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Article

The Freysnes downslope windstorm

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Abstract

A violent windstorm downstream of the mountain of Öræfajökull in SE-Iceland is studied with the help of observations from automatic weather stations and high-resolution simulations. In this windstorm, there is at the same time a strong downslope acceleration of the flow as well as an acceleration at the edge of the mountain. The downslope windstorm is associated with a low level stable layer and active wave breaking below a reverse wind shear in the lower troposphere. The meso- to synoptic scale flow of the Freysnes windstorm resembles the conditions during bora windstorms, but unlike the bora, there is warm air at the surface. The Freysnes windstorm is therefore suggested as a generic term for a warm bora-type downslope windstorm. The downslope wind speed is underestimated a few km downstream of the mountain, while the speed of the surface flow in the corner wind coming from the edge of the mountain is successfully reproduced by the numerical model. The method of Brasseur is applied for calculating the gusts, giving reasonably accurate gust factors. The study indicates that a reverse vertical windshear is a general characteristic of easterly windstorms in Iceland. Consequently, mountain wave breaking may also be more frequent than in many other windy places in the world.

Zusammenfassung

Ein sehr stürmischer Fallwind hinter dem Berg von Öræfajökull in Südost-Island wird anhand von Beobachtungen von automatischen Wetterstationen und hochauflösenden Simulationen untersucht. In diesem Fallwind gibt es gleichzeitig eine starke Beschleunigung der Luftströmung im Lee und an der Seite des Berges. Die leeseitigen Extremwinde sind mit einer stabilen Schicht in den unteren Niveaus und einer aktiven Schwerewelle verbunden, die unterhalb einer vertikalen negativen Windscherung in der unteren Troposphäre bricht. Die mesoskalige und synoptische Strömung der Luft während des Freysnes Fallwinds ähnelt den Bedingungen während der Bora, aber anders als in der Bora findet sich hier warme Luft am Boden. Der Freysnes Windsturm wird folglich als generelle Bezeichnung für eine warme Version der Bora vorgeschlagen. Die leeseitige Windgeschwindigkeit wird von unserem Modell einige Kilometer hinter dem Berg unterschätzt, während die bodennahe Windgeschwindigkeit der Luft, die den Berg umströmt, erfolgreich durch das numerische Modell reproduziert wird. Die Methode von Brasseur wird für die Berechnung der Böen angewandt und gibt eine recht genaue Böigkeit. Die Studie zeigt, dass eine negative vertikale Windscherung eine allgemeine Eigenschaft der östlichen Fallwinde in Island ist. Infolgedessen wird erwartet, dass das Brechen von Schwerewellen in der unteren Troposphäre in Island häufiger als in vielen anderen stürmischen Regionen auf der Erde zu beobachten ist.

1 Introduction

Strong, localized windstorms immediately downstream of mountains have been investigated by numerous authors. Such windstorms are generally associated with vertically propagating gravity waves in the troposphere. Favourable large-scale flow conditions for the generation of downslope windstorms include elements such as strong low-level winds and strong static stability at low levels. A reverse vertical windshear as described in SMITH (1985) may contribute to a downslope windstorm through trapping of wave energy, while a positive vertical windshear may also act positively through amplification of gravity waves (see review by DURRAN, 1990). Idealised cases of downslope windstorms and the associated gravity wave activity as well as real cases of downslope winds in many parts of the world have been studied by many authors. The real flow cases include the celebrated Boulder windstorms in westerly flow in North-America (e.g. DOYLE et al., 2000 and ref. therein), downslope windstorms in southerly flow in the Alps (e.g. JIANG and DOYLE, 2004), the bora windstorms in northeasterly flow in Croatia (SMITH, 1987; BELŬSIĆ and KLAIĆ, 2004; BELŬSIĆ et al., 2004 and ref. therein), windstorms in Norway in westerly flow (e.g. DOYLE and SHAPIRO, 2000; GRØNÅS and SANDVIK, 1999; SANDVIK and HARSTVEIT, 2005) and Greenland windstorms in westerly flow (DOYLE et al., 2005; RÖGNVALDSSON and ÓLAFSSON, 2003) as well as in easterly flow (ÓLAFSSON and ÁGÚSTSSON, 2006).

Downslope windstorms in Iceland have not taken up much space in the scientific literature so far. Yet, the

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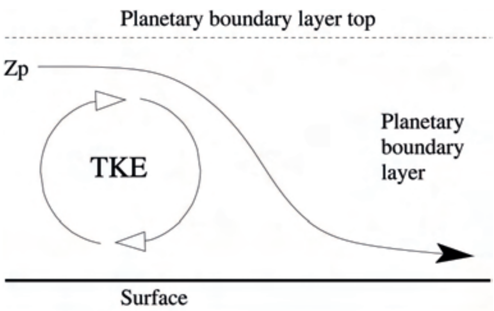
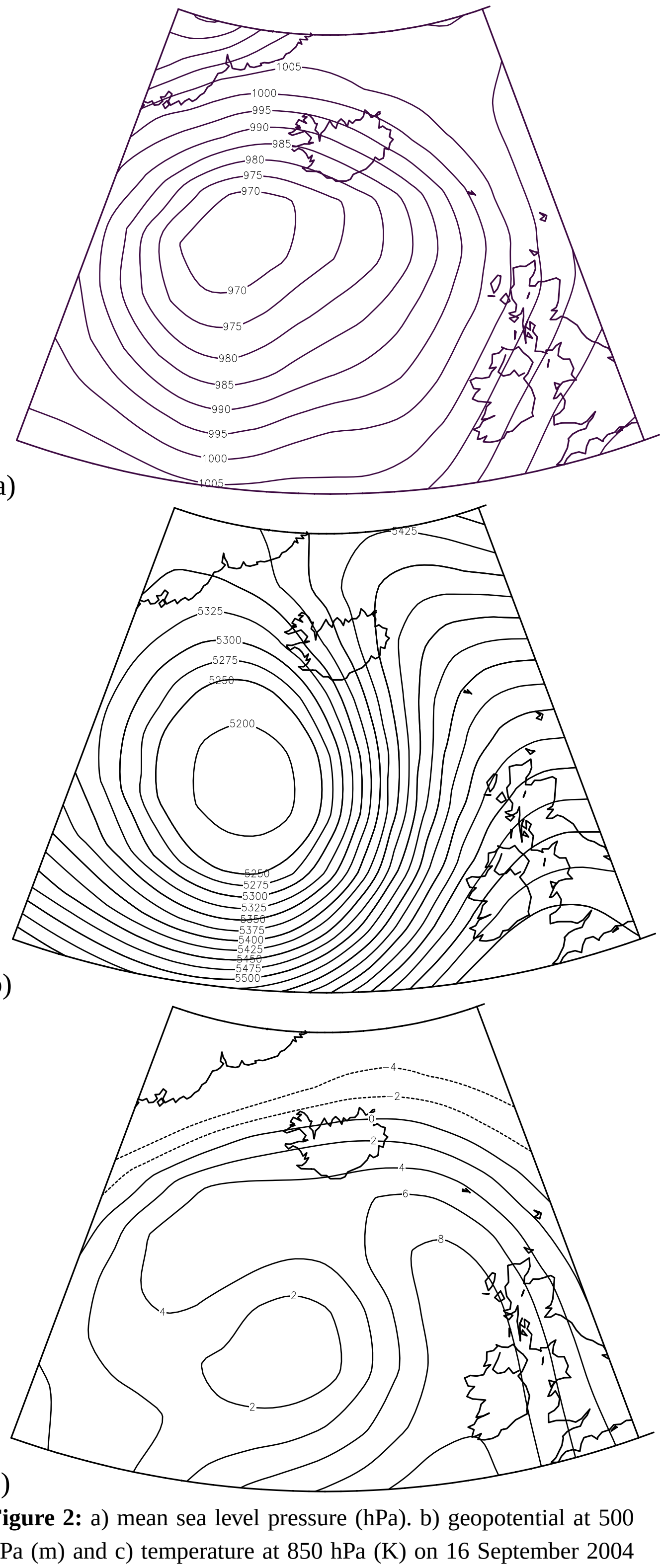


$$\frac{1}{z_p}\int_0^{z_p} TKE(z)\,\mathrm{d}z \geq \int_0^{z_p} \mathrm{g}\,\frac{\Delta\theta_v(z)}{\Theta_v(z)}\,\mathrm{d}z,$$

Figure 1: Illustration of Brasseur´s method of gust calculations. The left term represents vertically averaged turbulence kinetic energy (TKE) and the right hand term represents the vertically integrated buoyancy.

most violent winds in Iceland are in many if not most cases immediately downstream of mountains. There is a very long list of structural damage and accidents that can be associated with these windstorms. This was indeed the case in the Svínafell windstorm that hit the Freysnes and Skaftafell area on 16 January 1962. During this windstorm, a stone of 250 g was blown over a 7 m high house and blowing stones made a large number of holes in 0.7 mm thick roof-plates made of iron (SIGURÐSSON et al., 1963). Since 1999, a systematic collection of meteorological data has taken place in the mountainous Snæfellsnes peninsula in W-Iceland (The Snæfellsnes Experiment – SNEX). Numerous downslope windstorms have been observed during SNEX and two of them are documented in ÓLAFSSON et al. (2002). Both of the SNEX windstorms are associated with a warm layer close to the mountain top level and one of the two was a northerly windstorm with a reverse vertical windshear.

On the morning of 16 September 2004 a violent windstorm hit Freysnes, SE-Iceland. The windstorm was quite well forecasted in the region by the operational HRAS-system (ÓLAFSSON et al., 2006), which at that time ran the MM5 model (DUDHIA, 1993; GRELL et al., 1994) with a horizontal resolution of 9 km. Locally, the winds became however stronger than the direct model output indicated. Immediately downstream of the ice-covered Öræfajökull mountain (2110 m.a.s.l.) structural damage occurred, including a hotel that lost its roof. Here, the Freysnes windstorm is investigated by numerical simulations and observations from two nearby automatic weather stations. We employ the numerical model MM5 and nest down to a horizontal resolution of 1 km. Gusts are estimated with the method of BRASSEUR (2001). The 3D structure of the flow leading to the downslope windstorm is explored as well as the performance of our modeling system to reproduce the wind gusts and the mean winds at different horizontal resolutions. The observations of the windstorm are from Skaftafell which is located about 5 km downstream of the foot of the mountain, and from Öræfi which is lo-



a) b) c)

Figure 2: a) mean sea level pressure (hPa). b) geopotential at 500 hPa (m) and c) temperature at 850 hPa (K) on 16 September 2004 at 6 UTC. Provided by NOAA/CDC, based on NCEP/NCAR reanalysis.

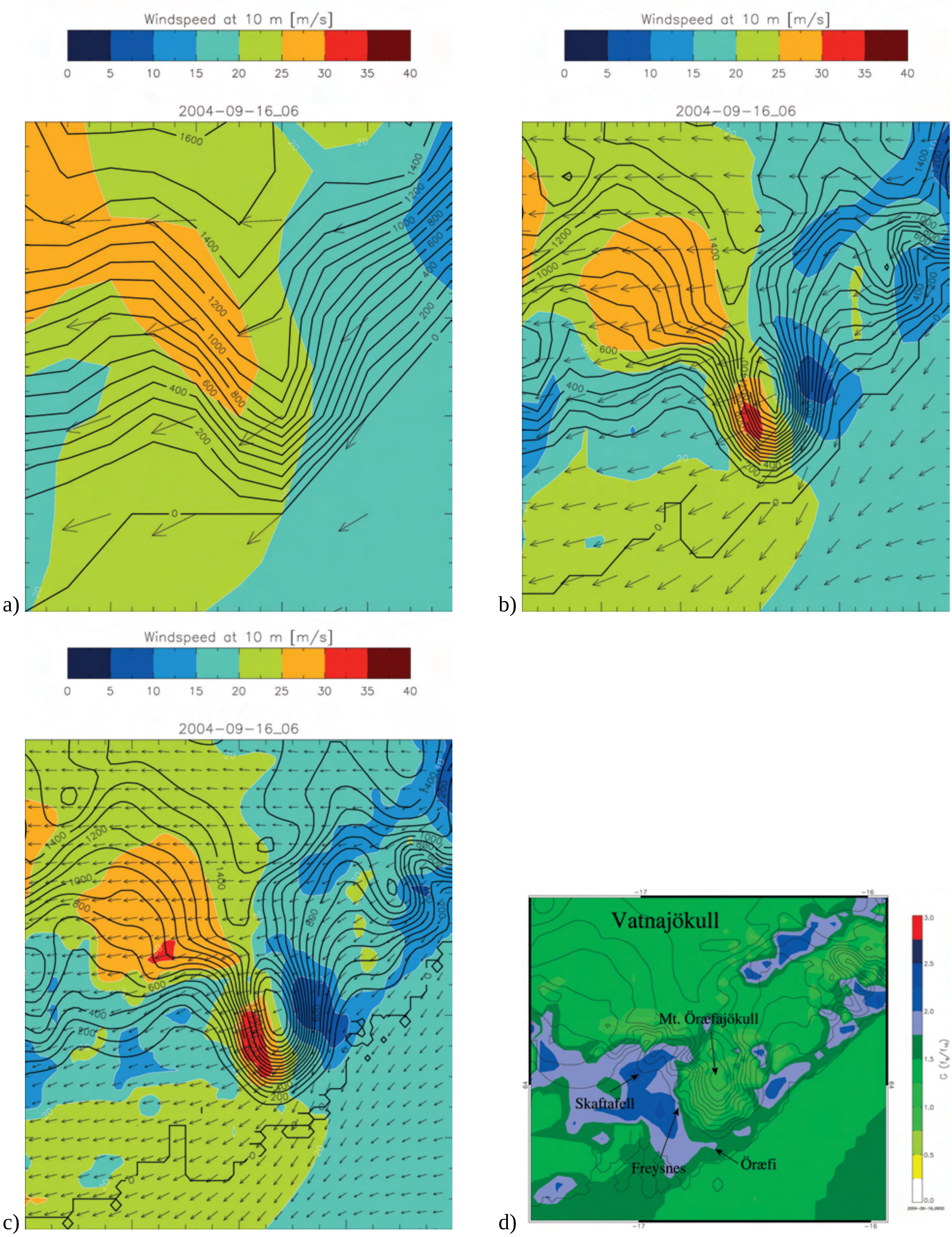


Figure 3: Simulated surface flow and topography (in m) SE-Iceland on 16 September 2004 at 06 UTC. a) surface wind speed (m s^{-1}) at a horizontal resolution of 9 km, b) surface wind speed (m s^{-1}) at a horizontal resolution of 3 km and c) surface wind speed (m s^{-1}) at a horizontal resolution of 1 km, d) gustfactors (calculated gusts divided by simulated mean wind speed), based on fields from the 1 km horizontal resolution.

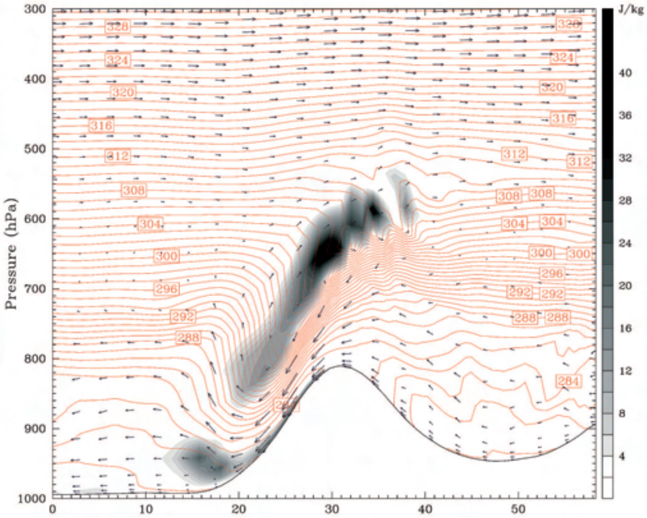


Figure 4: A cross section along the surface flow, across Öræfajökull mountain and Freysnes. The figure shows potential temperature (K), wind vectors and turbulence kinetic energy (J kg^{-1}).

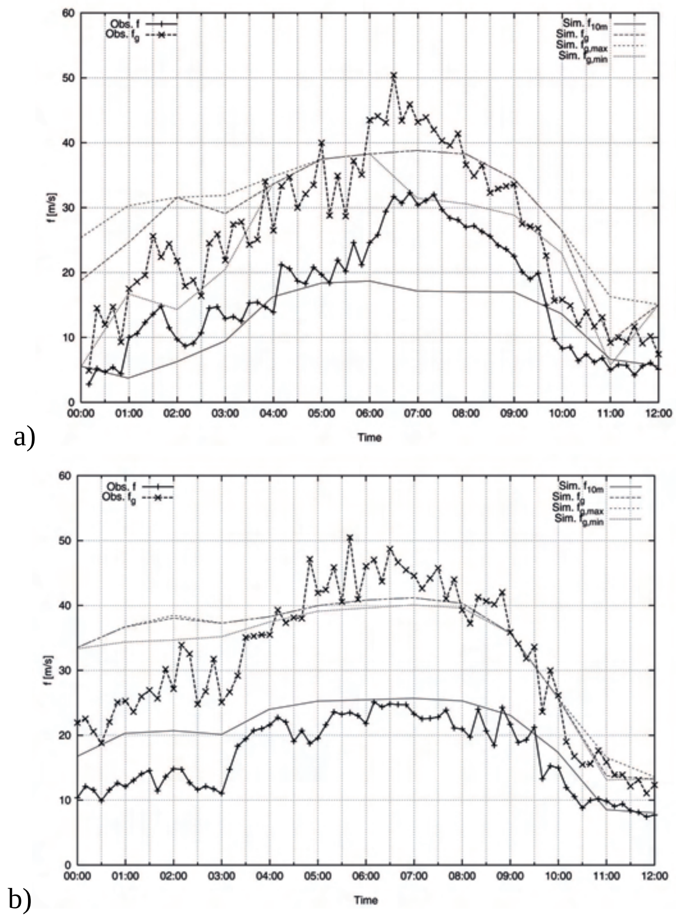


Figure 5: Observations and simulations of mean wind and wind gusts at a) Skaftafell (approx. 5 km downstream of the foothills of Öræfajökull mountain) and b) at Öræfi at the southern edge of Öræfajökull mountain (Time in UTC).

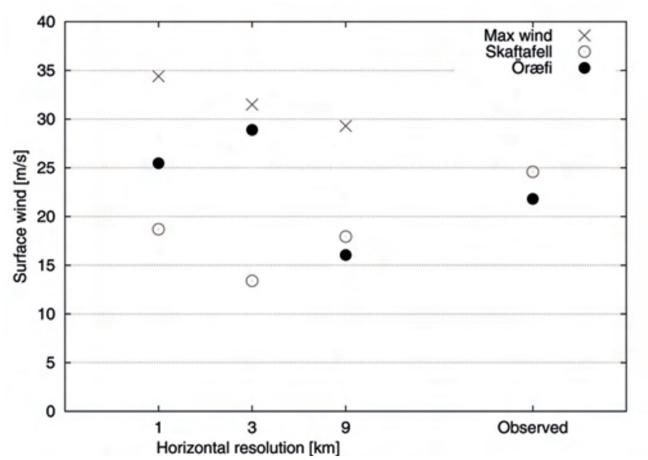


Figure 6: Observed and simulated maximum wind speed at Skaftafell (downslope) and Öræfi (corner wind) at different horizontal resolutions. The maximum simulated surface winds are also shown.

cated to the south of the mountain, in the flow speed-up at the mountain edge (corner wind). Structural damage occurred at Freysnes which is located less than 2 km from the foot of the mountain. The climatology of observed downslope windstorms in the area is explored as well as the general flow structure in easterly windstorms.

2 The numerical calculations of the flow and the gusts

In this study, the MM5 system is used (GRELL et al., 1994; DUDHIA, 1993) to simulate the atmospheric flow. The subgrid turbulence is parameterized using the ETA scheme (JANJIĆ, 1990; 1994). The calculations employ 40 levels in the vertical, reaching from the surface of the earth to about 100 hPa. The horizontal resolutions are 9, 3 and 1 km. The 9-km and 3-km simulation domains are centered over Iceland and they consist of 90 x 95 (9 km) and 148 x 148 (3 km) gridpoints. The 1-km domain has 157 x 175 points and is centered over the southern part of the Vatnajökull glacier. The initial and boundary conditions are from the operational analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF). The gusts are calculated with the method of BRASSEUR (2001). The method is based on the concept that surface wind gusts are equal to the strongest mean flow at a level (Zp), below which the vertically averaged turbulence kinetic energy exceeds the vertically integrated buoyancy. This method is illustrated in Fig. 1. The values of the parameters relevant for the gust calculations are retrieved from the innermost domain (1 km) of the MM5 simulation. Brasseur´s method for gust calculations has been tested with some success in windstorms by NORDSTRÖM (2005), in complex terrain by GOYETTE et al. (2003) and in bora downslope flow by

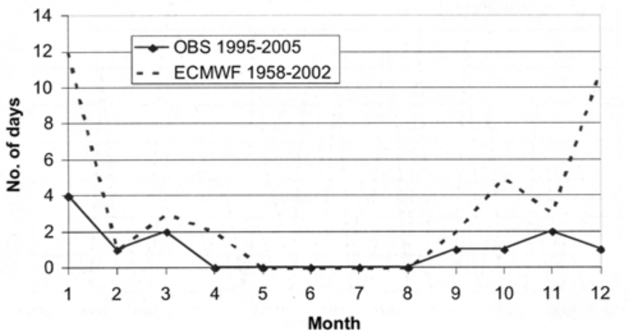


Figure 7: Seasonal variability of observed windstorms in Skaftafell (downslope) based on number of days with wind gusts greater than 40 m s^{-1} and the ECMWF reanalysis giving easterly (zonal) geostrophic wind speed at 1000 hPa greater than 40 m s^{-1}.

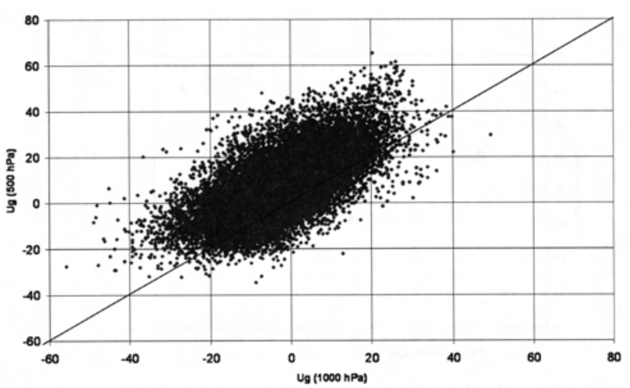


Figure 8: Zonal geostrophic wind speed (m s^{-1}) at 1000 hPa (x-axis) and at 500 hPa (y-axis) over SE-Iceland. Based on 12 hourly reanalysis from the ECMWF 1958–2002.

Belŭsić and Klaić (2004). To the knowledge of the authors of this paper, the method has not before been tested explicitly in a corner wind.

3 The Freysnes downslope windstorm on 16 September 2004

Figure 2 shows the mean sea level pressure, the geopotential height at 500 hPa and the temperature at 850 hPa at the time when windgusts of more than 50 m s^{-1} were observed at the Skaftafell and Öræfi weather stations (see Fig. 3d) for location of the stations). At the surface, the geostrophic winds are from the ESE, while over land the surface winds are from the ENE or NE (Fig. 3). At 500 hPa, the flow is weaker (20–25 m s^{-1}) and the wind direction is SSE. The temperature at 850 hPa corresponds to the difference between the pressure fields at 1000 and 500 hPa; there is a sector of warm air stretching from Ireland towards S-Iceland. In the early morning, the observed 2 m temperature at Skaftafell exceeded 13°C which is about 5°C above the seasonal average. The geostrophic wind at the surface is greater

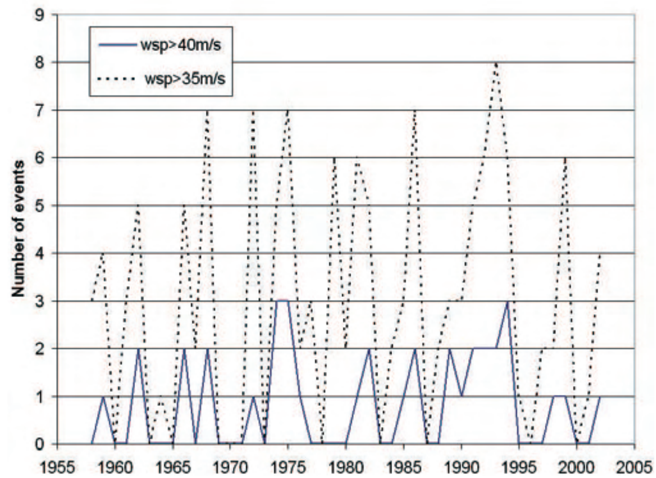


Figure 9: Annual number of cases with easterly (zonal) wind greater than 40 m s^{-1} and greater than 35 m s^{-1} over SE-Iceland. Based on geostrophic winds at 1000 hPa in the ECMWF reanalysis 1958–2002.

than 30 m s^{-1} and there is a directional and a reverse (negative) vertical wind shear in the lower part of the troposphere. Figure 3 reveals very strong winds over the Vatnajökull glacier and also locally over the lowlands. There is a pronounced wind speed maximum immediately downstream of the highest mountain (Öræfajökull). This maximum does not extend far downstream. There is also a local, but weaker maximum emanating from the edge of the same mountain. This maximum (the corner wind) extends far downstream. The flow is decelerated upstream of Öræfajökull. Figure 4 shows a cross section along the surface flow, over Öræfajökull, and through the area of maximum wind speed, which happens to be where Freysnes is located. The figure reveals very strong mountain wave breaking between approximately 800 and 550 hPa, a very stable layer at 750–800 hPa and very little wave activity above 500 hPa. There is strong turbulence associated with the wave breaking. At the surface, there is also a high concentration of turbulence kinetic energy.

4 Simulated and observed mean winds and gusts

Figure 5 shows that the simulation underestimates the maximum 10-min wind speed in the downslope flow at Skaftafell by about 13 m s^{-1}, while in the corner wind at Öræfi, the model reproduces the mean winds very well. The maximum gusts are underestimated by approximately 5–10 m s^{-1} at Öræfi and a little more at Skaftafell. The damage indicates that the winds were stronger at Freysnes than those observed at Skaftafell, which is located approximately 4 km further downstream than Freysnes. The mean wind simulation supports this (Fig. 3c), and so do the gust calculations, which indicate that the gusts at Freysnes may have been almost twice the mean wind speed. As can be seen in Fig. 6, the highest horizontal resolution (1 km) gives wind speeds that are in best agreement with observations, both at Skaftafell and Öræfi. The maximum simulated surface winds (34 m s^{-1}) are also greatest at 1 km horizontal resolution and the damage that occurred at Freysnes indicates that these winds are not being overestimated by the model. A major characteristic of this windstorm is the gustiness which was observed both at Skaftafell and Öræfi. The calculated gust factor field is shown in Fig. 3d). It is characterized by relatively low values over the ocean and over the Vatnajökull ice cap, but high values in the vicinity of the mountains, particularly on their downstream side. Upstream of Öræfajökull, the calculations also indicate a high gust factor. Over the ocean, as well as on the upstream side of the mountains, the gust factor may be somewhat overestimated, but there are no observations to verify this. At Skaftafell, the gust factor is somewhat overestimated, while the calculations underestimate the gust factor slightly in the corner wind at Öræfi (Fig. 5). The overall gust factor pattern is however quite realistic.

5 Climatology of the downslope windstorms

Regular wind observations have been carried out in Skaftafell since 1995. As expected, the windstorms occur only in winds from directions between north and east (not shown) and in winter (Fig. 7). The seasonal distribution is similar as in the reanalysis from the ECMWF. Both have a maximum in mid-winter and a complete absence of windstorms during the summer. Interestingly, both datasets figure a secondary minimum in February. Even though temperatures in Iceland are generally below average during northeasterly winds, the mean 2-m temperature at Skaftafell during the windstorms is 2,3°C above the seasonal average. From the ECMWF reanalysis the vertical structure of the atmosphere during the windstorms can be derived. Figure 8 shows a scatterplot relating the geostrophic wind over SE-Iceland at 500 hPa to the geostrophic wind at 1000 hPa during the period 1958–2002. The figure reveals that strong easterly windstorms at 1000 hPa, represented by the points furthest to the left on the graph, are without exception associated with a reverse vertical windshear, while in westerly windstorms (points furthest to the right on the graph) there is very often only a little vertical windshear and sometimes an increase in the zonal wind speed with height. According to the ECMWF reanalysis, there is no clear trend in the frequency of strong easterly windstorms in the southeast part of Iceland in the latter part of the 20th century, but there is a substantial interannual variability. (Fig. 9)

6 Discussion

The present case features spectacular breaking of a mountain wave. The atmospheric conditions are particularly favourable for the creation of the wave; strong winds and a stable layer close to mountain top level. The conditions for breaking the wave at low levels are also favourable; a reverse vertical wind shear and a change in wind direction with height. The simulation and the observations confirm that one can have a downslope windstorm and a strong corner wind at the same time. In fact, the previously mentioned stable layer contributes to both patterns. The climatological data indicates that strong easterly windstorms do not occur unless there is a reverse vertical windshear. To fulfill the thermal wind equation, such a windshear must be associated with a low-level north-south temperature gradient. The sector of warm air is therefore closely related to the reverse vertical windshear making these two features of the flow intimately linked to each other. The simultanous existence of a violent downslope wind, a strong corner wind and a zone with strongly decelerated air upstream of the mountain is of interest. According to classical linear theory (SMITH, 1989) and its extension into the non-linear regime (e.g. SMITH and GRØNÅS, 1993; MIRANDA and JAMES, 1992; ÓLAFSSON and BOUGEAULT, 1996; ÓLAFSSON, 2000; PETERSEN et al., 2005 and others), downslope windstorms, strong mountain waves and the so-called high-drag state are characteristics of flow with the non-dimensional mountain height (Nh/U) close to unity. For high values of Nh/U, the flow is strongly decelerated upstream and strong winds may occur at the edges of the mountain, while waves are damped and downslope flow is not fast. The numerical reproduction of the present case illustrates that in the complexity of the real flow, all these features may occur at the same time, given a favourable vertical structure of the flow.

The numerical simulation is in very good agreement with the observations in the corner wind (Öræfi), while the speed of the downslope flow at Skaftafell is underestimated. This may be because the model is underestimating the magnitude of the downslope windstorm, but another and perhaps more plausible explanation is that the model is underestimating the horizontal extension of the windstorm. In fact, DOYLE et al. (2000) showed that the structure of the wave breaking fields and the horizontal extension of the downslope windstorms is quite sensitive to both numerical dissipation and advection as well as representation of subgrid processes such as turbulence or eddy viscosity. The horizontal extension of downslope windstorms on the scale of the Freysnes windstorm will hopefully be dealt with in connection with the ongoing SNEX experiment in W-Iceland.

As in the bora flows, the wind gust estimate coincides with the maximum wind speed in the boundary layer (BELŬSIĆ and KLAIĆ, 2004), and an underestimation of the maximum gusts in the downslope flow at Skaftafell is probably associated with the underestimation of the mean winds. The underestimation of the strongest gusts in the corner wind (Öræfi) may be related to the maximum winds in the boundary layer being underestimated in a simulation where the slopes are inevitably a little more gentle than in reality. The ratio of gust strength to the mean wind is a little too high, but can be characterized as reasonably accurate in the downslope flow (Skaftafell). It is in accordance with the study of ÁGÚSTSSON and ÓLAFSSON (2004), where relatively high gust factors are observed a short distance downstream from high mountains. The simulated values of the gust factor over the ocean and over the Vatnajökull glacier are as high as 1.2–1.5 which may be a little high, but not unrealistic. The outcome of the gust calculations are therefore encouraging for the application of the method of Brasseur in both corner winds and downslope windstorms.

The climatology of the flows at low level and at 500 hPa indicates that there is always a reverse vertical windshear in the lower or middle troposphere during easterly windstorms in SE-Iceland (Ug less than about 35 m s^{-1}). Good conditions for trapping and downward reflection of wave energy can in other words often be expected to be present. Such downward deflection of wave energy has been associated with violent downslope winds at the surface. In this aspect, the easterly windstorms are fundamentally different from the westerly windstorms, where the wind speed increases often with height up towards the jetstream. The Freysnes windstorm does indeed resemble the bora windstorms in the sense that there is a statically stable layer at low levels and a reverse vertical windshear in the lower troposphere. However, unlike the bora, the Freysnes windstorms are warm close to the surface.

The topography appears to play a double role in generating the Freysnes windstorm. It is clear from the numerical simulations that the observed violent winds are associated with the downslope flow and the corner effect of Öræfajökull. However, from Fig. 2 and 3 it is evident that the larger scale low level flow turns anticlockwise as it meets the mountains of SE-Iceland. Over the coast, the winds are from the NE, while the offshore geostrophic surface wind is from the ESE/SE. Thus, the mountains of SE-Iceland contribute to a directional vertical windshear and presumably also to some speed-up of the low level flow, of which both encourage a previously described wave breaking.

The high frequency of violent easterly windstorms in SE-Iceland in December and January is of course related to the strength of the westerlies and the upper tropospheric jet being strongest in mid-winter. The rapid drop in February is however not in phase with the average frequency of intense windstorms in Iceland, but can be associated with the tropospheric flow being more meridional in February than in other parts of the winter season (JÓNSSON, 2002; 2003). In such a flow regime, a cyclone track into the Greenland sea is relatively common, giving high frequency of southerly windstorms, but relatively infrequent easterly and northeasterly windstorms.

7 Summary and conclusions

A violent windstorm in SE-Iceland, downstream of Öræfajökull mountain has been investigated. The area is known for violent downslope windstorms that on some occations have led to damage of strong constructions. This windstorm is named after the farm Freysnes, where a roof blew off a big building on the morning of 16 September 2004. The study has revealed a flow structure characterized by a low level stable airmass and a reverse vertical windshear in the lower to middle troposphere, leading to the generation and breaking of gravity waves over the mountain. The surface flow is however anomalously warm. These characteristics lead us to suggesting that the Freysnes windstorm may be used as a generic name for a warm version of the bora windstorms. This case features at the same time strong downslope and corner winds, underlining the fact that simple linear and even non-linear theories of uniform flows may indeed be very different from conditions in the real atmosphere. The study has revealed that strong low-level flow below weaker flows is a fundamental feature of easterly windstorms in SE-Iceland. This can be expected to be the case for Iceland in general.

At the observation site, the magnitude of the downslope windstorm is somewhat underestimated by the numerical simulations, and we suggest that this may be because of a too rapid deceleration of the flow once it has arrived in the lowland. The strong corner wind is very well reproduced and so are the gust factors as calculated by the method of Brasseur. When taking into account the overall flow pattern and the indirect wind observations by the structural damage at Freysnes, the study is quite conclusive on the forecasting benefits that can be gained from simulating the atmospheric flow numerically with a horizontal resolution of up to at least 1 km, and by applying Brasseur's method for gust forecasting.

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References

ÁGÚSTSSON, H., H. ÓLAFSSON, 2004: Mean gust factors in complex terrain. – Meteorol. Z. **13**(2), 149–155. Doi: 10.1127/0941-2948/2004/0013–0149.

BELŬSIĆ, D., Z. B. KLAIĆ, 2004: Estimation of bora wind gusts using a limited area model. – Tellus **56A**, 296–307.

BELŬSIĆ, D., M. PASARIĆ, M. ORLIĆ, 2004: Quasi-periodic bora gusts related to the structure of the troposphere. – Quart. J. Roy. Meteor. Soc. **130**, 1103–1121.

BRASSEUR, O., 2001: Development and application of a physical approach to estimating wind gusts. – Mon. Wea. Rev. **129**, 5–25.

DOYLE, J. D., M. A. SHAPIRO, 2000: A multi-scale simulation of an extreme downslope windstorm over complex topography. – Meteor. and Atmos. Phys. **74** (1–4), 83–101.

DOYLE, J.D., D. R. DURRAN, C. CHEN, B. A. COLLE, M. GEORGELIN, V. GRUBISIĆ, W. R. HSU, C. Y. HUANG, D. LANDAU, Y.L. LIN, G. S. POULOS, W. Y. SUN, D. B. WEBER, M. G. WURTELE, M. XUE, 2000: An intercomparison of model-predicted wave breaking for the 11 January 1972 Boulder windstorm. – Mon. Wea. Rev. **128** (3), 901–914.

DOYLE, J. D., M. A. SHAPIRO, Q. F. JIANG, D. L. BARTELS, 2005: Large-amplitude mountain wave breaking over Greenland. – J. Atmos. Sci. **62** (9), 3106–3126.

DURRAN, D. R., 1990: Mountain Waves and Downslope Winds. – In: BLUMEN, W. (Ed.): Atmospheric Processes over Complex Terrain, American Meteor. Soc. **23**, No. 45, 59–82.

DUDHIA, J., 1993: A nonhydrostatic version of the Penn State-NCAR mesoscale model: Validation tests and simulation of an Atlantic Cyclone and Cold Front. – Mon. Wea. Rev. **121**, 1493–1513.

GRELL, G. A., J. DUDHIA, D. R. STAUFFER, 1994: A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). – NCAR Tech. Note NCAR/TN-398+STR, 138 pp.

GRØNÅS, S., A. D. SANDVIK, 1999: Numerical simulations of local winds over steep orography in the storm over north Norway on October 12, 1996. – J. Geophys. Res. **104**, NO.D8, 9107–9120.

GOYETTE, S., O. BRASSEUR, M. BENISTON, 2003: Application of a new wind gust parameterization: Multiscale case studies performed with the Canadian regional climate model. – J. Geophys. Res. **198**, D13, 4374.

JANJIĆ, Z. I., 1990: The step mountain coordinate: Physical package. – Mon. Wea. Rev. **118**(7), 1429–1443.

—, 1994: The step-mountain eta coordinate model: Further development of the convection, viscous sublayer, and turbulent closure schemes. – Mon. Wea. Rev. **122**(5), 927–945.

JIANG Q. F., J. D. DOYLE, 2004: Gravity wave breaking over the central Alps: Role of complex terrain. – J. Atmos. Sci. **61**(18), 2249–2266.

JÓNSSON, T., 2002: Sveiflur III. Árstíðasveiflur á Íslandi. – Veðurstofa Íslands, Reykjavík, Iceland. Tech. Rep. no. 02033, 21 p. (In Icelandic, available at http://www.vedur.is/utgafa/greinargerdir/2002)

—, 2003: Langtímasveiflur IV - Illviðrabálkur. – Veðurstofa Íslands, Reykjavík, Iceland. Tech. Rep. no. 03020, 44 p. (In Icelandic, available at http://www.vedur.is/utgafa/greinargerdir/2003)

MIRANDA, P. M. A., I. N. JAMES, 1992: Non-linear three-dimensional effects on gravity-wave drag: splitting flow and breaking waves. – Quart. J. Roy. Meteor. Soc. **118**, 1057–1081.

NORDSTRÖM, M., 2005: Estimation of gusty winds. – Tech. Rep. **101**, (ISSN 1650-6553), Institute for Geosciences, University of Uppsala, Sweden. 42 pp.

ÓLAFSSON, H., 2000: The impact of flow regimes on asymmetry of orographic drag at moderate and low Rossby numbers. – Tellus **52A**, 365–379.

ÓLAFSSON, H., H. ÁGÚSTSSON, 2006: Observational and numerical evidence of strong gravity wave breaking in easterly flow over Greenland. – Inst. Meteor. Res. Reykavik, Iceland, Tech. Rep. 12 p.

ÓLAFSSON, H., P. BOUGEAULT, 1996: Nonlinear flow past an elliptic mountain ridge. – J. Atmos. Sci. **53**, 2465–2489.

ÓLAFSSON, H., H. ÁGÚSTSSON, H. SIGURJÓNSSON, 2002: SNEX – The Snæfellsnes Experiment. – Proc. Amer. Meteor. Soc., 10th Conf. Mount. Meteor., 2 p.

ÓLAFSSON, H., N. JÓNASSON, S. KARLSDÓTTIR, 2006: Háupplausnarreikningar til almennrar spágerðar (HRAS). – Tech. Rep. 06011, Veðurstofa Íslands, Reykjavík, Iceland. 24 p. (In Icelandic)

PETERSEN, G. N., J. E. KRISTJÁNSSON, H. ÓLAFSSON, 2005: The effect of upstream wind direction on atmospheric flow in the vicinity of a large mountain. – Quart. J. Roy. Meteor. Soc. **131**(607), 1113–1128.

RÖGNVALDSSON, Ó., H. ÓLAFSSON, 2003: A Case study of the Icelandic Trough. – Proc. Int. Conf. Alpine Meteor. (ICAM), Brig, Meteo-Suisse, CH, 4 p.

SANDVIK, A. D., K. HARSTVEIT, 2005: Study of a downslope windstorm over Southern Norway, Rjukan, 16. January 2000. – The Norwegian Meteorological Institute (met.no). Tech.Rep. 18/2005.

SIGURÐSSON, F. H., ARASON, H., M. LÁRUSSON, 1963: Veðrið, tímarit handa alþýðu, Útg. Félag íslenskra veðurfræðinga (Association of Icelandic Meteorologists). – Reykjavík, Iceland **2**, 60–62 (In Icelandic).

SMITH, R. B., 1985: On severe downslope winds. – J. Atmos. Sci. **43**, 2597–2603.

—, 1987: Aerial observations of the Yugoslavian bora. – Atmos. Sci. **44**, 269–297.

—, 1989. Hydrostatic airflow over mountains. – In: Advances in Geophysics **31**, 59–81.

SMITH, R. B., S. GRØNÅS, 1993: Stagnation points and bifurcation in 3-D mountain airflow. – Tellus **45A**, 28-43.