Útgáfufélagið Slemba

Rit Reiknistofu í veðurfræði

Stöðuskýrsla vegna þriðja árs RÁVAndar verkefnisins

REYKJAVÍK
DESEMBER 2009

Inngangur

Í júlí 2006 gerðu Háskóli Íslands (HÍ), Landsnet (LN), Landsvirkjun (LV). Orkustofnun (OS), Orkuveita Reykjavíkur (OR), Reiknistofa í veðurfræði (RV) og Veðurstofa Íslands (VÍ) með sér samning um styrkveitingu til rannsókna-verkefnisins "Reikningar á veðri - RÁV". Í ársbyrjun 2007 fékkst að auki öndvegisstyrkur frá Rannsóknasjóði Íslands til þessa verkefnis, hefur það því hlotið nýtt nafn: RÁVÖndin.

Stýrihóp verkefnisins skipa Haraldur Ólafsson (HÍ) – formaður, Ólafur Rögnvaldsson (RV) – dagleg umsjón, Halldór Björnsson (VÍ) og Óli Grétar Blöndal Sveinsson (LV).

Í stöðuskýrslu þessari verður farið yfir verkþætti sem unnir hafa verið á þriðja ári verkefnisins og mat lagt á framgang verkefnisins í heild sinni. Ennfremur eru gerð skil á ritrýndum greinum, ráðstefnuritgerðum og skýrslum sem unnar hafa verið í tengslum við verkefnið.

Að verkinu hafa unnið Einar M. Einarsson (RV), Guðrún Nína Petersen (VÍ), Halldór Björnsson (VÍ), Haraldur Ólafsson (HÍ), Hálfdán Ágústsson (RV), Hrafnkell Pálsson (RV), Jian-Wen Bao (NOAA/ESRL), Kristján Jónasson (HÍ), Ólafur Rögnvaldsson (RV), Tryggvi Edwald (RV), Þór Sigurðsson (RV) og Örnólfur E. Rögnvaldsson (RV).

Rétt er að taka fram að upphaflega var gert ráð fyrir að RÁV verkefninu yrði lokið á þriðja ársfjórðungi 2009. Vegna samlegðaráhrifa við Öndvegisverkefnið, og í raun samruna við það verkefni, sem og til að samnýta sem best reikniafl í Noregi fyrir LOKS (Lofthjúpsbreytingar og áhrif þeirra á OrkuKerfi og Samgöngur) verkefnið þá er ljóst að verklok RÁVAndarinnar verða ekki fyrr en á fyrsta ársfjórðungi 2010. Endanleg verkskil frestast því um rúmt hálft ár frá upphaflegum áætlunum, á móti kemur að verkefnið er nokkru viðameira en fyrstu áætlanir gerðu ráð fyrir.

Markmið

Markmið verkefnisins er að spá fyrir og kortleggja hita, úrkomu og vind í þéttu reiknineti við núverandi veðurfar. Ennfremur að þróa frekar tæki og hugbúnað til að kanna fyrrgreinda veðurþætti í núverandi og framtíðarveðurfari.

Verkþættir

Eftirfarandi verkþættir hafa verið unnir á þriðja ári RÁVAndarinnar

- Áframhaldandi þróun gagnagrunns og gagnaframsetningar
- Hermireikningar í hárri upplausn
- Uppsetning mælitækja á Gufuskálum og gagnavistun
- Vélbúnaðaruppbygging
- Vinna við jaðarlags- og hviðulíkan

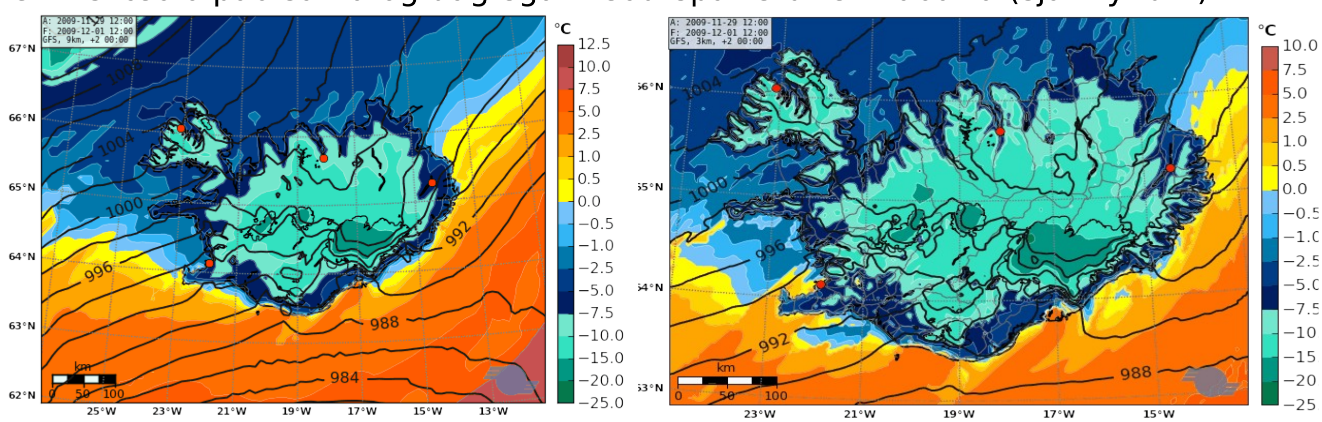
Þróun gagnagrunns og gagnaframsetning

Á öðru ári RÁVAndarinnar var settur upp svokallað OpENDAP hugbúnaðarkerfi sem leyfði vefaðgengi að DB2 gagnagrunni RV og völdum töflum úr gagnagrunni VÍ. Síðla sumars 2009 var komið á sítengingu við Gufuskála. Mælistöðvar í lægra mastrinu þar eru því sítengdar gagnagrunnsvél RV í Reykjavík og uppfærast gögn

á fimm mínútna fresti. Enn eru vandkvæði með gagnasendingar úr stærra mastrinu. Ákvörðun var tekin um að vista þessi gögn í PostGres gagnagrunni frekar en DB2. Ólíkt DB2 þá er PostGres opin hugbúnaðarlausn sem krefst ekki leyfisgjalda. Skrifaðar hafa verið stefjur til að varpa gögnum frá Vaisala mælibúnaði þeim sem er á Gufuskálum inn í PostGres grunn RV (sjá minnisblað um “MAWS Data Importer” í ítarefni).
Frá upphafi RÁV verkefnisins hefur verið lögð rík áhersla á opið aðgengi að niðurstöðum. Eftir því sem liðið hefur á verkefnið hefur komið betur í ljós að opið aðgengi eykur þörfina á notendavænni framsetningu gagna. Til að bæta úr þessu fór RV í samstarf við sprotafyrirtækið DataMarket um þróun á svokölluðu Gagnatorgi veðurupplýsinga, þar sem birta mætti niðurstöður verkefnisins, sem og aðrar veðurupplýsingar. Enn sem komið er hefur ekki verið gengið frá birtingu gagna úr verkefninu en það verkefni er í þróun. Nánari lýsingu á Gagnatorginu er að finna í ítarefni.

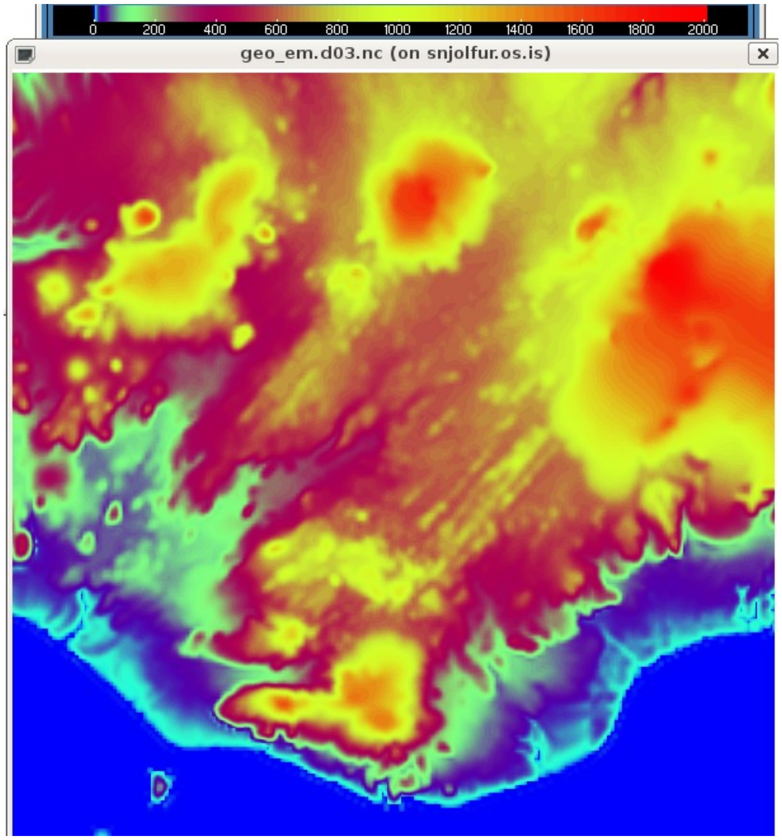
Hermireikningar

Hermireikningar fyrir tímabilið september 1994 til og með ágúst 2009 hófust snemmsumars 2009. Reikniupplausn er 9 og 3 km fyrir allt Ísland og er reiknisvæðið það sama og daglegar veðurspár eru reiknaðar á (sjá mynd 1).

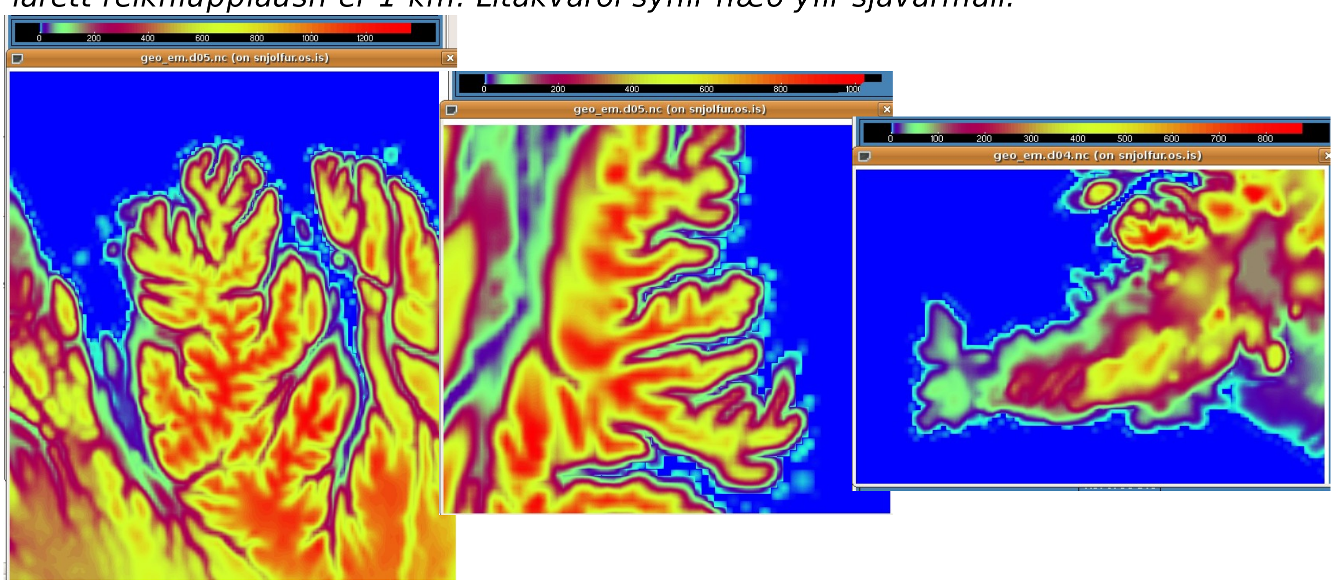


Mynd 1: Fjöldi hnútpunkta fyrir 9 km reiknisvæðið (vinstri) er 95x90 og196x148 fyrir 3 km reiknisvæðið (hægri). Kort eru af http://www.belgingur.is.

Til að ná fram samlegðaráhrifum við LOKS (Lofthjúpsbreytingar og áhrif þeirra á OrkuKerfi og Samgöngur) verkefnið var ennfremur ákveðið að herma veður í reiknineti með 1 km möskvastærð fyrir ákveðin svæði og yfir skemmri tímabil. Um er að ræða Þjórsár- Tungnaársvæðið fyrir vatnsárin 2002-2009 (sjá mynd 2), Svarfaðardal og nágrenni fyrir sumarið 2006, Reykjanesskaga fyrir sumarið 2007 og nágrenni Seyðisfjarðar fyrir sumurin 2008 og 2009 (sjá mynd 3). Val á síðustu þremur reiknisvæðum helgast af því að á viðkomandi tímabilum hefur þétt net úrkomumæla verið starfrækt á þeim.



Mynd 2: Reiknisvæðið sem nær yfir Þjórsár- Tungnaársvæðið er 202x202 hnitpunktar, lárétt reikniupplausn er 1 km. Litakvarði sýnir hæð yfir sjávarmáli.



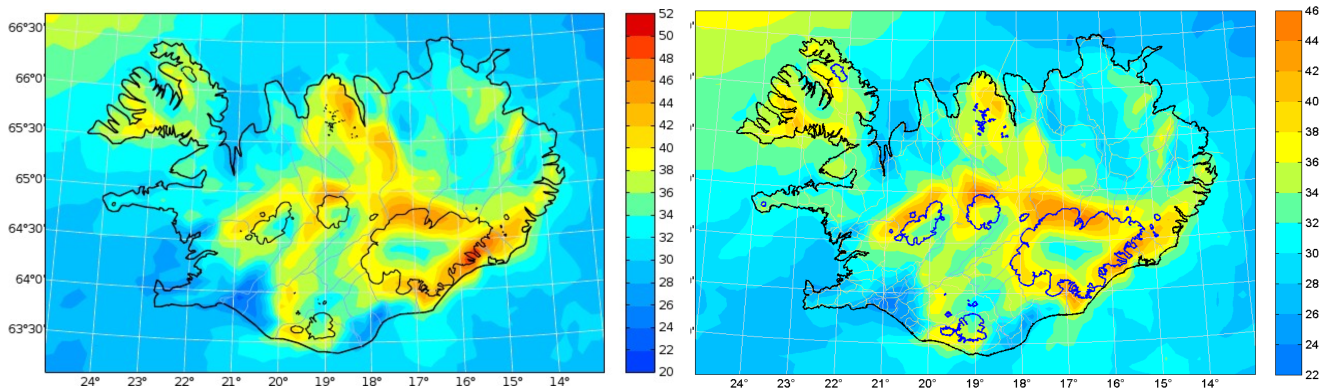
Mynd 3: Reiknisvæði sem afmarka Svarfaðardal (lengst til vinstri), Seyðisfjörð (miðja) og Reykjanes (lengst til hægri) eru 118x130, 73x64 og 112x79 hnitpunktar. Lárétt reikniupplausn er 1 km, athugið að litakvarði sem sýnir hæð yfir sjávarmáli er ekki samræmdur milli myndanna.

Hermireikningarnir eru unnir á öflugu tölvueyki Háskólans í Björgvin sem nefnist “Hexagon”. Fjöldi örgjörvastunda (þ.e. “cpu hours”) er gríðarlegur, en til marks um það má nefna að það tekur um 15.500 klst. að reikna eitt ár á reiknineti líku því

sem sýnt er á mynd 1. Þegar Þjórsár- Tungnaársvæðið (sbr. mynd 2) er tekið inn eykst reiknitíminn enn, eða í 61.700 stundir. Aukning vegna minni svæðanna sem sýnd eru á mynd 3 er e-ð minni, eða milli 5.000-10.000 örgjörvastundir fyrir hvert svæði. Gagnamagnið er ennfremur mjög mikið. Fyrir svæðin á mynd 1 gera það um 1.7 TeraByte á ári og 3.6 TeraByte þegar Þjórsár- Tungnaársvæðið er tekið með í myndina. Heildargagnamagn sem til verður vegna þessa verkefnis er því rúmlega 40 TeraByte og heildarfjöldi reiknistunda verður um 600.000 örgjörva-stundir.
Þegar þetta er ritað er hermireikningum lokið fyrir fjórtán ár af fimmtán og reikningar fyrir síðasta árið er á síðustu metrunum. Hluti reikniniðurstaða hefur þegar verið fluttur yfir á tölvur RV, ennfremur hafa gögn verið afrituð beint yfir á gagnadiska sem sendir voru til Noregs, en eru nú komnir heim. Unnið er að frekari uppbyggingu diskastæða.

Gagnaframsetning

Reiknuð gögn munu verða sett fram í formi korta, t.d. endurkomutímakorta sbr. mynd 4 hér að neðan, ennfremur verður leitast við að gera hrágögn aðgengileg á netinu.

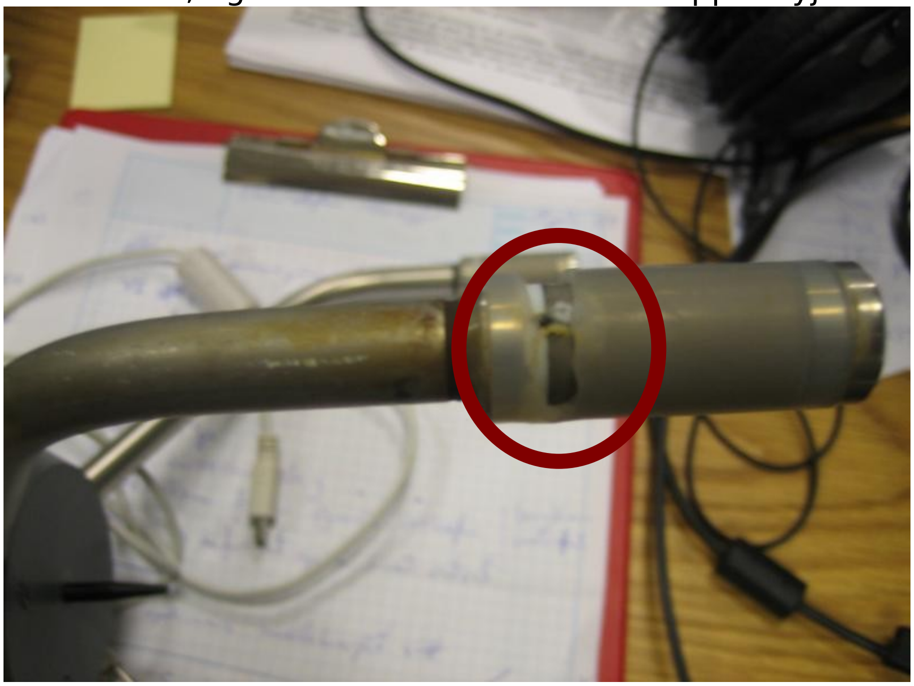


Mynd 4: Kort sem sýnir 50 ára endurkomutíma hámarksvindhraða [m/s]. Myndin til vinstri sýnir endurkomutíma m.v. Gumbel dreifingu en til hægri er gert ráð fyrir GEV dreifingu (General Extreme Value). Unnið upp úr hermireikningum á 9 km reiknineti fyrir tímabilið 1958 til 2007. Reiknaður vindhraði er lesinn út úr líkaninu á sex klst. fresti og ber að túlka sem 10 mínútna meðalvind.

Einstök punktgildi verða gerð aðgengileg á Gagnatorgi veðurupplýsinga (http://portal.belgingur.is). Ekki er talið gáfulegt að framreiða kort með 50 ára endurkomutíma upp úr reikniröð sem eingöngu spannar 15 ár. Í nýútkominni grein eftir Jónas Elíasson, Ólaf Rögnvaldsson og Trausta Jónsson (sjá greinalista) er t.d. sýnt fram á að gagnaröð þurfi helst að spanna 40 ár, eða meir, til að dreifing M5 endurkomustuðla verði ásættanleg. Áhættukort með 30 ára endurkomutíma eru þó talin vel gerleg.

Uppsetning mælitækja á Gufuskálum

Haustið 2008 voru fyrstu mælitækin sett upp í minna mastrið á Gufuskálum. Þegar tækjanna var vitjað sumarið 2009 kom í ljós að vegna rafmagnstruflana í október 2008 hafði gagnasöfnun farið forgörðum. Unnið hefur verið að endurbótum, m.a. með því að koma varaaflgjöfum fyrir framan bæði mælistöð úti við mastrið sem og fyrir framan gagnasöfnunarvél inni í öryggishúsnæði RÚV. Ennfremur hefur verið komið á sítengingu við gagnasöfnunarvél RV og sjálfvirka veðurstöð Veðurstofu Íslands. Við þessa úrbót eru gögn send á fimm mínútna fresti frá mælistöð.
Þegar mælistöðvar var vitjað sumarið 2009 kom í ljós að vindmælir í 40 metra hæð var ónýtur (sjá mynd 5). Ekki er á þessari stundu ljóst hvað olli því að mælirinn gaf upp öndina, ekki er hægt að útiloka eldingu þótt ýmis önnur merki þyki vanta, eða jafnvel fugla himinsins. Nýr mælir hefur verið sendur frá Vaisala, okkur að kostnaðarlausu, og er stefnt að koma honum upp á nýju ári.



Mynd 5: Sónískur vindhraðamælir af gerðinni Vaisala Windcap WS425. Takið eftir skemmdinni á gúmmífóðringu eins skynjarahöfuðsins.

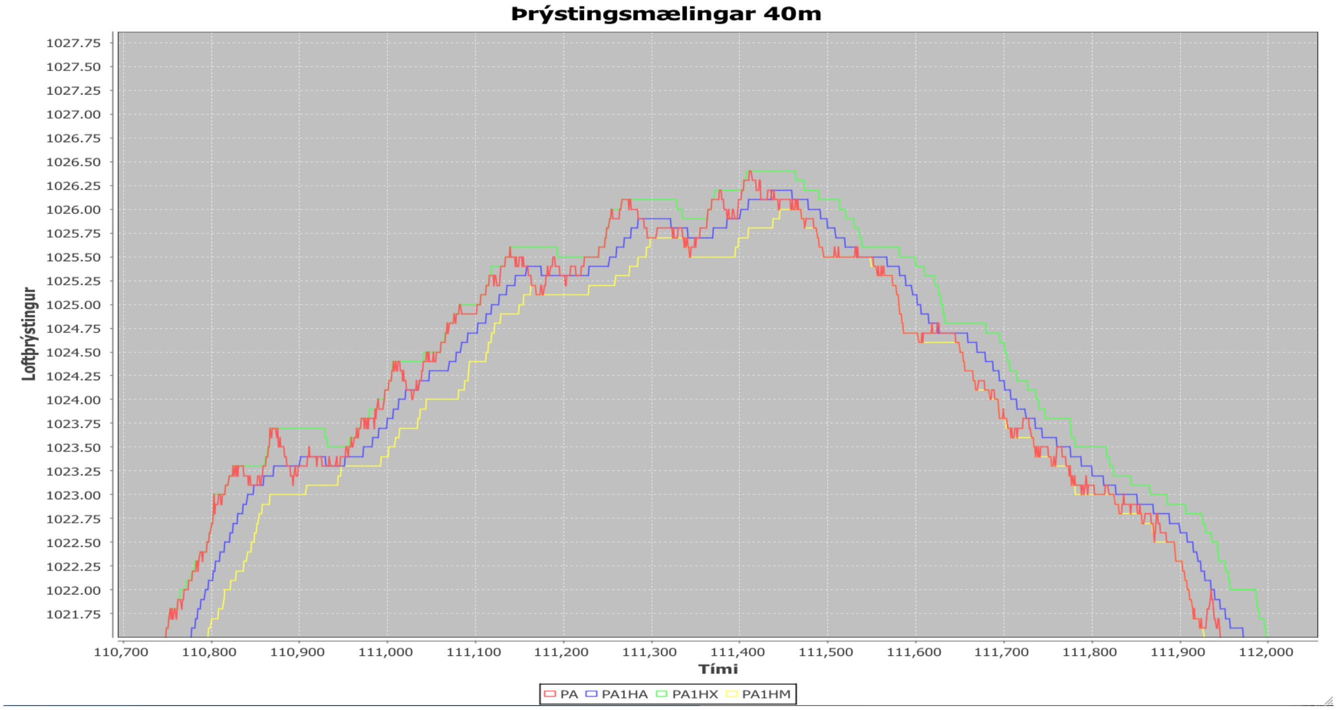
Í ágúst 2009 var enn farið að Gufuskálum og komið upp mælistöð neðst í stóra RÚV mastrið. Rafmagn var fengið úr mastrinu sjálfu. Mynd 5 sýnir staðsetningu mælibúnaðarins og mynd 6 sýnir mælistöðina sjálfa.
Verkefnið var ennfremur kynnt á EGU ráðstefnunni í Vínarborg og EMS ráðstefnunni í Toulouse (sjá veggspjald í ítarefni).

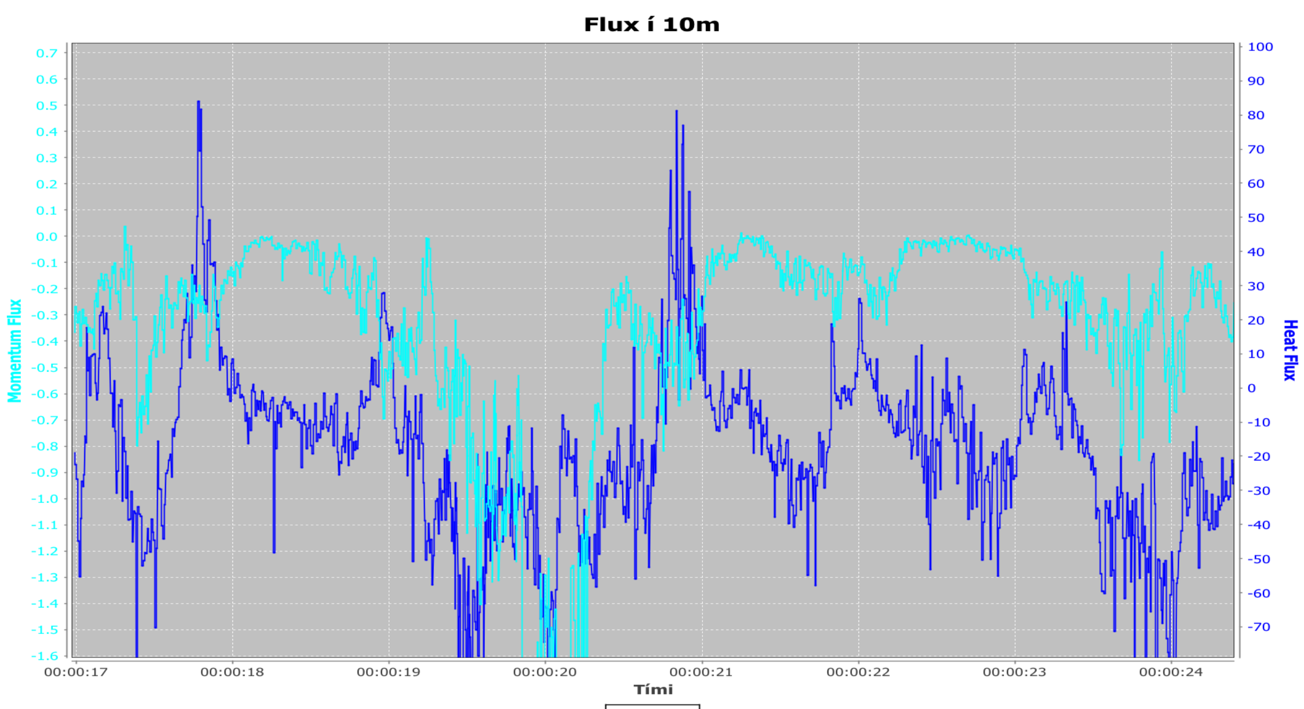
Mynd 6: Veðurmælistöð í neðsta palli stóra mastursins á Gufuskálum, hæð yfir jörð er u.þ.b. 10 metrar.

Mynd 7: Mælibúnaður, lengst til vinstri er tengibox fyrir flæðismæli (e. flux meter), því næst er tengibox ásamt loftþrýstingsmæli. Fyrir ofan það er hlíf með hita- og rakamæli. Á mynd fyrir miðju sést ennfremur, hægra megin við hitahlífina, loftnet fyrir VHF gagnasendingar. Ennfremur sést móta fyrir rörabúnaði út frá mastrinu fyrir flæðismælinn. Sá mælir er sýndur lengst til hægri en hann er af gerðinni Metek USA-1.

Gagnavistun

Með tilkomu sítengingar við Gufuskála opnaðist möguleiki á að flytja gögn yfir á gagnagrunnsvél RV því sem næst í rauntíma. Eins og staðan er núna eru gögn flutt yfir á fimm mínútna fresti, en gögn eru send frá mælistöð til móttökutölvu einu sinni á mínútu. Mynd 8 sýnir mældan þrýsting í 40 metra hæð og mælt skriðþungaflæði og hitaflæði í 10 metra hæð.





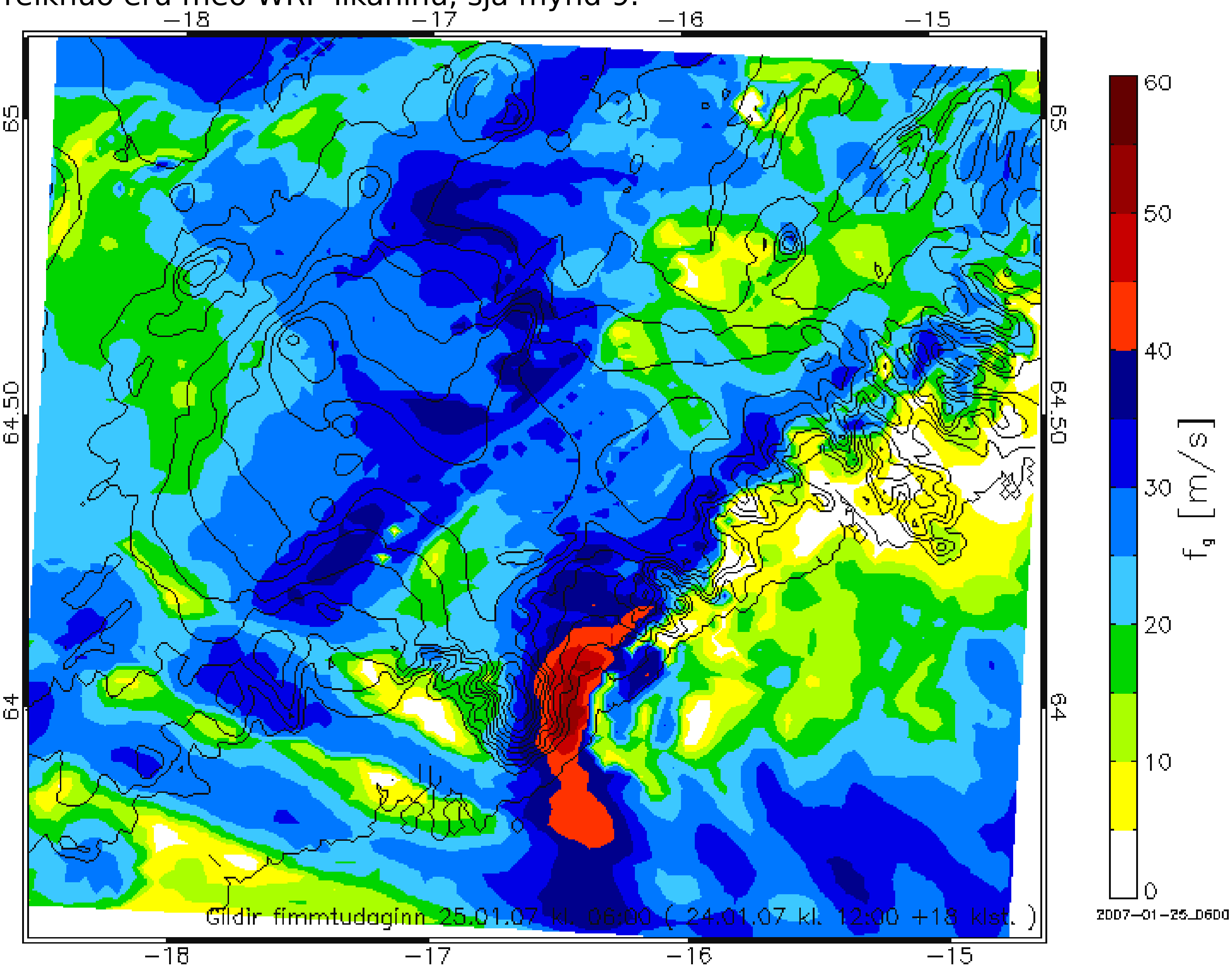
Mynd 8: Mældur loftþrýstingur í 40 metra hæð (efri mynd) og mælt skriðþungaflæði (e. momentum flux) og hitaflæði (e. heat flux) í 10 metra hæð. Tímakvarði er fjöldi mínútna frá því að mælingar hófust, eftir er að umreikna hann yfir í algildan tíma.

Vélbúnaðaruppbygging

Eins og vikið var að hér á undan þá er gagnamagn vegna hermireikninganna mjög mikið, eða ríflega 40 TeraByte í heild sinni. Á reiknieykjum RV eru nú þegar uppsett 15 TeraByte af RAID5 diskaplássi, og búið er að fjárfesta í 12 stykkjum af 1.5 TeraByte diskum sem munu skila um 12 TeraByte af RAID5 diskaplássi. Gert er ráð fyrir að fjárfest verði í 6 stykkjum af 1.5 TeraByte diskum í viðbót sem muni skila 6 TeraByte RAID5 diskaplássi. Af þessu er ljóst að grisja verður gagnasafnið niður um a.m.k. 7 TeraByte svo hægt verði að hýsa það á núverandi vélbúnaði ef ekki á að fara út í mjög kostnaðarsamar viðbætur.

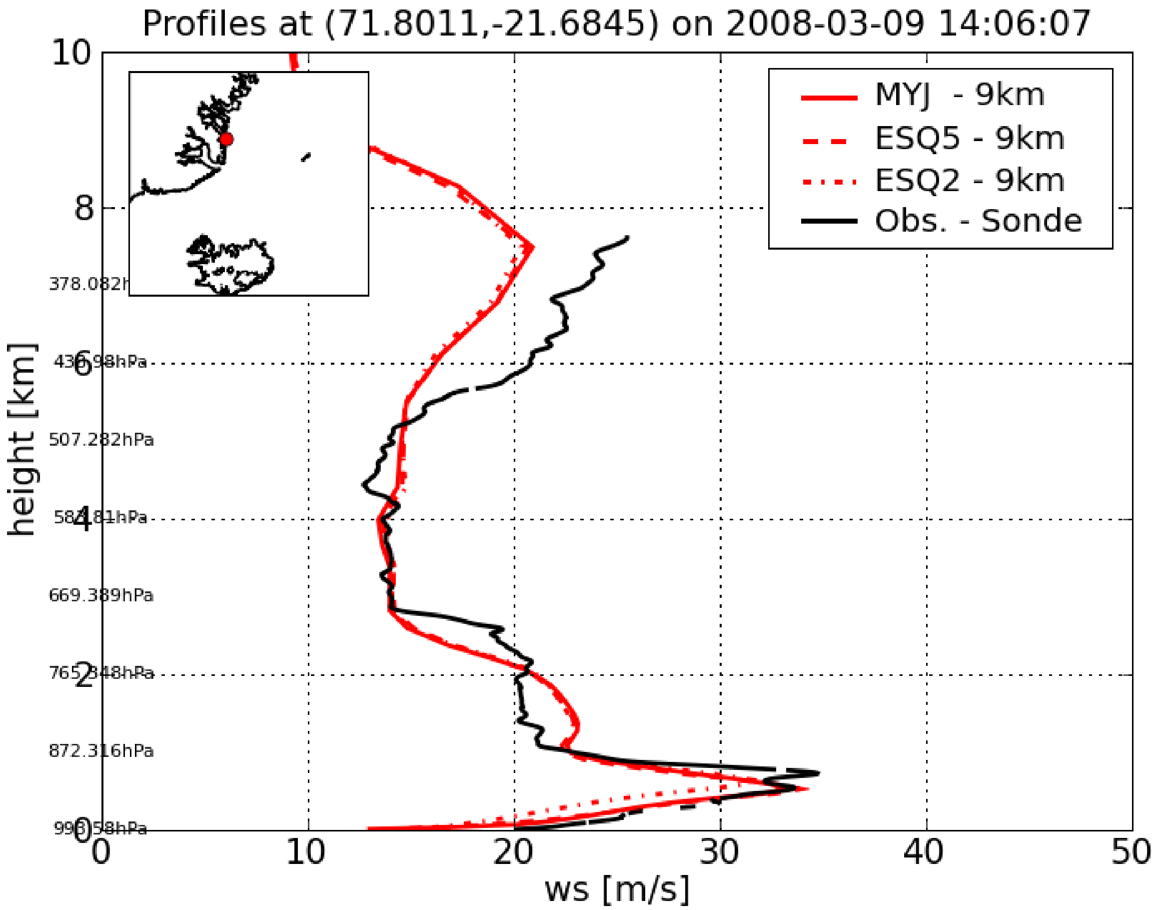
Vinna við hviðu- og jaðarlagslíkan

Á árinu kom út grein um reikninga á hviðum með aðstoð hermireikninga með lofthjúpslíkaninu MM5 auk þess að hviðuaðferðin er prófuð í innsendri grein um staðbundið óveður við Kvísker (sjá ítarefni). Ennfremur hafa hviðuspár verið gerðar aðgengilegar sem hluti af spákerfinu http://www.belgingur.is. Verið er að ljúka við prófanir við útgáfu hviðulíkansins sem vinnur á veðurgögnum sem reiknuð eru með WRF-líkaninu, sjá mynd 9.



Mynd 9: Reiknaðar hviður [m/s] (augnabliksgildi vindhraða) í staðbundnu óveðri við Kvísker austanmegin Öræfajökuls 25. janúar 2007. Beitt er aðferð Brasseurs við hviðureikningana.

Vinna síðasta árs við jaðarlagslíkanið laut að stærstum hluta að prófunum á líkaninu fyrir ýmis veðurfræðileg fyrirbæri og samanburði við önnur jaðarlagslíkön. Ennfremur hafa reikningarnir verið bornir saman við mælingar á veðri, t.d. úr veðurbelgjum úr rannsóknaflugum í Norður-Atlantshafi (sjá mynd 10) og frá fjarstýrðum flugvélum nærri Hofsjökli, svokölluðum SUMO- og KALI-vélum sem notaðar voru í FLOHOF-verkefninu.



Mynd 10: Samanburður á reiknuðum og mældum vindi úr mismunandi jaðarlags-líkönum og veðurbelg úr rannsóknaflugi nálægt Tóbínhöfða við Austur-Grænland 8. mars 2008.

Verkþáttum sem er ólokið

- Ólokið er við að reikna fjögur ár, 2005-06 til og með 2008-09. Af þessum fjórum árum eru reikningar hafnir við þrjú og verið er að vinna innlagsgögn fyrir síðasta árið. Gert er ráð fyrir að hermireikningum verði lokið um miðjan desember 2009.
- Vistun og grisjun reiknigagna. Ljóst er að e-ð þarf að grisja af gögnunum til að hægt verði að vista þau á vélum RV. Við gerum ráð fyrir að halda sem mestu af gögnum úr jaðarlaginu en minnka gagnamagn úr efri lögum lofthjúpsins. Ennfremur þarf að gera gögnin samfelld í tíma, en vegna takmarkaðs reiknitíma á tölvueykinu Hexagon hefur þurft að reikna tímaraðirnar í nokkrum skrefum sem veldur því að reikniraðir eiga það til að skarast í tíma.
- Lokavinnsla reiknigagna, framleiðsla á endurkomutímakortum fyrir vind og vindhviður. Framleiðsla á úrkomu- og hitakortum (mánuðir, árstíðir, ár og allt

tímabilið) sem og kortum af slydduísingarstika. Ennfremur vistun punktgilda á Gagnatorgi veðurupplýsinga.

- Kynning á niðurstöðum. Hér mætti hugsa sér að leita til Reykjavíkurborgar og halda veglega kynningu á verkefninu í Ráðhúsinu.

Samantekt

Ljóst er að vinna við RÁVAndar verkefnið hefur reynst heldur viðameiri en fyrstu áætlanir gerðu ráð fyrir. Helgast það að mestu af því að verkefninu hefur vaxið nokkuð fiskur um hrygg og leitast hefur verið við að samþætta vinnu sem best við önnur verkefni sem orðið hafa til á undanförnum árum. Má þar nefna mæliverkefni með SUMO flugvélunum og LOKS verkefnið. Ennfremur hefur komið á daginn að framleiðsla og meðhöndlun reiknigagna, í því gríðarlega magni sem um ræðir í þessu verkefni, hefur reynst töluvert tímafrekari en skipuleggjendur höfðu gert sér í hugarlund.
Þrátt fyrir þessa hnökra sem hlaupið hafa á tímasnurðu RÁVAndarinnar þykir okkur ljóst að verkefninu verði lokið með sóma á tímabilinu mars – apríl 2010. Leggjum við ennfremur mikla áherslu á að niðurstöður verkefnisins verði vel kynntar almenningi, t.d. með kynningu í Ráðhúsi Reykjavíkur, sem og hagsmunaaðilum. Loks er rétt að minnast þess að hægt verður að vinna frekari upplýsingar úr reikniniðurstöðum. Reiknaðan vind má t.a.m. nota til að fá grófa hugmynd af mögulegri vindorku yfir landinu og jafnvel meta áætlaðan niðritíma vindmylla á einstaka stöðum út frá hviðureikningum.

Reykjavík, 15. desember 2009.

Haraldur Ólafsson – formaður stýrihóps
Ólafur Rögnvaldsson – dagleg umsjón

Greinar, erindi og veggspjöld

Greinar

Hálfdán Ágústsson and Haraldur Ólafsson, Forecasting wind gusts in complex terrain. *Meteorology and Atmospheric Physics*, 103 (1–4), 173 – 185, mars 2009.

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RiV Software Project

MAWS Data Importer

A data converter from MAWS/MetMan log format to PostgreSQL

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1 Program Description

The mawsLogImporter is a program specifically made to suit to convert the Vaisala MetMan text files to data stored in a PostgreSQL table. It honors data integrity and takes care of "situations" like connection breaches by re-trying the inserts.

The program is written in Python and uses the PyGreSQL PostgreSQL connector.

2 Installation

On UNIX, Linux and Mac OS X:
Unzip the archive. Move the ".py" files and the conf directory to a location of your choice (recommended: "/usr/local/maws").
Create the file /etc/mawsLogImporter and insert the line "mLog=/usr/local/maws" (replacing the path with the actual path where you placed the contents of the archive), followed by *one blank line*.
Make the import.py executable (chmod 755 /usr/local/maws/import.py)
Edit the "/usr/local/maws/conf/maws.conf" and set the database connection parameters.
Import the SQL script into the database (psql database -U dbuser -W -h dbhost -p dbport < mawslog.sql — replacing the "database", "dbuser", "dbhost" and "dbport" with the actual values).
Add a crontab entry "*/5 * * * * /usr/local/maws/import.py" Done.

On Windows:
Unzip the archive into a temporary directory. Download the *right* version of Py2Exe (http://www.py2exe.org), PyGreSQL (http://www.pygresql.org) and PostgreSQL (http://www.postgresql.org) for your installed version of Python (N.B. Python 2.x is currently the recommended version to use since not all functionality and libraries have been updated to version 3.0) and install them. The PostgreSQL database does not have a Python preference. Once installed, enter the "Services" menu (Start->Programs->Administrative Tools->Services), select the PostgreSQL database service, stop it and change its state to "disabled".
Open a command-line prompt (Start->Run->Cmd) and use the "cd" command to mobe into the temporary directory where you unzipped the archive.
Enter the command: "python setup.py py2exe". This creates a Windows executable version of the import.py.

Create a directory where you want the importer to reside (eg. C:\Program Files\Importer) and copy the contents of the "dist" directory inside the temporary directory to that location. Also copy the conf directory from the temporary directory to the new location.
Create the directory C:\etc and therein the file mawsLogImporter. The file should contain one line "mLog=C:\Program Files\Importer" (replacing the path with the actual path to where the importer exists), followed by *one blank line*.
Edit the maws.conf file (eg. C:\Program Files\Importer\conf\maws.conf) and alter the connection parameters to match those of your database.
Copy the "mawslog.sql" to your database host and import it into the database using the psql command line tool. Create a new scheduled task (Start->Settings->Control Panel->Scheduled Tasks). When you are asked for a program to run, click "Browse..." and select the "import.exe" (C:\Program Files\Importer\import.exe if you used these guidelines). Give the task a name and select "Daily". Set the start time to 00:02 (giving the MetMan software ample time to finish its logging), every day and default start date. In the password fields enter the password of the user which the application will run as (if the user is not the user who is currently logged in, also alter the user name field). Click the "Open advanced properties for this task when I click Finish." checkbox, and click "Finish". In the new window which opened up, under "Schedule", click "Advanced", click the "Repeat task" checkbox and set the values to the following: Every 5 minutes, Until Time: 23:59. In the "Settings" tab change the "Stop the task if it runs for 72 hours 0 minutes" to 0 hours and 20 minutes. Click "Ok" and you are done.

3 Configuration Files

3.1 /etc/mawsLogImporter

The location of the file "mawsLogImporter" is critical - it must reside in the /etc directory (C:\etc on Windows). It should contain exactly two lines:

- Line 1: mLoc=/path/to/mawsLogImporter
- Line 2: [blank line]

This file defines the location of the python programs and the configuration directory.
On UNIX/Linux/Mac OS, this would be like: “mLoc=/usr/share/maws”, while on Windows, it would be like “mLoc=C:\Program Files\Importer”.

3.2 maws.conf

The “maws.conf” file contains configuration parameters for the mawsLogImporter. Since the file is essentially “executed” by Python, great care should be taken not to introduce errors in this file.

The keys recognised by the program are:

- csvPath - string - the path to the Vaisala MetMan data files (usually “C:\Program Files\MetMan\data”)
- dbname - string - the name of the database to connect to
- dbhost - string - the name of the server hosting the database (an IP number is also fine)
- dbport - integer - the port number which the database is residing on (usually 5432 for PostgreSQL)
- dbuser - string - the userID of the database user
- dbpass - string - the password of the database user
- shouldAddUnknownKeys - boolean - defines how unknown keys are handled. If “True”, the keys are added and the processing repeated, while if “False”, unknown keys are assumed to represent an error.

The case of the strings is important. Do not use “false” or “FALSE” where “False” is expected.

4 Program Files

4.1 import.py

This file is the "main" program file. It instantiates the LogImporter class (from "datainserter.py") and runs it.

4.2 setup.py

This file is required on Windows to create a Python-EXE version of the program. It serves no function for the system itself.

4.3 datainserter.py

This is the LogImporter itself. Several functions are defined:

- __init__()
  The class initiator - on initialisation it reads the config files, gets the translation table and list of stations.
- logError(errorString)
  When an error occurs which is not database connectivity related, it is logged to the database (see the table "mawslog") for later perusal.
- getLatestUpdate(station, colName='a.v_date')
  Returns the date of the latest update for a particular station.
- getTransTable()
  Reads the translation table from the database into a set.
- getStationList()
  Reads the list of available stations into a set. The list of stations defines which stations we should look for logfiles for. As such, no stations should exist in the stations list which aren't actively being logged. The active flag in the "stations" table defines an active (logging) station.

- addUnknownKey(keyval)
When an unknown measurement key is encountered and the addUnknownKey flag is set to "True", this function adds the key to the measurements table.

- isOlder(checkDate, station)
Checks if a certain date/time pair (usually the date and time of a log entry) are older than the date/time pair of the most recent log entry in the database for a particular station. Using this function relieves the program of failing on inserts of data already existing in the database.

- processFile(station,dataFile)
This function is the heart of the program. Here all processing decisions are taken, and the database inserts performed. Error checking is extensive on the database inserts, and all errors that happen and can be logged to the database will be logged. There is however no syntax checking on the input files, so damaged data files *may* trigger an yet unknown error, depending on the damage.

- readConfigFiles()
Reads the config files according to the location defined in /etc/mawsLogImporter (C:\etc\mawsLogImporter on Windows).

- makePathFromDate(station, whichDate='')
Creates a path string from the date string such that it conforms to the MAWS file naming convention. If the naming convention of the MetMan software data files is expected to change, this should preferrably be altered to use a set of config file rules.

- findOldest(dtype, theDir)
Finds the oldest directory/file based on its name. The MetMan software uses directory names which represent years and months, and the files themselves contain a full date. This function searches for the oldest file in the tree according to this criteria. The "dtype" parameter defines what type of entity is being examined ('y'=year, 'm'=month and 'f'=file).

- purge(pChar, pString)
To remove a certain character (pChar) from a string (pString) this function is called. Eg. purge('-','2009-05-05') returns '20090505'.

- isLeapYear(year)
Returns true if the "year" represents a year which is a leap-year. This function includes leap years for Gregorian dates before 1582.
(http://en.wikipedia.org/wiki/Leap_year#Leap_year_algorithms)

- parseFiles(station)
  This function retrieves the date of the latest update for a particular station and depending on the date being "today" or not, decides if all, some or one data file should be parsed.

- parseAllStations()
  This is the function which should be called by the program which instantiates this class. It traverses the station list and for each station calls the "parseFiles" function.

4.4 FileReader.py

This class is a simple file reader which I developed previously. It reads a file into memory, divided into sets based on a splitChar.

Gagnatorg veðurupplýsinga

Gagnatorg veðurupplýsinga er vefkerfi sem gerir netnotendum kleift að velja, skoða og vista veðurupplýsingar með mjög einföldum hætti. Frumútgáfa gagnatorgsins inniheldur eingöngu veðurmælingar úr gagnasafni Veðurstofu Íslands. Elstu mæliraðir ná aftur til ársins 1931 en rauntímamælingar eru uppfærðar einu sinni á sólarhring. Engir tæknilegir örðugleikar eru á því að birta jafnframt veðurupplýsingar sem safnað er af öðrum aðilum. Hér er einkum vísað til veðurmælinga Vegagerðarinnar, Landsvirkjunar, Siglingastofnunar og Flugstoða. Á sama máta eru engar tæknilegar hindranir við að birta veðurmælingar erlendis frá.

Notkun gagnatorgsins er einfaldur tveggja skrefa ferill:

1. Val á þeim gögnum sem óskað er eftir. Hér velur notandinn tímabil, veðurstöðvar og þær mælibreytur sem hann hefur áhuga á að sjá.
2. Skoðun eða úttak á völdum gögnum. Hér getur notandinn skoðað gögnin, ýmist sem myndrit eða töflu, raðað gögnunum eftir mælistærðum, þysjað myndritið inn að þrengra tímabili og fleira.

Torgið getur nýst hverjum þeim sem hefur áhuga á að skoða eða vinna frekar með veðurgögn hverskonar. Hingað til hafa þessi gögn ekki verið aðgengileg almenningi á einfaldan hátt.

Torginu fylgir jafnframt forritunarviðmót sem auðveldar tengingu þessarra gagna við önnur hugbúnaðarkerfi.

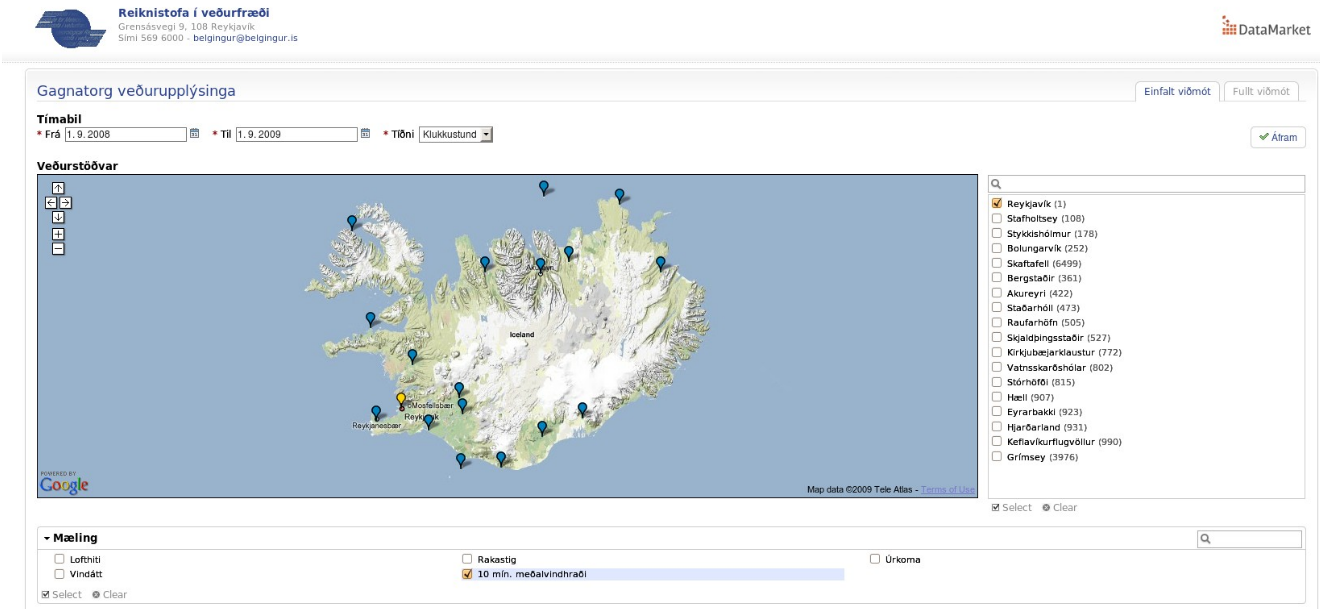
Með einföldum hætti mætti uppfæra gagnatorgið á þann veg að hægt væri að velja veðurspár Belgings[1] fyrir ákveðin svæði, punkta eða ferla.

Aðstandendur gagnatorgsins, sprotafyrirtækin DataMarket og Reiknistofa í veðurfræði[2], er sannfærðir um að það muni nýtast mörgum. Má þar nefna við kennslu í náttúrufræði og stærðfræði á grunn- og framhaldsskólastigum, áhugafólki um veðurfræði og samfélaginu öllu á margan þann hátt sem ekki er séð fyrir nú.

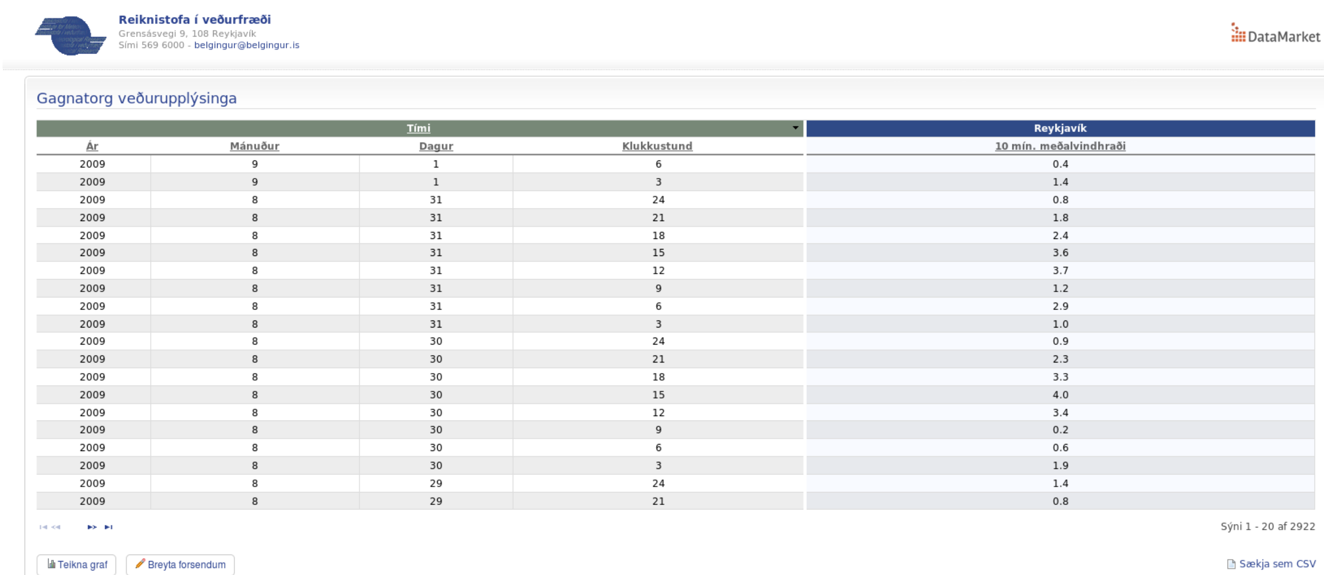
Myndir á næstu síðum sýna hvernig dæmigerð mæliröð er valin, í þessu tilviki mældur klukkustundar meðalvindhraði í Reykjavík síðustu tólf mánuði.

1 Reiknistofa í veðurfræði reiknar daglega veðurspár fyrir N-Atlantshafið, Grænland, Ísland, Færeyjar og V-Noreg. Spárnar eru birtar gjaldfrjálst á vefnum www.belgingur.is og eru uppfærðar fjórum sinnum á dag.

2 Nánari upplýsingar um fyrirtækin er að finna á heimasíðum þeirra, www.datamarket.net og www.riv.is.

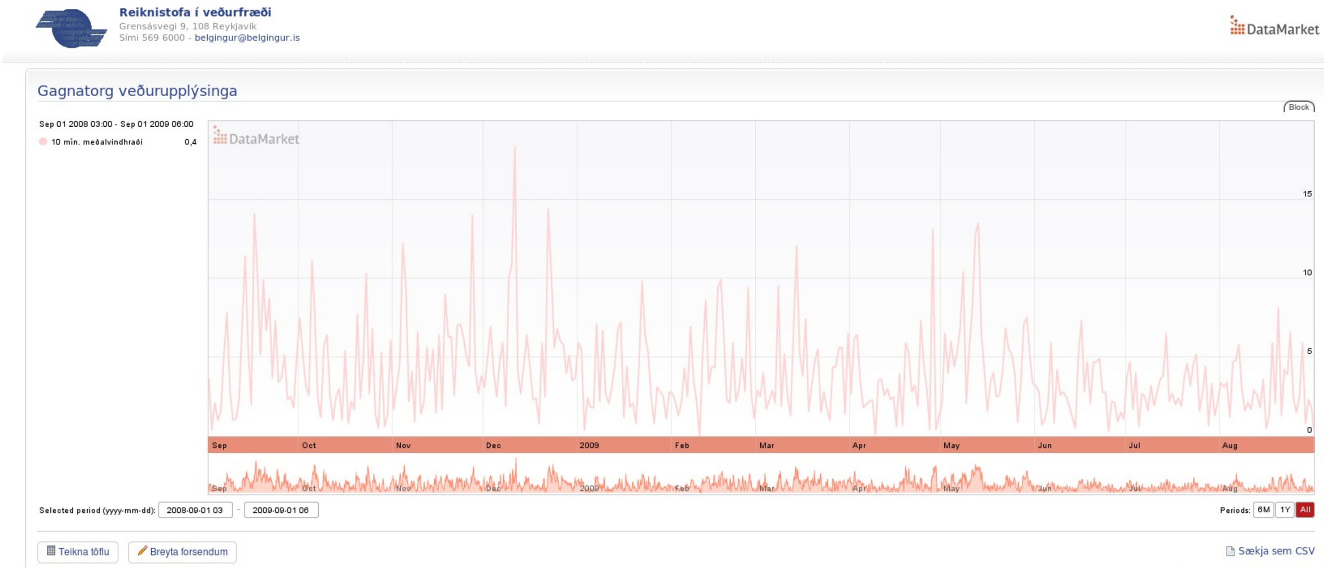


Mynd 1: Mælistöðvar eru valdar á gagnvirku korti þar sem hægt er að þysja og skruna á þægilegan hátt og velja þær stöðvar sem óskað er eftir með því að smella á þær á kortinu, eða afmarka svæði til að velja allar stöðvar innan. Ennfremur er hægt að velja stöðvar úr lista hægra megin við kortið. Tímabil mælinga er valið úr dagatalsviðmóti sem sprettur upp þegar dagsetningareitirnir eru valdir. Tíðni mælinga (ár, mánður, dagur, klukkustund) er valin úr einföldum fellilista. Mæligildi eru valin með því að haka við við þau gildi sem óskað er eftir. Því næst er smellt á "áfram" hnappinn. Í þessu tilfelli hefur verið valið að skoða mæld klukkustundargildi á vindhraða í Reykjavík síðustu tólf mánuði.

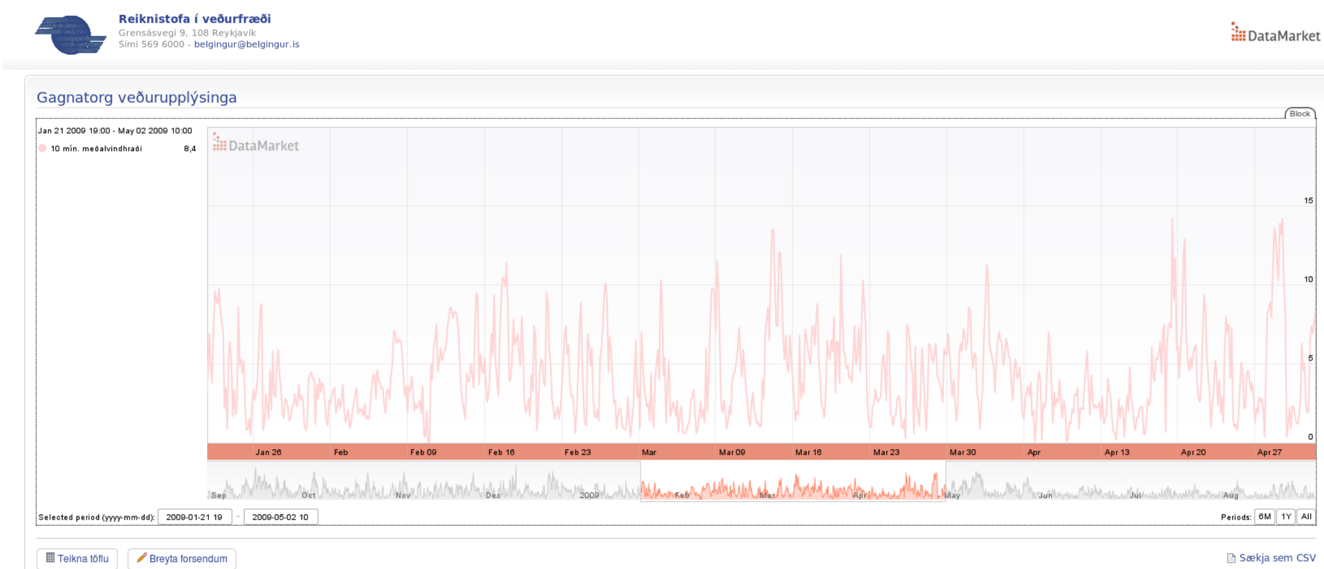


Tími				Reykjavík
Ár	Mánuður	Dagur	Klukkustund	10 mín. meðalvindhraði
2009	9	1	6	0.4
2009	9	1	3	1.4
2009	8	31	24	0.8
2009	8	31	21	1.8
2009	8	31	18	2.4
2009	8	31	15	3.6
2009	8	31	12	3.7
2009	8	31	9	1.2
2009	8	31	6	2.9
2009	8	31	3	1.0
2009	8	30	24	0.9
2009	8	30	21	2.3
2009	8	30	18	3.3
2009	8	30	15	4.0
2009	8	30	12	3.4
2009	8	30	9	0.2
2009	8	30	6	0.6
2009	8	30	3	1.9
2009	8	29	24	1.4
2009	8	29	21	0.8

Mynd 2: Eftir að hafa ýtt á "áfram" hnappinn birtist tafla með völdum mæligildum. Taflan er gagnvirk, þ.e. hægt er að breyta uppröðun á gögnum m.t.t. tíma (elstu mælingar fremst/aftast) og/eða gildum (hámarksgildi fremst/aftast o.s.frv.). Ennfremur má sækja gögnin og vista í einfaldri textaskrá.



Mynd 3: Loks má velja að teikna mæligildin upp sem fall af tíma. Þá kemur upp gagnvirkt línurit af þeim breytum sem voru valdar. Ef um fleiri en eina veðurstöð er að ræða teiknast gildi hverrar stöðvar með aðgreindum hætti.



Mynd 4: Hér er dæmi um hvernig gagnvirka línuritið virkar, búið er að þysja inn að styttra tímibil en upphaflega var valið. Allt tímabilið sést þó enn í neðri hluta grafsins.

Observations and simulations of severe turbulence in a lee-wave rotor in Southeast-Iceland

Hálfdán Ágústsson[12], Haraldur Ólafsson[234] and Ólafur Rögnvaldsson[1]
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[1]Icelandic Meteorological Office, [1]Bergen School of Meteorology
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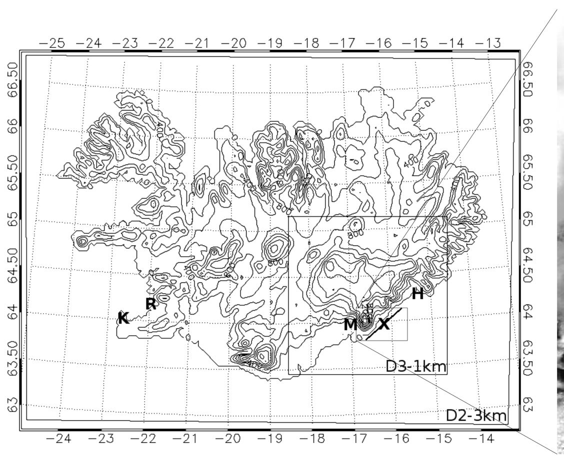
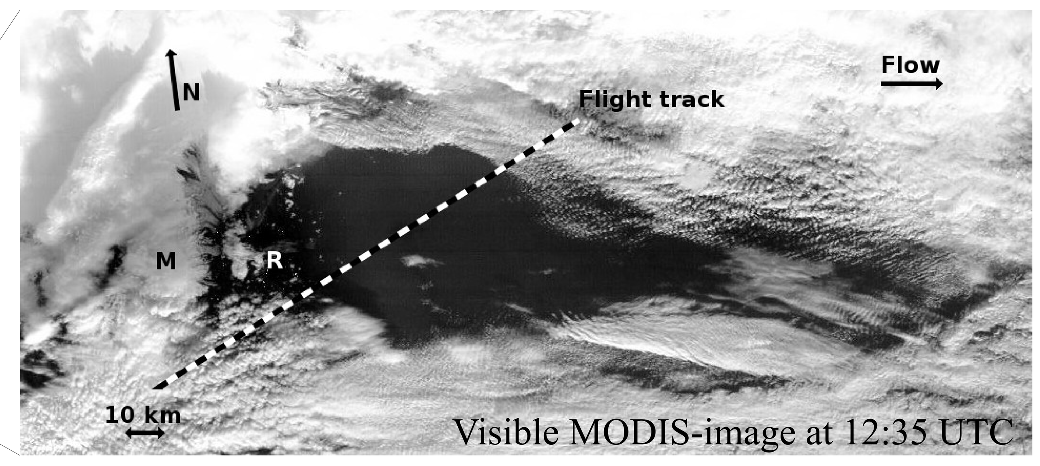
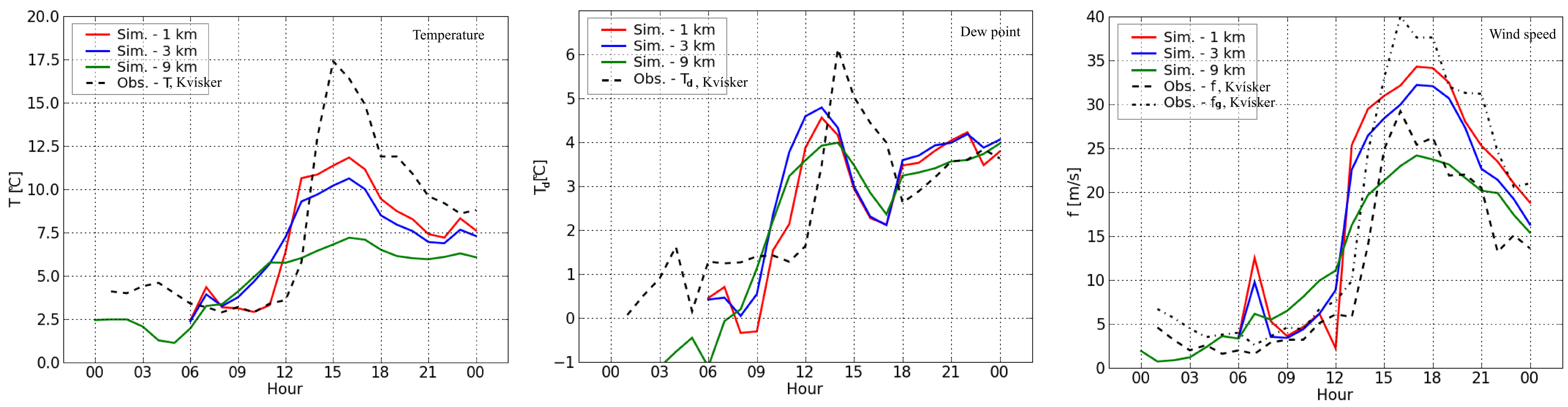
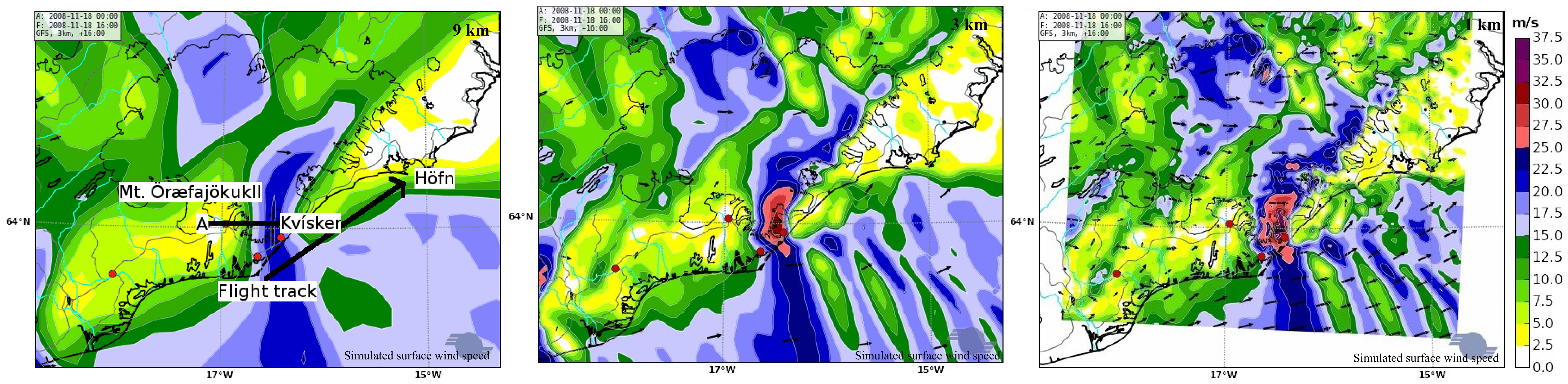
In the afternoon of 18 November 2008 severe and even extreme turbulence was encountered by a Cessna 406 Caravan II aircraft on a domestic route from Reykjavík (R) in Southwest-Iceland to Höfn í Hornafjörður (H) on the southeast coast. The aircraft flew eastwards with a strong tail wind along the south coast of Iceland and first encountered the turbulence (X) at 2.400 m east of the ice covered Mt. Öræfajökull (2110 m) at 16:35 UTC on 18 November 2008. The turbulence continued for 5-7 minutes while the aircraft descended to 900 m and continued towards Höfn. The pilots were experienced but had never encountered such strong and long periods of turbulence. They report that the acceleration was presumably close to 2.5-3 g.

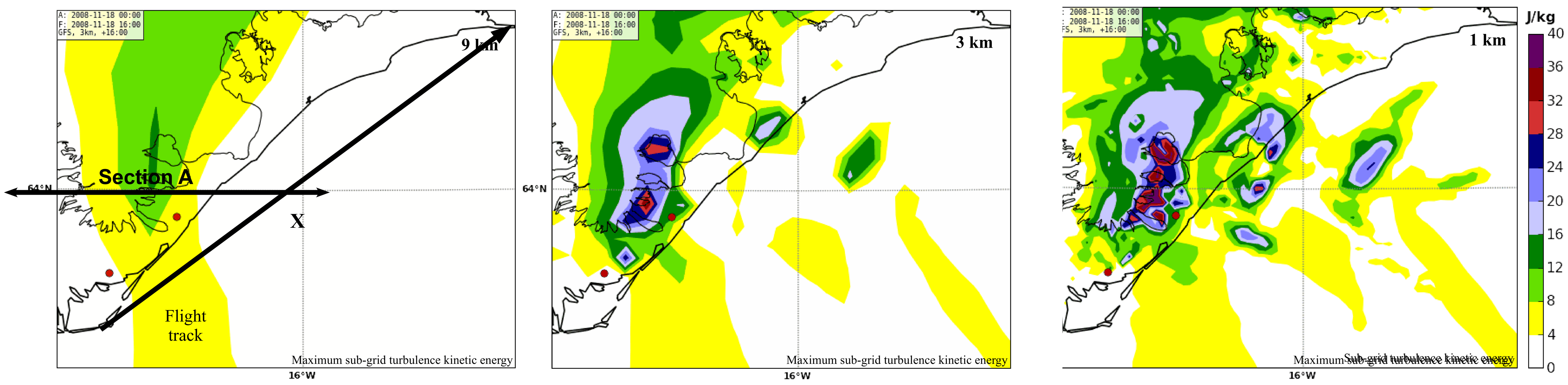






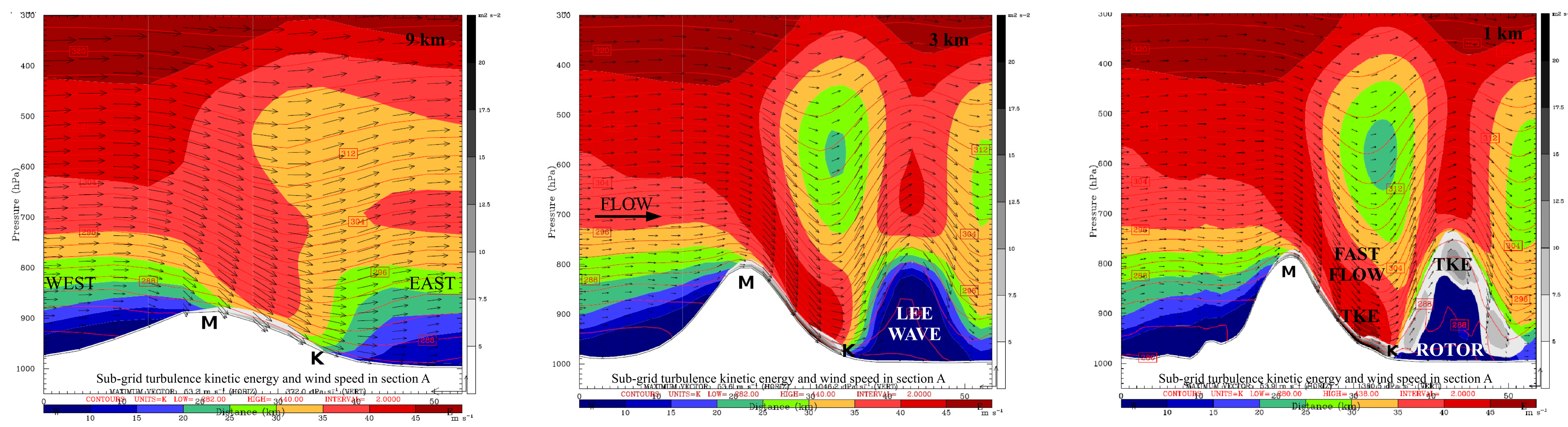
There was no warning, i.e. SIGMET, issued for this region until after the incident. At noon a downslope windstorm was first observed at Kvísker (K) below the leeslopes of Mt. Öræfajökull. The windstorm was captured correctly at Kvísker by the operational HRAS-system (http://belgingur.is) running the WRF-model at a resolution of 3 km, but not at 9 km. The 3 km forecast and a sensitivity simulation with a resolution of 1 km show strong surface winds over the leeslopes and alternating pattern of weak and strong surface winds to the east over the sea. Furthermore, satellite images show a cap cloud over Mt. Öræfajökull, a rotor cloud over the leeslopes and evidence of subsidence in the lee of the mountain.





At a resolution of 9 km no or very weak turbulence is simulated aloft and the surface winds are too weak. At a resolution of 3 km and greater the mesoscale model generates a train of large amplitude lee waves to the east of Mt. Öræfajökull. These orographic waves are generated when the flow is forced over the mountain. There is a rotor with positive vorticity below the first wave. The greatest values of turbulence kinetic energy are found below the wave, in the rotor and in the high-shear layer above the leeslope of Mt. Öræfajökull.

The track of the aircraft is through the first lee wave. Unfortunantly there is at the moment no dissemination of products such as turbulence and vertical motion in the lower troposphere from mesoscale forecasts running at high horizontal resolutions.



Here we present observations and simulations of turbulence in the lower troposphere. A domestic flight encounters severe and even extreme turbulence in a rotor below a lee wave in easterly flow over Iceland. The turbulence, the lee wave and rotor are reproduced with a mesoscale weather prediction model at resolutions of 3 km and greater.

The downslope windstorm at Kvísker is of Type S as presented by Ágústsson & Ólafsson (submitted to Meteor Amos Phys, 2009). The rotor of Type 1 is associated with the lee waves (Hertenstein & Kuettner, Tellus 57A, 2005) which is in agreement with the vertical profiles of wind and temperature. The non-stationarity of the waves is a matter of further investigation.

As is often 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 currently used in aviation forecasts. Their resolution is not adequate and is typically of the order of 10 to 30 km or even coarser. This event underlines the urgency of delivering products from fine-scale simulations over complex terrain to pilots, both for domestic flights in the lower troposphere as in the present case and for flights near the tropopause level as was previously presented by Ólafsson & Ágústsson (Meteor Atmos Phys 104, 2009).

MABLA
Monitoring the Atmospheric Boundary Layer
The Gufuskálar Project

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Introduction: Climate change, new challenges in fine-scale weather forecasting and unanswered questions on the nature of the atmospheric boundary layer and mountain meteorology have motivated a new project, Monitoring of the Atmospheric Boundary Layer in the Arctic (MABLA). The first goal of this project is to establish a monitoring of the atmospheric boundary layer in a more than 400 m high mast at Gufuskálar at the west coast of Iceland.

Figure 1: Location of the Gufuskálar mast at the tip of the Snæfellsnes peninsula in W-Iceland.

Observations at Gufuskálar: The Gufuskálar mast is situated at the tip of the Snæfellsnes peninsula, a short distance northwest of the almost 1.5 km high, but rapidly melting Snæfellsjökull Glacier (cf. Fig. 1). A manned weather station was operated at Gufuskálar 1970-1994 and an automatic weather station has been operated there since 1994. The Stykkishólmur weather station that has a temperature series dating back to the middle of the 19th century is only a little more than 65 km to the east of Gufuskálar. The main mast of Gufuskálar is 412 m high, while a smaller 40 m high mast is nearby. The taller mast was erected in 1963 and is currently used as a long wave radio transmitter.

Figure 2: Installation of equipments in the masts at Gufuskálar, W-Iceland in August 2008 and 2009.

The observations in the masts will consist of automated weather stations recording winds, temperature, pressure and humidity at roughly 10, 40, 100, 200 and 400 meters every 10 minutes.

In addition, there will be high-frequency observations to assess turbulent fluxes of heat and momentum at 10 and 100 meters and observations of short- and long-wave radiation. Measurements at 10 and 40 metres started in the fall of 2008 and installation of instruments at the remaining levels will be completed during the summer of 2010 (cf. Fig. 2).

Scientific Objectives: The Gufuskálar observations serve a multiple purpose. They are expected to provide a description of the atmospheric boundary layer inside a corner wind in northeasterly flow, an upstream blocking in northwesterly flow and in wakes or downslope windstorms in southeasterly flows (cf. Fig. 3). Being located close to the shoreline, observations from Gufuskálar can be expected to be useful in describing the marine boundary layer and for validating algorithms of remotely observed winds over the sea.

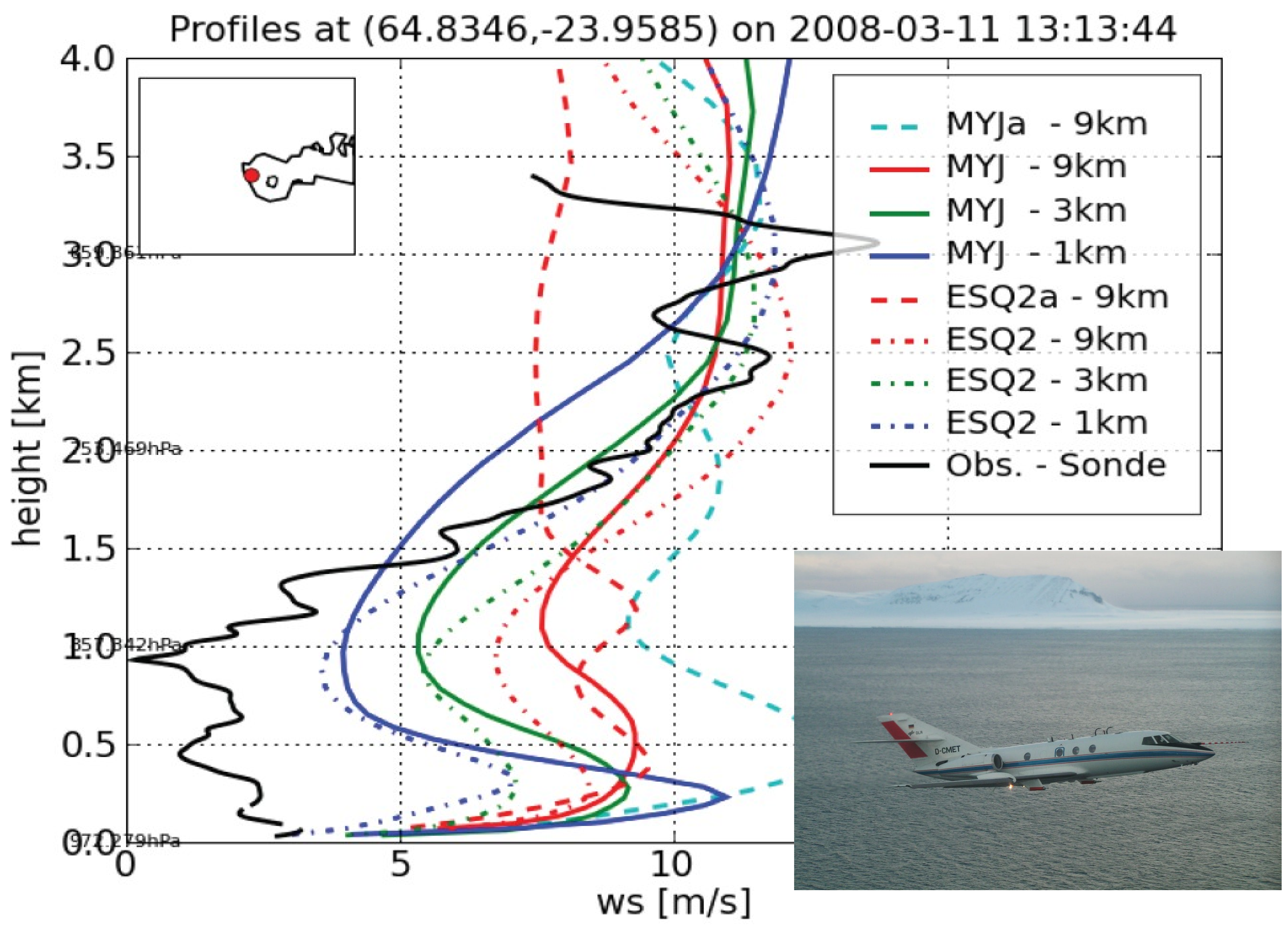

Figure 3: Observed (Falcon drop-sonde) and simulated (AR-WRF) windprofiles in easterly winds in the vicinity of Gufuskálar at 13:13 hours, 11 March 2008.

From a forecasting perspective, the data on turbulent transport of momentum down to the surface of the earth during windstorms is expected to give guidance for tuning of parameterization schemes with the aim of improving forecasts of surface mean winds and surface wind gusts [1,2]. From a climatic perspective, future observations from Gufuskálar are expected to complement the exceptionally long Stykkishólmur time-series of temperature. The Gufuskálar project is a long-term investment. The measurements are expected to monitor a plausible climate change associated with the predicted global warming and the retreat of the sea ice north of Iceland.

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Observations and simulations of severe turbulence in a lee-wave rotor in Southeast-Iceland

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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 2.500 m down to the ground. The situation is reproduced with the WRF-model at horizontal resolutions up to 1 km. The simulations show amplified lee waves and a Type 1 rotor which is in agreement with the vertical profile of wind and temperature. Very strong shear-turbulence is reproduced 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. At the surface, the observed severe downslope windstorm is generated by the gravity wave activity. From a forecasting perspective, this event could have been foreseen quite accurately, but not with the NWP tools that are currently in use for aviation forecasts. Their resolution is typically of 9 to 27 km and even coarser, and that is simply not adequate. This event underlines the urgency of delivering products from fine-scale simulations over complex terrain to pilots.

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1 Introduction

There is mounting evidence in the scientific literature that turbulence aloft over complex terrain may be succesfully forecasted using fine-scale 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, e.g. over Greenland as in FASTEX (Doyle et al 2005) and 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 are expensive and they are unfortunantly limited to intensive observations periods ranging from days to weeks at the best. Apart from large campaigns of this kind there are reported cases of turbulence aloft, for example from aviation reports over the Rocky mountains in Colorado (Lilly 1978) and Greenland. 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 while Ólafsson and Ágústsson (2009) focussed on an international flight encounter with severe turbulence at the tropopause level in easterly flow over Greenland. In this case the incident could presumably have been avoided as fine-scale simulations reproduced the breaking waves and the turbulence which reached above the tropopause.

In fact, 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 where clear air turbulence may be encountered when vertically propagating gravity waves overturn and break due to the strong and sudden change in atmospheric stability and even wind speed, as was e.g. the case above Greenland in Ólafsson and Ágústsson (2009). 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, as is the case in this study. 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 as well as in other projects (see Grubišić and Lewis 2004, and references therein) such as the pioneering lee wave study of Küttner (1938). For 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 (see 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.

The scientific literature describes two possible types of rotors, where the negative vorticity rotors with stronger and more intermittent turbulence are related to hydraulic jumps. Hertenstein and Kuettner (2005) classify the hydraulic jump rotor as a Type 2 rotor but there are few documented observations of these rotors. The Type 1 rotor forms below amplified lee waves and is characterized by positive horizontal vorticity and reversed flow near or at the surface. As discussed in Doyle and Durran (2002), one of the first papers employing atmospheric models in the study of rotors, the boundary layer flow separates from the surface at the lowest point of the wave as a result of the adverse pressure gradient set up by the trapped lee wave, given that the amplitude of the lee wave is sufficient. The turbulent surface layer which is characterized by strong forward wind shear and positive vorticity, contributes to the formation of the rotor when it is carried upwards in the rising part of the wave. The existence of the trapped lee wave is a prerequisite for the creation of the rotor and larger lee waves lead to stronger rotors. Idealized simulations with an atmospheric model suggest that friction is of paramount importance in the creation of the rotors in real flows (see e.g. Doyle and Durran 2002; Vosper 2004). The contribution of a strong temperature inversion near the mountain top has been investigated by e.g. Vosper (2004) 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 3-dimensional flow over orography (Doyle and Durran 2007) indicate that small scale and short lived subrotors are created by shear-instability on, and are swept along, the rotor and lee wave boundary. These subrotors may be enhanced in flow over complex orography as opposed to idealized mountains causing their turbulence kinetic energy to exceed that of the main rotor. That and their nonlocal and transient nature causes them to be possibly far more dangerous to aviation than the main rotors. These findings were verified in the first documented observations of subrotors during the T-REX (Doyle et al 2009).

Scorer (1949) provided the first theory on trapped lee waves. They are in simple terms generated in a layered and stably stratified airmass as it impinges on orography. Given favourable conditions, e.g. forward wind shear and/or weaker stability with height immediately above the mountain, the waves generated by the mountain may propagate vertically. If there is a second layer further aloft with significant reverse wind shear and/or an increase in stability with height the waves may become evanescent in this layer and (a part of) the wave energy is reflected downwards. Given that the downward going wave is at least partly reflected from the surface a superposition of up- and down going waves can create a train of trapped waves in the lee of the mountain. Durran (1990) provides a review of the theory related to gravity waves while Smith (e.g. 2004) discusses some of the more recent studies on atmospheric flow in complex terrain.

This study reports on observations of severe turbulence in the lower troposphere in an aviation incident near the coast of Southeast-Iceland in the afternoon of 18 November 2008. The atmospheric data, including the turbulence data, are described in the following section. In Sec. 3 the atmospheric flow and the turbulence are reproduced in a mesoscale numerical model at varying horizontal resolutions, which aids in assessing the gain of basing aviation forecasts upon high-resolution simulations. Discussions and concluding remarks are in separate sections at the end of the paper.

2 Atmospheric data

2.1 The turbulence incident

The turbulence was encountered by a Cessna 406 Caravan II aircraft which is a fast dual propeller jet that can carry 9 passengers. It was on a scheduled flight for the Ernir company from Reykjavík in Southwest-Iceland to Höfn í Hornafjörður on the southeast coast (Fig. 1). The aircraft flew eastwards with a strong tail wind along the south coast of Iceland and first encountered the turbulence at 2.400 m (8.000 ft) east of the ice covered Mt. Öræfajökull (2110 m) at 16:35 UTC on 18 November 2008. The severe, and even extreme, turbulence continued for 5–7 minutes while the aircraft descended to 900 m (3.000 ft) and continued towards Höfn. The pilot tried to veer a few km southward, i.e. away from the mountains, but the turbulence did not cease until the air-

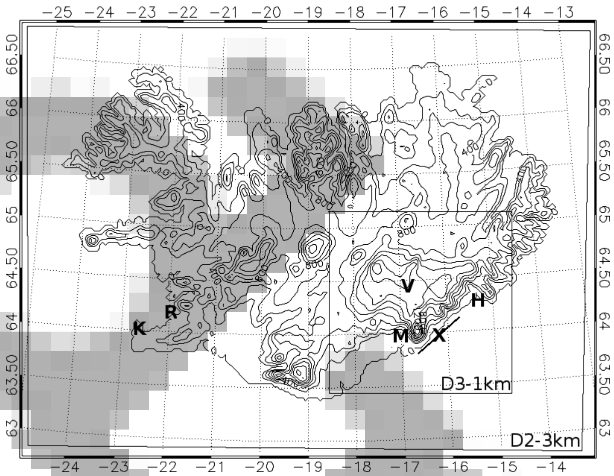

Fig. 1 Map of Iceland with terrain contours at an interval of 200 m. Also shown are the approximate track of the aircraft when it first encounters the turbulence (X), the locations of Reykjavík (R), Höfn (H), Keflavík (K), Mt. Öræfajökull (M), the Vatnajökull ice cap (V) and numerical domains with a horizontal resolution of 3 (D2) and 1 km (D3).

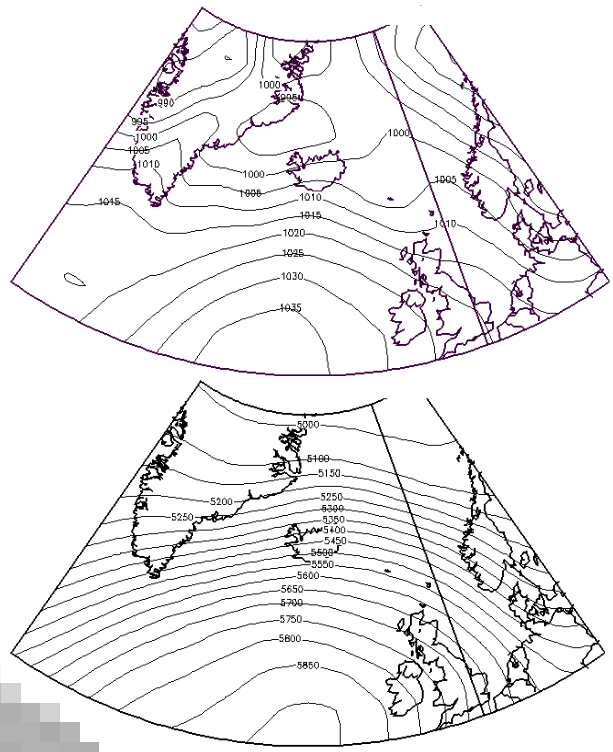

Fig. 2 Sea level pressure [hPa] (above) and geopotential height at 500 hPa [m] (below) at 18 UTC on 18 November 2008 (analysis from NOAA/CDC).

craft was close to landing at Höfn. There was no warning, i.e. SIGMET, issued for this region until after the incident.

The pilots were experienced but had never encountered such strong and long periods of turbulence. They report that the acceleration was presumably close to 2.5–3 g when the turbulence was strongest and they describe it as rapid but short up and down motion of the aircraft and approx. 45° changes in aircraft yaw. There were no clouds east of Mt. Öræfajökull while there was however a cap cloud over the mountain from approx. 3.700–6.100 m (12.000–20.000 ft). The temperature near 900 m (3.000 ft) was close to -3°C.

There were only minor personal injuries in the incident and the aircraft flew back to Reykjavík 1–2 hours later but this time it took a route over Vatnajökull glacier with a strong head wind but without encountering further turbulence.

2.2 The flow aloft

According to the analysis from NOAA (Fig. 2) there was a surface low to the north of Iceland while there was high pressure throughout the troposphere over the Atlantic Ocean south of Iceland, giving rise to westerly flow over Iceland.

Upper-air observations from the Keflavík station in Southwest Iceland (Fig. 3) confirm the strong westerly winds increasing from 25 m/s at 900 hPa to nearly 45 m/s at midtropospheric levels with weaker winds below the tropopause and stronger winds further aloft. There was an inversion at 900 hPa with a mixed layer below. A backward trajectory analysis reveals the southern origin of the airmass (not shown). The relatively strong winds contribute to a well mixed atmospheric boundary layer but the cooling from below by the colder ocean surface contributes to the shallowness of the boundary layer.

Satellite images (Fig. 4) from 12:35 UTC on 18 November 2008 reveal the cap cloud over Mt. Öræfajökull and the clear skies in a large wake-like region to the east of the mountain. Immediately east of the mountain, downwind of the termini of the outlet glaciers which descend down to the lowlands from the 2000 m high mountain plateau, is a single broken cloud at or above mountain top level which is reminiscent of a rotor cloud. Further east is a single elongated and possibly lenticular cloud.

2.3 Surface observations

At approximately 13 UTC a westerly windstorm is initiated at Kvísker (see Fig. 1 for location) with the 10-minute wind speed at approx. 7 m above ground level increasing suddenly from 5 m/s to 30 m/s and gusting to 40 m/s. At the same time there is significant warming and drying of the airflow as seen from the 2-metre temperature and relative humidity (Fig. 5).

The automatic weather station at Kvísker (WMO no. 04886) monitors a location on road no. 1 that is well known for severe local windstorms (Ágústsson and Ólafsson 2008). It is operated by Vegagerðin (The Public Roads Administration) and the data is stored and checked for systematic errors at Veðurstofa Íslands (VÍ). Observations from Kvísker and

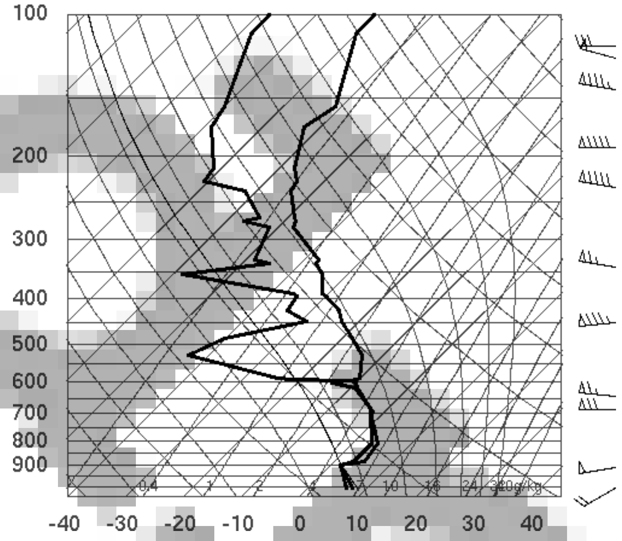

Fig. 3 Skew-T diagramme from the Keflavík upper-air station in Southwest-Iceland at 12 UTC on 18 November 2008. Shown are temperature [°C], dew point [°C] and wind barbs with temperature on the horizontal axis and height in hPa on the vertical (data provided by the University of Wyoming).

various other automatic weather stations are used for validating the atmospheric simulations.

2.4 Atmospheric simulations

The atmospheric flow is simulated with the non-hydrostatic mesoscale Advanced Research WRF-model (ARW, Skamarock et al 2005). The model is initialized and forced at its boundaries with model level data from the ECMWF operational analysis. It is run at a resolution of 9, 3 and 1 km with respectively 95x90, 205x157 and 190x175 gridpoints in the 2-way nested domains (Fig. 1). There are 40 σ-layers in the vertical, which are terrain following at lower levels but gradually flatten towards the top of the model at 50 hPa. The model is run for 6 hours before starting the nested domains which gives them approx. 10 hours of spin-up time before the time of interest. The boundary-layer parameterization uses the Mellor-Yamada-Janjic (ETA) scheme (Mellor and Yamada 1982; Janjić 2001 1994) which predicts the turbulence kinetic energy. Apart from the 1 km grid, the setup is nearly identical to that of the numerical simulations by Reiknistofa í veðurfræði (RV) which are used for operational forecasting at VÍ and published online at: "http://belgingur.is" (the HRAS-system).

3 Simulations of the windstorms

The structure of the simulated wind field in Southeast-Iceland reveals a great dependence on the horizontal resolution of the mesoscale model. There is a dramatic increase in detail in the wind field with greater horizontal resolution (Fig. 6). A wave pattern at the surface is not reproduced on the lee-side of Mt. Öræfajökull at a resolution of 9 km but appears at a resolution of 3 km. The pattern does not change much as the resolution is increased from 3 to 1 km but the lee-side winds are far stronger. In general, there is improvement in the model performance when the resolution is increased from 9 to 3 km, and to 1 km (Fig. 5). There is on average a shift of 1–2 hours in the time of start of the storm. The warming in the downslope flow is best captured at a resolution of 1 km while the model performs reasonably at 3 km but fails at a resolution of 9 km. The drying of the airmass, the decelerated lee-side flow before the start of the storm and the maximum wind speed during the storm are all reasonably captured at a resolution of 1 and 3 km but the model does much poorer at a resolution of 9 km. A comparison with observations from other automatic weather stations shows that the flow is also reasonably well reproduced at other locations in Iceland (not shown). Where applicable, scatterometer observations of sea surface winds are also in agreement with the simulated winds (not shown).

The winds at the 925 and 850 hPa levels (Fig. 7) reveal a wave pattern corresponding to that simulated at the surface (Fig. 6). There are patches of large values of turbulence kinetic energy (TKE) and weak winds downwind of Mt. Öræfajökull, in the path of the aircraft.

At all resolutions, the maximum values of simulated TKE (subgrid-scale) are in general found in the surface flow above the lee-side slopes of Mt. Öræfajökull. None or very weak turbulence is found east of the mountain at a resolution of 9 km but the turbulence is significant at a resolution of 3 km. It is found at the same locations as at 1 km where the turbulence is far stronger and more widespread (Fig. 8).

At a resolution of 1 and 3 km, section A (Fig. 9, see Fig. 6 for location of the section) along the main wind direction across Mt. Öræfajökull and over the sea reveals a series of large amplitude waves with large values of TKE in the region of strong wind shear below the waves and near the surface. No lee wave or only a small amplitude wave is simulated at a resolution of 9 km. The strongest winds and highest values of TKE are simulated at 1 km in the descending part of the first wave, above the slopes of the mountain, while the winds are weaker further downstream. There is strongly decelerated flow and a blocking at the upstream side of the mountain at a resolution of 3 and 1 km but this effect is far weaker at 9 km. A horizontal rotor with positive vorticity and reversed surface flow is simulated underneath the first wave, both at a resolution of 3 and 1 km. However, the wave pattern is not stationary and the waves become less steep and the turbulence increases from 16 UTC to 19 UTC (Fig. 9).

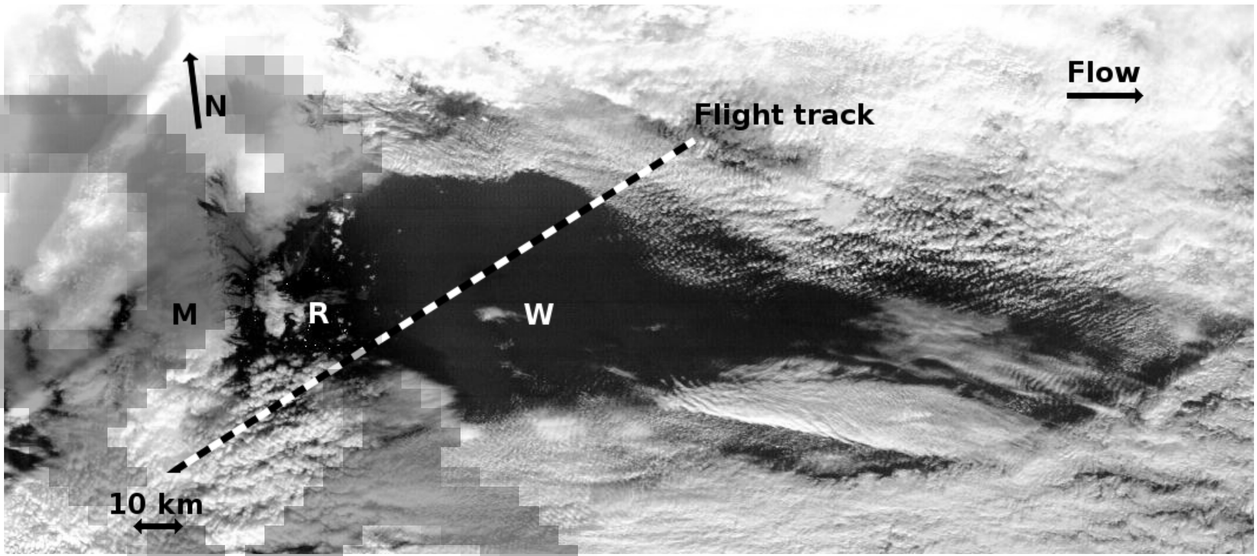

Fig. 4 MODIS-image (visible light) from the Terra satellite showing the part of Southeast-Iceland near Kvísker at 12:35 UTC on 18 November 2008. Also shown are the locations of Mt. Öræfajökull (M), the rotor cloud (R), a wave cloud (W), the approximate flight track and the flow direction. Kvísker is located below the rotor cloud.

4 Discussion

4.1 Atmospheric simulations

The atmospheric simulations reveal an impressive large amplitude lee wave and a rotor in westerly flow of the coast of Southeast-Iceland. There is strongly accelerated flow in the descending part of the first wave above Kvísker and a boundary layer separation occurs at the lowermost point of the wave. There are large values of TKE in the region of strong wind shear underneath the wave and at the rotor boundary. The turbulence incident occured when the aircraft flew through or near the upper part of this wave and the rotor.

Apart from the turbulence incident, there are no other direct observations aloft that verify the structure of the simulated train of lee waves, the rotor and the magnitude of the turbulence. However, satellite images show further evidence of the rotor and gravity wave activitity, i.e. the cap cloud over the mountain, the rotor cloud immediately downstream of the lee slopes and the cloud free region to the east of the mountain with the possibility of a single lenticular cloud topping the second lee wave (Fig. 4). Furthermore, the observations of the downslope windstorm at Kvísker, i.e. the sudden increase of wind speed as well as the warming and drying of the air are a manifestation of the gravity wave induced downslope windstorm above the slopes of Mt. Öræfajökull and they are in agreement with the results of the atmospheric simulations. The synoptic flow, as well as the wind and temperature profiles of the impinging flow are characteristic for westerly downslope windstorms of Type S (short downslope extent) at Kvísker with large amplitude gravity waves embedded in the turbulent flow of Southeast-Iceland (Ágústsson and Ólafsson 2009).

The fast flow near mountain top level is necessary for the generation of the wave and the strong forward wind shear and slight decrease in atmospheric stability facilitate the vertical propagation of the wave energy. The wave energy is at least partially reflected downwards at upper levels and upwards at the surface without excessive attenuation of the wave energy in the boundary layer. This contributes to the creation of the trapped lee waves and to their amplification. In fact, previous research on the interaction of lee waves and boundary layers (Jiang et al 2006; Smith et al 2006) indicates that long lee wave trains are more likely to occur over smooth oceans than rougher surfaces. Surface heating has the same effect but is presumably not relevant for lee wave absorption over the ocean as is the case here. However, surface heating over the lee slopes of Mt. Öræfajökull may increase the vertical extent of the rotors and decrease the distance to the downstream separation point as is discussed in Doyle and Durran (2002). Low and non-zero surface roughness has the same effect as the surface heating, causing a decrease in the wave drag and a possible weakening of the reverse flow in the rotor. The simulated gravity waves are not stationary and there is significant development in the rotor and turbulence during the windstorm. The upstream wind shear increases with time while the lee wave amplitude decreases and the turbulence in the rotor increases and becomes more widespread. The modifications of the lee side flow can not be explained by variations in the surface roughness but weaker surface heating in the late afternoon may contribute to the downstream propagation of the separation point and decrease in the vertical extent of the rotor.

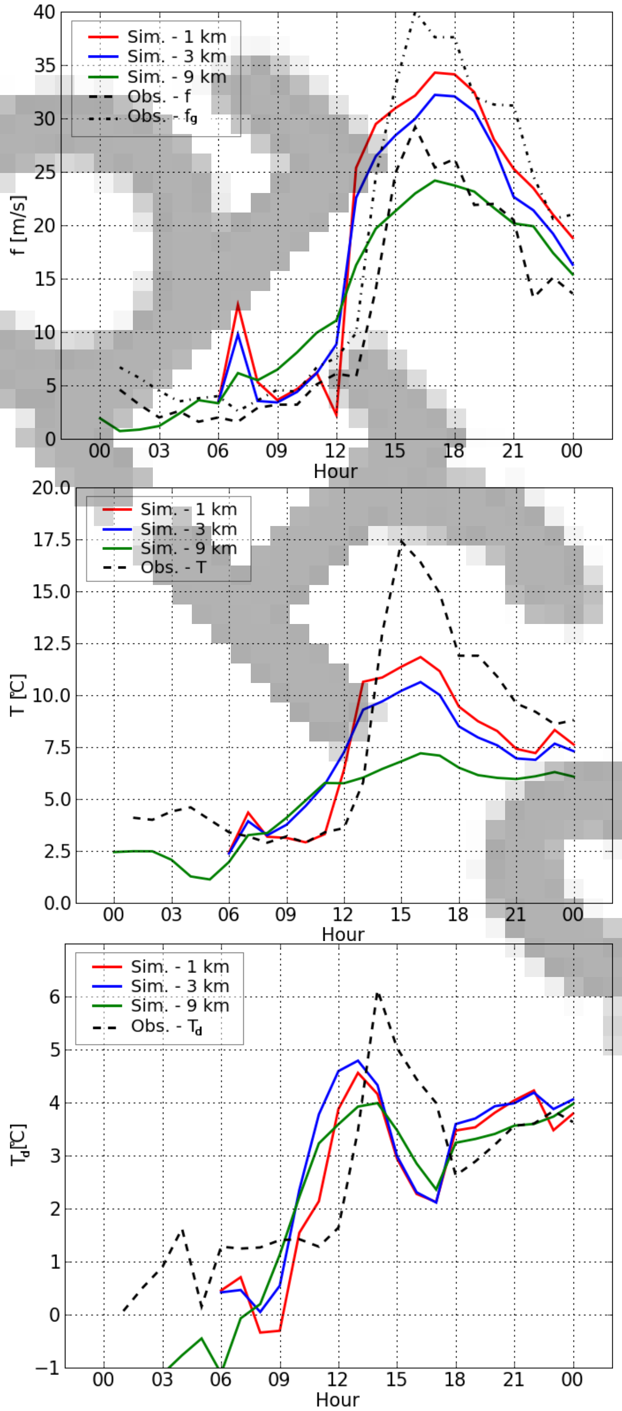

Fig. 5 Observed and simulated 10-minute wind speed at a resolution of 9, 3 and 1 km, f, and 3-second wind gusts, f_g, [m/s] (top) as well as temperature, t [°C] (centre), and dew point, t_d [°C] (bottom) at the Kvísker automatic station during 18 November 2008.

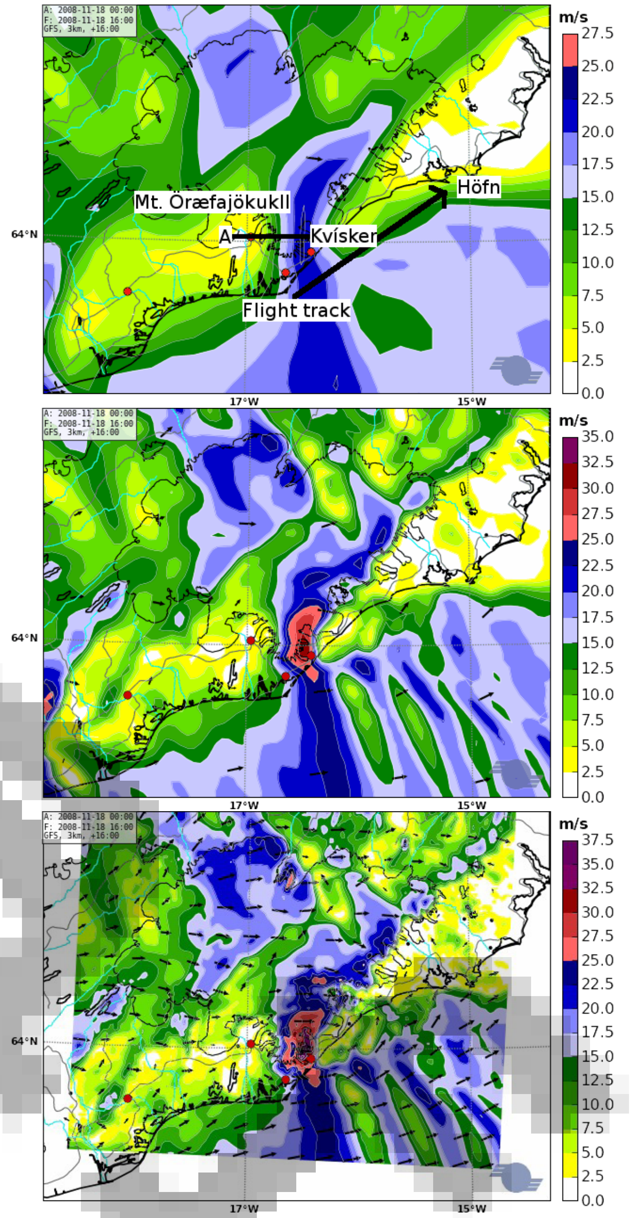

Fig. 6 Wind speed [m/s] and wind arrows at a horizontal resolution of 9 (top), 3 (centre), and 1 km (bottom) at 16 UTC on 18 November 2008. Also shown are the coast and glacier outlines and the locations of Kvísker, Höfn and Mt. Öræfajökull as well as the approximate track of the aircraft and the location of section A across Mt. Öræfajökull.

It does however not explain the increase in simulated turbulence and apparent weakening of the reversed flow in the rotor (Doyle and Durran 2002). The two-dimensional idealized studies of Nance and Durran (1997 1998) indicate that nonlinear effects may be more important to the nonstationarity of the trapped lee waves than changes in the mean background flow. There is a further contribution to the generation of the wave and the rotor by the strong inversion near mountain top level and the forward wind shear through it, capping the relatively shallow but well mixed boundary layer (Vosper 2004; Hertenstein and Kuettner 2005).

Compared to the observations, there is a forward shift on the order of 1–2 hours in the onset of the simulated windstorm at Kvísker. This shift is similar in magnitude at all resolutions which indicates that it may be related to slight errors in the boundary conditions forcing the atmospheric model. However, previous studies of downslope windstorms

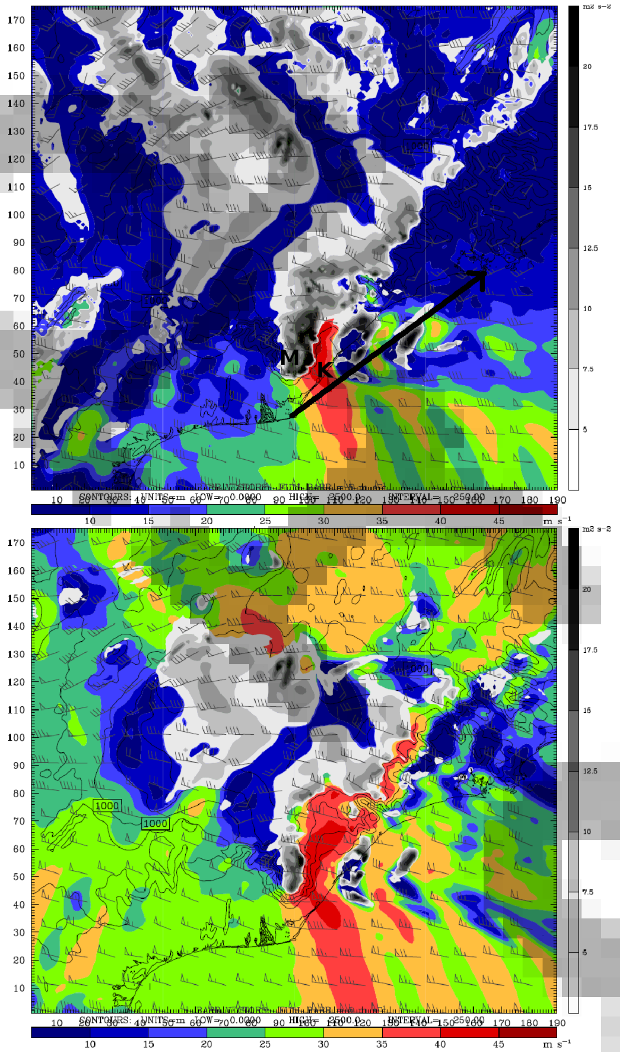

Fig. 7 Wind speed [m/s], wind barbs and turbulence kinetic energy [J/kg] at a horizontal resolution of 1 km at 925 hPa (above) and 850 hPa (below) at 16 UTC on 18 November 2008. Also shown are terrain contours with an interval of 250 m and the locations of Kvísker (K) and Mt. Öræfajökull (M) as well as the approximate track of the aircraft.

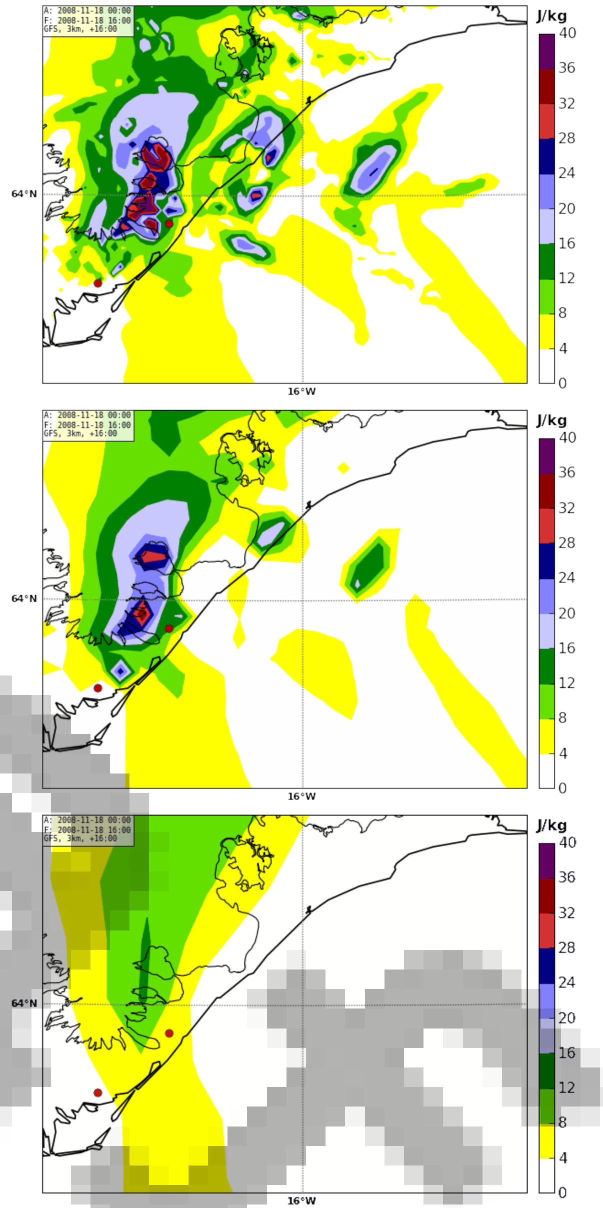

Fig. 8 Maximum values of turbulence kinetic energy [J/kg] at a horizontal resolution of 1 km (top), 3 km (centre) and 9 km (bottom) at 16 UTC on 18 November 2008. Also shown is the coastline and glacier outlines.

in Iceland (Ágústsson and Ólafsson 2007 2009) indicate that the error may also be due to an error in the horizontal extent of the windstorm which in this case increases too fast in the model, e.g. due to small errors in the development of the upstream conditions. In other words: it is possible that the timing of the onset of the downslope storm is correctly captured but that it was in reality limited to the upper slopes above Kvísker during the early hours of the storm and the simulation overestimated the speed which the windstorms propagated downstream. This is supported by the satellite image (Fig. 4) which shows evidence of significant gravity wave activity before the onset of the observed windstorm at Kvísker. Furthermore, recent studies of ensembles of simulations of downslope windstorms show a significant sensitivity to small scale features in the initial conditions (Reinecke and Durran 2009). The sensitivity depends on the synoptic-scale flow and it is not clear what aspects of the flow have the greatest impact on the predictability of the downslope windstorms.

Locally, the highest values of subgrid-TKE are found in a shallow layer in the descending flow over the lee-slopes of the mountain and are on the order of 40 J/kg in the 1 km mesh at 16 UTC. This turbulence and the embedded positive vorticity due to forward wind shear near the surface are carried upwards at the separation point and into the rotor circulation as discussed in Doyle and Durran (2002). The observed gustiness at Kvísker is a manifestation of the tur-

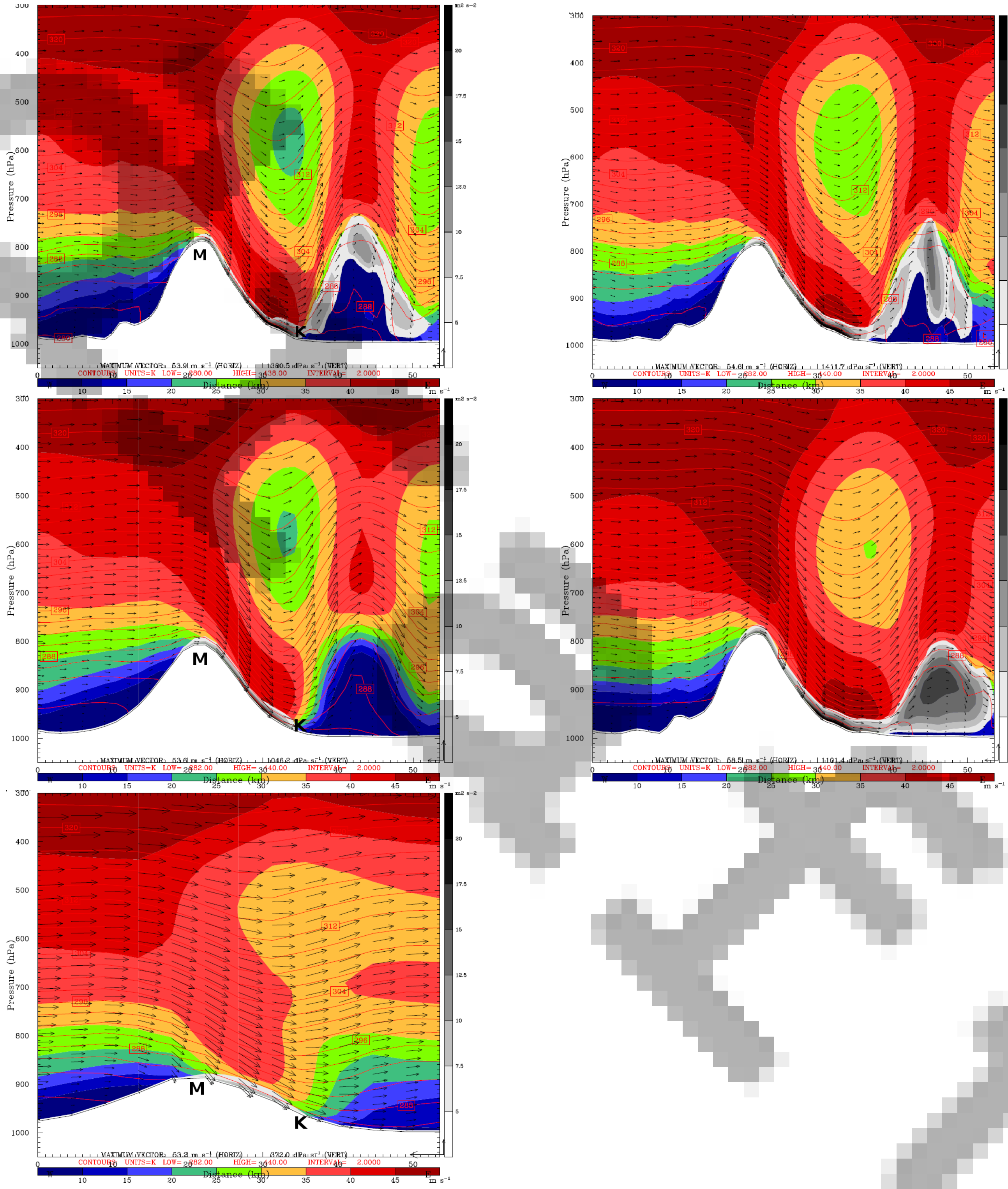

Fig. 9 Wind speed [m/s], wind arrows, turbulence kinetic energy [J/kg] and isolines of potential temperature [K] at a horizontal resolution of 1 km (top left and right), 3 km (centre left) and 9 km (bottom left) along section A at 16 UTC (left), 17 UTC (top right) and 19 UTC (bottom right) on 18 November 2008. Also shown is orography and the locations of Kvísker (K) and Mt. Öræfajökull (M). See Fig. 6 for the location of the section.

bulence over the lee-slope while the gust factor is not as high as might be expected, i.e. $f_g/f \approx 1.3-1.5$, from the proximity to Mt. Öræfajökull (Ágústsson and Ólafsson 2004). The total vertically integrated TKE is greatest in the lee wave rotor and is nearly 10 times as great as the maximum value, i.e. 400 J/kg at a resolution of 1 km at 16 UTC (not shown).

These values of TKE are approx. 25% lower at a resolution of 3 km while the values at 9 km are only 10% of the values at 1 km. In spite of the improvement in the simulations of the flow, it may be argued that a part of the subgrid-TKE at a resolution of 1 km is in fact also explicitly resolved by the atmospheric model and the boundary layer scheme (e.g. Deng and Stauffer 2006). The experience with this particular setup of the atmospheric model (ARW) is that this is not the case for resolutions near 1 km while it is however not clear what happens at higher resolutions, as is discussed for the MM5-model (Grell et al 1995) in Ágústsson and Ólafsson (2007).

The rotor is of Type 1 as classified by Hertenstein and Kuettner (2005) and this is in agreement with the wind and temperature profiles in the boundary layer and through the inversion (Fig. 10). However, the maximum TKE values in the rotor in the current study are 2–3 greater than in the idealized study of Hertenstein and Kuettner (2005) where the maximum TKE values were near 10 J/kg. From Fig. 10 it appears that relatively small changes in wind speed and shear in the impinging flow are needed to shift the rotor in the current study towards and even over the separation line between rotors of Type 1 associated with lee waves towards rotors of Type 2 which are associated with hydraulic jumps.

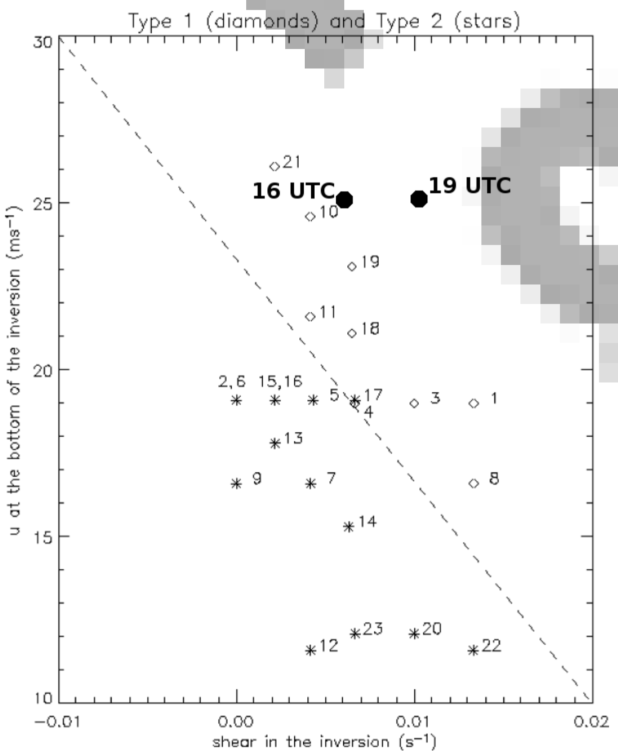

Fig. 10 Reproduced from Hertenstein and Kuettner (2005, Fig. 16) showing a scatter plot with initial flow at bottom of the inversion vs. initial shear through the inversion and resulting rotors of Type 1 (diamonds) and Type 2 (stars). The location of the rotor in the current study is indicated with black circles.

The turbulence in rotors of Type 2 appears to be more intense and transient than of in rotors of Type 1 (Hertenstein and Kuettner 2005) and it may be postulated that had the aircraft flown through a Type 2 rotor it could have had more serious consequences than was the case. The previous study of the Kvísker windstorms (Ágústsson and Ólafsson 2009) indicates that the westerly windstorms of Type S are gravity wave generated while it does however not exclude the possibility of westerly windstorms associated with hydraulic jumps, which may indeed possibly develop from overturning amplified lee waves as suggested by Vosper (2004). Furthermore and as is discussed in Ágústsson and Ólafsson (2009), the northerly downslope windstorms of Type E (extended downslope windstorm) at Kvísker are of this latter hydraulic kind and they may, in spite of no current observations of an associated rotor of Type 2, be more hazardous to aviation than the gravity wave generated windstorms in westerly flow.

4.2 Forecasting perspective

The quality of the atmospheric simulation is strongly correlated with the horizontal resolution of the model. At a resolution of 9 km the wave activity is badly captured and only a very weak windstorm is simulated at Kvísker. This resolution is approx. 2–3 times finer than the current resolution of the highest resolution global forecasts. At both the meso- and synoptic scale, the current aviation forecasts are based on numerical models with a resolution that is not adequate at forecasting turbulence in the lower troposphere above orographic regions as in this case or near the tropopause level as in the cases of Doyle et al (2005) and Ólafsson and Ágústsson (2009) in respectively southwesterly and easterly flow over Greenland. Also, amplification of gravity waves, overturning and breaking, as well as trapped lee waves are non-hydrostatic phenomena that can not be represented correctly in hydrostatic models. There are relatively few operational forecasts based on non-hydrostatic mesoscale models running at an adequate resolution and the only such system available for local forecasts in Iceland is the operational HRAS-system of RV. This system correctly simulated the wave activity and forecasted the resulting downslope windstorm at Kvísker at a resolution of 3 km, both with the WRF-model as well as the MM5-model (Grell et al 1995). This forecast was unfortunantly not taken into account and consequently, no SIGMET was issued for the region until after the turbulence incident. Although the full 4-dimensional structure of the atmosphere is forecasted in the HRAS-system there is at the moment no dissemination of the structure of the flow aloft over Iceland. In addition to forecasts of the surface flow, direct forecasts of e.g. of wind, turbulence and icing at the domestic (and the international) flight level might have been of further value to the pilots and the forecasters. In addition to making products from higher resolution aviation forecasts available, additional information could be made available to the forecasters. For example by classifying flow over complex terrain, e.g. above Mt. Öræfajökull, with the methods Feltz et al (2009) used to classify flow and gravity wave activity over the Rocky mountains. Satellite images are now available at a reasonable temporal resolution and they may be used in connection with long time series of climate simulations of weather in Iceland that are available at high horizontal and temporal resolution.

5 Summary and concluding remarks

This paper describes observations of severe turbulence in the lower troposphere in an amplified lee wave and a horizontal rotor in westerly flow of Southeast-Iceland. The turbulence, the lee waves and the rotor are reproduced in a numerical model, as well as a gravity wave generated downslope windstorm at Kvísker. We have a Type 1 rotor as classified by Hertenstein and Kuettner (2005), which is in agreement with the vertical profile of wind and temperature. There is strong shear-turbulence in the lee wave, at the wave and rotor interface, as well as inside the rotor. The waves are not stationary and it appears that relatively little changes to the mean flow could result in the development of a hydraulic jump and a rotor of Type 2 which contains stronger turbulence and is more dangerous to aviation than rotors of Type 1. Furthermore, it should be noted that the current resolution of the atmospheric model is not adequate for reproducing possible subrotors which may be even more hazardous to aviation than the simulated main rotor of Type 1 (Doyle and Durran 2007).

Observations of severe turbulence aloft are relatively rare but when they occur they provide important occasions to verify the performance of the atmospheric models. These observations also provide valuable tests of the gravity wave and rotor theory which has in many cases been tested and studied for idealized orography but less for real cases. However, intensive observations campaigns such as the T-REX (Grubišić et al 2008) have significantly improved the available data sets. Systematic three-dimensional observations at high temporal resolution would however be invaluable. The MABLA-experiment (Monitoring the Atmospheric Boundary Layer in the Artic) will adress this and is being prepared at Gufuskálar in West-Iceland where anemometers will be fitted to a 400 m high mast (Ólafsson et al 2009).

As is often 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 currently used in aviation forecasts. Their resolution is not adequate and is typically of the order of 10 to 30 km or even coarser. Previously, Ólafsson and Ágústsson (2009) showed that fine-scale simulations over complex terrain can successfully predict mountain wave induced turbulence near the tropopause level and consequently they may aid in avoiding turbulence incidents at the international flight levels. This event underlines the urgency of delivering such high-resolution products to pilots, for aviation needs in the lower troposphere where atmospheric turbulence may be most intense and most hazardous to aviation.

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The bimodal downslope windstorms at Kvísker

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Abstract Downslope windstorms at Kvísker in Southeast-Iceland are explored using a mesoscale model, observations and numerical analysis of the atmosphere. Two different types of gravity-wave induced windstorms are identified. 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 northerly flow and is not confined to the lee-slopes but continues some distance downstream of the mountain. 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 to the year 2050.

1 Introduction

Severe orographic windstorms are frequent in many places throughout the world. Many of these have been studied and described in the scientific literature but perhaps the best known are the celebrated Boulder windstorms in Colorado (e.g. Clark et al 1994) where the gusts have been reported to exceed twice the mean wind of nearly 25 m/s (see f. inst. a review by Durran 1990). The Bora-windstorms at the Adriatic coast of Croatia have also been extensively studied (see the recent review by Grisogono and Belušić 2009) and are in fact reminiscent of the Freysnes windstorms, 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, gusts are on average 160% of the mean 10-minute wind speed downstream of high mountains if 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 of the 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 and this has for example been attempted by Goyette et al (e.g. 2003) and Ágústsson and Ólafsson (2009) for windstorms in complex terrain by using a mesoscale model and a method based on Brasseur (2001). Brasseur's method is partly based on a quantification of turbulence in the atmospheric boundary layer and systematic observations of the turbulence are needed to verify this method and atmospheric models in general, but these are unfortunantly not widely available. There are however reported cases of strong turbulence aloft, for example in flow above Greenland (e.g. Doyle et al 2005; Ólafsson and Ágústsson 2009) that Lane et al (2009) have recently studied in a systematic manner to identify flow regimes that contribute to unstable gravity waves and turbulence aloft. Then there are the large observational campaigns such as Grubišić et al (2008); Renfrew et al (2008) but these are limited in time and space. Durran (1990) provides a nice review on the theory and literature related to gravity waves and downslope windstorms while some of the more recent studies on atmospheric flow in complex terrain are reviewed in Smith (2004).

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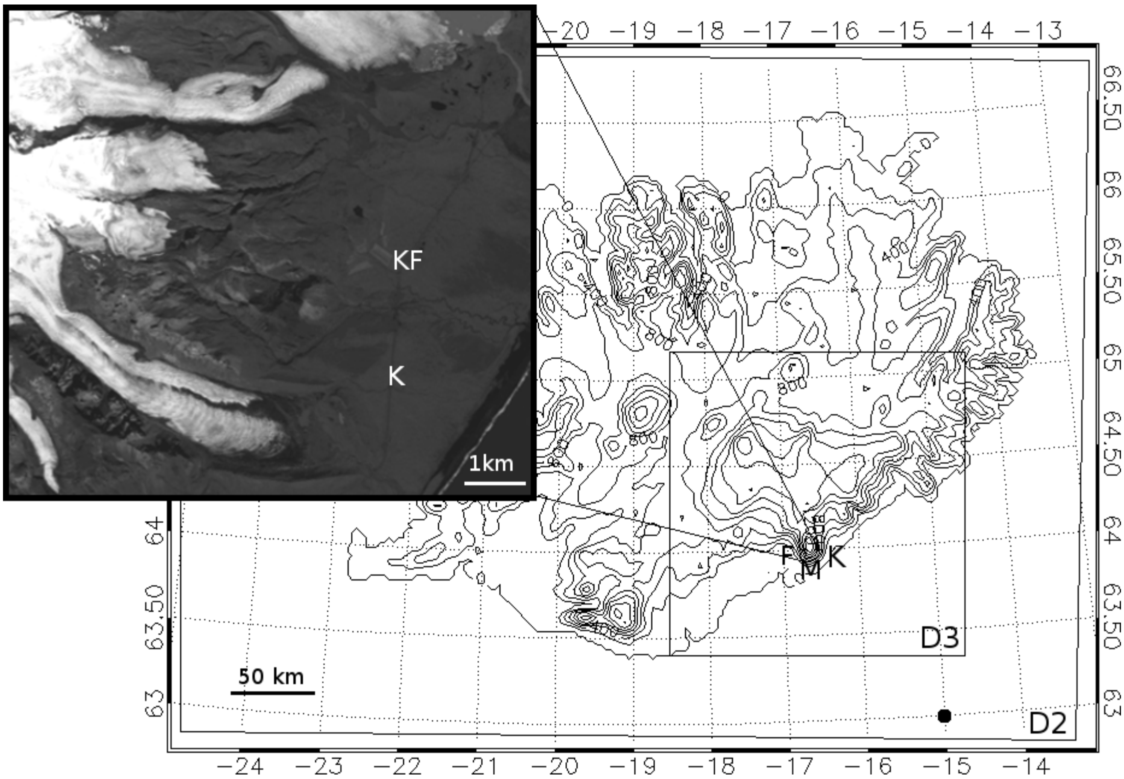

Fig. 1 The location of the farm at Kvísker (KF), the Kvísker weather station (K), the farm at Freysnes (F), Mt. Öræfajökull (M) and the numerical domains with a horizontal resolution of 3 (D2) and 1 km (D1). Terrain contours with an interval of 200 m. The location 63°N 15°W is marked with a black circle.

Orographic windstorms are common in Iceland and they often disrupt transportation on land and in the air as well as causing damage to property and infrastructure. In general, the worst storms occur during winter when winds are locally enhanced by orography during the passage of deep cyclonic systems. There are many such infamous places in Iceland and the recent effort in studies of local severe winds has revealed that the studied windstorms are all related to gravity wave activity aloft. Some of the first studies of the still ongoing SNEX-project focused on windstorms on both sides of the Snæfellsnes peninsula in West-Iceland (e.g. Ólafsson et al 2002) while the study of Ágústsson and Ólafsson (2007) focused on an extreme windstorm and breaking waves aloft in northeasterly flow over Northwest-Iceland. Here we turn our attention towards Kvísker in Southeast-Iceland on the eastern flank of Mount Öræfajökull (Fig. 1), where strong and gusty winds result in road closures and may even cause damage to the asphalt on the road. The easterly Freysnes downslope windstorms, named after the nearby farm at Freysnes in Öræfi on the western side of Mt. Öræfajökull, were the subject of previous studies (Ólafsson and Ágústsson 2007; Rögnvaldsson et al 2007). The Freysnes downslope windstorm may be characterized as a warm version of the Croatian Bora. It occurs in an environment of gravity waves in a stably stratified flow, below a negative vertical windshear. The frequency of the Freysnes windstorms showed no clear trend during the latter half of the 20th Century. In this paper, the Kvísker windstorms are explored in a similar manner, i.e. using observations from automatic weather stations that have been erected to monitor the windstorms and numerical analysis of the atmosphere. In addition, possible changes in windstorm frequency are investigated using future projections of the wind climate.

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

2 Atmospheric data

2.1 Observational data

At Kvísker (Fig. 1), there is an automatic weather station (WMO no. 04886), that was erected in 2002 to monitor the severe local windstorms. The weather station is located close to road no. 1 at 30 m.a.s.l. immediately east of Mt. Öræfajökull (2110 m). The observational data includes the 10-

minute mean wind and 3-second gusts at approx. 7 m above ground level. The station is operated by Vegagerðin (The Public Roads administration) and the data is stored at Veðurstofa Íslands (VÍ) where it has been checked for systematic errors. Additionally, data from various other automatic weather stations in Iceland are used for validating the simulations of the windstorms.

2.2 Atmospheric simulations

The windstorms are simulated with the non-hydrostatic mesoscale model, MM5 (Grell et al 1995). The model is initialized and forced at its boundaries with data from the ECMWF. It is run at a resolution of 9, 3 and 1 km with respectively 90x95, 148x196 and 160x190 gridpoints in the 1-way nested domains (Fig. 1). There are 40 σ-layers in the vertical, which are terrain following at lower levels but gradually flatten towards the top of the model at 50 hPa.

The relevant parameterization are the moisture scheme of Reisner et al (1998) which includes cloud and rain water, as well as simple and mixed ice phases. The ETA scheme (Janjić 1990 1994) is used for boundary-layer parameterizations as it predicts the turbulent kinetic energy. Model specifics are discussed in extensive detail in (Grell et al 1995). Apart from the innermost domain (1 km) the setup of the atmospheric model is the same as Reiknistofa í veðurfræði employs for high-resolution, realtime simulation of weather in Iceland and is published online at: “http://belgingur.is” and is used in operational forecasting at e.g. VÍ.

2.3 Atmospheric analysis and climate projections

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

To investigate the possible future wind climate at Kvísker we look at results from the downscaling of the climate projections of the Bjerknes Climate Model by the HIRHAM-model of the Norwegian Meteorological Office (METNO) which is a part of the ENSEMBLES-project (Hewitt and Griggs 2004). The model is run at 25 km using the A1B-scenario for the climate runs from 1950 to 2050 while the control run is performed using the ERA-dataset. As for the ECMWF-analysis, we extract the zonal and meridional wind components at 63°N 15°W on the 500 and the 850 hPa levels.

3 Analysis of the windstorms

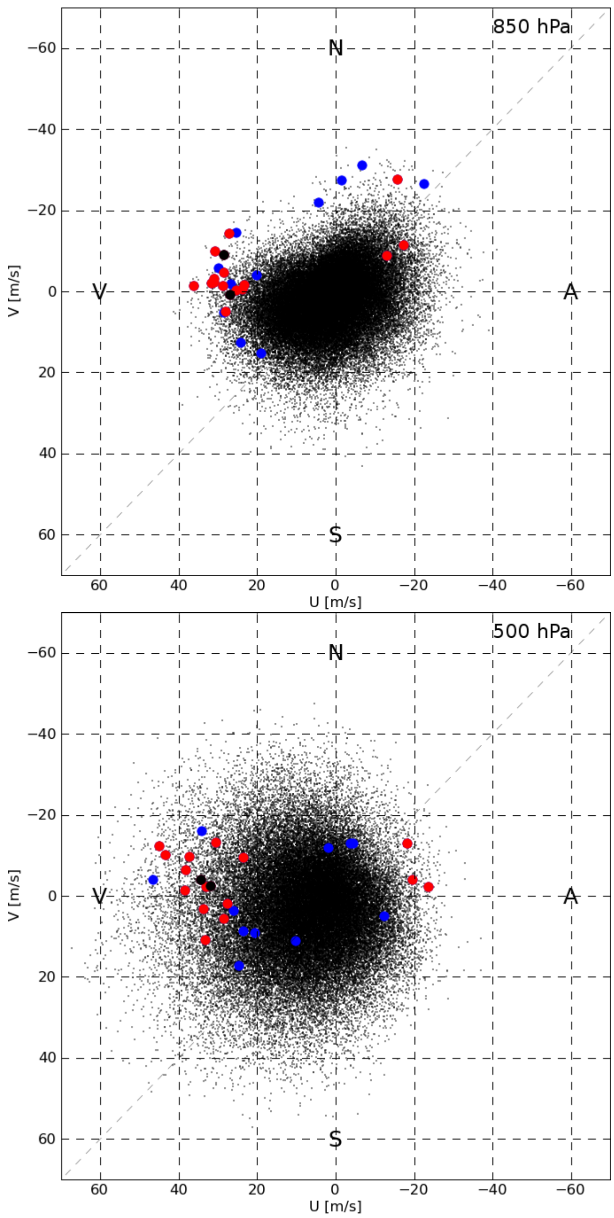

Fig. 2 Zonal and meridional wind components at 63°N 15°W at 850 (above) and 500 hPa (below) in the ECMWF-analysis (1967–2007) at 6 hour intervals. Blue, red and black dots correspond to observations of gusts at Kvísker exceeding 35, 40 and 50 m/s, respectively. The axes are reversed so the labelled wind direction correspond to the direction the wind blows from.

The hourly observational data includes a large collection of westerly and northeasterly windstorms at Kvísker, with 102, 52 and 2 observations of gusts exceeding respectively 35, 40 and 50 m/s during the period 2002-2007. The variability in observed wind directions during the windstorms begs for a further investigation of the windstorms (Fig. 2). The zonal and meridional wind components in the ECMWF-analysis at the 500 and 850 hPa levels reveal two very different classes of atmospheric states when windstorms ($f_g >$ 35 m/s) occur at Kvísker (Fig. 2). The first type of windstorms, here denoted as “Type S”, are characterized by strong westerly winds throughout the troposphere with a forward wind shear. This is also shown in Fig. 3 for a subset of

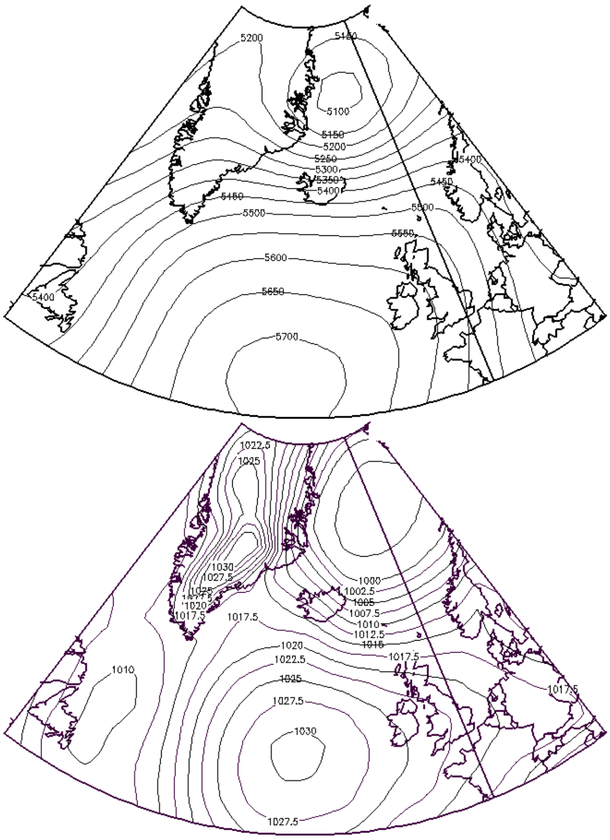

Fig. 3 Mean geopotential [m] and sea level pressure [hPa] at Kvísker during westerly windstorms when observed gusts at Kvísker exceed 40 m/s (analysis from NOAA/CDC).

the storms with gusts exceeding 40 m/s where there is on average at all tropospheric levels a low-pressure region to the north of Iceland and high pressure to the south. These westerly windstorms are more common and severe than the northerly storms with the observed gusts exceeding 50 m/s, e.g. in the morning of 25 January 2007 (Fig. 4). The mean wind speed during this windstorm was as high as 36 m/s but the windstorm was relatively short and lasted only for approximately 12 hours.

The northerly windstorms, classified as “Type E”, are in general not as strong as the westerly windstorms and they are characterized by strong northerly winds at lower levels and a reverse and a directional vertical wind shear with slightly weaker and more easterly winds aloft. On average there is a surface high over Greenland and a low to the Southeast of Iceland giving rise to a strong SE-NW oriented surface pressure gradient. Aloft there is a N-S oriented through above East-Iceland with the jet to the west and south of Iceland (Fig. 5).

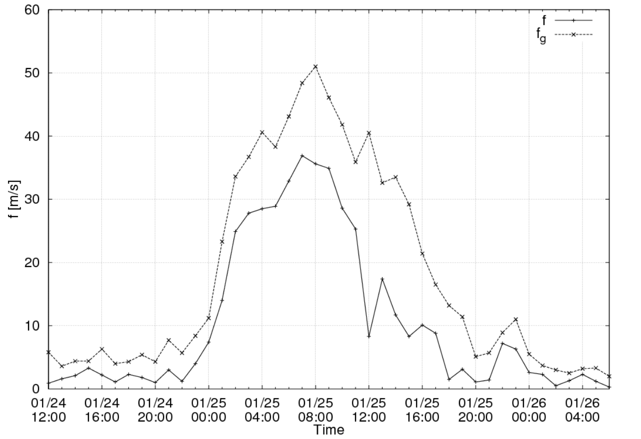

Fig. 4 Observations at Kvísker of mean winds, f [m/s], and gusts, f_g [m/s], during the windstorm of 25 January 2007.

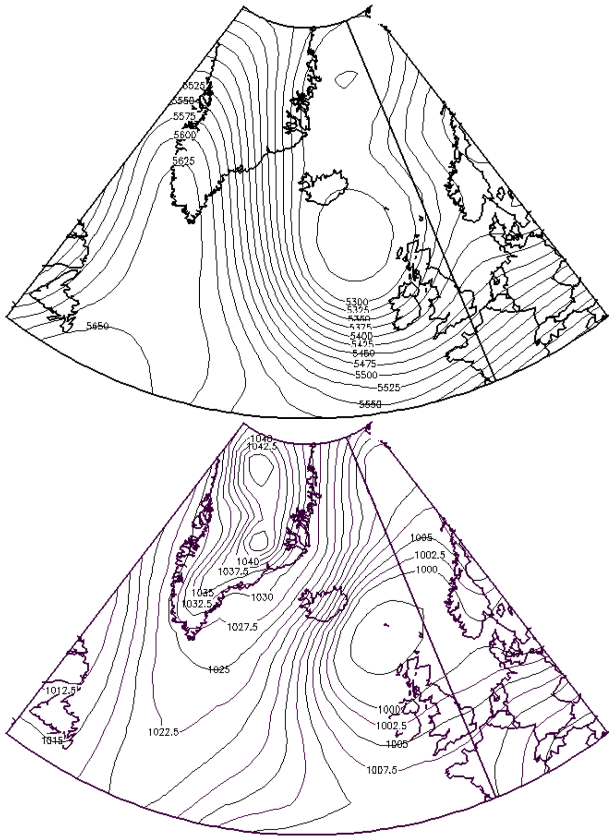

Fig. 5 Mean geopotential [m] and sea level pressure [hPa] at Kvísker during northerly windstorms when observed gusts at Kvísker exceed 40 m/s (analysis from NOAA/CDC).

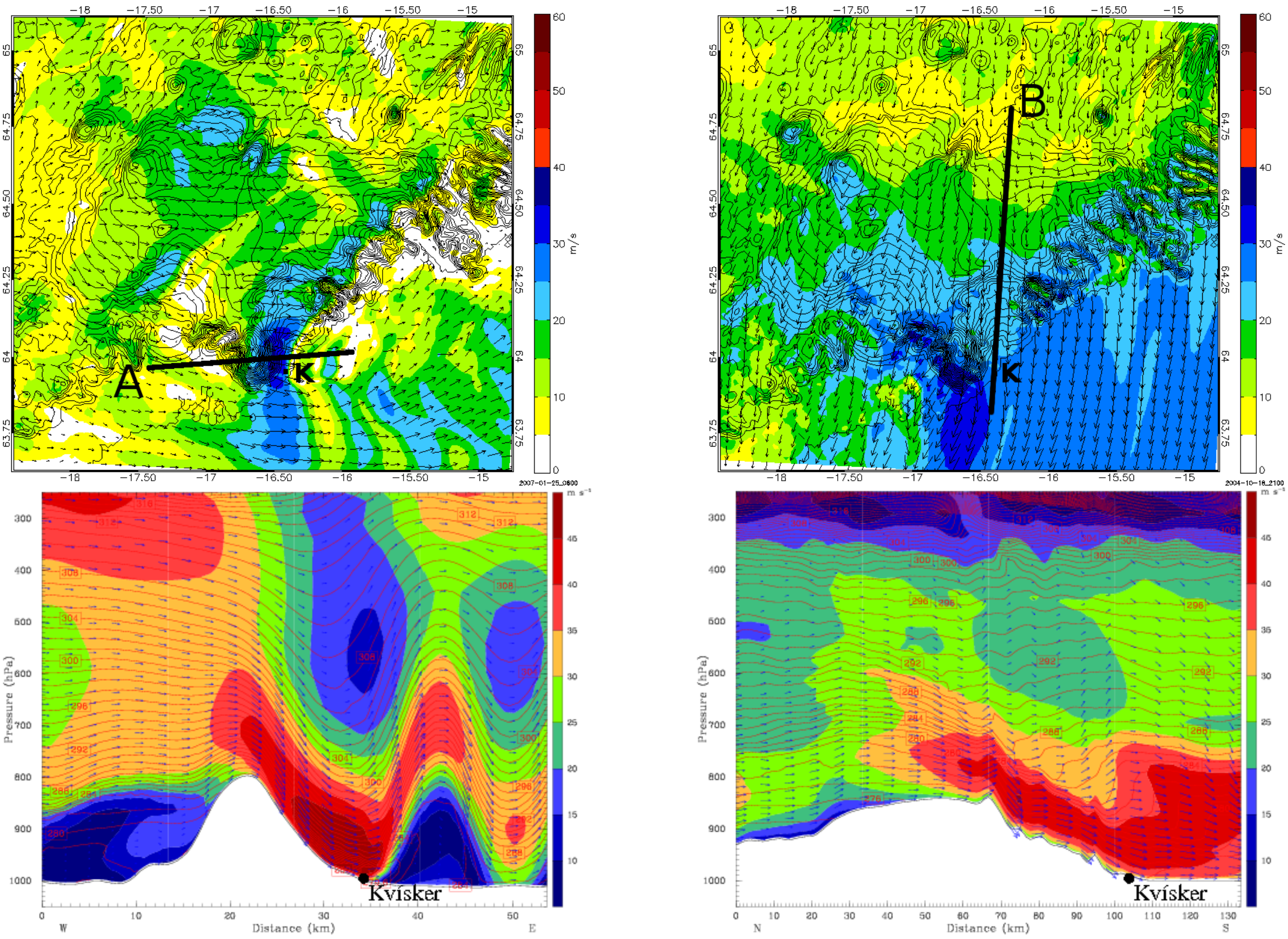

Fig. 6 Surface wind speed [m/s] and vectors, as well as terrain contours with a 100 m interval (above) and wind speed [m/s] and potential temperature [K] in sections A and B (below) at a resolution of 1 km at 06 UTC on 25 January 2007 (left) and at 21 UTC 18 October 2004 (right). Also shown is the location of Kvísker and sections A and B.

4 Simulations of the windstorms

Simulations of the strongest northerly windstorm (Type E) on 18 October 2004 show strong winds in a large area over the lee-slopes and downstream of the mountains, including Kvísker (Fig. 6). Above the lee-slopes along section B, the flow descends and accelerates until it reaches a feature similar to a hydraulic jump slightly downstream of the mountain. Here there are large values of widespread turbulence kinetic energy (TKE, not shown).

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

Observations from automatic weather stations and satellite derived sea surface winds verify the structure of the simulated large scale surface flow (not shown). The simulated structure of the wind field is more realistic as the horizontal resolution is increased from 9 km to 3 km to 1 km and the winds are in general in better agreement with the observations (not shown). The observed winds at Kvísker during the northerly windstorm of 18 October 2004 are well captured at a resolution 3 and 1 km (Fig. 7). The performance is poorer during the westerly windstorm of 25 January 2007 as the simulated wind speed oscillates from 4 m/s to 27 m/s in the early hours of the windstorm. The observed gusts are predicted at Kvísker (Fig. 8) using the same method as in

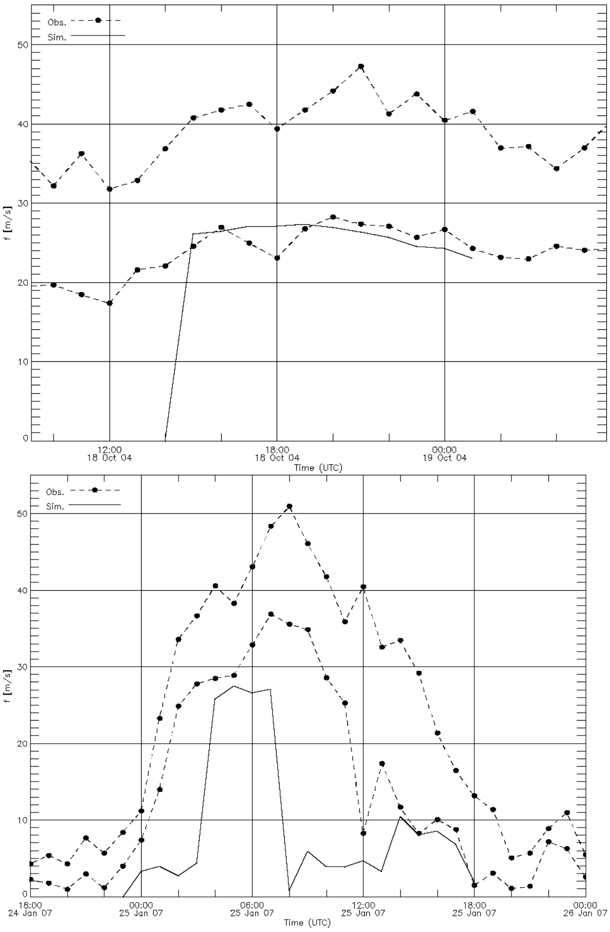

Fig. 7 Predicted wind speed at a resolution of 1 km and observed wind speed and gusts [m/s] at Kvísker during the windstorm of 18 October 2004 (below) and 25 January 2007 (above).

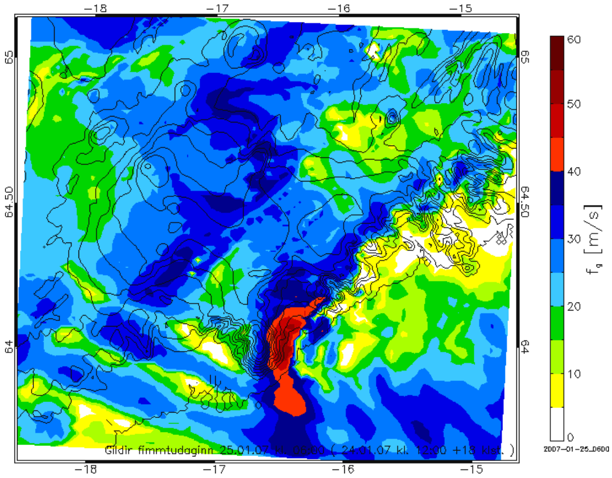

Fig. 8 Predicted gust strength [m/s] and 100 m terrain contours at a resolution of 1 km at 06 UTC on 25 January 2007.

Ágústsson and Ólafsson (2009) which is based on Brasseur (2001).

5 Past and future windstorm climate

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

The annual cycle (Fig. 10) of westerly windstorms at 500 hPa is characterized by the very few occurences of strong winds during the summer months, i.e. may–august. The set of observed windstorms is relatively small (same as in Fig. 2) but corresponds reasonably to the strongest westerly winds during the winter months. The peak in October is related to a single, long, event. On an annual basis there are strong variations in the strength of the westerlies (Fig. 9).

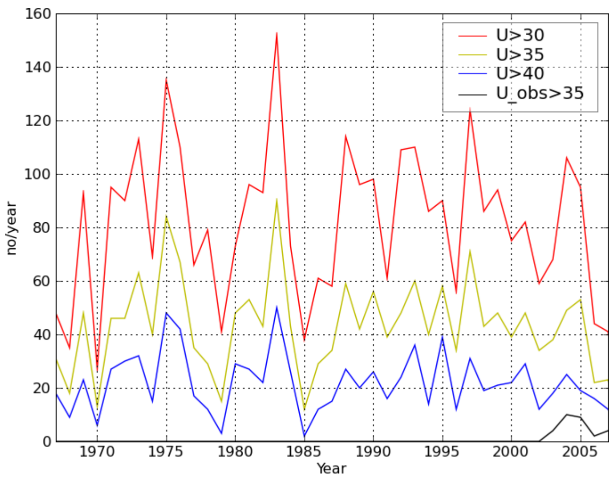

Fig. 9 Number of cases of westerly winds per year greater than 30, 35 and 40 m/s at 500 hPa at 63°N 15°W in the ECMWF-analysis (1967–2007) at 6 hour intervals. Also shown are the total number of observed windstorms per year observed at Kvísker.

The ECMWF-analysis at 63°N 15°W compares on average reasonably with the control simulation of the climate model forced by the ECMWF-analysis except for fewer occurences of strong southwesterly winds at 500 hPa and weaker south- and southwesterlies at 850 hPa in the climate model (not shown). However, the climate projections with the A1B-scenario produce somewhat weaker northerly and southerly winds and far too weak westerly winds at 500 hPa compared to the ECMWF-forced control run. At the 850 hPa level

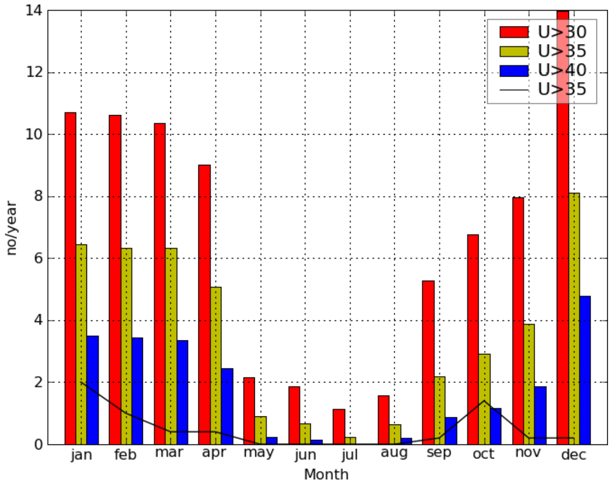

Fig. 10 Number of cases of westerly winds per month greater than 30, 35 and 40 m/s at 500 hPa at 63°N 15°W in the ECMWF-analysis (1967–2007) at 6 hour intervals. Also shown are the total number of observed windstorms per year observed at Kvísker.

the westerlies are far too weak and the easterlies slightly to strong in the A1B-scenario. These results are summarized in Fig. 11.

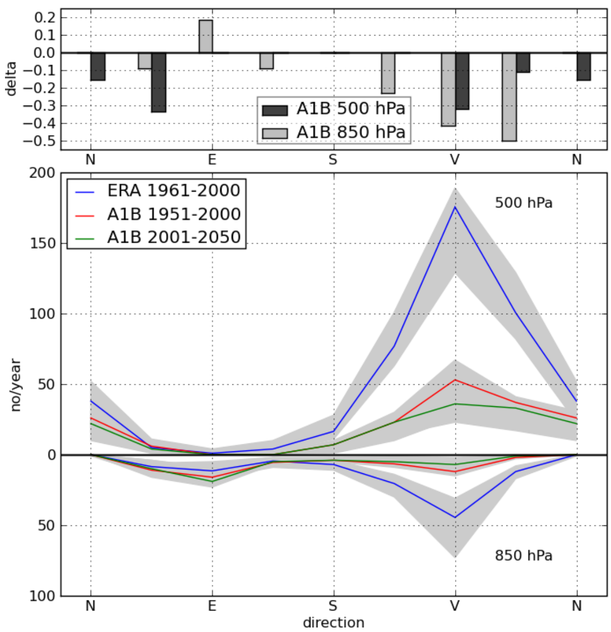

Fig. 11 Number of cases per year with winds greater than 20 m/s in the climate projections and the control simulation, as well as the change in frequency from 1951–2000 to 2001-2050. Data is from the 850 and 500 hPa levels at 63°N 15°W and the shaded region includes the two quartiles around the median.

6 Discussion

The atmospheric data presented here reveals a bimodal nature of the Kvísker downslope windstorms. The spectacular gravity wave induced windstorms are characterized by different vertical and horizontal structures of the atmospheric flow. The stronger of the two types are the westerly windstorms of Type S which are very localized and limited to the lee-side slopes of Mt. Öræfajökull. The flow aloft is characterized by a train of large amplitude lee waves. The airmass is of southern origin and it has been cooled from below on its way north. It has only a shallow boundary layer whose mixing is presumably due to strong winds. There is an inversion near mountain top level. The sounding at Keflavík for the windstorm on 12 UTC on 25 January 2007 represents well the Type S windstorm (Fig. 12). The sounding shows

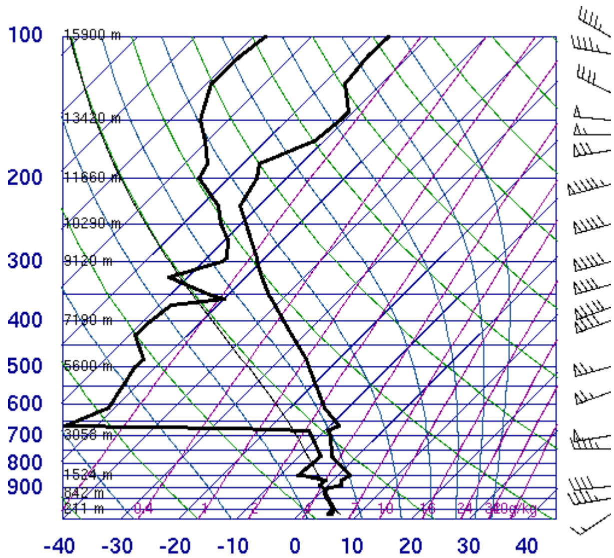

Fig. 12 Upper-air observations from Keflavík in Southwest-Iceland at 12 UTC on 25 January 2007 during a windstorm of Type S at Kvísker. Shown are windbarbs, temperature and dewpoint [°C] with pressure on the vertical axis (provided by the University of Wyoming).

the considerable forward wind shear as the wind speed increases upwards towards the jetstream which is on average zonally oriented over Iceland during the windstorms. The northerly windstorms of Type E are less frequent than the Type S windstorms. They feature a large region with turbulent and strong flow down the slopes of the mountain. There is a feature similar to a hydraulic jump at the foot of the mountain, yet the flow does not experience much deceleration. The flow aloft is characterized by a reverse and directional vertical wind shear and a deep and well mixed boundary layer with an inversion well above the mountain tops. These airmasses are of arctic origin but boundary layers of such airmasses tend to deepen when they travel southward over warmer seas (see e.g. Ólafsson and Økland 1994;

Brummer 1996). With the jet being located to the west of Iceland, the flow is far weaker aloft than at the surface and the gravity waves generated in the low level flow are unable to propagate vertically as in the westerly windstorms where the forward vertical wind shear contributes to the amplification of the waves. Consequently the waves in the Type E windstorm are less likely to amplify, instead they overturn and break at low levels. In this aspect the Freysnes downslope windstorm (Ólafsson and Ágústsson 2007) resembles the Type E windstorm in the northerly flow. However, the Freysnes windstorm does however not extend as far from the mountain as Type E does in this study. From a dynamic perspective, the Type S windstorm may be characterized as a more pure gravity wave generated windstorm, while the Type E bears a greater resemblance to local flow acceleration described by hydraulic theory, based on a flow transition from a supercritical to a subcritcial state (Durran 1990).

In the present two cases, there are no direct obsevations of the atmopsphere aloft. The simulations must be verified by comparison with observations at the ground, mainly from automatic weather stations. At Kvísker, the surface flow is well captured during the northerly windstorm of 18 October 2004 but the atmospheric model did worse during the westerly windstorm on 25 January 2007. There is in general an improvement in the model performance as the horizontal resolution is increased and a grid size of 3 km or less is necessary to capture the gravity wave activity. An in depth investigation of the simulated wind field during the westerly windstorm indicates that the storm and the amplitude of the gravity wave reach their peak sligthly too early in the atmospheric model and are not as strong as observed. This error may be related to an error in the boundary conditions, i.e. the large scale flow, which forces the mesoscale simulation model but it may also be related to errors in the development in the mesoscale structures in the vicinity of Mt. Öræfajökull. A small change in the large scale flow, may lead to a large local change in the winds but in a previous study (Doyle et al 2000) slight changes to structures in the lower stratosphere were shown to have a large impact on stratospheric wave-breaking. A premature decrease in the wave amplitude may thus be caused by a small change in the upstream flow, leading to the wave and the windstorm reaching a too short distance down the lee-side slope, thus leaving Kvísker out of the high-speed region after 7 UTC. In other words: the windstorm lasts too short at the site of Kvísker while the model still generates strong winds further upstream on the mountain slopes. This explains the poorer performance of the model during the very localized westerly windstorm and underlines the difference of these windstorms from a forecasting perspective. The widespread Type E windstorm is easier to forecast locally than the very local Type S windstorm. This is in fact a well known problem in interpreting and verifying atmospheric flow simulated at high resolution as e.g. pointed out by (Ágústsson and Ólafsson 2007) in an investigation of a windstorm in the complex terrain of Northwest-Iceland. Operational forecasting systems (e.g. the HRAS-system[1]) based on mesoscale models frequently forecast windstorms in complex terrain which reach a varying distance down the lee-side of big mountains like Mt. Öræfajökull but are however not always observed on the lowlands. Many of these windstorms are verified by mountain guides and climbers on treks starting in good weather at the lowlands but ending in very bad weather near 1100-1300 metres on Mt. Öræfajökull. In these situtaions, the mountain is often capped by a lenticular or cap cloud while the neighbouring region is less cloudy or even cloud free. In this way, the validity of the simulated flows in this study are supported by satellite images showing evidence of subsidence in the gravity waves on the lee-side of the mountains during both storms (not shown). As gravity waves may not always generate downslope windstorms which reach as far as Kvísker, it is indeed not clear how often Mt. Öræfajökull forces gravity waves in westerly flow but it may be expected to be quite frequent. Methods similar to those presented in Feltz et al (2009) may help to further classify the flow above Kvísker and identify situations of strong gravity wave activity, i.e. using both satellite based water vapour images as well as climate simulations of weather with a mesoscale model.

The strong gustiness observed at Kvísker is well reproduced with a method based on Brasseur (2001) which has previously been successfully applied during both downslope flow and a corner wind in Iceland (Ólafsson and Ágústsson 2007; Ágústsson and Ólafsson 2009). The strong gustiness is an artifact of the high values of TKE and strong winds aloft. The highest values of TKE are found near the regions of strong wind shear, i.e. near the surface and the inversion as well as below the lee wave in the westerly windstorm where there is a rotor with positive vorticity aligned in a north-south direction and return flow at the surface. This rotor is of Type I as classified by Hertenstein and Kuettner (2005) which is also in agreement with the wind profile. No rotor is generated in the northerly windstorm but the wind profile places the windstorm near the seperating line between Type 1 rotors associated with lee waves and Type 2 rotors associated with hydraulic jumps (Hertenstein and Kuettner 2005, Fig. 16). However, the winds at the inversion in the Type E windstorm are far stronger than in the idealized experiments presented by Hertenstein and Kuettner (2005, Fig. 16) and it is not clear that Type 2 rotors should be expected in the real atmosphere as there appears to be little observational evidence of Type 2 rotors in the scientific literature.

Since the start of observations at Kvísker in 2002 the annual cycle of observed windstorms has shown a good cor-

[1] http://belgingur.is

respondance with the number of strong westerlies in the ECMWF-analysis at 500 hPa (Fig. 9) and 850 hPa (not shown). Given a similar behaviour in the second half of the 20th Century it may be inferred that the number of westerly windstorms at Kvísker have varied greatly, e.g. with a minimum in 1985 and 1979 and a maximum in 1983 and 1975, but with no clear trend in their frequency. There is a maximum in the observed windstorm frequency and the strength of the westerlies during the winter (Fig. 10) and a clear minimum during early spring and summer. This is a reflection of the strength of the tropospheric jet. An investigation of the strength of the winds (63°N 15°W) in the climate projections reveals a similar behaviour as in the control simulations, i.e. the westerlies are strongest throughout the troposphere but the easterlies have a minimum at 500 hPa and a local maximum at the 850 hPa. There are indications of a decrease in the frequency of strong westerlies in the troposphere which may be interpreted as a possible decrease in the frequency of strong westerly windstorms at Kvísker. Although not as significant, there is also a very slight increase in the strength of the easterlies at 850 hPa which may have an impact on the easterly windstorms at Freysnes (Ólafsson and Ágústsson 2007).

7 Summary and conclusions

Here we have presented an investigation of downslope windstorms at Kvísker in Iceland. The windstorms are of two different types, a "Type S" westerly and a "Type E" northerly windstorm. The main difference between the two types at the surface is the horizontal extent of the windstorms, the Type S extending only a short distance downstream of the mountain, while the Type E extends far downstream. The northerly windstorm is slightly weaker and not as gusty as the westerly windstorm. The flow aloft during the Type S windstorm is characterized by an amplified gravity wave, a forward vertical windshear and a statically stable layer at the mountain top level, while the flow aloft during the Type E windstorm is characterized by a deeper boundary layer and a reverse vertical windshear. The Type S windstorm resembles a gravity wave windstorm, while the Type E windstorm has a resemblance to the pattern described by shallow-water hydraulic theory on super- and sub-critical flows, but with the absence of deceleration in a hydraulic jump.

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

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

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