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Interannual variability and long term changes in planetary wave activity in the middle atmosphere observed by lidar

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Abstract

The upwelling planetary wave activity (PW) from the troposphere controls the intensity of the equator to pole transport of stratospheric ozone by the Brewer-Dobson circulation and thereby modulates the total ozone content at mid- and high-latitudes. Rayleigh lidar temperature data obtained from 1981 to 2001 at mid-latitude were used to study the interannual variability of PW activity in winter (October to April). The spectrum of stratospheric temperature fluctuations exhibits 2 peaks corresponding to 2 dominant modes of free travelling Rossby waves known as 16 day- and 12 day-waves. The 12 day-wave activity is shown to be anticorrelated with the equatorial QBO wind at 40 hPa. During the period 1981–2000 the global PW activity shows a negative trend for months October to January and a positive trend in March and April.

1 Introduction

The middle atmosphere thermal structure is expected to change due to the increase of greenhouse gases and the depletion of stratospheric ozone. The radiative effect of greenhouse gases is positive in the lower and middle troposphere, but becomes negative as soon as the infrared optical thickness of the atmosphere is low enough to allow the thermal radiation to be emitted directly to space, i.e. in the upper troposphere, stratosphere and mesosphere. The temperature is also affected by changes in ozone which is an important greenhouse gases in the stratosphere. The decrease of stratospheric ozone until mid 1990s and its stabilisation afterwards have contributed significantly to the cooling of lower stratosphere (Ramaswamy et al., 2001).

The temperature in the winter polar stratosphere is controlled by the activity of planetary waves (PW) leading to sudden stratospheric warming (Labitzke, 1981). The meridional (equatorward or poleward) and upward propagation of PW, is driven by the thermal and wind structure of the middle atmosphere (Matsuno, 1971) and can be represented using a refractive index of PW (O'Neill and Youngblut, 1982). The PW

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forcing on the mean flow is characterized by the convergence of the EP flux. Expected radiative changes are latitude dependent and cause changes in the meridional gradient of pressure inducing a change in the propagation of planetary Rossby waves in the winter middle atmosphere. Cordero and Nathan (2005) have shown that changes in stratospheric ozone are sufficient to induce radiative changes in the temperature field that can modify the refractive index of PW and can affect the large-scale circulation. The sign of the radiative-dynamical feedback is still unknown. General climate models predict either intensification or weakening of stratospheric warmings during the next decades (Austin et al., 2003).

Following the reduction of CFCs emissions, the stratospheric ozone layer is expected to recover during the next decades. However mechanisms at the origin of ozone depletion are highly non-linear and any change in the thermal structure of the polar stratosphere may affect the rate of recovery. Chorine species involved in the catalytic cycle of ozone destruction are activated by heterogeneous reactions at the surface of PSC particles. If the temperature goes down faster than expected due to a decrease of PW activity, the frequency of occurrence of PSCs will strongly increase and the recovery will be delayed by several decades. On the contrary, if the temperature goes up due to an increase of PW activity, the recovery will be faster than expected.

The detection of changes requires long series of measurements and a good estimate of the natural variability (Keckhut et al., 1995). PW upward propagation represents one of the main causes of variability of the middle atmospheric temperature. Extratropical Rossby planetary waves are generated in the troposphere and can propagate upwards in the middle atmosphere during the period of westerly winds in the stratosphere from October to April. During the summer period their vertical propagation is blocked by easterly winds (Charney and Drazin, 1961). Unfortunately, they are very few dataset available to study changes in the dynamics of the upper stratosphere and the mesosphere, and when they exist most of them are limited in the length of the series, in the range covered or in the height resolution. One of the best available dataset is the one provided by the Rayleigh lidar at Haute-Provence Observatory (OHP; 44N, 6E), operated regularly since 1979 to measure vertical profiles of temperature from 30 to 80 km. This instrument is integrated in the Alpine station of the Network for the Detection of Atmospheric Composition Change (NDACC, formerly NDSC). Lidar and rocket data have been used for several studies of planetary wave propagation in the middle atmosphere (Hauchecorne and Chanin, 1983; Hauchecorne et al., 1987; Offermann et al., 1987; Bittner et al., 1994), but they were limited in time. In the present study we analyse OHP lidar data to estimate the planetary wave activity during each winter from 1981–1982 to 2000–2001. The evolution of the PW activity during these 20 years will be presented. The role of the Quasi-Biennial Oscillation (QBO) in the modulation of PW activity will be also discussed.

2 Database and data processing

Data are obtained using the Rayleigh lidar set-up at OHP. The lidar provides vertical profiles of temperature above about 30 km, in the region free of aerosols (Hauchecorne et al., 1980). Basically the method consists in measuring the atmospheric density in relative value, assumed to be proportional to the intensity of the backscattered Rayleigh signal. The temperature profile is obtained in absolute value by a downward integration of the hydrostatic law assuming a pressure at the top of the profile (~90 km) equal to the pressure of MSIS90 climatology (Hedin, 1991).

Lidar data are integrated during one night of measurement and are smoothed to suppress short scale fluctuations induced for instance by gravity waves (Hauchecorne et al., 1991). The resulting vertical resolution is 3 km and the vertical sampling is 1 km. The typical accuracy is better than 2 K up to 70 km, 5 K at 80 km and 20 K at 90 km (Keckhut et al., 1993).

2.1 Temperature evolution

For each year the period from 90 days before to 120 days after 1 January (from October to April) is selected. Temperature data are interpolated in time using modified cubic spline functions (Hauchecorne et al., 1991) at each altitude to fill gaps due to missing data. Figure 1 presents the temperature evolution during winter 1996–1997. Temperature perturbations with periods ranging from a few days to 20 days are clearly visible in the upper stratosphere and in the mesosphere. They are due to the propagation of PW. As expected, the amplitude is maximal in mid-winter when strong westerly winds favour the upward propagation of PW. For the interpretation of these observations we have to keep in mind that a fixed ground-based lidar samples temperature perturbations occurring above the site but does not separate reversible processes like free travelling planetary waves from irreversible ones like sudden stratospheric warmings.

2.2 Spectral analysis

Free planetary Rossby waves have preferential periods depending on their zonal wave number and their mode (Kasahara, 1980). In the north winter stratosphere, the so-called 16-day wave-zonal number 1 and 12-day-wave-number 2 are dominant because higher wave numbers are absorbed in the lower stratosphere. In order to detect if such waves are present, we perform at each altitude a spectral analysis of the temperature deviation from winter average. A Welch window is applied before the analysis to avoid side effects. Winters are classified according to the phase of the QBO defined as the sign of the averaged equatorial zonal wind in January-February at 40 hPa (Table 1). For both phases of the QBO, 2 maxima are observed in altitude, the first one in the upper stratosphere around 40 km, clearly associated to PW and limited to frequencies lower than 0.1 day^{-1} (periods longer than 10 days), and the second one in the mesosphere above 60 km, extending to higher frequencies and attributed by Hauchecorne et al. (1991) to a combination of PW and the effect of gravity wave breaking on the mean temperature. For QBO West (Fig. 2, top), a broad frequency peak is observed at

40 km at 0.050–0.055 day^{-1} (18–20 days). For QBO East (Fig. 2, bottom) two sharper peaks are detected at the same altitude at 0.055 day^{-1} (18 days) and at 0.075 day^{-1} (13 days). These two peaks correspond broadly to the two dominant 12 day- and 16 day-Rossby waves in the north winter stratosphere. The shift towards longer periods may be explained by the Doppler shift due to the wave propagation in westerly winds. Mesospheric results are more difficult to interpret due to a combination of effects, but the presence of the 18–20 days period is observed for all situations.

In order to see if the QBO is truly at the origin of the modulation of the 12 day-wave amplitude, the PW energy has been averaged for each winter in a period interval 10.9 to 14.6 days. This period interval is representative of the 12 day-wave. In the upper stratosphere, the energy of the 12-day wave exhibits clearly a quasi-biennial periodicity with some variation in the altitude of energy maxima between 38 and 45 km (Fig. 3). The evolution of its energy averaged over the altitude range 38–45 km (Fig. 4) is well correlated with the amplitude of the equatorial wind at 40 hPa. Each maximum in the energy curve corresponds to a minimum in the wind amplitude and the correlation coefficient is equal to -0.45 ± 0.21, significant at the 95% level (2 standard deviations).

The scatter plot presented in Fig. 5 visualizes this anticorrelation. There is some significant scatter around the regression line but the 3 years with highest energy (1984, 1987 and 1992) are in the QBO east category. The year 1987 is far over the regression line. It corresponds to winter 1986–1987 with a major stratospheric warming in January 1987 (Naujokat, 1987).

2.3 Trend in planetary wave activity

Changes in the atmospheric temperature and wind structure may induce modifications in the propagation of PW in the stratosphere. These modifications may have some seasonal evolution. It is therefore interesting to investigate if such a trend varies during the winter. In fact during the period 1982–2000 a negative trend is detected from October to January, a zero trend in February and a positive trend in March–April (Fig. 6).

This indicates that the maximum of PW activity is occurring later in the winter at the end of the period under study.

3 Discussion

The present work confirms the existence of preferential periods in the spectrum of PW in winter around 12–13 and 18 days. Similar periodicities have been reported in previous studies. Hauchecorne et al. (1983) using a much shorter series of OHP data demonstrated the continuous activity of planetary waves as long as prevailing winds at mid-latitude are westerly (from October to April) and detected the frequent occurrence of a 18 day-travelling Rossby wave. In a later publication, Hauchecorne et al. (1987) showed the presence of 12.5 day westward propagating Rossby wave during MAP-WINE campaign in winter 1983–1984 using lidar and rocket observations above Europe. The 12 day-wave was also detected by Offermann et al. (1987) with a harmonic analysis of temperature oscillations during the same campaign. The 2 periods around 18 days and 12–12.5 days correspond approximately to the 2 dominant 16 day-number 1 and 12 day-number 2 Rossby waves in the northern winter hemisphere (Kasahara et al., 1980).

The influence of the equatorial QBO on extra-tropics was first demonstrated by Holton and Tan (1980) who showed, using National Meteorological Center daily analyses, that the geopotential at 50 hPa in northern high latitudes was lower during the west phase of the QBO than during the east phase in both winter and summer. These authors found also intensification of the stationary PW number 1 during the east phase in November–December. This intensification was successfully simulated by Maillard et al. (1990) using a 3-D primitive equations model with a forced equatorial QBO. Our study shows an amplification of the 12 day-wave attributed to PW number 2 during the east phase of QBO. This result seems to be the opposite of the results of Holton and Tan (1980) who found an amplification of PW number 2 during the west phase (not statistically significant). However the results are not fully comparable because the lidar samples the propagating part of the PW field whereas Holton and Tan (1980) consider the stationary part.

The scatter plot of 12 day-wave energy versus QBO wind (Fig. 5) does not show a very linear anticorrelation but rather 2 families of data points, one below and one above the regression line, each of them showing a clear anticorrelation. Borchi et al. (2005), using a wavelet multi-resolution analysis, identified 2 types of transition in TOMS (Total Ozone Mapping Spectrometer) Arctic ozone series from high winter variance to low spring variance, a first type with a very abrupt and early transition to the spring regime and the second type with a smooth evolution of ozone variance and a late transition. It is interesting to note that the 3 winters with the highest PW energy (1984, 1987, 1992), all in QBO east phase, correspond to 3 winters of the second type. This seems to indicate that winters with a late transition to the quiet spring regime are also characterised by high average 12-day-wave energy.

The Brewer-Dobson circulation is at the origin of the poleward transport of ozone in the stratosphere. It is driven by the dissipation of PW in the middle atmosphere and any change in PW activity will affect the total ozone content at mid and high latitude. Fusco and Salby (1999) and Salby and Callaghan (2002) proposed that the interannual variation of total ozone in the Northern Hemisphere is correlated with upwelling PW activity from the troposphere, estimated by the Eliassen-Palm (EP) flux at the tropopause. Salby et al. (2002), using lidar data at OHP, showed that the interannual change in EP flux affects also the winter-time vertical structure of stratospheric ozone and temperature at mid-latitude. Randell et al. (2002) suggested that the EP flux entering into the stratosphere presents a general negative trend and contributes to ~20–30% of the observed trend in column ozone over 35–60° N between 1979 and 2000. There findings were confirmed by Hood and Soukharev (2005) who showed also a ~30% contribution to the mid-latitude ozone negative trend of the synoptic wave forcing, characterised by Ertel's potential vorticity, in February–March. The present work confirms the negative trend in PW activity for months October to January (Fig. 5) but shows also a partially compensating effect in early spring (March–April) with a positive trend. The northern mid-latitude negative trend in total ozone is maximal in March and decreases during the following months (Fioletov and Shepherd, 2005). It would be interesting to study if the increase in PW activity in March–April contributes to the reduction of the negative trend in spring.

4 Conclusions

20 years of middle atmosphere Rayleigh lidar temperature data at OHP (44° N) have been used to study the interannual variability of PW activity in winter (October to April). The main conclusions are as follows:

- the spectrum of the stratospheric temperature fluctuations exhibits 2 peaks around 16–20 and 12–13 days which are attributed to 2 dominant modes of free travelling Rossby waves known in the literature as the 16 day-number 1 and 12 day-number 2 waves;
- the 12 day wave activity presents a quasi 2 years periodicity anticorrelated with the equatorial QBO wind defined at 40 hPa;
- during the period 1981–2001, the PW activity shows a negative trend for months October to January, in agreement with previous studies showing a weakening of Brewer-Dobson circulation during these months (Salby and Callaghan, 2002; Randell et al., 2002; Hood and Soukharev, 2005), and a positive trend for March and April. It would be interesting to study if the increase in PW activity in early spring contributes to the reduction of the negative trend in northern mid-latitude total ozone observed by (Fioletov and Shepherd, 2005) between March and June.

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Table 1. Amplitude of equatorial wind in January–February at 40 hPa. QBO data series compiled by B. Naujokat, Stratospheric Research Group, Freie Universität Berlin, are available at http://strat-www.met.fu-berlin.de/products/cdrom/html/section5.html.

Year	Wind m/s	QBO sign	Year	Wind m/s	QBO sign
1982	–14	E	1992	–16.5	E
1983	15	W	1993	12.5	W
1984	–8	E	1994	–1.5	E
1985	–12	E	1995	5.5	W
1986	15	W	1996	3.5	W
1987	–9	E	1997	–24	E
1988	9	W	1998	12.5	W
1989	12	W	1999	–14	E
1990	–26	E	2000	12	W
1991	11.5	W	2001	–7	E

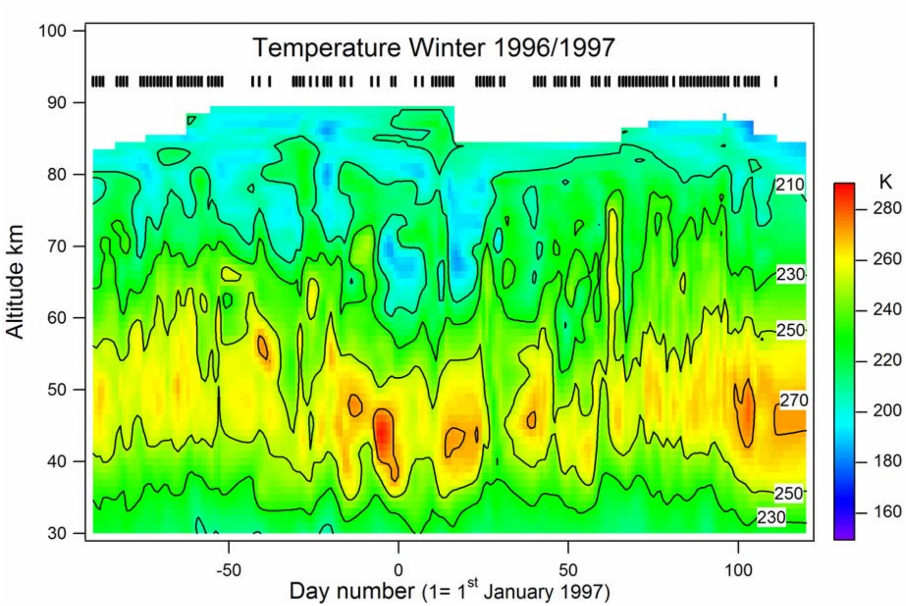

Fig. 1. Evolution of the temperature at OHP during winter 1996–1997. The days with measurements are indicated with a vertical bar at the top of the figure.

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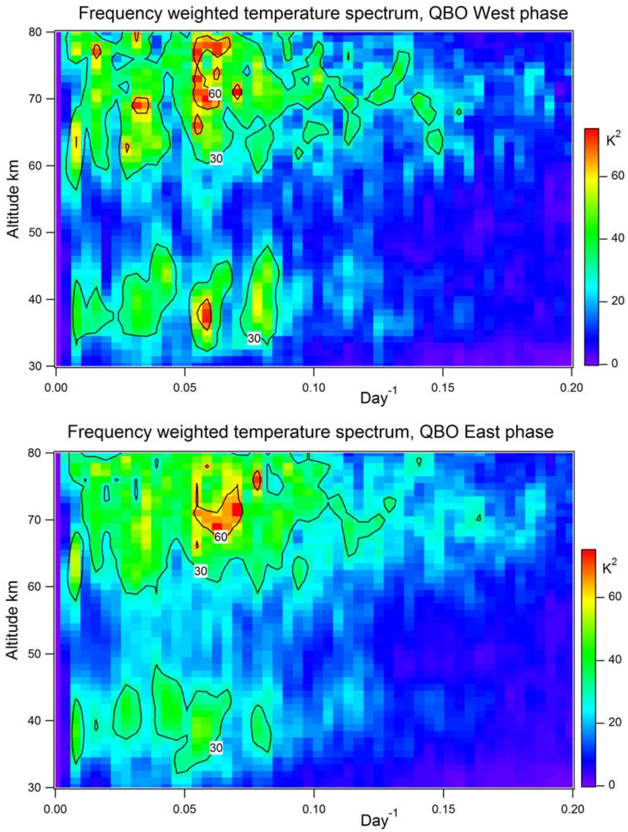

Fig. 2. Energy spectrum of temperature perturbations averaged over winters in QBO West phase (top) and QBO East phase (bottom). The spectrum is multiplied by the frequency to have a better visualisation of energy maxima due to dominant PW modes. The non-weighted spectrum is dominated by the decrease of energy with frequency. Consequently the unit is $K^2 day^{-1}/day^{-1}=K^2$. See Table 1 for the classification of QBO phases.

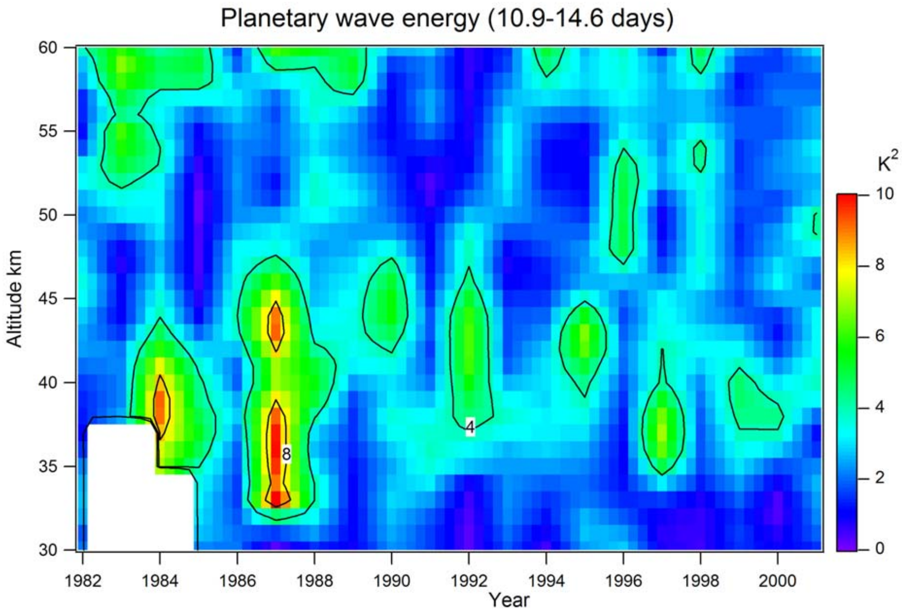

Fig. 3. Time-altitude section of the energy of the 12 day-wave. Years written on the x label axis correspond to the end of winters (1982 for winter 1981–1982).

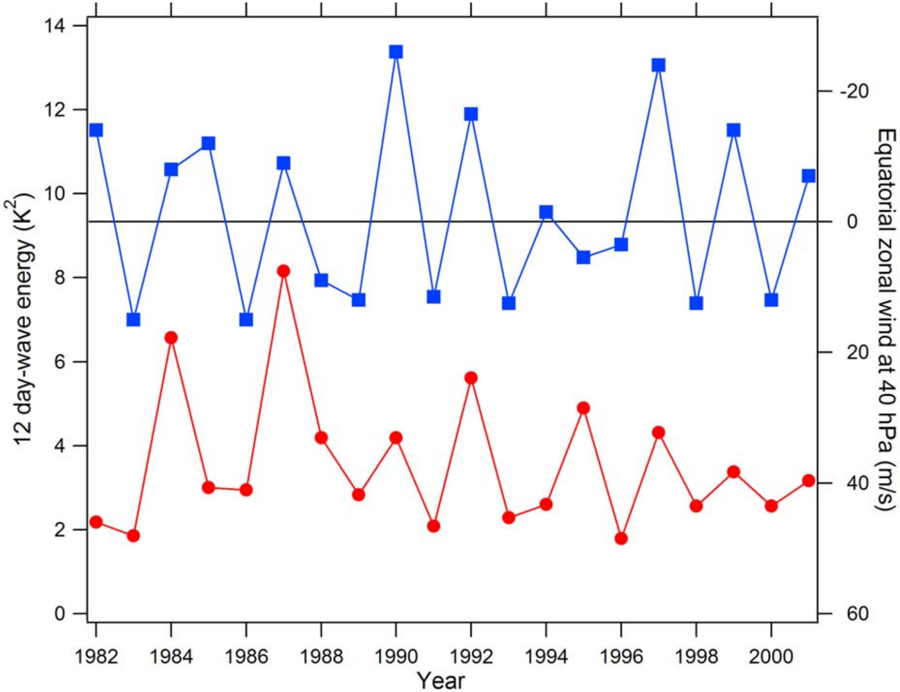

Fig. 4. Energy of 12 the day-wave averaged in the altitude range 38–45 km (bottom curve, left scale) and Equatorial zonal wind at 40 hPa (top curve, inverted scale on the right).

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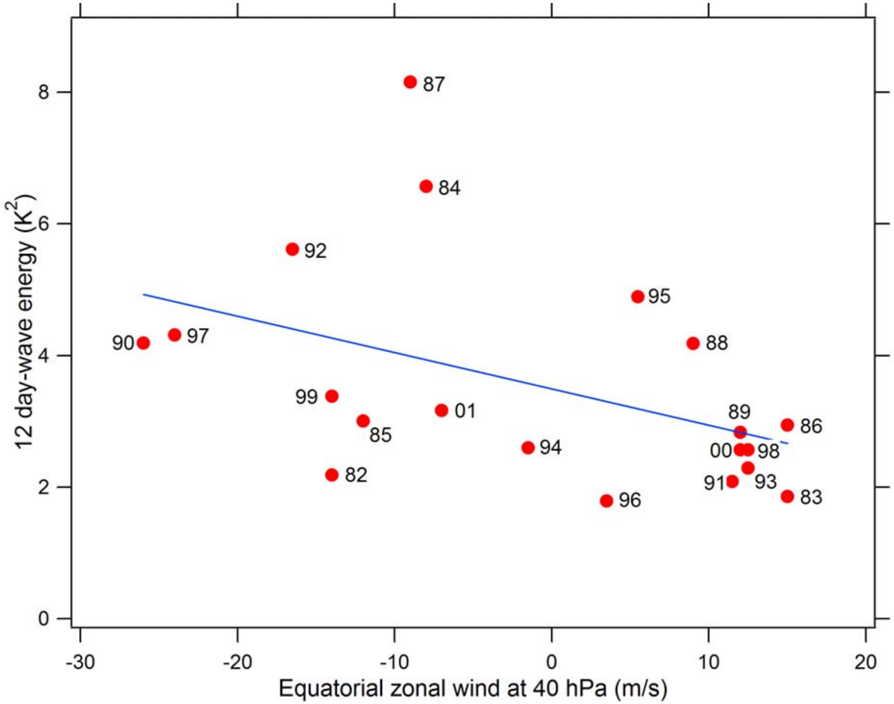

Fig. 5. 12 day-wave energy averaged in the altitude range 38–45 km versus Equatorial zonal wind at 40 hPa.

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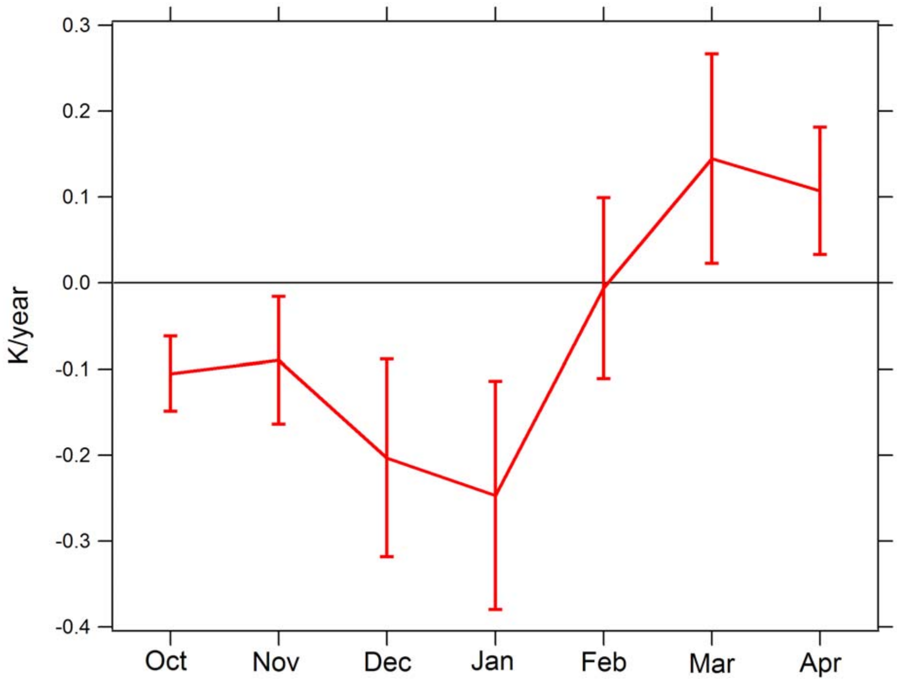

Fig. 6. Trend in planetary wave amplitude between 1982 and 2000 at 40 km from October to April. For each month, the PW amplitude is defined as the square root of the variance of temperature perturbations attributed to planetary waves (periods from 10 to 40 days).

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