
Published article:

Knippertz, P, Chagnon, JM, Foster, A, Lathouwers, L, Marsham, JH, Methven, J and Parker, DJ (2010) *Research flight observations of a prefrontal gravity wave near the southwestern UK.* Weather, 65 (11). 293 - 297. ISSN 0043-1656

http://dx.doi.org/10.1002/wea.632

Research flight observations of a prefrontal gravity wave near the southwestern UK

Peter Knippertz[1]
Jeffrey M. Chagnon[2]
Alan Foster[3]
Luc Lathouwers[3]
John H. Marsham[4]
John Methven[5] **and**
Douglas J. Parker[1]

[1]School of Earth & Environment, University of Leeds
[2]National Centre for Atmospheric Science, University of Reading
[3]Directflight Ltd, Cranfield Airport, Cranfield
[4]National Centre for Atmospheric Science, University of Leeds
[5]Department of Meteorology, University of Reading

Figure 1. The Facility for Airborne Atmospheric Measurements (FAAM) BAe146. (Photograph courtesy of BAE Systems; photographer David McIntosh.)

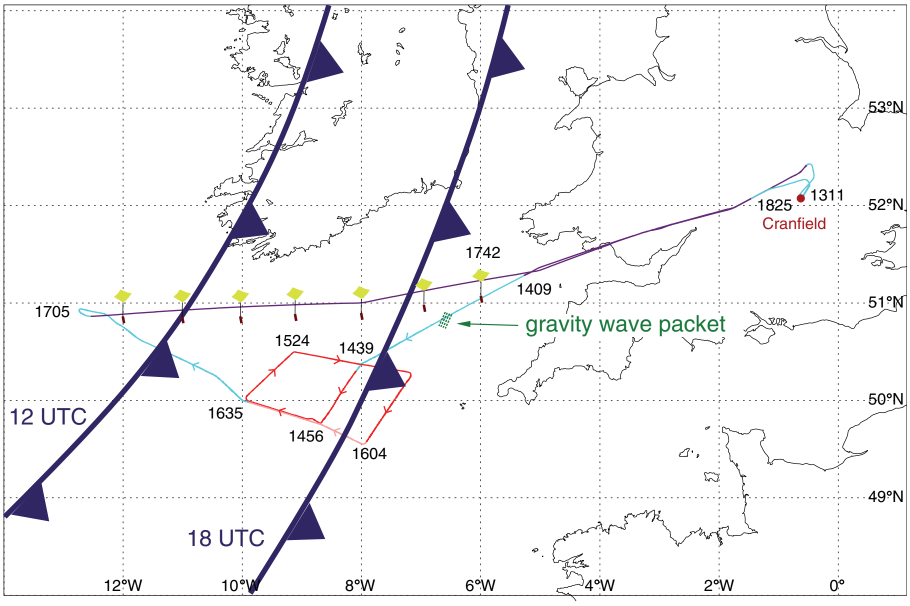

Figure 2. Flight pattern of B488 between 1311 and 1825 UTC on 24 November 2009 (red: marine boundary layer 150–450m; light red: 1500m; purple: cruising altitudes ~8km; light blue: profiles). The time of selected characteristic points is given in black and the locations of dropsonde releases are indicated. The positions of the cold front as analyzed on UK Met Office surface charts for 1200 and 1800 UTC are shown in blue. The position of the gravity wave packet under study here at about 1424 UTC is schematically depicted in green.

At 1311 UTC on 24 November 2009 the Facility for Airborne Atmospheric Measurements (FAAM) BAe146 (Figure 1) took off from Cranfield Airport (Figure 2) for research flight B488 and headed towards an intense, rearward-sloping, cold front over the UK Southwest Approaches. Around that time, the parent cyclone with a core pressure of about 966mbar was centred to the northwest of Ireland, with most of the UK lying in the warm sector under widespread stratocumulus (Figure 3). The classical elongated and rather two-dimensional cold front was characterized by high southwesterly winds on the warm side, typical of a well-developed warm conveyor belt (WCB) (Browning, 1990). Flight B488 was the third of a series of research flights in November 2009 funded by the National Centre for Atmospheric Science (NCAS). These flights constituted a pilot campaign to test and improve the ability of the BAe146 aircraft to observe frontal weather systems and storms affecting northwestern Europe, in preparation for UK participation in the international field campaign T-NAWDEX (THORPEX-North Atlantic Waveguide and Downstream impact Experiment), which is tentatively scheduled for 2013.

The flight pattern of B488 is depicted in Figure 2 together with the time evolution of the cold front. After take-off in Cranfield at 1311 UTC, the BAe146 ascended to a cruising altitude of about 7km (26 000ft) and then headed southwestward, crossing the coast of south Wales around 1351 UTC. Between 1409 and 1439 UTC the aircraft descended to 15m (50ft) over the sea surface to the northwest of Cornwall, at which point the pilots estimated the peak-to-trough wave heights to be between 6m and 12m and the winds to be Gale to Storm Force on the Beaufort scale. The first objective of the flight was to measure turbulent fluxes of temperature and humidity within the marine boundary layer during low-altitude straight and level runs in a box along and across the cold front (conducted between 1456 and 1604 UTC: Figure 2). The second aim was to obtain a vertical profile from the marine boundary layer through the WCB (1635–1705 UTC). Finally, a high-level west–east dropsonde leg was flown to characterize the flow and the moisture transport associated with the cold front and the WCB. The BAe146 returned to its base at Cranfield at 1825 UTC after a very smooth and successful operation, which was filmed by an onboard BBC team from the programme *Inside Out Southwest*. A serendipitous event during this flight was the observation of a compact, well-defined, gravity wave packet in the otherwise rather smooth and homogeneous stratocumulus deck over the UK Southwest Approaches well ahead of the surface cold front. This remarkable and interesting feature is documented and discussed in this article.

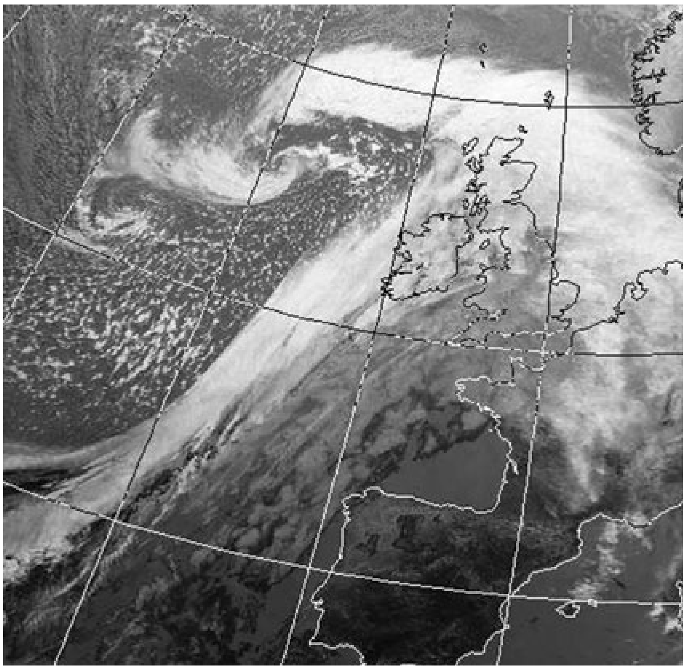

Figure 3. Meteosat SEVIRI channel 3 image (1.50–1.78μm near-infrared) for 1359 UTC on 24 November 2009.

Observations of the gravity wave packet

During the first descent over the UK Southwest Approaches (Figure 2) the BAe146 was approaching a fairly dense and homogeneous deck of stratocumulus with a top around 2.5km. The remarkably distinct, isolated, gravity wave packet with two clear ridges and one trough, an along wave-crest extent of the order of 20km, and an amplitude of around 200m (estimated by eye) was first identified visually by the captain of the aircraft and then photographed between 1418 and 1424 UTC by the onboard video cameras and one of the mission scientists (Figure 4). The photographs were taken from an altitude of about 4km, i.e. from more than a kilometre above the feature. The phase lines form an angle of approximately 45° with the aircraft track, thus having an orientation roughly parallel to the approaching cold front (Figure 2). The aircraft passed over the wave packet around 1424 UTC and then descended through the stratocumulus deck between 1427 and 1431 UTC. Surprisingly there was a shallow cloud-free layer in between this feature and the broken deck of shallow clouds at the top of the well-mixed maritime boundary layer, which the aircraft crossed around 1435 UTC.

Figure 4. Photographs of the pre-cold frontal gravity wave packet taken at about 4km above sea level (asl) by the forward-facing camera (top left) and through one of the left-rear windows of the BAe146 between 1418 and 1424 UTC on 24 November 2009.

Observations onboard the BAe146, made at an altitude well above the visible signs in the cloud deck during this period (Figure 5), reveal a wave-like signal. The wave is most evident in the vertical motion measurements with a very pronounced downdraught (marked T1 in Figure 5) flanked by regions of uplift (R1, R2). The absolute values should be regarded with caution, as the uncertainty of the vertical velocity measurements during a profile descent are of the order of 0.2ms^{-1} (Tjernström and Friehe, 1991). There is another weaker reduction and subsequent increase in the vertical velocity after the main wave packet. Given aircraft speed is about 100ms^{-1} and the crossing time from R1 to R2 was 50s, the wavelength of this packet was of the order of 5km. The direction of the horizontal wind changed from 225° to 230° immediately after the strong downdraught (i.e. between T1 and R2) and then back to 225° (Figure 5). There was no clear change in wind speed during this period. These observations suggest divergence associated with the strong downdraught T1 and convergence associated with the broader region of ascent (R2), and thus a maximum in vertical motion above the layer of sampling.

The potential temperature shows a wave-like signal roughly corresponding to the one in vertical motion, but with a phase shift of about a quarter wavelength, typical of a propagating gravity wave. Perturbations to a smooth profile reach up to 0.3K with the largest being observed between R1 and T1 (not shown). This is consistent with a wave amplitude of about 200m on the given background temperature profile. The perturbations are 'step-like', consistent with a slantwise descent through a sinusoidal wave structure.

Vertical structure

The descent of the BAe146 from about 7km down to the surface between 1409 and 1439 UTC allows us to discuss the vertical structure of the atmosphere, in which this gravity wave packet propagates. Figure 6 shows a tephigram depiction of temperature, dew point and wind measurements during this period. There is strong south-westerly flow from the surface to 350mbar. The slight backing of the winds in the lowest few hundredm is related to friction in the planetary boundary layer (PBL). The profiles indicate a well-mixed surface layer up to about 915mbar capped by a shallow isothermal layer, where wind speeds reach 38ms^{-1}. The temperature and dew-point curves do not indicate saturation in this layer despite the fact that the aircraft passed through a layer of broken clouds at the top of the PBL. This might to some degree be related to delayed response of the humidity sensors to the environment during descent.

The layer between 900mbar and 770mbar is again fairly well-mixed with temperature following a dry adiabat at the bottom and a moist adiabat in the saturated upper part of the layer, where a thick stratocumulus deck was observed. The high moisture content suggests that this air has either been lifted out of the PBL by WCB ascent ahead of the cold front or that mixing out of the PBL has moistened this layer. Horizontal winds decrease quite dramatically across this layer down to 25ms^{-1} at 770mbar. This strong shear combined with a near neutral stratification presumably allows active mixing through mechanically induced turbulence independent of the actual PBL[1]. This is consistent with the bumpiness of the flight across this layer and the increasing spikiness of the time series of vertical velocity after 1428 UTC (Figure 5).

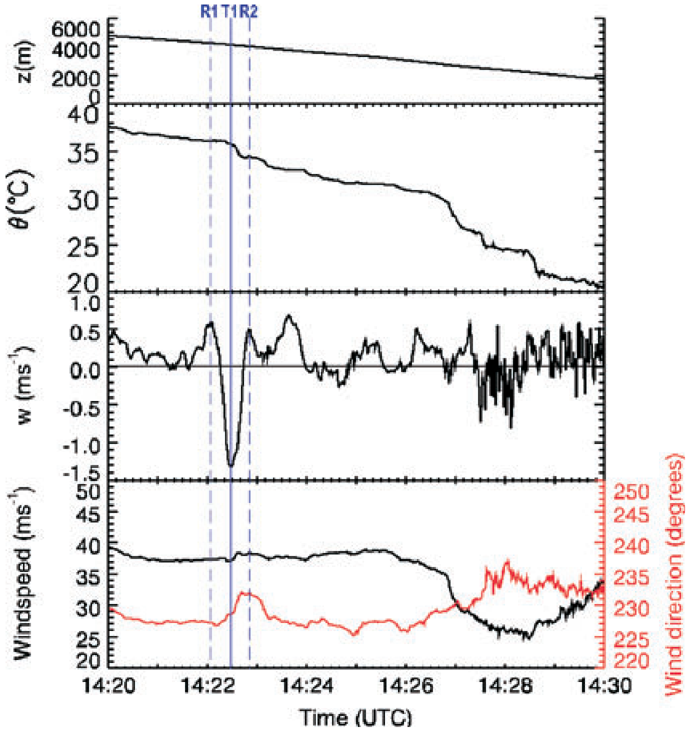

Figure 5. Time series of measurements onboard the BAe146 between 1420 and 1430 UTC on 24 November 2009 over the UK Southwest Approaches. From top to bottom the panels show height asl, potential temperature, vertical velocity, and horizontal windspeed and direction. Wave phases referred to in the text are marked in blue.

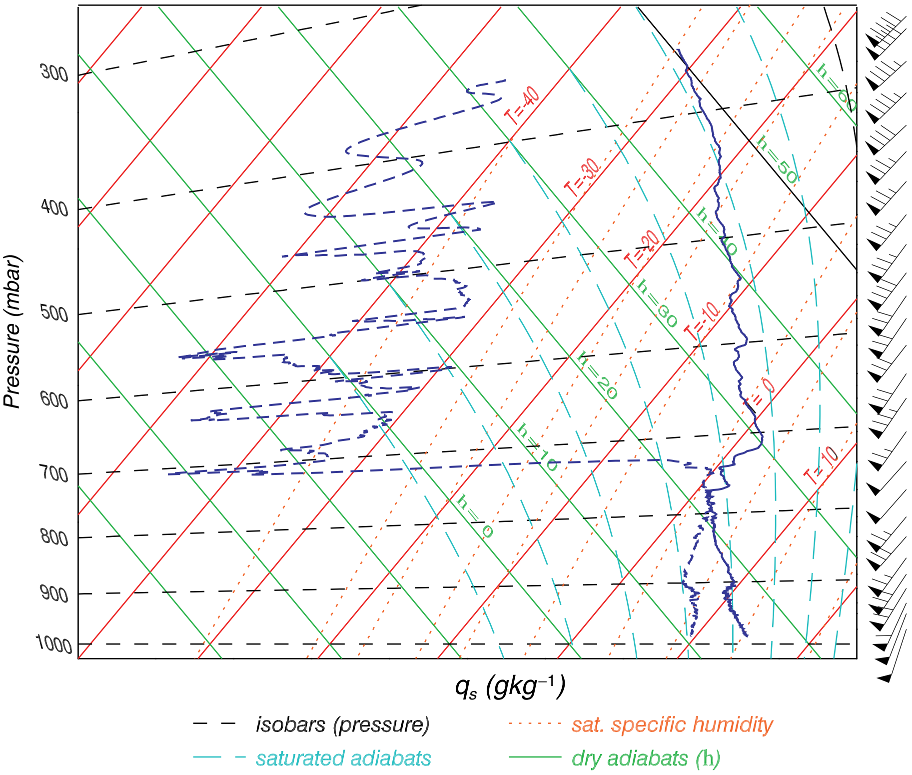

Figure 6. Tephigram plotted from the descent with the BAe146 between 1409 and 1439 UTC on 24 November 2009 over the UK Southwest Approaches (51.17°N, 5.61°W to 50.42°N, 7.86°W). The wind symbols are: 50kn for a filled triangle, 10kn for a long and 5kn for a short barb.

Around 750mbar there is a third moist mixed layer topped by a very stable layer up to 720mbar, across which the dew point decreases dramatically down to a relative humidity around 10% while the wind speed increases to 35ms^{-1}. It is likely that the elevated mixing has contributed to strengthening this stable layer, which provides excellent conditions for gravity wave propagation. The free troposphere is then characterized by very little moisture, a moderate stratification and a gentle increase in wind speed to 47ms^{-1} at 360mbar. The small curvature in the wind profile and the weak

---

[1] Richardson numbers are below the critical value of 0.25 for shear instability within this layer.

stratification are favourable for an upward propagation of gravity wave energy from the stable layer at the bottom into the free troposphere (Crook, 1988).

Comparison with model data

In order to place these observations into a wider context, numerical simulations were performed using the Met Office Unified Model (MetUM) at 4-km horizontal grid spacing. The MetUM is an operation-class numerical weather prediction system employing state-of-the-art numerical procedures and physical parameterization schemes (Davies *et al.,* 2005). The 4-km simulation was performed on a domain consisting of 340 by 480 grid points (latitude by longitude) encompassing the UK and Ireland and was initialized at 0000 UTC on 24 November 2009. The domain was nested within global and limited area domains having approximately 40-km and 12-km horizontal grid spacing, respectively, which were initialized from a European Centre for Medium-Range Weather Forecasts (ECMWF) analysis valid at 0000 UTC on 22 November.

Figure 7 shows vertical velocity at a fixed model elevation of 4.2km for 1600 UTC on 24 November 2009, i.e. about 1.5h after the observation of the gravity wave packet with the BAe146. At this time the cold frontal zone is located to the south and southwest of Ireland and is characterized by several inclined bands of upward and downward motion along the eastern edge and less organized ascent farther west. Intense localized updraughts are simulated closer to the low centre to the west of Ireland. About 100km ahead of the entire cold front and parallel to it is a conspicuous narrow band of strong subsidence. This feature is of much larger extent in amplitude, width and length than the more ordinary gravity waves caused by orography over the UK (Figure 7). A longitudinal section across this feature (Figure 8) shows remarkable structural similarities to the observed wave packet shown in Figure 5. In both figures the downward phase is dominant and is flanked by weaker regions of ascent. This structure is robust in the north–south direction as already suggested by Figure 7. There are, though, some notable differences from the observed wave packet. First, the simulated wave occurs about two hours later than the observed one. Secondly, it has a much longer wavelength of approximately 30km (compared with the 5km observed): this difference is at least partly due to the descent of the aircraft through the sloping wave phases. Thirdly, the amplitude is substantially smaller (0.3ms^{-1} cf $1.2 \pm 0.2\text{ms}^{-1}$) and, finally, the lateral extent spans the entire cold front whereas the visual observations suggest a much more isolated wave packet.

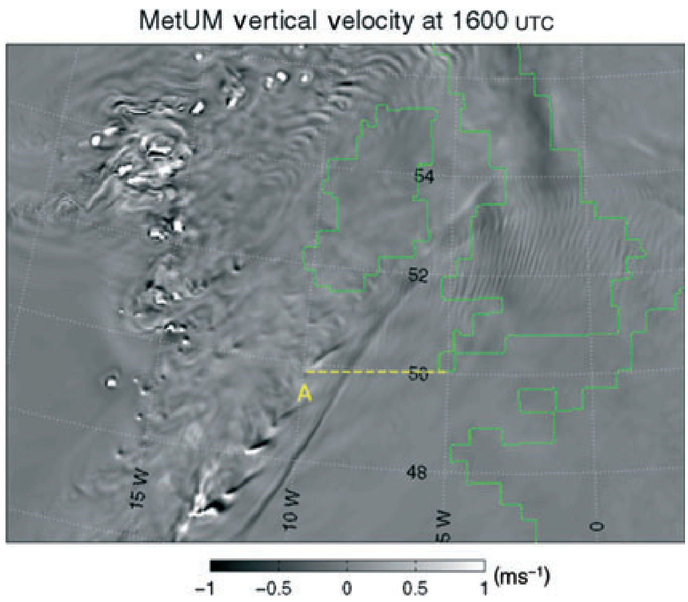

Figure 7. Horizontal distribution of simulated vertical velocity at 4.2km asl valid at 1600 UTC on 24 November 2009. Simulations were performed using the MetUM with 4km horizontal grid spacing. The dashed yellow line marked 'A' depicts the location of the sections shown in Figures 8 and 9.

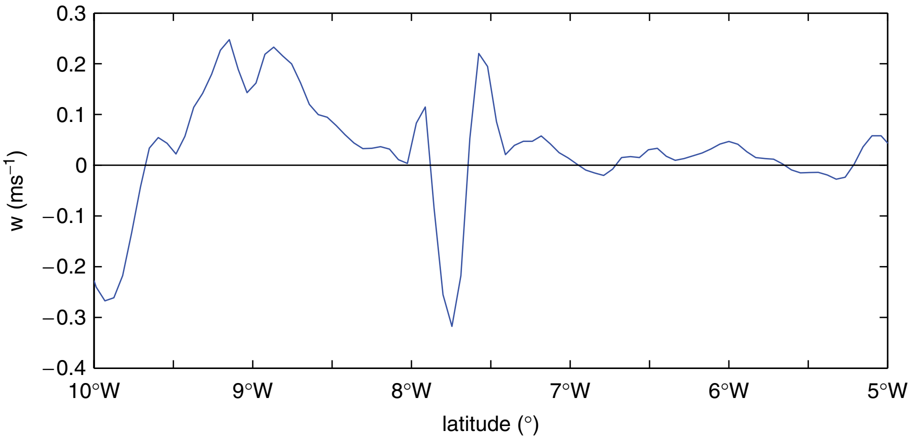

Figure 8. Simulated vertical velocity at 4.2km asl along Section A, valid at 1600 UTC on 24 November 2009 (see dashed line in Figure 7 for location).

In contrast to the observations, the model allows us to investigate the origin of the gravity wave packet. Figure 9 shows hourly vertical-longitudinal sections across the wave between 1300 and 1700 UTC The cold front is characterized by a coherent eastward propagating shallow region of marked updraught followed by more variable areas of deeper updraughts and downdraughts. First indications of the emanation of a wave packet from the frontal zone are found at around three to fourkm at 1400 UTC. One hour later, wave energy has already propagated ahead of the front and upwards into the dry mid-troposphere above the elevated inversion. This process continues until 1700 UTC when the wave packet appears to have separated from the actual front.

Discussion and concluding remarks

This short analysis adds evidence to the idea that intense mid-latitude cold fronts can emit distinct gravity wave packets that travel upwards and ahead of it. Despite the differences in wavelength, amplitude, timing and lateral extent, the structural similarities between the aircraft observations and the model simulations presented here are remarkable and were not expected *a priori*. Idealized work in the 1970s and 1980s showed that wave packets of moderate amplitude can be launched by fronts, even in the absence of any convective source, simply due to the geostrophic adjustment process (Ley and Peltier, 1978). This would explain why the wave occurs along the entire length of the front in the model. It would also suggest that the emanation of the wave packet could be related to a specific event (e.g. change in thermodynamic or wind-shear profile, deceleration of the front, or change in the frontal rainbands). Ralph *et al.* (1999), for example, examined prefrontal waves in the Great Plains and attributed their generation to a sudden cross-frontal acceleration, which

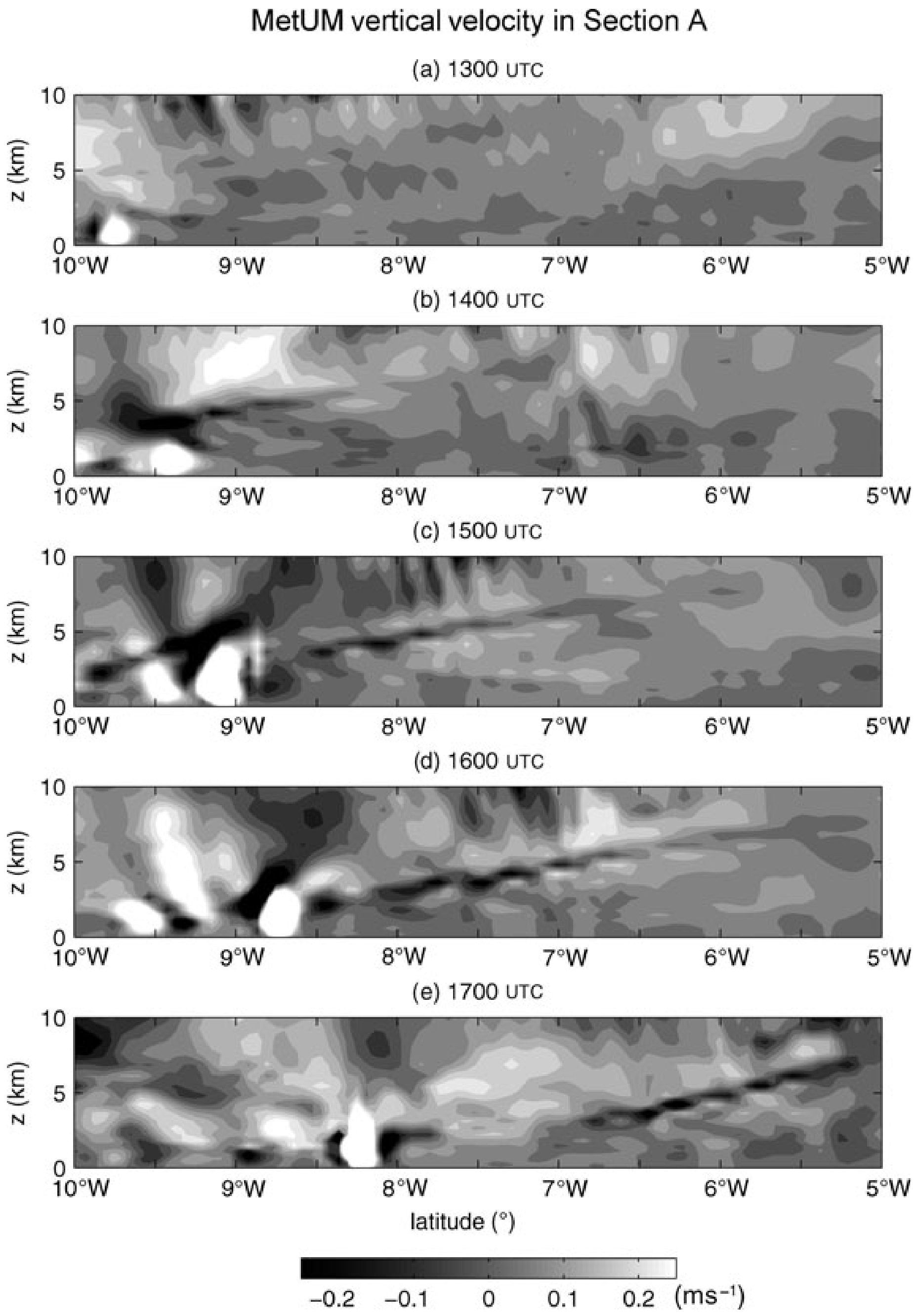

Figure 9. Height-longitude cross sections of simulated vertical velocity along the dashed line marked A in Figure 7 for five different times on 24 November 2009.

they associated with the interaction of the front with topography. It is conceivable that the compact wave packet observed in the real atmosphere in this case was triggered by an intense, more localized, event before larger-scale imbalances developed, the consequences of which were then not captured by the aircraft. This idea is consistent with the larger amplitude and the earlier occurrence of the wave in observations than in the model. A detailed investigation of these questions is beyond the scope of this article and is therefore left for future study. A more in-depth analysis of this case in the future should extend the employed observational database to operational remote sensing facilities on land.

A possible explanation for the differences in wavelength between observations and simulations found here is insufficient horizontal resolution. Therefore it is planned to repeat the numerical experiments with higher resolution to test whether the simulated wavelength converges towards the observed value for smaller grid spacings. Recent work on deep cumulonimbus convection over the UK has shown the importance of gravity wave propagation in initiation of storms (Marsham and Parker, 2006), and it has been found in these cases that careful attention must be paid in the numerical details of weather prediction models, if they are to represent such waves correctly. In particular, Mohebalhojeh and Dritschel (2000) have shown that the time-stepping scheme can trigger gravity waves associated with numerical imbalance and semi-implicit schemes deliberately slow gravity wave propagation. Therefore, closer analysis of the event described in this article may help in the evaluation of the UK's weather prediction model.

Acknowledgments

We gratefully acknowledge funding for research flight B488 through the National Centre for Atmospheric Science (NCAS). We would also like to thank the crew of the BAe146 (Gaynor Ottoway, Robbie Voaden), the flight manager Alan Woolley and the FAAM crew on the ground for a very smooth and successful flight operation that enabled us to document this interesting wave phenomenon. We also acknowledge the helpful comments from two anonymous reviewers.

References

Browning KA. 1990. Organization of clouds and precipitation in extratropical cyclones, in *Extratropical cyclones: The Erik H. Palmén Memorial Volume*. Newton C, Holopainen E (eds). American Meteorological Society, Boston, MA; pp 129–153.

Crook NA. 1988. Trapping of low-level internal gravity waves. *J. Atmos. Sci.* **45**: 1533–1541.

Davies T, Cullen MJP, Malcolm AJ, Mawson MH, Staniforth A, White AA, Wood N. 2005. A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Q. J. R. Meteorol. Soc.* **131**: 1759–1782.

Ley BE, Peltier WR. 1978. Wave generation and frontal collapse. *J. Atmos. Sci.* **35**: 3–17.

Marsham JH, Parker DJ. 2006. Secondary initiation of multiple bands of cumulonimbus over southern Britain. II: Dynamics of secondary initiation. *Q. J. R. Meteorol. Soc.* **132**: 1053–1072.

Mohebalhojeh AR, Dritschel DG. 2000. On the representation of gravity waves in numerical models of the shallow water equations. *Q. J. R. Meteorol. Soc.* **126**: 669–688.

Ralph FM, Neiman PJ, Keller TL. 1999. Deep-tropospheric gravity waves created by lee-side cold fronts. *J. Atmos. Sci.* **56**: 2986–3009.

Tjernström M, Friehe CA. 1991. Analysis of a radome air-motion system on a twin-jet aircraft for boundary-layer research. *J. Atmos. Ocean. Technol.* **8**: 19–40.

Correspondence to: Dr Peter Knippertz,
School of Earth & Environment,
University of Leeds,
Leeds LS2 9JT, UK

p.knippertz@leeds.ac.uk

DOI: 10.1002/wea.632