8.3 ON THE APPEARENCE OF INERTIA – GRAVITY WAVES ON THE NORTH-EASTERLY SIDE OF AN ANTICYCLONE

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1. ÍNTRODUCTION

From a study of ECMWF analyses we know that inertia-gravity waves (for short IGWs) appear not only over mountain regions in the atmosphere but are transiently observed in all no-mountain regions of the extratropics in dependence of Rossby wave propagation. In such cases the IGWs could be generated by other physical processes, like for instance due to geostrophic adjustment (e.g. O'Sullivan and Dunkerton, 1995), shear instability, convection and fronts (e.g. Fritts & Nastrom, 1992). Especially the link between Rossby wave breaking events and the appearance of IGWs was not in the focus of many investigations as known from literature.
In the atmosphere over Northern Germany, especially over Mecklenburg-Vorpommern, where there is no large orography (orography is smaller than 179 m), the above mentioned processes in connection with different phases of Rossby wave breaking events could be the cause for the possible appearance of IGWs.
The aim of this work is to investigate in a region without mountains, via a case study, the appearance of strong IGWs in the diffluent region north-eastwards of a downstream tilted anticyclone, that means during the second phase of a Rossby wave breaking event (Peters and Waugh, 1996).
IGWs have been the object of many investigations by radiosondes and VHF-radar measurements. A first report on a long series of radiosonde launches was given by Thompson (1978). VHF-radar measurements which detected IGWs in the troposphere and stratosphere were described for instance in the paper of Thomas et al. (1992).
We used ECMWF analyses winds to calculate the contour advection of EPV contours on 330 K surfaces in order to analyse the large-scale structure. Further, during a campaign, direct observations at Kühlungsborn (54.1° N, 11.8° E) by a series of radiosonde launches and VHF-radar measurements were realised to investigate the meso-scale structure. Results are presented in section 2. In section 3 IGW parameters estimated on the basis of both measurements are given.

2. OBSERVATIONS

During 17-19 December 1999 postprocessed ECMWF analyses data sets were used to examine the large-scale flow and possible IGW structure in the troposphere and stratosphere. The direct observations of these IGWs are made with a series of radiosonde ascents started at the Leibniz-Institut für Atmosphärenphysik in Kühlungborn (54.1° N, 11.8° E) placed near to the coast of the Baltic Sea as well as with VHF-radar measurements at the same place.
The hemispheric structure of the polar vortex can be characterised by the EPV field on the 500 K isentrope. The polar vortex shows a wave number 3 structure and is shifted to Europe so that the mean zonal wind has a value of 30 m/s in a band from Greenland to the island of Novaja Semlja. That means Northern Germany is placed under the edge of the polar vortex. Furthermore in the upper troposphere a planetary wave occurs with two low pressure systems over 40° W and over North Africa on the flanks of a large anticyclone. This ridge over the East Atlantic coast induces a strong regional wind jet (more than 30 m/s) on its north-easterly flank.

2.1 Radiosonde soundings

Our institute operates a balloon sounding system (Digicora MW15, Vaisala Inc., Finland) with radiosondes of type RS 80-30 with GPS wind finding. 17 balloons were released every 3 hr on 17-19 December 1999. These measurements show a tropopause jet which is increasing from 40 m/s at 00 UT to 60 m/s at 24 UT and strong variability. An indication of downward phase propagation is found in the height region between 15 and 20 km. A standard procedure is used to analyse the temperature and wind profiles (values are regressed in 50 m height increments) by fitting a polynomial of 4^{th} order (e.g. Guest et al., 2000) in specified height regions (1-10 km; 10-18 km; 18-30 km). It is assumed that the large structure is approximated by the polynomial fit and the perturbation is defined through the difference between the measured values and the fit. A calculation of the perturbation kinetic energy gives enhanced values in all three height regions in comparison to soundings at days with weak zonal wind. A Hovmöller diagram with meridional wind perturbations is plotted in Figure 1, for lower stratosphere (10-18 km). In the lower stratosphere the downward phase propagation is indicated by long dashed lines with a typical oscillation period of about 12.5 hr and about 2 km vertical wavelength. In contrast the troposphere shows upward phase propagation with a typical period of about 26 hr and about 3.5 km vertical wavelength. These periods and vertical wavelengths have been

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confirmed by wavelet analyses and a band-pass filter method, not shown here.

In order to determine the direction of the group velocity propagation in both height regions independently the method of area preserving energy spectra has been used.

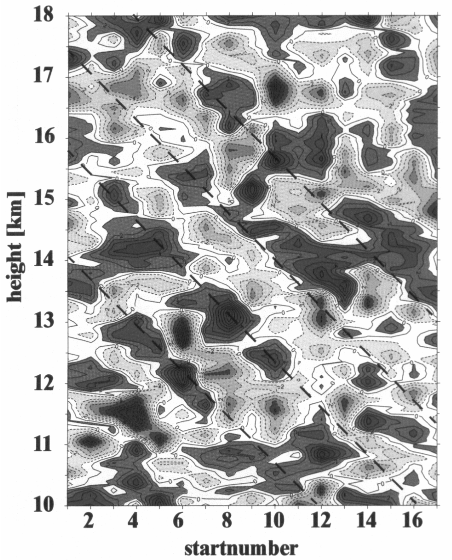

Figure 1: Height-time cross section (Hovmöller diagram) of meridional wind disturbances v´[m/s] between 10-18 km (a) and 1-10 km (b) as estimated from radiosondes started at Kühlungsborn. Dashed lines indicate phase propagation.

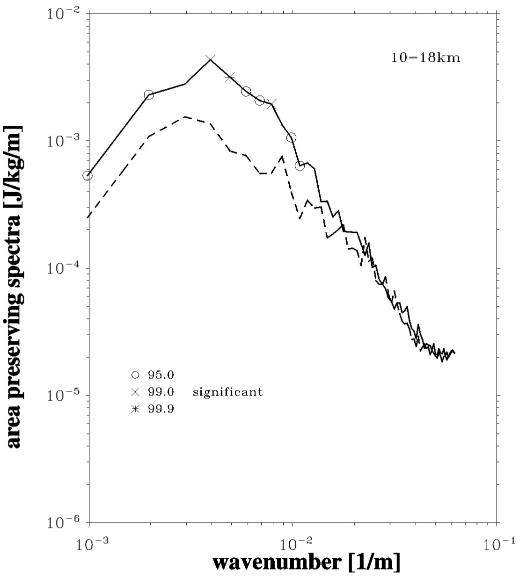

Figure 2: Averaged area preserving spectra [J/kg/m] for the cyclonic (dotted lines) and anticyclonic (full lines) components calculated from radiosondes started at Kühlungsborn with large perturbation kinetic energy. Significant differences between both curves are tested and marked by a symbol.

In Figure 2 the spectra are presented as an average over radiosonde starts (number of 10) with large perturbation kinetic energy (> 6 m^2/s^2). It was found that in the lower stratosphere, with height, the anticyclonically rotating component of the horizontal wind vector dominates and differs significantly up to wave number of 10^{-2} m^{-1} from the cyclonic one. This implies that the main energy propagation is upward. The spectrum maximum occurs for a vertical wavelength of nearly 2 km. In the troposphere the cyclonic part of the spectra is larger than the anticyclonic part for smaller wave numbers but the difference is not significant, so the upward and downward energy propagation are comparable. The spectrum maximum is given for a vertical wavelength of nearly 3.3 km. In the middle stratosphere (18-30 km) the phase propagation is also downward and the energy propagation is upward for larger wavelengths than in the lower stratosphere.

2b. Radar measurements

Since autumn 1999 a VHF–radar (53.5 MHz; 90 kW) has been operating on the ground of the IAP in Kühlungsborn. The radar system was designed for continuous measurements and is running either in the spaced antenna or in the Doppler beam swinging mode. The antenna array consists of 144 four-element Yagi resulting in a transmitting half-power beam width of 6.5°. The beam is steerable in the vertical direction and towards the North, East, South, and West with a used off-zenith angle of 7°. For this investigation we used 1024 – point complex time series sampled with 0.05 s. The radar resolves height regions from 1 to 18 km. Data are averaged over 30 minutes interval for further investigations.

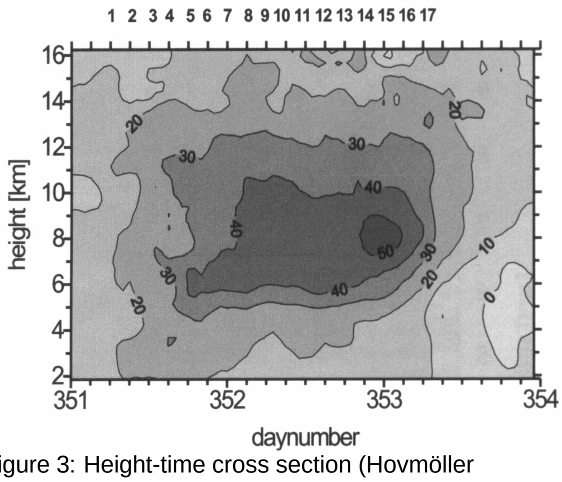

Figure 3: Height-time cross section (Hovmöller diagram) of radar zonal wind u [m/s]. Positive values are shadowed. The winds are pre-processed with 4 hr and 600 m running mean values. Gaps are filled up by linear interpolation.

In Figure 3 a Hovmöller diagram of radar measurements of zonal wind are presented starting on Julian day 351 (17 December 1999) and running over 3 days, thus overlapping the radiosonde sounding period. The zonal wind over Kühlungsborn increases up to day 353 (19 December; 00 UT) and then decreases. A mean wind of about 30 m/s occurs with a broad band of 40 m/s between 6 and 10 km. The maximum wind speed reaches 50 m/s. The meridional component shows a northerly wind with a maximum of 15 m/s about 12-18 UT on day 352 in coherence with the strong zonal jet but decays just before the zonal jet maximum occurs.

To examine possible IGW structure zonal and meridional radar measured winds are further analysed. First of all a wavelet analysis was used in order to find some of the dominant frequencies of the unfiltered data, these defining the window for band pass filtering. This was necessary because the variability changed during the 3 day period. We used a window of 14 – 30 hr and 0.8 – 4 km.

In the stratosphere the phase propagates upward with a typical oscillation period of 24 hr and a vertical wavelength of about 2.5 km. In the troposphere downward phase propagation was found about 12 hr with a vertical wavelength of about 4 km. In the lower stratosphere the direction of energy propagation is upward and in the troposphere downward but this is valid only for waves passing the applied band-pass filter.

Furthermore, radiosondes are moving away from Kühlungsborn through the wind (up to about 200 km in 2 hr) so the measured winds are not the same as the radar measured winds over Kühlungsborn. Nevertheless both measurements are useful for the identification of meso-scale wave patterns like the IGWs shown in Figure 1 if the Doppler-shifting is taken into account.

3. PARAMETER ESTIMATION

We now use linear wave theory (e.g. Gill, 1982) to estimate the wavelength and period of the observed IGW. A monochromatic IGW with a zonal wave number k and vertical wave number m is assumed to propagate upstream ($k < 0$) and downward ($m < 0$) in phase through the stratosphere as well as upward ($m > 0$) in phase through the troposphere but both in a zonal uniform background flow. Further the basic stream is parallel to the x axis so that no meridional dependence exists. In this case the intrinsic frequency w_{RS} (observed by moving with the basic stream; in a first approximation through radiosonde soundings, when the ascent rate is nearly constant and also the zonal drift velocity is constant) differs by the Doppler shifted frequency kU from frequency w_{RD} observed by fixed observer (for instance by radar measurements), it holds: $w_{RD} = w_{RS} + kU$.

For the lower stratosphere a clear picture was found in the observations. The stratospheric intrinsic frequency w^S_{RS} is known from radiosonde soundings with a typical oscillation period of 12.5 hr with upstream and downward phase propagation that means $w^S_{RS} = 1.396\ 10^{-4}\ s^{-1}$.

On the other hand the radar estimated period is 24 hr and shows a downstream phase propagation with $w^S_{RD} = -7.25\ 10^{-5}\ s^{-1}$. From the above mentioned Doppler shift it is possible to calculate the zonal wave number if the basic wind U is known. A mean value of 30 m/s was observed (Figure 3). With this value for U the following wave number results from (1): $k = (w_{RD} - w_{RS})/U = -7.08\ 10^{-6}\ m^{-1}$.

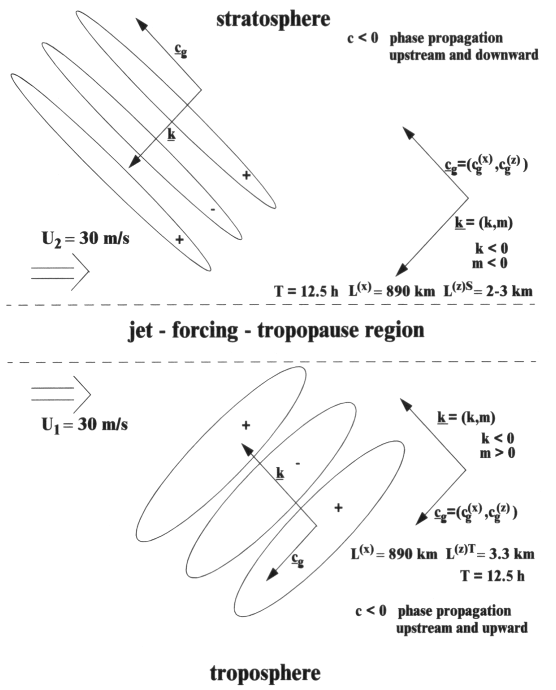

Figure 4: Scheme of primary IGW propagation and observed parameters.

A scheme of a typical wave including all observed parameters is derived in Figure 4 for this idealised IGW propagation in a constant background flow. In the stratosphere the phase propagation is upstream and downward that means the energy propagation is upstream and upward. In the troposphere the phase propagation is upstream and upward and the energy propagation is upstream and downward. The energy source is placed in the tropopause region. The characteristic vertical wavelength is about 2-3 km in the lower stratosphere and about 3.3 km in the troposphere. The zonal wavelength of nearly 890 km was observed with a typical period of nearly 12.5 hr in the lower stratosphere and troposphere. An estimation of the vertical group velocity with typical parameters of the lower stratosphere gives a value of about 2-10 km/day for a horizontal wavelength of 890 km. This is fast enough to reach the middle stratosphere during 3-5 days if the IGWs were generated in the region near the tropopause. The influence of the meridional wind gradient on the local diagnostics is relative small because of the width of the jet. But nevertheless the wind gradients play a very important role in determining the hemispheric propagation of IGWs (e.g. Dunkerton, 1984).

4. Summary

The study focuses on the appearance of IGWs downstream of a jet in the upper troposphere on the north-easterly side of an anticyclone over Mecklenburg-Vorpommern by a period from 17 to 19 December 1999. This wind streak is induced during the poleward Rossby wave breaking event (second phase) north-eastwards of the anticyclone and represents the precondition for the generation of the studied IGWs. 17 radiosonde ascents in an interval of 3 hr and VHF-radar measurements were made from Kühlungsborn during this period, and are the basis of this investigation.
In the lower stratosphere a clear picture was observed with downward and upstream phase propagation with a period of about 12.5 hr. The energy propagation was from the troposphere into the upper stratosphere. Together with the oscillation period of the VHF-radar measurements it is possible to estimate the horizontal wavelength of about 890 km under the assumptions of a uniform basic zonal wind and a monochromatic wave structure. This result is in good agreement with ECMWF analyses of the middle stratosphere. Further forecast data from German Weather Services (GME model) showed a strong IGW field in the height region from 5 to 30 km over Northern Germany. But nevertheless, in the middle stratosphere the additional generation of IGW through the polar vortex may be important.
In the troposphere the picture is more complex. Radiosonde ascents as well as VHF-radar measurements show both directions of energy propagation that means also energy propagation from the stratosphere into the boundary layer. Nevertheless from a re-evaluation of radiosonde ascents and from radar measurements in the troposphere upstream and upward IGW phase propagation with downward energy propagation was found.
By combining both results we conclude that one energy source is placed in the tropopause region just in the region of a zonal wind jet.
In summary for the studied case of an anticyclone with strong IGWs north-eastwards during the period from 17 to 19 December 1999 we found a horizontal wavelength of about 890 km and about 2-3 km in the stratosphere and about 3.3 km in the troposphere for the vertical wavelength. The IGWs are generated downstream of a jet and the phase propagation was upstream with an oscillation rate of about 12.5 hr. The energy propagation was upward in the lower stratosphere and downward in the troposphere. The possibility that an IGW could be exerted through ageostrophic instability of a special geostrophic background stream in the tropopause region is currently under investigation. The propagation of the internal IGWs into the middle stratosphere was possible through strong zonal winds over the whole height region due to the position on the edge of the polar vortex.
Under the assumption that poleward breaking Rossby waves are often observed in winter we conclude from the above discussed case that IGWs induced by breaking Rossby wave events can contribute essentially to the dynamics of the troposphere and stratosphere.

5. Acknowledgements

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