



The Tropical Tropopause Inversion Layer

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Abstract.

The Tropical Tropopause Layer (TTL) acts as a 'transition' layer between the troposphere and the stratosphere over several kilometers, where air has both tropospheric and stratospheric properties. Within this region, a fine-scale feature is located: the Tropopause Inversion Layer (TIL), which consists of a sharp temperature inversion at the tropopause and a corresponding increase in static stability above.

The high static stability values reached within the TIL theoretically affect the dispersion relations of atmospheric waves like Rossby or Inertia-Gravity waves and hamper stratosphere-troposphere exchange (STE). Therefore, the TIL receives increasing attention from the scientific community, mainly in the extratropics so far. Our goal is to give a detailed picture of the properties, variability and forcings of the tropical TIL, with special emphasis on small-scale equatorial waves and the QBO.

We use high-resolution temperature profiles from the COSMIC satellite mission, i.e. ~ 2000 measurements per day globally, between 2007 and 2013, to derive TIL properties and to study the fine-scale structures of static stability in the tropics. The meteorological situation at near tropopause level is described by the 100hPa divergence fields, and the vertical structure of the QBO is provided by the equatorial winds at all levels, both from the ERA-Interim reanalysis.

We describe a new feature of the equatorial static stability profile: a secondary stability maximum below the zero wind line within the easterly QBO wind regime at about at 20-25km altitude, which is forced by the descending westerly QBO phase and gives a double-TIL-like structure. In the lowermost stratosphere, the TIL is stronger with westerly winds. We provide the first evidence of a relationship between the tropical TIL strength and near-tropopause divergence, with stronger (weaker) TIL with near-tropopause divergent (convergent) flow, a relationship similar to the TIL strength with relative vorticity in the extratropics.

To elucidate possible enhancing mechanisms of the tropical TIL, we quantify the dynamical forcing of the different equatorial waves on the vertical structure of static stability in the tropics. All waves show maximum cooling at the thermal tropopause, a warming effect above, and a net TIL en-



hancement close to the tropopause. The main drivers are Kelvin, inertia-gravity and Rossby waves.
We suggest that a similar wave forcing will exist at mid and polar latitudes from the extratropical
30 wave modes.

1 Introduction

The Tropopause Inversion Layer (TIL) is a narrow region characterized by temperature inversion and enhanced static stability located right above the tropopause. This fine-scale feature was discovered by tropopause-based averaging of high-resolution radiosonde measurements by Birner et al. (2002)
35 and Birner (2006). Satellite GPS radio occultation observations (GPS-RO) show that the TIL is present globally (Grise et al., 2010).

Static stability is a parameter used in a number of wave theory approximations, thus affecting the dispersion relations of atmospheric waves like Rossby or Inertia-Gravity waves (Birner, 2006; Grise et al., 2010). Also, static stability suppresses vertical motion and correlates with sharper trace gas
40 gradients, inhibiting the cross-tropopause exchange of chemical compounds (Hegglin et al., 2009; Kunz et al., 2009; Schmidt et al., 2010). For these reasons, the TIL attracts increasing interest from the scientific community.

There is a considerable body of research about the TIL in the extratropics, establishing the TIL as an important feature of the extratropical upper-troposphere and lower-stratosphere (Gettelman et al.,
45 2011). In the tropics, the transition between the troposphere and the stratosphere is considered to happen over several kilometers, dynamically and chemically (Fueglistaler et al., 2009; Gettelman and Birner, 2007), but less is known about the tropical TIL, as the following review will show.

In the extratropics, climatological studies have shown that the TIL reaches maximum strength during polar summer (Birner, 2006; Randel et al., 2007; Randel and Wu, 2010; Grise et al., 2010),
50 whereas the TIL within anticyclones in mid-latitude winter is of the same strength or even higher from a synoptic-scale point of view (Pilch Kedzierski et al., 2015). Several mechanisms for extratropical TIL formation/maintenance have been studied: water vapor radiative cooling below the tropopause (Hegglin et al., 2009; Kunz et al., 2009; Randel and Wu, 2010), dynamical heating above the tropopause from the downwelling branch of the stratospheric residual circulation (Birner, 2010),
55 tropopause lifting and sharpening by baroclinic waves and their embedded cyclones-anticyclones (Wirth, 2003, 2004; Wirth and Szabo, 2007; Son and Polvani, 2007; Randel et al., 2007; Randel and Wu, 2010; Erler and Wirth, 2011), and the presence of small-scale gravity waves (Kunkel et al., 2014). A high-resolution model study by Miyazaki et al. (2010a, b) suggests that radiative effects dominate TIL enhancement in polar summer whereas dynamics are the main drivers in the remaining
60 latitudes and seasons.

On the other hand, very little research has focused on the tropical TIL. Bell and Geller (2008) showed the TIL from one tropical radiosonde station, and Wang et al. (2013) reported a slight weak-



ening of the tropical TIL between 2001–2011. Grise et al. (2010) included the horizontal and vertical variability of the tropical TIL in their global study about near-tropopause static stability, which is so far the most detailed description of the TIL in the tropics. They found the strongest TIL centered at the equator in the layer 0–1 km above the tropopause, peaking during NH winter. This agrees well with the seasonality and location of tropopause sharpness as described later by Son et al. (2011) and Kim and Son (2012). The horizontal structures in seasonal mean TIL in the tropics are reminiscent of the equatorial stationary wave response associated with climatological deep convection (Grise et al., 2010; Kim and Son, 2012). Grise et al. (2010) also noted that static stability is enhanced in the layer 1–3 km above the tropopause during the easterly phase of the quasi-biennial oscillation (QBO).

Equatorial waves influence the intraseasonal and short-term variability of the temperature structure near the tropical tropopause (Fueglistaler et al., 2009). Kelvin waves and the MJO were reported as the dominant modes of temperature variability at the tropopause region (Kim and Son, 2012). Equatorial waves cool the tropopause region (Grise and Thompson, 2013), and also produce a warming effect above it (Kim and Son, 2012). This wave effect forms a dipole that can sharpen the gradients that lead to TIL enhancement, but no study has quantified this effect so far.

Our study aims to describe the tropical TIL, its variability and forcings in detail, in order to increase the knowledge about its properties and highlight this sharp and fine-scale feature within the tropical transition layer between the troposphere and the stratosphere. Section 2 will show the datasets and methods used in our analyses. Section 3 will describe the vertical and horizontal structure and day-to-day variability of the TIL, its relationship with near-tropopause divergence, and the influence of the QBO on the vertical structure of static stability and TIL strength in particular. In section 4 we quantify the dynamical forcing of the different equatorial waves and their effect on the mean temperature and static stability profiles in tropopause-based coordinates. Section 5 will discuss the applicability of our results with equatorial wave forcing to the extratropical TIL, given the different wave spectrum in the extratropics, and section 6 sums up the results.

2 Data and Methods

2.1 Datasets

We analyze temperature profiles from satellite GPS radio occultation (GPS-RO) measurements. These have a high vertical resolution of 100 m from the surface up to 40 km altitude, comparable to high-resolution radiosonde data. The advantage of GPS-RO is based on its global coverage, high sampling density of ~ 2000 profiles/day, and weather-independence. We mainly use data from the COSMIC satellite mission (Anthes et al., 2008) for the years 2007–2013. For Figure 1 only, we added two earlier GPS-RO satellite missions: CHAMP (Wickert et al., 2001) and GRACE (Beyerle et al., 2005), which provide less observations (around 200 profiles/day together) for 2002–2007.



The meteorological situation at near-tropopause level is retrieved from the ERA-Interim reanalysis (Dee et al., 2011). We make use of divergence and geopotential height fields at 100hPa on a $2.5^\circ \times 2.5^\circ$ longitude-latitude grid and 6-hourly time resolution, and also daily-mean vertical profiles of the zonal wind at the equator, for the time period 2007-2013. We choose the 100hPa level because it's the standard pressure level from ERA-Interim that is closest to the climatological tropopause in the tropics (96-100hPa in summer, 86-88hPa in winter, Kim and Son (2012)).

2.2 TIL Strength Calculation

We define the tropopause height (TP_z) by the lapse-rate tropopause WMO criterion (WMO, 1957). Given the strong negative lapse-rate found above the tropopause near the equator, the lapse-rate tropopause nearly coincides with the cold-point tropopause most of the time. This is in agreement with earlier studies, which did not find substantial differences in their results applying different tropopause definitions (Grise et al., 2010; Wang et al., 2013). From the GPS-RO temperature profiles, vertical profiles of static stability are calculated as the Brunt-Väisälä frequency squared (N^2 [s^{-2}]):

$$N^2 = g/\Theta \cdot \partial\Theta/\partial z$$

where g is the gravitational acceleration, and Θ the potential temperature. Profiles with unphysical temperatures or N^2 values (temperature $<-150^\circ\text{C}$, $>150^\circ\text{C}$ or $N^2 > 100 \times 10^{-4} s^{-2}$) and those where the tropopause cannot be found have been excluded. TIL strength (sTIL) is calculated as the maximum static stability value (N_{max}^2) above the tropopause level. This sTIL measure is commonly used (Birner et al., 2006; Wirth and Szabo, 2007; Erler and Wirth, 2011; Pilch Kedzierski et al., 2015), because it makes sTIL independent of its distance from the tropopause and N^2 is a physically relevant quantity. Our algorithm searches for N_{max}^2 in the first 3km above TP_z , but most often finds it in the first kilometer.

2.3 Mapping of TIL Snapshots

The procedure to derive daily TIL snapshots in this study is similar to the method by Pilch Kedzierski et al. (2015), but with a longitude-latitude projection.

The daily TIL snapshots were estimated at a 5° longitude-latitude grid between 30°S - 30°N . For each grid point we calculate the mean N_{max}^2 from all GPS-RO profiles within $\pm 12.5^\circ$ longitude-latitude to account for the lower GPS-RO observation density in the tropics compared to the extra-tropics (Son et al., 2011). This setting avoids empty gaps appearing in the maps, and smooths out undesired small-scale features that cannot be captured with the current GPS-RO sampling.

We also produce similar maps of 100hPa divergence. For a fair comparison with the TIL snapshots, we equal the spatial scale and follow the same method, but instead of averaging N_{max}^2 values, we use the collocated divergence of each GPS-RO profile: the value from the nearest ERA-Interim



130 grid point and 6h time period to each observation. Examples of TIL snapshots can be found in Figure 2 (section 3.1.2). If plotted at full horizontal resolution, divergence would show small-scale features superimposed over the synoptic-to-large scale structures in Fig. 2, making the comparison with N_{max}^2 more difficult.

2.4 Wavenumber-Frequency Domain Filtering

135 Our purpose is to extract the temperature and N^2 signature of the different equatorial wave types on the zonal mean vertical profiles. For this, we follow Wheeler and Kiladis (1999), that studied equatorial wave signatures on the outgoing longwave radiation (OLR) spectrum observed from satellites by wavenumber-frequency domain filtering. Wheeler and Kiladis (1999) give an in-depth description of the theoretical and mathematical background of the filtering methods.

140 Theoretically, the equatorial wave modes are the zonally and vertically propagating, equatorially trapped solutions of the 'shallow water' equations (Matsuno, 1966; Lindzen, 1967) characterized by four parameters: meridional mode number (n), frequency (ν), zonal planetary wavenumber (s) and equivalent depth (h). Each wave type (Kelvin, Rossby, the different modes of Inertia-Gravity waves) has a unique dispersion curve in the wavenumber-frequency domain, given its mode n and equivalent
 145 depth h .

Wheeler and Kiladis (1999) found that the equatorial OLR power had spectral signatures that were significantly above the background. The signature's regions in the wavenumber-frequency domain match with the dispersion curves of the different equatorial wave types. Also, they found signatures outside of the theoretical wave dispersion curves that have characteristics of the Madden-Julian
 150 oscillation (MJO) (Madden and Julian, 1994).

Our method is similar to that of Wheeler and Kiladis (1999), but analyzes temperature and N^2 at all levels between 10-35km altitude instead of OLR. For filtering, the data must be periodic in longitude and time and cover all longitudes of the equatorial latitude band. Therefore, the COSMIC GPS-RO profiles (Anthes et al., 2008) need to be put on a regular longitude grid on a daily basis. We
 155 explain how this is done in the following section (2.4.1). More details about our proceeding with the filter, and the differences from Wheeler and Kiladis (1999) can be found in section 2.4.2. Note that this method is only used in Figs. 5 and 6 (section 4).

2.4.1 Gridding of GPS-RO profiles

The COSMIC GPS-RO temperature profiles between 10°S-10°N are gridded daily on a regular longitude grid with a 10° separation. At each grid point, the profiles of that day within 10°S-10°N and
 160 +5° longitude are selected to calculate a tropopause-based weighted average temperature profile and the corresponding N^2 vertical profile:

$$T_{grid}(\lambda, Z_{TP}, t) = \sum_i w_i T_i(\lambda, Z_{TP}, t) / \sum_i w_i$$



$$N_{grid}^2(\lambda, Z_{TP}, t) = \sum_i w_i N_i^2(\lambda, Z_{TP}, t) / \sum_i w_i$$

165 where λ is longitude, Z_{TP} is the height relative to the tropopause and t is time. The weight w_i is an e-fold function that depends on the distance of the GPS-RO profile from the grid center, taking longitude, latitude and time (distance from 12UTC):

$w_i = \exp(-[(D_x/5)^2 + (D_y/10)^2 + (D_t/12)^2])$, where D are the distances in °longitude (x subscript), °latitude (y) and time (t), divided by the maximum distance allowed from the grid point in
 170 each dimension: 5° longitude, 10° latitude, and 12 hours from 12UTC.

The gridded tropopause height (λ, t) is calculated with the same weighting of all profiles' tropopauses. The tropopause-based temperature and N^2 profiles are then shifted, as the last step, onto a vertical ground based scale from 10km to 35km altitude, obtaining a longitude-height array for each day for 2007-2013.

175 Most often 2-3 profiles are selected for averaging at a grid point with these settings, although one GPS-RO profile is sufficient to estimate a grid point. However, in a 6.5% of the cases the algorithm doesn't find any profile. To fill in the gaps, the longitude range to select the profiles is incremented to $\pm 10^\circ$ instead of $\pm 5^\circ$, which still leaves a 0.8% of empty grid-points. For this minority, profiles are selected within ± 1 day and $\pm 15^\circ$ longitude. In all cases the weighting function remains the same.

180 These exceptions are for a very small portion of the gridded data, and therefore don't affect the retrieved wave signatures after filtering.

Our method is essentially an update from Randel and Wu (2005). It is adapted for the higher number of GPS-RO retrievals of the COSMIC mission compared to its predecessors CHAMP and GRACE: Randel and Wu (2005) used a 30° longitude grid and selected profiles for ± 2 days, while
 185 we use 10° spacing and profiles of the same day. This leads to increased zonal resolution, as well as a minimized temporal smoothing. Another difference is that we do the averaging in tropopause-based coordinates, and also use latitude differences in the weighting function. Compared to earlier studies that filtered equatorial waves using GPS-RO data (Randel and Wu, 2005; Kim and Son, 2012), our daily fields with barely any running mean allow the analysis of waves with higher frequencies and
 190 wavenumbers (i.e. a wide part of the inertia-gravity wave spectrum) that otherwise are smoothed out and not accounted for.

2.4.2 Filter Settings

With the longitude-height-time array of gridded temperature and N^2 profiles obtained according to section 2.4.1, we proceed with the filtering in the wavenumber-frequency domain as follows. For
 195 each vertical level (from 10km to 35km height with 0.1km vertical spacing), a longitude-time array is retrieved, detrended and tapered in time. Then, a space-time bandpass filter is applied using a two-



dimensional Fast Fourier Transform. This is done using the freely available 'kf-filter' NCL function (Schreck, 2009).

The bandpass filter bounds in the wavenumber-frequency domain are defined for the following wave types: Kelvin waves, Rossby waves, and all modes of Inertia-Gravity waves: $n = (0,1,2)$. We separate westward-propagating (negative wavenumber s) Inertia-Gravity waves (WIG_n), the eastward-propagating ones (positive s , EIG_n), and the zonal wavenumber zero ($s=0$ IG_n) in the analysis. Including the MJO band (which doesn't belong to any theoretical dispersion curve), we end up with 12 different bandpass filters that are applied to the longitude-time array of gridded temperature and N^2 , at each vertical level separately. The exact filter bounds are listed in Table 1. They are similar to the ones used by Wheeler and Kiladis (1999) and take into account the faster and not convectively coupled Kelvin waves found by Kim and Son (2012) in the tropopause temperature variability spectrum. We also allow faster WIG_0 and Rossby waves in the corresponding filters. Note that the filter bounds defined in Table 1 never overlap in the wavenumber-frequency domain. After filtering, we obtain a daily longitude-height section with the 12 waves' temperature and N^2 signatures. We stress that the temperature and N^2 fields are filtered independently at each vertical level.

3 Three-Dimensional Structure and Variability of the TIL

3.1

3.1.1 Temporal variability of the vertical N^2 profile

We first focus on the variation of the equatorial N^2 profiles over time. Figure 1 shows the daily evolution of the equatorial (5°S - 5°N) zonal mean N^2 profile between 2002-2013, with zonal wind contours superimposed (black westerlies, and dashed easterlies), and a grey tropopause line. The years 2002-2006 appear noisier because the number of observations from the CHAMP (Wickert et al., 2001) and GRACE (Beyerle et al., 2005) satellite missions is about 10 times less than the amount of profiles from COSMIC (Anthes et al., 2008) used between 2007-2013. Therefore local anomalies have a bigger impact on the zonal mean vertical profile during 2002-2006.

The tropopause height in Fig. 1 has a seasonal cycle with a generally higher (lower) tropopause and higher (lower) values of N^2 right above it during the NH winter (summer) months, in agreement with the climatological seasonal cycle described by Grise et al. (2010).

The daily evolution of N^2 also shows a secondary maximum below the zero wind line (bold black), at the easterly side of the descending westerly QBO phase, between 20-25km height. The zero wind line (of the descending westerly QBO phase) usually crosses the $\sim 20\text{km}$ level in summer, while crossing the $\sim 25\text{km}$ level in the earlier winter. This happens in 2002, 2004, 2006, 2008 and 2013, with the exception of 2011 when the zero wind line crosses $\sim 25\text{km}$ in summer. The enhanced



N^2 is present under the zero wind line all the way from 35km altitude, but it is most evident in winter and spring (~ 25 km altitude and below). In winter and spring the secondary maximum of N^2 (red, about $8 \times 10^{-4} s^{-2}$) is close to the TIL strength (brown, about $9 \times 10^{-4} s^{-2}$ in the first kilometer above the tropopause), forming a double-TIL structure in static stability. In the case of 2011, when

the secondary maximum appears in summer it is much weaker, probably due to the fact that N^2 is generally weaker throughout the whole lower stratosphere in summer (Fig. 1). We also note that during the descending easterly QBO phase N^2 is enhanced above the zero wind line, again within the easterly wind regime. This time, the enhanced N^2 is much weaker than in the descending westerly QBO phase case, and only discernible in the lowermost stratosphere.

Grise et al. (2010) found a significant correlation of enhanced N^2 in the layer 1-3km above the TP when easterlies were present in the lowermost stratosphere, while no clear correlation was found in the 0-1km layer above the TP. From Fig. 1 we deduce that this correlation of the 1-3km layer originates in the secondary N^2 maximum found below the zero wind line of the descending westerly QBO (or above the zero line of the descending easterly QBO to a lesser degree, within the easterly QBO wind regime in any case). The QBO influence on the TIL, strictly the absolute N^2_{max} that is found in the first kilometer above the TP, is hard to discern in Fig. 1. We investigate this in more detail in the subsection 3.3.

3.1.2 Horizontal structure of TIL strength

Figure 2 shows daily snapshots of TIL strength ($sTIL$, N^2_{max}) and collocated divergence (see section 2.4.1) between $30^\circ S$ - $30^\circ N$, together with 100hPa geopotential height contours, for four different days: two winter cases (left) and two summer cases (right), as examples representative of the variability in strength and zonal structures of the tropical TIL between 2007 and 2013.

The first remarkable aspect of the tropical TIL is that the magnitude of N^2_{max} is much higher than in the extratropics. Values near the equator vary between 9 - $15 \times 10^{-4} s^{-2}$ and reach the $20 \times 10^{-4} s^{-2}$ mark sometimes, compared to a $sTIL$ of 8 - $10 \times 10^{-4} s^{-2}$ generally found in polar summer or within ridges in mid-latitude winter (Pilch Kedzierski et al., 2015). This can be attributed to the background temperature gradient in the lower stratosphere in the tropics, with a strong negative lapse-rate and a higher background lower-stratospheric N^2 . When a temperature inversion is added to this background profile, the potential temperature gradient just above the TP skyrockets, giving the enormous N^2_{max} values observed in Fig. 2. The N^2_{max} is very narrow and not always found at the exact same distance from the tropopause. Thus, when a zonal mean N^2 profile is computed, the high N^2_{max} values get slightly smoothed out (Pilch Kedzierski et al., 2015). This is why the N^2 values in the first kilometer above the tropopause in Fig. 1 are lower than in Fig. 2.

As observed by Grise et al. (2010), in Fig. 2 we find that the strongest TIL is almost always centered at the equator, pointing towards equatorially trapped wave modes as TIL enhancers (which we analyze in section 4). When the $sTIL$ zonal structure is compared to 100hPa divergence and



geopotential height, it can be observed that higher N_{max}^2 is in general near regions of divergent flow (blue in Fig. 2) and a higher 100hPa surface. This high-low behavior with stronger-weaker TIL highly resembles the cyclone-anticyclone relationship with sTIL found in the extratropics (Randel et al., 2007; Randel and Wu, 2010; Pilch Kedzierski et al., 2015).

So far, Figs. 1 and 2 confirm the vertical/horizontal structures of the TIL and its seasonality from earlier studies Grise et al. (2010); Kim and Son (2012), while reporting new features: the TIL relation with near-tropopause divergence (which we analyze next in section 3.2) and a secondary N^2 maximum above the TIL region driven by the QBO, whose influence on the TIL is analyzed in section 3.3.

3.2 Relationship with Divergence

In this subsection, we have a closer look at the relationship of the zonal structure of the tropical sTIL with its collocated divergence as shown in Fig. 2. For this, we bin sTIL and tropopause height depending on the divergence value collocated with each GPS-RO observation, and make a mean within each divergence bin, as previous studies did with relative vorticity in the extratropics (Randel et al., 2007; Randel and Wu, 2010; Pilch Kedzierski et al., 2015). The resulting divergence versus sTIL diagrams are shown in Figure 3. In both summer and winter (Figs. 3 a, b) sTIL increases with divergence: from $11\text{--}12 \times 10^{-4} \text{ s}^{-2}$ found with convergent flow (negative values) or near-zero divergence, increasing steadily up to almost $15 \times 10^{-4} \text{ s}^{-2}$ with increasingly divergent flow. The sTIL relation with divergence shown in the diagrams from Figs. 3 a and b is very similar to that of relative vorticity versus sTIL in the extratropics from earlier studies (Randel et al., 2007; Randel and Wu, 2010; Pilch Kedzierski et al., 2015). We also note that the N_{max}^2 in winter is always slightly higher than in summer for any divergence value, in agreement with the seasonality with stronger TIL in winter from Fig.1 and the climatology by Grise et al. (2010). There is no clear link between a higher tropopause and a stronger TIL. The variation of tropopause height with divergence is marginal (see Appendix A, figure A1).

Given the results with divergence from Figures 2 and 3, and the resemblance with the sTIL relationship with relative vorticity in the extratropics, the question arises whether the tropical and extratropical TIL could share the same enhancing mechanism. We postulate an affirmative answer.

The modelling experiments of Wirth (2003, 2004) showed that the stronger TIL in anticyclones in the extratropics was caused by two mechanisms: tropopause lifting and cooling (therefore the higher tropopause with anticyclonic conditions found by Randel et al. (2007); Randel and Wu (2010)); and vertical wind convergence above the anticyclone due to the onset of a secondary circulation between the cyclones and the anticyclones. In the tropics, the tropopause height effect is absent, but there is a clear relationship between sTIL and divergence (Fig. 3a and 3b). Such a horizontally divergent flow is coupled with vertical convergence for continuity reasons, which is a simplified balance in



the tropics in the absence of the Coriolis force. We propose that vertical wind convergence near the tropopause is the mechanism enhancing the TIL at both tropical and extratropical latitudes.

Vertical wind convergence is related to anticyclones within baroclinic waves in the extratropics, but tropopause lifting (cooling) and the stratospheric residual circulation also enhance the TIL at the same time (Birner, 2010). In a similar way, we expect that the (100hPa) vertical wind convergence in the tropics is related to the equatorial wave spectrum, enhancing the tropical TIL along with other mechanisms (e.g. radiative forcing from water vapor or clouds). The equatorial wave forcing of the tropical TIL is studied in detail in section 4.

3.3 QBO influence

In Fig. 1 we showed that a secondary maximum of N^2 forms within the easterly wind regime of the QBO, just below the zero wind line of the descending westerly QBO phase, giving a double-TIL structure in the vertical N^2 profile in the lowermost stratosphere. This secondary N^2 maximum is responsible for the correlation of enhanced N^2 in the layer 1-3km above the tropopause during the easterly phase of the QBO found by Grise et al. (2010). However, no correlation was found in the layer 0-1km above TP (strictly where the TIL shall be), and no clear difference in TIL strength can be observed (Fig. 1) during the different phases of the QBO. We investigate this in more detail here, looking at the N_{max}^2 values found right above the TP instead of averaging over a certain layer.

To define the QBO phase, we take the zonal wind regime in the lowermost stratosphere, nearest to the TIL: around 18-20km altitude, which can be observed in Fig. 1 (black and dashed contour lines). We take two seasons of the same QBO phase in each case from the period between 2007-2013. The easterly phase of the QBO is found in the summers of 2007 and 2012 and the following winters of 2007/08 and 2012/13; while the westerly phase of the QBO is found in winters of 2008/09 and 2010/11 and the following summers of 2009 and 2011.

Figure 4 shows the distribution of N_{max}^2 for both winter (left, DJF) and summer (right, JJA). The black lines denote the average distribution over the 2007-2013 period, compared to easterly QBO phase (blue) and westerly QBO (red) as defined in the paragraph above. Winter has a higher mean N_{max}^2 ($12.17 \times 10^{-4} s^{-2}$) than summer ($11.39 \times 10^{-4} s^{-2}$), in agreement with the results of Grise et al. (2010) and Figures 1 and 3. We find that, during the easterly phase of the QBO (blue lines), the N_{max}^2 distributions slightly narrow and shift to lower values, giving lower seasonal means of $12.06 \times 10^{-4} s^{-2}$ in winter and $10.92 \times 10^{-4} s^{-2}$ in summer. During the westerly QBO phase (red lines), the opposite happens: the N_{max}^2 distributions widen and shift to higher values compared to the average distribution, giving higher seasonal means of $12.74 \times 10^{-4} s^{-2}$ in winter and $11.49 \times 10^{-4} s^{-2}$ in summer.

In both winter and summer, the seasonal mean N_{max}^2 in the westerly QBO phase is $\sim 0.6 \times 10^{-4} s^{-2}$ higher than during the easterly QBO phase. This difference is highly significant: the standard deviation



tion of the seasonal mean is of the order of $0.02 \times 10^{-4} s^{-2}$ (sample size of ~ 20000 profiles for two seasons of a given QBO phase).

In summary, from Fig. 4 we conclude that the tropical TIL is stronger during the westerly QBO phase in the lowermost stratosphere. This is not related to changes in the divergence distribution (given the relationship shown in Fig. 3), and is also anticorrelated with the strength of the secondary N^2 maximum found above the TIL region (Fig. 1).

The reason for this behavior of stronger TIL with westerly QBO is probably the dynamical forcing by Kelvin waves (the dipole of cooling near the tropopause and warming above), which have a higher activity in the lowermost stratosphere with westerly shear, and a slower vertical propagation (Randel and Wu, 2005) which translates into a longer residence time and longer dynamical forcing near the tropopause region to enhance the TIL. The vertical propagation of Kelvin waves is faster with easterlies (they spend less time near the tropopause), and once they reach the zero wind line of the descending QBO phase, their propagation slows down. This could form a similar dipole under the zero wind line, forcing the secondary N^2 maximum shown in Fig. 1 while having enhanced the TIL less. How equatorial waves dynamically force the vertical temperature and N^2 structure is explained below in section 4.

4 Dynamical Forcing by Equatorial Waves

4.1 Effect on the zonal structure of tropopause height

This section describes how equatorial waves dynamically force the temperature and N^2 vertical structure in the tropics. As explained in section 2.4, the gridded temperature and N^2 fields are filtered independently with 12 different bandpass filters in the wavenumber-frequency domain. As in Wheeler and Kiladis (1999), no bandpass filters overlap in the wavenumber-frequency domain (see Table 1), and the 12 filters amount for Kelvin waves, equatorial Rossby waves, MJO, and the three modes $n = (0,1,2)$ of westward-propagating (negative wavenumber s) Inertia-Gravity waves (WIG_n), the eastward-propagating ones (positive s , WIG_n), and the zonal wavenumber zero $s=0$ WIG_n . For each wave type, a daily longitude-height section with its signature on temperature and N^2 is obtained.

Figure 5 shows examples of longitude-height sections with the N^2 signature of Kelvin (Fig. 5a), Rossby (Fig. 5b), WIG_n (Fig. 5c) and MJO band (Fig. 5d) at selected dates when the zonal structure of the tropopause (thick black line) is affected by the wave anomalies in an obvious way. In the case of WIG_n the three modes $n = (0,1,2)$ are superimposed: the resulting field is $WIG_n = WIG_0 + WIG_1 + WIG_2$. Note that the filtered N^2 fields include a wide range of wavenumbers, 1-14 in the case of Kelvin waves for example (see Table 1), so the signatures of planetary waves 1 or 2 as well as transient shorter waves (higher wavenumbers) are represented together, giving a patchy appearance



sometimes. Nevertheless, clear and coherent structures of the waves' N^2 signatures can be observed in Figure 5.

Temperature perturbations from Kelvin waves were observed to have their maximum near the tropopause in the study by Randel and Wu (2005). In Fig. 5, we see the same for all wave types:
 375 their highest amplitudes are generally found near and above the tropopause (black line). Also, zonal variations in tropopause height tend to be aligned with the wave's structure, with N^2 positive anomalies above the tropopause and negative anomalies below, which is consistent with tropopause cooling and/or warming above it. This tropopause adjustment happens where the anomaly's amplitude is very high. This is clearly evident in Fig. 5a within 0-75°E and 100-180°E for Kelvin wave anomalies and
 380 in Fig. 5b within 0-125°W and ~50°E for equatorial Rossby wave anomalies.

Although usually one wave type is dominant (therefore the choosing of separate dates in Fig. 5), different waves can influence the zonal structure of tropopause height at the same time: in Fig. 5 c and d (both of the same day, 2013-08-28), the MJO band creates a zonal variation of tropopause height within 50-125°E, while $El Ni\tilde{no}$ wave anomalies do so within 50-150°W. We note that in most
 385 of the cases the strongest wave signatures, as well as zonal variations of the equatorial tropopause, are caused by transient waves with higher wavenumbers (as in every panel in Fig. 5) rather than planetary, quasi-stationary waves 1 or 2.

In Fig. 5a, the Kelvin wave anomaly shows an N^2 enhancement around 25-26km altitude (apart from right above the tropopause), which is related to the descending phase of the QBO (see Fig. 1:
 390 the zero wind line before the end of 2007 is at ~27km). Therefore, the Kelvin wave anomaly (which propagates vertically with easterlies, and slows down/amplifies below the zero wind line) is also the cause of the secondary N^2 maximum found in Fig. 1, as anticipated in section 3.3.

It is worth highlighting the structures that appear in the MJO band, with high amplitudes near the tropopause. Their eastward propagation, speed and longitudinal location match with the described
 395 patterns of deep convection associated to the MJO (Madden and Julian, 1994), but the horizontal and vertical scales are shorter. The temperature anomalies from Fig. 5d are very similar to the composite temperature anomalies from the MJO band in the study by Kim and Son (2012), who found that MJO temperature anomalies near the tropopause have higher wavenumber due to their longer persistence compared to OLR anomalies.

400 When daily anomalies without running means are obtained as in Fig. 5, we see that the wave's temperature anomalies shape the zonal structure of the tropopause, apart from the tropical tropopause layer (TTL) temperatures.

4.2 Average effect on the seasonal, zonal-mean profile

As explained in section 4.1, Figure 5 shows that the tropopause adjusts to the horizontal and vertical
 405 structure of the different wave types, with positive N^2 anomalies tending to be placed right above it. A tropopause-based mean of the wave's signature then should show an average enhancement of the



TIL. The contribution of each equatorial wave type to the enhancement of the TIL is shown in Figure 6: for each wave type, a tropopause-based mean of the temperature and N^2 anomalies is done for all longitudes and winter days, achieving the average wave's effect on the seasonal, zonal-mean profile.

410 EIG_n (green), WIG_n (orange) and $_{s=0}IG_n$ (grey) are the sum of all their modes $n = (0,1,2)$.

In Fig. 6a, all waves produce a maximum cooling right at the lapse-rate TP and a warming around 1-2km above the tropopause. Our results are in agreement with the study by Grise and Thompson (2013) that showed a cooling effect near the climatological tropopause by equatorial planetary waves, and remind of the dipole with tropopause cooling and lower-stratospheric warming found by
 415 Kim and Son (2012) which they attributed to convectively coupled waves. In the study by Kim and Son (2012), Kelvin waves and the MJO were the dominant wave types in short-term TTL temperature variability. By deriving daily fields with no temporal smoothing (see section 2.4.1), we were able to ascertain the role of waves with higher frequencies and zonal wavenumbers than previous studies, pointing out new important features from Fig. 6a: 1) the cooling effect is maximized and
 420 centered right at the thermal tropopause, 2) all equatorial wave types give a similar signature, whose magnitude is dependent on the amount of the wave's activity, and 3) the role of transient waves with higher zonal wavenumbers and frequencies is significant: WIG_n , EIG_n and Rossby waves have a bigger impact than the MJO.

The resulting N^2 signature (Fig. 6b) is a maximum N^2 enhancement right above the tropopause,
 425 and two regions of destabilization: below the tropopause and 2-3km above it. The overall effect is a TIL enhancement tightly close to the thermal tropopause. In Fig. 5 we showed obvious examples of tropopause adjustment to the wave structure with positive N^2 anomalies right above the tropopause. Given that the signature in the seasonal zonal-mean profile is considerable in Fig. 6, it can be concluded that the tropopause adjustment to the different waves (and the resulting dipole of tropopause
 430 cooling / warming above) occurs continuously, but not always so clearly as in Fig. 5. We stress that the signatures seen in Figures 5 and 6 were obtained by filtering the temperature and N^2 fields directly and independently, without any filtering in the vertical dimension.

Looking at the different wave types separately in Fig.6, the Kelvin wave (blue) has the strongest temperature signature (Fig. 6a), but owing to its longer vertical scale (see Fig. 5a) the temperature
 435 gradient that the Kelvin wave produces is closer to the rest of the waves', giving an average N^2 enhancement of $0.35 \times 10^{-4} s^{-2}/day$. The signatures of EIG_n (green), WIG_n (orange) and Rossby (red) waves give an average TIL enhancement of $\sim 0.25 \times 10^{-4} s^{-2}/day$ each, followed by the MJO band (purple, $0.1 \times 10^{-4} s^{-2}/day$). The $_{s=0}IG_n$ wave type (grey), although lacking zonal structures by definition and having little activity, still gives a minor TIL enhancement. The relative N^2 minima
 440 below the tropopause and above the TIL region in the seasonal zonal-mean profile (e.g. Grise et al. (2010)) can be attributed to the equatorial wave forcing as well.

The total forcing of the equatorial waves on the equatorial zonal-mean seasonal temperature profile is a $\sim 1.1K/day$ cooling of the tropopause and a $\sim 0.5K/day$ warming above, with a resulting TIL



enhancement of $\sim 1.2 \times 10^{-4} \text{ s}^{-2}/\text{day}$. Fig. 6 shows the wave forcing during winter; the results are
 445 similar during summer (see Appendix B, figure B1) except for a slightly weaker effect of the MJO
 band, given its lower average activity in that season.

We acknowledge the possibility that the wave forcings shown in Figs. 5 and 6 may not be 100%
 dynamical: a radiative component is included if clouds are present near the tropopause (radiative
 cooling at the cloud top that creates a temperature inversion). Part of the equatorial wave spectrum
 450 in the TTL is known to be coupled with convection, a small part of which reaches the tropopause
 (Wheeler and Kiladis, 1999; Fueglistaler et al., 2009), and the occurrence of cirrus clouds is also
 related to equatorial waves (Virts and Wallace, 2010). Case studies using GPS-RO data have inves-
 tigated the temperature inversion generally found at cloud tops, for convective clouds (Biondi et al.,
 2012) and non-convective cirrus clouds (Taylor et al., 2011). The signal from any cloud coupled
 455 with an equatorial wave would be captured by its corresponding wavenumber-frequency domain
 filter, since the cloud signal would travel together with the wave in the same domain. Therefore a
 small part of the mean wave forcing shown in Fig. 6 could be due to the temperature inversion of
 (wave-coupled) cloud-tops near the tropopause, but quantifying this is beyond the scope of our study.

Our results from this section (Figs. 5 and 6) agree with earlier studies that derived equatorial
 460 wave anomalies from GPS-RO data (the Kelvin and MJO signatures and their amplification near
 the tropopause (Randel and Wu, 2005; Kim and Son, 2012)). Also, Fig. 6 confirms the effect of
 equatorial waves on the mean temperature profile (tropopause cooling and warming above forming a
 dipole (Kim and Son, 2012; Grise and Thompson, 2013)) and their crucial role in enhancing the TIL
 in the tropics (Grise et al., 2010). The novelty in our study resides in that we include small-scale,
 465 higher-frequency waves (e.g. Inertia-Gravity waves); and that we are able to quantify the effect of
 each equatorial wave type separately by tropopause-based averaging of the filtered wave anomalies.
 Also, the Kelvin wave forcing explains the occurrence of a secondary N^2 maximum above the TIL
 region with easterly QBO (see Figs. 1 and 5a) and why it is anticorrelated to the strength of the TIL
 (which is stronger with westerlies, see section 3.3).

470 5 Discussion: Applicability of the Wave Forcing in the Extratropics

As Fig. 6 showed, all equatorial wave types have the same effect on the temperature and N^2 sea-
 sonal zonal-mean vertical profiles, only varying in magnitude. Since all wave types have the same
 signature, one could expect a similar picture coming from the extratropical wave spectrum. Taking
 the extratropical baroclinic Rossby wave as an example: the embedded cyclones-anticyclones with
 475 lower-higher tropopause would be an example of tropopause adjustment to the anomalies associated
 with the wave, as in Fig. 5. Given that the zonal variability of TP_z at mid-latitudes is much higher
 than within the tropics (3km against 0.8km, see Appendix A) and that temperature gradients next to
 the jet stream are also of much higher magnitude, it is probable that the extratropical Rossby wave's



N^2 signature on the mid-latitude zonal mean profile is even stronger than the forcing observed from
 480 Kelvin waves in Fig. 6, which dominates in the tropics. Inertia-gravity waves are also widely present
 in the extratropics. Depending on the amplitude they reach next to the extratropical tropopause, this
 wave type shall also contribute to enhance the TIL, which is predicted by the modelling experiment
 by Kunkel et al. (2014).

The wavenumber-frequency domain filtering method used with the dispersion curves of extra-
 485 tropical wave modes would be suit to quantify the dynamical forcing of each wave mode on the
 extratropical TIL, in the same way our study has done with equatorial waves. A new study with this
 purpose is indeed underway.

6 Concluding Remarks

Our study explores the horizontal and vertical variability of the tropical TIL, the effect of the QBO,
 490 the role of near-tropopause divergence and the dynamical forcing of equatorial waves in enhancing
 the tropical TIL. Overall it gives an in-depth observational description of the TIL properties in the
 tropics and the mechanisms that lead to its enhancement in a region where research has focused very
 little so far.

Our results agree with the seasonality and location of the tropical TIL described by Grise et al.
 495 (2010), with stronger TIL centered at the equator and peaking during NH winter. We describe a new
 feature: a secondary N^2 maximum that forms above the TIL region within the easterly wind regime
 of the QBO, below the zero wind line of the descending westerly QBO (Fig. 1). This secondary
 maximum leads to a double-TIL-like structure in the stability profile, and explains the correlation
 of enhanced N^2 in the 1-3km layer above the tropopause with easterly QBO found by Grise et al.
 500 (2010). The behavior of the secondary N^2 maximum is anticorrelated with the TIL strength (strictly
 the N_{max}^2 found less than 1km above the tropopause): the TIL is stronger during the westerly phase
 of the QBO in the lowermost stratosphere (Fig. 4). We explain this anticorrelation by Kelvin wave
 forcing (see section 3.3, also section 4 and Fig. 5a).

The zonal structure of the tropical TIL shows a stronger (weaker) TIL with near-tropopause diver-
 505 gent (convergent) flow (Fig. 2). This sTIL-divergence relationship (Fig. 3) is very similar to the TIL
 strength with relative vorticity found in the extratropics (Randel et al., 2007; Randel and Wu, 2010;
 Pilch Kedzierski et al., 2015), and we suggest that vertical wind convergence is a TIL enhancing
 mechanism that the tropics (divergent flow) and extratropics (anticyclones) have in common.

We also quantified the dynamical forcing of the different equatorial waves on the seasonal zonal-
 510 mean temperature and N^2 profile (Fig. 6). All wave types have a maximum cooling effect at the
 thermal tropopause, and a warming effect above, enhancing the TIL strength very close to the
 tropopause. The way this dynamical forcing is done is by tropopause adjustment to the vertical
 structure of the wave's associated anomalies when these have high amplitudes (Fig. 5). While agree-



ing with earlier studies that used GPS-RO to investigate equatorial waves (Randel and Wu, 2005;
 515 Kim and Son, 2012), our results show the importance of small-scale, high-frequency waves due to
 our method with minimized temporal smoothing, which enables us to quantify and compare the role
 of each different equatorial wave type for the first time. Inertia-gravity and Rossby waves play a very
 significant role, with a bigger signature than the MJO, and Kelvin waves dominate the tropopause
 cooling, warming above and the resulting TIL enhancement. We suggest that this wave forcing will
 520 also be present in the extratropics with baroclinic Rossby and inertia-gravity waves as main contrib-
 utors, which will be the subject of a follow-on study.

Appendix A: Divergence vs Tropopause Height

Figure A1 shows divergence versus tropopause height (TP_z) diagrams, as in Fig. 3 with TIL strength
 (section 3.2). There is no clear link between a higher tropopause and a stronger TIL. In summer
 525 (Fig. A1 a), the relation of higher TP_z with divergent flow is rather marginal: the difference between
 convergent-divergent flow is only of 0.8km, while the difference in cyclones-anticyclones in the
 extratropics is over 3km (Randel and Wu, 2010). In winter (Fig. A1 b) this relation is non-existent:
 the tropical TP_z is around 17km at all divergence-convergence values.

Appendix B: Equatorial Wave Forcing in Summer

530 Figure B1 is the summer counterpart of Fig. 6 from section 4. The average effect of each wave in
 summer (Fig. B1) is very similar to the one from winter (Fig. 6), except for a smaller MJO forcing.

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References

- Anthes, R. A., Bernhardt, P. A., Chen, Y., Cucurull, L., Dymond, K. F., Ector, D., Healy, S. B., Ho, S.-P.,
540 Hunt, D. C., Kuo, Y.-H., Liu, H., Manning, K., McCormick, C., Meehan, T. K., Randel, W. J., Rocken,
C., Schreiner, W. S., Sokolovskiy, S. V., Syndergaard, S., Thompson, D. C., Trenberth, K. E., Wee, T.-K.,
Yen, N. L., and Zeng, Z.: The COSMIC/FORMOSAT-3 Mission: Early Results, *Bulletin of the American
Meteorological Society*, 89, 313, doi:10.1175/BAMS-89-3-313, 2008.
- Bell, S. W. and Geller, M. A.: Tropopause inversion layer: Seasonal and latitudinal variations and representa-
545 tion in standard radiosonde data and global models, *Journal of Geophysical Research (Atmospheres)*, 113,
D05109, doi:10.1029/2007JD009022, 2008.
- Beyerle, G., Schmidt, T., Michalak, G., Heise, S., Wickert, J., and Reigber, C.: GPS radio occultation with
GRACE: Atmospheric profiling utilizing the zero difference technique, *Geophysical Research Letters*, 32,
L13806, doi:10.1029/2005GL023109, 2005.
- 550 Biondi, R., Randel, W. J., Ho, S.-P., Neubert, T., and Syndergaard, S.: Thermal structure of intense con-
vective clouds derived from GPS radio occultations, *Atmospheric Chemistry & Physics*, 12, 5309–5318,
doi:10.5194/acp-12-5309-2012, 2012.
- Birner, T.: Fine-scale structure of the extratropical tropopause region, *Journal of Geophysical Research (Atmo-
spheres)*, 111, D04104, doi:10.1029/2005JD006301, 2006.
- 555 Birner, T.: Residual Circulation and Tropopause Structure, *Journal of Atmospheric Sciences*, 67, 2582–2600,
doi:10.1175/2010JAS3287.1, 2010.
- Birner, T., Dörmbrack, A., and Schumann, U.: How sharp is the tropopause at midlatitudes?, *Geophysical Re-
search Letters*, 29, 1700, doi:10.1029/2002GL015142, 2002.
- Birner, T., Sankey, D., and Shepherd, T. G.: The tropopause inversion layer in models and analyses, *Geophysical
560 Research Letters*, 33, L14804, doi:10.1029/2006GL026549, 2006.
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda,
M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N.,
Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V.,
Isaksen, I., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-
565 J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim
reanalysis: configuration and performance of the data assimilation system, *Quarterly Journal of the Royal
Meteorological Society*, 137, 553–597, doi:10.1002/qj.828, 2011.
- Erler, A. R. and Wirth, V.: The Static Stability of the Tropopause Region in Adiabatic Baroclinic Life Cycle
Experiments, *Journal of Atmospheric Sciences*, 68, 1178–1193, doi:10.1175/2010JAS3694.1, 2011.
- 570 Fueglistaler, S., Dessler, A. E., Dunkerton, T. J., Folkins, I., Fu, Q., and Mote, P. W.: Tropical tropopause layer,
Reviews of Geophysics, 47, RG1004, doi:10.1029/2008RG000267, 2009.
- Gettelman, A. and Birner, T.: Insights into Tropical Tropopause Layer processes using global models, *Journal
of Geophysical Research (Atmospheres)*, 112, D23104, doi:10.1029/2007JD008945, 2007.
- Gettelman, A., Hoor, P., Pan, L. L., Randel, W. J., Hegglin, M. I., and Birner, T.: The Extratropical Upper
575 Troposphere and Lower Stratosphere, *Reviews of Geophysics*, 49, RG3003, doi:10.1029/2011RG000355,
2011.



- Grise, K. M. and Thompson, D. W. J.: On the Signatures of Equatorial and Extratropical Wave Forcing in Tropical Tropopause Layer Temperatures, *Journal of Atmospheric Sciences*, 70, 1084–1102, doi:10.1175/JAS-D-12-0163.1, 2013.
- 580 Grise, K. M., Thompson, D. W. J., and Birner, T.: A Global Survey of Static Stability in the Stratosphere and Upper Troposphere, *Journal of Climate*, 23, 2275–2292, doi:10.1175/2009JCLI3369.1, 2010.
- Hegglin, M. I., Boone, C. D., Manney, G. L., and Walker, K. A.: A global view of the extratropical tropopause transition layer from Atmospheric Chemistry Experiment Fourier Transform Spectrometer O₃, H₂O, and CO, *Journal of Geophysical Research (Atmospheres)*, 114, D00B11, doi:10.1029/2008JD009984, 2009.
- 585 Kim, J. and Son, S.-W.: Tropical Cold-Point Tropopause: Climatology, Seasonal Cycle, and Intraseasonal Variability Derived from COSMIC GPS Radio Occultation Measurements, *Journal of Climate*, 25, 5343–5360, doi:10.1175/JCLI-D-11-00554.1, 2012.
- Kunkel, D., Hoor, P., and Wirth, V.: Can inertia-gravity waves persistently alter the tropopause inversion layer?, *Geophysical Research Letters*, 41, 7822–7829, doi:10.1002/2014GL061970, 2014.
- 590 Kunz, A., Konopka, P., Müller, R., Pan, L. L., Schiller, C., and Rohrer, F.: High static stability in the mixing layer above the extratropical tropopause, *Journal of Geophysical Research (Atmospheres)*, 114, D16305, doi:10.1029/2009JD011840, 2009.
- Lindzen, R. D.: Planetary Waves on Beta-Planes, *Monthly Weather Review*, pp. 441–451, 1967.
- Madden, R. A. and Julian, P. R.: Observations of the 40 50-Day Tropical Oscillation - A Review, *Monthly Weather Review*, 122, 814, doi:10.1175/1520-0493(1994)122<0814:OOTD>2.0.CO;2, 1994.
- 595 Matsuno, T.: Quasi-Geostrophic Motions in the Equatorial Area, *Journal of the Meteorological Society of Japan*, Ser. II, 44, 25–43, 1966.
- Miyazaki, K., Watanabe, S., Kawatani, Y., Sato, K., Tomikawa, Y., and Takahashi, M.: Transport and Mixing in the Extratropical Tropopause Region in a High-Vertical-Resolution GCM. Part II: Relative Importance of Large-Scale and Small-Scale Dynamics, *Journal of Atmospheric Sciences*, 67, 1315–1336, doi:10.1175/2009JAS3334.1, 2010a.
- 600 Miyazaki, K., Watanabe, S., Kawatani, Y., Tomikawa, Y., Takahashi, M., and Sato, K.: Transport and Mixing in the Extratropical Tropopause Region in a High-Vertical-Resolution GCM. Part I: Potential Vorticity and Heat Budget Analysis, *Journal of Atmospheric Sciences*, 67, 1293–1314, doi:10.1175/2009JAS3221.1, 2010b.
- 605 Pilch Kedzierski, R., Matthes, K., and Bumke, K.: Synoptic-scale behavior of the extratropical tropopause inversion layer, *Geophysical Research Letters*, 42, 10,018–10,026, doi:10.1002/2015GL066409, 2015GL066409, 2015.
- Randel, W. J. and Wu, F.: Kelvin wave variability near the equatorial tropopause observed in GPS radio occultation measurements, *Journal of Geophysical Research (Atmospheres)*, 110, D03102, doi:10.1029/2004JD005006, 2005.
- 610 Randel, W. J. and Wu, F.: The Polar Summer Tropopause Inversion Layer, *Journal of Atmospheric Sciences*, 67, 2572–2581, doi:10.1175/2010JAS3430.1, 2010.
- Randel, W. J., Wu, F., and Forster, P.: The Extratropical Tropopause Inversion Layer: Global Observations with GPS Data, and a Radiative Forcing Mechanism, *Journal of Atmospheric Sciences*, 64, 4489, doi:10.1175/2007JAS2412.1, 2007.
- 615



- Schmidt, T., Cammas, J.-P., Smit, H. G. J., Heise, S., Wickert, J., and Haser, A.: Observational characteristics of the tropopause inversion layer derived from CHAMP/GRACE radio occultations and MOZAIC aircraft data, *Journal of Geophysical Research (Atmospheres)*, 115, D24304, doi:10.1029/2010JD014284, 2010.
- Schreck, C.: Extract equatorial waves by filtering in the Wheeler-Kiladis wavenumber-frequency domain., https://www.ncl.ucar.edu/Document/Functions/User_contributed/kf_filter.shtml, 2009.
- 620 Son, S.-W. and Polvani, L. M.: Dynamical formation of an extra-tropical tropopause inversion layer in a relatively simple general circulation model, *Geophysical Research Letters*, 34, L17806, doi:10.1029/2007GL030564, 2007.
- Son, S.-W., Tandon, N. F., and Polvani, L. M.: The fine-scale structure of the global tropopause derived from COSMIC GPS radio occultation measurements, *Journal of Geophysical Research (Atmospheres)*, 116, D20113, doi:10.1029/2011JD016030, 2011.
- 625 Taylor, J. R., Randel, W. J., and Jensen, E. J.: Cirrus cloud-temperature interactions in the tropical tropopause layer: a case study, *Atmospheric Chemistry & Physics*, 11, 10 085–10 095, doi:10.5194/acp-11-10085-2011, 2011.
- 630 Virts, K. S. and Wallace, J. M.: Annual, Interannual, and Intraseasonal Variability of Tropical Tropopause Transition Layer Cirrus, *Journal of Atmospheric Sciences*, 67, 3097–3112, doi:10.1175/2010JAS3413.1, 2010.
- Wang, W., Matthes, K., Schmidt, T., and Neef, L.: Recent variability of the tropical tropopause inversion layer, *Geophysical Research Letters*, 40, 6308–6313, doi:10.1002/2013GL058350, 2013.
- Wheeler, M. and Kiladis, G. N.: Convectively Coupled Equatorial Waves: Analysis of Clouds and Temperature in the Wavenumber-Frequency Domain., *Journal of Atmospheric Sciences*, 56, 374–399, doi:10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2, 1999.
- 635 Wickert, J., Reigber, C., Beyerle, G., König, R., Marquardt, C., Schmidt, T., Grunwaldt, L., Galas, R., Meehan, T. K., Melbourne, W. G., and Hocke, K.: Atmosphere sounding by GPS radio occultation: First results from CHAMP, *Geophysical Research Letters*, 28, 3263–3266, doi:10.1029/2001GL013117, 2001.
- 640 Wirth, V.: Static Stability in the Extratropical Tropopause Region., *Journal of Atmospheric Sciences*, 60, 1395–1409, doi:10.1175/1520-0469(2003)060<1395:SSITET>2.0.CO;2, 2003.
- Wirth, V.: A dynamical mechanism for tropopause sharpening, *Meteorologische Zeitschrift*, 13, 477–484, doi:10.1127/0941-2948/2004/0013-0477, 2004.
- Wirth, V. and Szabo, T.: Sharpness of the extratropical tropopause in baroclinic life cycle experiments, *Geophysical Research Letters*, 34, 2809, doi:10.1029/2006GL028369, 2007.
- 645 WMO: Meteorology-A three-dimensional science, *WMO Bull.*, 6, 134–138, 1957.



Table 1. Parameters used to bound the filter of the different equatorial wave types, with the meridional mode n as subscript: t (period, in days), s (zonal planetary wavenumber) and h (equivalent depth, in m)

Wave type	t_{min}	t_{max}	s_{min}	s_{max}	h_{min}	h_{max}
Eq. Rossby	6	70	-14	-1	6	600
Kelvin	4	30	1	14	6	600
MJO	30	96	2	5	8	90
WIG_0	2.5	6	-10	-1	6	360
WIG_1	2	2.5	-15	-1	8	90
WIG_2	1	2	-15	-1	8	90
EIG_0	2.5	4	1	15	8	90
EIG_1	2	2.5	1	15	8	90
EIG_2	1	2	1	15	8	90
$_{s=0}IG_0$	3	6	-0.1	0.1	8	90
$_{s=0}IG_1$	2	3	-0.1	0.1	8	90
$_{s=0}IG_2$	1	2	-0.1	0.1	8	90

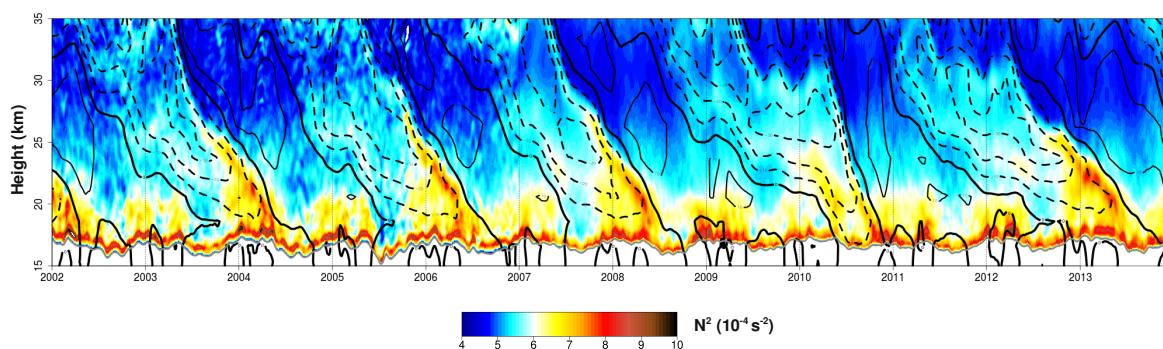


Figure 1. Daily evolution of the tropopause-based, equatorial (5°S - 5°N) zonal mean N^2 vertical profile between 2002-2013 (colors). The grey line denotes the tropopause height (TP_z). Thin black contours denote positive (westerly) mean zonal wind, with a thicker contour for the zero line, dashed contours for negative (easterly) winds, and a 10m/s separation. To improve visibility, each day shows the running mean N^2 profile and TP_z of ± 7 days. In the case of the winds, the running mean is made for ± 15 days.

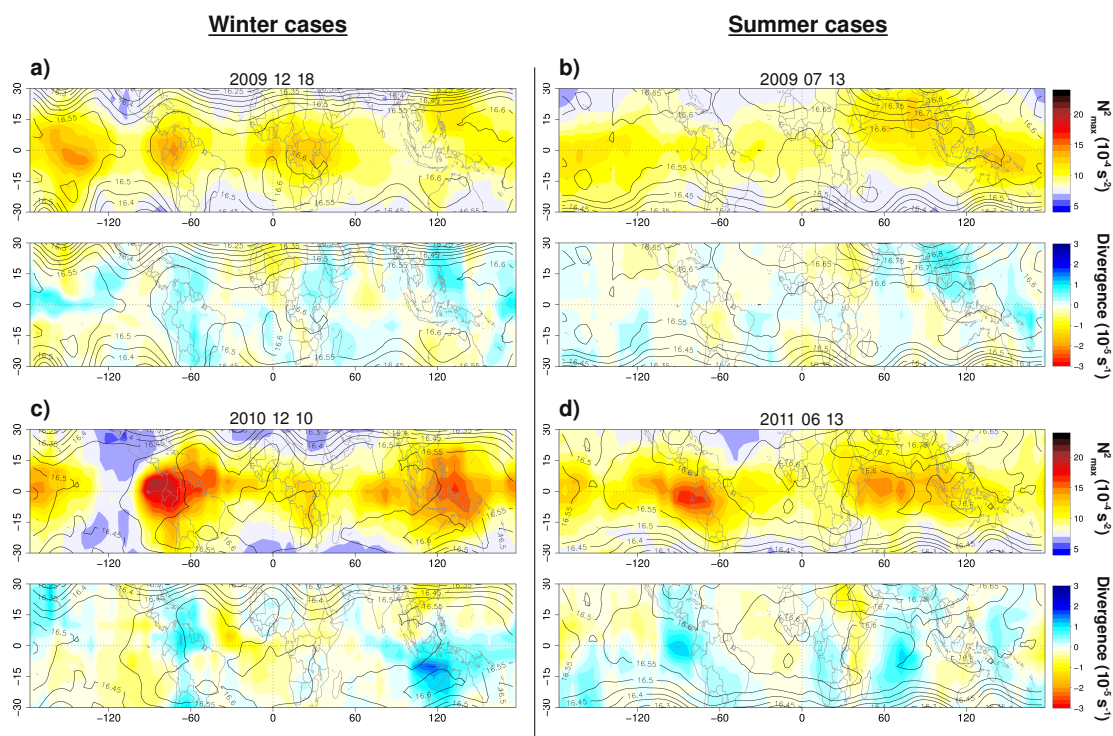


Figure 2. Maps of daily TIL strength (N_{max}^2 , first and third rows) and 100hPa divergence (second and fourth rows). Winter cases are on the left side, and summer cases are on the right side. Corresponding color scales are on the right end. Contour lines show the 100hPa geopotential height (in km' with 50m' interval).

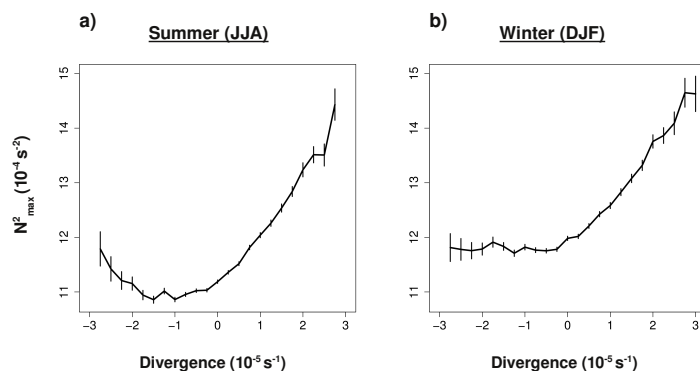


Figure 3. Diagrams of divergence versus TIL strength (N_{max}^2) for the latitude band 10°S - 10°N . a) belongs to the summer season (JJA), and b) to the winter season (DJF). Vertical bars denote one standard deviation of the mean value.

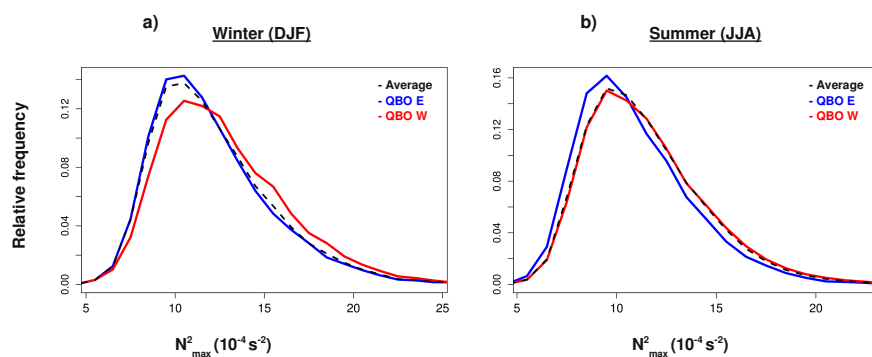


Figure 4. Histograms with relative frequency of TIL strength (N_{max}^2), for winter (a, DJF) and summer (b, JJA). The black dashed line denotes the average seasonal distribution. The blue line shows distributions during the easterly phase of the QBO in the lowermost stratosphere, and the red line shows the distributions during the westerly QBO phase.

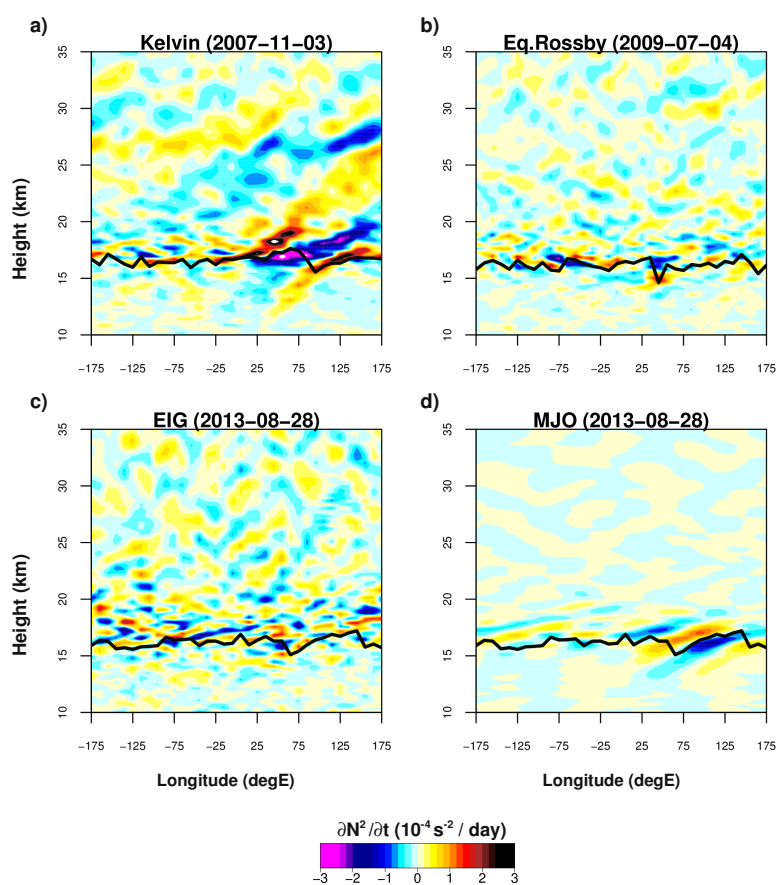


Figure 5. Longitude-height snapshots of the N^2 signature of different wave types at certain dates: a) Kelvin wave, b) Rossby wave, c) Eastward IGW (EIG_n), d) MJO band. The black line denotes the thermal tropopause.

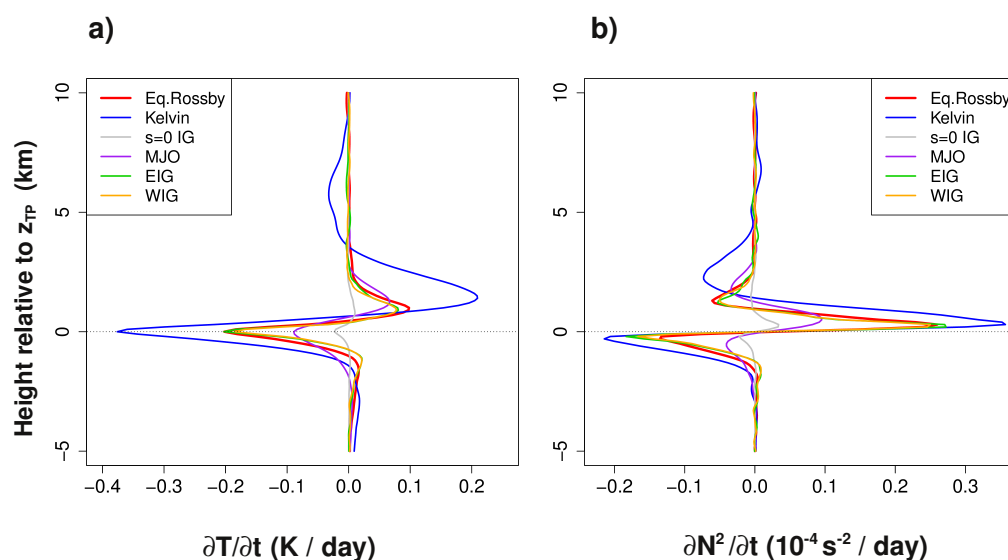


Figure 6. Winter (DJF) average signature of the different wave types, as the time rate of change of the (a) temperature and (b) N^2 equatorial zonal-mean vertical profiles (10°S - 10°N).

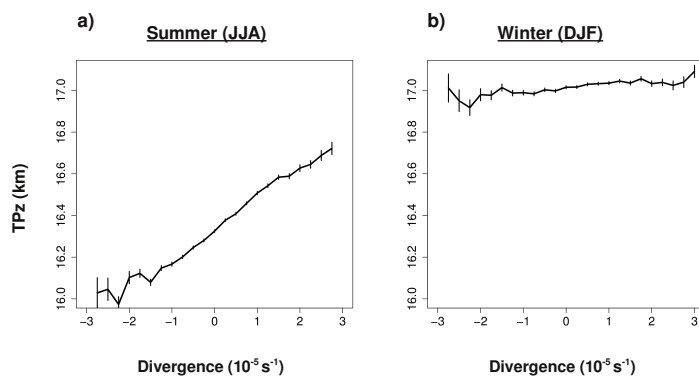


Figure A1. Diagrams of divergence versus tropopause height (TP_z , km) for the latitude band 10°S - 10°N . a) belongs to the summer season (JJA), and b) to the winter season (DJF). Vertical bars denote one standard deviation of the mean value.

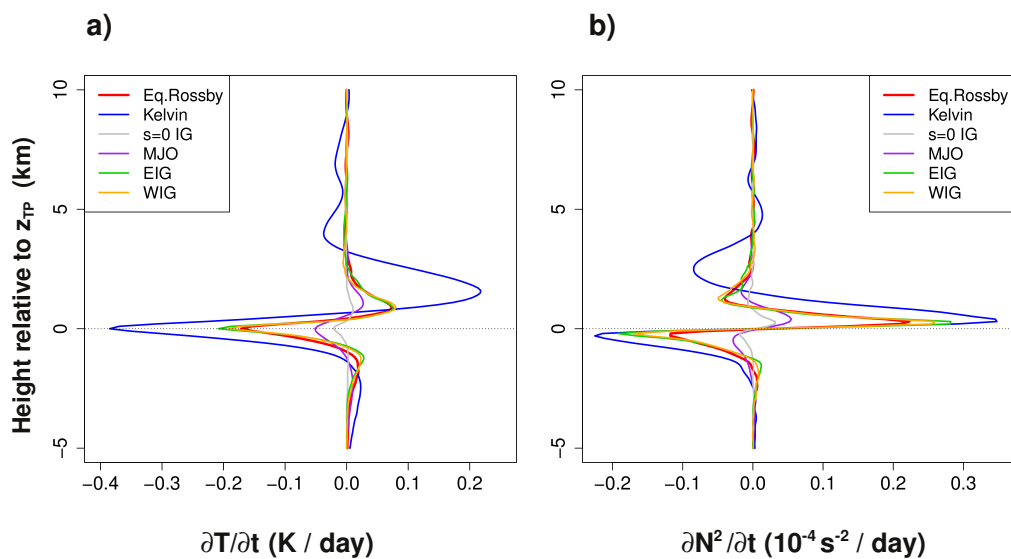


Figure B1. Summer (JJA) average signature of the different wave types, as the time rate of change of the (a) temperature and (b) N^2 equatorial zonal-mean vertical profiles (10°S - 10°N).