International Conference on Alpine Meteorology - Aviemore 2011 manuscript No.
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High-resolution simulations of mountain weather improved with observations from small unmanned aircraft

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Abstract Novel observations aloft with the SUMO, a small unmanned aircraft, are used to improve high resolution atmospheric simulations of weather in complex terrain in Iceland. The situation is captured by the atmospheric model when it is in addition to atmospheric analysis, forced with the observations of the vertical profiles of wind and temperature from the SUMO. Without the additional SUMO-observations, the model fails to reproduce the observed winds aloft as well as at the surface in a large region in the lee of the mountain. The case of 15 July 2009 presented here is a part of the international MOSO-project where the SUMO was used to observe local winds in Southwest-Iceland. Here, the high-resolution atmospheric simulations, as well as observations of weather at the surface and aloft with the SUMO were used to explore orographic winds near Mt. Esja (900 m) in Southwest-Iceland, near Reykjavík. The winds at mountain top level were weak and not indicative for gravity wave activity. Nevertheless, the observed low-level winds in the lee were strong, gusty and oriented down the mountain slopes, with weaker winds further aloft and near mountain top level. The strongest downslope flow did not reach the surface thus making only surface based observations inadequate in describing this situation correctly. With the SUMO-observations, the atmospheric model reproduces a weak localized gravity-wave induced downslope flow with a maximum in wind speed at approx. 100 m above ground in the lee of the mountain. This wind maximum is weaker and more diffuse a short distance further downstream. Other cases from the MOSO-project have used observations from the SUMO to explore and improve simulations of a sea-breeze situation. With the system being developed, in-situ observations from the SUMO may be feed in realtime into an atmospheric model for improved operational forecasting of high-impact local weather in complex terrain.

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1 Introduction

Successful atmospheric simulations of local weather in complex terrain depend strongly on the capability of the atmospheric model, sufficient model resolution and the quality of the atmospheric data forcing the model. The models are constantly being developed and improved, e.g. with regard to the representation of clouds, precipitation and boundary layer processes. Part of the effort goes into improving previous methods for describing physics and dynamics which may have been adequatly accurate at coarser resolutions, but are not applicable in the push towards higher resolutions. Operational systems are aiming at horizontal resolution of 1 km or better, and research models have long reached this resolution, but it is required for adequate representation of complex orography. High resolution is for example of great importance for correctly simulating windstorms in complex terrain (Ágústsson and Ólafsson, 2007) but it is also necessary for correctly capturing atmospheric flow far aloft above complex terrain as in Ólafsson and Ágústsson (2009). The high resolution is also a necessary condition for capturing correctly weak wind situations although it is found that it is not a sufficient condition for the current study.

Mesoscale atmospheric models must be initialized and forced at their boundaries by previously available atmospheric data. This data often originates from global atmospheric analysis or forecasts (e.g. GFS or ECMWF-data) at coarse horizontal resolutions, typically 15–50 km, while the temporal resolution is typically 3–6 hours. This atmospheric data is often not accurate enough for high-resolution simulations of very local features which may be dependant on small errors in the large scale flow, as e.g. pointed out by Nance and Durran (1997) in their study of lee waves. Therefore, the initial and forcing data is frequently improved with in-situ or remote observations through methods called nudging or assimilation. Here we use novel observations from aloft with a small unmanned aircraft (SUMO) to improve high resolution atmospheric simulations. The essentials of the setup of the observational SUMO-system are captured in Fig. 1. The system is described in detail in Reuder et al (2009), which also reports on tests of the system in the arctic near Svalbard. The system has furthermore been extensively tested in Iceland, in particular during the FLOHOF-experiment (Reuder et al, 2010) near Hofsjökull glacier in the central highlands.

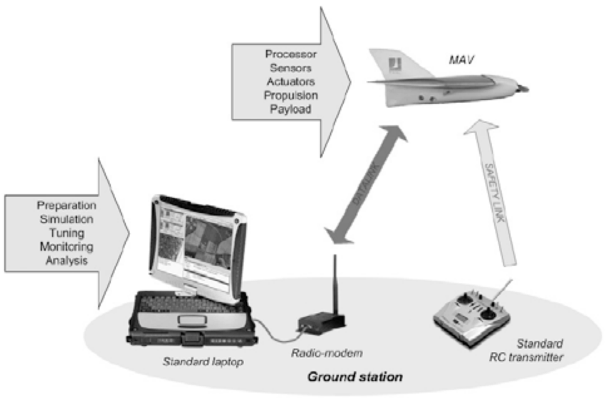

Fig. 1 The essentials of the SUMO-setup.

The current study uses SUMO-observations from 15 July 2009, collected during the MOSO-experiment in Southwest-Iceland. The event is characterized by weak easterly and northeasterly flow as indicated by the weak surface pressure gradient in Fig. 2. SUMO-observations in the lee of Mt. Esja during were expected to be performed inside a wake with weak westerly winds as indicated by unseccusful operational simulations used for weather forecasting (not shown). This was however not the case as shown in the following section describing the observational data and the subsequent section describing the downscaled flow in more detail. The last section of this paper gives a short summary and remarks on the most important findings of the study.

2 Observational data

SUMO-flights were performed at three different locations as shown by locations numbered 1–3 in Fig. 3. The first flight was at 11:19 UTC at location 2, with three more flights at:

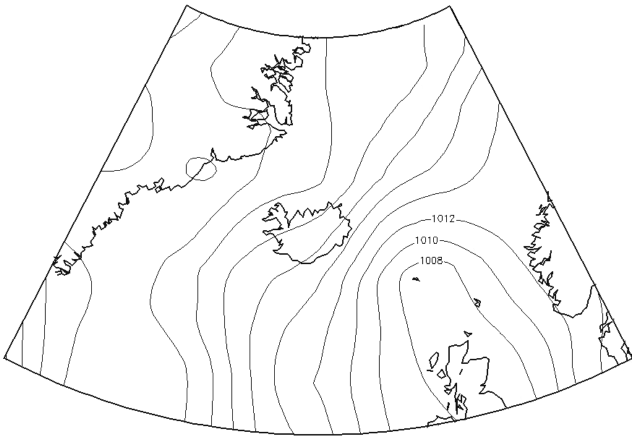

Fig. 2 Sea level pressure with an interval of 2 hPa at 12 UTC on 15 July 2009. Data from NOAA/NCEP.

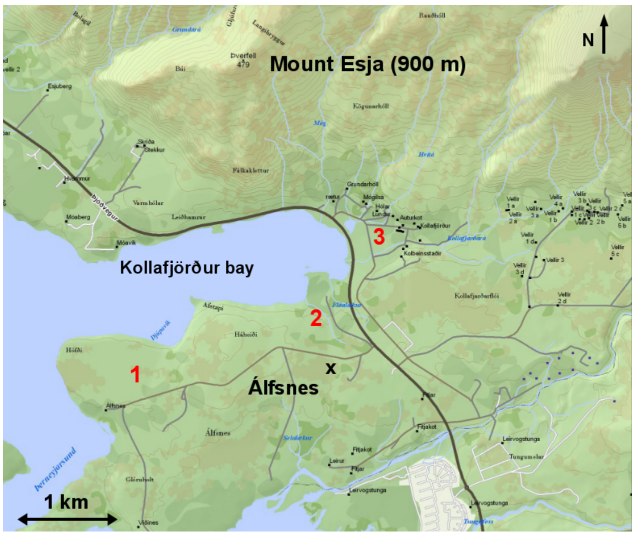

Fig. 3 Map showing locations of SUMO-flights (1,2 and 3), the Álfsnes station (x) and Mt. Esja (900 m). Note that Reykjavík is approx. 10 km to the southwest while Keflavík is 50 km to the westsouthwest.

11:47, 12:57 and 14:18. At 12:15 a flight was performed at location 3 and two flights at 13:27 and 13:48 were done at location 1. Fig. 4 shows observations from a few of the flights, one at each location. The SUMO observations reveal an unexpected wind profile that varied considerably both in time and space. The observed wind profiles at all locations were characterized by northerly winds increasing in strength from the surface up to 100–200 m above ground but weakening further aloft and in general veering to the east, with the weakest winds at or above mountain top level. The low level maximum is strongest has the smallest vertical extent close to the mountain, i.e. at location 3. The vertical extent increases and the strength of the maximum decreases further away from the mountain, while the easterly veering of the wind with height is smaller.

It should be noted that only qualitative observations of surface winds are available at the sites of the SUMO flights,

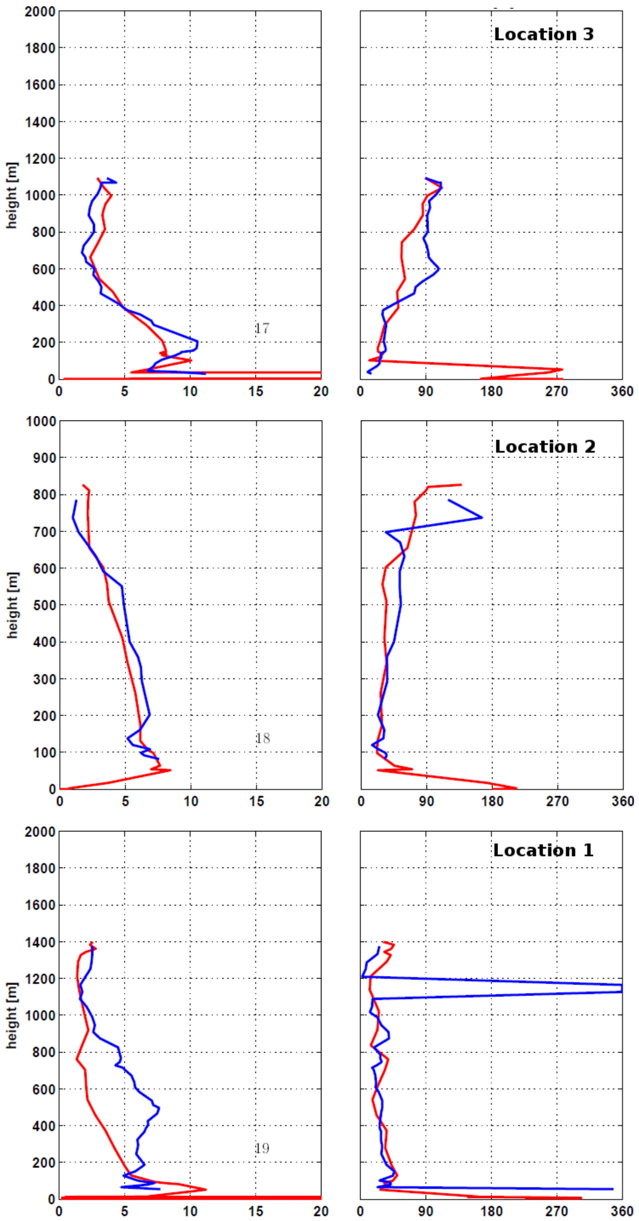

Fig. 4 Observations of wind speed [m/s] and direction [°] from the SUMO on 15 July 2009 at 12:15 (top), 12:57 (centre) and 13:27 UTC (bottom) at locations 3, 2 and 1, respectively.

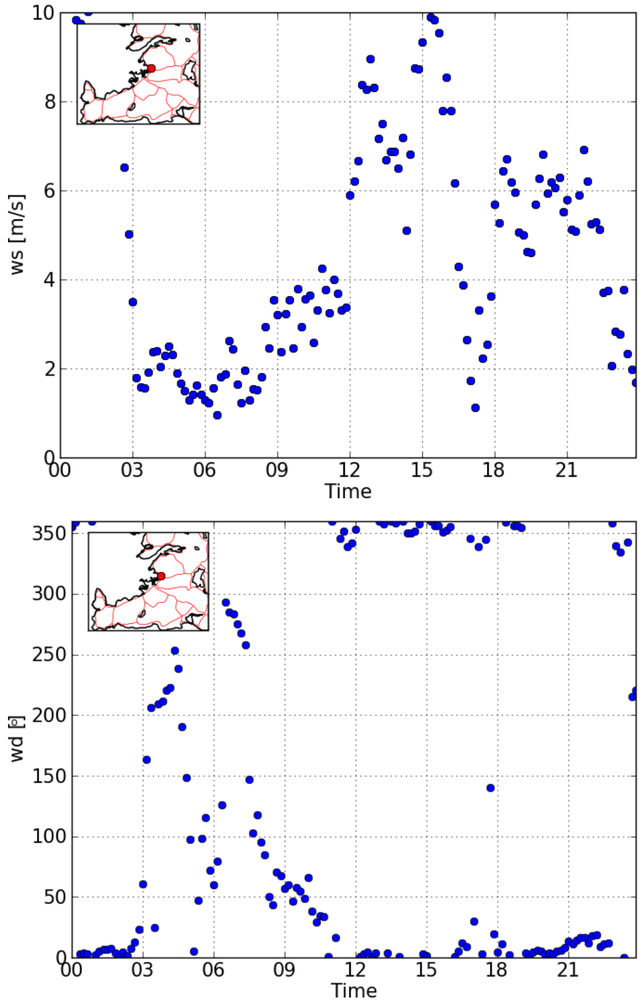

Fig. 5 Observations of surface wind speed [m/s] (above) and direction [°] (below) at Álfsnes (loc. x in Fig. 3).

3 Analysis of the windstorms

The structure of the observed wind profiles at locations 1–3 (Fig. 4) suggests gravity wave activity above Mt. Esja and a resulting accelerated flow down its leeside slopes, as is indicated by the conceptsual model in Fig. 6. The strongest

but these were northerly at all locations and gusty at locations 3 and 2, closest to the mountain. The northerly surface winds near the SUMO sites are verified by observations from a small mesonet of automatic weather stations available during the MOSO-experiment, e.g. as at Álfsnes (Fig. 5) where winds northerly winds of 6–8 m/s were observed in the early afternoon.

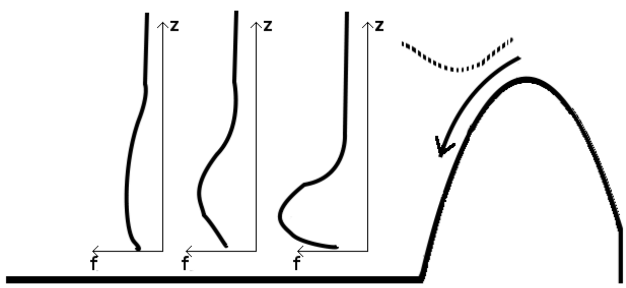

Fig. 6 Conceptsual model depicting a proposed gravity wave aloft and lee-side accelerated flow, as well as the resulting observed wind profiles at three locations in the lee of the mountain.

downslope winds do not penetrate to the surface and the wind speed maximum rapidly diffuses and weakens further downstream from the mountain.

To investigate the atmospheric flow in more detail the case is simulated with the non-hydrostatic mesoscale Advanced Research WRF-model (ARW, Skamarock et al, 2005). For the results discussed here, the model is initialized and forced at its boundaries with model level data from the ECMWF operational analysis. It is run at a resolution of 9, 3 and 1 km in the 2-way nested domains. The simulations use 50 σ-layers in the verticak, which are terrain following at lower levels but flatten gradually towards the top of the model at 50 hPa. The model is run for 6 hours before starting the nested domains which allows for approx. 10 hours of spin-up time before the time of interest. The boundary-layer parameterization uses the Mellor-Yamada-Janjic (ETA) scheme (Mellor and Yamada, 1982; Janjić, 2001, 1994) which is frequently used for both research and operational simulations. This scheme uses a level 2.5 second-moment closure for the turbulence and it is centered on the prognostic equation for the turbulence kinetic energy (TKE). Results from several sensitivity tests are not presented here but they all gave similar and expected results. Namely, the case was also simulated using GFS- and ECMWF-analysis on pressure levels, with increased horizontal and vertical resolution, as well as using other topography data and PBL-schemes available in the WRF-model. The setup of the simulations in the current study are very similar to that of the operational numerical simulations by Reiknistofa í veðurfræði (RV) which are used for operational forecasting at VÍ and published online at: "http://belgingur.is" (the HRAS-system).

With the setup of the atmospheric model described above the model fails to capture the observed flow in a large region downstream of the mountain, both at the surface (Fig. 7) and aloft. The model performs far better when the simulations are in addition to the atmospheric analysis, nudged with the observed vertical profiles of wind and temperature from the SUMO. The forcing is strongest in a column above the flight location and at the time of each observation, while the forcing decreases quite fast both spatially and temporally with increasing distance and time from the observations, for example as seen at Reykjavík approx. 10 km downstream from Mt. Esja (Fig. 8). The additional forcing improves the model results for a large region in the downstream direction and up to approx. 3 km height above the surface (Figs. 9 and 10).

The state of the atmosphere in the lee of the mountain is very different between the two simulations which have or have not extra forcing based on the SUMO-data. The main differences can be summarized as follows: Without SUMO-observations no gravity activity is simulated above Mt. Esja and the northeasterly flow to the north of the mountain curves clockwise around the mountain tip contribution to a a general northwesterly onshore flow in a large region.

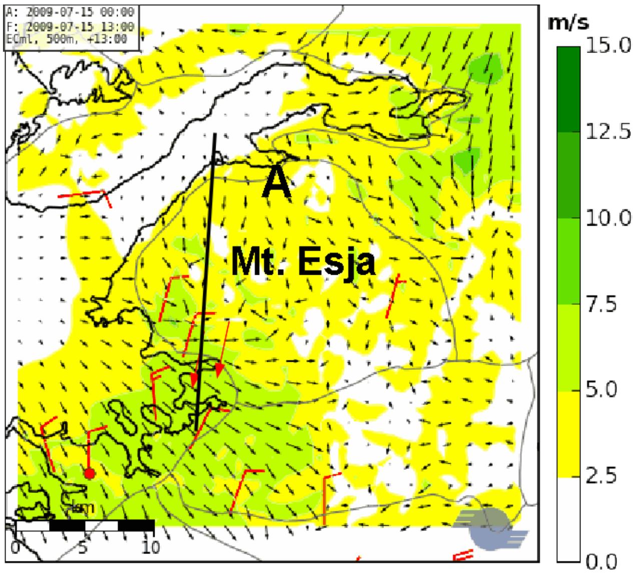

Fig. 7 Oberved and simulated winds at a resolution of 1 km at 13 UTC on 15 July 2009. Red arrows indicate direction of qualitatively observed strong and gusty winds. Also shown are coastline, main roads and location of section A.

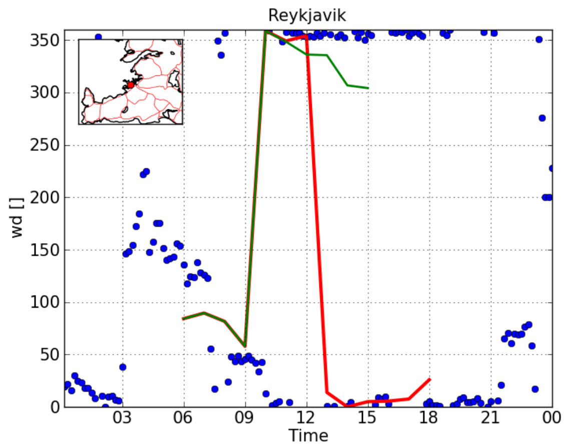

Fig. 8 Observed and simulated wind direction, with and without SUMO-data, at Reykjavík.

The onshore flow is reminiscent of a sea breeze, and is possibly partly thermally driven. When forced with the wind and temperature observations from aloft, the model produces a relatively small amplitude gravity wave above the leeslopes of Mt. Esja. Below the wave, the flow is accelerated as it descends down the mountain slopes. While this accelerated flow only partly reaches the surface it contributes to a general northeasterly flow in a large region downstream from the mountain.

It should be noted that the nudging is applied at model runtime and is different from other available assimilation methods in the WRF-model, which are a part of the preprocessing and are e.g. used to modify the initial and boundary data.

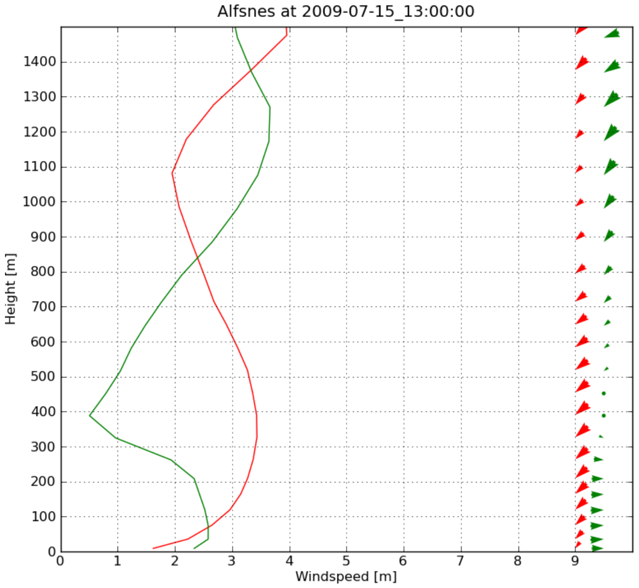

Fig. 9 Observed and simulated wind speed and direction at location 2.

4 Summary and conclusions

This study describes unique observations of winds aloft in a lee of a 900 m high mountain in Southwest-Iceland. Previously, it has not been possible to make observations like these in such economic and systematic manner. 11 and In light of the weak winds at mountain top level, the observations reveal unexpected gravity wave activity above the mountain with a resulting downslope accelerated flow above the leeslopes of the mountain. Aspects of the dynamics of the observed flow are still being investigated, for example in the context of the importance for simulations of weather and climate where gravity wave drag is normally parameterized. This is further underlined by recent observations and long time series of dynamically downscaled weather at high resolution which reveals highly persistant gravity wave activity over the Icelandic glaciers (**?**).

The observed features have a characteristic scale of only a couple of kilometres and vary considerably with time. They can not be reproduced with an atmospheric mesoscale model run at very high resolution, solely forced by coarse resolution atmospheric analysis (ECMWF or GFS). However, if in addition to the atmospheric analysis, the atmospheric model is forced/nudged by the observed profiles from the SUMO then it generates a weak gravity wave above the mountain and captures reasonably the observed winds at the surface and aloft. A system (http://sarweather.com/) is now being developed where observations from the SUMO are feed in realtime via a 3G-link into an online database from which they can be ingested into operational simulations with the WRF-model. In line with the results of this study, this system can improve considerably operational forecasting of local weather in complex terrain as the observations from the SUMO will help improve the data used to force and initialize the atmospheric model. Such a system can be of great importance, for example for wind energy applications and during search and rescue operations related to the airborne release of hazardous chemicals/gasses.

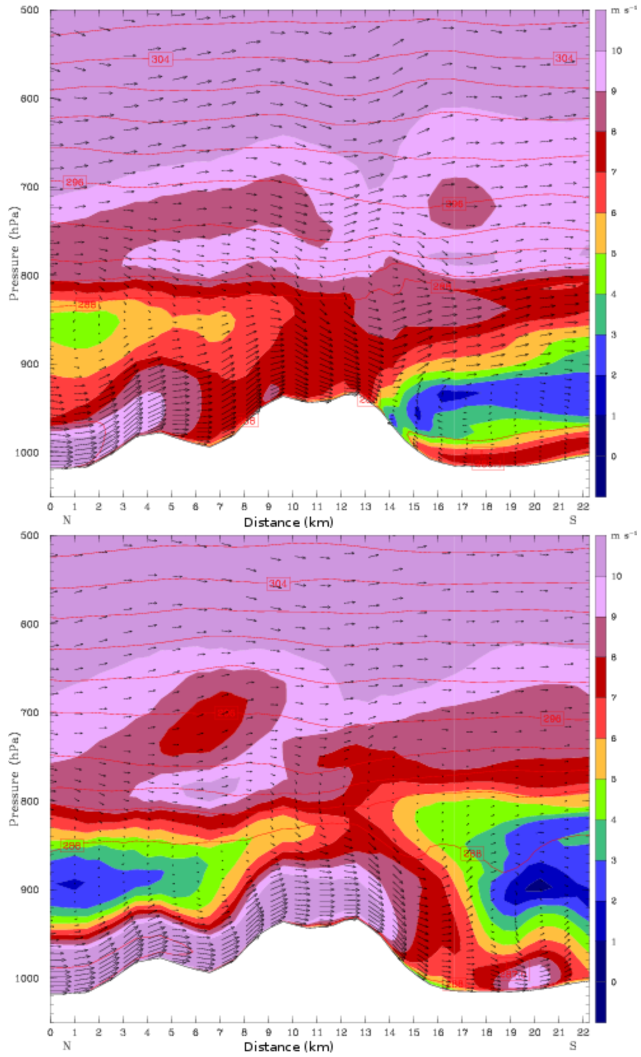

Fig. 10 Section A across Mt. Esja showing simulated isentropes [K] and winds [m/s] at a resolution of 1 km at 13 UTC, without SUMO-observations (above) and with SUMO-observations (below), on 15 July 2009.

The reasons for the failure of the non-observationally nudged model to capture the observed winds remain to be investigated. It is likely to be a result of errors in the large-scale atmospheric analysis forcing the model and consequently errors in the development of features in the impinging boundary layer flow. The boundary layer scheme may of course also fail to reproduce small-scale features in spite of sufficiently accurate large-scale forcing. More high-resolution experiments with different PBL-parameterizations as well as full three-dimensional turbulence calculations may be beneficial. More systematic three-dimensional observations of

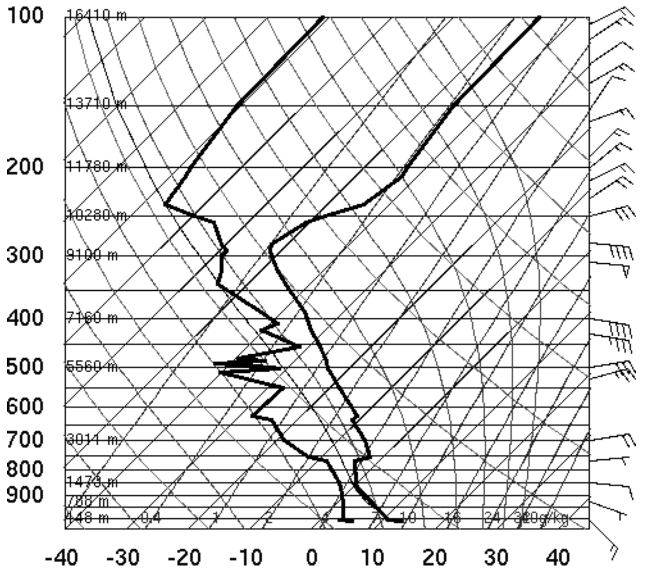

Fig. 11 Skew-T diagram showing upper-air observations from Keflavík (no. 4018) at 12 UTC on 15 July 2007 showing temperature and dew point as well as wind speed and direction.

boundary layer flow are needed to verify the simulations, for as a result of further field experiments with the SUMO. Observations at high-temporal resolution are ideal and in this context observations of wind, temperatures and turbulent fluxes will be available in the MABLA-experiment (Monitoring the Atmospheric Boundary Layer in the Artic) which is being prepared in the 400 m high mast at Gufuskálar in West-Iceland. (Ólafsson et al, 2009).

Acknowledgements We are grateful for the successful and ongoing collaboration with Bjarni G. P. Hjarðar at Sorpa and with ISAVIA, the Icelandic aviation authority.

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