Application of the LM to Investigate the Sharpness of the Extratropical Tropopause

Tamás Szabó, Volkmar Wirth

University of Mainz

1 Introduction

At the University of Mainz the *Lokal Model* (LM) is used to investigate unexplained climatological features of the extratropical tropopause. Previously, Birner et al. (2002) found that observed average profiles of buoyancy frequency squared (N^2) in the extratropics feature a sharp peak just above the tropopause corresponding to a strong thermal inversion in that region (Fig. 1). Their results were based on (1) a large number of high resolution radiosonde measurements and (2) an averaging method that considers the thermal tropopause as a common reference level. The inversion layer was found to have a thickness of 500 – 3000 m and showed characteristic variations with season and latitude (Birner 2005). The reason for the extreme sharpness of the extratropical tropopause must be considered as an unsolved problem. There are several processes which may contribute to this phenomenon, such as balanced dynamics, gravity waves, or radiation at cloud tops. However, the degree to which any of these processes is relevant in a climatological sense is unknown. In our work we concentrate on purely dynamical mechanisms, investigating the impact of synoptic scale dynamics on the tropopause sharpness as well as the potential impact of gravity waves.

2 Theoretical background

A possible explanation for the observed tropopause sharpness was suggested by Wirth (2003), implying balanced dynamics. He found different profiles of N^2 in idealized axisymmetric

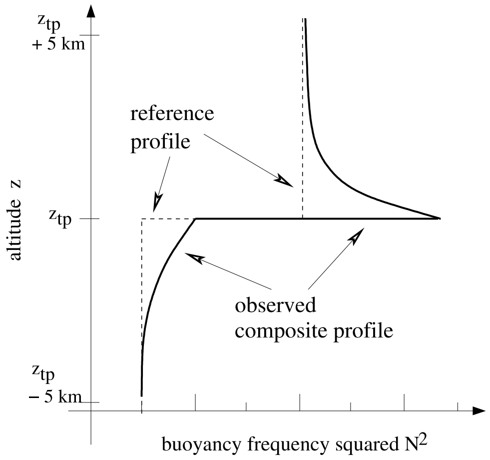

Figure 1: *Schematic representation of profiles of buoyancy frequency squared in the extratropical tropopause region. (Wirth 2004)*

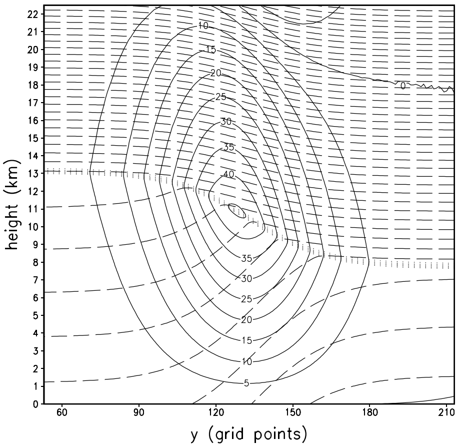

Figure 2: *Initial condition for the LM runs characterized by a jet (the solid lines depict the zonal wind in m/s) and piecewise constant N^2 (dotted). The dashed contours depict potential temperature.*

cyclonic and anticyclonic anomalies, which were produced with the help of a potential vorticity (PV) inversion technique. His anticyclones showed a sharp peak in N^2 just above the tropopause as well as increased values of N^2 below the tropopause compared to the reference profile. In contrast, his cyclones showed a smooth transition of N^2 in the tropopause region between tropospheric and stratospheric values. These features could be related to the specific partitioning of a given PV anomaly into a static stability anomaly and a vorticity anomaly, which differs between cyclonic and anticyclonic anomalies. The average N^2 from a large number of modeled profiles turned out to be qualitatively similar to the observed composite profile, showing in particular the peak just above the tropopause.

In a subsequent paper Wirth (2004) investigated the underlying mechanism. It was shown that the above-mentioned profiles are generated during the anomaly formation through the induced secondary circulation, and that the convergence of the vertical wind plays a major role during this process.

3 Model experiments and results

It is the aim of the current work to examine the proposed mechanism in a more realistic framework by performing simulations of baroclinic wave development. For this purpose the LM was configured in a channel version. Numerical experiments were carried through starting from an initial state (Fig. 2), which consists of a perturbed jet flow with piecewise constant buoyancy frequency in the troposphere ($N_t^2 = 1 \times 10^{-4}\mathrm{s}^{-2}$) and in the stratosphere ($N_s^2 = 4.5 \times 10^{-4}\mathrm{s}^{-2}$). Different model resolutions were tested, the highest of which was 0.3° in the horizontal and 125 m in the vertical direction. The high vertical resolution proved to be necessary to resolve the small scale processes in the tropopause region. In the experiments the atmosphere was dry, and a flat topography was used.

Figure 3 shows the simulation after 7 days of integration. Red and yellow colours indicate a sharp tropopause with large values of N^2 above the local tropopause, while blue and purple colours correspond to a smooth tropopause. As exemplified in this figure, the model simulations generally show a sharp tropopause in ridges and anticyclonic areas, but a smooth tropopause in troughs and cut-off cyclones. The main reason for this proved to be the convergence and divergence of the vertical wind generated during the baroclinic wave development. Figure 4 shows that a sharp tropopause appears downstream of the convergence region in an earlier stage of the wave development. This is in good qualitative agreement with the more idealized studies mentioned above.

Composite profiles of N^2 for the field in Fig. 3 are displayed in Fig. 5. The average over the entire area (red) indicates that by this stage of development the tropopause has overall slightly sharpened in comparison with the specified reference profile (black). Apparently, this is a result of averaging profiles from different locations with locally sharp or smooth tropopauses (cf. the blue and green lines in Fig. 5 and the profiles in Figs. 6 and 7). Again, this is in good qualitative agreement with the earlier studies.

However, there is at least one further mechanism in the LM simulations affecting the tropopause sharpness in addition to balanced dynamics. The single profiles in Figs. 6 and 7 indicate the presence of waves with short vertical wavelength, having a significant influence on the sharpness of the tropopause. In our simulations these waves could be identified as inertia-gravity waves, which are generated along the jet in the tropopause region during the baroclinic wave development (Figs. 8 and 9). This is in agreement with observations from the radiosonde network, which frequently show the presence of large amplitude gravity waves in the tropopause region. We tentatively conclude that these waves can influence the precise

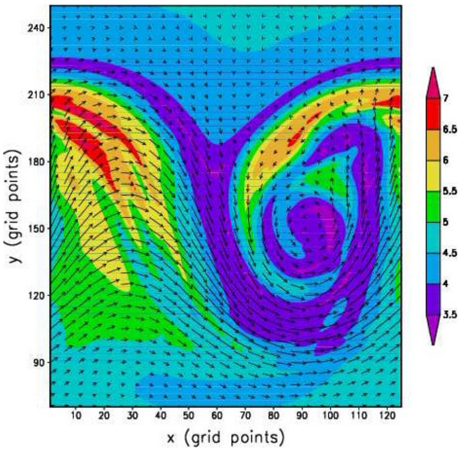

Figure 3: *Quasi-horizontal distribution of N^2 (colours, in $10^{-4}\mathrm{s}^{-2}$) and wind vectors on a surface which is 750 m above the tropopause after 7 days of integration.*

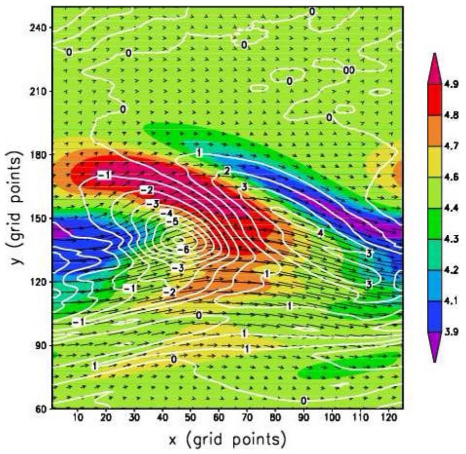

Figure 4: *Quasi-horizontal distribution of N^2 (colors, in $10^{-4}\mathrm{s}^{-2}$), wind vectors, and vertical divergence (contours, in $10^{-6}\mathrm{s}^{-1}$) on a surface which is 750 m above the tropopause after 3 days of integration.*

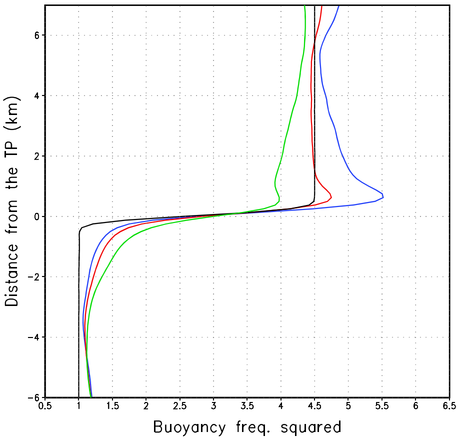

Figure 5: *Composite profiles of N^2 (in $10^{-4}\mathrm{s}^{-2}$) for the field shown in Fig. 3: average profile (red), average from the 25 percentile of profiles with the largest (blue) and the smallest (green) peaks. For comparison, the black line shows the reference profile.*

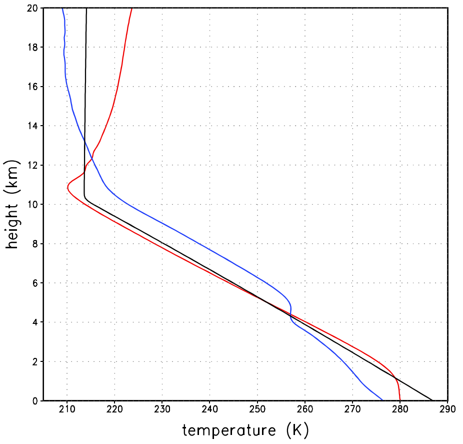

Figure 6: *Two selected temperature profiles from the field shown in Fig. 3: a profile located in the ride (red) and a profile located in the trough (blue). Also shown for comparison is the reference profile (black).*

location of the tropopause in such a way that a strong inversion — being part of the gravity wave — occurs just above the tropopause.

4 Conclusion

We have shown that synoptic scale dynamics during modeled baroclinic wave development plays a significant role for the sharpness of the extratropical tropopause. This corroborates the results from previous, more idealized studies. Key mechanism for the net sharpening is the convergence of the vertical wind during the generation of anticyclonic regions, which is more pronounced than the effect of the divergence of the vertical wind during the formation of cyclonic regions.

At the same time, our simulations indicate that there is more to the tropopause sharpness

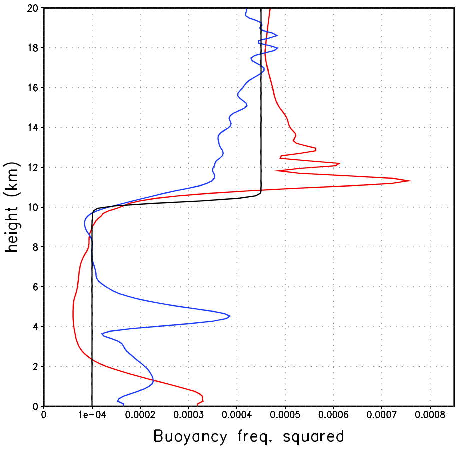

Figure 7: *Profiles of N^2 (in s^{-2}) corresponding to the profiles from Fig. 6.*

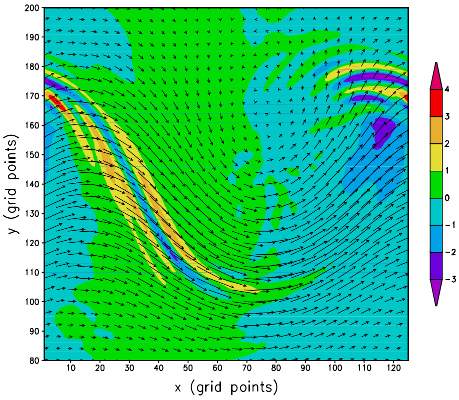

Figure 8: *Divergence of the vertical wind (colours, in $10^{-5}\mathrm{s}^{-1}$) and horizontal wind vectors at 12 km altitude after 6 days of integration.*

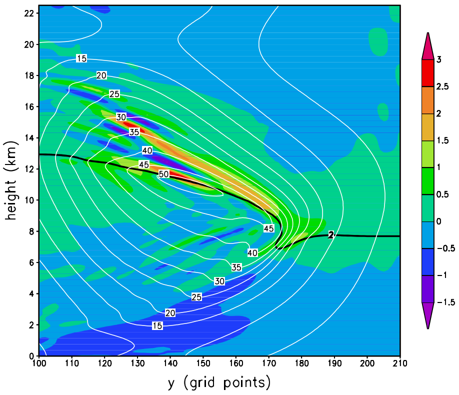

Figure 9: *Vertical cross-section of Fig. 8 at x=30, showing the divergence of the vertical wind (colours, in $10^{-5}\mathrm{s}^{-1}$), wind-speed (white contours), and the dynamical tropopause (defined as PV=2 PVU, black line).*

than just balanced dynamics. It is suggested that large amplitude gravity waves may also play an important role. We are currently investigating whether this can result in tropopause sharpening in a climatological sense.

References

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