# Dynamical formation of an extra-tropical tropopause inversion layer in a relatively simple general circulation model

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Received 2 May 2007; revised 6 July 2007; accepted 31 July 2007; published 5 September 2007.

[1] The key factors contributing to the formation and maintenance of the recently discovered extra-tropical tropopause inversion layer are presently unclear. In this study, it is shown that such a layer can form as a consequence of the turbulent dynamics of synoptic-scale baroclinic eddies alone, in the absence of explicitly parameterized, small-scale, radiative-convective processes. A simple general circulation model, initialized from a state of rest, and driven with idealized forcings, is found to *spontaneously* develop an inversion layer above the tropopause under a wide variety of parameter choices and model resolutions. Furthermore, such a model is able to capture, qualitatively, both the latitudinal and (in part) the seasonal dependence of the observed tropopause inversion layer. However, the inability of our simple model to capture some detailed quantitative features strongly suggests that other physical processes, beyond balanced synoptic-scale dynamics, are likely to play an important role.
**Citation:** Son, S.-W., and L. M. Polvani (2007), Dynamical formation of an extra-tropical tropopause inversion layer in a relatively simple general circulation model, *Geophys. Res. Lett.*, *34*, L17806, doi:10.1029/2007GL030564.

## 1. Introduction

[2] High vertical resolution radiosonde data has recently uncovered the existence of a well defined temperature inversion layer located just above the extratropical tropopause [*Birner et al.*, 2002; *Birner*, 2006; S. W. Bell and M. A. Geller, The tropopause inversion layer: Seasonal and latitudinal variations, representation in standard radiosonde data and global models, submitted to *Journal of Geophysical Research*, 2007, hereinafter referred to as Bell and Geller, submitted manuscript, 2007]. The ubiquity of this "tropopause inversion layer" (TIL), typically a few kilometers deep, has been confirmed by GPS radio occultation measurements; these have shown that it is present from the subtropics to the pole, in both hemispheres, and for all seasons [*Randel et al.*, 2007]. The global and persistent character of the TIL has potentially significant implications for chemical transport across the extratropical tropopause, and for the dynamical coupling between the stratosphere and the troposphere. However, owing to its recent discovery, no consensus exists regarding the formation and the maintenance of the TIL.

[3] On the one hand, the TIL may result from small scale radiative-convective processes. It is well known that strong convection is often accompanied by diabatic and/or adiabatic cooling in the upper troposphere. Since such cooling is highly localized near the tropopause [see, e.g., *Johnson and Kriete*, 1982, Figure 3a], it might be crucial to the formation of the TIL. More recently *Randel et al.* [2007] have suggested that the radiative effects due to ozone and water vapor near the tropopause may be important for the formation and maintenance of the TIL.

[4] On the other hand, *Wirth* [2003] has proposed that large scale dynamical processes might be responsible for the TIL. Using idealized, time-independent potential vorticity (PV) inversions, he showed that a TIL results from the asymmetries in the temperature fields associated with positive and negative PV anomalies. This idea has recently been extended to the time-dependent case, with short integrations of idealized baroclinic life cycles with a dry, non-hydrostatic, regional, weather prediction model [*Wirth and Szabo*, 2007].

[5] The aim of this letter is explore the role of dynamics in formation and maintenance of the TIL one step further, using a simple atmospheric general circulation model. Unlike previous work, we prescribe no initial PV anomalies, we start our global model from a state of rest, and integrate for thousands of days. The only external forcing in our model is an equilibrium profile to which the model's temperature is relaxed with a fixed time scale. Although this equilibrium profile decreases monotonically with height, we show that the model's internal dynamics *spontaneously* generate a TIL in a very robust fashion. This offers further evidence in support of Wirth's original idea that synoptic scale dynamics plays a key role in the formation and maintenance of the TIL.

## 2. Method

### 2.1. Model

[6] Our physical model consists of the dry, primitive equations in spherical geometry, which we integrate using the pseudo-spectral "dynamical core" developed at the Geophysical Fluid Dynamics Laboratory. For the reference integrations, referred to as HS, the model forcings are *identical* to those described by *Held and Suarez* [1994]. In a nutshell, the temperature is relaxed to equilibrium profile ($T_e$), and the momentum is dissipated by a simple surface drag; these forcings are zonally symmetric and the model surface is flat. The HS profile for $T_e$ at 65°N is illustrated in Figure 1 (black line): the equilibrium temperature decreases with height at a constant lapse rate in the troposphere, and is uniform in the stratosphere above a nominal tropopause level. Note that this profile, while

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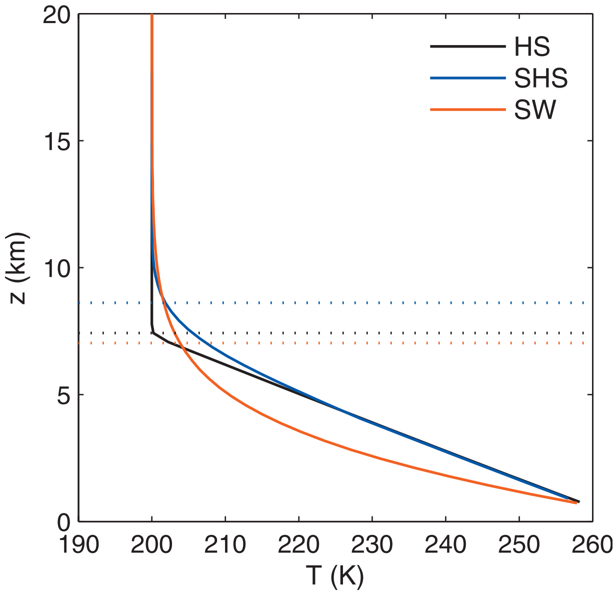


**Figure 1.** Vertical profiles of the equilibrium temperatures $T_e$ (at 65°N) used in this paper. HS denotes the profile of *Held and Suarez* [1994], SHS the smoothed version of the same, and SW the profile of *Schneider and Walker* [2006]. Dotted horizontal lines show the location of tropopause height associated with each $T_e$.

kinked around the tropopause, is continuous and never increases with height.

[7] Unless otherwise specified, we employ a horizontal triangular truncation at wavenumber 42 (referred to as "T42"), and 80 vertical levels (referred to as "L80"). In order to accurately resolve the region around the tropopause, we place it in the middle of the computational domain by setting the model top at 20 hPa (roughly 28 km); the levels are then equally spaced in log pressure, yielding a uniform vertical grid spacing of 350 m for a standard 80 level calculation. Robustness of the results to model vertical and horizontal resolution is discussed below. In all cases presented here, the primitive equations are initialized in a state of rest and integrated for 1300 days. The first 300 days are discarded, and the remaining 1000 days are used to compute the diagnostics.

### 2.2. Diagnostics

[8] The buoyancy frequency $N^2$ is the key diagnostic used to quantify the TIL in this study. Specifically, we identify the TIL with the region around the local maximum in $N^2$ immediately above the tropopause. As discussed by *Birner* [2006] and Bell and Geller (submitted manuscript, 2007), the advantage of using the $N^2$ profile, instead of the temperature profile, is that the amplitude and thickness of TIL are then more easily quantified (e.g. we define the amplitude as the maximum value of $N^2$ above the tropopause). The tropopause is here determined following the standard WMO definition [*World Meterological Organization*, 1957].

[9] In order to bring out the TIL one cannot naively compute, at each latitude-longitude grid point, the time average of the vertical profiles of $N^2$. Following *Birner et al.* [2002], we therefore construct composite profiles of $N^2$ using the tropopause-based coordinate $\tilde{z}$ as follows. At each horizontal grid point the time mean tropopause height is first computed. Then, the instantaneous $N^2$ profiles are vertically shifted so that the instantaneous tropopause is coincident to the time-mean tropopause at that grid point. This is done using a cubic spline interpolation from the vertical coordinate $z$ to the tropopause-based coordinate $\tilde{z}$. Finally, the shifted profiles are averaged, resulting in a composite profile of $N^2$ vs $\tilde{z}$ for each grid point.

## 3. Results

[10] Examples of such composite profiles of $N^2$ are shown in Figure 2, where the key results of this paper are presented. To allow a meaningful comparison with observations (which typically report vertical profiles from individual radiosonde sites), the composite profiles in Figure 2 are shown for a single grid point at 65°N and a random longitude. Of course, all curves here are independent of longitude, owing to the zonal symmetry of the model forcings and boundary conditions.

[11] In Figure 2a, the results for HS integrations at T42L80 resolution are shown. The composite vertical profile of $N^2$ (solid back line), obtained from 1000 days of model integration, exhibits a clearly distinct local maximum above the time-mean tropopause (dotted back horizontal line). Note that this maximum is absent from the $N^2$ profile associated with the equilibrium temperature $T_e$ (dashed back line), indicating that the resulting TIL is not a direct consequence of the relaxation imposed in the temperature equation. It owes its existence to the turbulent dynamics associated with synoptic scale eddies. This is confirmed by the red and blue lines, which are sub-composites based on the sign of relative vorticity at the grid point. As expected from PV thinking, the TIL is enhanced in the presence of anticyclonic disturbances (blue) and reduced for cyclonic one (red). Similar behavior has been reported in observations with GPS radio occultation data [cf. *Randel et al.*, 2007, Figure 6].

[12] While somewhat weaker and broader than in the observations, the TIL in our simple model is remarkably similar to that derived from Wirth's balanced PV inversions: contrast our Figure 2a with Figure 13a of *Wirth* [2003]. The key point is that the TIL here appears spontaneously, and is not artificially introduced by imposing PV anomalies. We stress that we have in no way tweaked parameters to get this result: the model forcings we use to compute Figure 2a are identical in every respect to those that appear in the box on page 1826 of *Held and Suarez* [1994].

[13] Although the results in Figure 2a are compelling, one might be legitimately concerned about the fact that the $T_e$ profile used to force the model in the canonical HS configuration is kinked at 100 hPa: this implies a discontinuity in $N^2$ at that level, and might arguably be crucial to the TIL formation in our model. To alleviate such concerns, we present a different model integration obtained using a smoothed $T_e$ profile, referred to as SHS. This smoothed profile, constructed by applying 40 times a simple 1-2-1 filter to the kinked $T_e$ profile in HS, is shown by the blue curve is Figure 1. The resulting $N^2$ profiles are shown in Figure 2b. Note that a clear TIL also forms when using a

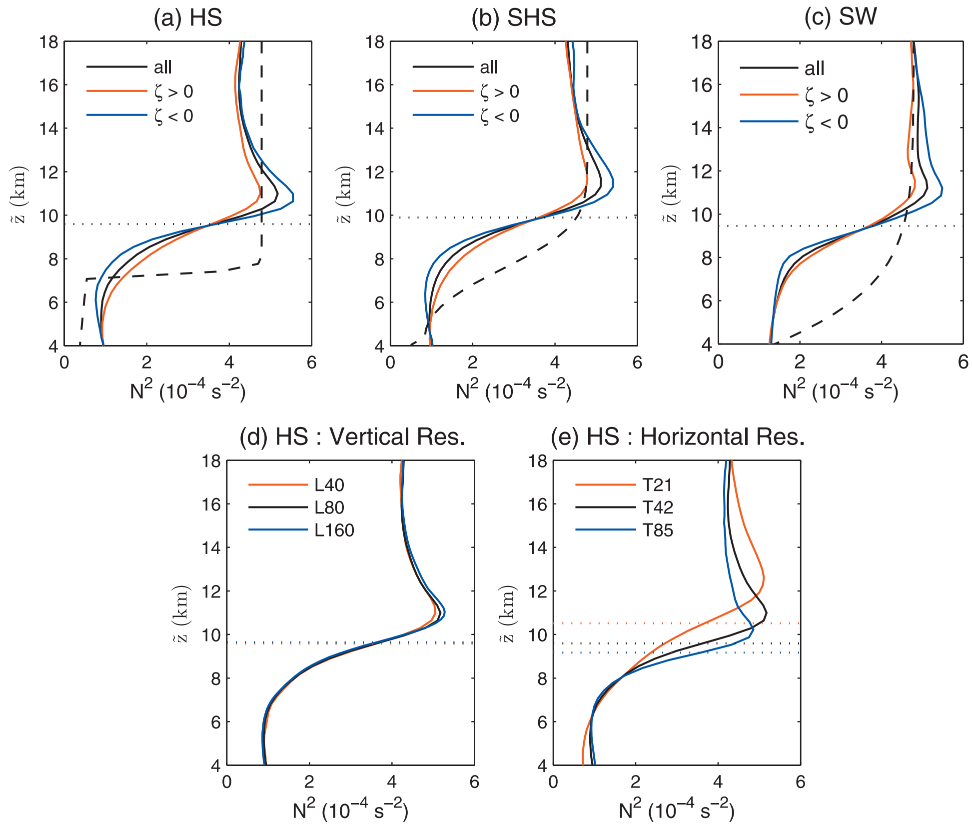


**Figure 2.** (top) Solid black lines showing composite $N^2$ at 65° from integrations of our simple model with (a) HS, (b) SHS, and (c) SW forcings, versus the tropopause-based vertical coordinate $\tilde{z}$; dashed black lines show the profile of $N^2$ associated with the equilibrium temperature $T_e$; solid red/blue lines show subcomposites for cyclonic/anticyclonic vorticity (only values greater/smaller than one standard deviation are included). (bottom) Composite $N^2$ at 65° for integrations (d) at T42 with 40, 80 and 160 vertical levels and (e) with 40 levels at T21, T42 and T85 horizontal resolutions. In all panels, the dotted horizontal line shows the time-mean tropopause height.

smoothed $T_e$ profile, albeit a slightly weaker and broader one (not surprisingly). We stress that the SHS integration is identical to the HS one in all respects, except for the $T_e$ profile.

[14] At this point, the skeptic reader might wonder whether the specific forcing choices suggested by *Held and Suarez* [1994] are, by some serendipitous coincidence, responsible for the formation of the TIL in the integrations just discussed, and whether different forcing choices would show no TIL formation. To explore this possibility, we have integrated our model with a distinct, albeit again highly idealized, set of forcings: those proposed by *Schneider and Walker* [2006], hereinafter referred to as SW. Their forcing choices are radically different from those in HS: the $T_e$ profile in SW is statically unstable (see the red curve in Figure 1), and thus the model needs to be stabilized using a dry convective adjustment. Following SW, this is done by adjusting the model temperature to a constant lapse-rate profile whenever it becomes unstable (the reader is referred to Appendix B of SW for further details). In Figure 2c, we present the $N^2$ profiles that results from a model integration with SW forcings, at the same T42L80 resolution. Again, although less cleanly, a TIL forms and is clearly correlated with the sign of vorticity, as in the previous cases. The dry convective adjustment in SW is constrained by enthalpy conservation, so that a low-level warming is compensated by upper-level cooling. As this could lead to the spurious formation of a TIL, we have carried out an SW-like integration without the enthalpy conservation constraint, and found this to yield $N^2$ profiles (not shown) that are very similar those in Figure 2c, i.e. with a clear TIL.

[15] Finally, as an ulterior validation of our results, we test robustness of the dynamical TIL formation as a function of the vertical and horizontal model resolution. Using standard HS forcings we compute at T42 with 40, 80 and 160 vertical levels; and with 80 levels at T21, T42 and T85 horizontal resolutions. The resulting $N^2$ profiles are shown in Figures 2d and 2e, respectively. Again, the key point is that a TIL emerges in all cases. Surprisingly, we find that the TIL (and the height of the tropopause itself) is highly insensitive to the model's vertical resolution, but quite sensitive to the model's horizontal resolution. From a number of additional model integrations (not shown), we have determined that this unexpected result is closely associated with the choice of sub-grid scale diffusion (in all cases presented here, we use 8th-order hyperdiffusion with a time scale of 0.1 days on the largest resolved scale), and may be thus a peculiar feature of the pseudo-spectral method.

[16] In any event, it should be abundantly clear that this study is not a parameter tweaking exercise where we try to "simulate" the observations; our model is much too simple

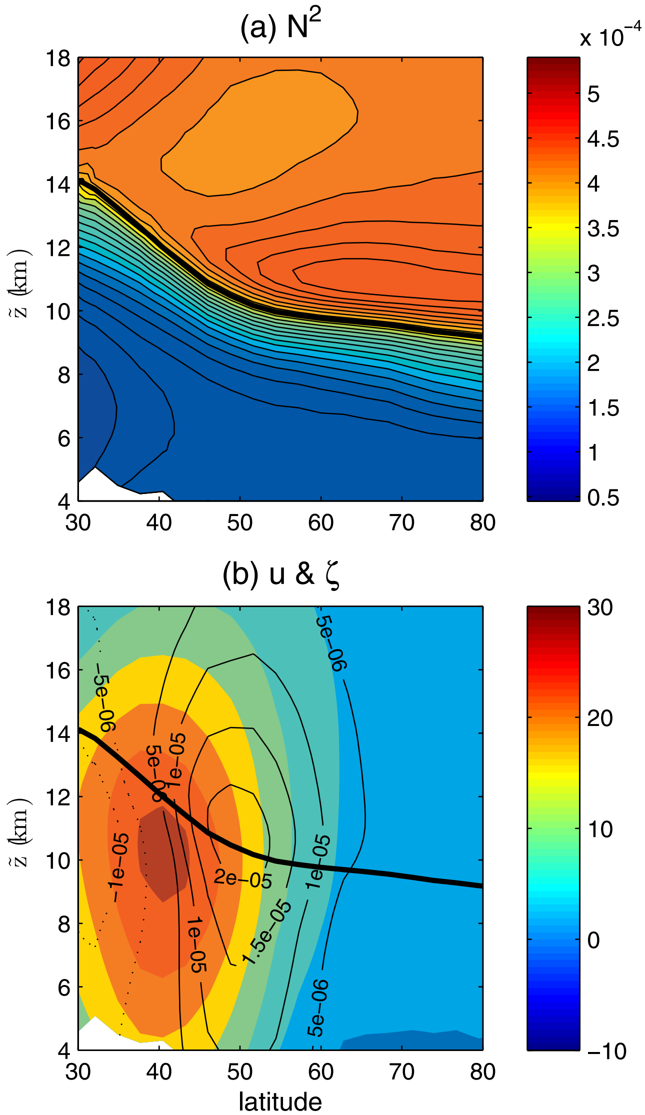


**Figure 3.** Latitude-$\tilde{z}$ profiles of (a) composite $N^2$ and (b) zonal wind (colors) and relative vorticity (contours), for the canonical HS integration. Contour/color intervals for each variable are $0.2 \times 10^{-4}$ $s^{-2}$, 5 $ms^{-1}$, and $5 \times 10^{-6}$ $s^{-1}$, respectively. Thick solid black lines in each panel show the composite tropopause height.

for that. Our aim is, quite simply, to demonstrate that synoptic scale dynamics is able to generate a reasonable TIL in the absence of other physical processes, and to do so in a very robust way. In addition, our simple model is able to capture, at least qualitatively, two other key observed features of the TIL.

[17] The first is the latitudinal dependence, illustrated in Figure 3a. Using data from the canonical HS integration (cf Figure 2a), we composite at each latitude the $N^2$ profiles from 10 grid points at random longitudes, in order to obtain a smooth map. Note how, as in the observations, the TIL in our simple model is well defined on the poleward side of midlatitude jet, shown in Figure 3b. Also, poleward of 55°N, the TIL varies little with latitude and is stronger and thicker than in mid-latitudes. This latitudinal structure is qualitatively identical to the one in the observations (compare our Figure 3a with Figure 4b of *Birner* [2006]) and, again, can be understood from simple balanced dynamics. On the poleward side of the jet, disturbances are dominated by cyclonic circulations whose amplitudes decrease with latitude (see black contours in Figure 3b). Since cyclonic disturbances tend to reduce the TIL (cf. Figures 2a–2c), stronger relative vorticity in mid-latitudes tend to reduce the TIL there, relative to the higher latitudes. Similarly, a distinct TIL would be also expected on the equatorward side of jet. However, this does not occur, either in our model or in the observations. This absence is perhaps related to the Hadley circulation, which can sporadically extend into the midlatitudes, but a full explanation will require further work.

[18] Second, it is known from observations that TIL shows a distinct seasonal dependence: it is much weaker and broader in winter than in summer [*Birner*, 2006; Bell and Geller, submitted manuscript, 2007]. A similar behavior can be captured, at least partially, with our simple model. Although our model is run without a seasonal cycle, we can mimic the seasonal difference by simply changing the amplitude $\Delta T$ of equator-to-pole temperature difference associated with the equilibrium temperature $T_e$ in our HS integrations. See *Held and Suarez* [1994, p. 1826] for the full analytic expression of $T_e$, and the appearance of the parameter $\Delta T$ herein. In addition to the canonical value $\Delta T$ = 60 K (used in Figure 2a above), we have integrated the model with $\Delta T$ = 40, 80, and 100 K. As shown in Figure 4, the TIL in our simple model becomes broader with increasing equator-to-pole temperature difference. We note, however, the amplitude of the TIL in our

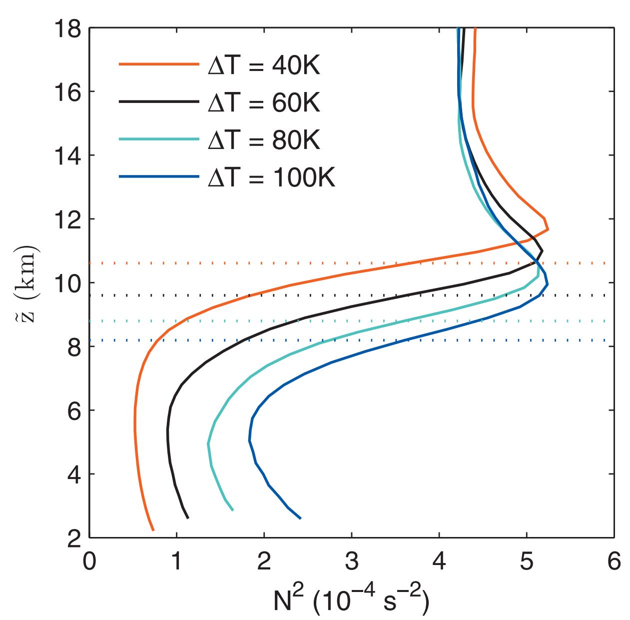


**Figure 4.** Composite $N^2$ profiles for different values of $\Delta T$, the equator-to-pole temperature difference in the equilibrium profile $T_e$, from T42L80 integrations with HS forcings. Black solid line: the canonical HS configuration ($\Delta T$ = 60 K). Other solid lines: different values of $\Delta T$, as indicated in the legend. Dotted lines show the corresponding time-mean tropopause heights.

integrations does not appear to be sensitive to $\Delta T$, and this points to a clear limitation of our simple model.

## 4. Discussion

[19] Having demonstrated, by direct numerical integration, how the turbulent dynamics associated with synoptic-scale eddies in a simple, dry, dynamical model is able to capture the generation and maintenance as well as the latitudinal and, in part, the seasonal dependences of the TIL, we now conclude by focusing on the key aspects where model falls short. First, from the integrations in Figure 2 (and many other not shown), the maximum amplitude of the TIL we have been able to produce in our model integrations is around $5.5 \times 10^{-4}$ s$^{-2}$; this is well below the maximum observed value, which can be in excess of $7 \times 10^{-4}$ s$^{-2}$. Second, our model appears unable to produce a TIL that is as sharp as the one in the observations, despite the fact that we have integrated our model to very high vertical resolution (160 levels corresponds to a vertical resolution of 175 m). Third, the amplitude of the TIL appears to be insensitive to the imposed equator-to-pole temperature difference.

[20] Since the shortcomings of our simple model are nearly identical to those reported by *Wirth* [2003], we are led to conclude that synoptic-scale balanced dynamics alone may not be sufficient to explain the precise quantitative features of the observed extra-tropical TIL. Perhaps, a proper stratospheric circulation is needed to get the correct amplitude and thickness. More likely, radiative-convective processes, as suggested by *Randel et al.* [2007], play an important role. Further modeling studies are needed to determine this.

[21] **Acknowledgments.** We are most grateful to Thomas Birner for a stimulating discussion in the early stages of this work, Tapio Schneider for the code necessary to carry out the integrations in Figure 2c (and the caveat regarding enthalpy conservation), and Marvin Geller and Bill Randel for copies of their manuscripts in advance of publication. This work is supported, in part, by a grant from the US National Science Foundation to Columbia University. LMP acknowledges the hospitality of the Morgan Stanley Children's Hospital of the New York-Presbyterian Medical Center, where the bulk of the manuscript was written.

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