Mesoscale aspects of atmospheric flow in complex orography

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Dissertation submitted in partial fulfillment of a
Philosophiae Doctor degree in Physics

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Abstract

The weather and climate in Iceland is to a large degree governed by synoptic scale weather systems and orographic forcing. This thesis is composed of 15 peer-reviewed papers pertaining to atmospheric processes in complex terrain, with a special focus on Iceland. Severe weather is the subject of most of the papers, either in the context of primary weather parameters such as wind, or in relation to secondary parameters such as atmospheric turbulence and icing.

In two papers, numerical simulations and observations of winds are used to map and analyze katabatic winds during a heatwave in South-Iceland as well as near the Hofsjökull ice cap in central Iceland. Observations of weak orographically forced winds are also the subject of another paper where asymmetric atmospheric vortices are shed in the lee of a large mountain in West-Iceland and advected 120 km towards and over Reykjavík. Five papers analyze simulations and observations of winds during severe windstorms in Southeast- and Northwest-Iceland. The performance of the atmospheric model with regard to model setup and the parameterizations of moisture physics and boundary layer processes is investigated and analyzed in two of the papers. The strongest winds are generally found below amplified and/or breaking gravity waves, as well as hydraulic jump-like features, on the lee side of large mountains. The papers reveal the importance of high horizontal resolution for resolving downslope windstorms in complex terrain and that interpolation from coarse-resolution simulations may lead to large errors, even if the mountains are to some extent correctly reproduced. The downstream extent of downslope windstorms depends strongly on the upstream structure of the atmosphere and its prediction is one aspect of numerical weather prediction that needs improvement. These papers also reveal that fine scale numerical simulations are not only needed to capture windstorms at the surface in complex terrain but also to correctly reproduce turbulence aloft, both at lower tropospheric levels in Iceland as well as at the tropopause, e.g. above Greenland. Wind gusts are analyzed and parameterized in two papers, where the observed gustiness is on average reproduced but how well depends strongly on the accuracy of the simulated turbulence aloft. Two papers show that observations from small unmanned aerial systems can be used to force and improve simulations of local weather in the lee of a mountain as well as regionally during a sea-breeze event. In the first case, the atmospheric model failed to capture the observed flow without the additional forcing, due to an error in the sharpness and strength of an inversion aloft. Sensitivity experiments pertaining to persistent downslope flows on the large Icelandic ice caps, and their dependance on surface friction and temperature, are discussed in one paper. The mass balance of an ice cap at the south coast of Iceland is analyzed and compared with simulated precipitation which is found to reproduce the observed winter accumulation on the ice cap. Finally, observed and simulated climatologies of wet-snow accretion in Southeast-Iceland are used to improve previous parameterization methods for wet-snow accretion, highlighting the dependance of the accretion process on wind speed and the liquid water content of the snow.

Additionally, the thesis includes wet-snow and in-cloud icing maps which were prepared within the scope of the thesis work. The maps identify regions prone to icing and highlight the complex spatial structure of the icing field, resulting from the orographic forcing on the weather of Iceland. For the sake of completeness, five conference papers on atmospheric icing are reproduced here, but conference papers are standard fare within the icing society.

Útdráttur

Veður og veðurfar á Íslandi ræðst af stærstu leyti af þeim veðrakerfum sem hingað koma og af áhrifum fjalla og landslags á þau. Í þessari ritgerð eru 15 ritrýndar fræðigreinar sem fjalla um veður í flóknu landslagi, með áherslu á veður á Íslandi. Óveður af ýmsum toga eru umfjöllunarefni flestra greinanna og fjalla m.a. um storma, ókyrrð og ísingu.

Í tveimur greinanna eru líkanreikningar og mælingar á vindi notaðar til að kortleggja og greina fallvinda á Suðurlandi í hitabylgjunni 2004 og nærri Hofsjökli 2007. Mælingar á hægum vindi eru einnig greindar í grein um ósamhverfa hvirfla sem mynduðust í loftstraumnum hlémegin Snæfellsjökuls og bárust um 120 km yfir Faxaflóa og Reykjavík. Fimm greinanna greina mælingar og hermireikninga á veðri í óveðrum á Vestfjörðum og nærri Öræfajökli. Gerð er greining á gæðum veðurreikninga m.v. uppsetningu líkans og vali á jaðarlags- og úrkomustikunum í tveimur greinanna. Mestur vindur í óveðrunum verður jafnan hlémegin hárra fjalla, undir straumstökkum er myndast í loftstraumnum, eða undir bröttum fjallabylgjum sem jafnvel ofrísa og brotna. Greinarnar bregða ljósi á mikilvægi þéttriðins reikninets ef vel á að ganga að reikna óveður í flóknu landslagi, og þær sýna að ekki er alltaf hægt að reiða sig á grófkvarða líkanreikninga til að leggja mat á aðstæður þar sem staðbundin óveður geta myndast, jafnvel þó landslagið sé að einhverju leyti rétt í grófkvarða reikningunum. Auk þess að vera forsenda þess að herma réttilega ókyrrð í neðri hluta veðrahvolfsins er þéttriðið reikninet einnig nauðsynlegt til að endurskapa ókyrrð nærri veðrahvörfunum, t.d. ofan Grænlands. Vindhviður eru greindar og reiknaðar í tveimur greinanna en hve réttilega mældar hviður reiknast er þó háð því hve vel ókyrrð í jaðarlaginu endurspeglar raunveruleikann. Tvær greinar sýna að mælingar á veðri, gerðar með flygildum, má nota til að bæta og þvinga reikninga á staðbundnu veðri hlémegin fjalla og fyrir hafgolu á stærri svæðum. Í fyrra tilvikinu er viðbótarþvingun með mælingum flygildanna nauðsynleg til að herma ástand lofthjúpsins, líklega vegna villu í þykkt og hitamun um hitahvarf ofan fjallsins. Næmnireikningar í tengslum við vindahámörk hlémegin í hlíðum stóru jöklanna, og tengsl þeirra við viðnám og yfirborðshita, eru til skoðunar í einni greinanna. Mælingar á afkomu Mýrdalsjökuls eru greindar og bornar saman við líkanreikninga sem herma að jafnaði vel vetrarákomu á hásléttu jökulsins. Að lokum, mælt og reiknað ísingarfar á Suðausturlandi er notað til að bæta líkön til hermireikningar á ísingu, og taka réttar tillit til vindhraða og vatnsmagns snævarins þegar meta á áhleðslu slyddu.

Til viðbótar við ofangreint inniheldur ritgerðin jafnframt slyddu- og skýjaísingarkort. Þekktir ísingarstaðir koma réttilega fram og kortin sýna greinilega þann mikla breytileika sem má búast við í ísingu í flóknu landslagi. Að auki er 5 ráðstefnugreinum um ísingu skeytt aftan við ritgerðina en í ísingarheiminum eru ráðstefnugreinar jafnan notaðar til að kynna og færa til bókar nýja þekkingu.

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1 Introduction

If you by happenchance find yourself in Iceland and lost for an appropriate way to initiate a conversation with one of the locals . . . just try mentioning the weather. Everybody in Iceland has an opinion on the weather, be it yesterday's windstorm, the heavy snow showers forecasted in the afternoon or the faint chances for a warm and sunny summer. The possible topics for a good and fruitful weather related conversation are in fact endless, as is the variety of Icelandic weather.

Chances are that your conversant will mention the last low pressure system that brought stormy weather to Iceland, but the frequent passage of extra-tropical lows is a result of Iceland's location in the northern part of the storm track across the North-Atlantic, as evident from Fig. 1.1 (cf. Serreze et al., 1997, and references therein). The lows are deepest and most frequent during winter but they bring changing weather, strong winds and precipitation in all months of the year. Long periods of high pressure over Iceland bring a different type of weather dominated by far weaker thermal winds (e.g. Bromwich et al., 2005), possibly bitter cold during winter and mostly warmer weather during summer.

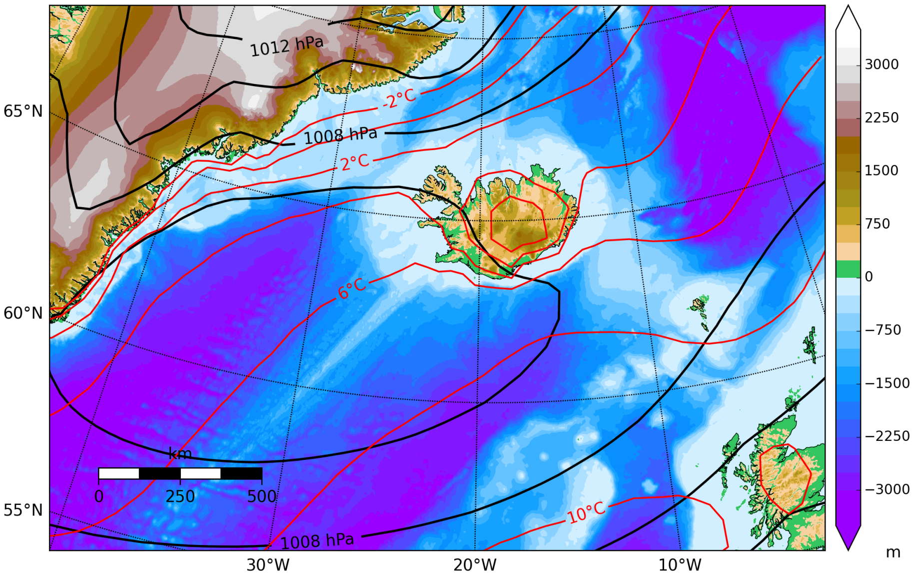

Figure 1.1. Orography and bathymetry in the North-Atlantic, with mean sea level pressure (black) and 2 m temperature (red), based on the ERA-interim analysis described in Dee et al. (2011).

However, even with the large variability in the synoptic conditions, local weather in Iceland would be far less interesting if it was not for the mountains. The orography of Iceland is complex (cf. Fig. 1.2) and the mountains enhance the climate wich is characterized by cool summers and mild winters, strong winds and frequent precipitation (Einarsson, 1976; Ólafsson et al., 2007, and references therein). The spatial structure of the weather and the climate is complex, both in the mountains as well as away from them. Weather extremes are amplified by the orographic forcing and, in fact, observed extremes of weather in Iceland are generally found in or near complex orography, as is particularly evident in the frequency and strength of observed windstorms and gustiness (Ágústsson and Ólafsson, 2004) as well as for precipitation (Jónsson and Ólafsson, 2005).

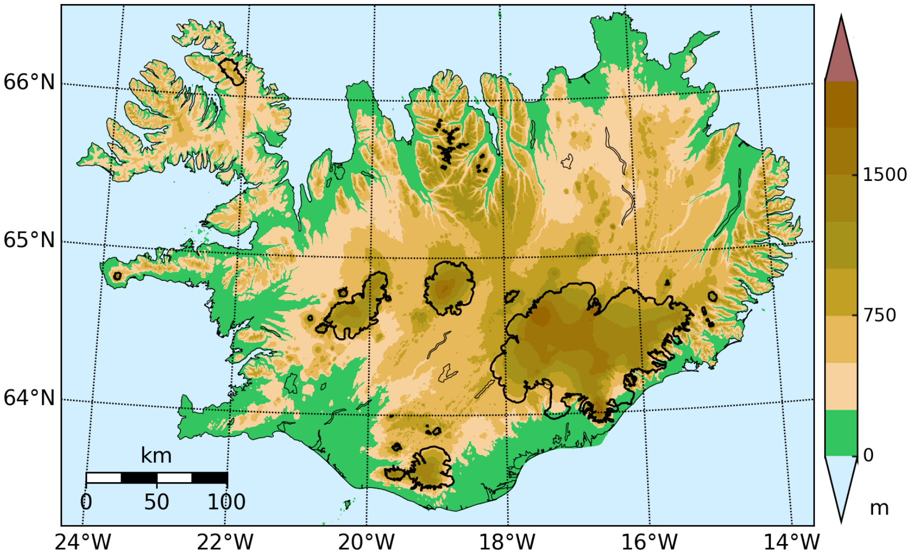

Figure 1.2. Orography and largest ice caps in Iceland.

The general public interest in weather in Iceland has its roots in Nordic culture and how dependant on weather and climate the people of Iceland have been since Iceland's settlement in the 9th century. The first settlers (i.e. the Vikings) brought with them knowledge of local and synoptic scale weather which they used to navigate across the North-Atlantic (Bergþórsson, 2000), as well as in coastal regions where they took the behaviour of the diurnal wind systems into account (Ólafsson and Ágústsson, 2009). Historical literature goes back more than a millenium and includes detailed chronicles of weather and the extent of sea ice, reflecting a society of farmers and fishermen critically dependant on the harsh weather and climate of Iceland (see Ogilvie et al., 2000; Ólafsson et al., 2007, and reference therein).

That said, this thesis deals with some of the scientific aspects of the weather and the climate in Iceland which depend strongly on the orographic forcing and its impact on the synoptic scale airflow (which is sometimes as picturesque as in Fig. 1.3). The peer-reviewed research papers of which this thesis is composed are all linked together through their connection with local weather in complex orography, e.g. in relation to the impact of mountains on windstorm structure and frequency, orographic precipitation and diurnal winds but special attention is also given to secondary atmospheric parameters, such as atmospheric turbulence aloft and icing on structures on the ground (see reviews by Smith, 1989a; Durran, 1990; Whiteman, 2000; Smith, 2004; Farzaneh, 2008; Chow et al., 2013). The overall objectives of the thesis can be summarized as follows: Firstly, to describe and understand the structure and behaviour of the observed mesoscale pheonomena, including their characteristics, short-term temporal behaviour, spatial distributions as well as their climatologies. Secondly, to analyze the role of the larger scale flow and the orography, including what aspects are necessary and important for the development of the mesoscale phenomena. Thirdly, to investigate the predictability of meso- and fine-scale weather, based on state-of-the-art atmospheric simulations. This includes an investigation of the importance of model resolution, the quality of the forcing data as well as an analysis of the performance of the models and the atmospheric parameterizations. The thesis also presents wet-snow and in-cloud icing maps for Iceland which were prepared within the framework of the IceWind project[1] of which the thesis is a part. In this context, five conference papers pertaining to research on atmospheric icing are included as secondary papers (not peer-reviewed) but they form the core of planned peer-reviewed publications.

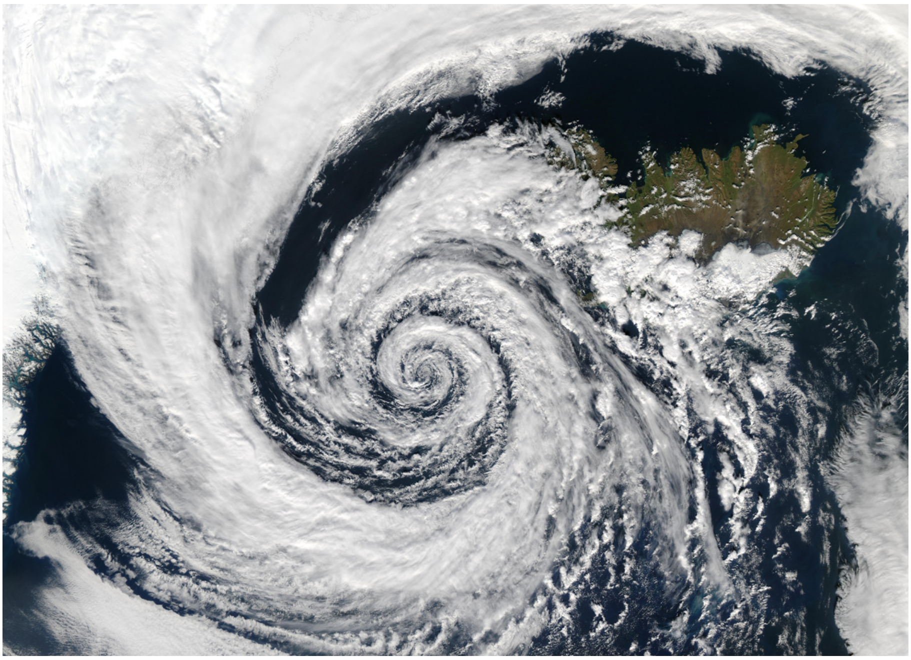

Figure 1.3. Iceland from space. Modis image from 1410 UTC 4 September 2003.

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[1] http://www.icewind.dtu.dk/

2 Flow in complex orography

Mountain flows have traditionally been diagnosed through a number of different parameters but a central parameter in this context is the non-dimensional mountain height Nh/U (inverse Froude number, Smith and Grønås (e.g. 1993)). Here, N is the Brunt-Väisälä frequency, h is the obstacle (mountain) height, and U the typical wind speed of the upstream background flow. Based on this parameter, Smith (1989a) describes the following basic flow regimes. Low values of Nh/U enable the flow to pass over the mountain without significant upstream deceleration (or stagnation) and typically gentle gravity waves are formed. For values of Nh/U close to unity, the flow becomes non-linear and enters a high drag state. In this state, there are typically amplified and even breaking gravity waves and strong downslope flow acceleration on the lee side of the mountain. For increasing values of Nh/U, the waves gradually become less prominent and an upstream blocking is a more dominant feature in the flow morphology. Downstream, there is most often a wake that may extend large distances away from the mountain, in which vorticity is produced (e.g. Smolarkiewicz et al., 1988; Smith, 1989b). Based on the work of Schär and Smith (1993); Grubišić et al. (1995); Smith et al. (1997) wake flow regimes are constructed as a function of mountain height, critical mountain height for internal wave breaking, and the Reynolds number. When the mountain height is well above a critical mountain height for wave breaking and the surface Reynolds number is large, there is vortex shedding inside the wake. A critical value of 0.4 of the Froude number is the upper limit of the regime of vortex shedding (see Etling, 1989, 1990).

2.1 Downslope windstorms

Strong, localized windstorms immediately downstream of mountains have been investigated by numerous authors. Such windstorms are generally associated with vertically propagating gravity waves in the troposphere. Favourable large-scale flow conditions for the generation of downslope windstorms include elements such as strong low-level winds and strong static stability at low levels. A reverse vertical windshear as described in Smith (1985) may contribute to a downslope windstorm through trapping of wave energy, while a positive vertical windshear may also act positively through amplification of gravity waves (see review by Durran, 1990). If the static stability increases with height and/or the wind decreases with height, the waves may overturn or break. At the breaking of the waves, the wave energy is returned to the airflow and intensive turbulence is created. Breaking mountain waves are not only important for the momentum budget of the atmosphere, but they also generate turbulence that may be hazardous to even large aircrafts.

Idealised cases of downslope windstorms and the associated gravity wave activity as well as real cases of downslope winds in many parts of the world have been studied by many authors. The real flow cases include the celebrated Boulder windstorms in westerly flow in North-America (e.g. Doyle et al., 2000, and ref. therein), downslope windstorms in southerly flow in the Alps (e.g. Jiang et al., 2006), the bora windstorms in northeasterly flow in Croatia (Smith, 1987; Belušić and Klaić, 2004; Belušić et al., 2004, and ref. therein)), windstorms in Norway in westerly flow (e.g. Doyle and Shapiro, 2000; Grønås and Sandvik, 1999) and Greenland windstorms in westerly flow (Doyle et al., 2005; Rögnvaldsson and Ólafsson, 2003) as well as in easterly flow as discussed in Paper V of this thesis.

2.2 Turbulence and rotors

Above and downwind of orography, gravity wave turbulence is primarily found at two height levels, as first was observed in the Sierra Wave Project in 1951–1955 (rediscussed in Grubišić and Lewis, 2004, see also references therein). First, at upper levels, e.g. near the tropopause, clear air turbulence may be encountered when vertically propagating gravity waves (see Durran (1990, 2003) for reviews of gravity wave theory) overturn and break due to the strong and sudden change in atmospheric stability and even wind speed. Clear air turbulence due to Kelvin-Helmholtz instability in regions of high wind shear, i.e. near the tropospheric jet, may also be encountered at the upper levels. Secondly, from ground level to a level well above the mountain tops there is a region where strong turbulence may be encountered, with the most intense turbulence often found in horizontally aligned rotors downstream of the mountains. The turbulence at these levels can be related to surface gustiness in the context of parameterizing the gusts as in Brasseur (2001); Goyette et al. (2003). Some of the first observations and a description of atmospheric rotors were made by Andrija Mohorovičić in 1888 in a study of orographic clouds during the Croatian Bora (Grubišić and Orlić, 2007). In the first half of the 20th century, atmospheric rotors were observed in the Sierra Wave Project (see Grubišić and Lewis, 2004, and references therein) as well as in other projects such as the pioneering lee wave study of Küttner (1938). In the latter half of the century there was considerably less effort dedicated to studies of rotors (Doyle and Durran, 2004) but this has changed, partly due to the recent Sierra Rotors Project (e.g. Grubišić and Billings, 2007) and the subsequent T-REX (Grubišić et al., 2008) which is the largest field campaign to date that is dedicated to observing rotors. Documented observations of rotors are relatively scarce, including those mentioned above, rotors in the Falkland Islands (Mobbs et al., 2005) and the UK (Sheridan et al., 2007), (as well as in Iceland as in Paper XIII).

Hertenstein and Kuettner (2005) describe two possible types of rotors. The Type 2 rotor is associated with hydraulic jumps and the Type 1 rotor forms below amplified lee waves (first theory given by Scorer (1949)) and is characterized by reversed flow near or at the surface. As discussed in Doyle and Durran (2002), one of the first papers employing high-resolution numerical models in the study of rotors, lee waves facilitate the creation of rotors. Idealized simulations with an atmospheric model suggest that friction is of paramount importance in the creation of rotors in real flows (see for example Doyle and Durran, 2002; Vosper, 2004), while a secondary barrier downstream may cause constructive or destructive wave interference and affect rotor formation (Stiperski and Grubišić, 2011). The contribution of a strong temperature inversion near the mountain top in two dimensional flows has been investigated by Vosper (2004), and in real flows (Sheridan and Vosper, 2006), and has in general been found to have an impact on the formation of rotors, downslope windstorms, low level turbulence and hydraulic jumps. Idealized simulations of 2 and three-dimensional flow over orography (Doyle and Durran, 2007) indicate that small scale and short lived subrotors are created by shear-instability on the rotor and lee wave boundary, as was verified in the first documented observations of subrotors during the T-REX (Doyle et al., 2009).

2.3 The forecasting aspect

Successful numerical simulations of local weather in complex topography are dependent on the model resolution being sufficient for resolving the dominating topography; both when downscaling the wind and termperature climate (Watterson, 2015) as well as when simulating extreme wind events in complex terrain (e.g. Horvath et al., 2012; Jonassen et al., 2013, and Paper II of this study) but also for capturing middle and upper level tropospheric flow above complex terrain (e.g. Doyle et al., 2005, and Paper V), as well as stratospheric flow (Dörnbrack et al., 1998). Operational systems are aiming at a horizontal resolution of 1 km or better, and research models have long reached this resolution. Considerable work is needed on many parameterization schemes which may not be applicable in the push towards higher sub-kilometre resolutions (e.g. Wyngaard, 2004; Horvath et al., 2012).

Another decisive factor for successful simulations of the weather is the quality of the atmospheric data used to initialize and force the models at their boundaries. This data often originates from global atmospheric re-analysis, operational analysis or forecasts at relatively coarse resolutions, typically 15–80 km in the horizontal, with a temporal resolution of 1–6 h. Frequently, the accuracy and spatial resolution of this data is not adequate for high-resolution simulations of local and small-scale flow features, which may be dependent on small deviations in the large-scale flow, as pointed out by e.g. Reinecke and Durran (2009) in their study of gravity wave activity above complex orography. In spite of the global coverage of remote sensing data which has significantly improved atmospheric analyses, such analyses may suffer in otherwise data-sparse and mountainous regions of the world. For such cases, the initial and forcing data can be supplemented and improved by assimilating additional in-situ or remote sensing observations, as in Stauffer and Seaman (1990, 1994); Schroeder et al. (2006); Mayer et al. (2012).

Furthermore, the atmospheric models and the parameterizations employed must be of sufficient complexity to take correctly into account the atmospheric processes affecting the flow at the relevant scales. One must, however, bear in mind that some aspects of the simulated flow may depend significantly on the model grid, setup, dynamical core and parameterizations as is evident in the model intercomparison studies of Doyle et al. (2000, 2011); Schmidli et al. (2011) as well as in the study of Dörnbrack et al. (2005) (and similarily in Paper VI).

3 Atmospheric icing

The general term “atmospheric icing” is used for the accretion of atmospheric water in solid form on structures, on which the water, either in frozen or liquid form, impinges. Studies of atmospheric icing in Iceland go back over 40 years and have their roots in the urgent need for mapping ice loads at the sites of planned powerlines accross the Icelandic highlands (Sigurðsson, 1971). In fact, since the first overhead conductors and telephone wires in the early 20th century, atmospheric icing on the conductors and wires has been one of the serious problems (see Fig. 3.1) frequently faced by the operators of the lines (Elíasson, 2005), as for example is discussed in Sigurðsson and Sigurðsson (1975), one of the first Icelandic publications on the subject.

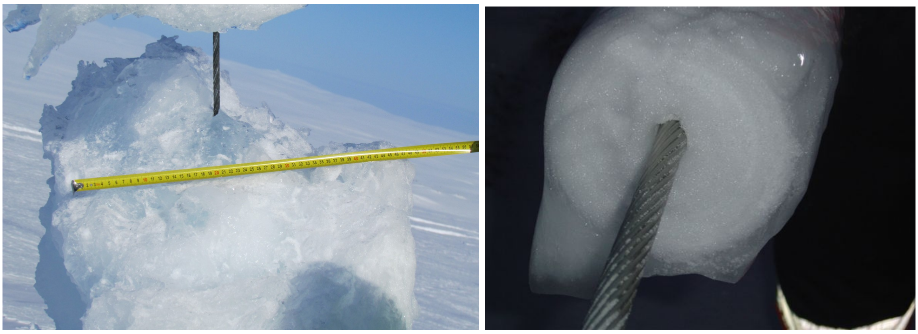

Figure 3.1. Left: In-cloud icing, measuring 48 cm in diameter, on a guy wire in a test span on Náttmálahæðir, West-Iceland, after failure due to extreme icing during December 2013 – March 2014. Right: Wet snow sample, measuring 21 cm in diameter midspan on a faulted transmission line conductor on Reykjaheiði, Northeast-Iceland, after the extreme wet-snow event of 10 September 2012. Photos: Árni Jón Elíasson.

Consequently, most studies on atmospheric icing in Iceland have focussed on the accretion on overhead wires and the needs of the transmission and distribution system operators and designers (e.g. Ísaksson et al., 1998; Ólafsson et al., 1998; Elíasson et al., 2000; Ólafsson et al., 2002a,b; Elíasson and Thorsteins, 2007), with the most recent study by Elíasson and Sveinbjörnsson (2015) and those presented in secondary papers of this thesis. The international efforts have been similar, with the early studies focusing on atmospheric icing on powerlines but now also heavily leaning towards the wind energy industry. Only recently, and in connection with the first large scale wind turbines in Iceland, has there been growing interest in icing pertaining to wind energy and turbines in Iceland. Albeit rather old in the context of the magnitude of the work done in the last decade, Fikke and coauthors (2007); Farzaneh (2008) give a nice review of the state of the art in studies and data collection on atmospheric icing.

Although accurate icing forecasts can be beneficial, and will certainly be important in the future, the main motivation of icing research within the framework of power lines is to estimate as accurately as possible the icing climate, e.g. accretion frequency and intensity, as well as its spatial and temporal variability which tends to be high in complex terrain. From this information, appropriate design loads can be derived for structures such as overhead power lines and telecommunication towers which must be carefully designed to take into account the properly estimated external mechanical load, caused by wind as well as accreted ice. Overdesigning, i.e. assuming to high external loads is expensive and a waste of valuable resources, while underestimating the proper loads can lead to faults or complete collapse of the structures and widespread blackouts.

There are mainly two types of atmospheric icing which are relevant in Iceland and can cause problems with overhead structures; wet-snow and in-cloud (rime ice) accretion.

3.1 Wet-snow accretion

In a global context, wet-snow accretion in Iceland is frequent and often causes problems and damage in the low-lands as well as in the mountains, more in some regions than others (e.g. Ólafsson et al., 1998, 2002a,b; Elíasson et al., 2000). Experience from the distribution network reveal a very strong dependency of the accretion intensity on the actual line orientation. Power lines oriented favourably with regard to main icing directions often have minimal wet-snow loads compared to nearby lines with a more unfavourable orientation, i.e. being more perpendicular to the main wind direction when accretion takes place. Globally, wet-snow events can be expected at all latitudes and altitudes where snowfall occurs, and they are typically associated with a maritime climate and complex terrain. The most widely known event occured in 2005 in Germany (Klinger et al., 2011) but large events have been reported in other countries such as Japan (Sakamoto, 2000), Italy (Bonelli et al., 2011) and France (Admirat, 2008), while a collection of smaller events in France is discussed in Ducloux and Nygaard (2014). Wet-snow events depend critically on a specific combination of temperature, humidity, precipitation and wind (Makkonen, 2000; Dalle and Admirat, 2011). Fig. 3.2 shows schematically the atmospheric conditions in which wet snow may form. Accretion occurs when the partly melted snowflakes impinge upon an object and stick to its surface, due to capillary forces associated with the liquid water in the snow (Sakamoto, 2000; Admirat, 2008). The accretion rate depends on the influx of snow and how well it adheres to the object, i.e. the stickiness of the snow which has a maximum in a narrow temperature interval just above 0°C. It has been suggested that the optimal liquid water content of the snow mass is 10–15%, which gives a maximum in the adhesive forces in the snow, with the forces quickly disappearing when the liquid water fraction goes below a few percent or above approximately a quarter of the total mass (Wakahama, 1979; Sakakibara et al., 2007). The importance of humidity is highlighted by Makkonen (1989) who showed that the wet bulb temperature must be positive for wet snow to occur, i.e. $T_w > 0°C$.

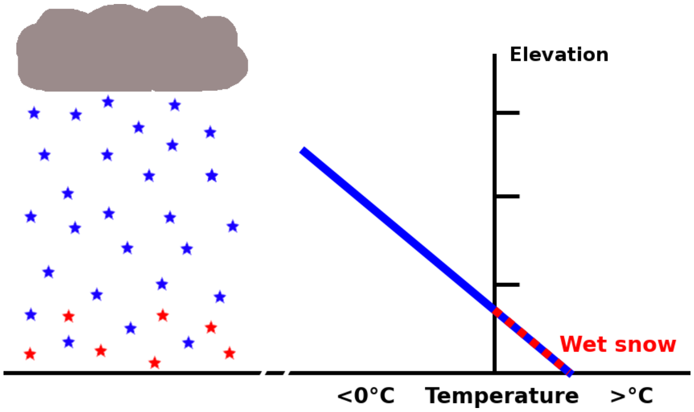

Figure 3.2. Schematic figure of atmospheric conditions necessary for wet snow accretion.

Overhead conductors are particularly vulnerable to wet snow accretion. Mass accreted on the upstream side of the conductors will, through the combined wind and gravitational forces; tend to either slide down and along the conductor or rotate the conductor, thus constantly exposing a new part of the conductor to the accretion. The whole conductor is quickly completely covered inside a cylindrically snow sleeve, increasing the structural strength of the wet-snow mass, which may complete several rotations during extreme events as reported from wet-snow samples in Iceland (Elíasson et al., 2000). The length of typical wet-snow events is on the order of hours but accreted snow may freeze solid on the conductors if the accretion period is followed by temperatures below freezing. Density of accreted wet snow varies considerably but observational data shows that it is typically higher (700–750 kg/m^3, Elíasson et al., 2000) in Iceland than in many other wet-snow prone locations. This is presumably a result of the prevalent strong winds and high liquid water content of the precipitation during wet-snow events in Iceland.

3.2 In-cloud accretion

In-cloud icing occurs when super-cooled cloud droplets freeze upon impact on structures and it is most common on isolated mountains as well as on upstream sides of mountains, especially in coastal regions. Schematics of typical atmospheric conditions are given in Fig. 3.3. Accretion may be continuous or intermittent for days and weeks, often with the final ice loads on the conductors only limited by the strength of the overhead structures themselves. In-cloud icing may occur in all parts of the world, at elevations which are typically above the cloud base during sub-zero temperatures, as discussed in Fikke (2005); Fikke et al. (2008) and references therein. A slightly off-topic but particularly nice discussion of in-cloud icing in high mountains is given by Whiteman and Garibotti (2013). In Iceland, in-cloud icing is frequent during winter above approx. 300 m. The

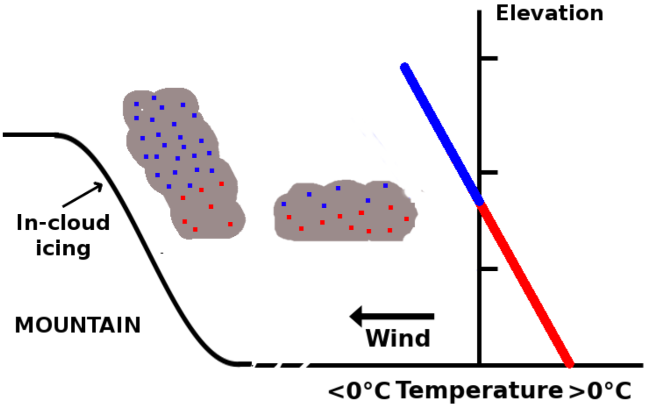

Figure 3.3. Schematic figure of atmospheric conditions in which in-cloud icing may occur.

maximum load observed in Iceland is 186 kg/m (ice mass per metre of conductor) on a test span in Northwest-Iceland in January 2014 as discussed in secondary paper IV while the maximum icing (305 kg/m) reported globally occured in 1961 on a power line near Voss, Norway, as described in Sigurðsson (1971); Nygaard (2013).

Cloud droplets form in environments which are super-saturated with respect to water and where so-called cloud condensation nuclei (CCN) are available. The CCN are certain aerosols on which liquid water may condense and form droplets, at far lower values of super-saturation than in environments lacking CCNs. Typical number concentrations of CCN vary by 1–2 orders of magnitude, depending on the origin of the air masses. The number may go below 50 in pristine arctic air and can exceed 500 in continental or polluted air masses. Typical cloud droplets diameters are near 10 μm but they grow in size by collision with other droplets until they reach drizzle and rain drop sizes (Rogers and Yau, 1989; Wallace and Hobbs, 2006). The cloud droplets may stay in liquid form at temperatures as low as approx. -35°C but aerosols which can act as so-called ice nuclei cause the droplets to freeze earlier, i.e. at considerably higher temperatures.

Clouds typically hold both cloud droplets as well as larger drizzle sized drops. In general, three types of in-cloud icing may form, depending on the meteorological conditions. Glaze is formed by freezing drizzle and during wet growth, when temperatures are typically too close to 0°C and accretion intensity is too high so that the latent heat released during freezing is not removed quickly enough. Consequently, a part of the water freezes as clear and dense ice, while the remainder forms a layer of water on the accretion surface, some of which may be lost as it drips off. Soft and hard rime form during dry growth when temperatures are low enough and accretion is not too intense, so all latent heat of freezing is removed and the accretion surface remains dry. With more intense accretion, i.e. stronger winds and larger atmospheric water content, hard rime is more likely to be formed (high density and structural strength) than soft rime (low density and weak structure). During wet growth, the accreted water mass is typically evenly distributed or may form icicles if there is abundant water. Hard and soft rime forms eccentric structures which point windward, and gravity and wind pressure may hence cause overhead conductors to rotate in a similar way as for wet-snow accretion. Variability in the meteorological icing conditions during extended icing events typically causes the accreted ice to be a complex mixture of glaze, as well as hard and soft rime.

3.3 Observational data

Studies of icing on overhead conductors in Iceland benefit from an unique database composed of: a) Reports of all observed icing events on overhead wires since the early 20th century, often with the icing diameter and even mass measured as well (Ísaksson et al., 1998). b) Data from nearly 60 test spans, measuring icing at 40 locations in Iceland. The first span was erected in 1972 and since 1989 the spans have gradually been modified to measure the icing load in realtime instead of only annual maxima (Elíasson and Thorsteins, 2007; Elíasson, 2013).

In short, a test span consists of two poles with a conductor strung between them, in which the tension is measured in real-time with a load cell. A detailed description of the test setup is given in Elíasson and Thorsteins (2007); Elíasson (2013). This setup may result in an overestimation of actual ice loading as the load cells measures the total load from both vertical (ice) and horizontal (wind) components. Other possible sources of uncertainty include calibration range of the load cells described in more detail in Elíasson and Sveinbjörnsson (2015) or a change in base stringing during icing events.

3.4 Parameterization of atmospheric icing

Even with the dense and accurate network of icing test spans available in Iceland, small scale details in the spatial variability of the icing climate can not be captured. Furthermore, all the necessary meteorological parameters for modelling accretion are not routinely measured and relatively few meteorological stations are located in the mountains and at the most severe icing locations. However, during the last decade or so, icing studies have benefitted from the increased complexity and accuracy of state-of-the-art atmospheric models, increasingly available and cheap computational power as well as more detailed and accurate observational data, of both weather and ice. With coupled atmospheric and accretion models, the state of the atmosphere and necessary weather parameters can be simulated at very high resolution in complex terrain, and used as input for modelling ice accretion in any given location, as done for in-cloud icing and locations in e.g. the USA, Japan and Iceland (Thompson et al., 2009; Nygaard et al., 2011; Podolskiy et al., 2012, and secondary papers I and IV of this thesis). The pioneering modeling studies of Ólafsson et al. (2002a,b) did not use a coupled accretion model for wet-snow in Iceland but such an approach is attempted in Paper X and secondary papers II, III and V of this thesis.

Within the scope of the current thesis wet-snow and in-cloud icing maps have been made for Iceland, based on long time series of downscaled weather. In this context it should be noted that the needs, on the one hand, of the transmission and distribution system designers and operators and, on the other hand, the wind energy industry are very different. The overhead network needs icing forecasts and estimates of maximum loads that can be expected for a given period, say a 50-year icing load, while the wind industry's main needs lie in forecasts and estimates of frequencies of icing episodes with intensities over a given threshold.

3.4.1 Atmospheric data

The atmospheric parameters needed as input for the accretion model are obtained from the RÁV-project (Rögnvaldsson et al., 2009) in which the weather and climate in Iceland was dynamically downscaled using version 3.0 of the non-hydrostatic mesoscale Advanced Research WRF-model (ARW Skamarock et al., 2008). The atmospheric modelling is done at high resolution, 9 km for 1957–2014 and at 3 km for 1994–2014 in the horizontal, with 55 levels in the vertical. The model is forced by atmospheric analysis from the European Centre for Medium-Range Weather Forecasts (ECMWF). The model takes full account of atmospheric physics and dynamics, and the relevant parameterization scheme for this study are the moisture scheme of Thompson et al. (2004, 2008) and the planetary boundary layer scheme of Janjić (2001), with other details of the setup of the model found in Rögnvaldsson et al. (2009). It should be noted in this context that atmospheric stability and uplift, hence atmospheric water and precipitation distributions, are strongly linked to both the moisture physics scheme and the boundary layer scheme.

Since the actual orography is smoothed considerably at the resolution of the atmospheric model, the atmospheric data is interpolated linearly upwards at each grid point to the true elevation of the orography. As the aim is to seek an upper bound on maximum icing loads, no attempt is made to correct for overestimated terrain elevation.

The dataset has previously been used in a number of studies of weather and climate in Iceland, including studies of orographic winds and precipitation (Papers XI, XII and XIII) as well as the climatology of wet-snow accretion in Southeast-Iceland as in Paper IX. The atmospheric model itself has previously been used in numerous icing studies, including Thompson et al. (2009); Nygaard et al. (2011); Podolskiy et al. (2012) and is used in secondary papers I-V.

3.4.2 The accretion model

The simulated data previously described is used as input to a time dependent numerical, rotating, cylindrical ice accretion model, based on the model of Makkonen and the methodology described in ISO 12494 (2001); Makkonen (2000). Rime icing and freezing drizzle/rain are treated separately from wet-snow accretion. The icing rate is described by

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 wAV, \tag{1}$$

where M(t) is the accreted ice mass [kg], V is particle velocity [m/s], A is the cross-sectional area [m^2] of the cylinder as seen by an impinging particle, and w is the liquid water content [kg/m^3] of the particle and is for in-cloud accretion chiefly due to cloud water but also due to drizzle and rain. V is here taken as the wind speed, with the size dependent fall speed of rain and drizzle particles taken into account according to Foote and Du Toit (1969). As the cylinder rotates, the accreted mass is spread evenly over its surface.

The three α-coefficients take values between 0 and 1. α_1 is the collision efficiency and is traditionally taken as 1 during wet-snow due to the large size and weight of the snowflakes. The far smaller cloud droplets may be diverted around the cylinder and their collision efficiency is calculated based on Finstad et al. (1988a) and a median volume diameter (MVD, Finstad et al., 1988b) of the impinging water particles and a fixed droplet number $N_d = 50$ droplets/cm^3. α_2 is the sticking efficiency and is equivalent for 1 for in-cloud icing as it is generally assumed that all impinging particles will stick to a wet as well as a dry accretion surface. For wet-snow, α_2 has frequently been parameterized as $1/V$ as in Admirat (2008) but Paper X proposes a different parameterization that gives better results for events in Iceland, and has in fact been used recently by other authors, including Ducloux and Nygaard (2014). α_3 is the accretion efficiency and is calculated based on estimates of the heat balance at the accretion surface (see Makkonen, 2000, and references therein), and may deviate significantly from 1 during wet growth when the latent heat released at the accretion surface is not removed efficiently enough (generally occurs at high accretion intensity, during weak winds and when temperatures are only slightly negative). During wet snow events, α_3 is equal to 1 as excess water will be drawn into the snow sleeve and is not lost. The density of the accreted cloud water (rime ice) is parameterized based on equation (4.1) in Makkonen (2000) while for freezing drizzle/rain the density is taken as 917 kg/m^3 (clear ice) and for wet-snow a constant density of 700 kg/m^3 is used based on in-situ observations Elíasson et al. (2000).

Ice shedding must be taken into account in modeling of atmospheric icing, especially in areas characterized by extreme and frequent icing conditions and where the temperature is on average near or below freezing (e.g Poots and Skelton, 1995). Main factors for ice shedding are: (i) melting, (ii) sublimation and (iii) mechanical ice break. Some attempts have been made to model ice shedding, as in e.g. Kollár et al. (2010), but no widely accepted model exists that has been validated with sufficient field data. Models that ignore (iii) can severely underestimate the intensity of ice loss processes as indicated by the results of secondary paper V of this thesis.

Here, based on experience from Iceland, accreted wet-snow is shed when there has been no accretion for 24 hours or when the temperature goes above 3°C. Shedding of rime ice is parameterized based on

$$dM_{shed} = max \begin{cases} k_{break} M_{ice} \\ k_{sublim} \pi D \end{cases} \tag{2}$$

which has previously given reasonable results in Icelandic studies of in-cloud icing (pers. comm. Egill Þorsteins). The shedding factor associated with ice fall is given by

$$k_{break} = \begin{cases} \frac{1}{3}(1+0.075V) & if T > 0°C \\ \frac{1}{3} & if T + 0.05V > 0 and T \leq 0°C \\ 0 & otherwise \end{cases} \tag{3}$$

with units of [hour^{-1}], and where M$_{ice}$ is the accreted mass of ice [kg], D$_{ice}$ is the icing diameter [m], T is the air temperature [°C] and k$_{sublim}$ is an estimated shedding factor associated with sublimation (0.0045 kgm^{-2}hour^{-1}).

3.4.3 Icing maps

Based on the methodology described above, icing maps were made for Iceland (Figs. 3.4 and 3.5). The maps are made separately for rime-ice and wet-snow and show the maximum loads parameterized during 1994-2014 (3 km grid size) near the ground, as well as in-cloud icing intensities at 50 m above the ground. Results from two different icing model configurations are shown: (i) in the vertical cylinder approach for in-cloud and wet-snow as well as from the (ii) horizontal cylinder approach for wet-snow. With a vertical cylinder the particle impact speed is always perpendicular to the object and hence the accretion is independent of wind direction. It is often considered valid to use a vertical cylinder when parameterizing in-cloud icing as spans and structures tend to accrede ice somewhat independent of wind direction. Wet-snow accretion is considered for a vertical cylinder as well as for four different horizontal cylinder directions: 0°, 45°, 90° and 135°. Accretion is reduced when the atmospheric water flux is not perpendicular to the cylinder, reflecting the directional dependency of wet-snow accretion on conductors with an orientation of, respectively, north-south, northeast-southwest, east-west and northwest-southeast. Line direction must in fact be considered for wet-snow as the accreted loads frequently varies greatly on nearby lines, with some lines having a more favourably orientation than other lines with regard to the predominant icing directions (Elíasson et al., 2000; Ólafsson et al., 2002a).

The wet-snow maps have already been discussed and presented in secondary paper V of this thesis. The general conclusion is that, qualitatively, there is a good correlation between areas with observed accretion and areas with modelled icing. High loads are simulated where the most severe accretion has been observed but similar loads have also been simulated where none have been observed, most likely often due to a favourable line direction at those sites. Test spans located in the central highlands, where no power lines are located, verify the low loads simulated there. There are indications that the accretion model is predicting too high accretion intensities during severe events but in that context it should be noted that loads greater than 15–20 kg/m may certainly be possible although they have yet to be observed. Furthermore, wet-snow accretion depends on a critical combination of strong winds and large precipitation amounts in a narrow temperature interval, where small deviations in temperature can have a large effect on the overall accreted load. In fact, improved results are found in individual case studies based on higher resolution simulations with updated parameterizations and input data as in secondary papers II and III. Similarily detailed high-resolution climatological datasets are however not available.

The in-cloud accretion parameterization used to generate the icing maps is also used in secondary paper V, where it generally performs well in complex terrain in Iceland. The largest errors are presumably associated with errors in the atmospheric input data or small-scale features not resolved by the atmospheric model. Accreted loads and timing of icing events are on average well captured but the most intense accretion rates are often underestimated. The parameterization of the often stochastic

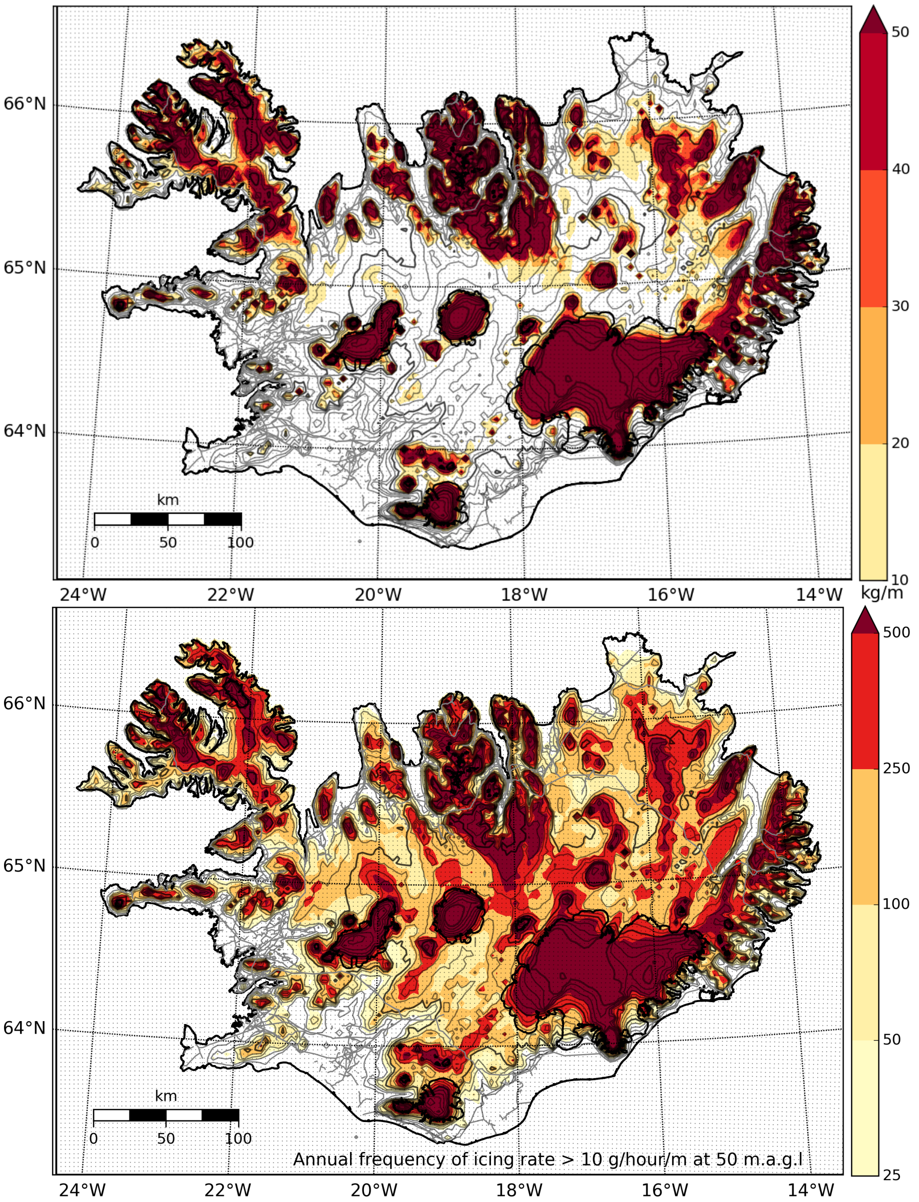

Figure 3.4. In-cloud icing during 1994–2014 at a 3 km horizontal resolution, on a vertical cylinder. Above: Maximum loads [kg/m] at the ground. Below: Frequency of icing intensity greater than 10 gm/hour at 50 m above the ground.

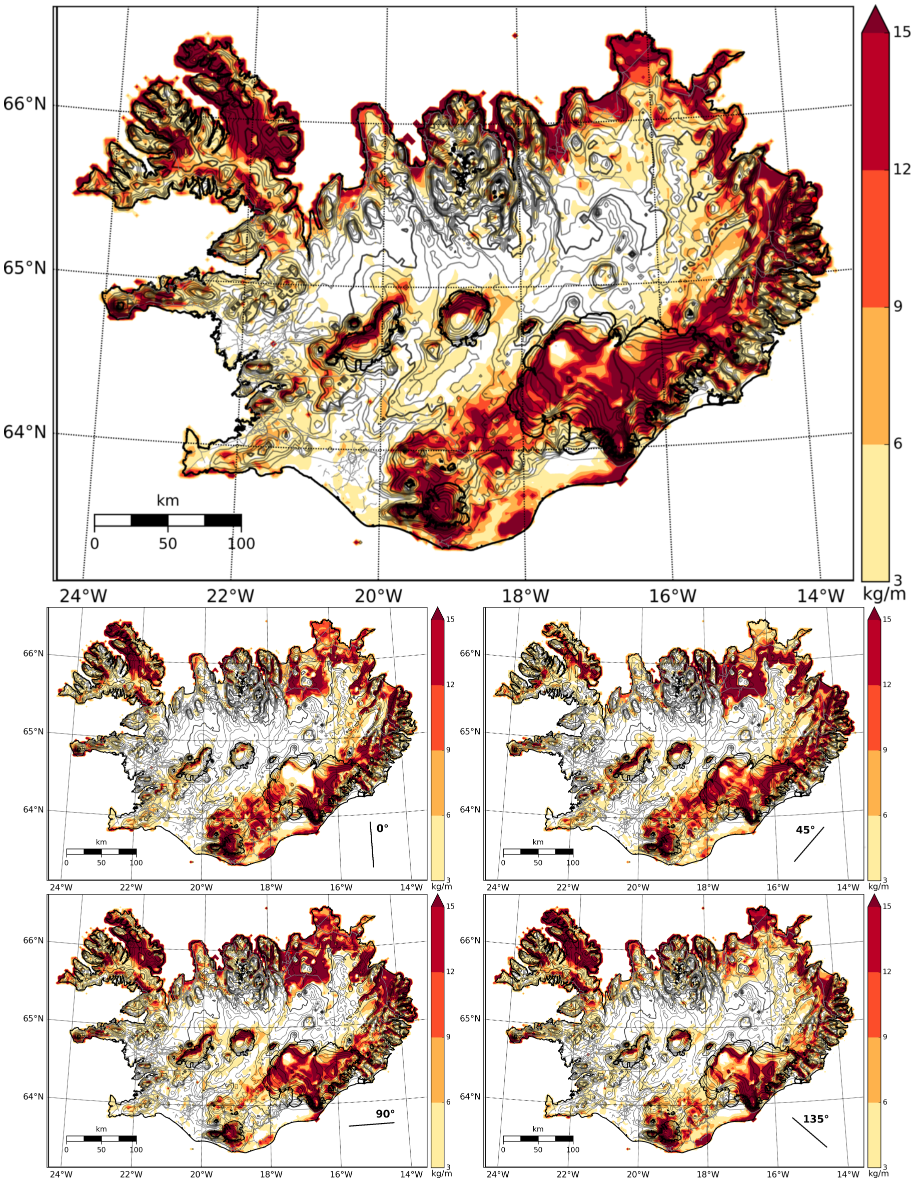

Figure 3.5. Maximum parameterized wet-snow load [kg/m] near the ground during 1994–2014 at a 3 km horizontal resolution, on a vertical cylinder (top), as well on horizontal cylinders with four different orientations as indicated (lower four panels).

ice-shedding is a weak point of all icing models but can be eliminated at sites where observations are available. That said, the icing maps presented here are quite realistic at locations where they have been compared with observational data or experience from in-cloud icing events. In-cloud icing is however very dependant on elevation and the local topography as is seen in the large spatial variability in the maps. With respect to the accretion sensitivity it should also be noted that the selected value of droplet size (N_d=50 droplets/cm^3) leads to a rather high accretion rate but no observational data is available on which a better estimate of N_d could be based.

While the above maps appear realistic, a more systematic comparison with available observational data should be taken. Such steps are under way, but in the meantime, the maps as well additional versions including a googleearth representation, are available online as a part of the Icelandic icing atlas[2].

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[2] http://tobediced

4 Summary of original papers

4.1 Paper I

***Hálfdán Ágústsson**, Joan Cuxart, Antoni Mira and Haraldur Ólafsson, 2007. Observations and simulation of katabatic flows during a heatwave in Iceland. Meteorol. Z., 16(1), 99–110.*

During August 8–14 2004 Iceland experienced a significant and wide-spread heatwave with observed temperatures exceeding 20°C for 7 consecutive days for Iceland as a whole, and for the first and only time, 4 consecutive days in Reykjavík. The highest 1 minute mean temperature at synoptic stations was 28.5° while the automatic stations recorded 29.2°. In spite of the relatively short summer night, the clear skies and weak synoptic winds contributed towards a nocturnal radiative surface cooling in excess of 10–15°C. Consequently, wide-spread and relatively strong katabatic flows developed at many locations.

The katabatic flows are explored based on observations of weather from a dense network of weather stations and a high resolution simulation with a numerical atmospheric model. The simulations and initial conditions are verified by comparison with 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 South-Iceland can be characterized as low Froude number "tranquil" flow, whereas the faster flow on the large outlets of Vatnajökull ice cap, may be classified as "shooting flow", based on the classification in Mahrt (1982). 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.

4.2 Paper II

***Hálfdán Ágústsson** and Haraldur Ólafsson, 2007. Simulating a severe windstorm in complex terrain. Meteorol. Z., 16(1), 111–122.*

The paper employs high-resolution numerical simulations, observations at the surface and satellite imagery to analyze a severe windstorm that occured in Iceland on 1 February 2002. The atmospheric model reproduces the windstorm and the observed spatial variability of the wind. The flow is reproduced with increasing accuracy as the horizontal resolution is increased, stepwise from 9 km to 1 km, while at a horizontal resolution of 333 m the flow pattern is realistic, but the quantitative improvement is not clear. The strongest surface winds are found in localized downslope windstorms below steep and amplified gravity waves which break in a reverse (negative) vertical wind shear near 600 hPa.

Several different setups of the MM5 model (Grell et al., 1995) were tested, varying the boundary layer, radiation and precipitation schemes. There is, as expected during such short storms, very little dependance on the radiation scheme. The surface winds are only moderately affected by the parameterization of surface friction but a more detailed moisture physics scheme has a positve impact on model performance. Surface winds are in general slightly overestimated and the model performs worst at locations where subgrid topography is expected to be of importance. The overestimating of the simulated surface wind speed is greatest immediately downstream and upstream of steep mountains.

Tests with modified topography show that if the next mountain downstream is too close, the magnitude of the surface windstorm can be reduced. This dampening may be explained by the fjord being too narrow to allow for a full development of the gravity wave or that the positive pressure anomaly created by the next downstream mountain is reducing the acceleration in the downslope flow further upstream.

The study indicates very strongly that every increase in horizontal resolution in steps from 9 km to 1 km and even beyond 1 km improves the representation of the local variability of winds in strong windstorms in complex terrain. Simulations at such high resolutions can be expected to be very beneficial for local weather forecasts.

4.3 Paper III

Haraldur Ólafsson *and Hálfdán Ágústsson, 2007. The Freysnes downslope windstorm. Meteorol. Z., 16(1), 123–130.*

Windstorms are frequent at and near the 2110 m high Mt. Öræfajökull in Southeast-Iceland and one such violent windstorm occured on 16 September 2004 and caused structural damage at the foot of the mountain. The windstorm is analyzed based on observations from two automatic weather stations and high-resolution simulations.

The observations and simulations reveal that there was at the same time a strong downslope acceleration of the flow as well as an acceleration at the edge of the mountain. The downslope windstorm was associated with a low level stable layer and active wave breaking below a reverse wind shear in the lower troposphere, between 800 and 550 hPa. The observed downslope wind speed is underestimated a few km downstream of the mountain, while the speed of the surface flow in the corner wind coming from the edge of the mountain is successfully reproduced by the numerical model. The method of Brasseur (2001) is applied for calculating the gusts, giving reasonably accurate gust factors.

The study furthermore indicates that a reverse vertical windshear is a general characteristic of easterly windstorms in Iceland. Consequently, mountain wave breaking may be more frequent than in many other windy places in the world. The meso- to synoptic scale flow of the Freysnes windstorm resembles the conditions during bora windstorms, but unlike the bora, there is warm air at the surface. The Freysnes windstorm is therefore suggested as a generic term for a warm bora-type downslope windstorm.

4.4 Paper IV

***Hálfdán Ágústsson** and Haraldur Ólafsson, 2009. Forecasting wind gusts in complex terrain. Meteorol. Atmos. Phys. 103(1–4), 173–185.*

The paper analyses parameterized wind gusts in a collection of simulations of atmospheric flows in complex terrain in the Snæfellsnes peninsula in West-Iceland during February to April 2007. The atmospheric data is a subset in a large collection of realtime numerical simulations used for forecasting in Iceland, prepared with the MM5 numerical weather prediction model (Grell et al., 1995). It is generated with 40 layers in the vertical and at horizontal resolutions of 9 and 3 km, and in two sensitivity tests at 1 km, forced with input data from the ECMWF. The region of interest is a roughly 75 km long west-east oriented peninsula with a width of approximately 15 km. The orography is complex and has a mean height of 800 m, with an 1446 m ice cap in the far west. The wind climate is characterized by frequent upstream blockings and downstream windstorm during northerly and southerly synoptic flow.

The gust prediction method of Brasseur (2001) is based on a considerations of parameterized turbulence kinetic energy, static stability and wind speed in the atmospheric boundary layer. The gust prediction method is implemented as post-processing and the calculated gust strength is compared with wind gust observations from several automatic weather stations located on the Snæfellsnes peninsula.

The estimated gusts are, as expected, strongly dependent on the quality of the simulated flow and are on average well captured when the mean winds are correctly simulated. Maximum gusts in downslope windstorms are often underestimated, which is in fact also the case for the mean downslope surface winds. The windstorms in the current study are presumably all related to gravity wave activity aloft and are better reproduced at higher resolutions than at a coarse resolution. There are cases of overestimated gusts on the upstream side of mountains, which may be related to an inadequate simulation of the upstream deceleration of the flow and overestimated surface winds in the upstream blocking. Gustiness in mountain wakes, away from the mountains, is frequently too great, which appears to be related to the boundary layer parameterization overestimating turbulence in the wakes.

4.5 Paper V

*Haraldur Ólafsson and **Hálfdán Ágústsson**, 2009. Gravity wave breaking in easterly flow over Greenland and associated low level barrier- and reverse tip-jets. Meteorol.*

Atmos. Phys., 104(3), 191–197.

The paper presents first evidence of severe turbulence in the lower stratosphere during easterly tropospheric flow over Greenland. The turbulence was observed at 200 hPa by a commercial jet flying from Iceland towards USA. The atmospheric situation and turbulence was re-created in a high resolution atmospheric simulation with a numerical weather prediction model. The turbulence is associated with gravity wave breaking at the intercontinental air traffic level in the lower stratosphere. The turbulence is substantially greater and more realistically reproduced when the horizontal resolution is increased from 9 km to 3 km.

The paper indicates very strongly that aviation forecasts of turbulence in this region are likely to improve if they are based on high-resolution real-time simulations. Furthermore, the climatology of the vertical wind profiles in atmospheric analyses of the ECMWF indicates that breaking waves at tropopause levels may be far more frequent over Greenland than over Iceland. Finally, the case shows that secondary wave breaking on the flanks of large mountains, as described in idealized flows (Ólafsson and Bougeault, 1996, 1997), exists in nature and a strong north-easterly barrier jet and a reverse tip jet may occur at low levels at the same time as the gravity wave breaking aloft.

4.6 Paper VI

Ólafur Rögnvaldsson, Jian-Wen Bao, ***Hálfdán Ágústsson*** *and Haraldur Ólafsson, 2011. Downslope windstorm in Iceland - WRF/MM5 model comparison, Atmos. Chem. Phys., 11, 103–120.*

The severe downslope windstorm of 16 September 2004 near Mt. Öræfajökull in Southeast-Iceland is simulated at high resolution using two different numerical weather prediction models, the PSU/NCAR MM5 and the Advanced Research WRF models (Grell et al., 1995; Skamarock et al., 2005). The models are run with the ETA/MYJ PBL schemes (Janjić, 1990, 1994, 2001) as well as a modified, two equation version of the same schemes (Bao et al., 2008). Six different micro-physics schemes, as well as a "dry" run, were tested, in combination with the MYJ PBL scheme in WRF. Both models are run at a horizontal resolution of 1 km using identical input data, prepared at 3 km with the MM5 model and atmospheric analyses from the ECMWF.

Both models capture gravity-wave breaking over Mt. Öræfajökull, while the vertical structure of the wave differs between the two models and the PBL schemes. Simulated downslope winds, using both the original and modified MYJ schemes in WRF, are in good agreement with the strength of the observed downslope windstorm. With MM5, the simulated surface winds, with the new two equation model, are in better agreement to observations than when using the original ETA scheme. The parameterization of atmospheric water and precipitation processes has a significant impact on atmospheric stability at lower tropospheric levels and consequently on the formation of the downslope windstorm. Only the Thompson et al. (2004, 2008) scheme captures the downslope windstorm, presumably as the other scheme do not capture the correct moisture distribution aloft.

The paper highlights some of the difficulties related to predicting severe downslope windstorms. Ensemble based studies (Reinecke and Durran, 2009) show a strong dependence of the predictability to small-scale features in the synoptic flow. Here, merely changing a parameterization related to atmospheric water is decisive for a successful forecast of surface winds.

4.7 Paper VII

Joachim Reuder, Markus Ablinger, ***Hálfdán Ágústsson****, Pascal Brisset, Sveinn Brynjólfsson, Markus Garhammer, Tómas Jóhannesson, Marius O. Jonassen, Rafael Kühnel, Stephan Lämmlein, Tor de Lange, Christian Lindenberg, Sylvie Malardel, Stephanie Mayer, Martin Müller, Haraldur Ólafsson, Ólafur Rögnvaldsson, Wolfgang Schäper, Thomas Spengler, Günther Zängl, Joseph Egger, 2012. FLOHOF 2007: An overview of the mesoscale meteorological field campaign at Hofsjökull, Central Iceland. Meteorol. Atmos. Phys., 116(1–2), 1–13.*

In this overview paper, the experimental setup of the FLOHOF field campaign and its first results are described. The campaign took place during 21 July to 24 August, 2007, on and around Hofsjökull ice cap in the central highlands of Iceland. During the campaign, 18 automatic weather stations recording temperature, humidity, wind speed, wind direction, pressure, and precipitation were deployed on and around the ice cap. In addition, atmospheric soundings were performed north and south of Hofsjökull by a tethered balloon, pilot balloons, and two unmanned aerial systems (UAS). An energy balance station, consisting of a net radiometer and an eddy correlation flux measurement station, was also installed.

The results described in the paper include an analysis of the extension of katabatic winds away from the glacier. Differential heating of the ice cap and the land outside the ice cap triggers daytime katabatic flows from the glacier and into its surrounding. The horizontal extent of the flows was typically 4–7 km from the edge of the glacier, with the greatest extent and strongest flows typically found in the afternoon, but hardly reaching further than 10 km from the ice margin. Unlike the nocturnal katabatic winds which are driven by radiative cooling, the solar heating generates the horizontal temperature gradients leading to the downslope flow observed here, but it also destroys them by quickly eroding the colder surface flows away from the ice cap.

4.8 Paper VIII

Hálfdán Ágústsson *and Haraldur Ólafsson, 2012. The bimodal Kvísker downslope windstorms. Meteorol. Atmos. Phys., 116(1–2), 27–42.*

The paper explores and analyzes downslope windstorms at Kvísker in Southeast-

Iceland. Two different types of gravity-wave induced windstorms are identified based on observations from an automatic weather station and atmospheric analysis from the ECMWF. Atmospheric simulations reveal that 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 Mt. Öræfajökull, 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 but the set of observed storms is too small for any statistical significance. 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 local weather in complex terrain.

4.9 Paper IX

*Marius O. Jonassen, Haraldur Ólafsson, **Hálfdán Ágústsson**, Ólafur Rögnvaldsson and Joachim Reuder, 2012. Improving a high resolution numerical weather simulation by assimilating data from an unmanned aerial system. Mon. Wea. Rev., 140(11), 3734–3756.*

Observed profiles of wind, temperature and humidity in the lower troposphere above Southwest-Iceland were obtained with an novel unmanned aerial system (UAS) in July 2009 during the international MOSO field campaign. The paper describes the profiles and demonstrates how they, through four-dimensional data assimilation, can be used to significantly improve high resolution simulations of the local atmospheric flow.

The observed data is used in two summertime cases (19 and 20 July 2009) of northeasterly flow in the southwestern lowlands of Iceland. Both situations were characterized by a strong diurnal temperature signal giving rise to thermally driven flow, predominantly in the form of a seabreeze circulation along the coast. The data assimilation leads to an improvement in the simulation of the horizontal and vertical extension of the sea breeze as well as of the local background flow. There was also, through a modification of the thermal low in Southwest-Iceland, a significant improvement in simulated flow more than 50 km away from the main region of interest. Sensitivity experiments show that both the assimilation of wind data as well as temperature and humidity data are important for the assimilation results. The results of the study indicated that an systematic assimilation of in-situ observed profiles of weather aloft may improve high-resolution numerical weather simulations and has a wide range of future applications such as in wind energy and targeted weather forecasts for search and rescue missions.

4.10 Paper X

*Bjørn Egil Kringlebotn Nygaard, **Hálfdán Ágústsson** and Katalin Somfalvi-Tóth, 2013. Modeling wet snow accretion on power lines: Improvements to previous methods using 50 years of observations. J. Appl. Meteor. Climatol., 52(10), 2189–2203.*

The paper uses unique datasets of measured wet-snow events and high resolution atmospheric simulations to build and compare observed and measured wet-snow climatologies in Southeast-Iceland. The observational data is based on an extensive icing database in which hundreds of observed wet-snow icing events have been systematically logged in detail, most of which include an estimate of the mean and maximum diameter of observed accretion on overhead power conductors and telephone wires (Ísaksson et al., 1998). The atmospheric data is based on over 50 years of weather, downscaled at 9 km horizontal resolution using a state-of-the-art numerical weather prediction model (Rögnvaldsson et al., 2011a).

The comparison between the observed and simulated climatologies allows for a comprehensive verification of wet-snow accretion models, and the authors are not aware of similar work reported in the scientific literature. Improvements to methods to model wet-snow accretion on structures are suggested. The existing models for wet-snow accretion on a standard cylinder are updated with realistic values for the terminal fall speed of wet snowflakes together with a snowflake liquid fraction–based criterion to identify wet-snow. The previously widely used parameterization (Admirat, 2008) of the sticking efficiency is found to strongly underestimate the accretion rate and extreme wet-snow loads. To compensate for this underestimation, two new parameterizations for the snowflake sticking efficiency are suggested. Both suggest a substantially higher accretion intensity, particularly at high wind speeds, and a physical dependance on the water content of the falling snow.

Application of the improved method is demonstrated in a high-resolution simulation for a case of observed widespread and intensive wet-snow icing in South-Iceland. The results form a basis for mapping the climatology of wet-snow icing in the complex terrain of Iceland as well as for preparing operational forecasts of wet-snow icing and severe weather for overhead power transmission lines in complex terrain.

4.11 Paper XI

***Hálfdán Ágústsson**, Hrafnhildur Hannesdóttir, Þorsteinn Þorsteinsson, Finnur Pálsson og Björn Oddsson, 2013. Mass balance of Mýrdalsjökull ice cap and comparison with observed and simulated precipitation. Jökull, 63, 91–104.*

The focus of the paper is threefold. It describes and analyzes mass balance measurements on the plateau of the Mýrdalsjökull ice cap in South-Iceland. Secondly, it gives a first estimate of the summer precipitation on the ice cap, based on synoptic observations of precipitation at sea level. Thirdly, it analyses and verifies simulations of orographic precipitation made with a high-resolution numerical atmospheric model.

The ice cap is in the wettest region of Iceland and the annual precipitation amounts are possibly only surpassed at the significantly higher Öræfajökull ice cap in Southeast-Iceland. Based on surveys from 2001 and annually since 2007, performed by volunteers from the Icelandic Glaciological Society, the measured specific winter balance at four locations above the equilibrium line was 3.4–7.8 m_{we} (water equivalent) with a maximum winter snow thickness in excess of 12 m. The summer mass balance was highly variable (-0.9 – -3.1 m_{we}) and the annual mass balance at the plateau had a high spatial and temporal variability (2.1–5.9 m_{we}).

Considerations of the mass balance and observed precipitation at sea level, give 1–1.8 m_{we} as a first observationally based estimate of the precipitation falling on the plateau of Mýrdalsjökull during summer. Atmospheric simulations performed at high horizontal resolution (3 km) compare well with the measured winter balance and the estimated summer precipitation at the survey sites. The winter balance as well as the precipitation are among the highest reported in Iceland, and the simulations indicate that parts of the ice cap, which are not surveyed, may annually receive up to 10 m_{we} of precipitation.

4.12 Paper XII

*Marius O. Jonassen, **Hálfdán Ágústsson** and Haraldur Ólafsson, 2014. Impact of surface characteristics on flow over a mesoscale mountain. Q. J. R. Meteorol. Soc., 140(684), 2330–2341.*

The paper is motivated by studies of dynamical downscaling of atmospheric flow in complex terrain that have revealed that prominent downslope accelerated flows in Iceland are not merely extreme events, but rather constitute a strong climatological signal over the larger ice caps and mountains. Here, the response of simulated downslope accelerated flow on the Hofsjökull ice cap in Iceland to changes in the surface roughness and surface temperature (equivalent to changing surface cooling) is analyzed. A series of sensitivity simulations of summertime flow reproduces previously known results, namely that smooth and cold surfaces, such on the ice caps, enhance downslope flows (e.g. Georgelin et al., 1994; Ólafsson and Bougeault, 1997). However, changing the surface roughness has in this case a far stronger impact on the accelerated downslope flow than merely changing the surface temperature. That is, the downslope flow signal is quite similar above a smooth glacier surface where the flow is cooled from below (surface always cold and below 0°C) and above a smooth non-glaciated surface where the flow is not cooled from below (surface temperature not forced to stay at/below freezing). The flow structure is also similar if both the glaciated and non-glaciated surface have higher roughness (similar to that of the surrounding non-glaciated highlands). Furthermore, the sensitivity experiments roughly correspond to an investigation of the impact of retreating glaciers on downslope flows in a rapidly warming climate.

4.13 Paper XIII

Hálfdán Ágústsson *and Haraldur Ólafsson. Simulating observed lee-waves and rotor turbulence, 2014. Mon. Wea. Rev., 142(2), 832–849.*

Direct, in-situ, observations and reports of severe turbulence aloft are rare but provide important and valuable data for use in verification of numerically simulated flows. One such event occured on 18 November 2008, when a relatively small commercial aircraft encountered severe turbulence while flying in westerly flow along the southeastern coast of Iceland and descending from 2500 m down to the ground for a safe landing.

The paper uses atmospheric simulations and observational data to explore and describe the event. Numerical simulations, performed at horizontal resolutions of 3 and 1 km, reproduce the situation, with an observed severe downslope windstorm at the ground as well as associated amplified lee waves and a rotor aloft. The event is not captured at the coarsest resolution of 9 km, underlining the importance of high resolution for simulations of such flows. Strong shear turbulence is simulated at the interface of the lee wave and the rotor, as well as inside the rotor. The waves are not stationary and the rotor turbulence increases while the lee-wave amplitude decreases in the late afternoon, but the turbulence increases temporarily while the rotor circulation breaks down. Furthermore, climate data, including simulated flow, observations of wind at the surface and satellite imagery indicate that all observed westerly windstorms in the region are of the same type and occur in a similarly structured atmosphere.

The aircraft presumably flew through the lee wave and into the rotor, and as often is the case, there was no warning (i.e. SIGMET) issued for this region until after the incident. However, it is evident that this event could have been forecast quite accurately, but not with the NWP tools used at that time in aviation forecasts. Their resolution is not adequate and is typically of the order of 10–30 km or even coarser, although steps have now being taken to develop better weather warning systems based on numerical models at significantly higher resolutions. The event described in the paper underscores the urgency of delivering such finescale products to pilots and forecasters, for aviation needs in the lower troposphere where atmospheric turbulence may be the most intense and the most hazardous to aviation.

4.14 Paper XIV

Hálfdán Ágústsson *and Haraldur Ólafsson, 2014. The advection of atmospheric vortices over Reykjavík. Mon. Wea. Rev., 142(10), 3549–3559.*

The paper is motivated by unique satellite imagery accquired over Iceland on 12

August 2009. A series of satellite images revealed asymmetric shedding of atmospheric vortices in the lee of Mt. Snæfellsjökull, and their passage a distance of 120 km across Faxaflói Bay and over the city of Reykjavík in West-Iceland. Furthermore, the vortices were detected by a network of surface weather stations after landfall, until their dissipation at least 25 km inland.

The observational data is presented and a high-resolution atmospheric simulation is employed in analyzing the situation in more detail. The observed vortices are discussed in view of existing theories of orographic wakes and vortex shedding. In general, the flow is in line with existing knowledge, but there is a remarkable absence of vortices with anticyclonic rotation. From a climatological perspective, conditions for vortices of this kind are most often favorable in late winter and spring. Forecasting such small scale phenomena is a challenge and critically dependent upon the accuracy of the initial and forcing data, e.g. the height of the upstream inversion and the ambient wind speed and direction.

4.15 Paper XV

Hálfdán Ágústsson *Haraldur Ólafsson, Marius O. Jonassen and Ólafur Rögnvaldsson, 2014. The impact of assimilating data from a remotely piloted aircraft on simulations of weak-wind orographic flow. Tellus, 66A, 25421.*

During the international MOSO field experiment in 2009 and 2011, winds aloft at several locations in Southwest-Iceland were observed using a small remotely piloted aircraft (RPAS). In particular, on 15 July 2009, orographic winds near a 914 m high mountain in Southwest-Iceland were explored with the RPAS, as well as with traditional observations and high-resolution atmospheric simulations.

While prominent gravity waves are not a typical feature of near-to-neutral flow that meets a mountain at only about 7 m/s, the observational data nevertheless revealed that winds in the lee of the mountain were indicative of flow locally enhanced by wave activity aloft. Winds descended along the lee slope with a prevailing direction away from the mountain. They were relatively strong and gusty at the surface close to the mountain, with a maximum at low levels, and weakening and becoming more diffuse a short distance further downstream. The winds weakened further aloft, with a minimum on average near mountain top level.

The situation was reproduced in a high-resolution atmospheric simulation forced with atmospheric analysis as well as with the observed lee-side profiles of wind and temperature below 1.4 km. Without the additional observations consisting of the lee-side profiles, the model failed to reproduce the winds aloft as well as at the surface in a region in the lee of the mountain, as was also the case for the operational numerical models at that time. A sensitivity simulation indicated that this poor performance is a result of the poorly captured strength and sharpness of the inversion aloft at about 2 km. The successfully simulated lee-side flow exhibits a hydraulic jumplike feature and a structure similar to that observed.

The study illustrates, firstly, that even at very low wind speed, in a close to neutral low-level flow, gravity waves may still be a dominating feature of the flow. Secondly, the study presents an example of the usefulness of lee-side atmospheric profiles, retrieved by simple model aircraft, for improving numerical simulations and short-term weather forecasting in the vicinity of mountains. Thirdly, the study confirms the sensitivity of downslope flow to only moderate change in the sharpness of an upstream inversion.

5 Summary of secondary papers

5.1 Secondary paper I

Árni Jón Elíasson, Egill Þorsteins, ***Hálfdán Ágústsson*** *and Ólafur Rögnvaldsson, 2011. Comparison between simulations and measurements of in-cloud icing in test spans. 14th* IWAIS*, Chongqing, China.*

The paper compares and analyzes measured and simulated in-cloud icing at Hallormsstaðaháls in East-Iceland. The icing measurements are done by Landsnet and are carried out in test spans which have frequent in-cloud icing. Icing calculations are based on a cylindrical icing model which uses simulated atmospheric data as input. The WRF-model is used to dynamically downscale the atmospheric analysis from the ECMWF to a horizontal resolution of 9, 3, 1, and 0.33 km. The high horizontal resolution allows the atmospheric model to reproduce accurately the atmospheric flow in the complex orography at the site, which is not well resolved at resolutions coarser than 1 km.

In general, icing calculations based on the atmospheric model identify correctly the observed icing events, but underestimate the load due to too slow ice accretion. This is most obvious when the temperature is slightly below 0°C and the observed icing is most intense. The model results improve significantly when the model is forced with additional observations of weather. Some of the errors in reproducing the observed icing can be explained by the large variability in the simulated atmospheric variables, which results in high temporal and spatial variability in the calculated ice accretion. Furthermore, there is high sensitivity of the icing model to the droplet size and the possibility that some of the icing may be due to freezing drizzle and/or wet-snow, which is not parameterized with the model, instead of in-cloud icing of super-cooled droplets. In addition, the icing model (e.g. Makkonen, 2000), is not calibrated for the highest ice loads and most intense accretion observed and, hence, its reliability for severe accretion remains unclear.

5.2 Secondary paper II

Árni Jón Elíasson, Egill Þorsteins, ***Hálfdán Ágústsson*** *and Guðmundur M. Hannesson, 2013. Modeling wet-snow accretion: Comparison of cylindrical model to field measurements. 15th* IWAIS*, St. Johns, Newfoundland, Canada.*

Cylindrical accretion models, forced with atmospheric data based on the results of high resolution numerical meteorological models (WRF), allow for a detailed analysis of wet-snow accretion in complex and datasparse regions. More so as several of the relevant atmospheric parameters are not routinely observed, such as the snow flux and its liquid water fraction, which is critically dependent on the wet bulb temperature, but has previously been based on in-situ observations of the air temperature.

This paper compares and analyzes measured and simulated wet-snow accretion during several wet-snow events in North-Iceland. The measurements are made with load cells in dedicated test spans and, in some cases, in operating transmission lines. They accurately identify the rate and size of accreted wet-snow, and normally include measurements of air temperature as well. The largest events include wet-snow accretion exceeding 15 kg/m in less than 10 hours, and they are associated with very large amounts of precipitation and/or gale force winds.

The accretion models are forced with observed weather parameters as well as simulated atmospheric data of the relevant parameters which are not observed. The simulated atmospheric data is created with the WRF-model at a horizontal resolution of 1 km, forced with atmospheric analysis from the ECMWF. The performance of the cylindrical accretion models is analyzed with special attention to the influence of sticking efficiency on the amount and timing of wet-snow accretion. The accretion models are sensitive to small variations in the relevant parameters but small and medium sized events are in general well captured while large events tend to be underestimated. The model presented in Paper X outperforms the model of Admirat (2008).

5.3 Secondary paper III

Árni Jón Elíasson, ***Hálfdán Ágústsson****, and Guðmundur M. Hannesson, 2013. Wet-snow accumulation: A study of two severe events in complex terrain in Iceland. 15th* IWAIS*, St. Johns, Newfoundland, Canada.*

This paper analyzes observed and simulated wet-snow accretion during two severe wet-snow storms in North-Iceland, both which caused extreme ice loads on many transmission and distribution lines in North Iceland. The event of 10 September 2012 was exceptional because of extreme snowfall so early in the autumn. The snowfall was associated with average wind speeds in excess of 20 m/s, causing widespread accumulation of wet-snow within a certain altitude interval in North-Iceland. In the latter event of 30 December 2012, heavy snowfall and gale-force winds, as well as extreme wet-snow loading, were more localized, occurring mostly in the lee of the complex orography of Northwest-Iceland.

The observed wet-snow data were collected during detailed in-situ inspections of accumulated wet-snow on overhead powerlines, from load cells installed in the powerlines as well as from special test spans. The collected load data are unique in the sense that they describe in detail both the exact timing and magnitude of the severe wet-snow accumulation. Meteorological observations of wind, temperature and precipitation are moreover available from synoptic and automatic weather stations in the areas.

The atmospheric flow is analyzed, based on weather observations and simulations at high resolution with an atmospheric model. The simulated data are subsequently used as input for a cylindrical wet-snow accretion model. The measured and simulated wet-snow loading are analyzed and put in relation with the weather during the event, highlighting several key aspects of the flow and the accretion process that needs further attention. The performance of the accretion model is highly sensitive to the accuracy of the input data and smaller loads are in general better reproduced than severe loads which are underestimated.

5.4 Secondary paper IV

*Árni Jón Elíasson, **Hálfdán Ágústsson**, Guðmundur M. Hannesson and Egill Þorsteins, 2015. Comparison of measured and simulated icing in 28 test spans during a severe icing episode. 16th* IWAIS*, Uppsala, Sweden.*

This paper presents an analysis of simulated in-cloud icing and a comparison of the results with detailed field measurements from 28 test spans at 19 test sites in North- and East-Iceland for a period of 99 days during the extreme icing winter of 2013–2014. Ice accretion was extensive with the maximum ice load measured equal to 47 kg/m, the greatest total accumulation in one test span during the winter was 177 kg/m and the total accumulation at the 28 test spans was 1076 kg/m. The icing simulations are based on a time dependant, horizontal, cylindrical accretion model using atmospheric data from a high resolution numerical weather prediction model as an input.

Model results are presented as time-series of icing at locations of test spans, as well as summaries of total accretion loads and intensities at the spans. Results are highly sensitive to the performance of the atmospheric model, while the timing of individual icing periods is nevertheless on average correctly captured. Small and medium size accretion events are generally better captured than more extreme events which are often underestimated due to too weak accretion intensity, presumably related to errors in the input data. A novel method is used to remove the complicating and random effect of ice-shedding: the icing model is forced to shed ice in unison with the observations, with total simulated accretion compiled for each span during periods when accretion is actually observed.

The analysis presented in this study is made possible by the detailed observations available from a large number of test spans. The overall performance of icing model is good at the observational sites and it appears that the largest errors can be traced back to the atmospheric input data. This indicates that the accretion model is in general also reliable at other locations and its results can be used to assess ice loads in complex terrain where observational data is generally sparse or missing, given that the atmospheric input data is of adequate quality.

5.5 Secondary paper V

Árni Jón Elíasson, Sigurjón P. Ísaksson, ***Hálfdán Ágústsson*** *and Egill Þorsteins, 2015. Wet-snow icing: Comparing and simulated accretion with observational experience. 16th* IWAIS*, Uppsala, Sweden.*

Coupled icing and mesoscale atmospheric models are a valuable tool for assessing ice loading for overhead power lines. This paper presents an analysis of how well an icing model captures wet-snow accumulation in areas that are historically known to be exposed to wet-snow icing in Iceland. wet-snow icing maps were prepared using an accretion model forced with 21 years of simulated atmospheric data. The weather parameters used in the accretion model, i.e., wind speed, temperature, precipitation rate and snowflake liquid water fraction, were derived by simulating the state of the atmosphere with WRF-model at a horizontal resolution of 3 km.

The icing maps were compared to data from an icing database that contains long term historical information icing events on the overhead power lines in Iceland. Qualitatively, there is a good correlation between areas with observed accretion and areas with modelled icing. High ice loads are simulated in areas where the most severe accretion has been observed. In some cases high loads are simulated where similar loads have not been observed but these cases can often be explained by the strong dependence on the actual line direction compared to main icing direction, highlighting that the icing model must take into account the actual direction of the power line.

6 General conclusions

The general and most significant conclusions of the papers of this thesis can be summarized as follows:

- Numerical simulations at high spatial resolutions are a valuable tool for forecasting severe weather in the vicinity of complex terrain. Interpolation from coarse-resolution simulations may lead to large errors, even if the mountains are to some extent represented.

- Systematic and operational high-resolution simulations of mesoscale atmospheric flow in and above complex orography can be used to improve aviation forecasting, both in the lower troposphere as well as at international flight levels above the tropopause. Such products need to be developed taking into account the transient nature of the flows and the hazards.

- Secondary wave breaking on the flanks of large mountains, as described in idealized flows, exists in nature. A strong north-easterly barrier jet and a reverse tip jet may indeed occur at low levels at the same time as there is gravity wave breaking aloft over Greenland in easterly flow.

- The Freysnes easterly downslope windstorms are associated with a strong wave gravity wave breaking aloft, in an environment of reverse vertial wind shear, while there may at the same time be accelerated flow at the foot of the mountain. The conditions resemble those during bora windstorms, except that the air at the surface is warm, not cold.

- Not only is the parameterization of boundary layer turbulence important but a correct representation of microphysical processes and moisture distribution can be decisive for a successful windstorm prediction.

- Observed lee waves and rotor turbulence, as well as an associated downslope windstorm, have been successfully reproduced, based on high-resolution atmospheric simulations. Such events appear to be a prominent feature of the regional windstorm climate in Southeast-Iceland.

- Two different types of windstorms in Southeast-Iceland have been identified, based on their downstream spatial extent. The Type S (Short) is confined to the lee-slopes of the mountain (with an amplified gravity wave aloft) while the Type E (Extended) continues some distance downstream of the mountain (with an elevated inversion and reverse vertical windshear).

- Sensititity tests with modified orography show if a wide fjord is narrowed a downslope windstorm may be dampened significantly.
- Wind gusts can be realistically parameterized based on atmospheric simulations of flow in complex orography. Depending, however, on how well the mean winds and turbulence aloft are reproduced, with a frequent gust underestimate in downslope windstorms and an overestimate in mountain wakes.
- Prominent downslope accelerated flows are a strong climatological signal over large ice caps in Iceland. Increased surface roughness distinctly dampens these downslope flows while the effect of changing the surface temperature is minimal.
- Even at very low wind speeds, in a close to neutral low-level flow in complex orography, gravity waves may still be a dominating feature of the flow above complex orography.
- Downslope flows can be sensitive to only moderate change in the sharpness of an upstream inversion.
- Small remotely airborne systems are a novel instrument platform with a large potential within the atmospheric sciences, e.g. in the context of improving simulations of local weather.
- Differential heating of Icelandic ice caps and their surrounding triggers daytime katabatic flow from the ice caps into their surrounding. The flows are strongest and reach furthest during the late afternoon.
- Conditions associated with the asymmetric shedding of atmospheric vortices in the lee of Mt. Snæfellsjökull are most often favourable in late winter and spring, and they are a forecasting challenge.
- In-cloud ice accretion has been simulated and analyzed for severe icing periods in Iceland, e.g. based on a novel method which removes the complicating and random effect of ice-shedding on the analysis.
- Models for the accretion of wet-snow icing have been improved based on a snowflake liquid fraction–based criterion and a more realistic impact of wind speed on the sticking efficiency of wet snow.

7 Concluding remarks and future outlook

This thesis focuses on different aspects of mesoscale flow in the complex orography of Iceland. The analysis is mainly made possible by two different sources of atmospheric data, as is in general the case for studies of weather and climate in complex orography.

First, accurate and detailed observations of weather are critically important; both from surface based weather stations as well as from aloft. Overall, the status in Iceland is very good with a dense network of automatic weather stations, with nearly all data available through the Icelandic Meteorological Office. There has been a recent effort to reduce the number of stations, both synoptic and automatic. This is an unfortunate development which may reduce the quality and applicability of individual time series as well as the entire dataset, e.g. with regard to the analysis of a changing climate and return periods of extreme weather. Most primary atmospheric parameters such as wind speed and temperature are routinely observed but observations of many other parameters are nonetheless important but are unfortunantly often unavailable. These include observations of turbulence, aerosols and cloud droplet size, which are rarely observed except during large international field experiments such as Grubišić et al. (2008); Renfrew et al. (2008) and the recent DEEPWAVE (Fritts et al., 2015), and using specialized airborne instruments as in Dörnbrack et al. (2010). Many of the studies presented here would in fact have benefitted from additional observational data, both for mapping the relevant atmospheric phenomena (as in Paper XV) but also for verification of numerical simulations of the flow and the forcing data (as for the icing model in secondary papers I-V). This is especially true for systematic three-dimensional observations aloft which are as a rule only performed at upper-air stations or using expensive remote sensing equipment. In this context, RPASs have been shown to be a valuable additional tool, as presented in e.g. Mayer et al. (2012) and Papers VII, IX and XV, but occasional and subjective observations of atmospheric turbulence also provide important opportunities for analysis of weather as was the case in Papers V and XIV.

As the terrain gets more complex, the observations from one site may differ greatly from observations at a nearby site, possibly in the same basin near a sea-breeze or a katabatic front (e.g. Papers I and IX) or downstream from mountains during windstorms (Paper III). In this context, a higher concentration of observational sites may help but this is costly and in reality limited to a small region. Therefore, the observational dataset is frequently corroborated by a second, simulated, dataset, especially in complex orography. However, adequate horizontal and vertical resolution is necessary to resolve the relevant topographical features and the rule of thumb is that the higher the resolution available, the better, as is the case here (Papers III, IV and V) and has in fact become common knowledge. Due to limitations in model parameterizations, the push towards high resolution is still mostly limited to roughly 1 km in the horizontal, below which is the so-called Terra Incognita (Wyngaard, 2004). We have shown the benefits of going to even higher resolution (as in Paper II) but future studies will benefit when the gap between traditional mesoscale models and LES models has been fully bridged, allowing for a full two-way coupling of the models and a seamless simulation of weather from the synoptic scales down to at least a 100 metre resolution, as is for example discussed in Rotach and Zardi (2007). This is especially true for the analysis of small-scale features such as gustiness, localized downslope windstorms, lee wave rotors and atmospheric vortices (Papers II, IV, XIII, XIV).

However, as the resolution of the numerical models is increased, new challenges arise in relation with the accuracy and quality of the input data as well as with the verification of the simulated data (see overview by Roebber et al., 2004). In Papers IX and XV, as well as in Mayer et al. (2012), the forcing data for the atmospheric model is shown to be improved with in-situ observations from aloft, a subject which is likely to receive more attention in the context of improving local, short term, weather forecasts. Furthermore, with increased horizontal resolution, simulations of downslope windstorms become more accurate and detailed, although this increase is not necessarily well reflected in the performance at individual weather stations (Papers II and XIII) as a small spatial error in windstorm extent may lead to a large error in storm magnitude. In, fact, the variable downslope extent of different types of downslope windstorms (Paper VIII) needs more attention, especially in relation with the predictability of operational forecasting of severe weather. In this context, studies of idealized flow over real as well as smooth topography should be undertaken, aiming to fill in the gaps of the regime diagrammes of Vosper (2004); Hertenstein and Kuettner (2005); Sheridan and Vosper (2006) and to map the extent of thermal winds and mesoscale flow features in Iceland under idealized atmospheric conditions.

That said, future studies pertaining to the diverse subjects of the thesis will benefit from the large observational datasets which are available as well as from improved analysis data such the ERA-Interim reanalysis as Dee et al. (2011), which recently has become available. However, if the dominant orography and land use characteristics are to be resolved by atmospheric simulations, an effective resolution greater than 1 km in the horizontal must be used and sufficiently accurate high resolution land use and elevation data must be made available. Model forcing data should be corroborated with in-situ observations where available, and carefully analyzed, as errors in the large scale flow may influence the development of local mesoscale structures in the vicinity of mountains (Nance and Durran, 1997, 1998; Durran and Gingrich, 2014). It can be postulated that an ensemble based approach may aid in improving operational fine scale simulations of high impact weather. That is, an ensemble of high resolution forecasts is more likely to correctly identify and reproduce critical atmospheric conditions, which may be sensitive to errors in model input data (as in Papers IX and XV) or model parameterizations (as in Papers II and VI), than a single deterministic forecast (Roebber et al., 2004). This holds true for the predictability of gravity wave activity aloft and downslope windstorms as for example discussed in the ensemble based study of Reinecke and Durran (2009), but also when forecasting wet-snow accretion which only occurs in a narrow temperature interval (Paper X).

Paper I

Observations and simulation of katabatic flows during a heatwave in Iceland

Hálfdán Ágústsson, Joan Cuxart, Antoni Mira and Haraldur Ólafsson

Meteorol. Z., **16**(1), 99–110, 2007

Hálfdán Ágústsson lead and initiated the work on the paper. He performed all simulations, analyzed observed and simulated data, prepared the figures, and wrote the manuscript.

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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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Paper II

Simulating a severe windstorm in complex terrain

Hálfdán Ágústsson and Haraldur Ólafsson

Meteorol. Z., **16**(1), 111–122, 2007

Hálfdán Ágústsson lead and initiated the work on the paper. He performed all simulations, analyzed observed and simulated data, prepared the figures, and wrote the manuscript.

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Article

Simulating a severe windstorm in complex terrain

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Abstract

The severe windstorm that hit Iceland on 1 February 2002 is analyzed using high-resolution numerical simulations, conventional observations at the ground and satellite images. The windstorm and the great mesoscale variability in the observed wind are reproduced by the numerical simulations, with increasing accuracy as the horizontal resolution is increased, stepwise from 9 km to 1 km. At a horizontal resolution of 333 m the flow pattern is realistic, but the quantitative improvement is not clear. The strongest surface winds are found in localized downslope windstorms below steep and amplified gravity waves which presumably break in a reverse (negative) vertical wind shear at middle tropospheric levels. Surface winds are in general slightly overestimated and the model performs worst at locations where subgrid topography is expected to be of importance. The overestimating of the simulated surface wind speed is greatest immediately downstream and upstream of steep mountains. The surface winds are only moderately affected by the parameterization of surface friction and the magnitude of the downslope windstorms shows some sensitivity to the distance to the next downstream mountain. The study indicates that the turbulence is overestimated immediately upstream of mountains at 1 km horizontal resolution.

Zusammenfassung

Das starke Sturmereignis vom 1. Februar 2002 auf Island wird mit hoch auflösenden numerischen Simulationen, konventionellen Bodenbeobachtungen und Satellitenbildern untersucht. Das Windfeld und seine mesoskalige Variabilität werden durch die numerischen Simulationen, deren Genauigkeit mit der schrittweise von 9 km auf 1 km erhöhten räumlichen Auflösung steigt, wiedergegeben. Bei der höchsten räumlichen Auflösung von 333 m ist das Strömungsmuster zwar realistisch, eine weitere quantitative Verbesserung aber unklar. Die stärksten bodennahen Windgeschwindigkeiten werden in örtlich eng begrenzten Fallwinden hinter Gebirgszügen unterhalb von steilen und verstärkten Schwerewellen, die vermutlich in einer invertierten vertikalen Windscherung in der mittleren Troposphäre brechen, gefunden. Die Bodenwinde werden im Allgemeinen leicht überschätzt, wobei die schlechtesten Ergebnisse in Gebieten auftreten, in denen ein Einfluss der kleinskaligen, vom Rechengitter nicht aufgelösten Orographie erwartet werden muss. Diese Überschätzung ist am stärksten unmittelbar vor und hinter steilen Bergen. Die Parametrisierung der Bodenreibung hat nur mäßigen Einfluss auf die bodennahe Windgeschwindigkeit, die leeseitigen Fallwinde zeigen aber eine gewisse Abhängigkeit vom Abstand zur nächstfolgenden Bergkette. Die Untersuchung legt den Schluss nahe, dass in der 1 km-Auflösung die Stärke der Turbulenz unmittelbar stromauf von Bergen überschätzt wird.

1 Introduction

Severe windstorms are one of the big threats of weather to vegetation, infrastructure and lives. The greatest danger in such storms is related to fluctuations in the wind speed at periods as short as a few seconds, otherwise known as wind gusts. In extreme windstorms in complex terrain, the gust strength may easily exceed twice the 10-minute mean wind speed at 10 metres above ground, (e.g. DURRAN, 1990; GRØNÅS and SANDVIK, 1999). At weaker winds, gusts are far weaker and more similar to the mean wind (e.g. NAESS et al., 2000; ÁGÚSTSSON and ÓLAFSSON, 2004b).

Gustiness is a manifestation of atmospheric turbulence, which is primarily found close to the surface of the earth, i.e. in the atmospheric boundary layer. Here, turbulent motion arises due to the low static stability and high vertical wind shear caused by surface friction. Aloft, turbulence is also found, for example in regions of wind shear near the tropospheric and stratospheric jets as well as in deep convective cells. Of greater interest in the context of this study is the turbulence produced by large amplitude gravity (buyoancy) waves, which may form in a stably stratified atmosphere above mountainous regions. The turbulence is produced aloft, either in regions of high wind shear or due to local convective instability where the waves break, and may reach down to the surface of the earth, accompanied by strong wind gusts. The gustiness has been suggested to be associated with wave breaking (CLARK and FARLEY, 1984) but also with Kelvin-Helmholtz instability (SCINOCCA and PELTIER, 1989; PELTIER and SCINOCCA, 1990). A

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Paper III

The Freysnes downslope windstorm

Haraldur Ólafsson and Hálfdán Ágústsson

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Hálfdán Ágústsson participated actively in the work on the paper. He performed all simulations and gust calculations, prepared many figures, participated in analyzing observed and simulated data as well as in writing the manuscript.

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Article

The Freysnes downslope windstorm

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Abstract

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

Zusammenfassung

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

1 Introduction

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

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

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Paper IV

Forecasting wind gusts in complex terrain

Hálfdán Ágústsson and Haraldur Ólafsson

Meteorol. Atmos. Phys. **103**(1–4), 173–185, 2009

Hálfdán Ágústsson lead and initiated the work on the paper. He performed all simulations and gust calculations, including coding the gust method, analyzed observed and simulated data, prepared the figures, and wrote the manuscript.

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Forecasting wind gusts in complex terrain

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With 10 Figures

Received 25 October 2007; Accepted 20 November 2008

Summary

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

1. Introduction

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

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Paper V

Gravity wave breaking in easterly flow over Greenland and associated low level barrier- and reverse tip-jets

Haraldur Ólafsson and Hálfdán Ágústsson

Meteorol. Atmos. Phys., **104**(3), 191–197, 2009

Hálfdán Ágústsson participated actively in the work on the paper. He performed all simulations, prepared most figures, participated in analyzing observed and simulated data as well as in writing the manuscript.

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ORIGINAL PAPER

Gravity wave breaking in easterly flow over Greenland and associated low level barrier- and reverse tip-jets

Haraldur Ólafsson · Hálfdán Ágústsson

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Abstract A first evidence of severe turbulence in the lower stratosphere during easterly tropospheric flow over Greenland is presented. A numerical simulation shows the turbulence to be associated with gravity wave breaking and that simulating with a horizontal resolution of 3 km gives substantially greater and more realistic turbulence than at a 9 km horizontal resolution. It is concluded that real-time simulations at high resolutions would improve aviation forecasts. As the atmospheric flow impinges on South-Greenland a barrier jet, a reverse tip jet and amplified mountain waves with secondary wave breaking are generated at the same time.

1 Introduction

When stably stratified flow impinges on topography, gravity waves are generated. These waves may propagate vertically through the troposphere and into the stratosphere, depending on the vertical profile of the background flow. If the static stability increases with height and/or the wind decreases with height, the waves may overturn or break. At the breaking of the waves, the wave energy is returned to the airflow and intensive turbulence is created. Breaking mountain waves are not only important for the momentum budget of the atmosphere, but they also generate turbulence that may be hazardous to even large aircrafts. It is therefore of great importance to predict wave breaking as accurately as possible.

A comprehensive overview of this wave motion is given in Durran (1990) and fundamental studies and review of the onset and impact of wave breaking in simplified flows are found in Smith (1985, 1989) and Smith and Grønås (1993). Amplification and breaking of mountain waves and associated downslope windstorms in more complex flows is described in a series of papers such as Richard et al. (1989), Miranda and James (1992), Ólafsson and Bougeault (1996, 1997a, b), Wang (1999) and Teixeira and Miranda (2005). Mountain wave breaking in real atmospheric flows has been described in connection with PYREX (Ólafsson and Bougeault 1997a), over the Rocky mountains by Doyle et al. (2000), during MAP (Smith et al. 2007) and in Iceland by Ólafsson and Ágústsson (2007) and Ágústsson and Ólafsson (2007). In these studies and many others (referred to in the above papers), amplification and/or breaking of mountain waves is linked to the underlying topography and features of the flow such as the vertical profiles of wind and temperature. There are strong indications that Greenland may be able to generate gravity waves that are not less and even greater than waves over other major mountain ranges that have gained more attention so far (Limpasuvan et al. 2007 and the FASTEX case reported by Doyle et al. 2005 and Rögnvaldsson and Ólafsson 2003).

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Paper VI

Downslope windstorm in Iceland - WRF/MM5 model comparison

Ólafur Rögnvaldsson, Jian-Wen Bao, Hálfdán Ágústsson and Haraldur Ólafsson

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Hálfdán Ágústsson assisted with atmospheric simulations and participated in analyzing observed and simulated data as well as contributing towards the writing of the manuscript.

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Atmospheric Chemistry and Physics

Downslope windstorm in Iceland – WRF/MM5 model comparison

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Abstract. A severe windstorm downstream of Mt. Öræfajökull in Southeast Iceland is simulated on a grid of 1 km horizontal resolution by using the PSU/NCAR MM5 model and the Advanced Research WRF model. Both models are run with a new, two equation planetary boundary layer (PBL) scheme as well as the ETA/MYJ PBL schemes. The storm is also simulated using six different micro-physics schemes in combination with the MYJ PBL scheme in WRF, as well as one "dry" run. Output from a 3 km MM5 domain simulation is used to initialise and drive both the 1 km MM5 and WRF simulations. Both models capture gravity-wave breaking over Mt. Öræfajökull, while the vertical structure of the lee wave differs between the two models and the PBL schemes. The WRF simulated downslope winds, using both the MYJ and 2EQ PBL schemes, are in good agreement with the strength of the observed downslope windstorm. The MM5 simulated surface winds, with the new two equation model, are in better agreement to observations than when using the ETA scheme. Micro-physics processes are shown to play an important role in the formation of downslope windstorms and a correctly simulated moisture distribution is decisive for a successful windstorm prediction. Of the microphysics schemes tested, only the Thompson scheme captures the downslope windstorm.

1 Introduction

Iceland is a mountainous island located in the middle of the North Atlantic Ocean in the northern part of the storm track. Due to this, the climate and weather of Iceland are largely governed by the interaction of orography and extra-tropical cyclones. This interaction can be in the form of cold air damming by mountains or warm downslope descent. The atmosphere-mountain interaction can also cause local acceleration of the airflow or a forced ascending motion, causing extreme precipitation. As a result of this interaction, downslope windstorms are quite common in Iceland.

Mountain waves and downslope windstorms have long been a target of research campaigns as well as theoretical and numerical researches. Such windstorms are generally associated with vertically propagating gravity waves in the troposphere. Favourable large-scale flow conditions for the generation of downslope windstorms include elements such as strong low-level winds and strong static stability at low levels. A reverse vertical windshear, as described in Smith (1985), may contribute to downslope windstorm through trapping of wave energy, while a positive vertical windshear may also act positively through amplification of gravity waves (see review by Durran, 1990). The prime objective of the T-REX (Terrain-induced Rotor EXperiment) campaign (Grubišić et al., 2008) in Sierra Nevada was on observations of mountain waves, rotor flow and low- and upper-level turbulence. This was done by means of ground-based observations and state of the art remote sensors and airborne observing systems. Recently, a number of papers based on the observations of T-REX have emerged, e.g. Jiang and Doyle

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Paper VII

FLOHOF 2007: An overview of the mesoscale meteorological field campaign at Hofsjökull, Central Iceland

Joachim Reuder, Markus Ablinger, Hálfdán Ágústsson, Pascal Brisset, Sveinn Brynjólfsson, Markus Garhammer, Tómas Jóhannesson, Marius O. Jonassen, Rafael Kühnel, Stephan Lämmlein, Tor de Lange, Christian Lindenberg, Sylvie Malardel, Stephanie Mayer, Martin Müller, Haraldur Ólafsson, Ólafur Rögnvaldsson, Wolfgang Schäper, Thomas Spengler, Günther Zängl, Joseph Egger

Meteorol. Atmos. Phys., **116**(1–2), 1–13, 2012

Hálfdán Ágústsson participated in the FLOHOF field campaign and contributed towards the paper. He analyzed the observed data presented in Section 3.4 of the paper, prepared Figs. 5 and 6 and wrote the relevant text.

Meteorol Atmos Phys
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ORIGINAL PAPER

FLOHOF 2007: an overview of the mesoscale meteorological field campaign at Hofsjökull, Central Iceland

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Abstract The FLOHOF field campaign took place in the period July 21 to August 24, 2007 on and in the surroundings of Hofsjökull glacier in Central Iceland. During the campaign, 18 automatic weather stations (AWS) recording temperature, humidity, wind speed, wind direction, pressure, and precipitation were deployed on and around the glacier. In addition, atmospheric soundings were performed N and S of Hofsjökull by a tethered balloon, pilot balloons, and two unmanned aerial systems (UAS). An energy balance station, consisting of a net radiometer and an eddy correlation flux measurement station, has also been installed. This paper describes the experimental setup of the campaign and presents first results of the data analysis with respect to transience of mountain-induced gravity waves, the extension of katabatic winds into the surrounding of the glacier, the occurrence of katabatic microfronts, and report on novel approaches to probe the vertical structure of the atmospheric boundary layer by UAS. The observed pressure perturbations related to transient gravity wave activity due to changing inflow conditions were between −2 and 2 hPa in general, with positive values upstream and negative values downstream. Differential heating of the glacier and its surrounding is triggering daytime katabatic flow from the glacier into its surrounding. During the campaign, those katabatic winds typically reached out 4–7 km from the edge of the glacier. During late night in clear sky conditions, frontal-like microstructures have been observed frequently with typical repetition times in the order of 30–60 min indicating the interaction of large-scale synoptic and nighttime katabatic

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Paper VIII

The bimodal Kvísker downslope windstorms

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Meteorol. Atmos. Phys., **116**(1–2), 27–42, 2012

Hálfdán Ágústsson lead and initiated the work on the paper. He performed all simulations, analyzed observed and simulated data, prepared the figures and wrote the manuscript.

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ORIGINAL PAPER

The bimodal downslope windstorms at Kvísker

Hálfdán Ágústsson · Haraldur Ólafsson

Received: 28 August 2009 / Accepted: 10 June 2010

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 Öræfajökull, 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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Paper IX

Improving a high resolution numerical weather simulation by assimilating data from an unmanned aerial system

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Mon. Wea. Rev., **140**(11), 3734–3756, 2012

Hálfdán Ágústsson was one of the PI of the MOSO field campaign and participated actively in the collection of the observational data. He assisted in analyzing observed and simulated data presented in the paper, as well as in the writing of the manuscript.

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Improving High-Resolution Numerical Weather Simulations by Assimilating Data from an Unmanned Aerial System

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ABSTRACT

In this study, it is demonstrated how temperature, humidity, and wind profile data from the lower troposphere obtained with a lightweight unmanned aerial system (UAS) can be used to improve high-resolution numerical weather simulations by four-dimensional data assimilation (FDDA). The combined UAS and FDDA system is applied to two case studies of northeasterly flow situations in southwest Iceland from the international Moso field campaign on 19 and 20 July 2009. Both situations were characterized by high diurnal boundary layer temperature variation leading to thermally driven flow, predominantly in the form of sea-breeze circulation along the coast. The data assimilation leads to an improvement in the simulation of the horizontal and vertical extension of the sea breeze as well as of the local background flow. Erroneously simulated fog over the Reykjanes peninsula on 19 July, which leads to a local temperature underestimation of 8 K, is also corrected by the data assimilation. Sensitivity experiments show that both the assimilation of wind data and temperature and humidity data are important for the assimilation results. UAS represents a novel instrument platform with a large potential within the atmospheric sciences. The presented method of using UAS data for assimilation into high-resolution numerical weather simulations is likely to have a wide range of future applications such as wind energy and improvements of targeted weather forecasts for search and rescue missions.

1. Introduction

A numerical weather model's ability to accurately simulate atmospheric dynamical and physical processes depends critically on several factors. These are among others the spatial grid resolution and the parameterization schemes used to represent processes connected to clouds, radiation, precipitation, and turbulence (e.g., Pleim and Xiu 1995; Alapaty et al. 2001; Teixeira et al. 2008). In addition, the quality of the data used to initialize and force the model is essential for the success of a numerical simulation. These data often originate from global atmospheric analyses or forecasts [e.g., from the Global Forecast System (GFS) or the European Centre for Medium-Range Weather Forecasts (ECMWF)] with resolutions typically being 15–50 km in the horizontal

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Paper X

Modeling wet snow accretion on power lines: Improvements to previous methods using 50 years of observations

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J. Appl. Meteor. Climatol., **52**(10), 2189–2203, 2013

Hálfdán Ágústsson actively participated in the work presented in the paper. He prepared the atmospheric climate data and performed the simulations, prepared many figures, analyzed observed and simulated atmospheric data. He prepared and analyzed observed ice accretion data, excluding the analysis of icing return times. He collaborated on improving the accretion model, wrote Sections 3 and 4 of the manuscript and contributed to the text in other sections.

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Modeling Wet Snow Accretion on Power Lines: Improvements to Previous Methods Using 50 Years of Observations

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(Manuscript received 13 December 2012, in final form 18 April 2013)

ABSTRACT

Methods to model wet snow accretion on structures are developed and improved, based on unique records of wet snow icing events as well as large datasets of observed and simulated weather. Hundreds of observed wet snow icing events are logged in detail in an icing database, most of which include an estimate of the mean and maximum diameter of observed icing on overhead power conductors. Observations of weather are furthermore available from a dense network of weather stations. The existing models for wet snow accretion on a standard cylinder are updated with realistic values for the terminal fall speed of wet snowflakes together with a snowflake liquid fraction–based criterion to identify wet snow. The widely used parameterization of the sticking efficiency is found to strongly underestimate the accretion rate. A calibrated parameterization of the sticking efficiency is suggested on the basis of long-term statistics of observed and modeled wet snow loads. Application of the improved method is demonstrated in a high-resolution simulation for a case of observed widespread and intensive wet snow icing in south Iceland. The results form a basis for mapping the climatology of wet snow icing in the complex terrain of Iceland as well as for preparing operational forecasts of wet snow icing and severe weather for overhead power transmission lines in complex terrain.

1. Introduction

Atmospheric icing is a general term for the accretion of atmospheric water in a solid form on the surfaces of structures on which it impinges. It includes precipitation icing (freezing rain and wet snow) and in-cloud (rime) icing as well as hoarfrost. It occurs under varying weather conditions, and its severity depends critically on specific combinations of temperature, precipitation, cloud species, humidity, and wind (Fikke et al. 2007; section 2 in Dalle and Admirat 2011).

Wet snow is of particular interest to the scientific and engineering communities, as snow accretion on structures such as overhead power lines, cables, poles, and telecommunication towers (Admirat 2008) causes an external mechanical load to the system. In particular, overhead lines are vulnerable to wet snow accretion because the accreted snow often forms a compact, cylindrical snow sleeve with strong adhesive forces to the conductor (Sakamoto 2000). First, the conductors tend to rotate (unless especially designed not to) during the ice buildup, resulting in a round snow deposit completely covering the conductor. Second, the accreted snow tends to slide around the cable. In fact, the risk for faults, blackout, or complete collapse is critically dependent on the inclusion of the appropriate local climatic conditions of wet snow loads in the design and operation of overhead lines in all regions of the world where snowfall may occur. Furthermore, the necessary design loads will vary significantly between different climatic regions and locally within regions of complex terrain. On the other hand,

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Paper XI

Mass balance of Mýrdalsjökull ice cap and comparison with observed and simulated precipitation

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Jökull, **63**, 91–104, 2013

Hálfdán Ágústsson is the PI of the mass balance surveying of the Mýrdalsjökull ice cap and organizes and leads the field trips on the ice cap. He lead and initiated the work on the paper, prepared and analyzed simulated and observed atmospheric data. He prepared the figures and wrote the manuscript, excluding Figs. 1–3 and the parts pertaining to the detailed analysis of the snow cores.

Reviewed research article

Mass balance of Mýrdalsjökull ice cap accumulation area and comparison of observed winter balance with simulated precipitation

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Abstract — *The Mýrdalsjökull ice cap at the south coast of Iceland receives precipitation from the frequently passing extratropical lows, making the region the wettest in Iceland. Most of the ice cap's accumulation area is a gently sloping plateau (1350–1510 m a.s.l.) within the caldera rim of Katla central volcano, feeding large outlets to the north and east. The oldest mass balance survey data are from 1944 and 1955. Here, mass balance measurements on the plateau, carried out 2001 and annually since 2007, are described and analyzed. Additionally, the winter mass balance is compared with precipitation estimates based on synoptic observations of precipitation at sea level and from high-resolution numerical simulations made with an atmospheric model. The measured specific winter balance at four locations above the equilibrium line was in the range 3.4–7.8* m_{we} *(water equivalent) with a maximum winter snow thickness in excess of 12 m. The summer mass balance was highly variable (-0.9 – -3.1* m_{we}*) and the annual mass balance at the plateau had a high spatial and temporal variability (2.1–5.9* m_{we}*). A comparison between measured winter balance and observations of precipitation at sea level, suggests that the plateau of Mýrdalsjökull receives on average 1–1.8* m_{we} *of precipitation during summer. Results from the atmospheric simulations compare well with the measured winter balance and the estimated summer precipitation at the survey sites. The winter balance as well as the precipitation are among the highest reported in Iceland, and parts of the ice cap may annually receive up to 10* m_{we} *of precipitation.*

INTRODUCTION

Mýrdalsjökull ice cap on the south coast of Iceland (Figure 1) covers an area of ≈590 km^2 with a volume of ≈140 km^3 (Björnsson and Pálsson, 2008), and is the fourth largest ice cap in Iceland.

The ice cap rises relatively steeply from 120 m to 1510 m above sea level (a.s.l.), with an ice-filled caldera plateau (60 km^2) at an altitude of 1300–1350 m a.s.l., surrounded by peaks rising 100–200 m above the plateau which is the main accumulation area of the ice cap. Numerous surface depressions,

Paper XII

Impact of surface characteristics on flow over a mesoscale mountain

Marius O. Jonassen, Hálfdán Ágústsson and Haraldur Ólafsson

Q. J. R. Meteorol. Soc., **140**(684), 2330–2341, 2014

Hálfdán Ágústsson contributed towards the motivation behind the work presented. He prepared and analyzed the atmospheric data presented in Figs. 1–3, and he participed in collecting the observed data of the FLOHOF field campaign, presented in the paper. He contributed towards analyzing the observed and simulated data presented, as well as towards the text of the manuscript.

Quarterly Journal of the Royal Meteorological Society *Q. J. R. Meteorol. Soc.* 140: 2330–2341, October 2014 A DOI:10.1002/qj.2302

Impact of surface characteristics on flow over a mesoscale mountain

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Dynamical downscaling of atmospheric flow over Iceland has revealed that prominent downslope accelerated flows are not merely extreme events, but rather constitute a strong climatological signal over the larger ice caps. Ice caps are characterised by smooth and cold surfaces and both of these properties have previously been found to enhance downslope flows. In this article, we investigate the response of downslope accelerated flow over Hofsjökull in Central Iceland to an increase in surface roughness and a change in surface temperature corresponding to the effect of melting Hofsjökull's ice cap. We do so by exploring the flow over Hofsjökull for a summertime case by means of several numerical sensitivity experiments. In the experiments, we find a stronger downslope flow acceleration with than without the ice cap. While an increased surface roughness distinctly dampens the downslope flow, the effect of changing the surface temperature is minimal. This study is both of general relevance through its exploration of factors affecting downslope acceleration of stably stratified flow and also of interest because glaciers diminish rapidly in a changing climate.

Key Words: gravity waves; downslope winds; surface roughness; surface heating; Iceland

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1. Introduction

Several investigations have revealed a damping effect of surface friction on mountain waves and downslope flow acceleration (e.g. Richard *et al.*, 1989; Georgelin *et al.*, 1994; Ólafsson and Bougeault, 1997a; Epifanio and Qian, 2008). The suppressing effect of surface friction on waves in real flows has also been confirmed for a collection of flows during the PYREX campaign (Ólafsson and Bougeault, 1997b) and subsequently for several individual cases of downslope flow. Peng and Thompson (2003) hypothesized that the reduction in mountain-wave amplitude and drag in the presence of surface friction is due to the reduction in the slope of the atmospheric boundary-layer (ABL) height compared with the terrain height, which is based on the comprehensive standpoint of viewing separately the ABL and the stratified layer above.

Among the first to document analytically the effect of surface heat fluxes on mountain flow was Raymond (1972), who solved a diabatic form of Long's equation. He found surface heating to have a damping effect on mountain waves and surface cooling to have the inverse effect. These results are in line with newer studies using 2D idealised simulations, such as that by Smith and Skyllingstad (2009) who studied the effect of surface heat fluxes on internal gravity wave (IGW) breaking and downslope flows. Using a similar numerical set-up to Smith and Skyllingstad (2009), Smith and Skyllingstad (2011) studied the impact of surface heating and cooling on downslope flows in the presence of a strong elevated inversion. They found that surface cooling in conjunction with a low-level inversion, where strong downslope flow can be attributed to a shallow-water transition rather than IGW breaking, facilitated the generation of strong downslope flows. Surface heating, on the other hand, was found to reduce the low-level inversion strength or change the wind velocity and stratification below the inversion which in turn prevented the downslope windstorm. Furthermore, Smith and Skyllingstad (2011) found a significant contribution from drainage flow in the acceleration of the flow far downstream when a strong low-level inversion was present. For a higher inversion, the katabatic contribution was minimal anywhere in the downstream jet. These simulations support the work of Vosper (2004) on low-level inversions and downslope accelerated flow. The results on surface heating and cooling and the presence of strong low-level inversions are in agreement with downslope windstorms being more frequently observed at night than during daytime (e.g. Brinkmann, 1974; Jiang and Doyle, 2008; Valkonen *et al.*, 2010).

Mountain flows have been diagnosed through a number of different parameters. A central parameter in this respect is the non-dimensional mountain height Nh/U (also known as the inverse Froude number) (e.g. Smith and Grønås, 1993), in which N is the Brunt–Väisälä frequency, h is the obstacle (mountain) height, and U the typical wind speed of the upstream background flow. Based on this parameter, Smith (1989) describes the following basic flow regimes. Low values of Nh/U enable the flow to pass over the mountain without any upstream stagnation and typically gentle gravity waves are formed. Nh/U can be seen as a measure of the nonlinearity in the flow, and linear theory

Paper XIII

Simulating observed lee-waves and rotor turbulence

Hálfdán Ágústsson and Haraldur Ólafsson

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Hálfdán Ágústsson initiated and lead the work on the paper. He performed all simulations, analyzed observed and simulated data, prepared the figures and wrote the manuscript.

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Simulations of Observed Lee Waves and Rotor Turbulence

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ABSTRACT

On 18 November 2008 a commercial aircraft encountered severe turbulence while flying in westerly flow along the southeastern coast of Iceland and descending from 2500 m down to the ground for a safe landing. Numerical simulations at horizontal resolutions of 9, 3, and 1 km are compared to the available observations. The simulations reproduce the situation, with an observed severe downslope windstorm at the ground as well as associated amplified lee waves and a rotor aloft, while climate data indicate that all observed westerly windstorms in the region are of the same type and occur in a similarly structured atmosphere. Strong shear turbulence is simulated at the interface of the lee wave and the rotor, as well as inside the rotor. The lee waves and the turbulence patterns are not stationary and as the upstream vertical wind shear increases, the lee wave becomes less steep, but the turbulence increases temporarily while the rotor circulation breaks down. From a forecasting perspective, this event could have been foreseen quite accurately, but not with the NWP tools that were in use for aviation forecasts, as their resolution was simply not adequate for resolving hazardous features of flow in and above complex terrain on the scale of this event. This event underlines the urgency of delivering products from finescale simulations over complex terrain to pilots and forecasters. Such products need to be developed taking into account the transient nature of the flows and the hazards.

1. Introduction

There is mounting evidence in the scientific literature that turbulence aloft over complex terrain may be successfully forecasted using finescale numerical simulations of the atmosphere. The verification of such simulations is, however, complicated by the lack of systematic three-dimensional observations aloft. Extensive observations of atmospheric turbulence are currently limited to large field experiments using specialized aircraft, such as over Greenland in the Fronts and Atlantic Storm Track Experiment (FASTEX; Doyle et al. 2005), the Greenland Flow Distortion Experiment (Renfrew et al. 2008), and the Terrain-Induced Rotor Experiment (T-REX) in the Sierra Nevada (Grubišić et al. 2008). These projects have gathered invaluable data, but they are expensive and unfortunately limited to intensive observations periods ranging from days to weeks, and may therefore miss extreme events. Apart from large experiments of this kind there are reported cases of turbulence aloft, for example, from aviation reports over Greenland and the Rocky Mountains in Colorado, as in Lilly (1978) where the turbulence was in fact observed by both commercial and research aircraft. Lane et al. (2009) studied a collection of turbulence events over Greenland in a systematic manner to identify flow regimes that contribute to unstable gravity waves and turbulence over Greenland. Ólafsson and Ágústsson (2009) focused on an international flight encounter with severe turbulence at the tropopause level in easterly flow over Greenland; an incident that could presumably have been avoided as finescale simulations reproduced the breaking waves and the turbulence that reached above the tropopause.

In fact, above and downwind of orography, gravity wave turbulence is primarily found at two height levels, as

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Paper XIV

The advection of atmospheric vortices over Reykjavík

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Hálfdán Ágústsson initiated and actively participated in the work on the paper. He performed all simulations, as well as analyzing observed and simulated data. He prepared most of the figures and wrote parts of the manuscript, excluding parts pertaining to the climatology and the dynamics of the flow.

The Advection of Mesoscale Atmospheric Vortices over Reykjavík

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(Manuscript received 14 February 2013, in final form 12 February 2014)

ABSTRACT

On 12 August 2009, a series of satellite images revealed asymmetric shedding of atmospheric vortices in the lee of Mt. Snæfellsjökull, and their passage a distance of 120 km across Faxaflói Bay and over the city of Reykjavík in West Iceland. After landfall, the vortices were detected by a network of surface weather stations. These observations are presented and with the aid of a numerical simulation, they are discussed in view of existing theories of orographic wakes and vortex shedding. In general, the flow is in line with existing knowledge, but there is a remarkable absence of vortices with anticyclonic rotation. Atmospheric conditions for vortices of this kind are most often favorable in late winter and spring and they are a forecasting challenge.

1. Introduction

Downstream of mountains, there is frequently an extended area of weak winds, referred to as a wake. Mountain wakes are of particular interest in studies of weather and climate because they feature a flow pattern and flow speed that may be very different from the ambient flow, which is most often reasonably well reproduced by numerical models, while the wake flow may not be well reproduced.

In general, mountain wakes are associated with background flow (upstream of the mountains) of strong static stability, weak winds, high mountains or all of the above. At values well above 1 of Nh/U, where N is the Brunt–Väisälä frequency, h is the mountain height, and U is the wind speed, the atmospheric flow is blocked on the upstream side of a mountain. Downstream, there is most often a wake that may extend large distances away from the mountain.

It is well established that vorticity may be produced in stratified flow that impinges on an obstacle (e.g., Smolarkiewicz and Rotunno 1989a,b; Smith 1989b; Hunt et al. 1997) and that potential vorticity and a reduction in the value of the Bernoulli function inside the wake is preceded by mixing and dissipation that may be distributed widely inside the wake region or be concentrated in regions of gravity wave breaking (Schär and Smith 1993a; Schär and Durran 1997).

Based on the work of Schär and Smith (1993a,b) and Grubišić et al. (1995), Smith et al. (1997) present wake flow regimes as a function of mountain height, critical mountain height for internal wave breaking, and the Reynolds number. When the mountain height is well above a critical mountain height for wave breaking and the surface Reynolds number is large, there is vortex shedding inside the wake. Earlier, a critical value of 0.4 of the Froude number had been established as an upper limit of the regime of vortex shedding (see Etling 1989, 1990). An extensive description of vortices in the atmospheric boundary layer downstream of a smooth mountain, based on numerical simulations with ultrahigh resolution and including series of sensitivity tests is given in Heinze et al. (2012).

On 12 August 2009, unique observations were made of vortex shedding downstream of Mt. Snæfellsjökull in West Iceland and the advection of the vortices over a dense network of automatic weather stations. This case is presented and discussed in the present paper.

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Paper XV

The impact of assimilating data from a remotely piloted aircraft on simulations of weak-wind orographic flow

Hálfdán Ágústsson, Haraldur Ólafsson, Marius O. Jonassen and Ólafur Rögnvaldsson

Tellus, **66A**, 25421, 2014

Hálfdán Ágústsson was one of the PI of the MOSO field campaign and participated actively in the collection of the observational RPAS data presented. He lead and initiated in the work on the paper, and performed all simulations, analyzed observed and simulated data, prepared the figures and wrote the manuscript.

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The impact of assimilating data from a remotely piloted aircraft on simulations of weak-wind orographic flow

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(Manuscript received 9 July 2014; in final form 2 November 2014)

ABSTRACT

Orographic winds near a 914 m high mountain in Southwest-Iceland are explored using unique observations made aloft with a small remotely piloted aircraft, as well as with traditional observations and high-resolution atmospheric simulations. There was an inversion well above mountain top level at about 2 km with weak winds below. Observed winds in the lee of the mountain were indicative of flow locally enhanced by wave activity aloft. Winds descended along the lee slope with a prevailing direction away from the mountain. They were relatively strong and gusty at the surface close to the mountain, with a maximum at low levels, and weakening and becoming more diffuse a short distance further downstream. The winds weakened further aloft, with a minimum on average near mountain top level. This situation is reproduced in a high-resolution atmospheric simulation forced with atmospheric analysis as well as with the observed lee-side profiles of wind and temperature below 1.4 km. Without the additional observations consisting of the lee-side profiles, the model fails to reproduce the winds aloft as well as at the surface in a region in the lee of the mountain, as was also the case for the operational numerical models at that time. A sensitivity simulation indicates that this poor performance is a result of the poorly captured strength and sharpness of the inversion aloft. The study illustrates, firstly, that even at very low wind speed, in a close to neutral low-level flow, gravity waves may still be a dominating feature of the flow. Secondly, the study presents an example of the usefulness of lee-side atmospheric profiles, retrieved by simple model aircraft, for improving numerical simulations and short-term weather forecasting in the vicinity of mountains. Thirdly, the study confirms the sensitivity of downslope flow to only moderate change in the sharpness of an upstream inversion.

Keywords: downslope flow, complex orography, small remotely piloted aircraft, observational nudging

1. Introduction

The relatively recent improvement in atmospheric simulations of mesoscale and small-scale mountain weather is the cumulative result of several important factors, some of which are the higher spatial resolution, made available by increasing computing power; the improvements made to the parameterizations of physical and dynamical processes related to, for example, atmospheric water, radiation and fluxes (e.g. Teixeira et al., 2008; Gilliam and Pleim, 2010; Hu et al., 2013) and the more numerous and accurate atmospheric observations available for preparing global atmospheric analyses and feeding-improved assimilation systems (e.g. Langland et al., 1999; Alapaty et al., 2001; de Rosnay et al., 2014).

Successful numerical simulations of local weather in complex topography are dependent on the model resolution being sufficient for resolving the dominating topography; both when downscaling the wind climate as well as when simulating extreme wind events in complex terrain (e.g. Ágústsson and Ólafsson, 2007; Horvath et al., 2012; Jonassen et al., 2013), but also for capturing middle and upper level tropospheric flow above complex terrain (e.g. Doyle et al., 2005; Ólafsson and Ágústsson, 2009). Operational systems are aiming at a horizontal resolution of 1 km or better, and research models have long reached this resolution. Part of the work on the parameterisation

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(page number not for citation purpose)

Secondary Paper I

Comparison between simulations and measurements of in-cloud icing in test spans

Árni Jón Elíasson, Egill Þorsteins, Hálfdán Ágústsson, and Ólafur Rögnvaldsson

IWAIS, Chongqing, China, 2011

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Hálfdán Ágústsson performed and analyzed the atmospheric simulations, analyzed observed meteorological data, prepared several figures and wrote parts of the text pertaining to the atmospheric data and the analysis.

Comparison of measured and simulated icing in 28 test spans during a severe icing episode

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***Abstract*: This paper presents an analysis of simulated in-cloud icing and a comparison of the results with detailed field measurements from 28 test spans at 19 test sites in North- and East-Iceland for a period of 99 days during the winter of 2013-2014. Ice accretion was extensive with the maximum ice load measured equal to 47 kg/m, the greatest total accumulation in one test span was 177 kg/m/winter and the total accumulation at the 28 test spans was 1076 kg/m/winter. The icing simulations are based on cylindrical accretion model using atmospheric data from a high resolution atmospheric model as an input.**

Model results are presented as time-series of icing at locations of test spans, as well as summaries of total accretion loads and intensities at the spans. Results are highly sensitive to the performance of the atmospheric model, while the timing of individual icing periods is nevertheless on average correctly captured. Small and medium size accretion events are generally better captured than more extreme events which are often underestimated due to too weak accretion intensity. In an attempt to remove the complicating and random effect of ice-shedding, the icing model is forced to shed ice in unison with the observations, with total simulated accretion compiled for each span during periods when accretion is actually observed.

Keywords: In-cloud icing, measurements, modelling, test spans

INTRODUCTION

Long time series of systematic observations of atmospheric icing events are invaluable for mapping the icing climate and developing methods to parameterize icing. Accurate observations of extreme events are particularly important, especially within the framework of overhead power lines where appropriate design loads are critically dependent upon an accurate estimate of the maximum expected ice load for a given return period. Although, the observational sites are typically too few and far apart to describe adequately the spatial structure of the icing climate in complex orography, their data can be corroborated with parameterized icing based on simulated atmospheric data and numerical accretion models, as done for in-cloud icing in the USA, Japan and Iceland [1], [2], [3], [4].

In this light, the extreme icing winter of 2013-2014 presents an invaluable opportunity to test the current methods for parameterizing ice accretion and explore their strength and weaknesses. Special attention is given to the accretion process and the complicating influence of ice-shedding on the analysis is eliminated by forcing the accretion model to shed ice simultaneously with observed icing.

I. ICING MEASUREMENTS

Iceland has an extensive network of nearly 60 operational test spans at more than 40 locations, measuring ice accretion in real-time. Locations of test spans used in this study are shown in Figure 1.

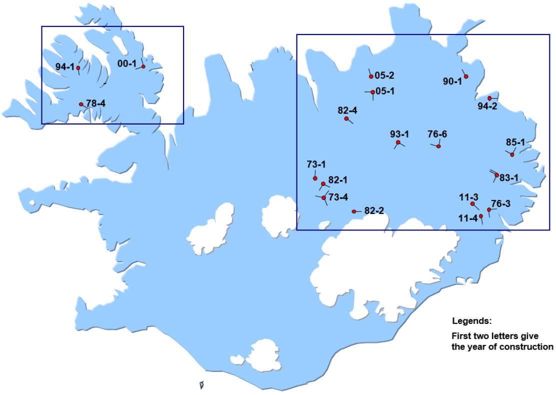

Figure 1: Locations of test span used in this paper, with black lines indicating the direction of each test span. Boundaries of the 1 km model domains are shown with black boxes.

Secondary Paper II

Wet-snow accumulation: A study of two severe events in complex terrain in Iceland.

Árni Jón Elíasson, Hálfdán Ágústsson and Guðmundur M. Hannesson

IWAIS, Canada, 2013

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Hálfdán Ágústsson performed and analyzed all the atmospheric simulations. He analyzed observed meteorological data as well as simulated accretion data, and wrote parts of the manuscript pertaining to the atmospheric data and the analysis.

Wet snow icing - Comparing simulated accretion with observational experience

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***Abstract*: Coupled icing and mesoscale atmospheric models are a valuable tool for assessing ice loading for overhead power lines. This paper presents an analysis of how well icing model captures wet snow accumulation in areas that are historically known to be exposed to wet snow icing in Iceland. Wet snow icing maps were prepared using a snow accretion model with 21 years of data. The weather parameters used in the accretion model, i.e., wind speed, temperature, precipitation rate and snowflake liquid water fraction, were derived by simulating the state of the atmosphere with WRF model at a horizontal resolution of 3 km. The icing maps were compared to data from an icing database that contains long term historical information on icing events on the overhead power lines in Iceland.**

Keywords: wet snow accretion, modelling, icing observations

I. INTRODUCTION

Wet snow accretion on overhead power lines can cause mechanical overloading and can lead to a failure of the supporting structures. Historically, wet snow accumulation has led to many severe failures of power lines in the distribution grid in Iceland. Especially before adequate knowledge and experience had been obtained regarding the most severe icing areas and the main icing directions. An important step in the quantification of the risk was taken in 1977 when a systematic registration of known icing events on all overhead power lines in the country was initiated.

In recent years a huge step has been taken in further understanding of the wet snow accretion risk with use of icing models. The improved icing accretion models combined with weather parameters that are derived by simulating the state of the atmosphere, for example with the WRF model, are very powerful tools to gain further understanding and quantification of the wet snow accretion risk. Especially in complex orography and in areas where no prior operational experience of power lines exists. An increased use of icing models to assess the risk of wet snow accretion is foreseen in coming years.

The paper presents an analysis of icing model performance based on a comparison with observed wet snow icing. Icing maps containing maximum predicted accretion mass in the period 1994-2014 were prepared for the analysis. The main focus of the study is on how well the predicted wet snow accumulation reflects areas prone to icing as well as how icing in complex terrain is reproduced.

II. HISTORICAL OBSERVATIONS OF WET SNOW ACCRETION

In a global context, wet snow accretion is a frequent occurrence on overhead power lines in Iceland. It may occur in all regions but some parts are more exposed than others and the frequency and the amount has varied greatly between locations. Experience from the overhead network reveals a dependence of accretion on predominant icing directions. Power lines oriented favourably with regard to the predominant icing directions often experienced far less and minimal accretion compared to nearby lines with a more unfavourable orientation.

A systematic collection of data and registration of all icing events on power lines was started in 1977 due to the impact of the icing on the operational reliability of the power lines. The registration has been continuous from the start and an effort has also been made to find information on events prior to 1977. A reasonable good overview is now reaching back to 1930, with the database containing data from power lines of all voltages as well as on some older telephone lines. The largest part of the records is related to wet snow accretion on the 11-33 kV distribution net. Records of individual icing events are done for all affected line sections and contain estimates, and in some cases actual measurements, of typical and maximum ice diameters on the section, type of accretion, information on wind and eventual failures. Figure 1 shows the number of broken poles from 1960 that have been registered in the database in relation to icing, with most failures due to wet snow icing. The reduction in failures rate from 1995 is related to a program where distribution lines exposed to severe wet snow icing were put underground. The data is collected, organized and hosted by Landsnet, the transmission system operator in Iceland, and has previously been described in [1].

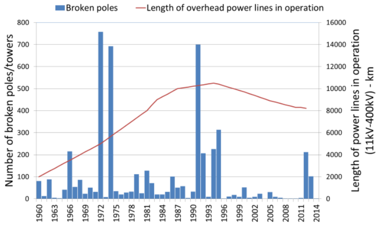

Figure 1: Number of broken poles registered in the database since 1960. Most failures are due to wet snow icing on 11-33 kV lines.

Figure 2 shows the location of overhead power lines in Iceland. Most of the power lines, and especially those in the distribution grid, are located in coastal regions. Some of the 132 kV and 220/400 kV lines are located inland and on the boundary of the central highlands. No overhead power lines have so far been built in the central part of the country, but several test spans have been installed. All power lines can be expected to get wet snow accretion but the amount and frequency varies greatly. Line sections of where the highest and most extreme wet snow loads have been observed are marked in Figure 2. Wet snow accretion has been observed on many line sections not marked, but to a lesser extent.

Secondary Paper III

Wet-snow accumulation: A study of two severe events in complex terrain in Iceland

Árni Jón Elíasson, Hálfdán Ágústsson, and Guðmundur M. Hannesson

IWAIS, Canada, 2013

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Hálfdán Ágústsson lead the work on the paper. He performed and analyzed all the atmospheric simulations as well as a part of the icing simulations. He analyzed observed meteorological data, prepared several figures and parts of the manuscript pertaining to the atmospheric data and the analysis.

Wet-snow accumulation

A study of two severe events in complex terrain in Iceland

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Abstract— **On 10 September 2012 and 30 December 2012, two severe northeasterly wet-snow storms caused extreme ice load on many transmission and distribution lines in North Iceland. The wet-snow accretion was combined with strong winds, resulting in broken wooden poles and H-frame towers. The September event was exceptional because of extreme snowfall so early in the autumn. The snowfall was associated with average wind speeds in excess of 20 m/s, causing widespread accumulation of wet snow within a certain altitude interval in North Iceland. In the latter event, heavy snowfall and gale-force winds, as well as extreme wet-snow loading, were more localized, occurring mostly in the lee of the complex orography of Northwest Iceland. The wet snow data are based on: 1) detailed in-situ inspection of accumulated wet snow on conductors of transmission and distribution lines in the affected areas. 2) accurate measurements of accumulation with load cells installed in suspension towers of operating overhead transmission lines and special test span in the areas where the most extreme accumulation occurred. The collected load data are unique in the sense that they describe in detail both the exact timing and magnitude of the wet snow accumulation. Meteorological observations of wind, temperature and precipitation are moreover available from synoptic and automatic weather stations in the areas. The atmospheric flow during the events is analyzed, based on weather observations and simulations at high resolution with an atmospheric model. The simulated data are subsequently used as input for a cylindrical wet-snow accretion model. The measured and simulated wet-snow loading are analyzed and put in relation with the weather during the event, highlighting several key aspects of the flow and icing process that needs further attention.**

I. INTRODUCTION

Wet-snow accumulation on overhead structures is of particular interest to both the scientific and engineering communities as such accumulation causes external mechanical load on the structures [1], and is needed for their safe operation and design. In this context, the accretion on overhead power lines has received special attention due to the vulnerability of the system to the accretion and the societal impacts of faults and blackouts. This vulnerability was in particular evident in the wet snow storm of 2005 in Germany, where 82 transmission towers collapsed and 250 000 people were without electricity for days [2]. Severe events have been documented in other high latitude and/or high altitude regions of the world, e.g., in Europe [1] and [3], Japan [4], and Iceland as documented in [5], [6] and [7], as well as reported here for two severe events occurring in the latter half of 2012 in North Iceland.

Wet-snow accretion on overhead conductors is particularly effective due to the strong adhesive forces within the compact snow sleeve which forms on the conductor as it rotates or the accreted mass slides around it [4]. The accretion process itself is critically sensitive to small variations in the wind speed and direction, surface characteristics of the conductor, atmospheric water mass loading as well as the liquid water content of the falling snow, which, among other things, depends on the (wet bulb) temperature in the lowest layers of the atmosphere. Wet-snow loading has traditionally been parameterized based on observational data (e.g., [1], [8] and [9]). Such methods suffer from the lack of accurate estimates of atmospheric parameters that are not routinely observed, but it has been shown that better results can be gained based on output from state-of-the-art mesoscale atmospheric models (e.g., [10]). Accurate and physically sound parameterizations of the wet-snow loading are needed to aid in forecasting wet-snow events and estimating climatological and regional design loads with regard to a given return period. These loads must by necessity be based on output from atmospheric models instead of observational data and are critically dependent on correct representation of the atmospheric flow in complex terrain as well as accurate wet-snow accretion parameterization. Systematic and extensive observations during wet-snow events are however necessary for verifying the accretion methods, as was done in [10], based on simulated and observed climatology of wet-snow events in Southeast Iceland.

This paper presents an analysis of weather and wet-snow accumulation during two severe wet-snow storms occurring in northern Iceland in 2012. Both storms caused extreme wet-snow loading on transmission and distribution lines in the affected regions. The wet-snow accretion was combined with strong winds, resulting in many broken wooden poles in the distribution system and 132 kV H-frame transmission towers, as well as, e.g., significant damage to property and loss of livestock. Unique and detailed data of accumulated wet snow on conductors during the events as well as extensive weather observations, are used to investigate the wet snow accumulation and highlighting, in particular, the differences in the spatial extent of accretion as well as several key aspects requiring special attention.

II. THE ATMOSPHERIC SITUATION

The two events of 10 September and 29 December 2012 share some similarities with each other, as well as with other significant wet-snow events in northern Iceland. Both events occur in relation to a northward moving and deepening extratropical low off the east coast of Iceland, as seen in the

Secondary Paper IV

Comparison of measured and simulated icing in 28 test spans during a severe icing episode

Árni Jón Elíasson, Hálfdán Ágústsson, Guðmundur M. Hannesson and Egill Þorsteins

IWAIS, Sweden, 2015

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Hálfdán Ágústsson lead the work on the paper and is responsible for the novel methods employed for comparing observed and simulated results. He performed and analyzed all the atmospheric simulations as well as performing all the icing simulations. He analyzed observed meteorological data and participated in analyzing the simulated icing data, and wrote the main part of the manuscript.

Modeling wet-snow accretion

Comparison of cylindrical model to field measurements

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Abstract—**Field measurements of wet-snow accretion have been made for numerous events in Iceland. The measurements are made with load cells in special test spans and, in some cases, in operating transmission lines. They can accurately identify the rate and size of accumulation and normally include measurements of air temperature as well. The largest events include wet snow accumulation above 15 kg/m within 10 hours, and they are associated with very large amounts of precipitation and/or gale force winds. Six cases are selected and used to evaluate how well two existing cylindrical accretion models of wet snow can predict the accretion of wet-snow icing. The weather parameters that were not directly measured in-situ and are needed for the accretion models, i.e., wind speed, precipitation rate and snowflake liquid water fraction, are derived by using A-WRF simulations that were specially made for the cases at high resolution, and by studying observations of weather from a dense network of weather stations. The performance of the cylindrical accretion models is analyzed with special attention to the influence of sticking efficiency on the amount and timing of wet-snow accretion. The strong and weak points of the models are discussed.**

I. INTRODUCTION

Wet-snow icing is often an important aspect of structural loading for overhead transmission lines (OHTL), especially at low altitude. Wet-snow events are relatively rare, and it is thus often difficult to collect sufficient field data for statistical evaluation of the loading. It is important to use all available data when evaluating the risk of wet-snow icing, and today it is becoming more feasible to use icing models to calculate the wet-snow icing risk. The icing models need reliable input data, e.g., different weather parameters, and these can be prepared with state-of-the-art numerical atmospheric models. Several different wet snow models have been developed, but there is a lack of field data to verify the models.

Wet-snow icing has posed a great threat to overhead lines in Iceland, as revealed by an extensive data collection program, which has been in operation for decades [1]. The associated database contains detailed information on all known icing events on overhead lines, including wet-snow events, which are especially frequent and serious in coastal areas. The amount of wet snow accumulation varies greatly depending on the direction of the OHTLs and topography; often the most affected sites are found in downslope winds on the lee side of mountains. The wet snow accumulation in Iceland is usually combined with relative high wind speed compared to events in many other countries, due to orographically enhanced flow as well as the relatively low surface roughness associated with sparse vegetation. At the time of accumulation, the 10-minute average wind speed often ranges from 10 to 25 m/s, concurrent with heavy precipitation, as revealed by observations from a dense network of weather stations [2]. This often leads to high ice load and relatively high density of the snow sleeve ([3] and [4]). Additionally, numerous events of wet-snow accretion have been documented in detail by a network of dedicated test spans in Iceland. The field measurements can accurately identify the rate and magnitude of accumulation and normally include measurements of air temperature at conductor height. The measurements include events with loading above 15 kg/m, and the largest events are associated with very large amounts of precipitation and/or gale force winds. In this study, measurements from six cases of wet-snow accretion are used to evaluate how well two existing cylindrical accretion models of wet snow can predict the accretion of wet-snow. The weather parameters that were not directly measured in-situ and are needed for the accretion models, i.e., wind speed, precipitation rate and snowflake liquid water fraction, are derived from high-resolution A-WRF simulations and observations of weather from a dense network of weather stations. The performance of the cylindrical accretion models is analyzed with special attention to the influence of sticking efficiency on the amount and timing of wet-snow accretion.

II. ICING MEASUREMENTS

Field measurements of icing are made in many places in Iceland [5]. Most of the measurements are made in special test spans, but measurements are also made on some operating transmission lines. The measurements are made with load cells measuring loading at a frequency of 0.5-1.0 Hz and store maximum, minimum and average values for each at 10-minute intervals. The test spans are 80 m long, and the conductors are strung on wooden poles 10 m above the ground. End tension measurements are made, and the unit load of icing is derived by assuming equally distributed ice load on the measuring span and the guy wires supporting the poles. In operating overhead lines the loading is measured in suspension attachments. The measured loading includes both ice and wind load. By using estimated wind speed and fluctuation in load measurements, it is possible to subtract the wind load from the measured data to evaluate the ice load.

III. SIMULATION OF WEATHER

The atmospheric parameters needed as input for the wet-snow accretion models, including those not directly measured in-situ, are prepared based on atmospheric simulations with the non-hydrostatic mesoscale Advanced Research WRF-model [6]. The atmospheric model is forced with input data from the ECMWF, and the simulations are done at a horizontal

Secondary Paper V

Wet-snow icing: Comparing and simulated accretion with observational experience

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Comparison between simulations and measurements of in-cloud icing in test spans

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***Abstract*— In this paper a comparison is made between measured in-cloud ice loading in 80 m long test spans and calculated ice loading. The work is based on numerical data describing the state of the atmosphere at high spatial and temporal resolution. The icing measurements are carried out in test spans which have frequent in-cloud icing. The atmospheric data is created by dynamical downscaling of atmospheric analysis to a horizontal resolution of 9, 3, 1, and 0.33 km. The high horizontal resolution allows the atmospheric model to reproduce accurately the atmospheric flow in complex orography, e.g. in high and steep mountains where overhead transmission lines can be located, not resolved at coarser resolutions. In general, icing calculations based on the atmospheric model identify correctly the observed icing events, but underestimate the load due to too slow ice accretion. This is most obvious when the temperature is slightly below 0°C and observed icing is most intense. The model results improve significantly when additional observations of weather are used for forcing the atmospheric model. However the large variability in the simulated atmospheric variables results in high temporal and spatial variability in the calculated ice accretion. Furthermore, there is high sensitivity of the icing model to the droplet size and the possibility that some of the icing may be due to freezing drizzle or wet snow instead of in-cloud icing of super-cooled droplets. In addition, the icing model (Makkonen) may not be accurate for the highest icing observed.**

I. INTRODUCTION

Recent development in numerical weather prediction models (NWP) combined with increased computing power has lead to new opportunities to assess historical and/or make short term forecast of atmospheric icing on structures. Simulated weather from NWP models can be used to evaluating icing in areas with limited observations of weather. The development in NWP models is rapid and future improvements will surely improve the prediction capability, in particular improvements to the parameterization of atmospheric moisture. Studies have been made to compare predicted icing based on results from NWP models to measured icing e.g. [5] and [11] but quantitative measurements of icing are often limited. In this context the extensive datasets of observed atmospheric icing in Iceland are invaluable. Test spans to measure icing have been operated since 1972 in Iceland. Totally there have been erected 86 spans in 56 locations. Many of the locations are in areas with frequent in-cloud icing and more than 1000 icing events have been registered. The maximum load observed is 67 kg/m. The observations of icing collected in the test spans are very suitable for exploring the feasibility of basing prediction of atmospheric icing on results from NWP models.

In this paper a comparison is made between prediction of icing based on NWP simulations and icing measured in a test span at Hallormsstadahals, East-Iceland. Four icing events are used for the comparison and the peak ice load measured in these events ranged between 4 and 36 kg/m. Most of the ice accretion is in-cloud icing but it may partly be mixed with freezing drizzle and wet snow icing.

II. ICING MEASUREMENTS

The measurements in test span A at Hallormsstadahals started in 1983 and have been continuous since. The measuring site is located 575 m above sea level and in-cloud icing occurs frequently every year. A description of the measuring site is given in [2].

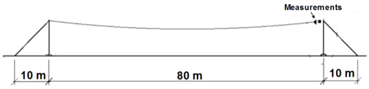

Figure 1. Test span with 80 m measuring span. Conductor tension is measured in attachment to guyed pole 10 m above ground.

Fig. 1 shows the setup of the test span. The spans are 80 m long and the conductor is strung on poles that are 10 m above ground. Description of ice load measurement in test spans is given in [1]. Measurements are made on conductor tension force and temperature. An automatic weather station with unheated anemometer is also operated at Hallormsstadahals. Unit load of icing is derived by assumptions of equally distributed ice load on the measuring span and the guy wires that supports the poles. Figure 2 shows the effects of other distribution of icing. The factor η is defined as the ratio of actual icing on the measuring span compared to predicted icing with the assumption of equal distributed load. It is believed that actual ice load is most often well predicted with the assumption of equally distributed load.

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