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**Increase of UTLS
wave baroclinicity**

J. M. Castanheira et al.

Increase of upper troposphere/lower stratosphere wave baroclinicity during the second half of the 20th century

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Abstract

A strengthening of the equatorward temperature gradient in the upper troposphere/lower stratosphere (UTLS), at subtropics and midlatitudes, is consistently reproduced in several modelling studies of the atmospheric response to the increase of greenhouse gas radiative forcing. Some of those studies suggest an increase of the baroclinicity in the UTLS region because of the enhanced meridional temperature gradient.

This study presents observational evidence of an increase of UTLS wave baroclinicity, during the second half of the 20th century. The evidence is given by significant positive trends in the energy of baroclinic normal modes of the NCEP/NCAR reanalysis, and significant positive trends in the eddy available potential energy of the ERA-40 reanalysis as well as in the eddy available potential energy of the JRA-25 reanalysis. Significant positive trends in the frequency of double tropopause events in radiosonde data are also interpreted as a manifestation of an increase of the UTLS wave baroclinicity.

1 Introduction

In an assessment of several coupled chemistry-climate models, Eyring et al. (2006) showed that all models consistently simulate a stratospheric cooling trend during the second half of the 20th century. Using the GFDL coupled atmosphere-ocean-land climate model, Schwarzkopf and Ramaswamy (2008) showed a similar cooling trend of the stratosphere and a warming trend of the troposphere. Additionally, the general features of the simulated temperature trends are in agreement with observed trends (Randel et al., 2009).

Moreover, it is well known that the changeover from tropospheric warming to stratospheric cooling occurs at lower altitudes in the extratropics due to the fact that the tropical tropopause is higher than the extratropical one. Thus, the deep warming of the

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tropical troposphere and the cooling of the lower extratropical stratosphere leads to the strengthening of the meridional thermal gradients in the upper troposphere/lower stratosphere (UTLS) at the subtropical and midlatitudes (e.g. Garcia and Randel, 2008; Ramaswamy and Schwarzkopf, 2002, for simulations) and (Kanukhina et al., 2008; Allen and Sherwood, 2008; Randel et al., 2009, for observations). This strengthening of the meridional thermal gradients will cause an increase of baroclinicity in the subtropical and midlatitude UTLS regions (Eichelberger and Hartmann, 2005). In fact, model simulations of the temperature response to increasing radiative greenhouse gas forcing show a decrease of lower troposphere large-scale baroclinicity at middle latitudes and an increase of baroclinicity of the UTLS at the same latitudes (Geng and Sugi, 2003, and references therein). The decrease of lower troposphere baroclinicity, in the Northern Hemisphere, is mainly attributed to the decrease of near surface meridional temperature gradient, which is explained by the fact that, when global warming happens, the high latitudes usually warm more than the lower latitudes due to the positive feedback of sea ice and snow cover in winter (Geng and Sugi, 2003).

Based on the above mentioned studies, our hypothesis is that global warming must be associated with a change of the vertical structure of baroclinicity; such change of baroclinicity must manifest itself in a change of the vertical structures of the most excited/amplified baroclinic waves. Accordingly, a study of the trends in the energy associated with baroclinic waves decomposed on a basis of vertical structure functions seems adequate to test our hypothesis. Results will show that an increase (decrease) of the UTLS (lower troposphere) large-scale wave baroclinicity may be already diagnosed during the second half of the 20th century both in reanalyzed data and in radiosonde data.

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2 Data and method

2.1 Normal mode expansion

Part of the study is based on NCEP/NCAR reanalysis and covers the 1958–2006 period. We analyze the Northern Hemisphere cool season (November to April) daily means of the horizontal wind components (u , v) and of the geopotential height, available on 17 standard pressure levels from 1000 to 10 hPa, on a $2.5^\circ \times 2.5^\circ$ horizontal grid.

The global horizontal wind (u , v) and geopotential (ϕ) fields were expanded in terms of the normal modes of the NCEP/NCAR reference atmosphere (see Liberato et al., 2007, and references therein for details), i.e.,

$$\begin{bmatrix} u \\ v \\ \phi \end{bmatrix} = \sum_{m=0}^{\infty} \sum_{s=-\infty}^{\infty} \sum_{l=0}^{\infty} \sum_{\alpha=1}^3 w_{msl}^{\alpha}(t) G_{m(p)} \exp(is\lambda) \mathbf{C}_m \begin{bmatrix} U(\theta) \\ iV(\theta) \\ Z(\theta) \end{bmatrix}_{msl,\alpha} \quad (1)$$

where λ , θ and p are the longitude, latitude and pressure, respectively. The functions $G_m(p)$ represent separable vertical structures, and $\mathbf{C}_m = \text{diag}[(gh_m)^{1/2}, (gh_m)^{1/2}, gh_m]$ is a diagonal matrix of scaling factors, with g representing the earth's gravity and h_m the equivalent heights. Each horizontal structure function is given by the product of a zonal wave with wavenumber s and a vector $[U(\theta), iV(\theta), Z(\theta)]_{msl,\alpha}^T$ which defines the meridional profile of the wave, where l is a meridional index which may be regarded as an indicator of the meridional scale of the motion. The index $\alpha=1, 2, 3$ refers to westward traveling inertio-gravity waves, Rossby waves and eastward traveling inertio-gravity waves, respectively. The coefficients $w_{msl}^{\alpha}(t)$ are the complex amplitudes, where t is the time.

Each vertical structure $G_m(p)$ has m nodes, with $m=0$ and $m \geq 1$ denoting barotropic and baroclinic vertical structures, respectively (Fig. 1). The equivalent heights h_m decrease with the index m , and we will refer to the modes with $m < 5$ as the deeper modes and modes with $m > 5$ as the shallower modes. As it may be observed in Fig. 1, the

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vertical structures of the first four baroclinic modes ($m < 5$) have the largest amplitudes and their nodes in the UTLS, whereas the shallower baroclinic modes ($m > 5$) have larger amplitude and several nodes in the lower troposphere. These features make the deeper baroclinic modes more sensitive to the UTLS circulation variability, whereas the shallower baroclinic modes will be relatively more sensitive to lower troposphere circulation variability (see Appendix A for more details).

The total (i.e. kinetic+available potential) energy of each normal mode is proportional to the square of its amplitude ($E_{msl}^\alpha(t) \propto |w_{msl}^\alpha(t)|^2$); and the energy $E_m(t)$, associated with a given vertical structure m and a given subset of wave numbers ($1 \leq s \leq N$) of Rossby or gravity type, is obtained by summing the energy associated with all meridional indices l for the N wave numbers.

The energy of the NCEP/NCAR reanalysis was calculated for both daily coefficients $w_{msl}^\alpha(t)$ and low pass filtered (period > 10 days) coefficients. Afterwards, energy of high frequency waves was derived as the differences between the energies calculated with unfiltered and with low pass filtered $w_{msl}^\alpha(t)$ coefficients. Finally, for each energy time series $E_m(t)$, a linear trend was calculated applying a least square deviation fit to the November–April means in the 1958–2006 period.

A strengthening of the equatorward gradient of the UTLS zonal mean temperature was already diagnosed in the NCEP/NCAR reanalysis (Kanukhina et al., 2008). Then, one could try to assess the trend in the baroclinicity using the Eady growth-rate maximum, $\sigma_{Bl} \approx 0.31 (g/T N) |\nabla T|$, where T is the temperature, and N is the Brunt-Väisälä frequency (Geng and Sugi, 2003, and references therein). However, UTLS temperatures in reanalysis data are sensitive to changes in assimilation input data, in particular the inclusion of satellite data beginning in 1979, and they are not suitable for the study of the UTLS baroclinicity trend (Allen and Sherwood, 2008; Randel et al., 2009). Although we expect that normal mode energy will be more resilient to the data inhomogeneities because it accounts for the meridional and zonal spatial variability of both geopotential and horizontal wind fields, the results based on normal mode energy were tested by two independent analyses.

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Normal modes are a useful tool since they allow for the filtering of Rossby waves in both horizontal and vertical spatial scales. The filtering will reduce the noise and makes easier to uncover significant trends in the sensitive vertical structures. However, because 3-D normal modes are global functions, the connection between trends in modal structure and local changes in the physical space is not direct. In order to relate trends in modal structure and local changes in the physical space, we computed the trends in the eddy available potential energy, $A_E(\theta, p) = 1/2 c_p \gamma \overline{T'^2}$, where T' is the temperature deviation from the zonal mean \overline{T} , γ is the stability parameter and c_p is the specific heat at constant pressure. We performed this analysis on the three following reanalysis data sets: Reanalysis 2 data from the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP-2); ERA-40 Reanalyses from the European Centre for Medium-Range Weather Forecasts (ECMWF); and the Japanese 25-year Reanalysis (JRA-25) from the Japan Meteorological Agency. The ERA-40 reanalysis covers the period 1958–2001, while the NCEP-2 and the JRA-25 reanalyses cover the period 1980–2008. The energy A_E was computed for each six-hourly reanalysis time, then it was averaged for the November–April season and finally the interannual trends were obtained for each level and latitude. Besides to show the local changes in the physical space, these calculations also constitute one test to the results obtained with the normal mode energetics.

2.2 Multiple tropopause events

Another test to the hypothesis of an increase of baroclinicity in the UTLS region is given by the analysis of the trends in the frequency of double tropopause events in a subset of radiosoundings. The radiosonde data were obtained from the Integrated Global Radiosonde Archive (Durre et al., 2006) at the NOAA National Climatic Data Center (NCDC). Single and double tropopause events were identified using the World Meteorological Organization thermal lapse rate definition of tropopause (WMO, 1957):

(a) The first tropopause is defined as the lowest level at which the lapse rate decreases to 2 K km^{-1} or less, provided also the average lapse rate between this level and all higher levels within 2 km does not exceed 2 K km^{-1} .

(b) If above the first tropopause the average lapse rate between any level and all higher levels within 1 km exceeds 3 K km^{-1} then a second tropopause is defined by the same criterion as under (a). This tropopause may be either within or above the 1 km layer.

Daily or twice daily radiosonde observations from a 187-station global network, described by Añel et al. (2008), were analyzed for the 1970–2006 period. The soundings retained in the analysis satisfy the following homogenization criteria: I) the 50 hPa (70 hPa) level must be reached in the tropics (extratropics); II) there must be at least one reported level in the vicinity of each of the following mandatory pressure levels: 500, 400, 300, 200, 150, 100, 70, and 50 hPa; III) the sounding station must report soundings satisfying condition I) and II) at least in five different years for each of the following periods: 1970–1979, 1980–1989, 1990–1999, and 2000–2006. Different homogenization criteria were tested. In particular, the trends were recalculated without applying condition III) or requiring its validity for only two or three decades. Using different conditions III) imply the inclusion or exclusion of some sounding stations. The results remained qualitatively the same even if all available soundings were considered without the application of any homogenization criterion.

Figure 2 shows the radiosonde stations considered in the study of Añel et al. (2008). The solid symbols represent the stations retained for the computations of the trends in the frequency of double tropopause events.

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3 Results

3.1 Baroclinic wave energy trends

The vertical spectrum of the November–April mean energy associated with the baroclinic Rossby waves with wave number $1 \leq s \leq 10$ is shown on the top panel of Fig. 3. The energy peaks at $m=5$ and then decreases monotonically. This energy peaking at $m=5$ suggests again a distinction between the deeper ($m < 5$) and the shallower ($m > 5$) baroclinic modes. The trends of the energies associated with each of the first nine baroclinic modes are shown on the bottom panel of Fig. 3. The linear change of the energy in the 1958–2006 period is given as a percentage of the mean energy shown in the top panel of Fig. 3. The solid symbols indicate significant trends at the statistical level of 99% ($p=0.01$). The energy values of both high and low frequency waves associated with the deeper baroclinic modes increased during the analyzed period, while the energy associated with the shallower baroclinic modes decreased.

Observing the energy values in the top panel of Fig. 3, it may be concluded that it is the mode $m=4$ which shows the largest trend of energy. Incidentally, this vertical mode is the most sensitive to variability in the UTLS region (see Appendix A). Thus, results suggest that most of the increase in baroclinic energy comes from the UTLS region.

Figure 4 shows the time series of the November–April mean energy of Rossby waves with wave numbers $s=1, \dots, 10$. The upper row represents the energy sum for the deeper baroclinic modes ($m < 5$). The left panel shows the time series of the energy of all frequencies and the right panel shows the energy of high frequency waves. Both panels show positive energy trends. The linear increases in the energy of all waves and in the energy of high frequency waves are 10.8% and 13.8% of their respective mean values in the period 1958–2006. The lower row in the figure shows similar time series but for the sum of the energy of the shallower baroclinic modes ($m > 5$). In this case, the total and high frequency wave energies present linear decreases of 11.7% and 6.9% of their respective mean values. All linear trends in Fig. 4 are statistically significant at the 99% level.

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Particularly remarkable is the fact that the time series of the energy of deeper modes ($m < 5$), which are sensitive to the UTLS and the middle stratosphere, do not show significant changes between the trends before and after the year 1979, i.e. between pre-satellite and pos-satellite reanalysis data.

5 A meridional mode decomposition, similar to the vertical mode decomposition, could, in principle, give information on the horizontal location of the sources of increased baroclinicity. Instead of doing that analysis, we computed the trends in the available potential energy, A_E , of the ERA-40, NCEP-2 and JRA-25 reanalysis (Figs. 5 and 6). In order to make more clear the contribution of each latitude band for the total energy measured by the normal modes, Figs. 5 and 6 show the trends in the area weighted eddy available potential energy ($A_E \cos \theta$). The UTLS region are clearly characterized by positive trends in A_E , with a Northern Hemisphere maximum extending from subtropics to midlatitudes. In the Southern Hemisphere (SH) UTLS, the maximum appears shifted poleward, according with the fact that the analysis was performed for the
10 respective warm season. The subtropical and midlatitude lower troposphere is dominated by negative trends; the exception occurs in the SH where a positive maximum centered at the mid troposphere extends to the surface. Both in the UTLS and in the lower troposphere there are regions where the trends have high statistical significance, above the 99% level. The trend patterns remain consistent considering both the pre- and pos-satellite period (ERA-40) and the pos-satellite period only (NCEP-2 and JRA-
20 25). The overall picture confirms the results of Fig. 3: the energy increase of deeper $m < 5$ baroclinic waves must be due to increased baroclinicity in the subtropical and midlatitude UTLS, whereas the energy decrease of shallower $m > 5$ baroclinic waves must be due to a decrease of baroclinicity in lower troposphere.

25 3.2 Double tropopause trends

Randel et al. (2007) suggested that the occurrence of double tropopauses is due to the excursions of the low latitude (tropical) tropopause to higher latitudes, overlying the lower extratropical tropopause. Consequently, the occurrence of double tropopauses is

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typical of baroclinic circulation in the UTLS region. Thus, an event of double tropopause must be associated either with the generation of high frequency baroclinic waves or with the amplification of stationary baroclinic waves, with vertical structures which may explain the circulation variability in the UTLS region. If, as shown in the previous section, the wave baroclinicity of the UTLS has increased during the last five decades, it may also be expected that an increase in the frequency of double tropopause events has occurred. To verify this possibility, we calculated the trends in frequency of double tropopause events in the subset of radiosoundings described in the Data and Method section.

In fact, a general increase in the relative frequency of double tropopause events is found. Figure 7 shows the relative frequency of double tropopause events in the 30° – 60° N and 30° – 60° S latitudinal belts. These latitudes correspond to the regions where maximum frequency of double tropopause events has been diagnosed in previous studies (Randel et al., 2007; Añel et al., 2008). In the 30° – 60° N band there was an increase of 4.8% (3.3%) per decade in the cool season (annual mean) frequency of double tropopause events. For the same calendar periods, the frequency of double tropopause events in the band 30° – 60° S increased 5.7% (6.6%) per decade in the warm season (annual mean). All these trends are statistically significant at the 99% level. As it may be concluded by the comparison of the seasonal (November–April) and annual frequencies, the double tropopause events are more frequent during the cool season in each hemisphere. Such results also match with the above suggested importance of baroclinicity for the occurrence of double tropopause events.

The trends in the relative frequency of double tropopause are stronger in the Southern Hemisphere. This is consistent with the larger cooling trends observed in the Antarctic lower stratosphere during spring and summer (September to February), in association with the development of the Antarctic ozone hole (Randel et al., 2009; Schwarzkopf and Ramaswamy, 2008). In fact larger cooling trends at high southern latitudes should imply a larger trend in the equatorward temperature gradient and a corresponding increase of UTLS baroclinicity.

4 Concluding remarks

Observational evidence of an increase of midlatitude UTLS wave baroclinicity during the last five decades is presented in this study. As mentioned in the introductory section, the simulated response of climate models to the increase of greenhouse gas radiative forcing is quite consistent, showing a deep warming of the tropical troposphere and cooling of the stratosphere. This warming and cooling pattern leads to the strengthening of meridional thermal gradients in the subtropical and midlatitude UTLS regions. Since positive trends in the UTLS equatorward thermal gradients, during the last three or four decades, have been confirmed by several recently published observational studies, our results may constitute another evidence of climate change due to changes in radiative forcing agents.

The results here presented are very robust because they remained basically the same considering different methods of analysis and different data sets.

Appendix A

3-D Normal Mode Scheme

The normal mode complex amplitudes, w_{msl}^α , are obtained by means of a vertical projection onto the vertical structure functions

$$(\hat{u}, \hat{v}, \hat{\phi})_m^T = \frac{1}{\rho_s} \int_0^{p_s} (u, v, \phi)^T G_m(p) dp, \quad (\text{A1})$$

followed by an horizontal projection onto the horizontal structure functions

$$w_{msl}^\alpha = \frac{1}{2\pi} \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} (\mathbf{H}_{msl}^\alpha)^* \mathbf{C}_m^{-1} \cdot (\hat{u}, \hat{v}, \hat{\phi})_m^T \cos \theta d\theta d\lambda, \quad (\text{A2})$$

where it is assumed that the vertical structure functions, $G_m(p)$, and the horizontal structure functions, $\mathbf{H}_{msl}^\alpha(\lambda, \theta) = \exp(is\lambda) [U(\theta), iV(\theta), Z(\theta)]_{msl, \alpha}^T$, have unitary norms.

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Superscripts T and $()^*$ respectively denote the transpose and the complex conjugate of the transpose. The constant pressure, p_s , represents a prescribed isobaric surface near the Earth's surface. In our calculations, we chose p_s as the mean sea-level pressure of the NCEP/NCAR reanalysis dataset ($p_s=1011.3$ hPa).

5 For $s \geq 1$, the total (i.e. kinetic+available potential) energy per unit area associated with a given mode is proportional to the squared norm of the respective complex amplitude, w_{msl}^α (Liberato et al., 2007, and references therein)

$$E_{msl}^\alpha(t) = \frac{p_s h_m}{2} |w_{msl}^\alpha(t)|^2. \quad (A3)$$

10 The projection onto the horizontal modes allows for the decomposition of circulation field into inertio-gravity and Rossby waves. However, if we do not separate these waves and perform only the vertical decomposition, the energy associated with a vertical mode m is given by

$$E_m = \frac{p_s}{4\pi g} \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \left(\frac{\hat{u}_m^2 + \hat{v}_m^2}{2} + \frac{\hat{\phi}_m^2}{2gh_m} \right) \cos \theta d\theta d\lambda. \quad (A4)$$

A1 Energetics of idealized anomalies

15 Consider an idealized geopotential anomaly given by

$$\phi(\lambda, \theta, p) = A \sqrt{\frac{p_s}{p}} \exp \left[- \left(\frac{z-z_0}{B} \right)^2 \right] \psi(\lambda, \theta), \quad (A5)$$

where A , B and z_0 are constants, ψ represents the horizontal structure of the anomaly field, and $z = -H \ln(p/p_s)$, with $H=7$ km. Using geostrophy, the energy of vertical mode m will be given by

$$20 E_m = \frac{p_s}{4\pi g} \frac{\hat{\Phi}_m^2}{2} \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \left[\frac{\psi^2}{g h_m} + \left(-\frac{1}{f a} \frac{\partial \psi}{\partial \theta} \right)^2 + \left(\frac{1}{f a \cos \theta} \frac{\partial \psi}{\partial \lambda} \right)^2 \right] \cos \theta d\theta d\lambda, \quad (A6)$$

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where f is the Coriolis parameter and $\hat{\Phi}_m$ is the vertical projection of the pressure dependent part of the anomaly field.

Considering that the zonal and meridional spatial scales of ψ are L_x and L_y , respectively, the energy is approximated by

$$E_m \cong \frac{\rho_s}{4\pi g} \frac{\hat{\Phi}_m^2}{2} \left[\frac{1}{g h_m} + \left(\frac{1}{f L_y} \right)^2 + \left(\frac{1}{f L_x} \right)^2 \right] \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \psi^2 \cos \theta d\theta d\lambda. \quad (\text{A7})$$

The left panel in Fig. A1 shows the vertical profile of three idealized anomaly fields. The constants in Eq. A5 were chosen to reproduce anomalies centered at the middle troposphere, in the UTLS region and in the middle stratosphere.

Both the anomaly fields and the respective energy spectra (Fig. A1, right panel) were normalized to their respective maximum values. The energy spectra were calculated considering $(f L_x)^2 = (f L_y)^2 \sim 10^5$, corresponding to spatial scales between $10^6 - 10^7$ m for a central latitude of 45° . If we choose $L = 10^6$ m or $L = 10^7$ m, the spectra remain qualitatively the same. As it may be observed, the shallower modes ($m > 5$) represent tropospheric anomalies, whereas the deeper modes ($m < 5$) represent anomalies in the UTLS and in the stratosphere.

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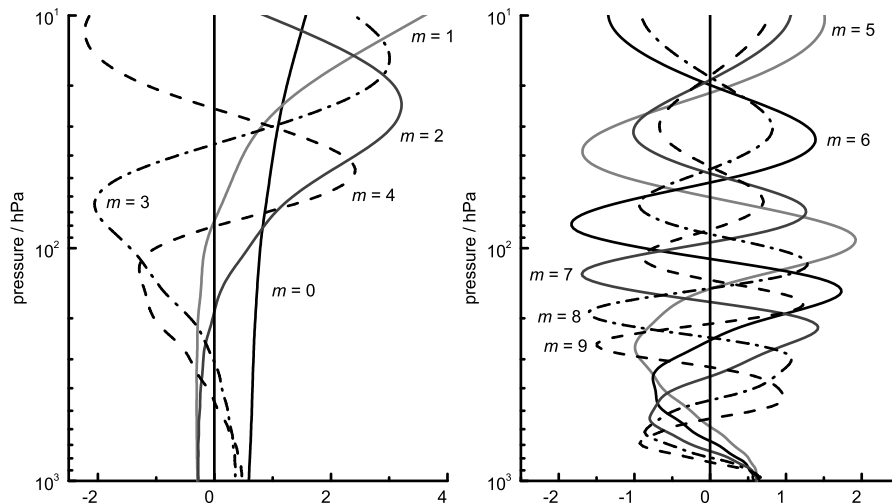


Fig. 1. Vertical structure functions of the barotropic ($m=0$) and first nine baroclinic modes ($m=1, \dots, 9$) of the NCEP/NCAR atmosphere. For $m \geq 2$ one node appears above 10 hPa and it is not represented.

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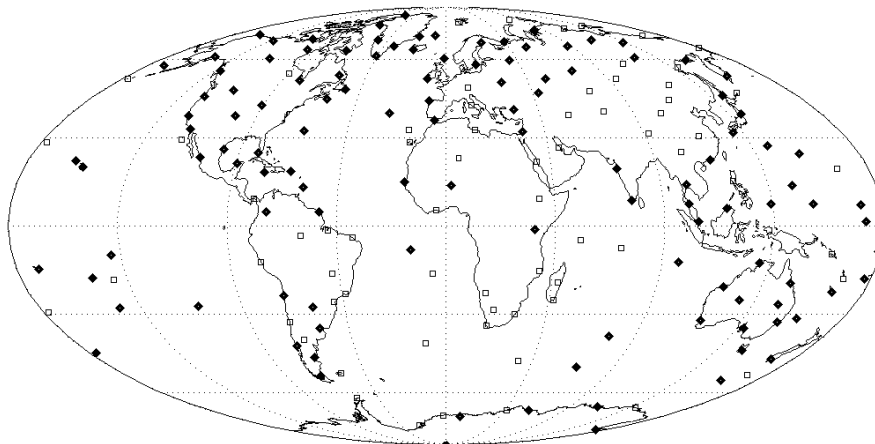


Fig. 2. Radiosonde stations considered in the study of Añel et al. (2008). The solid diamonds represent the stations which passed the homogenization criteria in this work, and which were retained for the computations of the trends in the frequency of double tropopause events.

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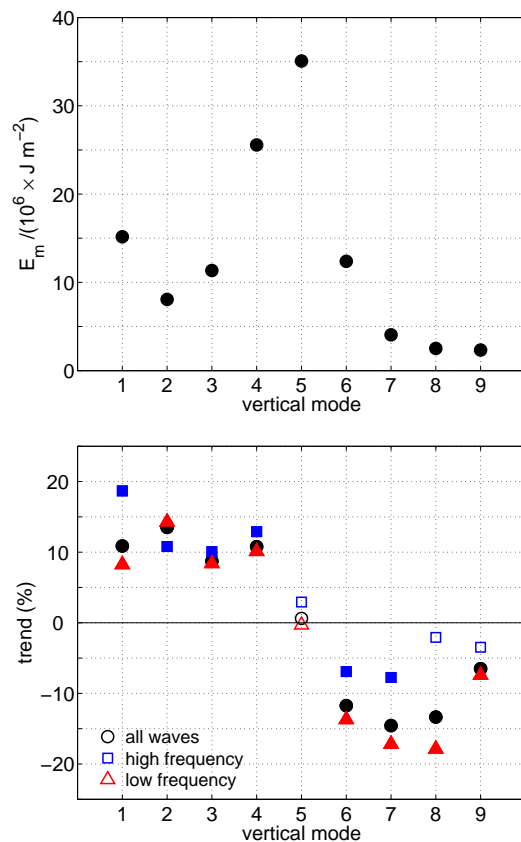


Fig. 3. Top: Vertical spectrum of the mean energy (E_m) associated with the baroclinic Rossby waves of wave numbers $s=1, \dots, 10$. Bottom: Linear trends of the November–April mean energy associated with the Rossby waves of wave numbers $s=1, \dots, 10$, for the first 9 baroclinic modes. The trends are given as percentages of the respective mean energies in the period of 1958–2006. Solid symbols indicate significant trends at the statistical level of 99% ($p=0.01$).

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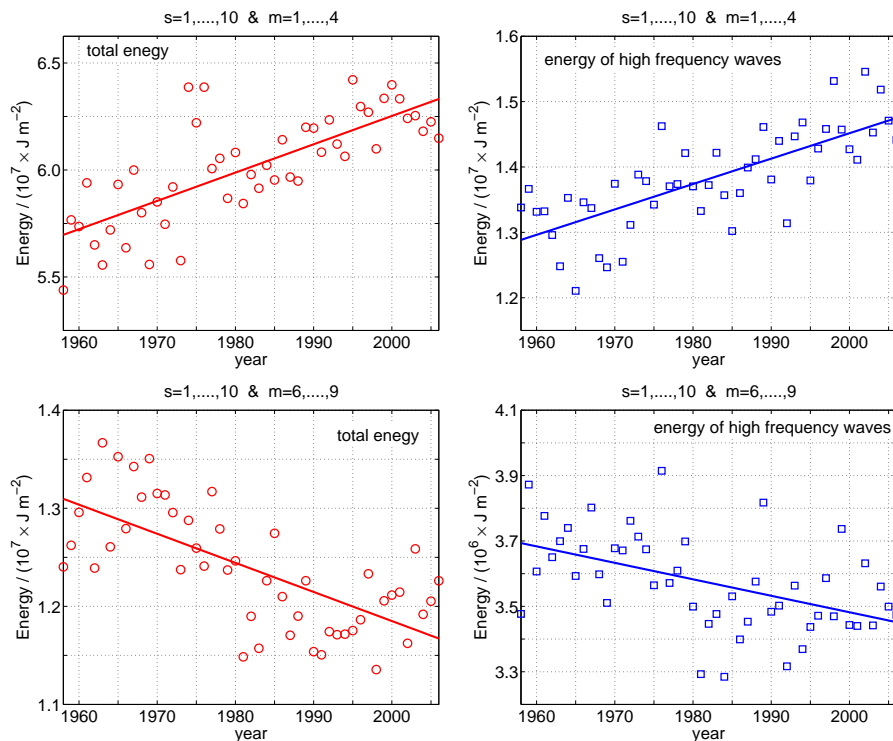


Fig. 4. November–April mean energy associated with baroclinic Rossby waves of wave numbers $s=1, \dots, 10$: (upper row) sum of the energy of the deeper baroclinic modes ($m=1, \dots, 4$), and (lower row) sum of the energy of the shallower baroclinic modes $m=6, \dots, 9$.

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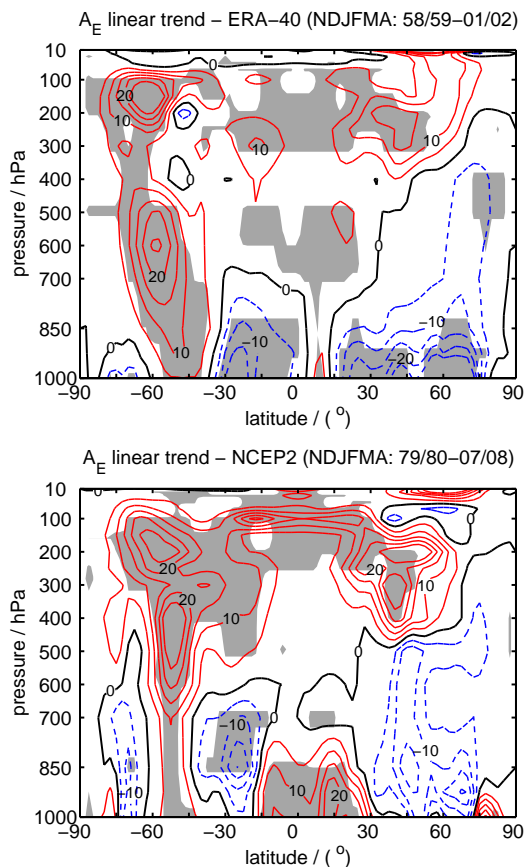


Fig. 5. Interannual trends in the area weighted eddy available potential energy ($A_E \cos \theta$) of the ERA-40 (top) and NCEP-2 (bottom) reanalysis. Units are $\text{J m}^{-2} \text{hPa}^{-1} (\text{decade})^{-1}$. Dashed contours represent negative values, and the shaded areas represent trends statistically significant at the level of 99%.

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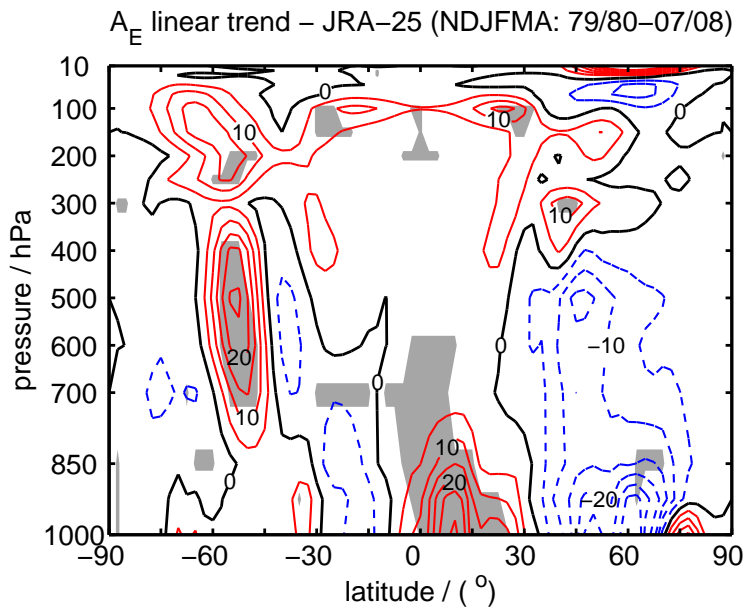


Fig. 6. As in Fig. 5 but for the JRA-25 reanalysis.

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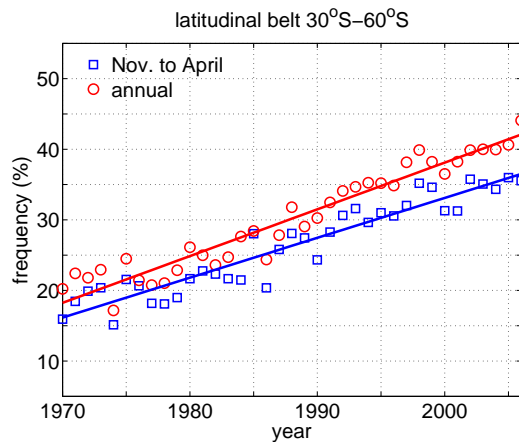
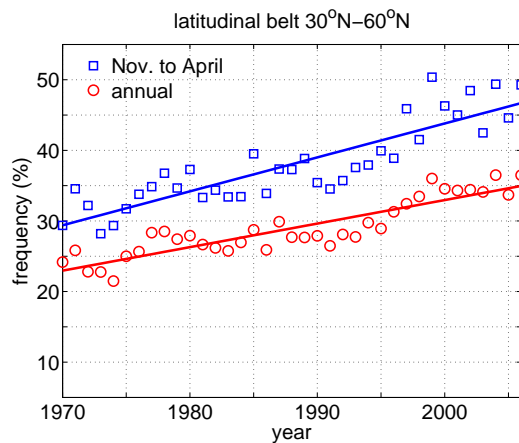


Fig. 7. Relative frequency of double tropopause events in the 30° N–60° N (upper panel) and 30° S–60° S (lower panel) latitude belts.

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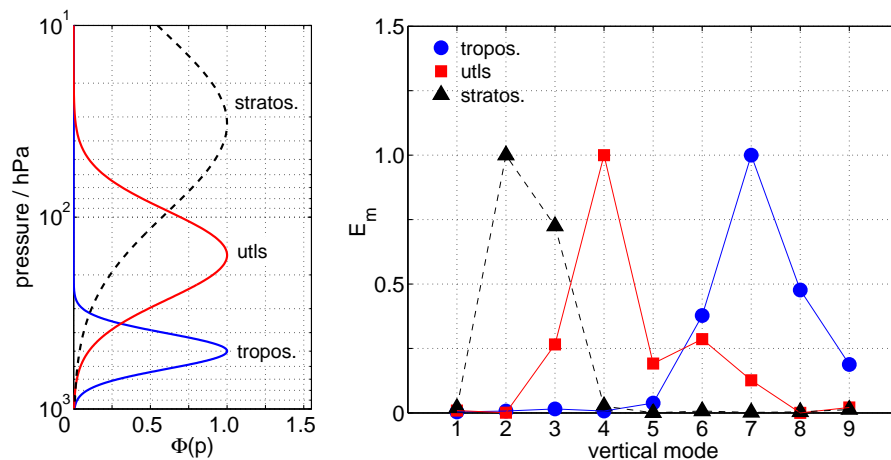


Fig. A1. Vertical energy spectra (right) of three idealized geopotential anomalies (left) centered at the middle troposphere, in the UTLS region and in the middle stratosphere. The spectra and the anomalies were normalized to their respective maxima.

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