The Effect of the Stratospheric Circulation on the Extratropical Tropopause Inversion Layer in a Relatively Simple GCM

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Abstract

Idealized GCM integrations have shown that, in the absence of complex radiative-convective processes, the dry dynamics associated with synoptic-scale baroclinic eddies are able to produce an extratropical tropopause inversion layer (TIL). This inversion layer is qualitatively similar to the observations, but weaker in amplitude and thicker in the vertical. Extending that study, the impact of the stratospheric circulation on the extratropical TIL is examined by introducing a polar vortex and a topographically-induced stratospheric variability in the idealized GCM. It is found that the stratospheric circulation only weakly affects the extratropical TIL. In particular, all integrations show that the summer hemisphere TIL is comparable to the one in the winter hemisphere, in stark contrast to the observations. While further studies are need, these results suggest that the stratospheric circulation is not a key player in setting the characteristics of the extratropical TIL. Other physical processes, notably radiation and convection, are likely to play an important role, especially for determining the different TIL structure in the summer and winter hemispheres.

Observations

- Existence : Tropopause-based ($\tilde{z}$ coordinate) T profiles show a significant inversion layer (TIL) right above the tropopause (Fig. 1).
- Amplitude & Depth: TIL is stronger & deeper in high latitudes (Fig. 2).
- Seasonal Variation : TIL is stronger & sharper in summer time (Fig. 2).

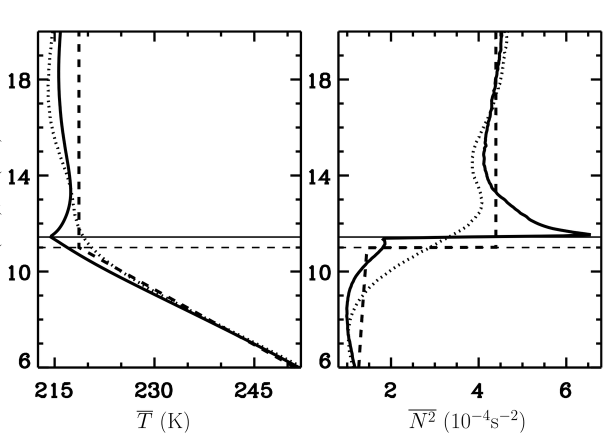


Figure 1: Averaged profiles representative of about 45°N of (left) temperature and (right) N^2. All U.S. radiosonde observations within latitude range from 41.5°N to 49.0° are included. Dotted lines indicate standard average (z coordinate), solid lines indicate tropopause-based average ($\tilde{z}$ coordinate), and dashed lines indicate profiles of the U.S. standard air at 45°N. Horizontal lines denote tropopause height. From Birner (2006).

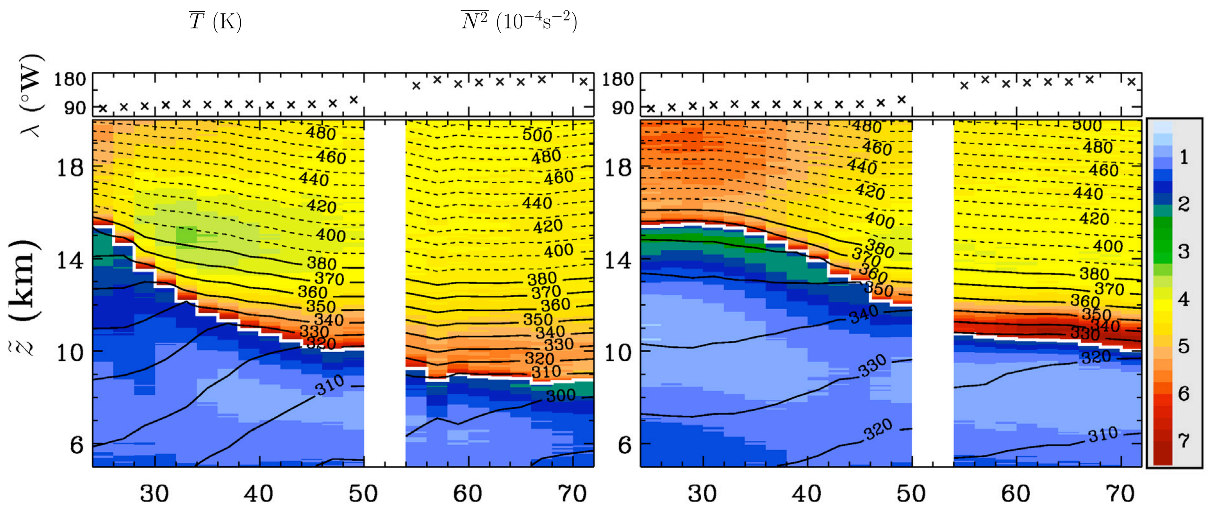
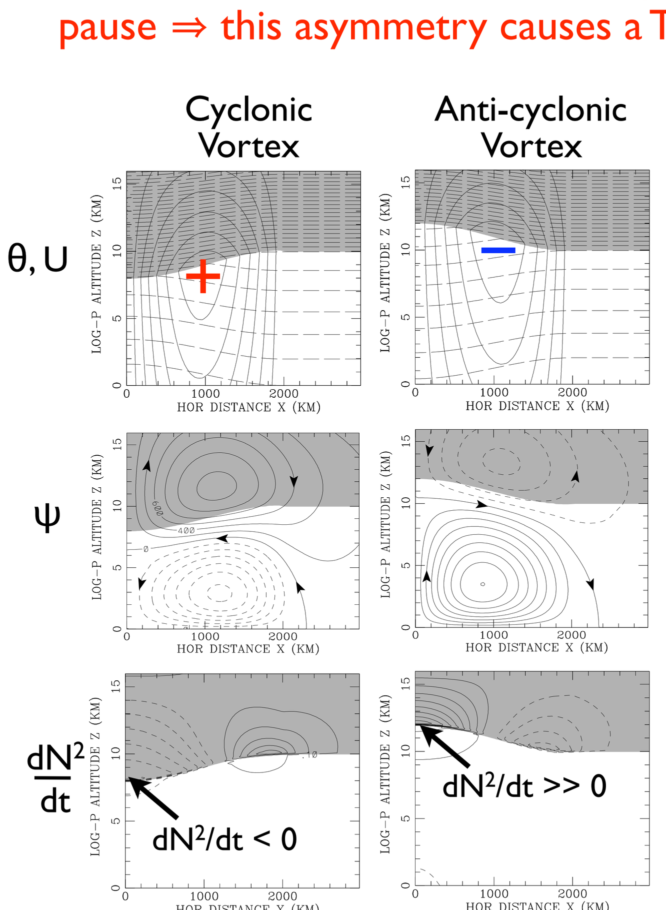


Figure 2: Zonally averaged climatological tropopause-based N^2 average for (left) DJF and (right) JJA. Shading interval is $10^{-4}s^{-2}$. Thick white area represent data gaps. Top parts of the diagrams show the average longitude at tropopause level. From Birner (2006).

Balanced PV dynamics

- Through PV inversion, Wirth (2004) found a distinct TIL associated with idealized axisymmetric vortices: very strong N^2 for anticyclonic vortices but weak N^2 for cyclonic vortices above the tropopause ⇒ this asymmetry causes a TIL.



Log-p coordinate

$$\frac{DN^2}{Dt} = -N^2\left(\frac{\partial w}{\partial z}+\frac{\kappa}{H}w\right) - \frac{g}{T_s}\frac{\partial u}{\partial z}\frac{\partial T}{\partial x} - \frac{g}{T_s}\frac{\partial v}{\partial z}\frac{\partial T}{\partial y} + \frac{g}{T_s}\frac{\partial Q}{\partial z}e^{-\kappa z/H}.$$

Assume
vortex symmetry (d/dy=0),
large horizontal scale (d/dx≈0),
small vertical scale

$$\frac{DN^2}{Dt} = -N^2\frac{\partial w}{\partial z} + \frac{g}{T_s}\frac{\partial Q}{\partial z}e^{-\kappa z/H}$$

dynamic forcing   diabatic forcing

Figure 3: Reference state corresponding to a large scale slab symmetric balanced flow with (left) a cyclonic and (right) an anticyclonic anomaly in the tropopause region: (top) potential temperature and tangential wind, (middle) azimuthal circulation, and (bottom) dN^2/dt. Shading depicts areas with stratospheric PV ≤ 2 PVU. Figures are adapted from Wirth (2004).

Questions & Approaches

- The internal variability of the stratosphere may change the TIL by modifying the vertical structure of w. How much? The effect of stratospheric circulation on the TIL is examined by introducing a polar vortex and topography to the idealized GCM (Gerber and Polvani 2008).
- GFDL dynamic core AGCM with a Held-Suarez configuration (T42L40): temperature is relaxed to the zonally symmetric equilibrium temperature profile Te, and the momentum is dissipated by a simple surface drag.
- Use last 1000 days from 1300-day long integrations. All fields are generated on the tropopause-based $\tilde{z}$ coordinate for 10 randomly chosen points.

Results

I. Equilibrium Te and N²

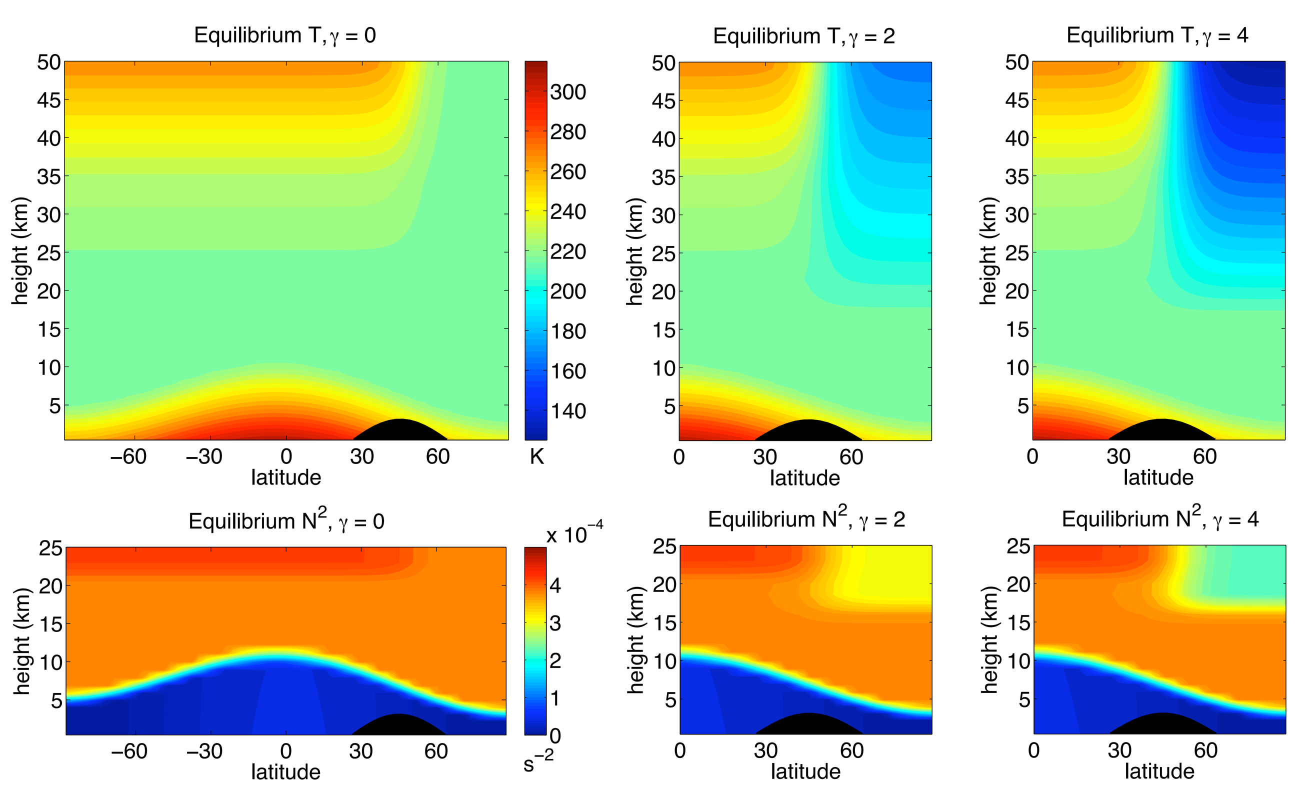


Figure 4: Te and N^2 profiles for the winter Hemisphere runs. Topography (3-km high mountains at 45°N with zonal wave number 2 pattern) is shown in black. The summer Hemisphere run is identical to γ=0 run but latitudinal structure of Te is reversed.

II. Winter Hemisphere Results

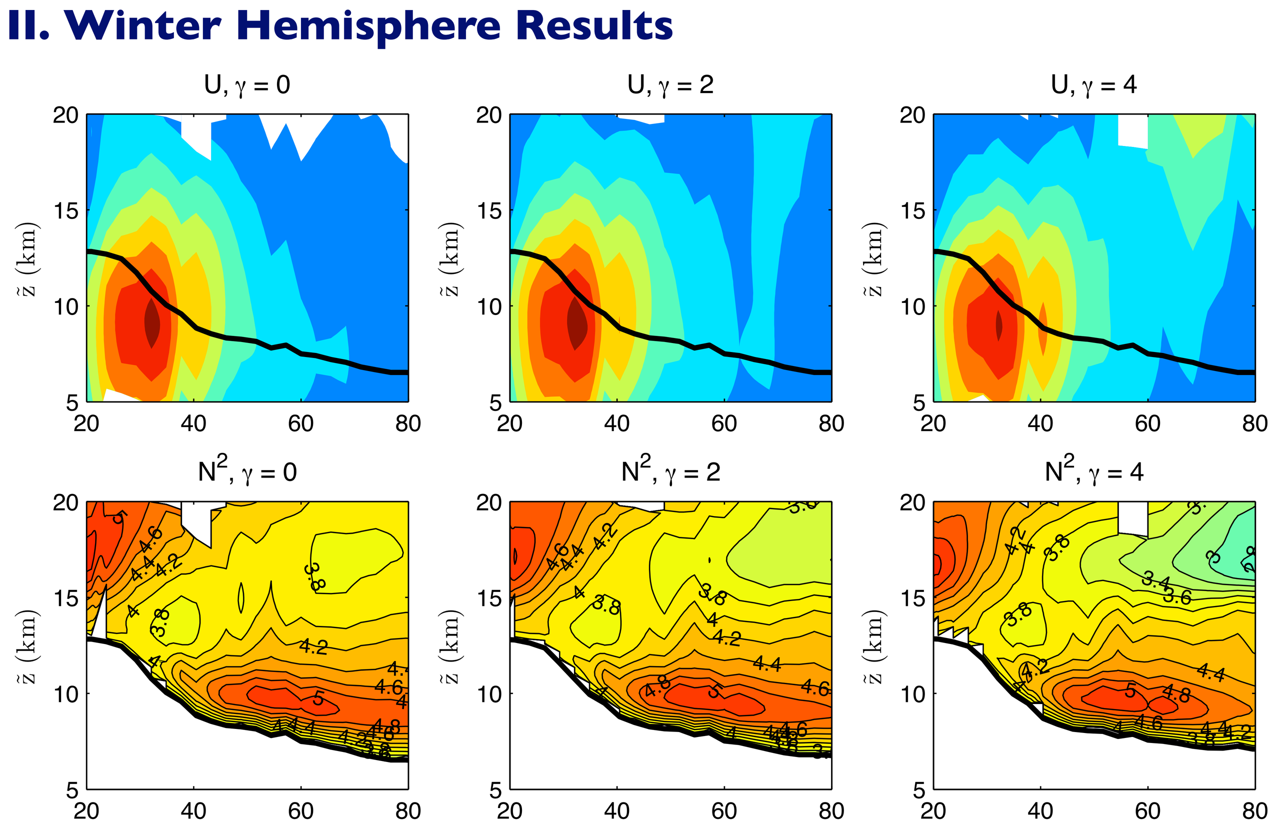


Figure 5: Results of winter Hemisphere runs: (top) $\tilde{z}$-based composite U and (bottom) N^2.

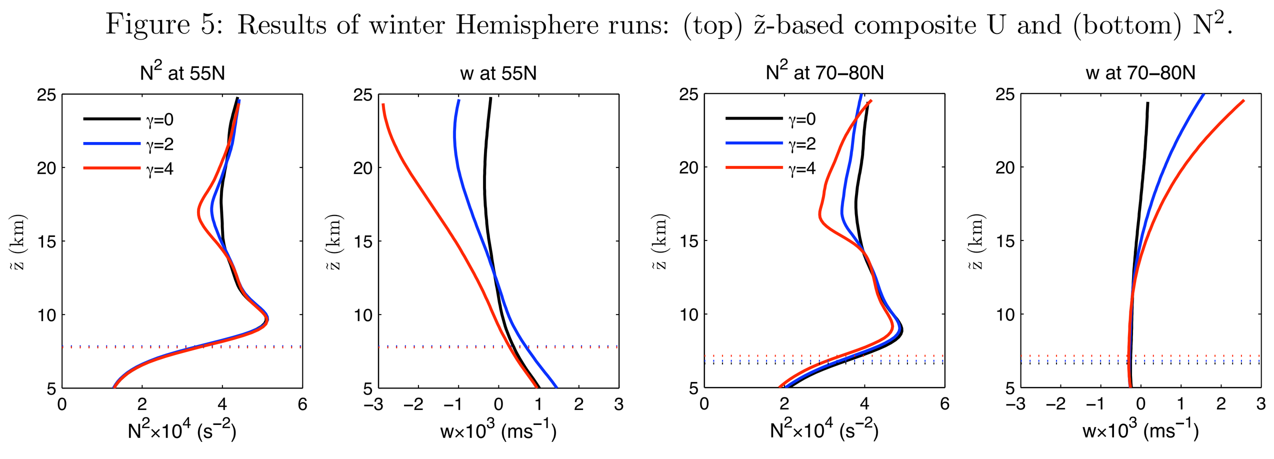


Figure 6: Results of winter Hemisphere runs: (1st, 3rd) $\tilde{z}$-based composite N^2 at 55°N and 70-80°N mean, and (2nd, 4th) w. Dotted lines denote composite tropopause height.

DEFINITIONS

TIL : Tropopause Inversion Layer. TIL amplitude : Maximum value of N^2. TIL depth : Distance from maximum to local minimum N^2. $\tilde{z}$: tropopause-based height coordinate. z : standard height coordinate.

III. Summer Hemisphere Results

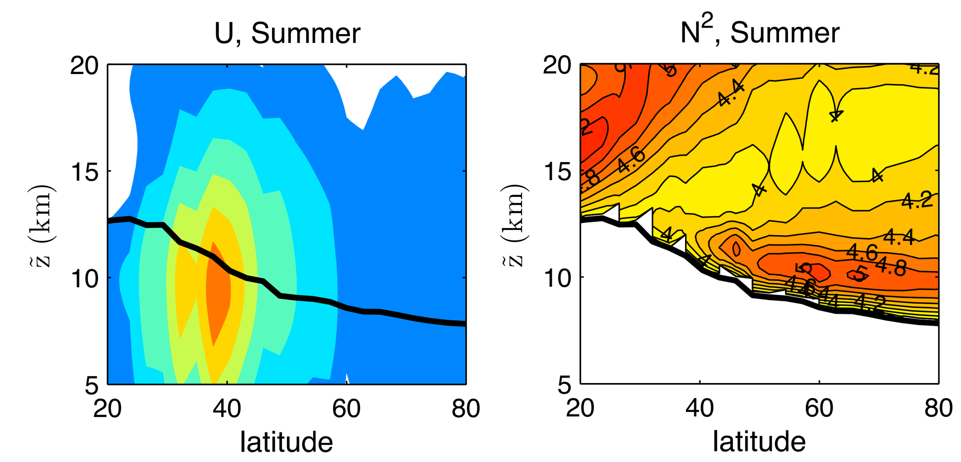


Figure 7: Results of summer Hemisphere run: (left) $\tilde{z}$-based composite U and (right) N^2.

IV. Sensitivity Tests: No Topo. & Lower Vortex

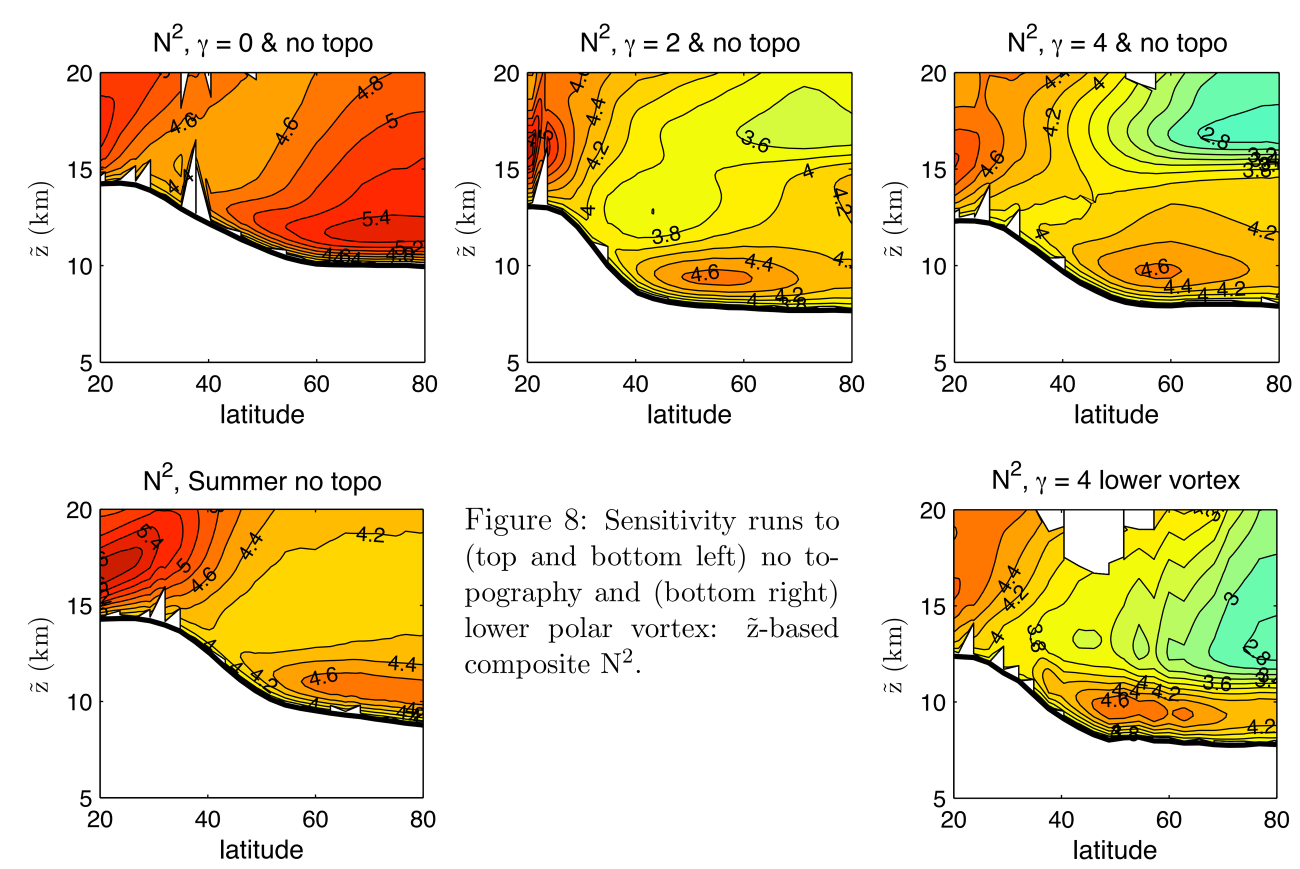


Figure 8: Sensitivity runs to (top and bottom left) no topography and (bottom right) lower polar vortex: $\tilde{z}$-based composite N^2.

RESULTS

1. Te & N^2 profiles (Fig. 4) : Te does not have a local maximum in N^2 immediately above the tropopause → No TIL in the forcings.
2. Winter Hemisphere TIL (Fig. 5) : TIL amplitude does not change as γ increases, i.e. as polar vortex strengthens.
3. Winter Hemisphere N^2 and w (Fig. 6) : w varies systematically by changing γ in the mid stratosphere. But, no change is found near the tropopause, resulting in no change in N^2 near the tropopause → No sensitivity of TIL.
4. Summer Hemisphere TIL (Fig. 7) : The summer hemisphere TIL amplitude is comparable to the one in the winter hemisphere (compare with Fig. 5 right).
5. TIL sensitivity to topography (Fig. 8) : Substantial sensitivity is found.

CONCLUSIONS

1. Impact of stratospheric circulations to TIL : Relatively weak.
2. Seasonal variations : Modeled TIL is quantitatively similar in two seasons.
3. Comparisons to observations (Fig. 2 vs. Figs. 5,7) : Modeled TIL is weaker than one in the observations. Our integrations fail to recover the seasonal difference of the TIL in the Northern Hemisphere extratropics.
4. Concluding Remarks : Although dynamical processes are able to produce the qualitative structure of the TIL, they can not capture the quantitative aspects. Other physical processes, such as radiation and convection (e.g. Randel et al. 2007), seems to be crucial for the formation the extratropical TIL.
5. Future Work : i) Longer integrations to get smoother profiles, ii) Sensitivity tests to the location of polar vortex & different topography.

References

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