Meteorol Atmos Phys 103, 173–185 (2009)
DOI 10.1007/s00703-008-0347-y
Printed in The Netherlands

Meteorology
and Atmospheric
Physics

[1] Institute for Meteorological Research, Reykjavík, Iceland
[2] University of Iceland, Reykjavík, Iceland
[3] Icelandic Meteorologic Office, Reykjavík, Iceland
[4] Bergen School of Meteorology, Geophysical Institute, University of Bergen, Bergen, Norway

Forecasting wind gusts in complex terrain

H. Ágústsson[1,2], **H. Ólafsson**[2,3,4]

With 10 Figures

Received 25 October 2007; Accepted 20 November 2008

Summary

Wind gusts are calculated in a collection of simulated atmospheric flows in complex terrain. This study focuses on a region in West-Iceland during February to April 2007 which includes several windstorms. The atmospheric data is a subset in a large collection of realtime numerical simulations used for forecasting in Iceland. It is generated at horizontal resolutions of 9 and 3 km, and in two sensitivity tests at 1 km. The gust prediction method is based on turbulence kinetic energy, static stability and wind speed in the atmospheric boundary layer. The gust prediction method is implemented as post-processing. The calculated gust strength is compared with wind gust observations from several automatic weather stations. The estimated gusts are strongly dependent on the quality of the simulated flow and are on average well captured when the mean winds are correctly simulated. Maximum gusts in downslope windstorms are however frequently underestimated. The error is presumably related to an inadequate simulation of the downslope surface winds which are also too weak. The windstorms in the current study appear to be related to gravity wave activity aloft and are better reproduced at higher resolutions than at coarse resolution. There are cases of overestimated gusts on the upstream side of mountains, which may be related to an inadequate simulation of the upstream deceleration of the flow and overestimated surface winds. Gustiness in mountain wakes is frequently too great, which appears to be related to overestimated turbulence in the wakes.

1. Introduction

The strongest winds in severe windstorms are related to fluctuations in the wind speed at periods as short as a few seconds. These fluctuations are known as wind gusts and are often described with the ratio of the instantaneous wind speed to the 10 minute mean wind speed. This ratio is typically 1.2–1.6 at 10 m above ground in relatively weak winds (e.g. Mitsuta and Tsukamoto 1989; Ágústsson and Ólafsson 2004) but frequently exceeds 2 in extreme windstorms in complex terrain, as is documented in e.g. Durran (1990), Grønås and Sandvik (1999), Ólafsson et al. (2002b). The gustiness is a manifestation of atmospheric turbulence which is primarily found in the atmospheric boundary layer (BL), but may also be found aloft, e.g. near upper level jets where it may be a danger to aircrafts. The turbulent motion is driven by strong vertical wind shear and/or low static stability. Readers are refered to Stull (1988) for an overview of turbulence in the BL. Of importance for this study is the turbulence created in atmospheric flow in and above complex terrain.

Correspondence: Hálfdán Ágústsson, Reiknistofa í veðurfræði, Orkugarði, Grensásvegi 9, 108 Reykjavík, Iceland (E-mail: halfdana@hi.is)

There is in fact strong evidence indicating that major gust events may be related to turbulence aloft, created by local convective instability in regions where gravity (buoancy) waves break (e.g. Clark and Farley 1984) or in regions of high wind shear, i.e. Kelvin-Helmholtz instability, as suggested by Peltier and Scinocca (1990), Afansyev and Peltier (1998) and more recently by e.g. Belušić et al. (2007). Such extreme weather events in Iceland have previously been documented by Ólafsson and Ágústsson (2007) and Ágústsson and Ólafsson (2007) and in other parts of the world such as in Croatia by Belušić et al. (e.g. 2007) (and references therein) and in Norway by Grønås and Sandvik (1999) The Boulder windstorms (e.g. Clark et al. 1994) are probably the best known downslope windstorms. The maximum wind gusts can easily exceed 50 m/s during these events, which is nearly twice the mean wind speed (Durran 1990).

As wind gusts are the main threat during severe windstorms, an increased understanding of wind gusts and their relation to atmospheric turbulence is of great importance, both for operational forecasting of gusts and for estimating the local wind climate, i.e. finding locations and describing situations with the potential for strong gustiness and extreme winds. Several gust prediction systems have been devised, some which use statistical methods (e.g. Weggel 1999; Jungo et al. 2002; Ágústsson and Ólafsson 2004). Other methods use similarity-theory (e.g. Nielsen and Petersen 2001), while still others are based on a physical model of the formation of gusts. Even though such methods may initially not perform better than e.g. statistical methods, they may help improve the understanding of the mechanisms of gust formation and consequently improve the method itself. One such method, which is based on the parameterization of turbulence and atmospheric stability in numerical models, is the method of Brasseur (2001). The method has previously been applied in both the complex terrain in Switzerland and the relatively flat topography of Belgium, where the method was found to perform well (Goyette et al. 2003). Belušić and Klaić (2004) showed that the method successfully reproduced the strong wind gusts in a bura flow in Croatia while Ólafsson and Ágústsson (2007) successfully applied the method in a corner wind and a downslope windstorm in Southeast-Iceland, which they referred to as a "warm bora".

Currently, wind gusts have been estimated in a large collection of dynamically downscaled flow over Iceland. For clarity, this study focuses on a chosen period in the Snæfellsnes peninsula in West-Iceland. The peninsula has an east-west orientation and a mean width of approx. 15 km. It is characterized by complex terrain, and the average mountain height is approx. 800 m while the Snæfellsjökull glacier at the tip of the peninsula has an elevation of 1446 m. Severe windstorms with gusts in excess of 40 m/s are frequently reported in the region and have for example been documented in the Snæfellsnes experiment (SNEX, Ólafsson et al. 2002a, b). Observations from automatic weather stations in complex terrain are used to investigate the performance of the method, e.g. the strength and the temporal correlation of the predicted gusts. The next section discusses the methodology applied in the study, including a description of the simulations of the atmospheric flow, the gust prediction method and the observational data. Section 3 shows some of the results of the gust prediction and compares them to the available observations. The discussion of the most significant results is given in Sect. 4, while the last section includes a summary and concluding remarks.

2. Methodology

2.1 The atmospheric flows

Here, wind gusts are predicted in a subset of a large collection of simulated flow over Iceland. The flow is dynamically downscaled with the mesoscale atmospheric model, MM5 (Grell et al. 1995), which solves the fully compressible nonhydrostatic set of governing equations. The atmospheric data is a part of the ongoing HRAS-project (Ólafsson et al. 2006) for high-resolution, realtime simulation of weather in Iceland, which is used in operational forecasting, e.g. at Veðurstofa Íslands (VÍ).[1] Previous studies of weather which is represented in this collection include, e.g. Ágústsson et al. (2007), Ólafsson (2004) as well as other references in (Ólafsson et al. 2006).

---

[1] Icelandic Meteorological Office

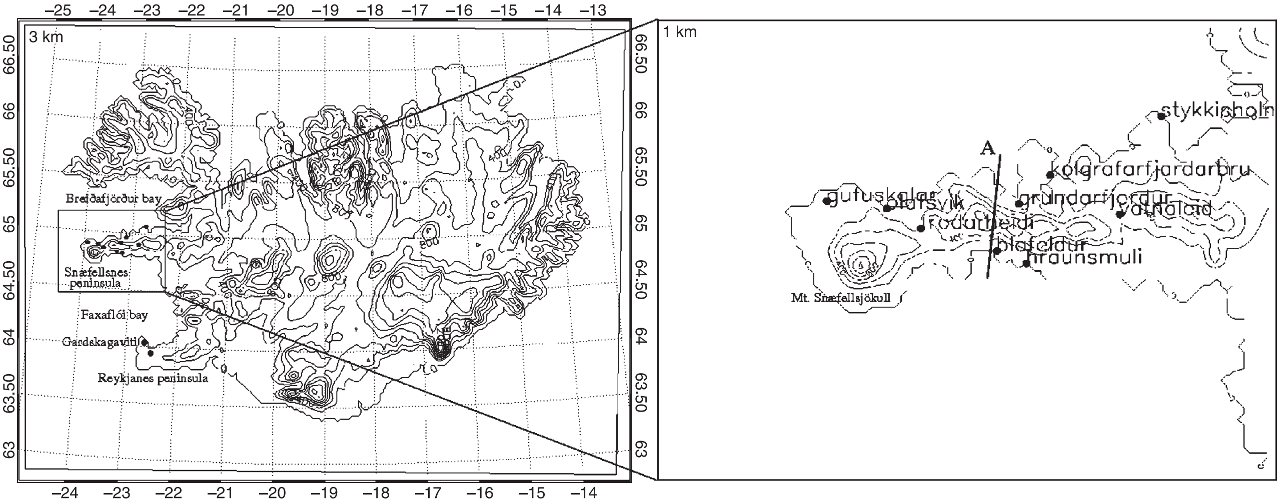

Fig. 1. The numerical domains with a horizontal resolution of 3 and 1 km, as well as locations of chosen weather stations and the location of section A (cf. Fig. 10) across the Snæfellsnes peninsula. Terrain contours with an interval of 200 m

The atmospheric model is initialized and forced at its boundaries with the operational analysis and forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF). The model is run with a horizontal resolution of 9 and 3 km, with respectively 90×95 and 148×196 gridpoints in the 1-way nested domains. The domains operate simultaneously and the outer domain defines the boundary and initial conditions for the inner domain. The vertical grid uses forty σ-layers. These are terrain following at lower levels but gradually flatten towards the top of the model at 10 hPa. Individual weather events and selected regions have also been simulated at a resolution of 1 km, as is the case here for two sensitivity tests (see Fig. 1 for the location of the domains). The two tests use either the previously mentioned 40 σ-layers or 50 layers with double the vertical resolution in the lower part of the troposphere.

The relevant parameterization are the moisture scheme of Reisner et al. (1998) which includes cloud and rain water, as well as simple and mixed ice phases. The ETA scheme (Janjić 1990, 1994) is used for boundary-layer parameterizations, as it gives the turbulent kinetic energy which is necessary for the gust prediction. Further information on the setup of the atmospheric model is found in Ólafsson et al. (2006) while model specifics are discussed in extensive detail in Grell et al. (1995).

2.2 The gust prediction

Most mesoscale models give wind-information that can be interpreted as a mean wind, averaged over a few minutes, while estimates of wind gusts are not readily available. In fact, even at high spatial and temporal resolution, an atmospheric model may not reproduce the observed variability in windspeed (Árnason et al. 2005). The poor model performance at high frequencies is expected but there are no clear indications why the models can not capture some of the variability at lower frequencies. The models do however contain information that may be used to estimate the surface gusts, i.e. the surface type and the associated roughness length, the topography and the vertical structure of wind, turbulence and stability in the boundary layer (BL). One such method is the method of Brasseur (2001) where it is proposed that strong surface gusts may be created by turbulent eddies that deflect air parcels flowing aloft in the BL down to the surface. Due to the general increase of wind speed with height and the short time span surface friction acts to decelerate the air parcels, they will be observed as a gusty wind at the surface. Here, the turbulent kinetic energy (TKE) is of primary importance for the creation of wind gusts and may be obtained from numerical models. The positive atmospheric stability (buoyancy forces) opposes the vertical deflection of air parcels. The method is mathematically expressed as

$$\frac{1}{z_p}\int_0^{z_p} E(z)\mathrm{d}z \geq \int_0^{z_p} \mathrm{g}\frac{\Delta\theta_v(z)}{\Theta_v(z)}\mathrm{d}z, \tag{1}$$

where z_p, $E(z)$, Θ_v and $\Delta\theta_v$ are respectively the height of the parcel, the TKE, the virtual potential temperature and its variation for the parcel when deflected to the surface. The estimated wind gust, f_g, is chosen as the maximum wind speed of all parcels which satisfy (1) in the BL but since turbulence is generally weak above the BL, air parcels originating there are not expected to be able to reach the surface of the earth. Here, we define the top of the BL as the height where the TKE is first reduced below 1% of its maximum below. Also, while not discussed specifically in this particular study, Brasseur (2001) argues that the method can give a bounding interval for the estimated gusts. The upper bound, $f_{g,\max}$, is taken as the maximum wind speed in the BL. The lower bound, $f_{g,\min}$ is found by using the local turbulence derived from only the vertical variance of the wind, as opposed to the mean TKE in the left-hand side of (1). An in depth explanation of the method is given by Brasseur (2001), Brasseur et al. (2002).

The gust prediction method is implemented as post-processing within the IDL-environment, into which the simulated MM5-data is imported using the MM5IDL-package[2]. Work is currently under way to implement the method directly as a part of the current BL-scheme, as well as its counterpart in the newer WRF-model (Skamarock et al. 2005).

2.3 Observations

The current study uses data from automatic weather stations which belong to VÍ and Vegagerðin (Vg)[3]. The station locations in the region of interest are shown in Fig. 1. Observations include the 10-minute mean wind speed and direction, as well as the 3-second maximum wind gusts. In some cases, high frequency (0.5 and 1.0 Hz) observations are also available. The wind is observed at either 10 m or approx. 7 m above the ground. The difference in observation heights is not expected to be important due to the non-local nature of the wind gusts.

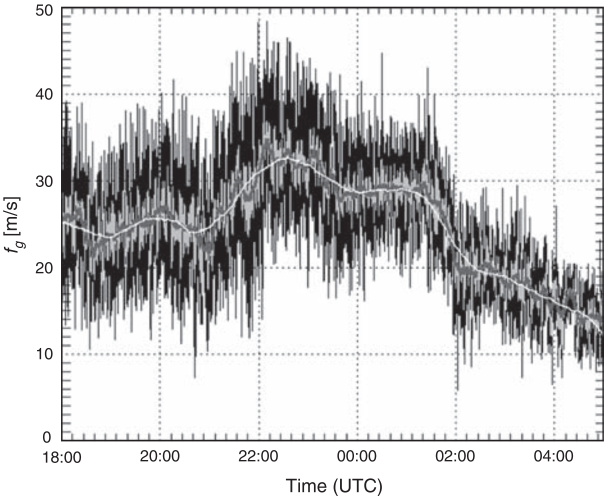

Fig. 2. Wind speed [m/s] during the evening of 5 March 2007 at Hraunsmúli with a sampling period of 0.5 Hz, as well as 1 and 10-minute, and hourly mean value

The data is stored and checked for errors at VÍ, except a part of the high frequency observations which is stored at Reiknistofa í veðurfræði (ReV)[4].

The chosen period from 14 February to 14 April 2007 is characterized by several northerly windstorms in the Snæfellsnes peninsula with observed mean winds exceeding 30 m/s and gusts as great as 50 m/s, and a couple of somewhat weaker southerly wind events with gusts exceeding 40 m/s. There are periods of far weaker winds in between the windstorms. During the windstorms, the upstream winds are much weaker than the downslope winds. Observations from Hraunsmúli (Fig. 2) show one such downslope windstorm on the evening of 5 March 2007. The extreme wind speed and the strong temporal variability of the wind speed are evident, and reminiscent of the observations of bora gusts presented in Belušić et al. (2004).

3. The wind gusts

3.1 Gust estimates from 14 February to 14 April 2007

Figures 3 and 4 compare the observed and predicted gust strength during a period of two months, at Bláfeldur on the southern side of the peninsula

---

[2] http://os.is/~or/mm5idl

[3] The Public Roads Authority

[4] Institute for Meteorological Research

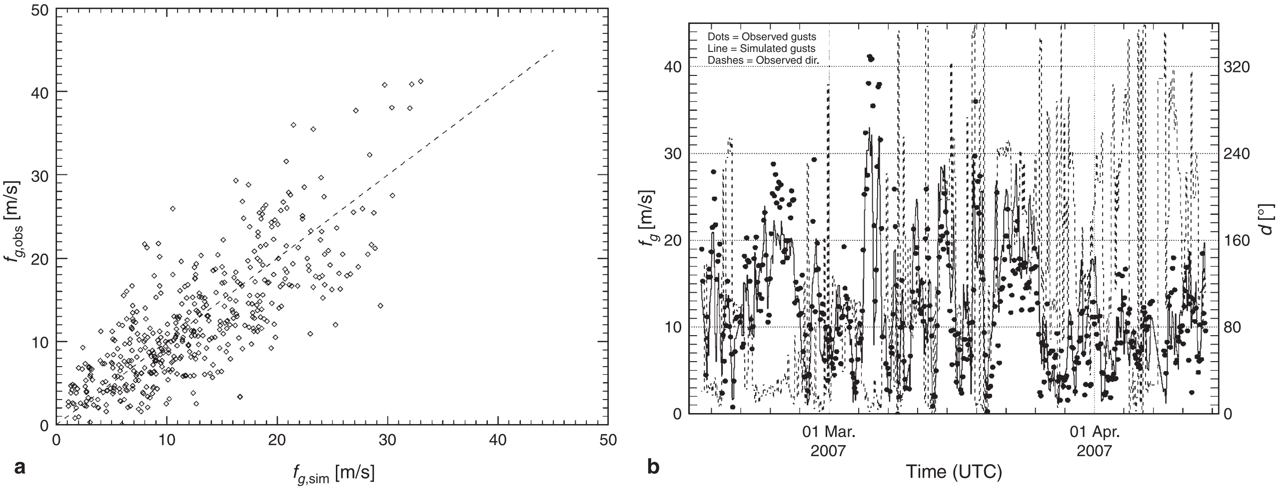

Fig. 3. Hourly values of observed and simulated wind gusts f_g [m/s] and wind direction d [°], in a 3 km grid, at the Bláfeldur station from 14 February to 14 April 2007. The 21 and 24 hour forecast times are used

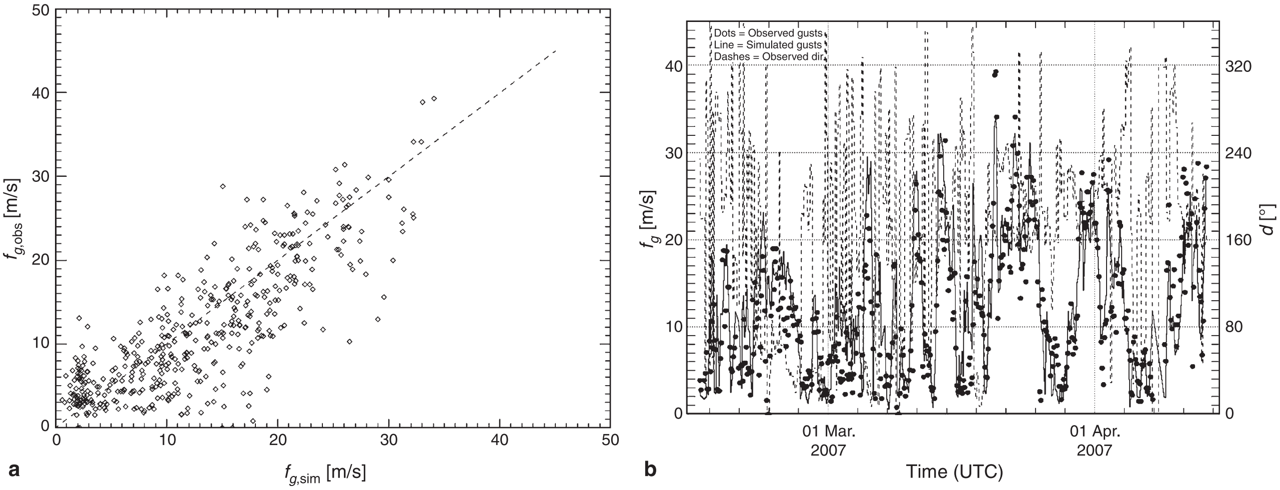

Fig. 4. Hourly values of observed and simulated wind gusts f_g [m/s] and wind direction d [°], in a 3 km grid, at the Grundarfjörður station from 14 February to 14 April 2007. The 21 and 24 hour forecast times are used

and at Grundarfjörður on its northern side. It is apparent that on average, the predicted gusts correlate well with the observed gusts at both stations. The temporal behaviour is well captured with a linear correlation index of approx. 0.8 which indicates considerably good correlation as 0 and 1 signify, respectively no and perfect correlation (the Pearson method gives a single valued measure of how the observed and estimated gusts are associated (e.g. Wilks 2006)). The greatest errors are at the downslope locations in northerly and southerly flow, when the flow is nearly perpendicular to the peninsula. At these times, the winds are generally strong and gusty. The strongest winds are observed at Bláfeldur (southern side) on 5–6 March, during a severe northerly windstorm and a somewhat weaker windstorm is observed at Grundarfjörður (northern side) on 20 March. During these events, winds are far weaker on the upstream side and the gust prediction is in general more accurate on the upstream side than on the downslope side. Similar results are seen at other stations in the peninsula, both on the upstream and downslope side. Gusts at other locations, e.g. inland in the mountains, are on average well captured (not shown).

We now look more closely into the performance of the gust prediction method during the windstorms on 5–6 and 20 March.

3.2 The northerly windstorm on 5–6 March 2007

On the evening of 5 March, a surface low was located south of Iceland (Fig. 5). There was a high over Greenland and a strong E–W pressure gradient over western Iceland and the Denmark strait, causing strong northeasterly winds. Aloft, there was a relatively flat and broad depression and consequently relatively little veering of the wind with height but a significant reverse wind shear with the strongest winds near mountain top level.

The predicted gusts (Figs. 6b and 7c, d) are strongest, as expected, everywhere on the south-

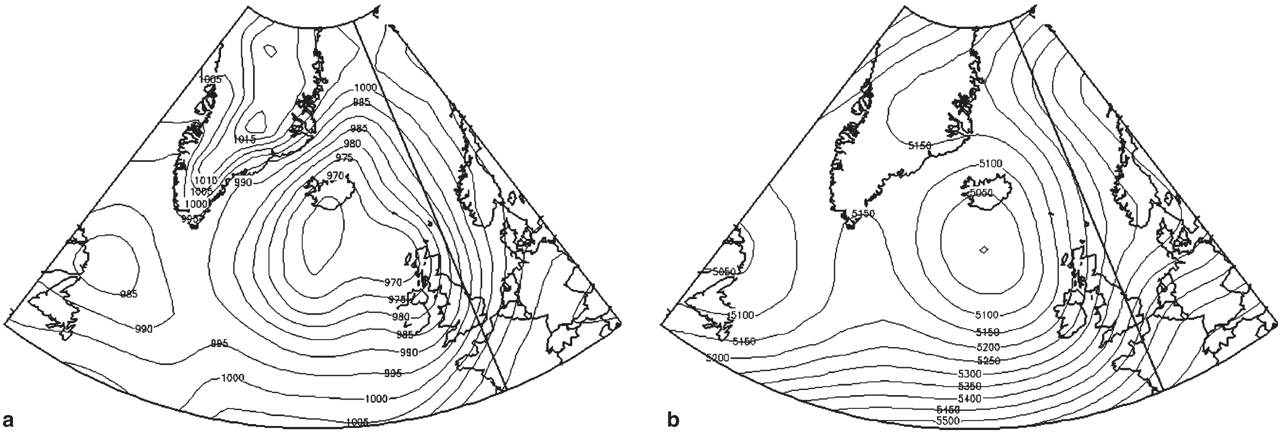

Fig. 5. The mean sea-level pressure [hPa] (**a**) and the geopotential height [m] at 500 hPa (**b**) at 00 UTC on 6 March 2007, based on NCEP/NCAR reanalysis and provided by NOAA/CDC

Table 1. Observed and simulated, at a horizontal resolution of 3 and 1 km (values for respectively 40 and 50 σ-layers), mean winds, f_{10}, and gusts, f_g [m/s], as well as gust factors, $G = f_g/f_{10}$, at chosen stations at 22 UTC on 5 March 2007

Station	$f_{10,\mathrm{obs}}$	$f_{10,\mathrm{sim1}}$	$f_{10,\mathrm{sim3}}$	$f_{g,\mathrm{obs}}$	$f_{g,\mathrm{sim1}}$	$f_{g,\mathrm{sim3}}$	G_{obs}	G_{sim1}	G_{sim3}
Grundarfjörður (N)	13.2	8.8/8.1	13.5	21.5	27.2/21.9	24.1	1.63	3.08/2.70	1.78
Kolgrafarfj. (N)	15.9	16.3/13.9	16.5	25.8	24.8/21.2	25.5	1.62	1.52/1.52	1.54
Stykkishólmur (N)	10.2	12.9/10.5	12.9	18.7	20.7/21.2	20.4	1.83	1.60/2.01	1.58
Bláfeldur (S)	32.1	19.6/20.1	16.8	40.8	34.1/34.6	30.3	1.27	1.74/1.66	1.80
Hraunsmúli (S)	29.2	17.9/16.9	16.4	49.5	30.8/28.8	28.3	1.70	1.72/1.70	1.73
Vatnaleið (S)	16.9	12.1/11.7	11.7	28.8	24.2/26.7	22.9	1.70	2.00/2.28	1.96

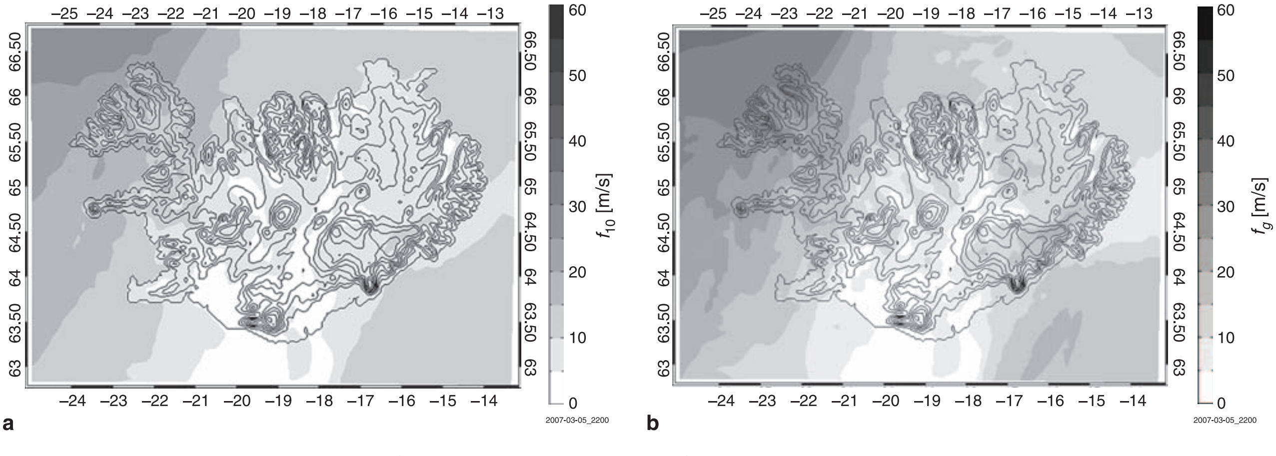

Fig. 6. Simulated surface wind, f_{10} [m/s] (**a**), and wind gusts, f_g [m/s] (**b**) on the Snæfellsnes peninsula at 22 UTC on 5 March 2007, with a horizontal resolution of 3 km at the 34 hour forecast time. Terrain height with a contour interval of 200 m

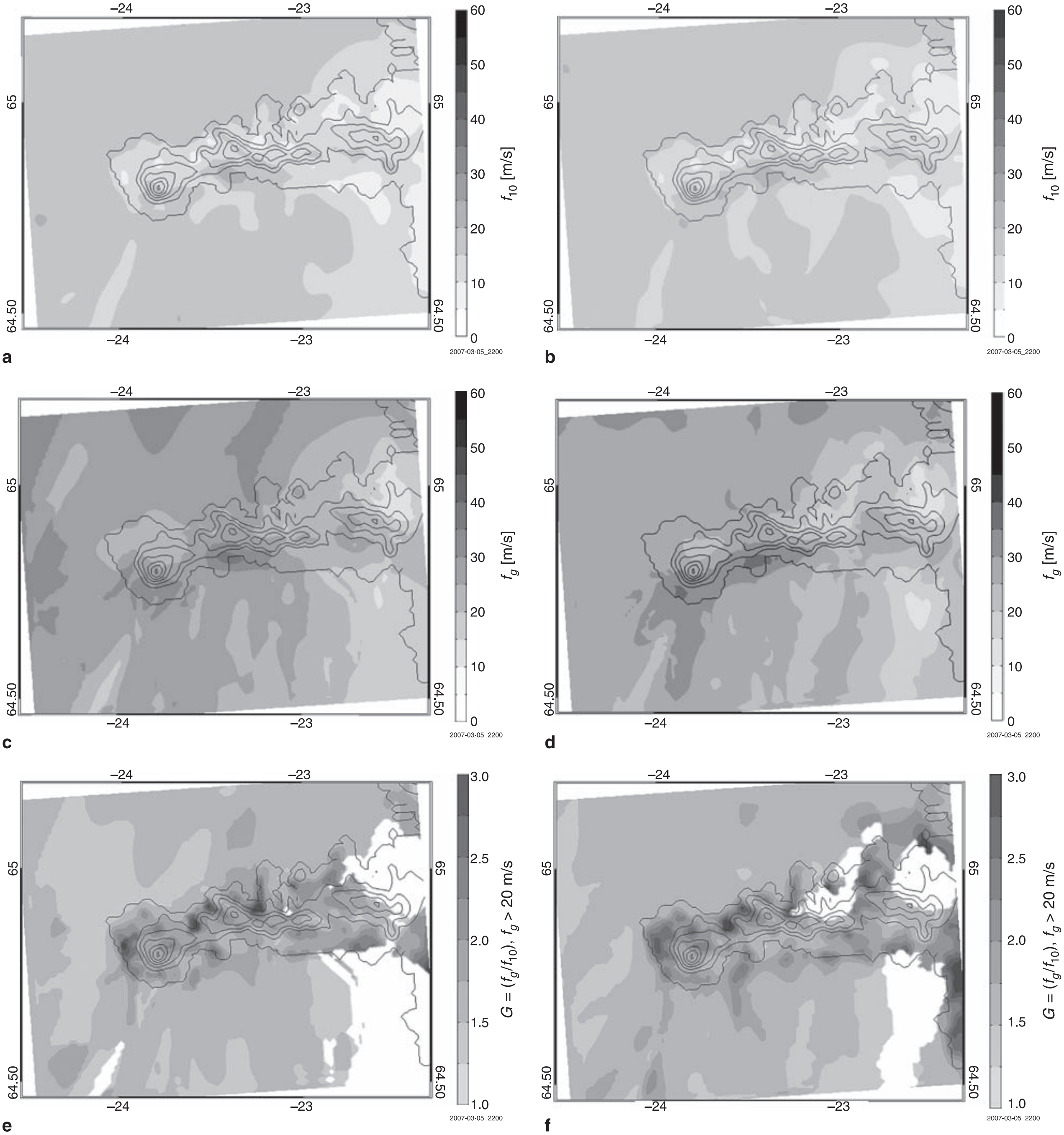

Fig. 7. Simulated surface wind, f_{10} [m/s] (**a**, **b**), and wind gusts, f_g [m/s] (**c**, **d**) as well as gust factors, $G = f_g/f_{10}$ with $f_g \geq 20\,\text{m/s}$ (**e**, **f**) on the Snæfellsnes peninsula at 22 UTC on 5 March 2007, with a horizontal resolution of 1 km using 40 (**a**, **c**, **e**) and 50 (**b**, **d**, **f**) σ-layers, at the 34 hour forecast time. Terrain height with a contour interval of 200 m

ern side of the peninsula with a maximum near the locations of Bláfeldur and Hraunsmúli. Weaker winds and gusts are predicted in the upstream decelerated flow. The surface winds are on average reasonably well simulated on the northern side, e.g. at Stykkishólmur, Kolgrafarfjarðarbrú and Grundarfjörður (Table 1 and Figs. 6a and 7a, b). The observed gusts are mostly within or very near the bounds of the predicted gusts and the temporal behaviour of the observed gusts is well captured. However, the atmospheric model does not capture the strongest mean winds on the southern side. During the maximum of the windstorms, the mean winds are greatly underestimated at several stations, e.g. at the downslope stations of Bláfeldur and Hraunsmúli, while there are however stations where the performance is much better, e.g. at the Vatnaleið station in the centre of the eastern part of the peninsula (Table 1).

Two sensitivity tests were performed for the northerly windstorm, where the horizontal resolution was increased to 1 km with and without increased vertical resolution as well (Fig. 7). The increased horizontal resolution reveals greater spatial detail in the surface wind and gust fields. The downslope gust strength field is more realistic, i.e. increased lee-side gusts, and there is some improvement at several of the observation sites, while the gusts are still too weak. There is a noticable degrade in the quality of upslope mean winds at Grundarfjörður which are too weak at the greater horizontal resolution (Table 1). However, the downslope winds are improved where a downslope wind maximum appears near the southern location of Hraunsmúli and Bláfeldur (cf. Figs. 6a and 7a, b). When the vertical resolution is increased there appears to be a slight improvement to the spatial distribution of mean wind speed and gust strength (Fig. 7). The lee-side winds and gusts are somewhat stronger while they weaken slightly in some upstream parts of the peninsula. However, overall there are very little changes, and only a slight improvement is observed at some of the weather stations while at other stations the performance is somewhat worse with the increased vertical resolution (Table 1).

The predicted gust factors (Fig. 7e, f) are very high where the mean winds are relatively weak, such as on the northern slopes of the peninsula. The highest gust factors are indeed found in patches of too weak mean winds, e.g. near Grundarfjörður and Ólafsfjörður. The factors are captured at Stykkishólmur and Kolgrafarfjarðarbrú but somewhat overestimated at the Vatnaleið station. On the downslope side, strong mean winds give gust factors that are lower than on the upstream side. The gust factor is well captured at Hraunsmúli in spite of the poorly estimated mean winds and gusts, while at the nearby station at Bláfeldur, the gust factor is overestimated. Over the sea, the approx. range of gust factor values is 1.4–1.8.

3.3 The southerly windstorm on 20 March 2007

The W–E oriented surface pressure gradient was strong in West-Iceland at noon on 20 March (Fig. 8), giving rise to strong southerly winds and gusts as great as 42 m/s for a few hours on the northern side of the peninsula. There was low pressure between Iceland and Greenland and a ridge of the east coast of Iceland. Aloft, there was a ridge above Iceland (Fig. 8), with a strong NW–SE oriented pressure gradient. Consequently, there was a moderate clockwise veering of the wind with height while winds were generally strong throughout the troposphere.

Simulated mean winds at 12 UTC on 20 March are mostly below 20 m/s near and in the Snæfellsnes peninsula (Fig. 9a). The winds are however slightly stronger on the downslope side and there is a slight upstream deceleration of the

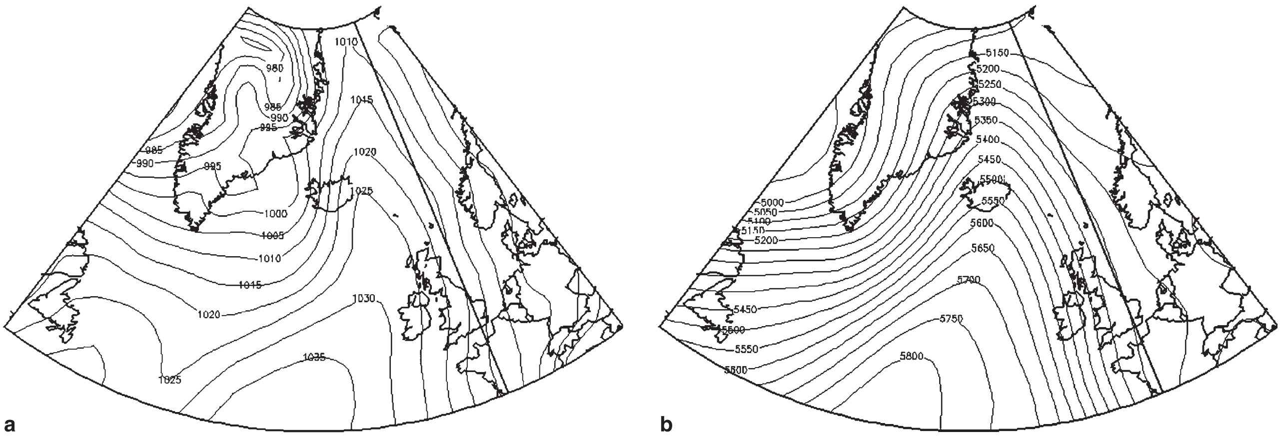

Fig. 8. The mean sea-level pressure [hPa] (**a**) and the geopotential height [m] at 500 hPa (**b**) at 12 UTC on 20 March 2007, based on NCEP/NCAR reanalysis and provided by NOAA/CDC

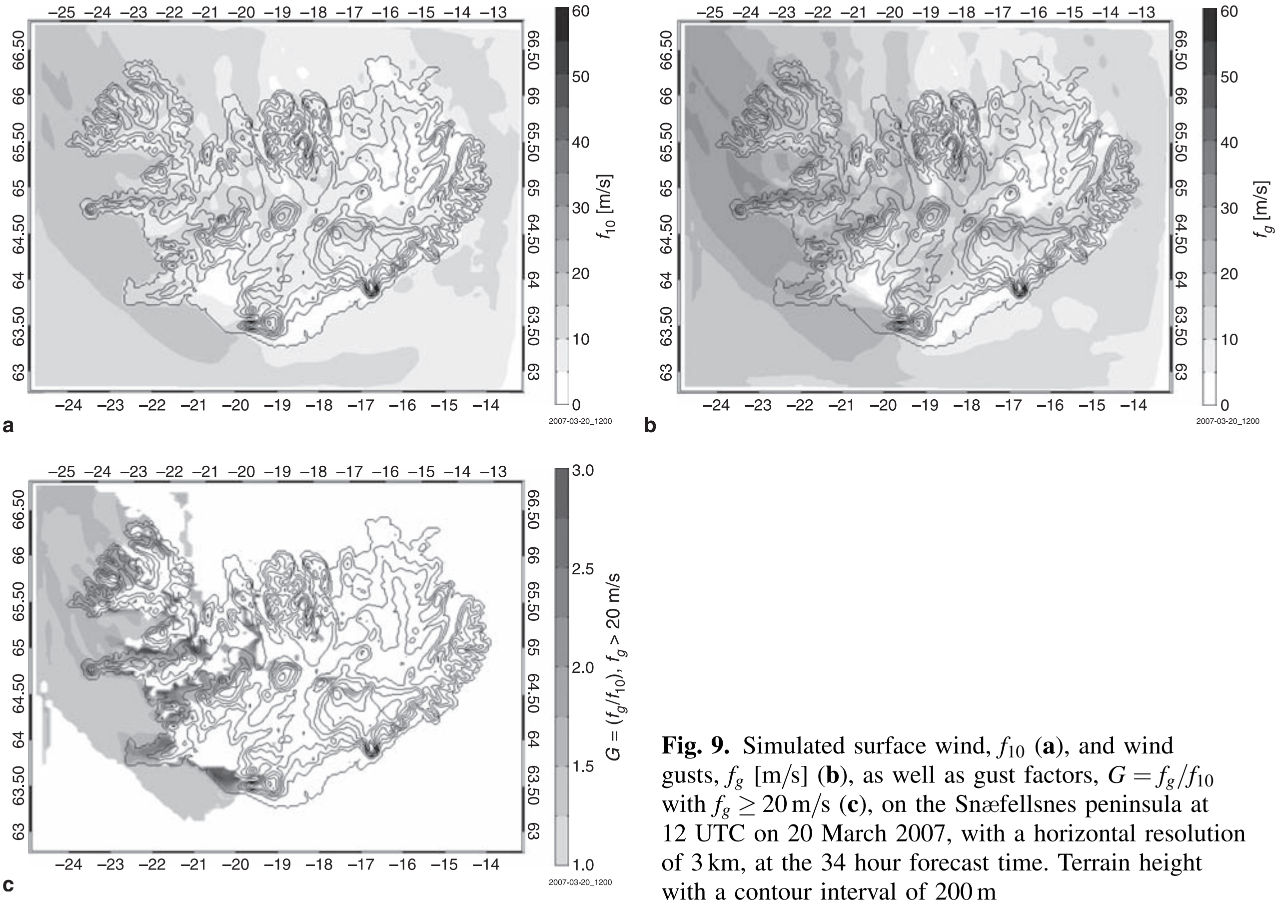

Fig. 9. Simulated surface wind, f_{10} (**a**), and wind gusts, f_g [m/s] (**b**), as well as gust factors, $G = f_g/f_{10}$ with $f_g \geq 20$ m/s (**c**), on the Snæfellsnes peninsula at 12 UTC on 20 March 2007, with a horizontal resolution of 3 km, at the 34 hour forecast time. Terrain height with a contour interval of 200 m

Table 2. Observed and simulated, at a horizontal resolution of 3 km, mean winds, f_{10}, and gusts, f_g, [m/s], as well as gust factors, $G = f_g/f_{10}$, at chosen stations at 12 UTC on 20 March 2007

Station	$f_{10,\mathrm{obs}}$	$f_{10,\mathrm{sim3}}$	$f_{g,\mathrm{obs}}$	$f_{g,\mathrm{sim3}}$	G_{obs}	G_{sim3}
Grundarfjörður (N)	20.8	16.8	39.3	34.7	1.89	2.01
Kolgrafarfjarðarbrú (N)	14.4	20.3	29.4	29.7	2.04	1.46
Stykkishólmur (N)	11.1	10.5	27.4	30.1	2.47	2.87
Bláfeldur (S)	12.7	12.5	17.9	25.5	1.41	2.04
Hraunsmúli (S)	14.0	13.5	20.2	24.5	1.44	1.81
Vatnaleið (S)	13.6	15.0	25.3	23.0	1.86	1.53

flow. This is to some extent similar to the observations, shown in Table 2. The mean winds are better reproduced upstream, and in the mountains, than on the downslope side. The sea surface winds are validated, at an earlier and at a later time, with observations derived from the Seawinds scatterometer aboard the QuickSCAT satellite[5] (not shown). As is seen both in the observations as well as the simulations (Table 2 and Fig. 9b), the gustiness is far greater in the downslope windstorm than on the upstream side. The gusts tend to be slightly overestimated in the weaker winds on the upstream side and underestimated near the mountains on the downslope side, while the gusts in the mountains are more accurately captured. As for the northerly windstorm, the estimated gust factors (Fig. 9c) are generally greater in the weaker winds on the upstream side than at downslope locations, and are overestimated at Bláfeldur and Hraunsmúli as a result of the overpredicted gust strength. The gust factors are better captured in the moun-

---

[5] http://manati.orbit.nesdis.noaa.gov/hires/

tains, and near Grundarfjörður on the downslope side but worse at the nearby station at Kolgrafarfjarðarbrú.

4. Discussion

The observed gusts are on average well captured, both their strength and the temporal behaviour. There is in some cases a relatively large overprediction of the gust strength in weak winds at locations upstream of mountains but in such cases, an accurate gust prediction is in fact not as important as in stronger winds. This upstream error may be related to an inadequately simulated deceleration of the flow or a tendency towards boundary-layer blocking (e.g. Chen and Smith 1987) not being captured by the model. There may also be cases where the surface flow is well captured while the decelerated flow is too shallow and the winds brought down from aloft by the gust method may therefore be too strong. Increasing the vertical resolution in the lower troposphere, including the boundary layer, does not appear to have any significant impact. Although the peninsula is mountainous, it is quite narrow and the steep mountains are reduced in height and steepness at the model resolution. Steep and high mountains are indeed more efficient at decelerating the flow than lower and gentler sloping mountains (e.g. Bauer et al. 2000). This inadequate deceleration of the flow has in fact previously been studied and observed in simulated flow at high resolution near, e.g. Bíldudalur in Northwest-Iceland (Ágústsson and Ólafsson 2007). It is clear that high frequency three-dimensional observations of the upstream flow, and in particular of the mean winds and the turbulence, are needed to investigate this matter more closely and consequently improve the simulations of the flow. Unfortunantly, no such observations are currently available in Iceland, but they are planned near Gufuskálar at the westernmost tip of the Snæfellsnes peninsula.

Although the simulations are run at a high horizontal resolution, it is reasonable that some of the errors may be accounted for by subgrid topography or inaccuracy in the simulation of the horizontal extent of accelerated or decelated flow. This is plausible both on the upstream side and the lee-side. Indeed, Ágústsson and Ólafsson (2007) show that a relatively large error in the upstream winds may only be due to a moderate error in the extension of the area of upstream deceleration. At the lee-side, previous studies have in fact suggested that errors in the horizontal extension of windstorms may at least be partly responsible for discrepancy in comparison to the observed winds, e.g. during the Freysnes windstorm in Southeast-Iceland (Ólafsson and Ágústsson 2007). This is for example evident at the southerly stations of Bláfeldur and Hraunsmúli which show large differences in the gust strength in spite of the short distance between them. In the northern part of the peninsula, similar pattern may be observed at Kolgrafarfjarðarbrú and Grundarfjörður during both storms. However, while Fig. 1 shows significant improvement in the representation of the topography when the horizontal resolution is increased, the subgrid topography does not explain the reduction in performance on the upstream side when going from 3 to 1 km in horizontal resolution. This part of the results remains unexplained.

The worst performance is seen in downslope windstorms when an accurate gust estimate is in fact most important. The downslope gusts were strongly underestimated during the northerly windstorm of 5 March which is not unexpected as the method is strongly dependent on the simulated mean winds which were also far too weak. At one of the two downslope stations an excep-

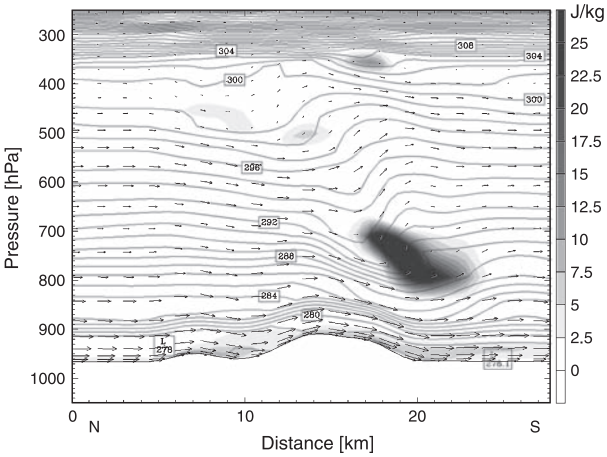

Fig. 10. Section A (cf. Fig. 1) from north to south across the peninsula, at a resolution of 1 km with 40 σ-layers and at the 34 hour forecast time. Shown are isolines of potential temperature [K], wind speed vectors and turbulent kinetic energy [J/kg] at 22 UTC on 5 March 2007

tionally high gust factor is correctly reproduced, indicating that the gust estimation method may be good. The horizontal variability and the magnitude of the downslope winds are however not correctly reproduced, but both are most likely due to subgrid topography. A study of the structure aloft in this northerly windstorm reveals breaking waves above the Snæfellsnes peninsula (Fig. 10). The conditions for wave breaking are indeed favourable, strong winds at mountain top level and a reverse wind shear with a minimum in wind speed above 500 hPa. The flow pattern is reminiscent of the description by Smith (1985) of downslope windstorms. Below the laminar flow there is a large concentration of TKE in the region of the breaking waves. There is accelerated flow below the turbulent region, and above the lee-side slopes of the peninsula, i.e. at the Bláfeldur and Hraunsmúli stations. The wave signal is stronger, and the downslope winds are more accurately captured, at a resolution of 1 km than at 3 km, implying the importance of high resolution for the simulation of gravity waves aloft. This underlines the need for high resolution 4-dimensional observations to verify the wave structure in flows of this kind.

The observed gusts in the downslope windstorms are captured more accurately in the southerly flow on 20 March than in the northerly flow on 5–6 March. Although the conditions for gravity wave formation were also favourable during the southerly windstorm, the absence of a negative vertical wind shear facilitates the gravity wave to propagate upwards without breaking as in the 5 March case of northerly flow and low level wave breaking. The vertical wave structure is therefore quite different from what it is in the northerly windstorm and this may influence the performance of the gust method.

In some instances, the predicted gust factor field estimates correctly the observed gust factor in spite of the incorrect mean wind and gusts. Although the gust strength is incorrectly predicted, a correctly predicted gust factors is of substantial value for forecasting as it implies that at least the ratio of gust strength and mean wind speed is reasonably estimated.

There appears to be a systematic error in the strength of the predicted gusts over the sea where the gust factor is expected to be less than 1.4 (Ágústsson and Ólafsson 2004) but is simulated to be considerably greater. The areas of overestimated gust factors are in the region of strong winds, but are mostly limited to wake-like regions extending far downstream of large mountains or mountain ranges, e.g. downstream of the Snæfellsnes peninsula and the Reykjanes peninsula in Southwest-Iceland (Figs. 7e, f and 9c). To shed some light on this, one can look at flow across the Reykjanes peninsula in SW-Iceland during a southeasterly windstorm. Observations at Garðskagi, which is in the wake of the peninsula and close to the Keflavík upper air observations reveal a mean wind of 15 m/s and gusts of 23 m/s. The mean winds are correctly reproduced, but the gusts are overestimated. The Keflavík radiosonde (WMO no. 0418) shows a strong increase in wind with height with a maximum of 30 m/s just above 950 hPa. The simulated static stability in the lowest 1000 metres is slightly greater than the observed stability. As there are no direct observations of turbulence in the flow, and especially in the mountain wakes, it is difficult to verify the spatial distribution of the TKE. However, the overestimation of the gusts indicates that there is too much modelled TKE in the mountain wakes, which may cause the gust prediction to fail as it will be able to bring down strong winds from too far aloft in the BL.

5. Conclusions

Wind gusts have been parameterized in a collection of atmospheric simulations of flow over Iceland. Here we discuss the performance of the gust prediction during a period of two months, which includes severe windstorms, in complex terrain in the Snæfellsnes peninsula in West-Iceland.

The results of this study are consistent with previous studies on the use of the gust prediction method, e.g. Belušić and Klaić (2006), Ólafsson and Ágústsson (2007). The quality of the predicted gusts is strongly correlated with the ability of the model to correctly simulate the mean surface winds. Where the mean surface winds are correctly captured, the predicted gusts are on average in reasonable agreement with the observations. The greatest errors in the gust prediction are an underestimation of the gusts during severe downslope windstorms. This is presumably related to the inadequate simulation of the downslope surface winds by the atmospheric model. Gusts also tend to be overestimated at locations where the upstream deceleration of the flow is too weak or possibly too shallow. There is also a systematic overestimate of the gust strength downstream in mountain wakes. This appears to be caused by too much turbulence in the atmospheric model. These problems may be further investigated with different BL schemes and TKE parameterizations, as well as different atmospheric models, e.g. the WRF-model (Skamarock et al. 2005), with different dynamics. However, the issue will not be solved without direct observation of the atmospheric turbulence and other key atmospheric fields in the BL. In this context it would be invaluable to have such observations in the Snæfellsnes peninsula.

For the creation of a continous field of wind gust prediction, the gust method appears superior to statistical methods in the sense that it can correctly take into account localized conditions and flow patterns, provided the atmospheric model is run at high horizontal resolution. Such local effects may be unrepresented in a statistical ensemble created with observations from several locations. Also, through the atmospheric model, it takes into account the dynamics and the structure of the flow which strongly influence the surface gusts and can only be represented in very simple terms in statistical methods.

Furthermore, the results of the study indicate that gusts can be successfully predicted in the complex terrain in Iceland. This is of special interest in the context of operational weather forecasting where gust forecasts may give valueable information, for example regarding road safety and possible damage to structures during severe windstorms.

Acknowledgements

This study is partly funded by the ongoing RÁV-project, RANNÍS (The Icelandic Centre for Research), Rannsóknarnámssjóður (The Icelandic Research Fund for Graduate Students), Vegagerðin, Landsvirkjun (the National Power Company) and Minningarsjóður Helgu Jónsdóttur og Sigurliða Kristjánssonar (The Memorial Fund of Helga Jónsdóttir and Sigurliði Kristjánsson.). We are grateful to the anonymous reviewers whose comments helped improve the manuscript.

References

Afansyev YD, Peltier WR (1998) The three-dimensionalization of stratified flow over two-dimensional topography. J Atmos Sci 55(1): 19–39

Ágústsson H, Ólafsson H (2004) Mean gust factors in complex terrain. Meteorol Z 13(2): 149–55

Ágústsson H, Ólafsson H (2007) Simulating a severe windstorm in complex terrain. Meteorol Z 16(1): 111–22

Ágústsson H, Cuxart J, Mira A, Ólafsson H (2007) Observations and simulation of katabatic flows during a heatwave in Iceland. Meteorol Z 16(1): 99–110

Árnason S, Ágústsson H, Ólafsson H (2005) Temporal oscillations in downslope windstorms. Proc. Joint International Conf. on Alpine Meteorology and the Mesoscale Alpine Programme

Bauer MH, Mayr GJ, Vergeiner I, Pichler H (2000) Strongly nonlinear flow over and around a three-dimensional mountain as a function of the horizontal aspect ratio. J Atmos Sci 57(24): 3971–91

Belušić D, Klaić ZB (2004) Estimation of bora wind gusts using a limited area model. Tellus 56A: 296–307

Belušić D, Klaić ZB (2006) Mesoscale dynamics, structure and predictability of a severe Adriatic bora case. Meteorol Z 15(2): 157–68

Belušić D, Pasarić M, Orlić M (2004) Quasi-periodic bora gusts related to the structure of the troposphere. Quart J Roy Meteor Soc 130(598): 1103–21

Belušić D, Žagar M, Grisogono B (2007) Numerical simulation of pulsation in the bora wind. Quart J Roy Meteor Soc 133(627): 1371–88

Brasseur O (2001) Development and application of a physical approach to estimating wind gusts. Mon Wea Rev 129: 5–25

Brasseur O, Gallée H, Boyen H, Tricot C (2002) Reply. Mon Wea Rev 130: 1936–42

Chen W-D, Smith RB (1987) Blocking and deflection of airflow by the Alps. Mon Wea Rev 115(11): 2578–97

Clark TL, Farley RD (1984) Severe downslope windstorm calculations in two and three spatial dimensions using anelastic interactive grid nesting: a possible mechanism for gustiness. J Atmos Sci 41(3): 329–50

Clark TL, Hall WD, Banta RM (1994) Two- and three-dimensional simulations of the 9 January 1989 severe Boulder windstorm: comparison with observation. J Atmos Sci 51(16): 2317–43

Durran DR (1990) Mountain waves and downslope winds. In: Blumen W (ed) Atmospheric processes over complex terrain. American Meteorological Society Monographs 23(45). Amer Meteor Soc, Boston, pp. 59–81

Goyette S, Brasseur O, Beniston M (2003) Application of a new wind gust parametrization: multiscale case studies performed with the Canadian regional climate model. J Geophys Res 108(D13): ACL 1–(1–16). 4374; DOI: 10.1029/2002JD002646

Grell GA, Dudhia J, Stauffer DR (1995) A Description of the Fifth-Generation PennState/NCAR Mesoscale Model (MM5), Technical Report NCAR/TN-398 + STR, National center for atmospheric research. Available at http://www.mmm.ucar.edu/mm5/doc1.html (May 2004)

Grønås S, Sandvik AD (1999) Numerical simulations of local winds over steep orography in the storm over North-Norway on October 12, 1996. J Geophys Res 104(D8): 9107–20

Janjić ZI (1990) The step mountain coordinate: physical package. Mon Wea Rev 118(7): 1429–43

Janjić ZI (1994) The step-mountain eta coordinate model: further development of the convection, viscous sublayer, and turbulent closure schemes. Mon Wea Rev 122(5): 927–45

Jungo P, Goyette S, Beniston M (2002) Daily wind gust speed probabilities over Switzerland according to three types of synoptic circulation. Int J Climatol 22: 485–99

Mitsuta Y, Tsukamoto O (1989) Studies on spatial structure of wind gust. J Appl Meteor 28: 1155–60

Nielsen NW, Petersen C (2001) Calculation of wind gusts in DMI-HIRLAM, Scientific report 01–03, Danish Meteorological Institute, Copenhagen

Ólafsson H (2004) Sandfoksveðrið 5, október 2004. Náttúrufræðingurinn 72(3–4): 93–4

Ólafsson H, Ágústsson H (2007) The Freysnes downslope windstorm. Meteorol Z 16(1): 123–130

Ólafsson H, Ágústsson H, Sigurjónsson H (2002a) Two cases of downslope windstorms observed during the Snæfellsnes experiment (SNEX). Proc. 23rd Nordic Meteorological Meeting. Available at http://www.vedur.is/starfsmenn/haraldur/(May 2004)

Ólafsson H, Sigurjónsson H, Ágústsson H (2002b) SNEX – The Snæfellsnes experiment, Proc. of the 10th conference on mountain meteorology, American Meteorological Society, Boston, pp 400–1

Ólafsson H, Jónasson N, Karlsdóttir S (2006) Háupplausnar reikningar til almennrar spágerðar (HRAS), lokaskýrsla. Technical Report 06011, Veðurstofa Íslands, Reykjavík. Available at http://www.vedur.is/utgafa/greinargerdir/ (March 2006)

Peltier WR, Scinocca JF (1990) The origin of severe downslope windstorm pulsations. J Atmos Sci 47(24): 2853–70

Reisner J, Rasmussen RM, Bruintjes RT (1998) Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. Quart J Roy Meteorol Soc 124B(548): 1071–107

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG (2005) A description of the Advanced Research WRF version 2. Technical Report NCAR/TN-468 + STR, National Center for Atmospheric Research

Smith RB (1985) On severe downslope winds. J Atmos Sci 42(23): 2597–603

Stull RB (1988) An introduction to boundary layer meteorology. Kluwer Academic Publishers, Dordrecht

Weggel JR (1999) Maximum daily wind gusts related to mean daily wind speed. J Struct Eng 125: 465–8

Wilks DS (2006) Statistical methods in the atmospheric sciences. Int Geophys Series, Vol. 91, 2nd edn. Academic Press, UK