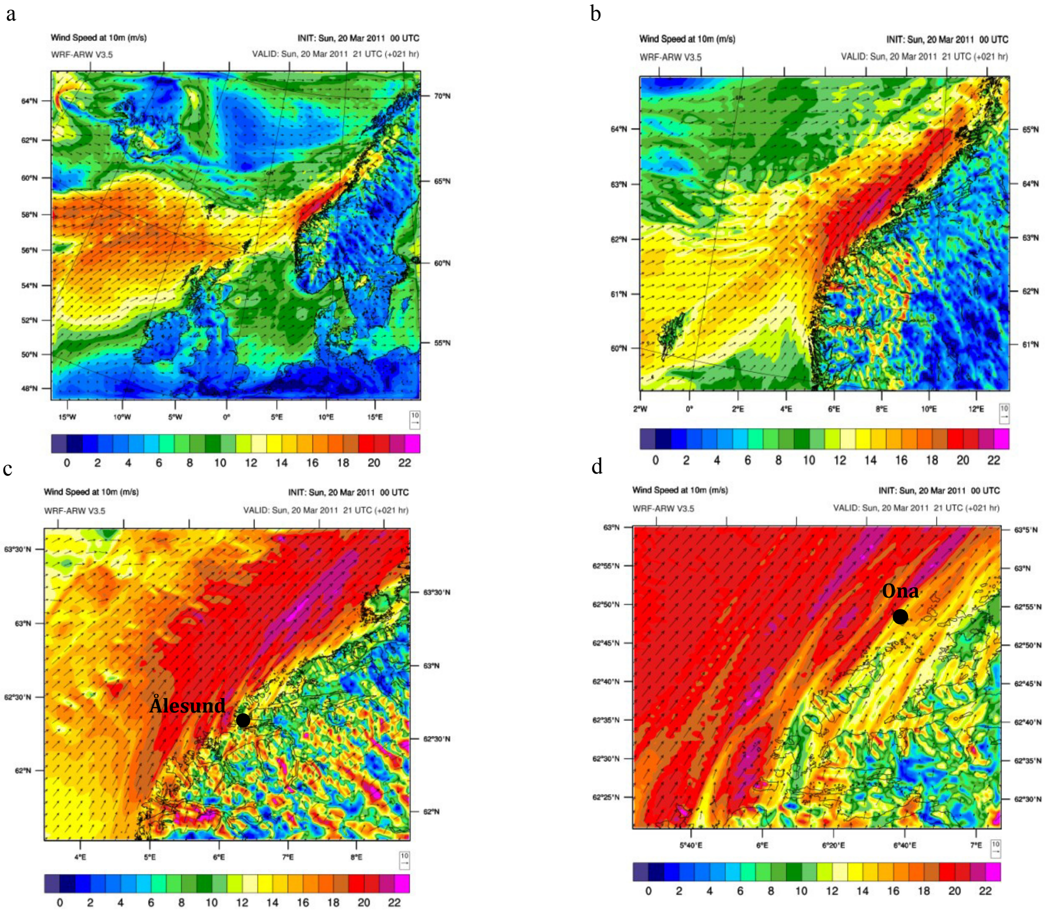


Figure 6. Wind speed at 10 m at 21:00 UTC 20.03.2011 for the four model domains.

For the analysis of the mesoscale structure of the LLCJ, vertical cross sections of the wind speed normal to LLCJ direction (Figure 7, a) were presented in Figure 7 for different times, (b) 19:00, (c) 20:00 and (d) 21:00 UTC. The results show that the LLCJ extents approximately 1km vertically and 30-40 km horizontally. The maximum wind speeds in the core of the LLCJ are observed at the height of 500-800 m ASL and at 15-20 km off the coast. At these heights, the wind speeds exceed 30 m/s. Relative lower speed flow (20 – 28 m/s) prevails above the LLCJ. For heights above 2.5 km, a high level jet with wind speed, greater than 28 m/s, is observed.

Figure 8 presents the variation of the wind speed at 60 m above the ground normal to the LLCJ at 19:00, 20:00 and 21:00 UTC. It shows that the wind speed increases significantly from 0-5 m/s (onshore) to 20 m/s (offshore) producing a strong horizontal wind shear normal to the jet direction. Figure 9 presents the wind speed at 80 m (as the nacelle height) ASL as a function of α (calculated between 60 m and 120 m, as the rotor disk diameter) at Ona during the LLCJ event. The lowest value of α is 0.01 and the maximum 0.26. The results shows that the most of α value (85.4%) are higher than 0.1 representing moderate to strong wind shear. On the other hand, only the 14.6% of α is less than 0.1 indicating low wind shear.

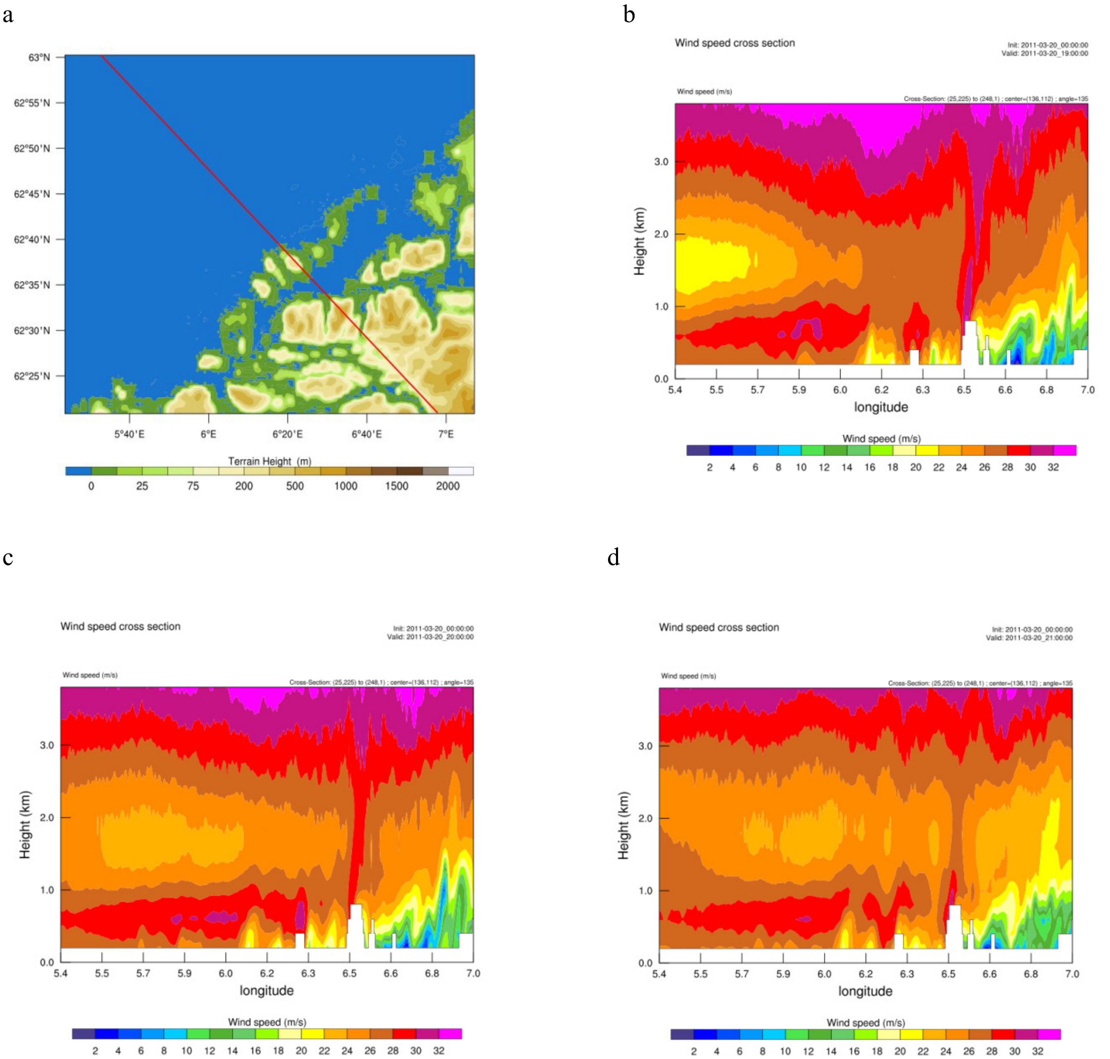


Figure 7. (a) The topography of Havsul region (the red line is normal to LLCJ direction). Cross sections of the wind speed normal to the LLCJ direction for different time, (b) 19.00 UTC, (c) 20.00 UTC and (d) 21.00 UTC.

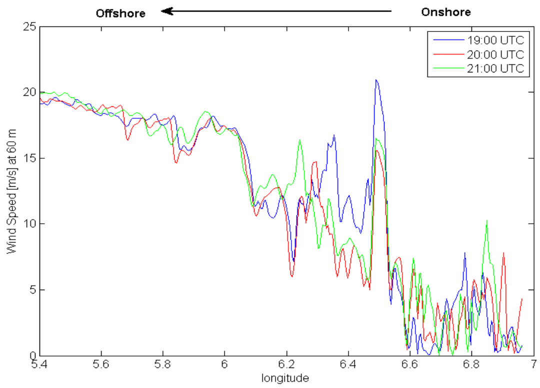


Figure 8. Spatial variation of wind speed at 60 m above the ground along the red line (Figure 7,a)

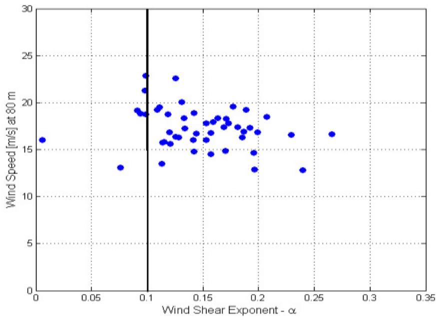


Figure 9. Wind shear exponent (α) as a function of wind speed at 80 m.

6. Model evaluation

In this section, different parameters were computed to evaluate the performance of the model against the observations at Ona during the LLCJ event. Mean, standard deviation (σ) of the observed and model data, bias, RMSE (Root Mean Square Error), and the normalized RMSE to the mean of the observed values, SI(Scatter Index) were calculated and illustrated in Table 2. The results show a bias of -0.35 m/s, RMSE of 2.35 m/s and SI of 0.14. In order to further evaluate the model results, Q-Q plot between WRF and observed wind speeds at 60 m is presented at Figure 10. For wind speed lower than 18 m/s, the model performs quite well since the points in the Q-Q plot are closely following the 45° reference line (y=x). For higher wind speeds, the model slightly underestimates the wind speed.

Table 2. Statistical parameters for the wind speed at 60 m at Ona.

	Mean [m/s]	σ [m/s]	Bias [m/s]	RMSE [m/s]	SI
Obs	16.88	1.98	-	-	-
WRF	16.53	2.17	-0.35	2.36	0.14

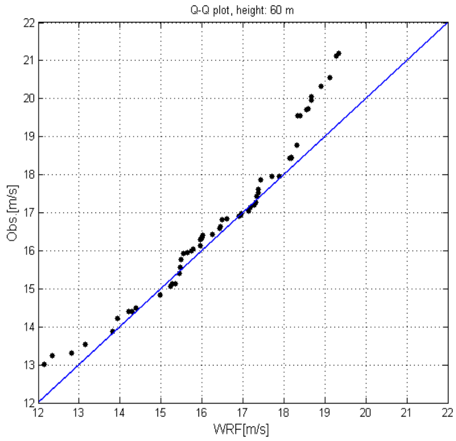


Figure 10. Q-Q plot: WRF wind speed compared with Ona observations at 60 m for the period March 20 at 00 UTC to March 21 at 00 UTC.

7. Summary and conclusion

In the present study an analysis was performed to investigate a LLCJ event at the northern part of western Norway using both observations and model results. The observations indicate a high wind energy potential of the LLCJ since the wind speeds varies from 12 to 22 m/s during the event. Moderate turbulence intensity between 5 % and 12 % was calculated. The turbulence intensity curve follows the increase of wind speed reaching the maximum values both around 18 UTC. The model simulation illustrates that the width of LLCJ had a range of 30 - 40 km which comes to an agreement with the analysis of SAR image. The maximum wind speed (greater than 30 m/s) was observed at the height from 500 to 800 m ASL. Furthermore, due to a significant increase of wind speed from onshore to offshore, a strong horizontal wind shear normal to the jet direction was observed. Finally, using the model outputs for the location of Ona, the wind shear was calculated as a function of wind speed at 80 m ASL. The analysis shows that the 85.4 % of the exponent α corresponded to moderate – strong wind shear.

References

[1] Christopher G. Nunalee, Sukanta Basu. (2013) Mesoscale modeling of coastal low-level jets: implications for offshore wind resource estimation. Wind Energy.

[2] Garreaud, RenéD., Ricardo C. Muñoz, (2005): The low-level jet off the west coast of subtropical south America: structure and variability. Mon. Wea. Rev., 133, 2246–2261. doi: http://dx.doi.org/10.1175/MWR2972.1

[3] Jackson, Peter L., D. G. Steyn, (1994): Gap Winds in a Fjord. Part I: Observations and Numerical Simulation. Mon. Wea. Rev., 122, 2645–2665. doi: http://dx.doi.org/10.1175/1520-0493(1994)122<2645:GWIAFP>2.0.CO;2

[4] Markowski P., Richardson Y. Mesoscale meteorology in midlatitudes. Wiley,Advancing Weather and Climate Science, page 149, 2010.

[5] Gerber, H., Simon Chang, Teddy Holt, 1989: Evolution of a marine boundary-layer jet. J. Atmos. Sci., 46, 1312–1326. doi: http://dx.doi.org/10.1175/1520-0469(1989)046<1312:EOAMBL>2.0.CO;2

[6] Low-level coastal jets. COMET Program, http://www.meted.ucar.edu/mesoprim/coastaljets/frameset.htm.

[7] Blackadar, A. K. et al., 1957: Studies of wind structure in the lower atmosphere, Dept. of Meteor, and Ocean., New York Univ., 164 pages.

[8] Barta R. M, Stable-boundary-layer regimes from the perspective of the low-level jet, Acta Geophysica, (2008), Vol. 56, Issue 1, pp 58-87

[9] Lamar Low-Level Jet Program (LLLJP) by NREL, http://www.esrl.noaa.gov/csd/projects/lamar/llj.html

[10] Barstad I, Gronas S. Southwesterly flows over southern Norway mesoscale sensitivity to large-scale wind direction and speed. Tellus, 57A:136 - 152, 2005.

[11] Wharton S, Lundquist J. K , Assessing atmospheric stability and its impacts on rotor-disk wind characteristics at an. onshore wind farm, Wind Energy, 15 (4) (2012), pp. 525–546

[12] Christakos K, Reuder J, Furevik B. R, Experimental Characterization of the Marine Atmospheric Boundary Layer in the Havsul Area, Norway, Energy Procedia, Volume 35, 2013, Pages 121-127, ISSN 1876-6102.

[13] Kaiser K, Hohlen H, Langreder W. Turbulence correction for power curves. Proceedings European Wind Energy. Conference and Exhibition (Madrid). 2003

[14] Sonia W, Lundquist J. K. Atmospheric stability affects wind turbine power collection. Environmental Research Letters, 7(1):014005, 2012.

[15] Wagner R,, Jørgensen H E, Paulsen U S, Larsen T J, Antoniou I and Thesbjerg L. Remote sensing used for power curves, IOP Conf. Ser.:

Earth Environ. Sci. 1 012059 doi:10.1088/1755-1315/1/1/012059

[16] Rareshide E, Tindal A, Johnson C, Graves A M, Simpson E, Bleeg J, Harris T and Schoborg D(2009). Effects of complex wind regimes on turbine performance Proc. American Wind Energy Association WINDPOWER Conference (Chicago, IL,)

[17] Eggers A. J., Digumarthi Jr.R., and Chaney K.. Wind shear and turbulence effects on rotor fatigue and loads control. J. Sol. Energy Eng., 125(4):402-409, 2003.

[18] Elliott D L, Holliday C, Barchet W, Foote H and Sandusky W 1987 Wind Energy Resource Atlas of the United States (Golden, CO:Solar Energy Research Institute, DOE/CH 10093-4) p 210

[19] Christakos K., Characterization of the coastal marine atmospheric boundary layer (MABL) for wind energy applications, Master Thesis (2013), University of Bergen, URI: http://hdl.handle.net/1956/7186

[20] Stoffelen, A. and D.L.T. Anderson, ERS-1 scatterometer data and characteristics and wind retrieval skills, Proceeding of First ERS-1 Symposium, Eur. Space Agency Spec. Publ., ESA SP-359, 1993

[21] Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D., Duda, M. G., Huang, X.-Y., and Wang, W.: A Description of the Advanced Research WRF Version 3, NCAR Technical Note, TN-468+STR, 113 pp., 2008

[22] Hong, Song-You, Jimy Dudhia, Shu-Hua Chen, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. Mon. Wea. Rev., 132, 103–120. doi: http://dx.doi.org/10.1175/1520-0493(2004)132<0103:ARATIM>2.0.CO;2

[23] Hong, Song-You, Yign Noh, Jimy Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. Mon. Wea. Rev., 134, 2318–2341.doi: http://dx.doi.org/10.1175/MWR3199.1

[24] Zhang, D-L., and R. A. Anthes, 1982: A high-resolution model of the planetary boundary layer—Sensitivity tests and comparisons with SESAME-79 data. J. Appl. Meteor., 21, 1594–1609.

[25] Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley, 2003: Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. J. Geophys. Res.,22 ,8851 , doi:10.1029/2002JD003296