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ORIGINAL PAPER

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

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

1 Introduction

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

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

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Incidents of strong turbulence at intercontinental flight-levels over Greenland have been reported by commercial aircrafts, but to the knowledge of the authors of this paper, such cases have so far not been investigated. As in the FASTEX case (Doyle et al. 2005), most of the turbulence observations over S-Greenland are made in strong westerly flows and satellite images often reveal associated wave signatures. The wave breaking close to tropopause levels is common in westerly winds because of the positive vertical wind shear in the troposphere, permitting vertical propagation of wave energy. In easterly low-level flows, the vertical profile is generally not so favourable. However, on 6 December 2005, a commercial aircraft flying in easterly winds in the lower stratosphere encountered severe turbulence over South-Greenland. This observation is, to our knowledge, unique and provides an opportunity to study extreme wave activity in easterly flow above Greenland. Here, the 6 December case is simulated. The wave activity and other flow features are described and discussed in relation to theories of idealized orographic flows. The flow is simulated with different horizontal resolutions in order to assess the value of basing forecasts for aviation upon high-resolution simulations.

2 Observational data and numerical simulations

The observations are from a commercial jet of the type Boeing 757, flying out of Keflavik, Iceland towards Boston in the USA (flight number FI631). The aircraft experienced severe turbulence and very abrupt changes in wind speed over S-Greenland at about 200 hPa on 6 December 2006 at about 1700 UTC. The upward force exerted on the aircraft was estimated to reach 2g and the cube root of the eddy dissipation rate can be estimated to have exceeded 0.7 $m^{2/3}$ s^{-1} (Meteorological Service for International Air Navigation, Annex 3 2007). In spite of the severe turbulence, there were neither any significant structural damages nor injuries on board. In order to describe the flow to which the observed turbulence is associated, the atmosphere is simulated with the numerical model MM5 (Grell et al. 1994; Dudhia 1993), using the Eta PBL parameterization (Janjic 1994). Initial and boundary conditions are from the ECMWF and the flow is simulated from 06 UTC until 18 UTC on 6 December 2005, allowing for 11 h for the flow to stabilize in the fine-scale grid before the time of the incident. The vertical resolution is 40 levels and the horizontal resolutions are 9 and 3 km, respectively. The topography of S-Greenland and the simulation domains are shown in Fig. 1. The surface flow is in reasonable agreement with observed winds (QuikSCAT) and available upper air observations (Fig. 2).

3 Results

Figure 2 shows the simulated flow and a radiosounding from Narsarsuaq, S-Greenland at 12 UTC on 6 December 2005. The sounding shows strong easterly winds throughout most of the troposphere. At low levels, the airmass is conditionally unstable, but there is a stable layer above ~700 hPa. Above ~200 hPa, there are weaker south-westerly winds. The condition of the atmosphere above Narsasuaq is well reproduced by the simulation. All the characteristics of the vertical profile are present, but the wind speed is slightly overestimated at low levels and

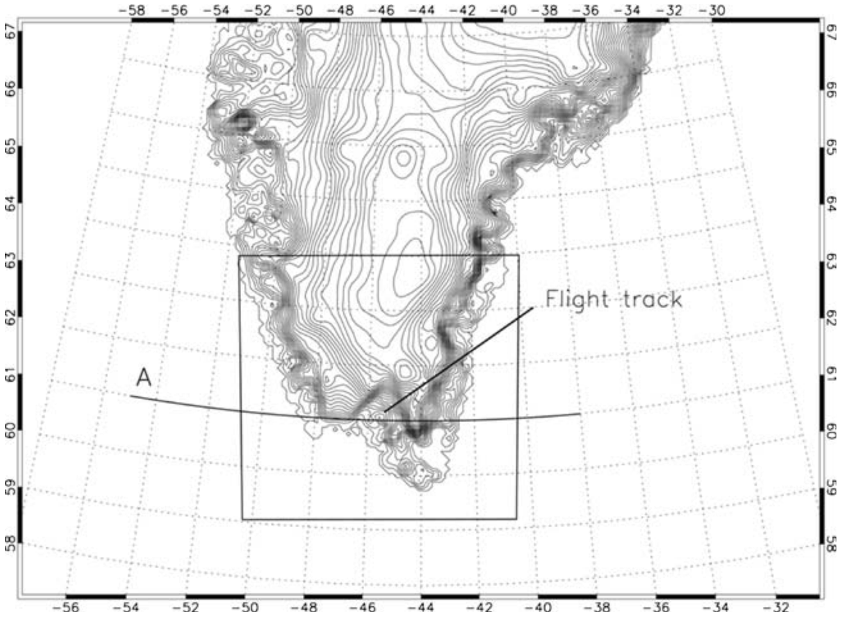

Fig. 1 Topography, with a contour interval of 100 m, in the numerical simulations. Shown are domains with a horizontal resolution of 9 and 3 km as well as the flight track and the location of *section A*

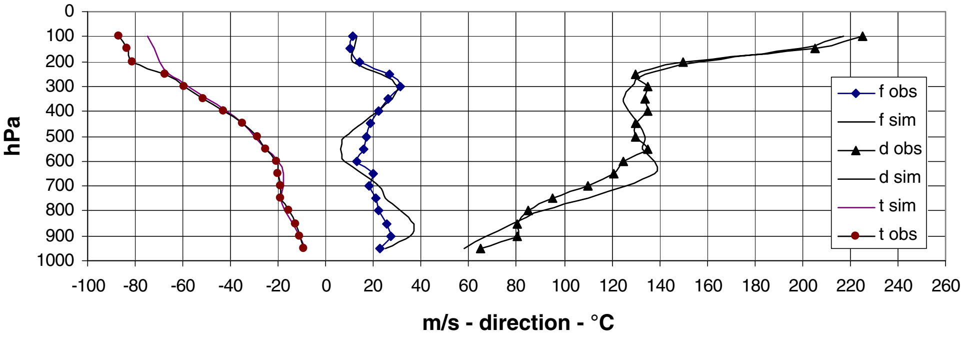

Fig. 2 Observed and simulated (3 km domain) profile of the atmosphere above Narsarsuaq, South-Greenland at 12 UTC on 6 December 2005

slightly underestimated at middle tropospheric levels. The wind directions are well reproduced and so are the tropospheric temperatures. The model gives some overestimation of stratospheric temperatures, but at these levels, there are strong fluctuations in temperature and large horizontal temperature gradients due to the wave breaking. Figure 3 shows the simulated flow at 200 hPa (close to the flight level) and a cross section along the low-level flow for horizontal resolutions of 9 and 3 km. There is indeed pronounced wave activity throughout the troposphere. The steepness of the waves and the turbulence indicate some breaking at middle tropospheric levels, but also above the tropopause, where severe turbulence was observed by the aircraft. The stratospheric waves and the associated turbulence are greater and more pronounced and in better agreement with the observed turbulence in the 3 km simulation than in the 9 km simulation.

Figure 4 shows surface winds, mean sea level pressure and temperature at 925 hPa. There is a barrier jet at the east coast of Greenland and a corner wind (reversed tip jet) downstream of the southernmost mountains. The strongest winds are found over Greenland, further to the north, below the amplified waves. Downstream of the strongest winds, there is a wake with weak winds.

4 Discussion

This is the first time to the knowledge of the authors of this paper that evidence is given of gravity wave amplification and tropospheric and stratospheric wave breaking in easterly flow over Greenland. In this case, the atmospheric conditions for mountain wave generation are indeed good: strong low level winds perpendicular to the mountains and a stable layer at mountain top level. Weakening of the winds with height at middle tropospheric levels contributes to the breaking of the waves at these levels (e.g. Durran 1990; Smith 1989). In spite of the tropospheric breaking, some of the wave energy is evidently able to penetrate up to the stratosphere, where the waves break and generate turbulence, which is in agreement with the observation of the aircraft. Compared to the 9 km simulation, the 3 km simulation has a better representation of the steepness of the topography. Consequently, most details of the resulting flow perturbations are more pronounced at 3 km. The complex topography in this region of the world has indeed variations on all scales, continuing well below 3 km. Some local features will therefore undoubtedly be better reproduced at resolutions greater than 3 km. To what extent such simulations may be useful for intercontinental air traffic remains, however, unanswered.

In order to assess the climatology of these weather conditions, the zonal components of winds at 850 hPa and at 300 hPa in the reanalysis from the ECMWF are plotted in Fig. 5. Each dot corresponds to winds at these two levels at a given time. The red dot on the right hand side indicates the position of 6 December 2005 12UTC in the ECMWF dataset, while the red dot to the left indicates winds from the Narsarsuaq sounding (S-Greenland) at the same time. Figure 5 reveals first that this event is far from unique in terms of magnitude of the zonal winds. Second, to the extent that they are comparable, the shape of the scattergram is surprisingly different from a similar graph for Iceland (Ólafsson and Ágústsson 2007). Over S-Greenland, there is a low correlation between the low-level winds and the high-level winds. Apparently, situations with strong positive vertical windshear in easterly flows (i.e. increase of the easterly component of the wind speed with height) are more common over S-Greenland than over Iceland. Yet, both S-Greenland and Iceland have a similar position relative to the mean N-Atlantic upper jet. The reason for this is unclear, but may be related to the influence of the topography of Greenland on the large-scale flow.

At the east coast of Greenland, the north–south low-level geopotential gradient is stronger than further upstream (east). This can be attributed to the accumulation of low-level dense air at the foothills of the Greenland mountains (see the sloping isentrope upstream of Greenland in Fig. 3). Associated with this gradient in the low-level geopotential, there is a northeasterly low level (barrier) wind along the east side of the S-Greenland mountains. There is a strong ageostrophic component in this flow, as well as in a reverse tip

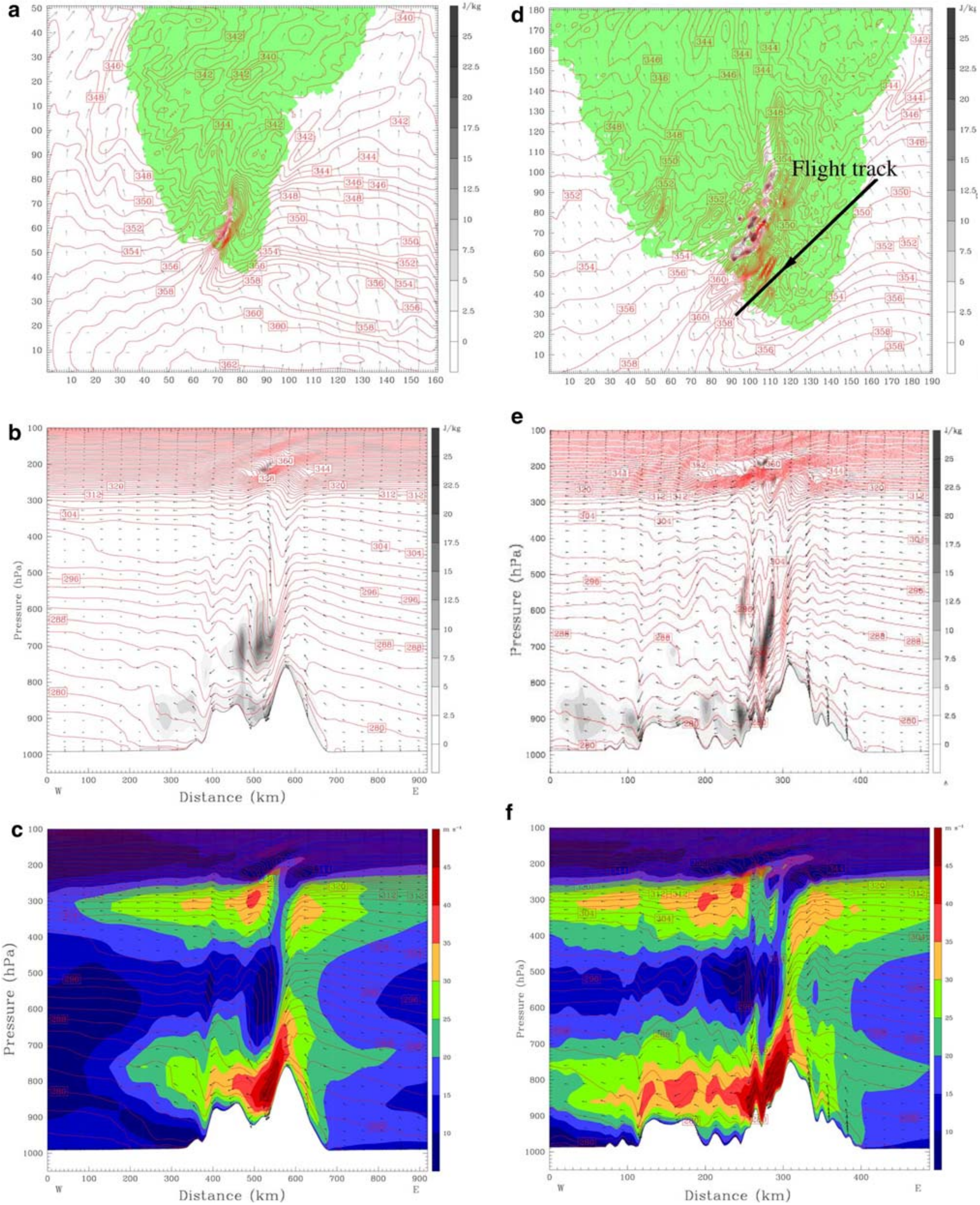

Fig. 3 Simulated flow with a horizontal resolution of 9 km: **a** potential temperature (K), turbulence kinetic energy (J/kg) and wind vectors at 200 hPa, **b** potential temperature (K) and turbulence kinetic energy (J/kg) in cross section A along the flow over S-Greenland and **c** potential temperature (K) and wind speed (m/s) in the same cross section as in (**b**). **d**, **e** and **f** are as **a**, **b** and **c**, but with a horizontal resolution of 3 km

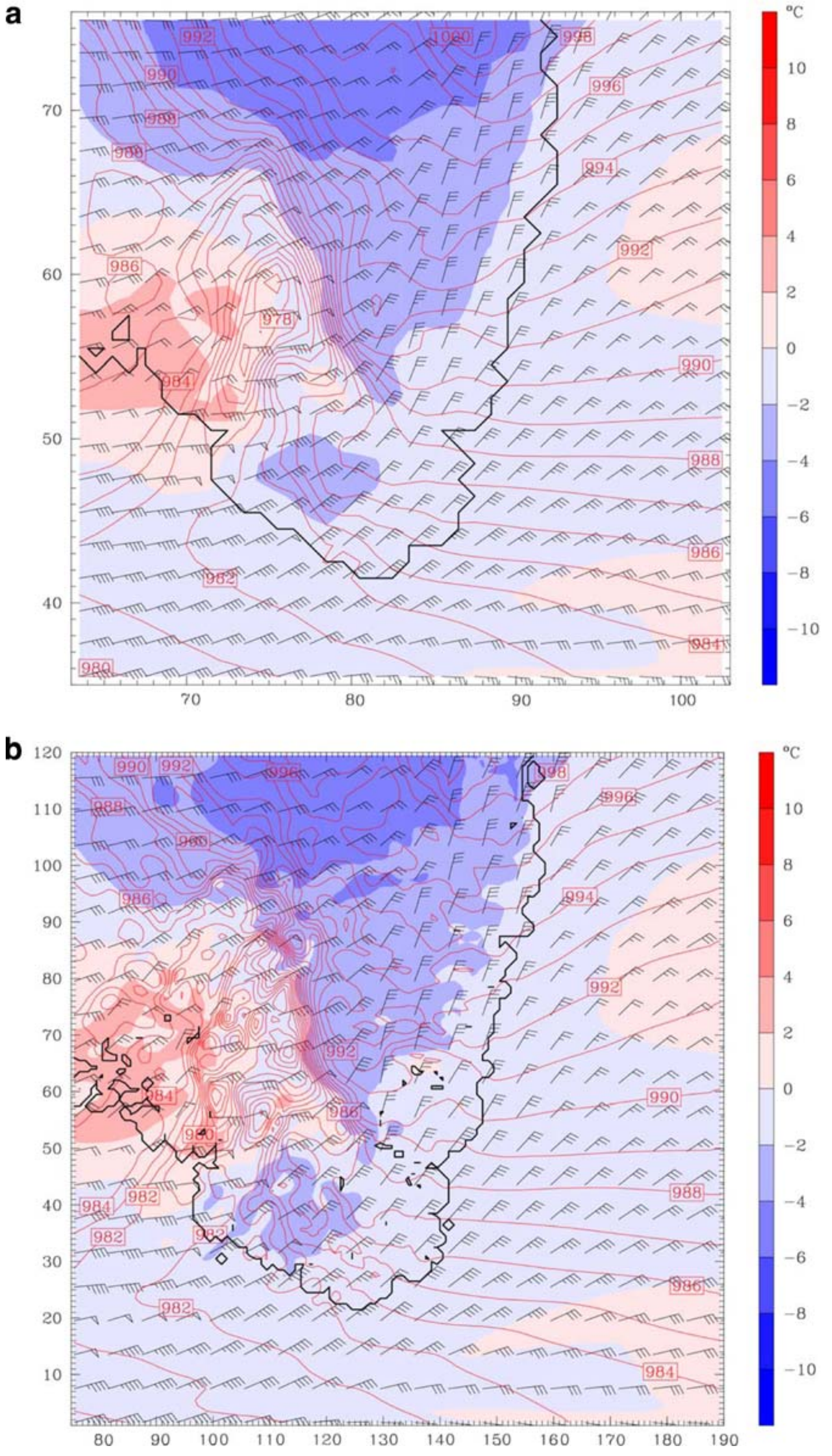

Fig. 4 Temperature (K) at 925 hPa, mean sea level pressure (hPa) and wind barbs (one full wind-barb corresponds to 5 m/s) in a simulation with horizontal resolution 9 km (**a**) and 3 km (**b**)

jet that can be found off the southernmost part of Greenland and in the shooting flow below the waves and downstream of the mountains. These local winds that are generated around Greenland in easterly flows are known to forecasters, but they have so far not been the object of many scientific studies apart from Moore and Renfrew (2005) (see also Doyle and Shapiro 1999 for the westerly tip jet). This may change soon, with results emerging from the Greenland Flow Distortion Experiment (Renfrew et al. 2008 (see also http://lgmacweb.env.uea.ac.uk/e046/

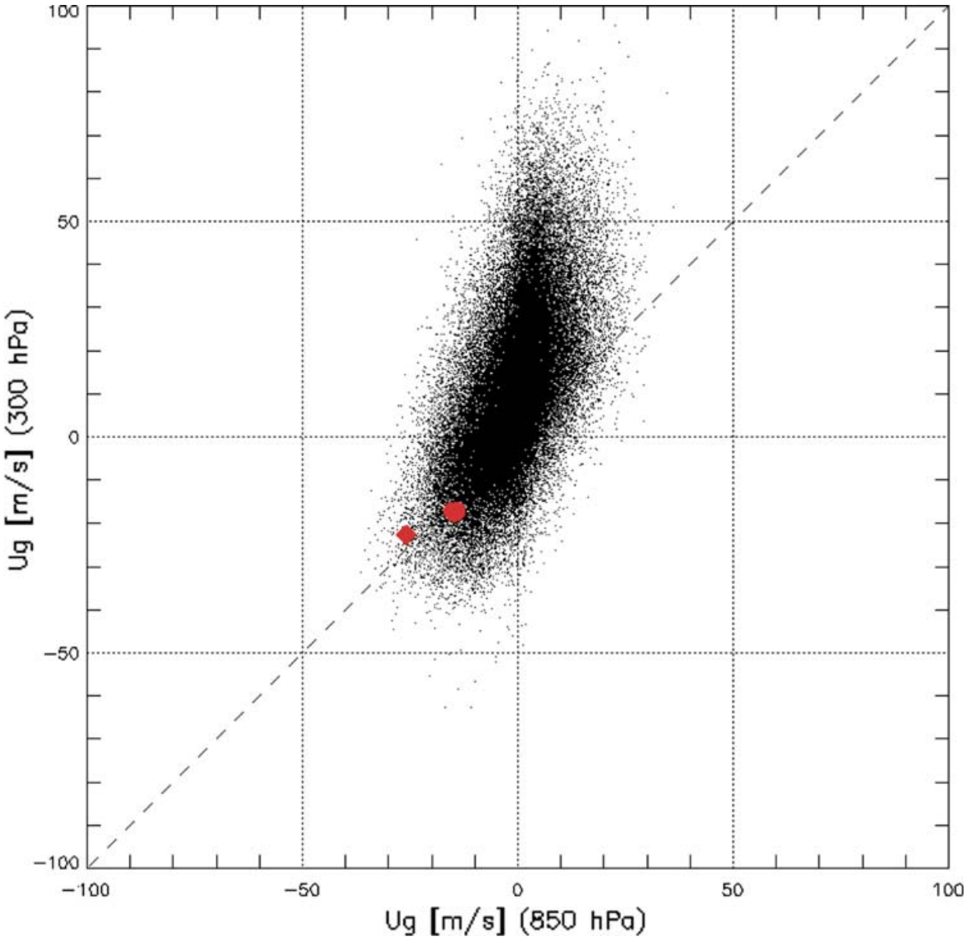

Fig. 5 The zonal wind component in datasets from the European Centre for Medium-Range Weather Forecasting (ECMWF) at 850 hPa and at 300 hPa at 61.5 N and 40.0 W. For the period 1958–2001 the data is from the ERA40 dataset, but for 2001–2006 the data is from the operational analysis. The *red point* (*large dot*) on the right hand side indicates the current case, while the *red point* (*large dot*) on the left hand side shows values from the Narsarsuaq sounding

research/gfdex). The fact that all the above flow features occur at the same time underlines the complex nature of real atmospheric flow; in idealized flows, amplified gravity waves on one-hand and barrier- and tip jets on the other hand are generally attributed to different flow regimes that do not occur simultaneously. An estimation of the non-dimensional mountain height below mountain top level, upstream of S-Greenland gives Nh/U close to 2. At such a value, the flow should indeed be expected to be blocked, and indeed, it is in the sense that the low-level air mass flows along the barrier and not across it. It is attempting to attribute the wave activity to the favourable vertical profile of the flow, but a closer look at experiments of idealized flows shows that this real flow event is a manifestation of secondary wave breaking as described in the idealized framework of Ólafsson and Bougeault (1996), enhanced on the left flank at low Rossby numbers (Ólafsson and Bougeault 1997a, b). The impact of the upstream flow direction not being perpendicular to the mountains, but shifted to the northeast also favours the wave breaking at high values of Nh/U (Petersen et al. 2005).

The results from this study raise questions on the importance of events of this kind for the interaction between the troposphere and the stratosphere, both in terms of turbulent mixing of air masses as well as well as larger scale impacts on the synoptic-scale flow and the downstream development. Some answers can undoubtedly be retrieved through extensive numerical simulations, but in situ observations in the line of Whiteway et al. (2003) or Reichardt et al. (2004) will be very helpful in describing the apparently intense and most likely highly non-stationary process of breaking waves over Greenland. Such observations should be undertaken.

5 Conclusions

Breaking of gravity waves over Greenland is possible in easterly flows and it can indeed be a hazard to aviation. The climatology of the vertical wind profiles indicates that breaking waves at tropopause levels may be far more frequent over Greenland than over Iceland. Moving from 9 km horizontal resolution to 3 km increases the simulated breaking intensity and makes it more realistic at the intercontinental air traffic level in the lower stratosphere. This indicates very strongly that aviation forecasts of turbulence in this region are likely to improve if they are based on high-resolution real-time simulations. This case shows that secondary wave breaking on the flanks of large mountains, as described in idealized flows, exists in nature and a strong north-easterly barrier jet and a reverse tip jet may occur at low levels at the same time as the gravity wave breaking aloft.

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