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Article

Observations and simulation of katabatic flows during a heatwave in Iceland

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Abstract

Katabatic flows during a heatwave in August 2004 in Iceland are studied using observations and a high-resolution simulation with a numerical atmospheric model. In relation with the very high daytime temperatures, weak synoptic winds and clear skies, a radiative surface cooling in excess of 10–15°C was observed during the night throughout Iceland. The simulations and initial conditions are compared to available observations. Most of the observed winds, including patterns where weak synoptic winds or katabatic flow interact with orography, are reproduced well. They reveal that the katabatic flow in Southern Iceland can be characterized as low Froude number 'tranquil' flow. The simulations also give valuable indications of locations of relatively strong katabatic winds where no observations are currently available and where katabatic flows are presumably of importance for the local wind climate.

Zusammenfassung

Katabatische Winde während einer Hitzewelle in Island im August 2004 werden mit Beobachtungen und einer hochauflösenden Simulation mit einem numerischen atmosphärischen Modell studiert. In Zusammenhang mit sehr hohen Tagestemperaturen, schwachen synoptischen Winden und klarem Himmel, wurde am Boden eine Abkühlung durch Ausstrahlung von mehr als 10–15°C während der Nacht beobachtet. Die Simulation und die Ausgangsbedingungen der Simulation werden mit verfügbaren Beobachtungen verglichen. Die meisten beobachteten Winde, einschließlich vom Gebirge erzeugte Strömungsmuster bei schwachen synoptischen Winden sowie katabatische Strömungen, sind gut reproduziert, und die Strömung wird durch eine niedrige Froude-Zahl als 'tranquil' charakterisiert. Die Simulationen geben auch wertvolle Hinweise auf Orte mit verhältnismäßig starken katabatischen Winden, von denen keine Beobachtungen zur Verfügung stehen, und wo katabatische Winde vermutlich von Bedeutung für das lokale Windklima sind.

1 Introduction

Katabatic flows are a prominent feature in sloping topography and stable boundary layers (e.g. STULL, 1988). In a simple conceptual model, the flows develop when the air at the surface of the earth cools relative to the air aloft, e.g. due to radiative surface cooling on clear nights. The cold and heavy air flows downslope in a relatively shallow layer due to its negative buoyancy while the flow is dampened due to the turbulent drag (e.g. EGGER, 1990). However, the dynamics and thermodynamics of katabatic flows vary widely (MAHRT, 1982) with regard to the driving and damping mechanisms.

Katabatic flows have been extensively studied and described by many authors. Some of the perhaps earliest theories were given by PRANDTL (1942) and FLEAGLE (1950). Recent studies have for example focused on improving the older theories, e.g. GRISOGONO and OERLEMANS (2001a,b) who extended the simple analytical, but successful model of PRANDTL (1942), to allow for a more realistic eddy diffusivity profile. Observations of katabatic winds have been described in various studies, e.g. CUXART et al. (2000b); SUN et al. (2002) and in particular in Iceland by OERLEMANS et al. (1999). The observations described in the last paper form the basis for studies of katabatic flows on the Breiðamerkurjökull outlet glacier of Vatnajökull in Iceland, e.g. VAN DER AVOIRD and DUYNKERKE (1999); SMEETS et al. (1999); PARMHED et al. (2004) who investigated turbulence and surface fluxes in the flows and SÖDERBERG and PARMHED (2006) who attempted to model the katabatic winds.

This study is partly based on a similar study on the island of Mallorca in the western Mediterranean sea (CUXART et al., in press). In the complex orography of Mallorca, katabatic winds are found to be of considerable importance in a situation of weak synoptic-scale

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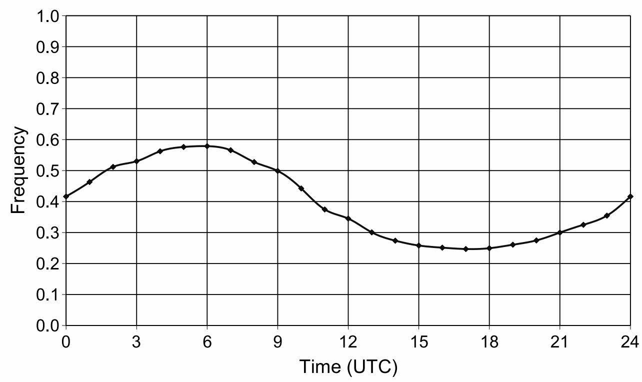

Figure 1: Relative frequency of northeasterly winds during summer (May–Sept., 1999–2005) at Skálholt in SW-Iceland (cf. Fig. 3).

winds and the observed flow in the lowlands is organized by the surrounding orography.

In Iceland, katabatic winds are presumably strongest during winter in anticyclonic situations with weak pressure gradients, a strong radiative surface cooling throughout the long polar night and a weak daytime surface heating. Katabatic winds can for example be expected to be of importance in relation with minimum surface temperature records (JÓNSSON, 2003), which are generally set in relatively flat terrain where there is only little inflow or outflow of air at distant slopes. The arrival of katabatic winds into these areas can mix the airmass vertically, bringing down warmer air while the outflow of air, e.g. along very gentle slopes, can be related to the subsidence of warmer air from aloft. Both mechanisms will increase the surface temperatures.

Katabatic winds are however also of importance during summer in Iceland, both over the glaciers (OERLEMANS and GRISOGONO, 2002) as well as away from them as suggested by BROMWICH et al. (2005) and indicated by observational data in Fig. 1. During summer at Skálholt in Southwest-Iceland, northeasterly winds are twice as frequent during nighttime than during the day. At least a part of this difference can be interpreted to be of katabatic origin. Here we investigate surface observations and simulations of katabatic winds during the night between 11 and 12 August 2004 in the complex terrain of Iceland. During these days, a heatwave in Iceland was at it strongest and maximum temperature records fell throughout Iceland, including 24.8°C observed in Reykjavík.[1] In relation with the high daytime temperatures, clear skies and weak synoptic winds, a surface radiative cooling in excess of 10–15°C was observed (Fig. 2) throughout Iceland in spite of the relatively short summer night (sunset and sunrise are at approx. 22 and 5 UTC, respectively, but the sun is however relatively low on the horizon for several hours before sunset and after sunrise). Simulations of such very stable boundary layers are a challenge for any atmospheric model and success is in itself noteworthy. Here, we strive to describe the structure and extent of the relatively strong katabatic winds observed during the aforementioned period. The study is also expected to give valuable information with regard to the origin of the katabatic winds and how the katabatic winds interact with orography. In light of the considerable importance of katabatic winds at certain times, the study also serves as a step towards a detailed description of the wind climate in Iceland.

As opposed to the somewhat similar study of SÖDERBERG and PARMHED (2006), which was limited to one of the big outlet glaciers in SE-Iceland, all of Iceland (Fig. 3) is included here due to the apparent importance of katabatic winds for the flow throughout Iceland. For practical reasons, the current discussion is however limited to an area in Southwest-Iceland. This area is relatively flat with an approximate horizontal extent of 75 km x 75 km. It is surrounded by mountains and complex terrain to the east and west while there is a gentle slope towards north and the central highlands of Iceland. Towards the south, the area extends out to the Atlantic Ocean. A more detailed description of the topography and terrain slopes than may be inferred from Fig. 3 can for example be found in BJÖRNSSON (2003). The basin scale is similar to that in CUXART et al. (in press).

A priori, it is difficult to state where and from where to expect katabatic flows to arrive into the area of interest. It depends strongly on the local and large scale topography. The smallest scales on the local slope may be expected to influence the flow nearest the surface, while the flow aloft may be influenced by larger scales and/or more distant slopes (e.g. MAHRT et al., 2001). Also, the flow depth may depend on the slope angle and length (e.g. KONDO and SATO, 1988; SMITH and SKYLLINGSTAD, 2005).

Section 2 is a description of the chosen synoptic situation. The observations used for validation of the numerical simulations are described in Section 3, while the setup of the atmospheric model is described in the following section. The simulated flow is shown and compared to available observations in Section 5. Discussions are in Section 6 and the summary and main conclusions are given in the final section.

2 The synoptic situation

During 11–12 August 2004, Iceland was in a region of high surface pressure and weak pressure gradients giving rise to weak north- and easterly synoptic winds (Fig. 4). Skies were generally clear except for low-level clouds or fog over the surrounding ocean and some coastal areas (not shown).

The analysis and atmospheric simulation (cf. Fig. 7, upper panel) show that the airflow at low levels in the north is blocked and diverted around Iceland. This is

[1] http://www.vedur.is/vedurfar/yfirlit/molar/

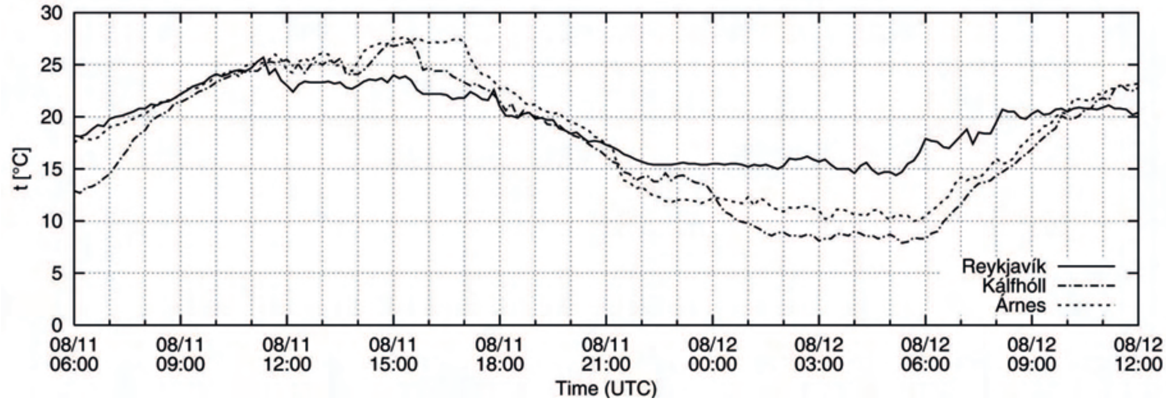

Figure 2: Observations of 2-m temperature, *t* [°], at 3 locations in SW-Iceland (cf. Fig. 3).

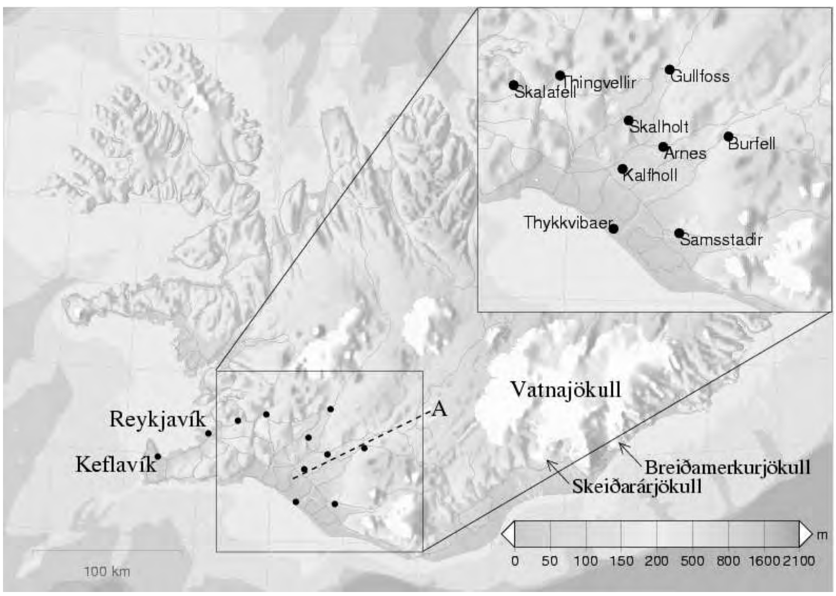

Figure 3: Topography of Iceland (in metres above sea level) with the area of main interest, the location of section A and chosen weather stations.

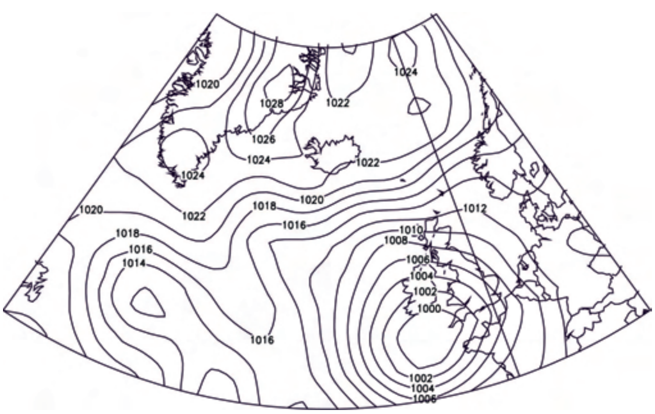

Figure 4: Sea level pressure [hPa] at 00 UTC on 12 August 2004 according to analysis from NCEP/NCAR.

further supported by the simulated flow aloft, the radiosounding at 00 UTC on 12 August (not shown) at the Keflavík upper-air station and observations (not shown) from the weather station at the top of Mount Skálafell (approx. 770 m). There are no indications of low-level flow over the topography, and the surface flow, especially in South-Iceland, may be expected to be determined by the surface and topographic forcings and only minimally affected by the large scale flow. However, at 1000 metres above ground level, the flow can not be considered to be blocked as weak north- and northeasterly flow is simulated above most of Iceland (not shown).

3 Observations

In the area of greatest interest, i.e. Southwest-Iceland, there are a number of weather stations with observations readily available (cf. Fig. 3). Most of the chosen stations belong to Veðurstofa Íslands[2] while a few stations belong to Landsvirkjun[3] and Vegagerðin[4]. Exclud-

[2]The Icelandic Meteorological office
[3]The National Power Company
[4]The Public Roads Administration

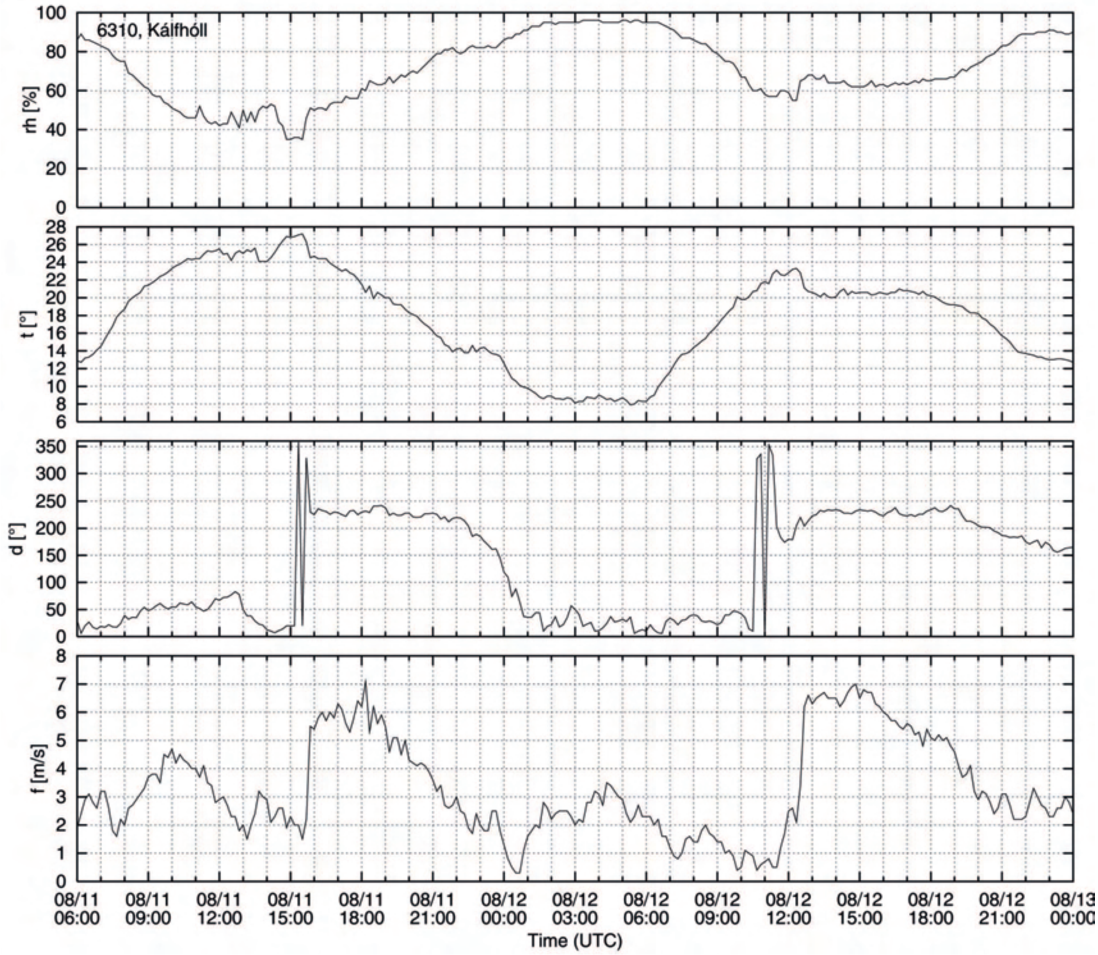

Figure 5: Observations at Kálfhóll station of relative humidity, *rh* [%], and temperature, *t* [°C], at 2 metres, and wind speed, *f* [m/s], and direction, *d* [°], at 10 metres.

ing Skálafell and Búrfell, all the stations are located at low altitudes and in relatively flat terrain. Upper air observations are made at Keflavík.

Observations of the 10-minute mean wind speed, wind direction, temperature and relative humidity are available at 10-minute intervals from all stations, excluding Keflavík. The temperature and relative humidity are observed at 2 metres above ground level, while the wind is either observed at 10 m or at the top of a 6-m mast raised approx. 1 m above its immediate surroundings (Gullfoss and Skálholt stations). All data is checked for errors at Veðurstofa Íslands.

Examples of observations at Kálfhóll are shown in Fig. 5. The strong diurnal oscillation is evident in all variables, i.e. temperature, relative humidity and wind, as well as an inverse correlation between temperature and relative humidity (correlation coefficient of –0.96, where –1.0 is complete inverse correlation).

4 Simulation setup

Previous studies of katabatic flows in Iceland benefit from the existence of a dataset including observations of the vertical structure of the boundary layer (e.g. OERLEMANS et al., 1999). Here, this is not the case and with the absence of observations aloft in the boundary layer it is difficult to directly study the katabatic flows. Mesocale modeling is a natural alternative.

The 24 hours from 12:00 UTC on 11 August 2004 until 12:00 UTC the following day are simulated with the Meso-NH atmospheric model (LAFORE et al., 1998). The model can be applied to very different scales, ranging from studies of synoptic disturbances to very small scales, i.e. large eddy simulations (LES). In fact, the performance of the model in the stable boundary layer regime has recently been tested extensively (e.g. JIMÉNEZ and CUXART, 2005; CUXART et al., in press; CUXART and JIMÉNEZ, in press).

Here, the model is run on one domain with a horizontal grid size of 4 km (Fig. 6) which is compatible with the HRAS-system which is used in operational weather forecasting at Veðurstofa Íslands (ÓLAFSSON et al., 2006). Analysis from the European Centre of Medium-Range Weather Forecasts (ECMWF) are used as initial conditions and to force the model at its boundaries.

Table 1: The mean observed wind speed $mean_f$ [m/s], as well as the mean and standard deviation of the difference of observed and simulated wind speed f [m/s] and direction d [°], $mean_{\Delta(f,d)}$ and $sd_{\Delta(f,d)}$, respectively (cf. Figs. 8–10).

Station	Gullfoss	Árnes	Kálfhóll
$mean_f$ [m/s]	3.4	2.5	2.5
$mean_{\Delta f}$ [m/s]	0.6	0.2	0.9
$sd_{\Delta f}$ [m/s]	1.0	2.0	1.6
$mean_{\Delta d}$ [°]	20	40	–26
$sd_{\Delta d}$ [°]	119	116	70

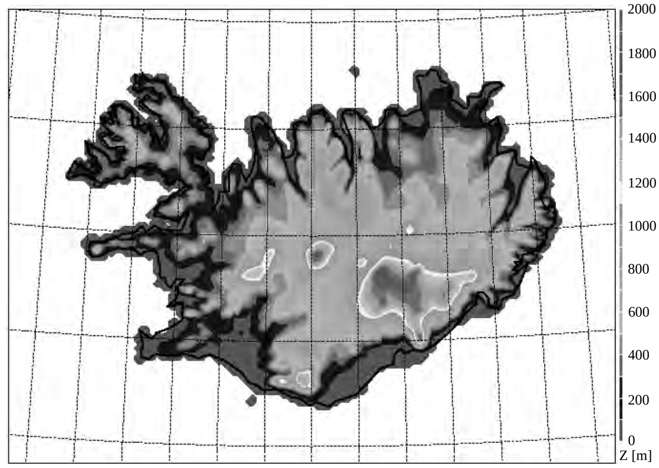

Figure 6: Terrain height, Z [m], at a horizontal resolution of 4 km.

As in CUXART et al. (in press), a high vertical resolution is used near the surface. The model uses 85 vertical levels with a spacing of 3 m near the surface, increasing upwards to the model top at 300 hPa. This fine vertical resolution is needed to capture all the details of the katabatic flows which presumably develop in shallow layers at low levels. The thickness of the flows may be on the order of tens of metres with the nose of the jet above 50 metres (e.g. CUXART et al., 2000b) while it may also be shallower and thinner as observed on the Vatnajökull glacier and described in e.g. VAN DER AVOIRD and DUYNKERKE (1999). The high vertical resolution is computationally very costly due to the increasing number of grid points and very short timesteps needed (especially near steep mountain slopes).

Here, the relevant physics schemes are the radiation scheme adapted from MORCRETTE (1990), a flux-corrected second order centred advection scheme, the ISBA soil scheme (NOILHAN and PLANTON, 1989) which forecasts the temporal evolution of surface fluxes and parameters, and finally the turbulence scheme of CUXART et al. (2000a) with the Bougeault-Lacarrère mixing length (BOUGEAULT and LACARRÈRE, 1989) as a closure parameter and only the vertical part of the turbulence activated, as is appropriate at this horizontal resolution.

A nearly identical simulation to this study has been performed with the MM5 mesoscale model (GRELL et al., 1994) of PSU/NCAR. An intercomparison of the results for the two models is under way but it is beyond the scope of this paper. However, preliminary results of the MM5-simulations support the results of this study.

5 The simulated flow

5.1 The surface flow

Near the end of the night, i.e. at 05:00 UTC on 12 August 2004 the surface flow at 10 m (Fig. 7) is relatively stationary and the structure varies little with time.

Comparison with observations from automatic stations spread throughout the whole of Iceland and with observations of sea surface winds, derived from the Seawinds scatterometer aboard the QuickSCAT satellite[5], indicate that the large scale surface flow (upper panel, Fig. 7) is well captured by the atmospheric simulation (not shown). In particular, the decelerated surface flow in and off North-Iceland is well presented by the atmospheric simulation, as well as the currents in the central highlands and on the big glaciers, to the extent they can be validated on the relatively data sparse glaciers and mountains. The greatest differences are observed near complex topography, e.g. the narrow fjords and steep mountains, and are presumably related to sub-grid features which are poorly resolved by the model at the current resolution. The accuracy of the simulated large scale flow is indeed deemed more than adequate to allow for a thorough investigation of the local flow in the region of interest in Southwest-Iceland.

The simulation appears to generate gravity driven currents in basins at several scales (lower panel, Fig. 7). Late in the night, the largest currents are northeasterly and descend from the central highlands into the region of interest, near the stations of Árnes and Gullfoss. Smaller currents are generated on the slopes of many of the surrounding mountains, but are difficult to verify as they do not pass any of the observation sites. The evolution of the surface flow appears to be best captured at the Kálfhóll automatic station (Fig. 8). The wind direction is well captured and especially the veering of the wind from southwest to northeast in the early evening, and back again to southwest in the late morning. The wind speed appears accurately simulated and is only underestimated during the early evening of 11 August. There are as well indications that in some cases, the simulation captures correctly some of the variability with a period similar to 1 hour. There is also reasonably good agreement between the simulation and observations at Gullfoss and Árnes (Figs. 9 and 10). The greatest errors at

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

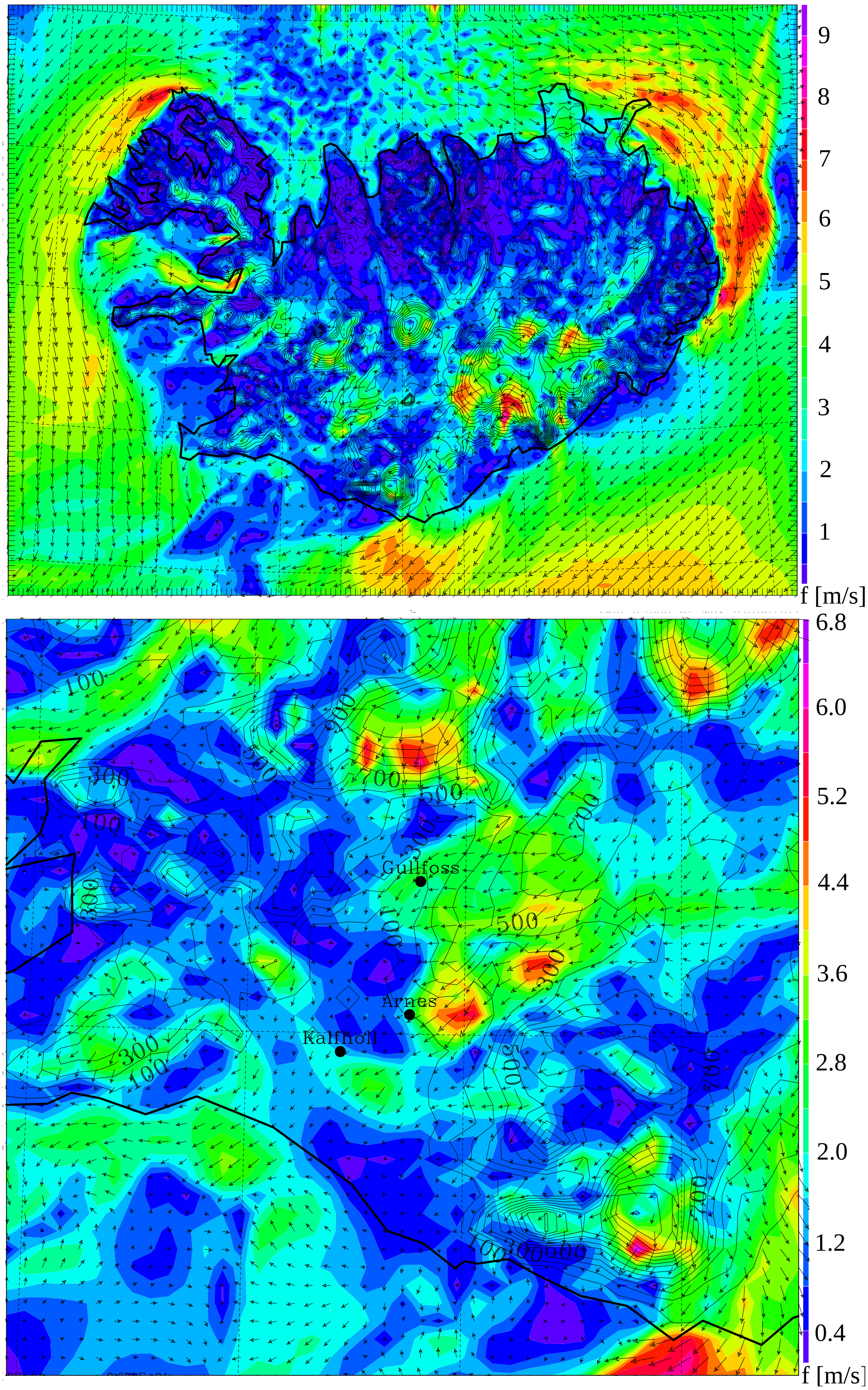

Figure 7: Simulated surface wind, f [m/s], (colour scale and arrows) at 05:00 UTC on 12 August 2004 for the whole simulation domain (upper panel) and a subdomain in SW-iceland (lower panel, same as marked region in Fig. 3). Also marked are locations of 3 weather stations. Black lines are terrain contours.

these stations are related to the timing of the turning of the wind. A quantative summary of the comparison between observed and simulated surface wind in Figs. 8–10 is given in Table 1. Observed surface winds are on average underestimated while the large deviations of the wind direction are partly related to the relatively large directional variability of weak winds.

As for the large scale flow (upper panel, Fig. 7), most of the errors in the simulated flow in SW-Iceland (lower panel, Fig. 7 and Figs. 8–10) may be accounted for by

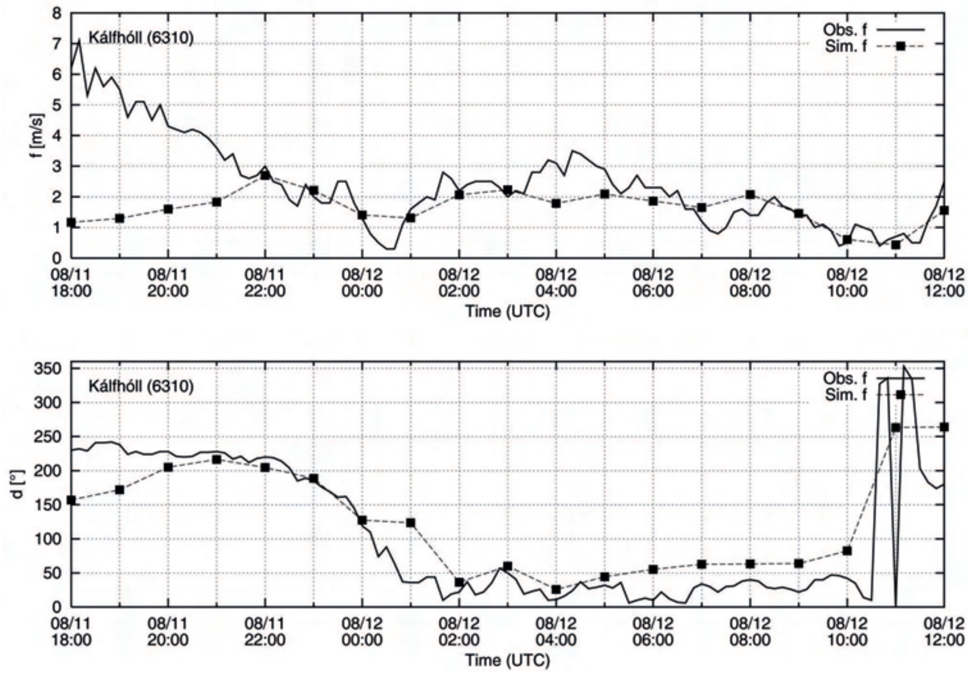

Figure 8: Simulated and observed wind speed, f [m/s], and wind direction, d [°], at the Kálfhóll automatic station.

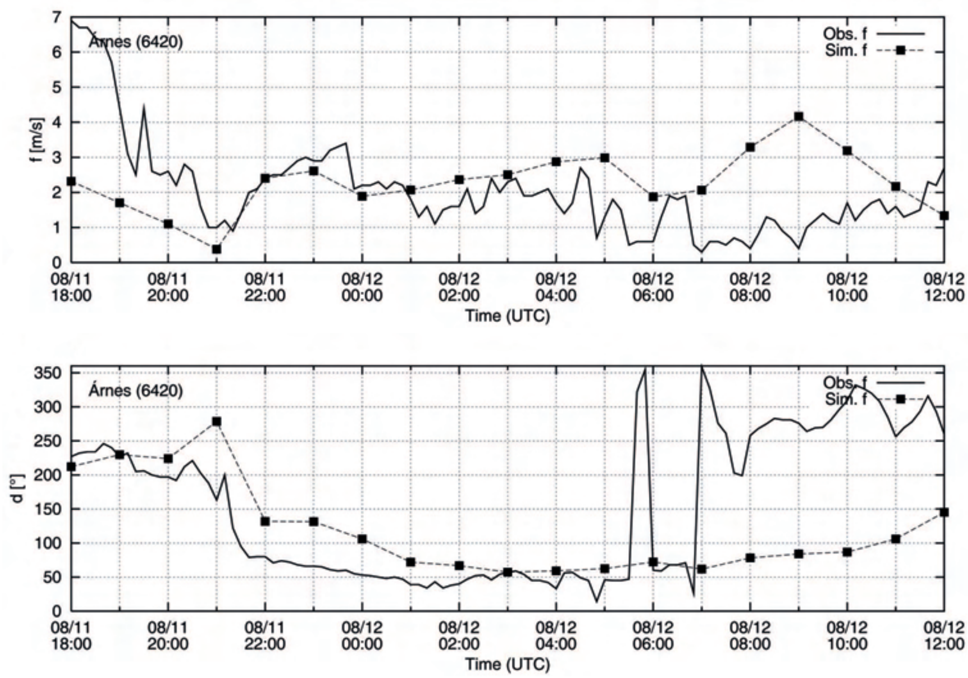

Figure 9: Simulated and observed wind speed, f [m/s], and wind direction, d [°], at the Árnes automatic station.

sub-grid topography. It can be argued that a horizontal resolution of 4 km is not adequate for correctly representing the topography. In this context, the poorer performance of the model at Gullfoss and Árnes than at Kálfhóll may then be partly explained by the greater topographic variability near Gullfoss and Árnes than near Kálfhóll (cf. Fig. 3). An error in the timing of the onset of katabatic winds may also be partly related to an error in the initial or simulated surface conditions but this is difficult to verify and partly discussed later (Section 6).

5.2 The flow aloft

As there are unfortunantly no direct observations of the flow aloft in the region of interest, it is difficult to verify the 3-dimensional structure of the simulated flow.

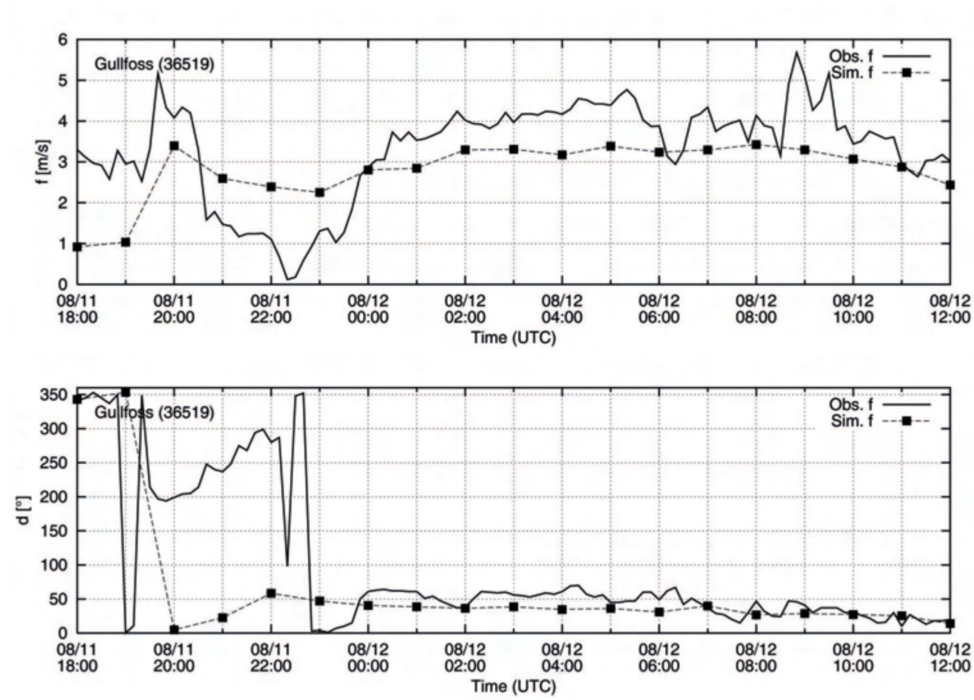

Figure 10: Simulated and observed wind speed, f [m/s], and wind direction, d [°], at the Gullfoss automatic station.

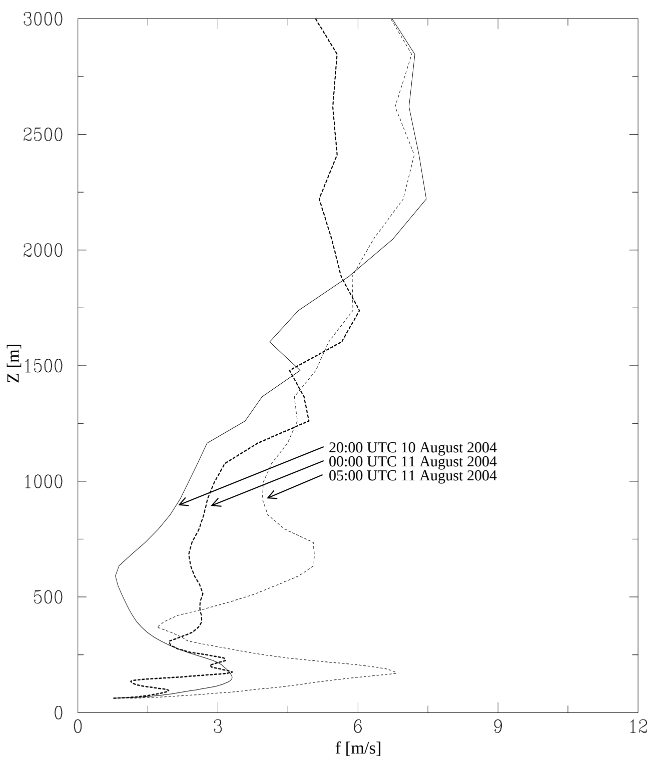

Figure 11: Vertical profiles of simulated wind speed, f [m/s], above Kálfhóll.

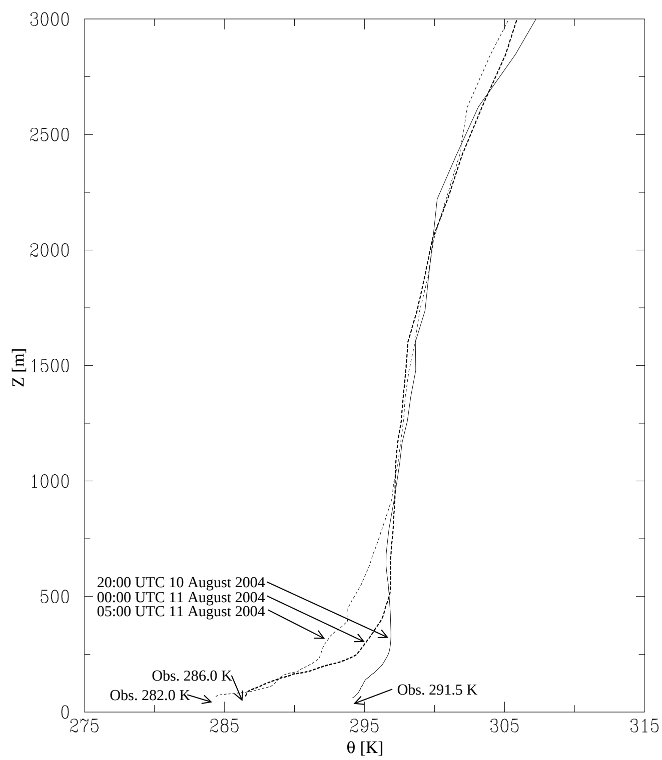

Figure 12: Vertical profiles of simulated potential temperature, θ [K], above Kálfhóll.

Satellite observations are of limited help as skies were generally clear during the period and the upper-air station at Keflavík is too distant. However, in the early evening above Kálfhóll, the simulation shows a wind maximum of approx. 3 m/s at a height of approx. 100 m (Fig. 11). The height and strength of this maximum are relatively constant during the beginning of the night although a much weaker jet appears closer to the surface. Towards the morning, a far stronger jet (7 m/s) appears. The wind maxima develop in the boundary layer above

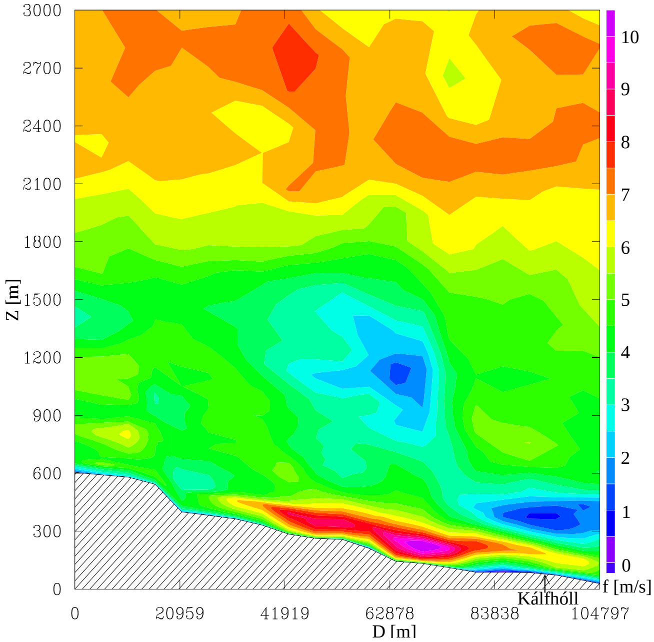

Figure 13: Simulated wind speed, *f* [m/s], along section A (cf. Fig. 3) at 05:00 UTC on 12 August 2004. Distances are in metres.

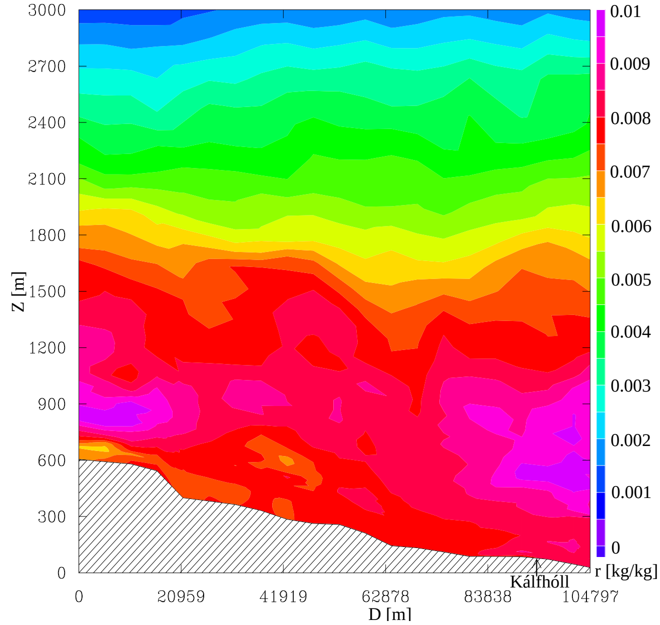

Figure 15: As in Fig. 13 but for the simulated water vapour mixing ratio *r* [kg/kg].

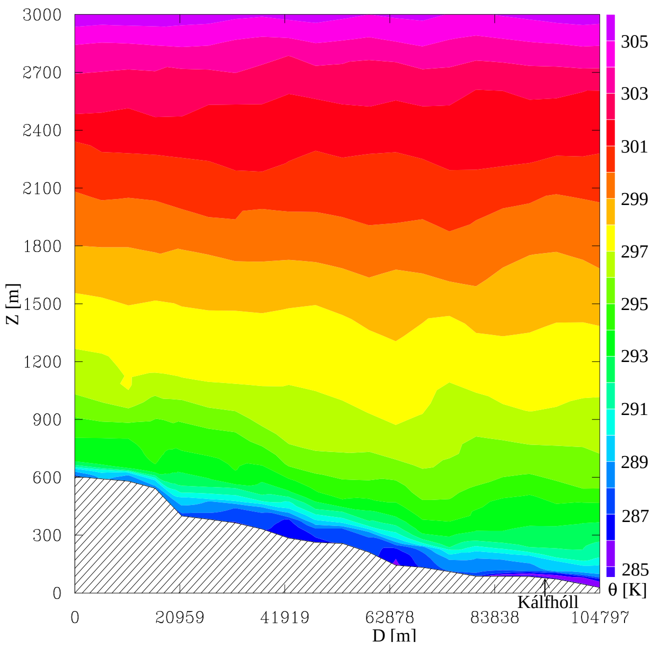

Figure 14: As in Fig. 13 but for the simulated potential temperature θ [K].

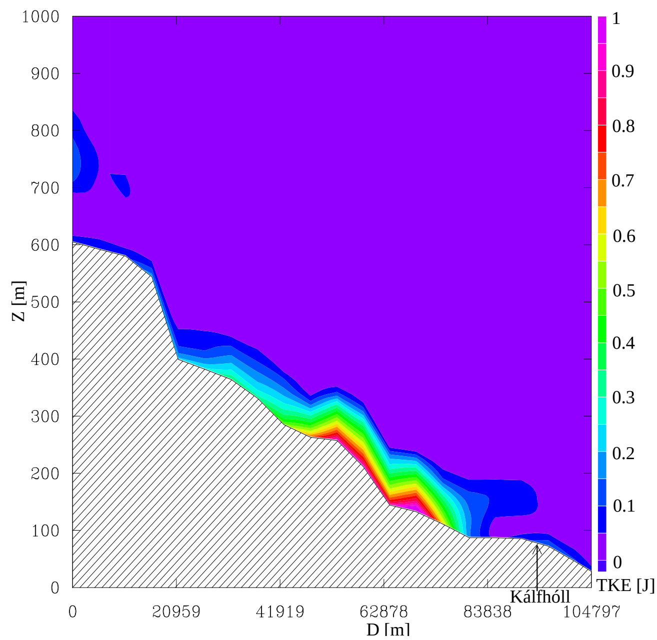

Figure 16: As in Fig. 13 but for the simulated turbulent kinetic energy TKE [J]. Note that the vertical scale is different from that in Figs. 13–15.

Kálfhóll which is already stably stratified at 20:00 UTC and has a depth of approx. 200 m. Most of the surface cooling at Kálfhóll happens between 18:00 UTC and 22:00/00:00 UTC, or in excess of 10°C, while the stable boundary layer continues to deepen throughout the night (Fig. 12).

Turbulence (Fig. 16) is confined to the jet and the zones below the jet where the greatest vertical wind shear is found. The mean turbulent kinetic energy is as large as approx. 1 J in, and below, regions of steep surface slope. Incidently, above the TKE maximum, the jet is strongest.

A northeast-southwest oriented cross-section (Fig. 3) passing near Árnes and Kálfhóll (cf. Fig. 3 for exact location) shows a jet at low levels directed along the section. The current seen at the surface in Fig. 7, below the cross-section, is a part of this jet. The jet is detached from the flow above, and has a vertical extent of approx. 200 m with winds stronger than 10 m/s at approx. 100 m above ground level. The current is thinner and more elevated from the surface near Kálfhóll than further upstream. The jet is found in the stable nocturnal boundary layer, where there is a strong vertical gradient in the potential temperature, and just below the residual layer, i.e. the previous daytime neutral boundary layer (Fig. 14). The top of the residual layer is at approx. 2000 m.a.s.l., as is readily seen in the water vapour mixing ratio (Fig. 15), while it is not as evident in the smoother potential temperature field.

6 Discussion

Gravity flows are generated and governed by surface forcings, e.g. surface cooling and turbulent drag, in stably stratified boundary layers as opposed to synoptic or mesoscale pressure gradients (e.g. MAHRT, 1982; EGGER, 1990). A correct description of the surface characteristics and forcing mechanisms is therefore necessary in a numerical atmospheric simulation. For example, poorly initialized surface temperatures and/or moisture can generate errors in the timing and amount of surface cooling, which directly affects the generation of gravity flows, their strength and the timing of their onset. Therefore, a first attempt was made to compare observed radiative surface temperatures, prepared from NOAA-satellite images, with the simulated temperature. The temperatures show similar characteristics with the main structures well captured (not shown), but the comparison of observed and radiative surface temperatures is, however, by no means simple and is the subject of a different study (MIRA et al., 2006).

In Southwest-Iceland, southwesterly or what may be considered upslope winds are observed at many stations late in the day, but the wind turns towards northeast, or downslope, in the early evening (e.g. Figs. 8–10). The observations and the atmospheric simulation indicate that the daytime winds may to some extent be related to sea breezes, which are indeed common in coastal and inland regions of Iceland under similar conditions (e.g. JÓNSSON, 2002). During the evening and night the winds are presumably of katabatic origin, as in Fig. 7, generated by surface cooling in the central highlands and the surrounding mountains. This may be further supported by observations of changes in relative humidity which can be connected with the advection of cold and moist air or mixing of warmer and drier air from aloft by katabatic winds. However, this is difficult to verify as changes in relative humidity may also be a direct consequence of changes in surface heating/cooling, as is perhaps the case for the observations shown in Fig. 5.

It is interesting that at Kálfhóll, as well as some other stations, none or little surface cooling is observed after a certain time during the night (cf. Fig. 5), while the observed temperature drops constantly at other stations. There are in fact also indications of a reduced simulated surface cooling rate during the latter half of the night, i.e. as in Fig. 12. This phenomenon may have several possible explanations. For example the downwards turbulent mixing of warmer air due to the arrival of katabatic flows or perhaps the release of latent heat because of cooling and saturation of water vapour at the surface. Indications of both processes may be seen in observations from the Kálfhóll automatic station, i.e. Fig. 5.

The height and the depth of the flow above Kálfhóll (Figs. 11–16) is considerably greater than in e.g. CUXART et al. (in press) or SMITH and SKYLLINGSTAD (2005). This is presumably related to the length of the slope, which is far longer than in the previously mentioned studies, but katabatic flows tend to deepen with distance along the slope. Also, the stably stratified boundary layer is deeper in the lowlands than in the mountains and central parts of Iceland (cf. the structure at low levels in Fig. 14). This is partly in agreement with SMITH and SKYLLINGSTAD (2005) where the slope flow and stably stratified boundary layer may deepen downstream of locations of where a steep surface slope changes to a more gentle slope. The flow of the jet above the apparent cold pool downstream of Kálfhóll is similar to what is observed in the study of CUXART et al. (in press). The intrusions of moister air at both ends of section A in Fig. 15 are related to inflow of moister air aloft from the north and at all levels from the west. There appears to be no reason that this moist inflow should affect the surface flow. The strong turbulence below the jet, upstream of Kálfhóll, is much stronger than simulated in the study of CUXART et al. (in press). Where present, the turbulent mixing prevents the surface layer from decoupling from the layer above, and contributes towards a more accurately simulated surface layer.

Following the scale analysis in MAHRT (1982) the simulated gravity currents can be classified according to the dominant driving and damping mechanisms. The previously discussed flow above Kálfhóll has a small Froude number, $Fr = U^2/g'H \lesssim 0.1$. Here U is the characteristic velocity of the katabatic flow, H the flow thickness, $g' = g\Delta\theta/\theta_0$ is the reduced gravity where buoyancy has been taken into account and $\Delta\theta$ is the difference in potential temperature in the gravity flow and outside it, θ_0. The mean slope angle is on the order of 0.5°. MAHRT (1982) defines a katabatic flow in this regime as a "tranquil flow" where the buoyancy acceleration is balanced by the retarding effect of the thermal wind contribution due to increasing depth and temperature deficit along the slope, i.e. increase in stability. This balance leads to weak flows which retain their small Froude number. Looking at much shallower and faster downslope flow on the Vatnajökull glacier, e.g. down the Skeiðarárjökull outlet glacier, we find a mean slope in excess of 2° and a Froude number, $Fr \simeq 3$. The thermal wind contribution is far smaller than the buoyancy acceleration and is not of importance here. The relatively fast flow classifies as a "shooting flow", where the acceleration due to negative buoyancy is primarily balanced by the downslope advection of momentum and turbulent drag at the surface. This is partly in accordance with a previous study of a katabatic current on the Breiðamerkurjökull outlet glacier which was found to be in the same regime (SÖDERBERG and PARMHED, 2006). The steep, constant slope, flow in SMITH and SKYLLINGSTAD (2005) is indeed of the same type, as is the katabatic flow analyzed in CUXART et al. (in press), although the advection term is only found to be of importance at some points in the flow. The advection and turbulent drag are of much less importance in the thicker and slower "tranquil flow" above Kálfhóll.

7 Summary and conclusions

In this study, katabatic flows during a heatwave in Iceland have been studied and simulated with the Meso-NH atmospheric model and observations.

In a weak northerly synoptic flow, North-Iceland acts as a barrier on the impinging flow at low levels. In spite of the short summer night, a surface radiative cooling in excess of 10–15°C is observed and katabatic winds develop and descend into South-Iceland from the central higlands and the surrounding mountains. These nocturnal wind systems are organized by the local orography, and at low levels there appears to be no or little interconnection with the flow on a meso- or synoptic scale. In general the simulations appear to be in good agreement with the available surface based observations, where the flow can be classified as "tranquil" according to the analysis by MAHRT (1982). The simulations indicate that the strongest and deepest currents descend into the region of interest from the central highlands in the north. These flows persist throughout the night with weaker and/or shallower flows descending into the region from the surrounding, steep mountains.

As in CUXART et al. (in press), the low-level simulated flows vary in a slow and continuous manner as opposed to the observations which show sudden changes in the flow configuration. Also, this appears to be a common feature of simulations of stably stratified boundary layers (CUXART et al., in press; JIMÉNEZ and CUXART, 2005).

As far as the authors are aware of, this is the only study of this kind of both regional and local winds in a stably stratified boundary layer in Iceland, away from the main glaciers. The study indicates where strong katabatic winds can be expected and it gives valuable additional information towards the beginning of a mapping of the wind climate in Iceland (RÖGNVALDSSON and ÓLAFSSON, 2005). We note that due to katabatic flows, a relatively large difference in the meteorological variables may be observed at two nearby locations in the same basin. This is of concern in the context of the representativity of a meteorological station during anticyclonic and weak wind situations. Also, the study shows where and how weak synoptic or katabatic winds interact with orography.

Throughout the period simulated here, strong katabatic flows are seen descending in all directions of the large Icelandic glaciers. This may be taken as indications that in the absence of synoptic forcing, katabatic winds will develop on the large glaciers and descend down all their large outlet glaciers with a significant fetch (slope length). This is partly in agreement with previous studies on the Icelandic glaciers (e.g. VAN DER AVOIRD and DUYNKERKE, 1999; OERLEMANS and GRISOGONO, 2002; PARMHED et al., 2004; SÖDERBERG and PARMHED, 2006), where gravity flows on the Breiðamerkurjökull outlet glacier of Vatnajökull are studied. BJÖRNSSON et al. (2005) found similar results for several of the large outlet glaciers of Vatnajökull but also showed that the katabatic flows may strengthen, and directly lead to enhanced melting at the glacier snouts when temperatures in the immediate surroundings of the glaciers are high, such as during the heatwave.

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