

The bimodal downslope windstorms at Kvísker

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Received: 28 August 2009 / Accepted: 10 June 2010
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Abstract Downslope windstorms at Kvísker in Southeast Iceland are explored using a mesoscale model, observations and numerical analysis of the atmosphere. Two different types of gravity-wave induced windstorms are identified. At the surface, their main difference is in the horizontal extent of the lee-side accelerated flow. Type S (Short) is a westerly windstorm, which is confined to the lee-slopes of Mount Öraefajökull, while a Type E (Extended) windstorm occurs in the northerly flow and is not confined to the lee-slopes but continues some distance downstream of the mountain. The Type S windstorm may be characterized as a more pure gravity-wave generated windstorm than the Type E windstorm which bears a greater resemblance to local flow acceleration described by hydraulic theory. The low-level flow in the Type E windstorm is of arctic origin and close to neutral with an inversion well above the mountain top level. At middle tropospheric levels there is a reverse vertical windshear. The Type S windstorm occurs in airmasses of southerly origin. It also has a well-mixed, but a shallower boundary-layer than the Type E windstorms. Aloft, the winds

increase with height and there is an amplified gravity wave. Climate projections indicate a possible decrease in windstorm frequency up to the year 2050.

1 Introduction

Severe orographic windstorms are frequent in many places throughout the world. Many of these windstorms have been studied and described in the scientific literature but the best known are perhaps the celebrated Boulder windstorms in Colorado (e.g. Clark et al. 1994). During the Boulder windstorms the gusts (i.e. the wind speed oscillations at periods on the order of seconds) have been reported to exceed twice the mean wind speed of nearly 25 m/s (see for instance a review by Durran 1990). Another example of extensively studied orographic windstorms is the Bora-windstorm at the Adriatic coast of Croatia (see the recent review by Grisogono and Belušić 2009). The Croatian Bora is in fact reminiscent of the Freysnes windstorms in Iceland, which have been characterized as a “warm Bora” by Ólafsson and Ágústsson (2007). The gustiness is an important characteristic of the downslope windstorms, and of flow downstream of mountains in general. According to a study based on a very large set of observations, the gust strength is on average 160% of the mean 10-min wind speed a short distance downstream of high mountains, provided that the mean winds are greater than 10 m/s (Ágústsson and Ólafsson 2004). Several recent studies, such as Belušić et al. (2004, 2007), focus on the nature of gustiness in downslope windstorms, which is generally considered to be associated with the pulsating nature of waves aloft (e.g. Clark and Farley 1984). From a forecasting perspective there is much to be gained by forecasting the gusts. It has for example been attempted by Goyette et al. (2003) and Ágústsson and Ólafsson (2009) for

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windstorms in complex terrain by using a mesoscale model and a method based on Brasseur (2001). Brasseur's method is partly based on a quantification of turbulence in the atmospheric boundary layer. Systematic observations of the turbulence are needed to verify this method and atmospheric models in general, but these are unfortunately not widely available. There are however reported cases of strong turbulence aloft in orographically disturbed flow, for example in flow above Greenland (e.g. Doyle et al. 2005; Ólafsson and Ágústsson 2009) that Lane et al. (2009) have recently studied in a systematic manner to identify flow regimes that contribute to unstable gravity waves and turbulence aloft. In addition, there are the large observational campaigns such as Grubišić et al. (2008), Renfrew et al. (2008) but these are limited in time and space. Durran (1990) provides a nice review on the theory and literature related to gravity waves and downslope windstorms while references to some of the more recent studies on atmospheric flow in complex terrain are for example found in the review by Smith (2004).

Orographic windstorms are common in Iceland and they frequently disrupt transportation on land and in the air, as well as causing damage to property and infrastructure. In general, the worst storms occur during winter when winds are locally enhanced by orography during the passage of deep cyclonic systems. There are many such infamous places in Iceland and the recent effort in studies of local severe winds has revealed that the studied windstorms are all related to gravity wave activity aloft. Some of the first studies of the still ongoing SNEX-project focused on windstorms on both sides of the Snæfellsnes peninsula in West Iceland (e.g. Ólafsson et al. 2002) while the study of Ágústsson and Ólafsson (2007) focused on an extreme windstorm and breaking waves aloft in northeasterly flow over Northwest Iceland. Here we turn our attention towards Kvísker in Southeast Iceland on the eastern flank of Mount Örfajökull (Fig. 1), where strong and gusty winds result in road closures and may even cause damage to the asphalt on the road. The easterly Freysnes downslope windstorm, named after the nearby farm at Freysnes in Örafi on the western side of Mt. Örfajökull, was the subject of previous studies (Ólafsson and Ágústsson 2007; Rögnvaldsson et al. 2010). The Freysnes downslope windstorm may be characterized as a warm version of the Croatian Bora. It occurs in an environment of gravity waves in a stably stratified flow, below a negative vertical windshear. The frequency of the Freysnes windstorms showed no clear trend during the latter half of the twentieth century. In this paper, the Kvísker windstorms are explored in a similar manner, i.e. using observations from automatic weather stations that have been erected to monitor the windstorms, as well as using global and dynamically downscaled numerical analysis of the atmosphere. In addition, possible changes in windstorm frequency are investigated using future projections of the wind climate.

The following section describes the atmospheric data and numerical simulations used in this study. An analysis of the windstorms using observational data as well as atmospheric analysis is given in Sect. 3 while the subsequent section shows results from high resolution simulations of the windstorms. Sect. 5 discusses the climatology of the Kvísker windstorms and the possible change in their frequency in a warmer future climate. Discussions and concluding remarks are given in the last two sections.

2 Atmospheric data

2.1 Observational data

At Kvísker (Fig. 1), there is an automatic weather station (WMO no. 04886), that was erected in 2002 to monitor the severe local windstorms. The weather station is located close to road no. 1 at 30 m above mean sea level, immediately east of Mt. Örfajökull (2110 m). The observational data includes the 10-min mean wind and 3-s (instantaneous winds) gusts at approx. 7 m above ground level. The station is operated by Vegagerðin (The Public Roads Administration) and the data is stored at Veðurstofa Íslands (VÍ) where it has been checked for systematic errors. Additionally, data from various other automatic weather stations in Iceland are used for validating the simulated large scale flow during the windstorms.

2.2 Atmospheric simulations

The windstorms are simulated with the non-hydrostatic mesoscale model, MM5 (Grell et al. 1995). The model is

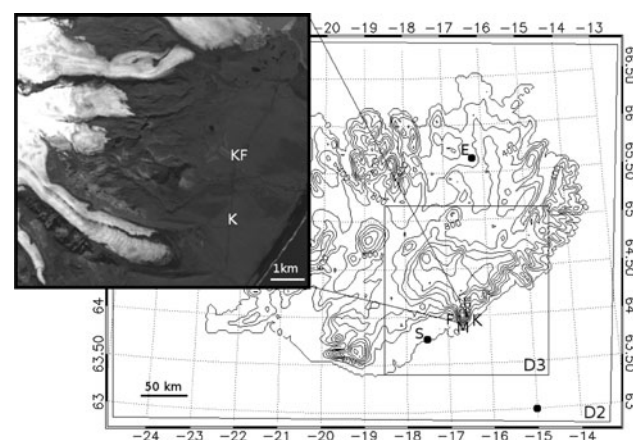


Fig. 1 The location of the farm at Kvísker (KF), the Kvísker weather station (K), the farm at Freysnes (F), Mt. Örfajökull (M) and the numerical domains with a horizontal resolution of 3 (D2) and 1 km (D3). Terrain contours have an interval of 200 m. Also marked with black circles are the locations of upstream vertical profiles E and S as well as the location 63°N 15°W

initialized and forced at its boundaries with operational analysis from the ECMWF. It is run at a resolution of 9, 3 and 1 km with 90×95 , 148×196 and 160×190 grid-points, respectively in the 1-way nested domains (Fig. 1). There are 40 σ -layers in the vertical, which are terrain following at lower levels but gradually flatten towards the top of the model at 50 hPa.

The relevant parameterization of moisture is the 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 predicts the turbulence kinetic energy. Model specifics are discussed in extensive detail in Grell et al. (1995). Apart from the innermost domain (D3, 1 km), the setup of the atmospheric model is the same as Reiknistofa í veðurfræði employs for high-resolution, realtime, simulation of weather in Iceland which is published online at: “<http://belgingur.is>” and is used in operational forecasting at e.g. VÍ.

2.3 Atmospheric analysis and climate projections

The zonal and meridional wind components southeast of Kvísker, at the point 63°N 15°W at the 500 and the 850 hPa levels are extracted from the ECMWF-analysis, using the ERA-dataset for the years 1967–1999 and the operational analysis for 2000–2007. The NCEP/NCAR-analysis is used to create composites of the atmospheric flows during the two types of windstorms that are revealed by the data.

In order to investigate a possible future extreme wind climate of the Kvísker region, we explore dynamic downscalings of two projections, one by the Bjerknes Climate Model (BCM) and one by the Hadley Centre simulations (HadAM3H). The downscalings were made with the HIRHAM modelling system, which is described together with the input data in Haugen and Haakenstad (2006) and Haugen and Iversen (2008). The data is provided through the ENSEMBLES-project (Hewitt and Griggs 2004). The global simulations are based on the IPCC A1B emission scenario. The HIRHAM downscalings are run in a domain that includes most of continental Europe and extends to the west and north of Greenland. It has a horizontal resolution of 25 km. In addition to a control run (1951–2000) and a future projection (2001–2050) the reanalysis from the ECMWF (ERA dataset, 1961–2000) was downscaled for evaluation of the control run. The data for this study are extracted from a point at 63°N 15°W at 850 and 500 hPa (Fig. 1).

3 Analysis of the windstorms

The hourly observational data from the period 2002–2007 (45,000 observations) include a large collection of

windstorms at Kvísker, with 102, 52 and 2 observations of gusts exceeding 35, 40 and 50 m/s, respectively. The observations are from 25 storms, some of which last more than one day, with approx. 3–5 occurring every year. A quarter of the storms are northeasterly while the remainder is westerly. This bimodal variability in the observed wind direction during the windstorms is investigated further using atmospheric analysis.

The zonal and meridional wind components in the ECMWF-analysis at the 500 and 850 hPa levels reveal two very different classes of atmospheric states when windstorms ($f_g > 35$ m/s) are observed at Kvísker (Fig. 2). The first type of windstorms, here denoted as Type S (Short), is characterized by strong westerly winds throughout the troposphere with a forward vertical wind shear. As discussed in the subsequent sections, Type S refers to their short horizontal extent as opposed to the northerly windstorms which are characterized by a greater horizontal extent. For a subset of the westerly windstorms with observed gusts exceeding 40 m/s there is, according to the NOAA/CDC analysis, on average at all tropospheric levels a low-pressure region to the north of Iceland and high pressure to the south (Fig. 3). These westerly windstorms are more common and severe than the northerly storms with the observed gusts exceeding 50 m/s, e.g. on the morning of 25 January 2007 (Fig. 4). The mean wind speed during this windstorm was as high as 36 m/s but the windstorm was relatively short and lasted only for approximately 12 h.

The northerly windstorms, classified as Type E (Extended), are in general neither as strong or as common as their westerly counterparts. They are characterized by strong northerly winds at lower levels and a reverse and a directional vertical wind shear (weaker and more easterly aloft). For a subset of the northerly storms with gusts greater than 40 m/s there is on average a surface high over Greenland and a low to the southeast of Iceland giving rise to a strong SE-NW oriented surface pressure gradient. Aloft there is a N-S oriented trough above East Iceland with the jet to the west and south of Iceland (Fig. 5).

4 Simulations of the windstorms

The flow during the strongest windstorms of both types has been simulated. These windstorms are characterized by similar large scale systems as in Figs. 3 and 5.

The large scale simulated flow at 3 km horizontal resolution is on average in good agreement with the observed winds from a collection of automatic weather stations (Fig. 6) and satellite-derived sea surface winds (not shown). The simulated structure of the wind field becomes more realistic as the horizontal resolution is increased from

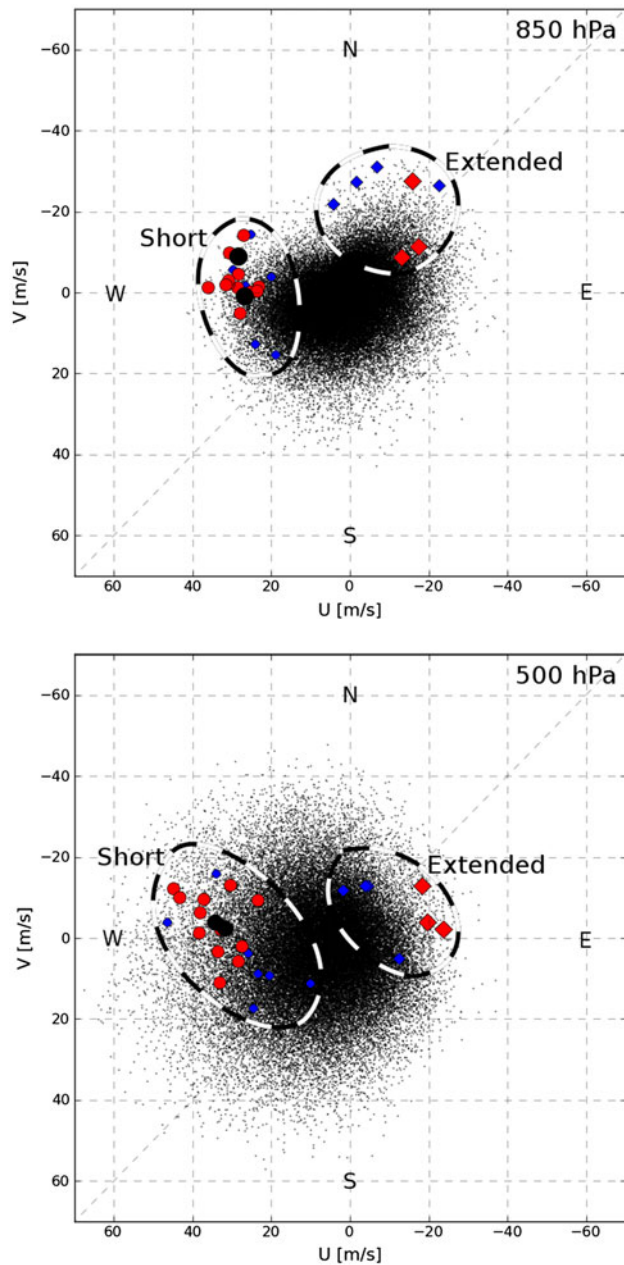


Fig. 2 Zonal and meridional wind components at $63^{\circ}\text{N } 15^{\circ}\text{W}$ at 850 (above) and 500 hPa (below) in the ECMWF-analysis (1967–2007) at 6 h intervals (small black dots). Atmospheric states coinciding with observations of gusts at Kvísker exceeding 35, 40 and 50 m/s, are marked with blue (small), red (medium) and black (large) symbols, respectively. Also indicated are the sets of atmospheric states coinciding with observed westerly windstorms of Type S (Short) and observed northeasterly windstorms of Type E (Extended). The axes are reversed so the labelled wind directions correspond to the direction the wind blows from

9 km to 3 km and from 3 km to 1 km (1 km in Fig. 7) and the winds are in general in better agreement with the observations from various stations throughout Iceland (not shown). The simulated flow is characterized by the large

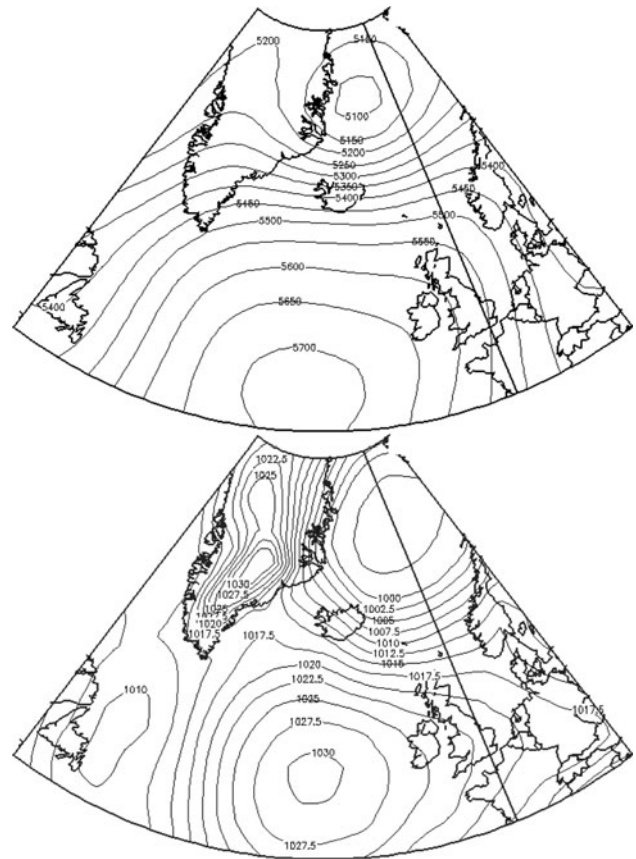


Fig. 3 Mean geopotential, m (above) and sea level pressure, hPa (below) during westerly windstorms when observed gusts at Kvísker exceed 40 m/s (17 dates from NOAA/CDC analysis)

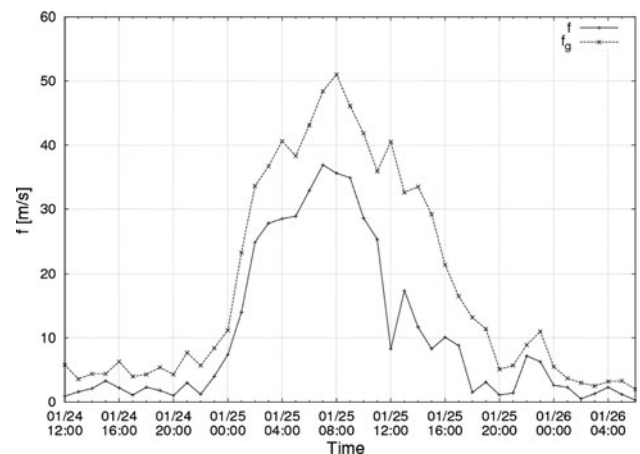


Fig. 4 Observations at Kvísker of mean winds, f (m/s), and gusts, f_g (m/s), during the windstorm of 25 January 2007

spatial variability in the surface winds. There are regions of decelerated flow as weak as 0–5 m/s in regions of sheltering, e.g. upstream of mountains, and there are regions of accelerated flow in excess of 30 m/s in corner winds and on the lee-side slopes of mountains.

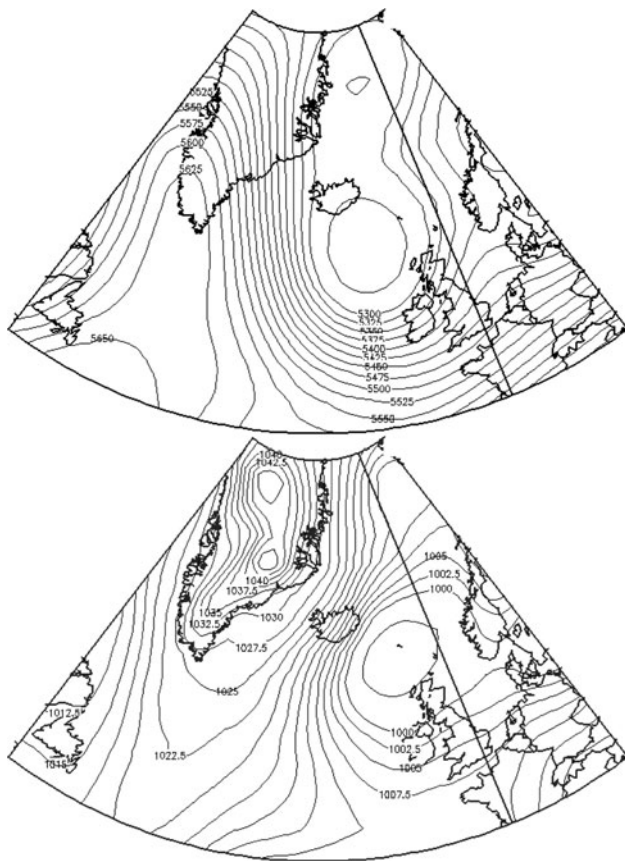


Fig. 5 Mean geopotential, m (*above*) and sea level pressure, hPa (*below*) during northerly windstorms when observed gusts at Kvísker exceed 40 m/s (3 dates from NOAA/CDC analysis)

The most striking difference between the simulated surface flow during the two windstorms is the downstream extent of the lee-side accelerated flow. Simulations of the strongest northerly windstorm (Type E, Extended) on 18 October 2004 show strong winds in a large area over the lee-slopes and downstream of the mountains, including at Kvísker (Figs. 6, 7, 8). Above the lee-slopes along section B, the flow descends and accelerates until it reaches a feature similar to a hydraulic jump slightly downstream of the mountain. Here there are large values of widespread turbulence kinetic energy (TKE, not shown).

In the westerly windstorm (Type S, Short) of 25 January 2007, the strong and gusty winds predicted at Kvísker are very localized and confined to the lee-side slopes of the mountain. The maximum easterly extent of the high winds region is near the weather station at Kvísker. Section A across Mt. Öraefajökull reveals large amplitude gravity waves aloft and Kvísker is located below the descending part of the first wave where the winds are strongest and just upstream of the bottom of the wave. The winds are much weaker only slightly further downstream. There are significant amounts of TKE in the region of high wind shear

near the surface and in the descending part of the wave, as well as in the rising part of the first wave (not shown). There is a rotor with positive vorticity beneath the first lee-wave with reversed flow near the surface. Section A shows only the first wave in a short series of lee-waves.

The observed winds and gusts at Kvísker during the northerly windstorm of 18 October 2004 are well captured at a resolution 3 and 1 km (1 km in Fig. 9). The performance is poorer during the westerly windstorm of 25 January 2007 as the simulated wind speed oscillates from 4 to 27 m/s in the early hours of the windstorm, and again to 5 m/s before the end of the observed windstorm. The observed gusts are in general well captured when the surface winds are correctly simulated. The observed gusts are predicted (Figs. 9, 10) using the model output at 1 km and the same method as in Ágústsson and Ólafsson (2009). This method is based on Brasseur (2001) and the concept that surface gusts are equal to the strongest mean winds at a level aloft, below which the vertically averaged TKE exceeds the vertically integrated buoyancy.

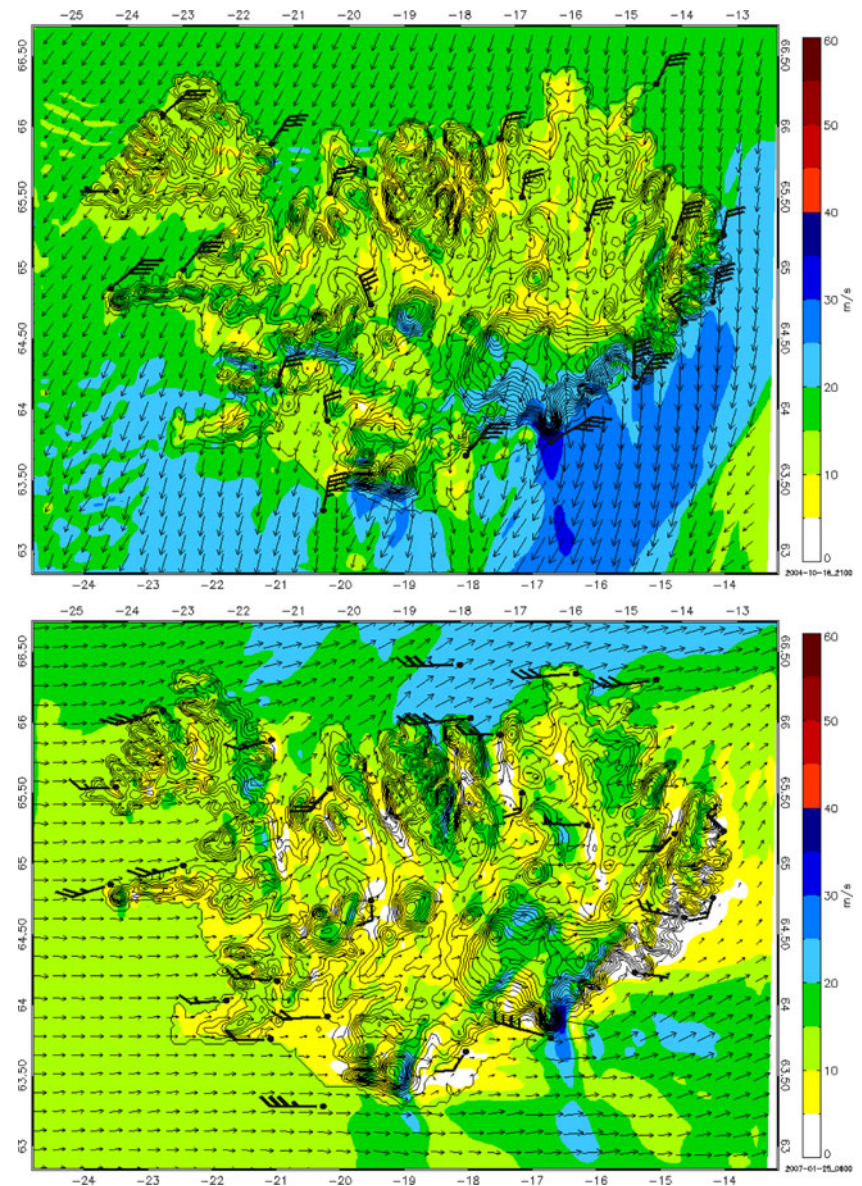
The predicted gust field shows similar features as the simulated surface winds, i.e. very strong lee-side gusts of nearly 50 m/s and widespread downstream extent of the strong gustiness during the Type E windstorm but a localized maximum on the mountain slopes during the Type S windstorm.

There is a clear difference between the upstream conditions during the northeasterly and the westerly windstorms (Fig. 11, locations S and E in Fig. 1). The westerly windstorm of 25 Jan 2007 is characterized by a relatively well mixed and shallow boundary layer, with strong forward wind shear at lower levels. The conditions during the northeasterly windstorm on 18 Oct 2004 are characterized by a much deeper boundary layer and on average a reverse and directional vertical wind shear above the boundary layer.

5 Past and future windstorm climate

Figure 2 shows that the winds at 850 hPa exceed 20 m/s during the westerly windstorms of Type S. A similar criterion for the northerly windstorms of Type E is not as clear but the winds are however on average northeasterly and greater than 20 m/s. There is a significant number of outliers with stronger winds which are not associated with observed windstorms at Kvísker. As previously mentioned, the westerly windstorms are associated with a positive wind shear and they are in general stronger at 500 hPa than at 850 hPa. The windstorms are however not associated with the strongest winds at 500 hPa. The opposite is true for the northerly windstorms with winds slightly weaker and more easterly at 500 hPa than at 850 hPa.

Fig. 6 Simulated surface wind speed (m/s) and vectors, as well as terrain contours with a 100 m interval at a resolution of 3 km at 21 UTC on 18 October 2004 (*above*) and at 06 UTC on 25 January 2007 (*below*). Also shown are observed winds at chosen weather stations

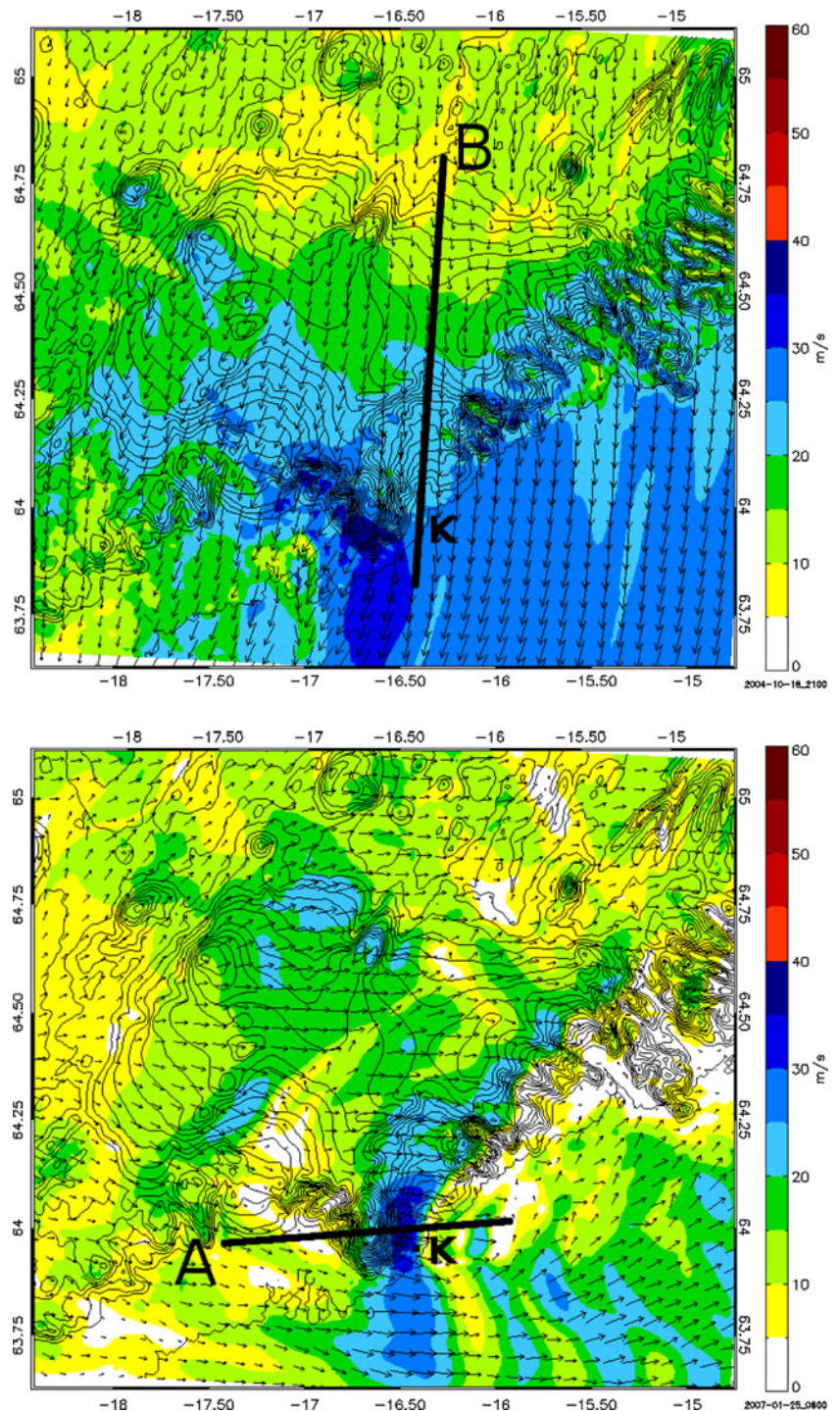


The seasonal cycle (Fig. 12) at 500 hPa is characterized by very few occurrences of strong winds during the summer months, i.e. May–August. The westerly winds are on average strongest during the early winter while the northerly winds have a maximum in late autumn and late winter. In spite of the relatively small set of observed windstorms, there is a correlation with the strongest winds aloft during the winter months. The peak in October is related to a single, long event. On an inter-annual basis there are strong variations in the strength of the winds aloft (Fig. 13). The increase in the number of observed windstorms from 2002 and 2005, and the subsequent decrease in their number in 2007, correspond to the variations in the strength of the winds aloft. The set of observed windstorms is however too small for any statistical significance.

There is on average an agreement between the ECMWF-analysis at 63°N 15°W and the dynamical downscaling of the same analysis by the HIRHAM model (not shown). The main discrepancy is related to weaker southwesterly winds at 500 hPa as well as weaker south and southwesterlies at 850 hPa in the climate model than in the ECMWF-analysis.

The dynamical downscaling of the two climate simulations shows far too weak westerlies in the control run (1951–2000) when compared to the downscaled ECMWF-data. Both future projections for 2001–2050 show a decrease in the westerlies at 500 hPa on the order of 3–4 events per year which is statistically significant at the 99% level. At 850 hPa there is a disagreement between the future projections for the possible change in the frequency of strong westerly and easterly winds. These results are summarized in Fig. 14.

Fig. 7 Simulated surface wind speed (m/s) and vectors, as well as terrain contours with a 100 m interval at a resolution of 1 km at 21 UTC on 18 October 2004 (*above*) and at 06 UTC on 25 January 2007 (*below*). Also shown is the location of Kvísker and sections A and B

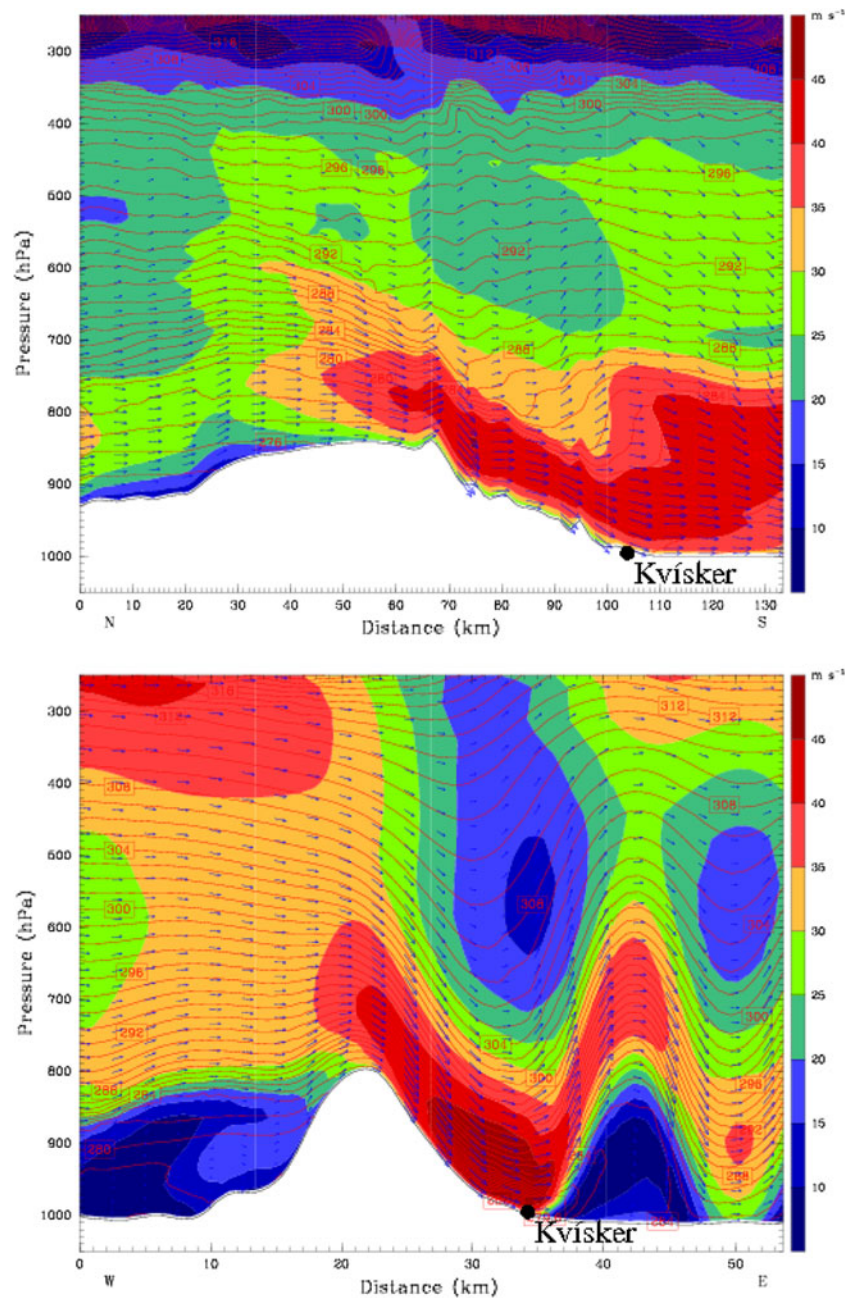


6 Discussion

The atmospheric data presented here reveals the bimodal nature of the Kvísker downslope windstorms. The spectacular gravity-wave induced windstorms are characterized by different vertical and horizontal structures of the atmospheric flow. The stronger of the two types of downslope windstorms are the westerly windstorms of Type S

which are very localized and limited to the lee-side slopes of Mt. Örfajökull. The flow aloft is characterized by a short series of large-amplitude lee-waves. The airmass is of southern origin and it has been cooled from below on its way north. It has only a shallow boundary layer whose mixing is presumably due to strong winds. There is an inversion near the mountain top level. The upstream observed sounding at Keflavík for the windstorm on 00

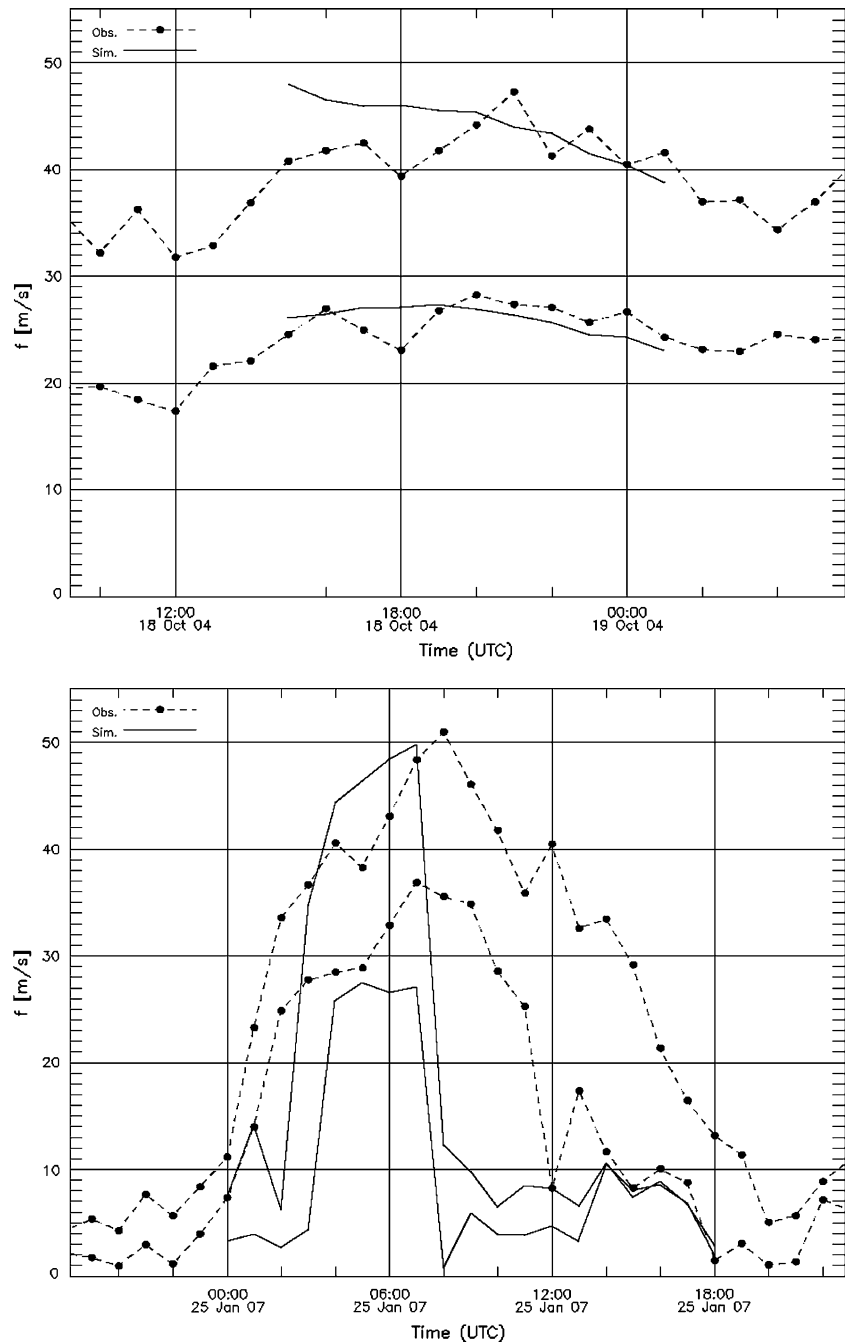
Fig. 8 Simulated wind speed (m/s) and isentropes (K) in sections A and B at a resolution of 1 km at 21 UTC on 18 October 2004 (*above*) and at 06 UTC on 25 January 2007 (*below*). Also shown is the location of Kvísker



UTC on 25 January 2007 represents well the Type S windstorm (Fig. 15). The sounding shows the considerable forward wind shear as the wind speed increases upwards towards the jetstream which is on average zonally oriented over Iceland during the windstorms. The northerly windstorms of Type E are less frequent than the Type S windstorms. They feature a large region with turbulent and strong flow down the slopes of the mountain. There is a feature similar to a hydraulic jump at the foot of the mountain, yet the flow does not experience much deceleration. The flow aloft is characterized by a reverse and directional vertical wind shear and a deep and well mixed

boundary layer with an inversion well above the mountain tops. These airmasses are of arctic origin but boundary layers of such airmasses tend to deepen when they travel southward over warmer seas (see e.g. Ólafsson and Økland 1994; Brummer 1996). With the jet being located to the west of Iceland, the flow is far weaker aloft than at the surface and the gravity waves generated in the low-level flow are unable to propagate vertically as in the westerly windstorms where the forward vertical wind shear contributes to the amplification of the waves. Consequently the waves in the Type E windstorm are less likely to amplify, instead they overturn and break at low levels. In this aspect

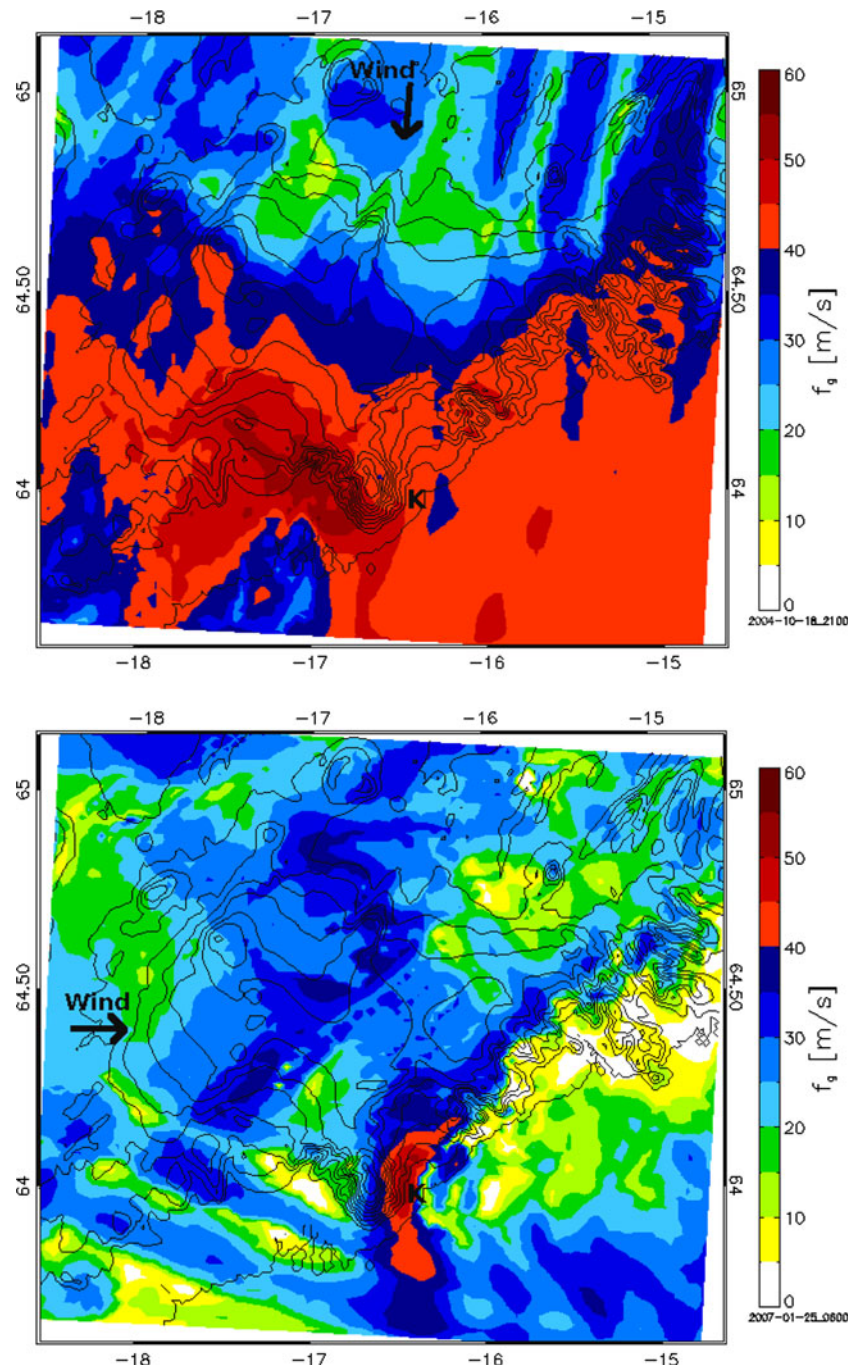
Fig. 9 Observed and predicted wind speed and gusts (m/s) at a resolution of 1 km at Kvísker during the windstorm of 18 October 2004 (*above*) and 25 January 2007 (*below*)



the Freysnes downslope windstorm (Ólafsson and Ágústsson 2007) resembles the Type E windstorm in the northerly flow. However, the Freysnes windstorm does not extend as far from the mountain as Type E does in this study. From a dynamic perspective, the Type S windstorm may be characterized as a more pure gravity-wave generated windstorm, while the Type E bears a greater resemblance to local flow acceleration described by hydraulic theory, based on a flow transition from a supercritical to a subcritical state (Durrán 1990).

In the present two cases, there are no direct observations of the atmosphere aloft. The simulations must be verified by comparison with observations at the ground, mainly from automatic weather stations. In general, the greatest errors in the simulated flow, both speed and direction, are found near complex (subgrid) topography or at locations where surface roughness may be expected to be overestimated in the model, as is e.g., possibly the case in the southwestern lowlands (cf. Fig. 6). At Kvísker, the surface flow is well captured during the northerly windstorm of 18

Fig. 10 Parameterized gust strength (m/s) and 100 m terrain contours at a resolution of 1 km at 21 UTC on 18 October 2004 (*above*) and 06 UTC 25 January 2007 (*below*). Also shown are the large scale wind direction and the location of Kvísker



October 2004 but the atmospheric model did worse during the westerly windstorm on 25 January 2007. There is in general an improvement in the model performance as the horizontal resolution is increased and a grid size of 3 km or less is necessary to capture the gravity wave activity. At coarser resolutions the mountains are simply not sufficiently high and steep to successfully reproduce the gravity waves. An in depth investigation of the simulated wind field during the westerly windstorm indicates that the storm and the amplitude of the gravity wave reach their peak

slightly too early in the atmospheric model and are not as strong as observed at Kvísker. This error may be related to an error in the boundary conditions, i.e. the large scale flow, which forces the mesoscale simulation model but it may also be related to errors in the development in the mesoscale structures in the vicinity of Mt. Öraefajökull. A small change in the large scale flow, may lead to a large local change in the winds, as was for example the case in the ensemble based study of Reinecke and Durran (2009) where the predictability of downslope windstorms was

Fig. 11 Skew-T diagrams from simulation at a resolution of 1 km, for the northeasterly windstorm (*above*, loc. E in Fig. 1) at 21 UTC on 18 October 2004 and for the westerly windstorm (*below*, loc. S) at 06 UTC on 25 January 2007. Shown are wind barbs, temperature and dew point ($^{\circ}\text{C}$)

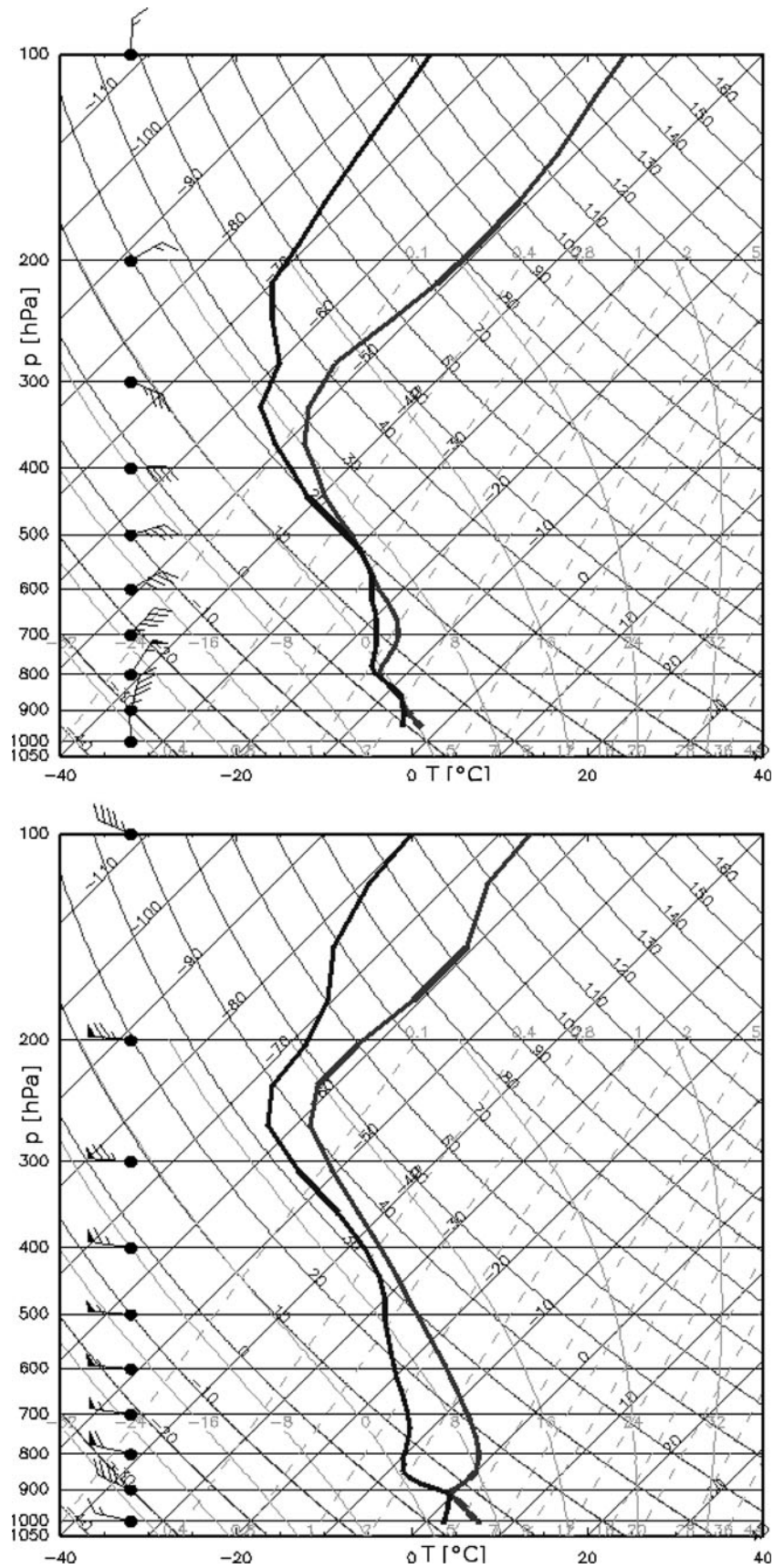
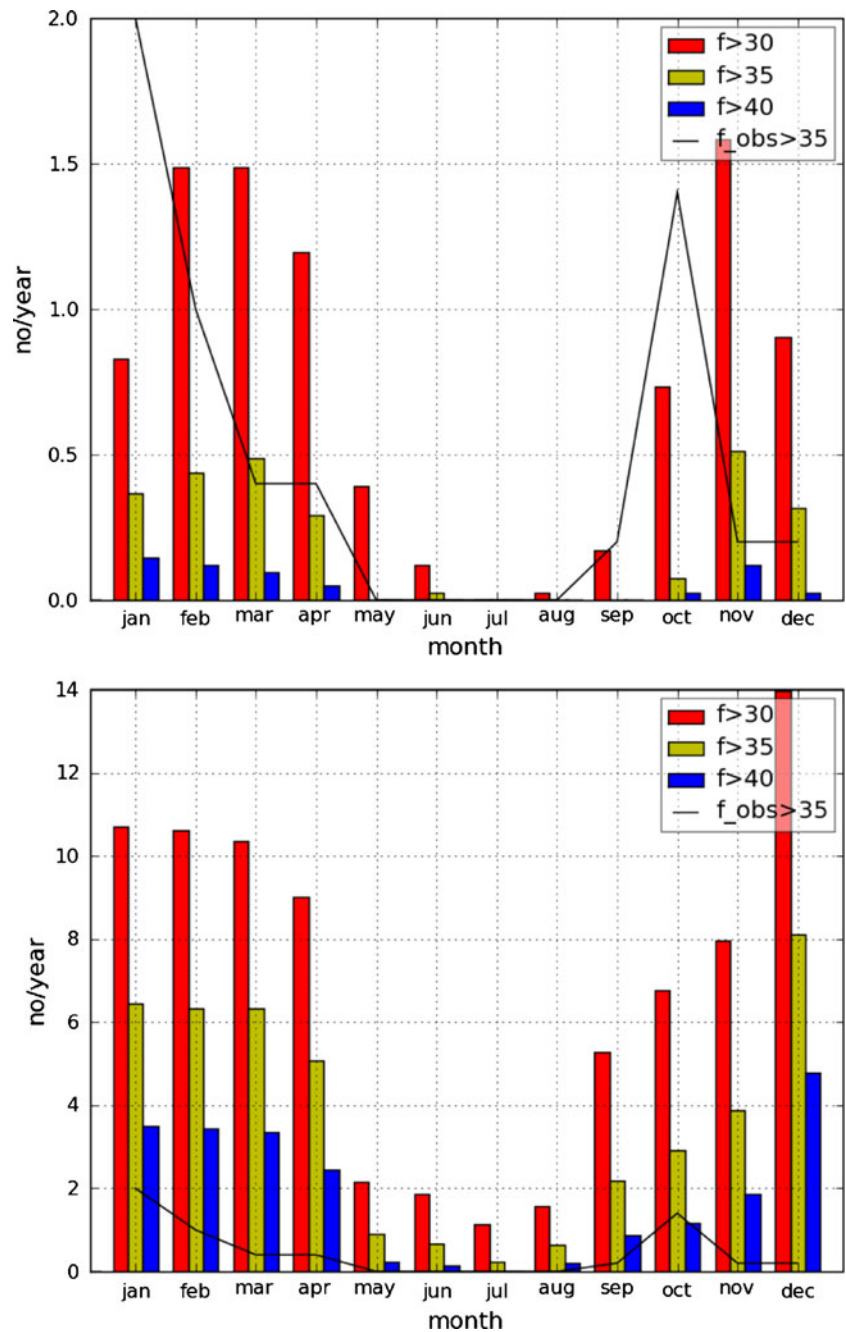


Fig. 12 Number of cases of northerly (*above*) and westerly (*below*) winds per month greater than 30, 35 and 40 m/s at 500 hPa at 63°N 15°W in the ECMWF-analysis (1967–2007) at 6 h intervals. Also shown is the total number of observed windstorms per month observed at Kvísker (*solid line*)



found to be very sensitive to small modifications in the upstream conditions. Similarly, in a previous study (Doyle et al. 2000) slight changes to structures in the lower stratosphere were shown to have a large impact on stratospheric wave-breaking. A premature decrease in the wave amplitude may thus be caused by a small change in the upstream flow, leading to the wave and the windstorm reaching a too short distance down the lee-side slope, thus leaving Kvísker out of the high-speed region after 7 UTC. In other words: the windstorm lasts too short at the site of

Kvísker while the model still generates strong winds further upstream on the mountain slopes. This explains the poorer performance of the model during the very localized westerly windstorm and underlines the difference of these windstorms from a forecasting perspective. The widespread Type E windstorm is easier to forecast locally than the very local Type S windstorm. This is in fact a well known problem in interpreting and verifying atmospheric flow simulated at high resolution as e.g. pointed out by Ágústsson and Ólafsson (2007) in an investigation of a

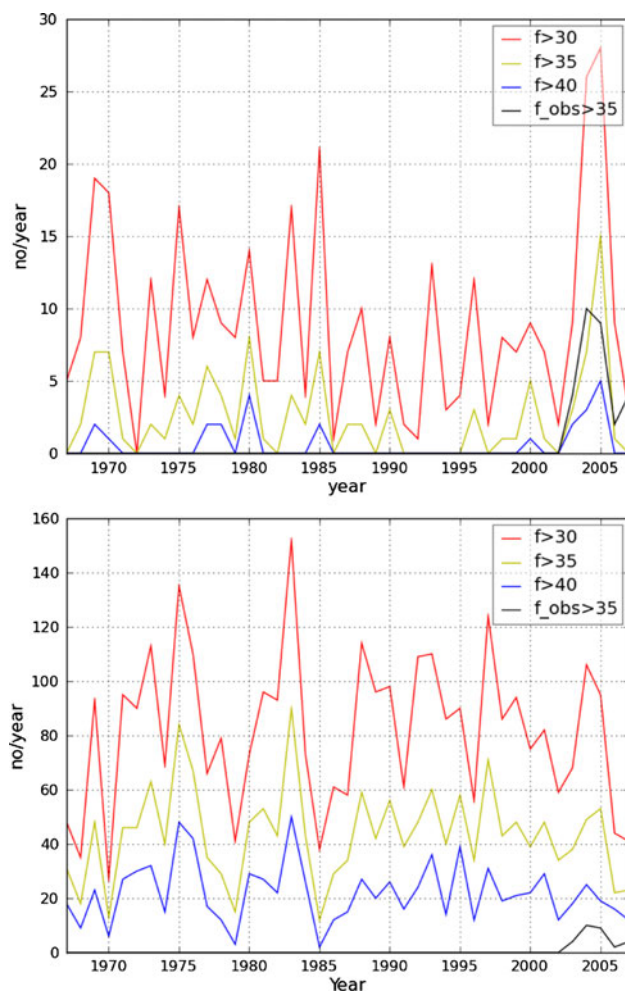


Fig. 13 Number of cases of northerly (*above*) and westerly (*below*) winds per year greater than 30, 35 and 40 m/s at 500 hPa at 63°N 15°W in the ECMWF-analysis (1967–2007) at 6 h intervals. Also shown is the total number of observed windstorms per year observed at Kvísker (*solid line*)

windstorm in the complex terrain of Northwest Iceland. Operational forecasting systems (e.g. the HRAS-system¹) based on non-hydrostatic mesoscale models frequently forecast windstorms in complex terrain which reach a variable distance down the lee-side of big mountains like Mt. Öræfajökull but are however not always observed on the lowlands. Many of these windstorms on Mt. Öræfajökull are verified by mountain guides and climbers on treks starting in good weather at the lowlands but ending in very bad weather near 1100–1300 m on the mountain. In these situations, the mountain is often capped by a lenticular or cap cloud while the neighbouring region is less cloudy or even cloud-free. In this way, the validity of the simulated flows in this study are supported by satellite images showing evidence of subsidence in the gravity waves on

¹ <http://belgingur.is>.

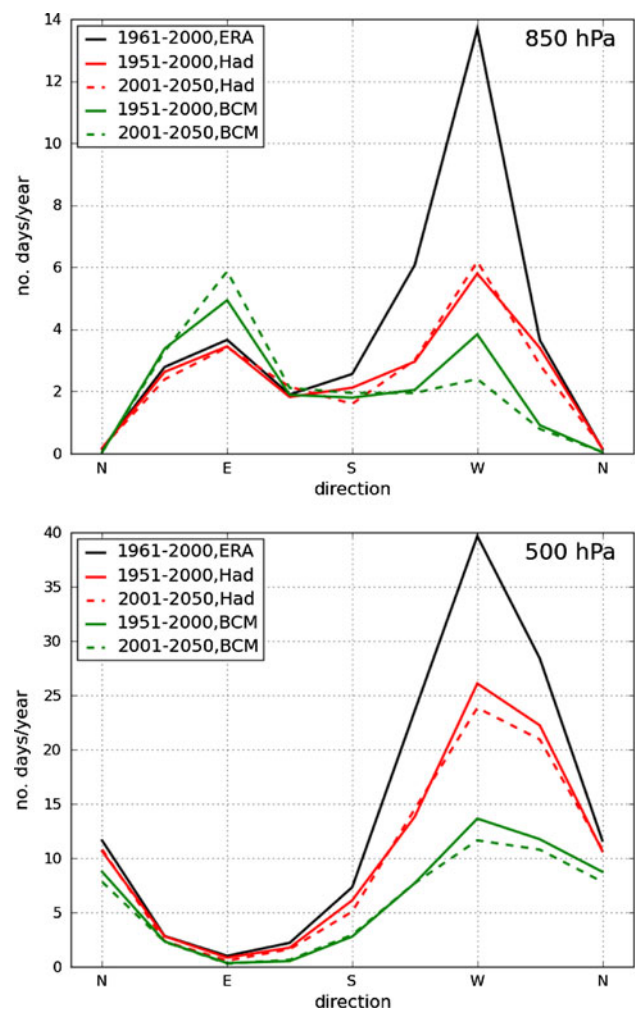


Fig. 14 Number of days per year with winds greater than 20 m/s in the dynamically downscaled control run (1951–2000) and climate projections (2001–2050) of the Bjerknes Climate Model (BCM) and Hadley Centre (Had) climate simulations, as well as the downscaled ERA-data (1961–2001). Data is from the 850 (*above*) and 500 hPa (*below*) levels at 63°N 15°W

the lee-side of the mountains during both storms (not shown). As gravity waves may not always generate downslope windstorms which reach as far as Kvísker, it is indeed not clear how often Mt. Öræfajökull forces gravity waves in westerly flow but it may be expected to be quite frequent. Methods similar to those presented in Feltz et al. (2009) may help to further classify the flow above Kvísker and identify situations of strong gravity wave activity, i.e. by using both satellite-based water vapour images as well as dynamically downscaled weather at high resolution.

The strong gustiness observed at Kvísker is well reproduced with a method based on Bresseur (2001) which has previously been successfully applied during both downslope flow and a corner wind in Iceland (Ólafsson and Ágústsson 2007; Ágústsson and Ólafsson 2009). The strong gustiness is an artifact of the high values of TKE and

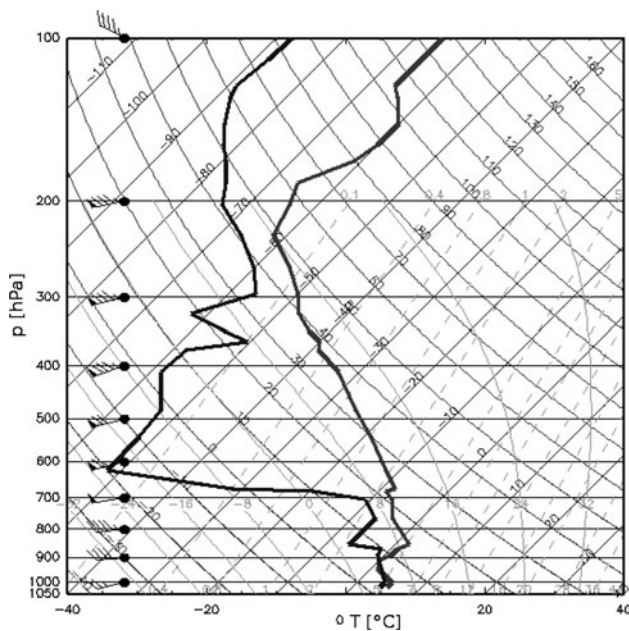


Fig. 15 Skew-T diagram of upper-air observations from Keflavík in Southwest Iceland at 00 UTC on 25 January 2007 during a windstorm of Type S at Kvísker. Shown are wind barbs, temperature and dew point (°C)

strong winds aloft. No observations are available to verify the very strong gustiness predicted in the downstream wake during the Type E windstorm. The gusts are possibly overestimated as a result of too strong simulated turbulence in the wake of mountains which will be able to bring down stronger winds to the surface from further aloft. This has previously been found to be a problem at similar locations in the mesoscale model (Ágústsson and Ólafsson 2009). The highest values of TKE are found near the regions of strong wind shear, i.e. near the surface and the inversion as well as below the lee-wave in the westerly windstorm where there is a rotor with positive vorticity aligned in a north-south direction and return flow at the surface. This rotor is of Type I as classified by Hertenstein and Kuettner (2005) which is also in agreement with the wind profile. No rotor is generated in the northerly windstorm but the wind profile places the windstorm not far from the separating line between Type 1 rotors associated with lee-waves and Type 2 rotors associated with hydraulic jumps (Hertenstein and Kuettner 2005, Fig. 16). However, the winds at the inversion in the Type E windstorm are far stronger than in the idealized experiments presented by Hertenstein and Kuettner (2005) and it is not clear whether Type 2 rotors should be expected in the real atmosphere as there appears to be little observational evidence of Type 2 rotors in the scientific literature.

Since the start of observations at Kvísker in 2002, the inter-annual cycle of observed windstorms appears to be correlated with the number of cases of strong westerlies in

the ECMWF-analysis at 500 and 850 hPa (Fig. 13). The set of observed storms is too small for any statistical significance but provided that there is a similar behaviour in the second half of the twentieth century it may be inferred that the number of westerly windstorms at Kvísker have varied greatly but with no clear trend in their frequency. The ECMWF-data indicates for example possible minima in 1985 and 1979 and possible maxima in 1983 and 1975. On a seasonal basis, there is a maximum in the observed windstorm frequency and the strength of the westerlies during the early winter (Fig. 12) and a clear minimum during spring and summer. The northerlies are on the other hand strongest in late autumn and late winter. This is presumably a reflection of the seasonal variation of the strength of the tropospheric jet above Iceland. Namely, in early winter the tropospheric jet is on average located above Iceland with strong winds related to the frequent passage of extratropical cyclones. These weaken during the winter as the tropospheric jet migrates southwards and in late winter, Iceland is well inside the cold polar air mass and the strength of low-level northerlies is relatively high.

There is a negative bias for the westerly winds in the control runs of the climate simulations when compared to the ERA-dataset. This remains to a large extent unexplained but is an apparent weakness of the climate models. In spite of the negative bias there is however a consistency in the downscaled climate projections and control runs of both climate models, and the bias appears not to be related to the limited area model used for the dynamical downscaling. An investigation of the strength of the winds (63°N 15°W) in the climate projections reveals that the westerlies are strong throughout the troposphere while the easterlies have a minimum at 500 hPa and a local maximum at the 850 hPa. This is also the general characteristic of the winds in the control run. There is a statistically significant decrease in the frequency of strong westerlies in the troposphere. This may be interpreted as a possible decrease in the frequency of strong westerly windstorms at Kvísker in the first half of the twenty-first century. Although not statistically significant, there is also a slight increase in the strength of the easterlies at 850 hPa which may have an impact on the easterly windstorms at Freysnes (Ólafsson and Ágústsson 2007).

7 Summary and conclusions

Here we have presented an investigation of downslope windstorms at Kvísker in Iceland. The windstorms are of two different types, a Type S westerly and a Type E northerly windstorm. At the surface, the main difference between the two windstorm types is their horizontal extent. The Type S extends only a short distance downstream of

the mountain, while the Type E extends far downstream. The northerly windstorm is slightly weaker and not as gusty as the westerly windstorm. The flow aloft during the Type S windstorm is characterized by an amplified gravity wave, a forward vertical windshear and a statically stable layer at the mountain top level, while the flow aloft during the Type E windstorm is characterized by a deeper boundary layer and a reverse vertical windshear. The Type S windstorm resembles a gravity wave windstorm, while the Type E windstorm has a resemblance to the pattern described by shallow-water hydraulic theory on super- and sub-critical flows, but with the absence of deceleration in a hydraulic jump.

The study raises questions on what elements of the large-scale flow are important for the horizontal extent of the downslope windstorms. The answers to such questions are not only of a general scientific value, but they are also of value for forecasting of events (and non-events) of this kind. Numerical simulations will undoubtedly be important in this quest, but direct observations of the four-dimensional flow structure during windstorms is also of importance. Data of that kind will hopefully be available soon from the 413 m high Gufuskálar mast which is located at Mt. Snæfellsjökull in West Iceland. Direct observations of turbulence aloft are particularly needed to further verify the turbulence calculations.

The windstorms revealed here are in some aspects similar to the easterly windstorms at the nearby farm Freysnes (Ólafsson and Ágústsson 2007). As in the Type S windstorm, there is an amplified gravity wave over the lee-slope of the mountain and the downslope Freysnes windstorm does not extend far downstream. In the Freysnes case, the wave does however break in the zone of reverse vertical windshear, which is reminiscent of the Type E, and not the Type S windstorm in this paper. The frequency of the Freysnes windstorms showed no clear tendency since the 1960s and this seems also to be the case with the Kvísker windstorms although there is high inter-annual variability. However, there are indications that the windstorms may weaken and be fewer in the first half of this century than in the current climate.

Acknowledgements This study is partly funded by Kvískerjasjóður and is carried out in connection with the RÁV project which is supported by the Icelandic Research Fund (RANNÍS). We also acknowledge the contribution of Vegagerðin to the monitoring of the windstorms. Furthermore, the contribution of two anonymous reviewers is acknowledged.

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