

MOUNTAIN WAVES OVER GREENLAND AND THE ICELANDIC TROUGH

Ólafur Rögnvaldsson¹ and Haraldur Ólafsson²

¹Institute for Meteorological Research and University of Bergen

*²University of Iceland, Icelandic Meteorological Office and
Institute for Meteorological Research*

ABSTRACT

During FASTEX IOP-8 intensive wave activity was observed over the southeast slopes of Greenland. At the same time an extratropical cyclone passed to the northeast between Iceland and Greenland, leaving behind a trough with a secondary low in the surface pressure field.

Numerical simulations reveal that the waves are very sensitive to horizontal resolution and by simulating at coarse-gridded resolution, they can be almost eliminated. In spite of being large and amplified, the waves have very little impact on the synoptic flow field in the trough. Both the trough and the secondary low are nonetheless a product of the Greenland topography, not through waves but via permanent descent of potentially warm air in the Greenland wake. Orographic PV is produced, but much less in simulations with no wave breaking than in simulations where the waves are damped. Yet, the upstream flow is blocked. At very coarse resolution, the topography of South Greenland is reduced significantly and so is the southernmost part of the surface pressure trough.

1 INTRODUCTION

One prominent feature of mean surface pressure maps for the northern hemisphere is the “Icelandic low”, situated to the southwest of Iceland. The wintertime Icelandic low is relatively deep (less than 1000 hPa) and positioned close to the east coast of South Greenland, while in late summer the low is much shallower (about 1009 hPa) and centered close to the south coast of Iceland. At the 500hPa level, there is a vortex centre over NE-Canada, but not a well defined trough in the region of the Icelandic low, e.g. [11], suggesting that the Icelandic low is primarily a low level feature.

In an extensive study, [4, 5] analyzed all cyclones over the N-Atlantic from satellite images during a 2 years period and several characteristics of cyclones in the area between Iceland can be deduced from their results. Firstly, the cyclones in this area are much more frequent in autumn and winter than in spring or summer. This is indeed a general result for the whole N-Atlantic, but the seasonal variation appears to be greater between Iceland and Greenland than in most other areas covered by the study. Secondly, the winter cyclones in the area are preferably of a rather small size with a particularly high concentration of cyclones 200-400 km in diameter. Thirdly, almost 70% more cyclones leave the area than there are cyclones entering the area. Furthermore, there is a strong tendency for cyclones to remain in the area all their life (58%). In short, the wintertime area of the Icelandic low is a preferred spot for creation of mesocyclones of which many do not travel far. A combined case of a

deformed cyclone with a trough between Greenland and Iceland and a mesocyclone was the object of a numerical study by [10], (hereafter KM99). The mesocyclone (“residual” low), which they found to be largely barotropic, formed inside the Icelandic trough that formed after the “mother” low had passed through the area. Being barotropic, the residual low had the characteristic of a lee vortex in blocked flows as described by [13] and [16]. If the topography of Greenland was removed the residual low did not appear, but the mother cyclone became deeper.

The KM99 case gives very convincing evidence that the topography of Greenland is indeed contributing to the Icelandic low through its impact on a passing extratropical weather system. It does however not rule out other possible sources, such as thermal forcing. In fact, an Icelandic low still appears in large scale simulations after topography has been removed [6].

The main object of this study is to investigate the impact Greenland has on the formation of the Icelandic trough, either through gravity waves aloft or through other orographic processes such as blocking of the airflow. For this purpose we have chosen to study in depth a case from the Fronts and Atlantic Storm Track EXperiment (FASTEX) campaign [7] where numerous surface and upper air observations were provided in addition to the regular operational observation network. FASTEX was an international field project that took place in January and February 1997 to make detailed observations of extratropical cyclones over the North Atlantic. During FASTEX several Intensive Observational Periods, or IOP’s, were conducted and we use one of these, the IOP-8, which took place on the 27th to the 29th of January 1997. Most importantly, this FASTEX IOP provides dropsonde observations of

intensive wave activity over Greenland. In the following section there is a short description of the numerical model used in this study and the setup of experiments. Section 3 describes the synoptic flow in the case and presents the results of the simulations. These are discussed in section 4 which is followed by a short concluding summary.

2 MODEL SETUP

The numerical model used for this study is the fifth generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model MM5 [3, 17].

Unless otherwise stated, the simulations are run with a twofold nesting; a horizontal resolution of 12 km inside a mother domain with 36 km resolution and a 4 km resolution in the innermost domain. As can be seen in Fig. 1, the mother domain covers most

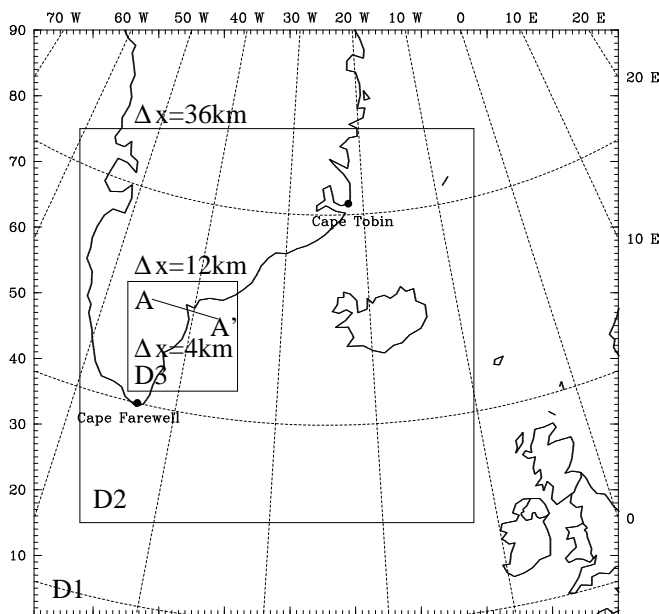


Figure 1: The FASTEX IOP-8 model setup, the straight line, (AA’) in domain 3, indicates the location of cross-sections.

of Greenland, all of Iceland and extends to Great Britain in the east. The mother domain size is $3200 \times 3200 \text{ km}^2$, domain two is $2160 \times 2160 \text{ km}^2$ and domain three is $600 \times 600 \text{ km}^2$ in dimension.

Three types of vertical resolution have been employed, 25, 40 and 65 σ layers (referred to as FX25, FX40 and FX65, respectively). The model top is at 100 hPa in all cases, except for FX65, where it is set to be at 50 hPa. At the top level a radiation boundary condition minimizes the reflection of

vertically propagating gravity waves [9]. The model employs a parameterization scheme for subgrid turbulence [12]. Initial conditions and boundary values were acquired from the ECMWF reanalysis.

3 RESULTS

3.1 Synoptic overview and comparison with observations

Figure 2 shows the evolution of the mean sea level pressure and the low level temperature fields as simulated in FX40. At 28/12 UTC (t_0+00h), there is a 1004 hPa low between Iceland and Green-

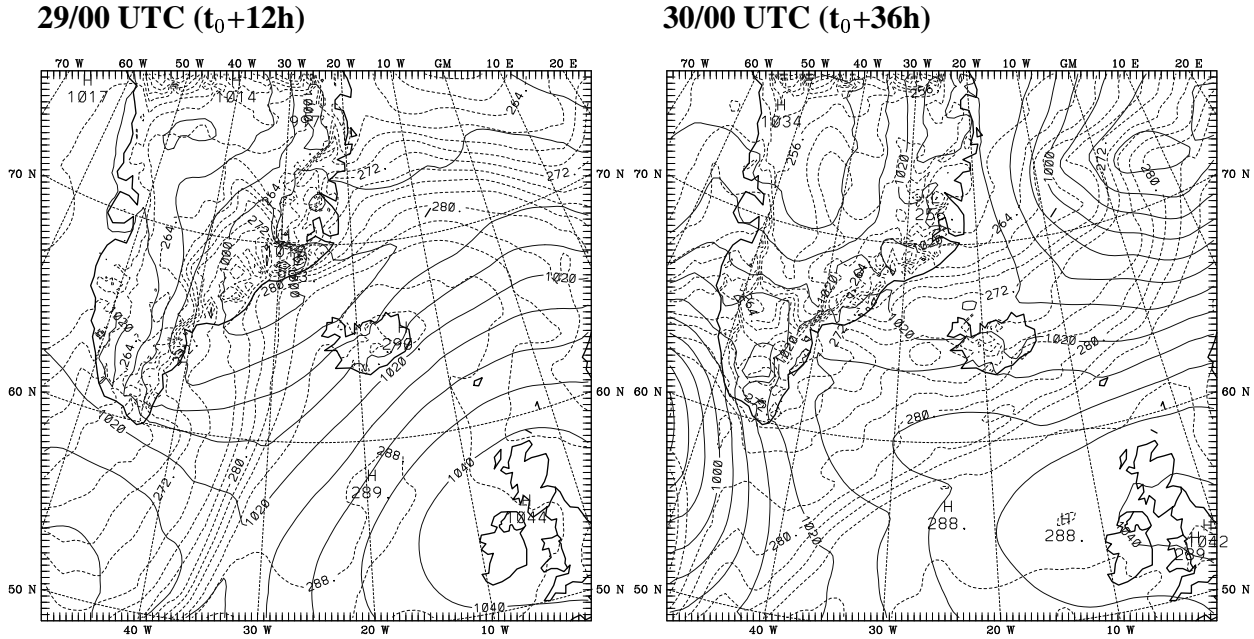


Figure 2: Synoptic overview: Mean sea level pressure [hPa] and potential temperature [K] at 850 hPa for FX40.

land and a stationary high over Great Britain. The low moves to the NE and deepens, but leaves behind a trough with a secondary pressure minimum along the southeast coast of Greenland. At 30/00 UTC (t_0+36h), the main low has deepened to 984 hPa and passed Jan Mayen and the trough

Table 1: Comparison of measured mean sea level pressure (MSLP) and geopotential height (GH) at 500 hPa and calculated one. Pressure is in hPa and geopotential height in meters.

Location	Meas. MSLP	Calc. MSLP	Diff.	Meas. 500 hPa GH	Calc. 500 hPa GH	Diff.
Jan Mayen	996	998	+2	5270	5270	0
Scoresbysund	1000	1005	+5	5100	5100	0
Keflavík	1012	1013	+1	5370	5380	+10
Narssarssuaq	1023	1022	-1	5280	5290	+10
Thorshavn	1029	1029	0	5650	5650	0

with the secondary low has disappeared. The deepening of the main low is associated with a low level temperature gradient and there is a relatively warm airmass at low levels in the trough behind. The evolution of the 500 hPa flow field is shown in Fig. 3. As in a classical example of a developing

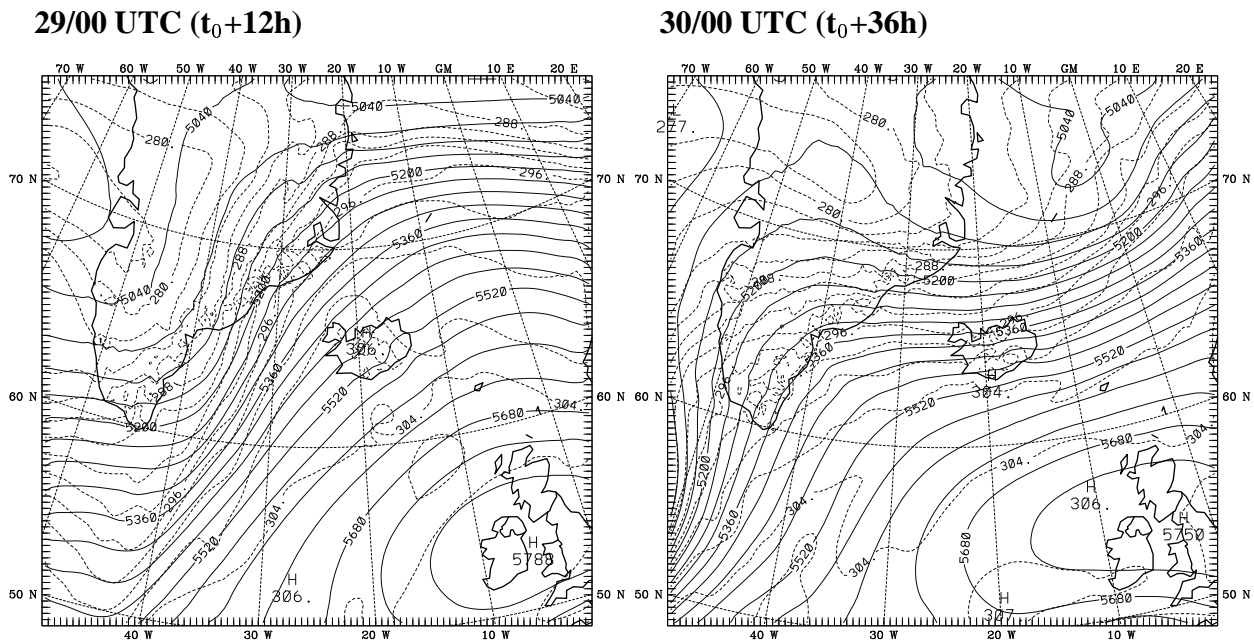


Figure 3: Synoptic overview: 500 hPa geopotential height [m] and potential temperature [K] for FX40.

baroclinic wave, the upper level trough is situated behind the surface low. At 28/12 UTC (t_0+00h), the 500 hPa trough is to the SSW of cape Farewell and during the following 36 hours it moves to the NE and ends up over Jan Mayen, being less pronounced than at the beginning. The flow is definitely baroclinic. The simulated flow described in Figs. 2 and 3 is in very good agreement with surface and upper air observations from Greenland, Iceland and Jan Mayen, including all supplementary observations of the FASTEX campaign. Comparison of measured and calculated mean sea level pressure and geopotential height at 500 hPa is shown in table 1. The validation time is 29/12 UTC (t_0+24h). It is only at Scoresbysund that the mean sea level pressure deviates considerably from measurement, this is most likely due to strong local topographical effects. We may therefore regard this as a reference flow or control simulation. The choice of case for this study is heavily

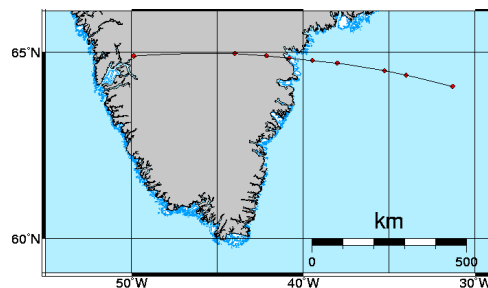


Figure 4: Position of dropsondes.

based on the high-resolution dropsonde data from the flight of the NOAA Gulfstream aircraft in FASTEX IOP-8. During this IOP, the flow disturbance over Greenland was given particular attention. as

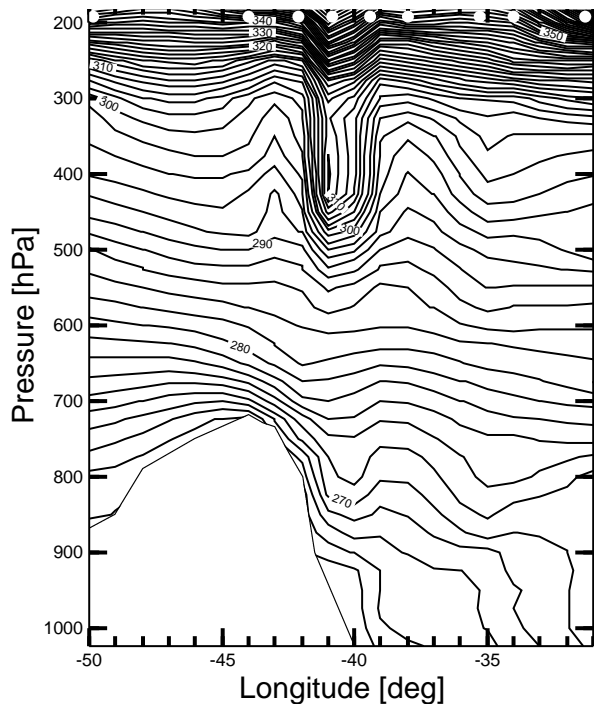
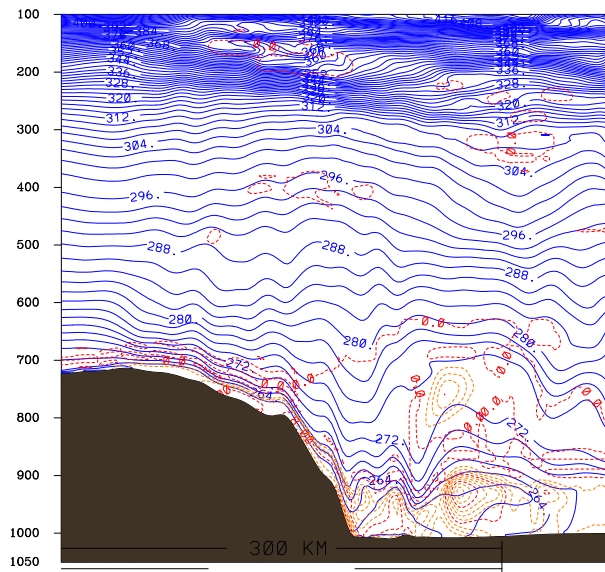


Figure 5: A cross section along the line in figure 4 showing potential temperature [K] at approximately 29/12 (t_0+24h).

can be seen in Fig. 4, which shows the position of dropsondes during the flight. Figure 5 shows the potential temperature field constructed from the dropsonde observations. There is obviously very strong wave activity and presumably wave breaking, reaching from the stratosphere down to approximately 500 hPa. From 500 hPa and down to about mountain top level the flow is smoother, while further below there are steep waves and possibly wave breaking. The flight took place at approximately 200 hPa and at that level there was significant turbulence (M. Shapiro, personal communication). Simulation of the flow in the same section as in Fig. 5, using 65 σ -levels, reveals indeed strong and steep waves (Fig. 6). The flow is highly non-stationary, but both time-steps shown in Fig. 6 show more waves and wave breaking below 600 hPa and in the stratosphere than in the upper troposphere. Between 500 hPa and the tropopause, the simulated flow is in other words more smooth than observed. The model produces however some turbulence at these levels, but less than at the lower levels.

29/12 UTC (t_0+24h)



29/14 UTC (t_0+26h)

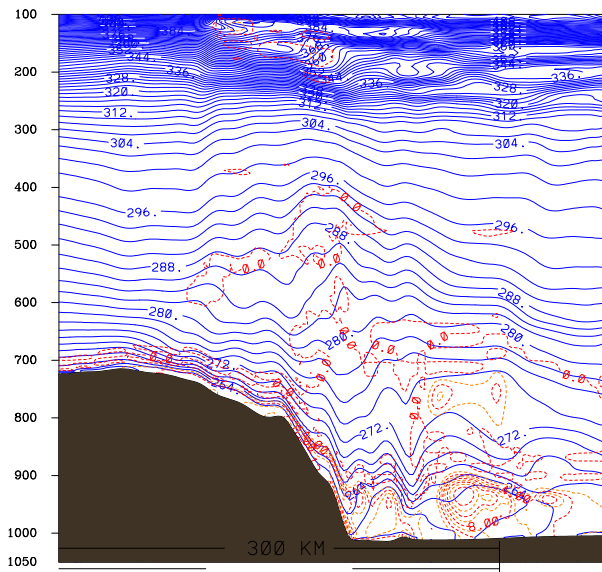


Figure 6: Cross-section AA': Simulated potential temperature [K] and TKE [J/kg] for FX65. Contour intervals for TKE is 2 J/kg and 2 K for isotherms.

3.2 Sensitivity tests

3.2.1 Horizontal and vertical resolution

To test the impact of the nesting, the same case was simulated using only the first domain, (Fig. 1), with a horizontal resolution of 36 km. This is comparable to many of the NWP models that are run operationally in the area. The resulting surface flow field between Iceland and Greenland is almost identical to the nested simulation. With decreased horizontal resolution, i.e. the 36 km run, the flow is smooth with only little wave activity in the troposphere as well as in the stratosphere. Turbulence kinetic energy (TKE) is also much less compared to the breaking waves in the nested run.

To give a more complete view of the impact of resolution, the horizontally nested flow has been run with different numbers of vertical levels. There is no qualitative difference between these simulations. Both have intense wave activity in the lower troposphere and in the stratosphere, with more smooth flow inbetween.

3.2.2 No-Greenland

Previous experiments with variable horizontal resolution, of which some almost eliminate the gravity waves over Greenland, do all show almost identical development of the surface pressure pattern in the lee of Greenland. Our next step in investigating the connection between the Greenland topography and the flow field between Iceland and Greenland is to reduce the height of Greenland down to one meter. Figure 7 shows the resulting sea level pressure and potential temperature at 850 hPa. Comparing this to Fig. 2 shows large differences. In the No-Greenland run, there is no trough left behind the main low and the surface pressure at the east coast of Greenland is some 20 hPa greater than in the control run. At Cape Tobin (70°N), the No-Greenland simulation gives on the other hand about 10 hPa lower surface pressure than the control run. Figure 8 shows the difference between Control and

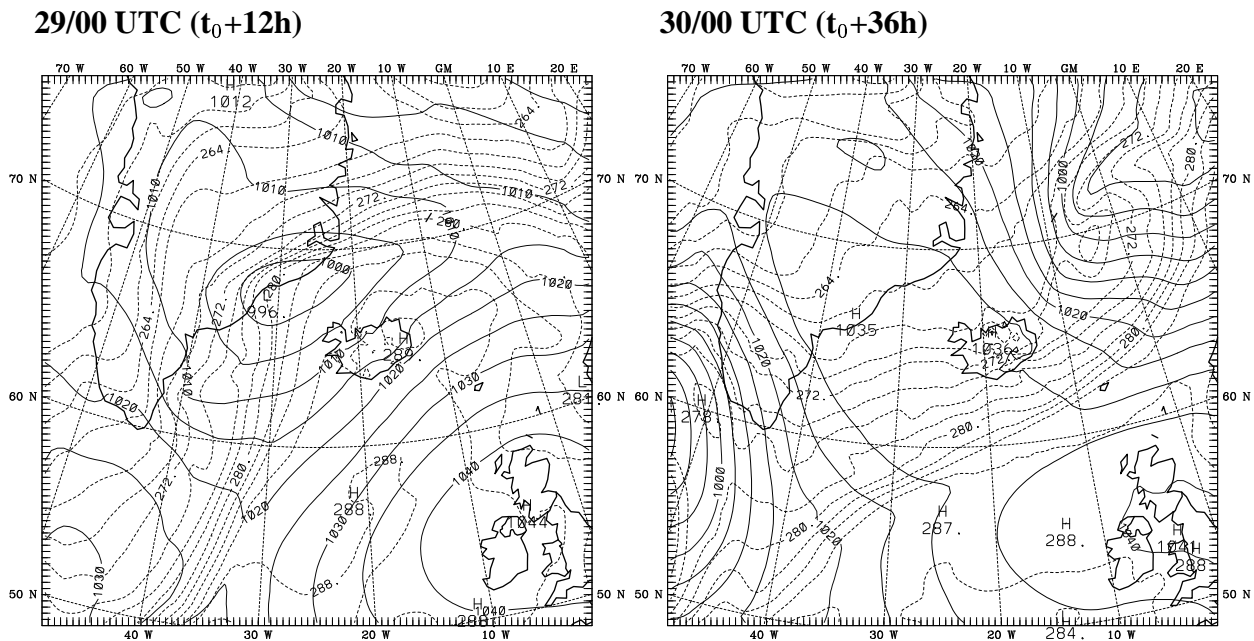


Figure 7: Synoptic overview: Mean sea level pressure [hPa] and potential temperature [K] at 850 hPa when the topography of Greenland has been reduced to one meter.

No-Greenland in potential temperature at 850 hPa. It is especially interesting to note the warm zone

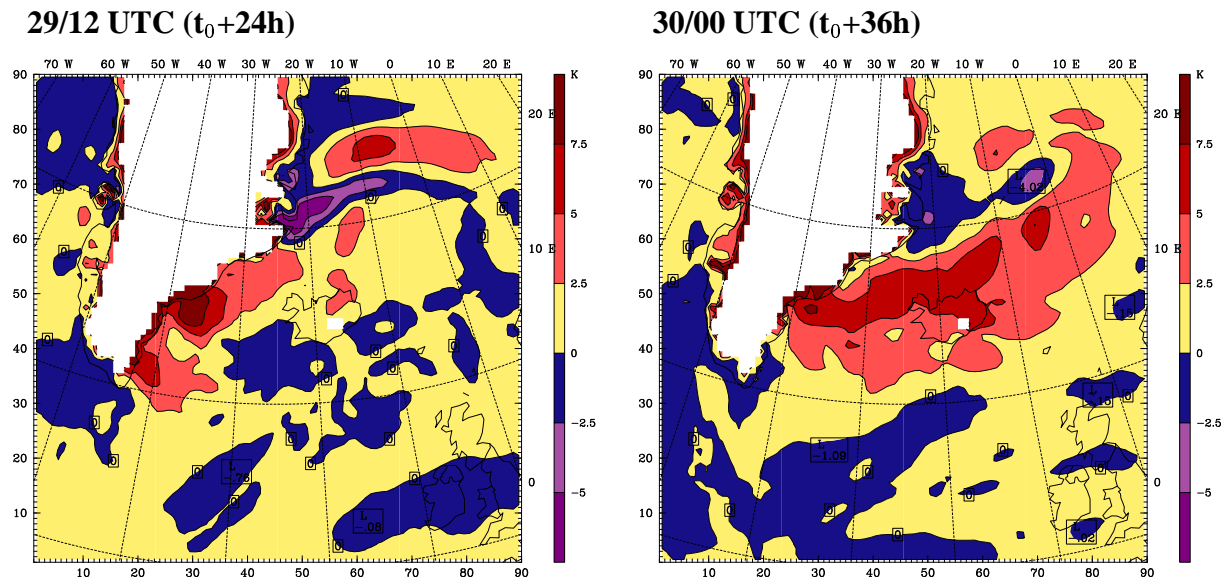


Figure 8: Difference in potential temperature [K] between Control and No-Greenland (Control - No-Greenland) at 850 hPa.

east of Greenland that advects to the east. At the 500 hPa level there is a slight trough over Cape Tobin at 30/00 UTC (t_0+36h) in the control run which is not present in the No-Greenland run. Apart from this, the 500 hPa flow fields are almost surprisingly similar, in view of the large differences in the sea level pressure field.

3.2.3 Potential Vorticity

When Greenland is present in the simulations, there are streamers of PV that originate over the mountains and extend far downstream. Figure 9 compares these streamers for the area of our smallest domain at different resolutions. The magnitude and structure of the PV streamers clearly depend on the horizontal resolution, showing both finer structure and much higher values at 4 km resolution than at 36 km resolution. In agreement with the anticyclonic flow field, there is little or negative PV in the No-Greenland case.

4 DISCUSSION

The simulations presented here manage to a certain extent (although not quite as well as [2]), to reproduce the observed strong wave activity over the eastern slopes of South Greenland. The steep and presumably breaking waves in the stratosphere and lower troposphere are simulated, while observations indicate wave activity that is stronger than simulated in the upper troposphere. Very high vertical and horizontal resolutions do not alter this. The surface and 500 hPa pressure fields to the east of Greenland and over Iceland are very well reproduced in the simulations. If horizontal resolution is decreased from 4 to 36 km over the Greenland lee slopes, the waves are largely eliminated and yet the surface flow field east of Greenland is almost unchanged. Small values of TKE in the 36 km simulations confirm that a possible effect of wave breaking is not being dealt with by the subgrid turbulence scheme. The apparent lack of connection between the waves and the surface flow field is an

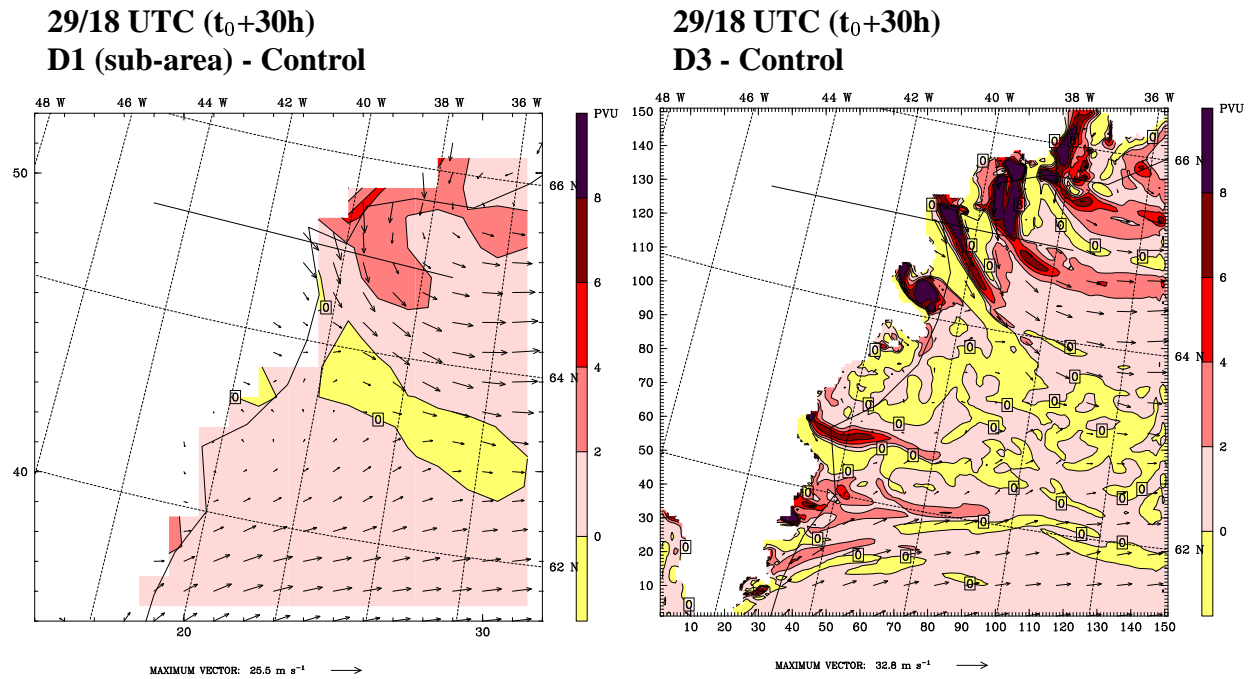


Figure 9: Comparison of potential vorticity [PVU] for different horizontal resolution at 925 hPa height. The sub-area of Domain 1 is the area which Domain 3 covers. Arrows indicate horizontal wind speed.

interesting result, since the scale of the observed waves is large enough to allow for some geostrophic adjustment and thereby an impact on the synoptic flow.

Removing Greenland has large impact on the surface pressure field, but small effect at 500 hPa. The elimination of the residual trough that the mother low leaves behind between Iceland and Greenland is in agreement with the case investigated by KM99. They explained this by Greenland's blocking effect, hindering advection of cold low level air to the west of the mother low. Another way of looking at this is to compare the low level flow field (Fig. 2) and the difference in potential temperature at 850 hPa in the control run and the No-Greenland run (Fig. 7). From these figures it becomes apparent that Greenland forces a permanent descent of warm air to levels below the mountain top, similar to the idealized setup of blocked flow in [14]. The residual low appears as a source for the warm air that is being advected to the east, over Iceland. The removal of Greenland reduces the sea level pressure at Cape Tobin, an effect that we also relate to blocking of Greenland. The dense low level air is diverted to the south along the east coast of Greenland (north of 70°N) giving a pressure rise compared to the No-Greenland flow. This feature is also present in KM99, confirming that their results have a more general value than in the case they studied. The similarity of the 500 hPa flow fields in simulations with and without Greenland, is somewhat surprising since the perturbations over the lee slope travel easily up through the troposphere. This is however consistent with the aforementioned climatology showing the Icelandic low to be mainly a low level phenomenon.

The difference in PV in the lee of Greenland in simulations with and without wave breaking is consistent with the results of [1], indicating that dissipation by wave breaking is actively contributing to the generation of PV. The streamers of PV in the coarse resolution experiment are in fact also related to steepening of isentropes in a hydraulic jump-like flow pattern. In this aspect, the flow is more reminiscent of the non-blocked wave breaking case of [16], and yet the flow in our case is indeed blocked. The result of KM99 and the present study indicate that the "Icelandic trough" is to a large

extent a result of the interaction between the topography of Greenland and the airflow. Consequently, a poor representation of Greenland in coarse resolution GCM's may lead to an overestimation of surface pressure between Greenland and Iceland and erroneous interpretation of changes in the regional wind climate. The economic impact of this may be significant. The surface wind field and particularly the frequency of strong southwesterly winds are known to influence the biological conditions in the ocean and the growing condition of cod larve at the southwest coast of Iceland [8, 15]. As fishing is of primary importance in the economy of this region, indications of changes in the wind climate have a potentially large economic value.

5 CONCLUSIONS

The numerical experiments of the Fastex IOP-8 case of waves over Greenland indicate that the synoptic flow, especially the deformation of a cyclone passing between Iceland and Greenland is not significantly influenced by the mountain waves over Greenland, in spite of the waves being amplified and breaking. Greatly damped wave activity by reduced horizontal resolution has significant impact on the structure and the magnitude of the PV generation in the lee of Greenland, suggesting that although the low level flow is blocked, wave breaking can remain an important dissipation mechanism preceding the creation of PV in real flow around mountains. The numerical simulations presented here have confirmed mountain waves and mountain wave breaking to be a highly transient process, which is more sensitive to horizontal resolution in the range of 4-36 km than to vertical resolution from 25-65 sigma levels. This may of course be site and case dependent. Although the simulations show little connection between the Greenland mountain waves and the surface trough and residual low between Iceland and Greenland, the topography of Greenland appears nevertheless to be a governing factor in the deformation of the passing cyclone, not through gravity waves, but blocking of cold air at low levels and permanent downward deflection of potentially warm air.

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