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Interannual variability of total ozone and its relation with the Asia Pacific Wave

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ABSTRACT

Analysis of the NCEP/NCAR reanalysis wind data shows the presence of a stationary Rossby wave in the lower stratosphere during May. This wave is seen prominently below 70 hPa level, confined between 10°N and 50°N latitudes and has a zonal wave number of 6 or 7. It is an extension into the stratosphere of the Asia Pacific Wave (APW) of the troposphere documented by Joseph and Srinivasan (1999). As in the troposphere, in the lower stratosphere this wave shows a phase shift of 20° longitude between deficient and excess Indian summer monsoon rainfall (ISMR) years. This wave has maximum amplitude at about 200 hPa. The amplitude of the wave decreases both above and below 200 hPa level. The large-amplitude portion of this wave is thus situated in the break region between the tropical and extratropical tropopauses around 30°N latitude. It is suggested that this large-amplitude APW exchanges the tropical and extratropical airmasses through the tropopause break, making the APW signature seen in the satellite monitored total ozone (TOMS data). APW is found to exist in the following monsoon season (June to September) with the same phase as in May and its signature is also seen in that season in total ozone.

1. Introduction

Joseph and Srinivasan (1999) (in the following JS), using NCEP/NCAR reanalysis data (Kalnay et al., 1996), showed the presence of a large-amplitude standing Rossby wave in the upper tropospheric westerlies during May confined between 10°N and 50°N latitudes. This wave has a wavelength of about 50–60° longitude (zonal wave number 6 or 7) and has a spatial shift of about 20° longitude between deficient and excess Indian summer monsoon rainfall (ISMR) years. According to JS, the spatial shift is due to the shift in the longitudinal position of the convective heat sources associated with the Inter Tropical Convergence Zone. The Equatorial Convective Cloudiness Maximum (ECCM), commonly known as ITCZ, is at the equator in April over the Indian and West Pacific oceans. Over this area in May the ECCM moves north of the equator in connection with the onset of the Asian summer monsoon. The convective heat source (caused by release of latent heat) and the upper tropospheric divergence associated with it can serve as a source to perturb the westerlies in the latitude belt 10–50°N (Sardeshmukh and Hoskins, 1988). This Rossby wave source in May shows large shift in the east–west direction between deficient and excess monsoon years. Due to its geographical location, this stationary Rossby wave was named the Asia Pacific Wave (APW). JS reported that this wave has a large amplitude around 200 hPa, and the amplitude decreases with decreasing height in the troposphere. Although the lower portion of this wave has been studied in detail,

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the nature above 200 hPa has not been documented. It would be interesting to know whether the APW is seen above 200 hPa in the lower stratosphere, because this region is rich in ozone.

The global ozone distribution, its trend and variabilities from synoptic to decadal timescales have been studied intensively using satellite, ozonesonde and ground-based ozone measurements and numerical models (Bowman, 1989; Fusco and Salby, 1999; Hadjinicolaou et al., 1997; Hamilton, 1995; Logan, 1985; 1994; Trenberth, 1990; Wirth, 1993). Using a simple one-dimensional model, Holton (1989) showed that horizontal advection by the mean Hadley circulation can account for much of the observed meridional asymmetry of the Quasi Biennial Oscillation (QBO) in total ozone. Hadjinicolaou et al. (1997) attributed the year-to-year variations of mid-latitude total ozone to the meteorological variations in the stratosphere. Interannual variability in the total ozone amount and the plausible mechanisms behind this variability has been studied during recent years.

In the present work the nature of the APW above 200 hPa level is studied. The importance of the location of the APW and possible meridional mass exchange including that of ozone by this wave is highlighted. It is also shown how the environmental conditions associated with extreme ISMR affect the distribution of total ozone amount over an area in the interannual timescale.

2. Data

Gridded wind (both u and v) and temperature data with a horizontal resolution of 2.5° latitude × 2.5° longitude are available for 17 levels, from surface to 10 hPa in the NCEP/NCAR reanalysis data (Kalnay et al., 1996). Monthly mean values of wind at 300, 200, 150, 100, 70, 50, 30, 20 and 10 hPa levels for the period 1979–94 were used. Temperature data at all 17 levels have been analysed to understand the tropopause break. Gridded monthly mean total ozone data (version 7) measured by the TOMS instrument onboard Nimbus-7 spacecraft was used for the ozone analysis (McPeters et al., 1996). This data set has 1° latitude × 1.25° longitude spatial resolution and covers the period November 1978 to April 1993.

Table 1. *Indian summer monsoon rainfall (mm) (data from Parthasarathy et al., 1994)*

Year	Percentage departure (mm) from 1871–1993 mean
1979	−16.96
1980	3.57
1981	−0.02
1982	−13.73
1983	12.12
1984	−1.84
1985	−10.86
1986	−12.83
1987	−18.20
1988	12.80
1989	1.68
1990	6.61
1991	−7.91
1992	−7.91
1993	2.89

Indian summer monsoon rainfall (ISMR) data were adopted from Parthasarathy et al. (1994). ISMR is the area-weighted average June to September rainfall of 306 stations well distributed over India. The long-period average ISMR is 852.4 mm and its standard deviation is 84.69 mm. Table 1 gives the ISMR for the 1979–93 period. The 3 DRY years are the years of maximum rainfall deficiency while the 3 WET years are the years of maximum rainfall excess. During the period 1979–93 the years 1979, 1982 and 1987 are DRY monsoon years and 1983, 1988 and 1990 are WET monsoon years. All these years have rainfall excess/deficiency more than one standard deviation from the long period average except 1990 (Table 1).

3. The Asia Pacific Wave in the lower stratosphere

In order to study the characteristics of the APW, gridded NCEP/NCAR mean meridional wind data during the month of May were used. Data for the 13-yr period 1982–94 available in the CD-ROM supplied along with Kalnay et al. (1996) for the 9 levels considered (300, 200, 150, 100, 70, 50, 30, 20, 10 hPa) were used to calculate meridional wind anomalies at each grid point for composites of DRY and WET years.

In Fig. 1 meridional wind anomalies for the

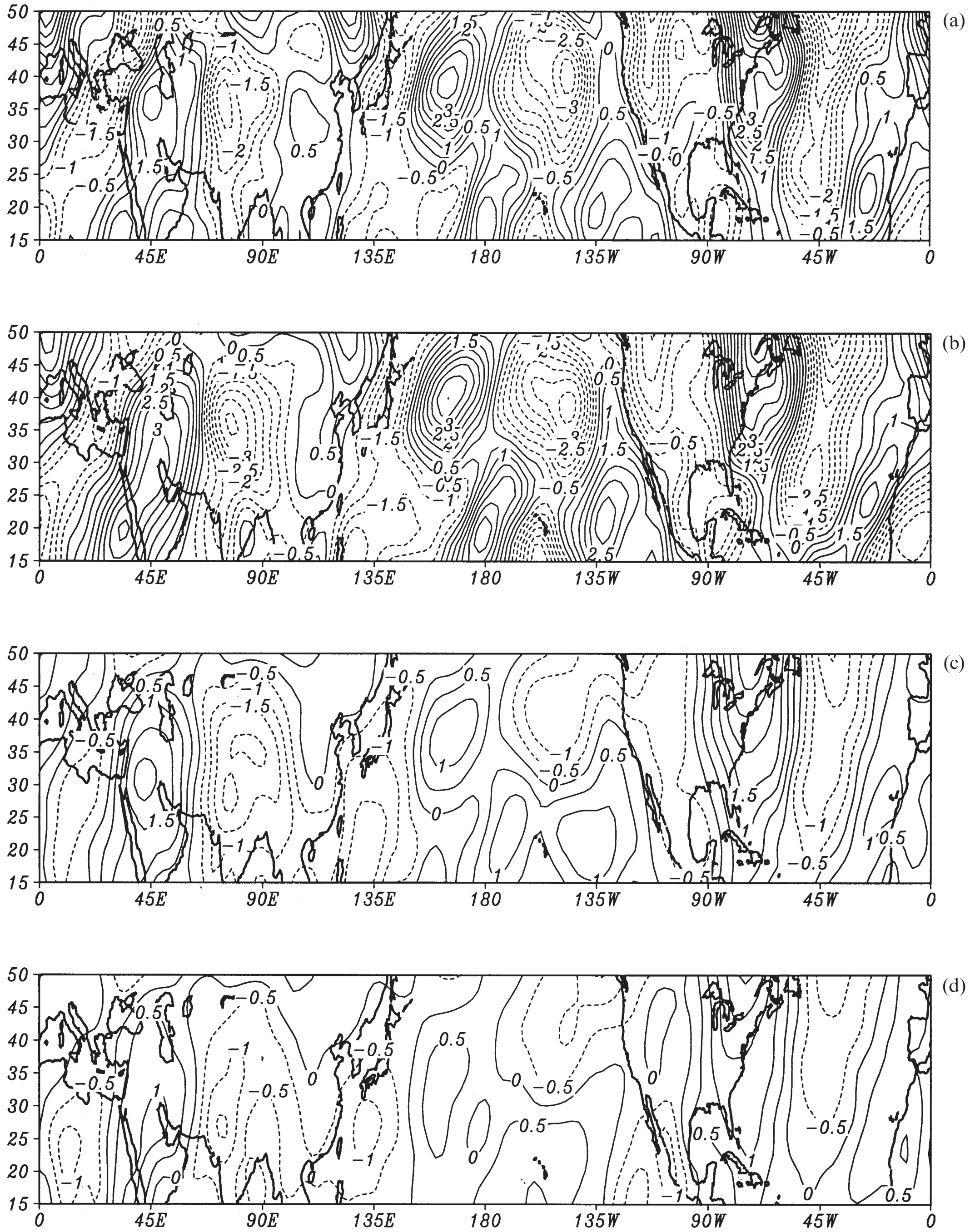

Fig. 1. Meridional wind anomalies (m s^{-1}) of (a) 300, (b) 200, (c) 100 and (d) 70 hPa levels for WET composite. The contour interval is 0.5 m s^{-1} .

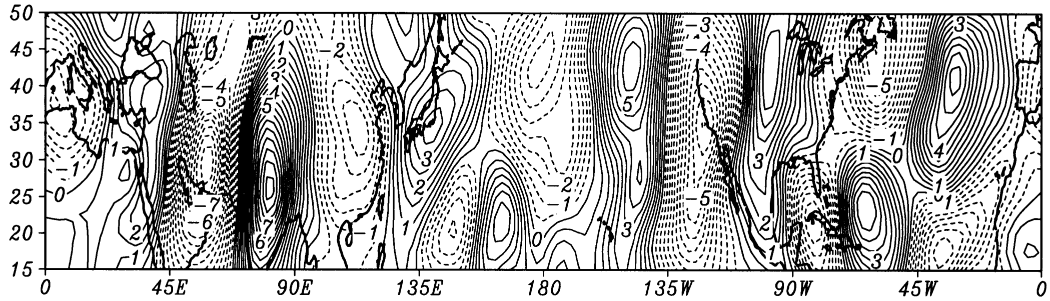

Fig. 2. Meridional wind anomalies (m s^{-1}) of 200 hPa for DRY composite. The contour interval is 0.5 m s^{-1}.

composite WET years for 4 levels, viz. 300, 200, 100 and 70 hPa are given, and in Fig. 2 meridional wind anomalies for the composite DRY ISMR years for 200 hPa level only are presented. A prominent stationary Rossby wave signal is seen in these figures at all levels. It has a wave number 6 or 7 in zonal structure and is confined between 10°N and 50°N latitudes. It is seen from Fig. 1 that the areas of southerly and northerly meridional wind anomalies of the WET composite above 200 hPa levels match with the same at 200 hPa and below. Thus, the wave seen above 200 hPa level is an integral part of the APW reported by JS for 200 hPa and below. The amplitude of this wave decreases both above and below 200 hPa and the wave is very weak above 70 hPa (figures not shown).

From Fig. 1 and the study by JS it is clear that the wave is present between 500 and 70 hPa levels, with maximum amplitude around 200 hPa. Above and below 200 hPa its amplitude decreases. Over the Indian region, northerly anomalies are seen during WET years and southerly anomalies during DRY years. It is seen from the 200 hPa WET (Fig. 1c) and DRY (Fig. 2) composites that the APW shows a phase shift of about 20° longitude between extreme ISMR years as reported by JS. It is clear from this study that the APW affects both the upper troposphere and the lower stratosphere. JS showed that the APW at 200 hPa and below possesses major characteristics of a stationary barotropic Rossby wave, which has no phase shift with height. It is clear from Fig. 1 that the wave above the 200 hPa level also does not show any phase shift with height.

4. The Asia Pacific Wave and meridional mass exchange

The APW follows the subtropical westerly jet stream over the Asian region and then moves southeastwards to North America. Although the wave shows north–south displacement in some regions, generally it is confined between 10°N and 50°N latitudes with large amplitude between 300

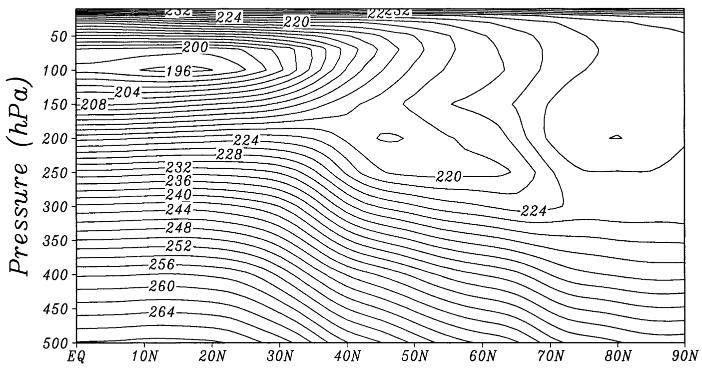

Fig. 3. Latitude–height plot of the temperature averaged between 50°E and 100°E longitudes for May 1989.

and 150 hPa levels. The latitude–height plot of the mean May temperature values of 1989 (a normal ISMR year) averaged between 50°E and 100°E longitudes (the Indian region) for the Northern Hemisphere is presented in Fig. 3. The tropical tropopause is situated around 100 hPa and the extratropical tropopause between 200 and 300 hPa levels. Over 30°N and adjoining latitudes, the tropical tropopause lies above the extratropical tropopause and a break region exist between them, which is the tropopause break.

The 14-yr (1979–92) mean May total ozone distribution for the Northern Hemisphere (0–55°N) is presented in Fig. 4. The total ozone increases from the equator towards the pole. The ozone gradient is weak in the tropics and high in the extratropics. In Fig. 5 the mean vertical distribution of the ozone concentration according to observations at different latitudes is given (adopted from Brasseur and Solomon, 1984). It is clear from this figure that in the height range 8–20 km there is a considerable difference in the ozone concentrations between 20° and 60° latitudes. It is within this latitude belt and height range the tropopause break is located. The large-amplitude portion of the APW train is situated in this tropopause break region.

The maximum amplitude of APW is in the tropopause break. It is suggested that the large-amplitude meridional wind anomaly associated with APW is able to transport ozone-rich extratropical lower stratospheric air into tropical upper troposphere and ozone-poor upper tropospheric air into the extratropical lower stratosphere effectively through the tropopause break region, which in turn can affect the total ozone distribution.

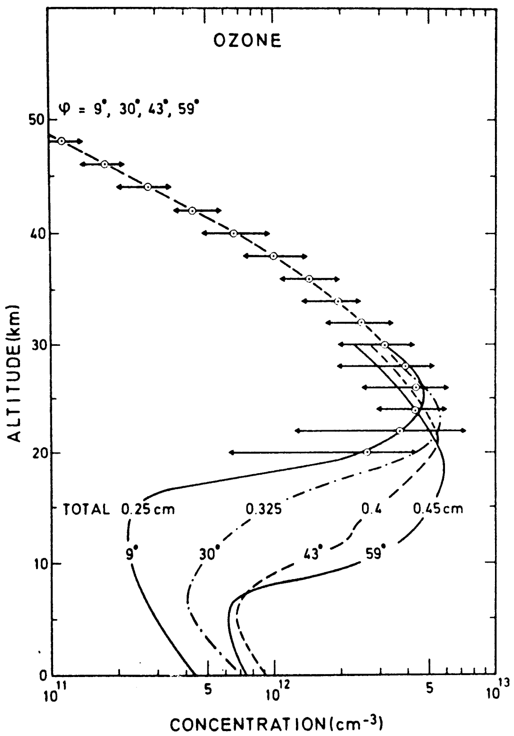

Fig. 5. Mean vertical distribution of the ozone concentration according to observations at different latitudes (adopted from Brasseur and Solomon, 1984).

5. Signature of the Asia Pacific Wave in total ozone

In order to check the possible presence of APW-induced meridional mass exchange via the tropopause break, we examined the total ozone anomaly

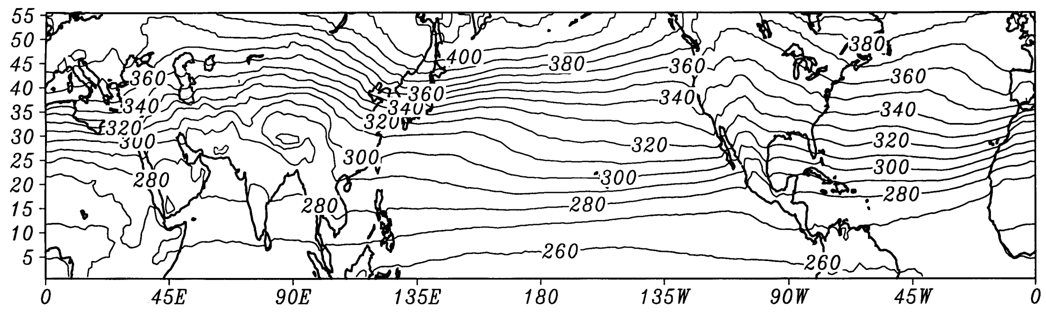

Fig. 4. Total ozone climatology of May. The contour interval is 10 DU.

of May. Ozone is an ideal tracer for this study because relatively long-period satellite-measured total ozone data are available on a global scale. Gridded mean May TOMS total ozone data in the latitude range 0.5–50.5°N for the period 1979–92 were available for analysis. Total ozone anomalies from the 14-yr climatology were computed for May for each grid point. In Fig. 6 total ozone anomalies for the composites of WET and DRY years are presented. Areas of positive and negative total ozone anomalies are seen in the zone between 10°N and 50°N latitudes. It has a wave number 6 or 7 structure in the zonal direction, just like the APW. Areas of positive (negative) total ozone anomalies correspond to northerly (southerly) meridional wind anomalies of the APW. Thus, over north India in May of DRY (WET) years there are negative (positive) anomalies in total ozone, as can be seen from Fig. 6. In some regions the areas of total ozone anomalies show a small eastward shift when compared to the corresponding locations of the meridional wind anomalies. It is interesting to note that the Indian summer monsoon is associated not only with the spatial phase of the APW but also with the total ozone distribution around the globe in the interannual timescale.

6. The Asia Pacific Wave during the monsoon season

The APW is also seen in the monsoon season. In Fig. 7 the 200 hPa meridional wind anomalies

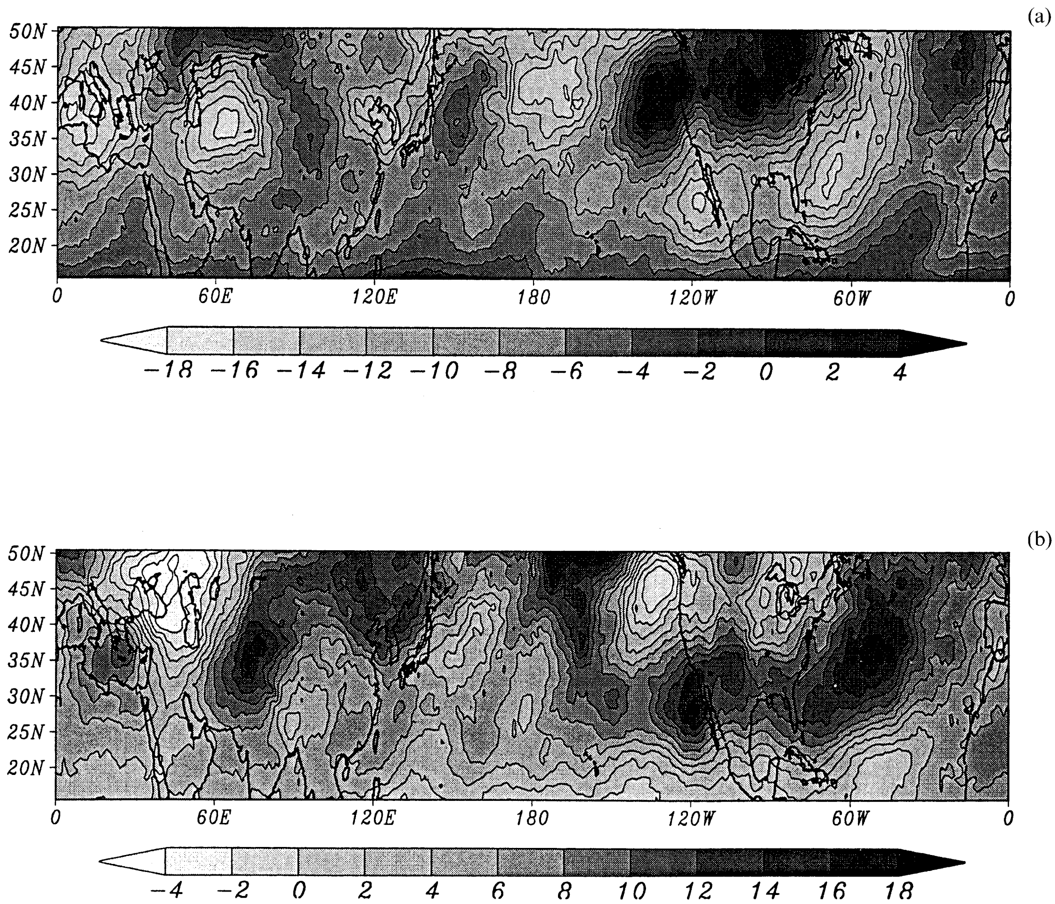

Fig. 6. Total ozone anomaly (DU) of May for (a) WET and (b) DRY composites. (The scale is different for each figure.)

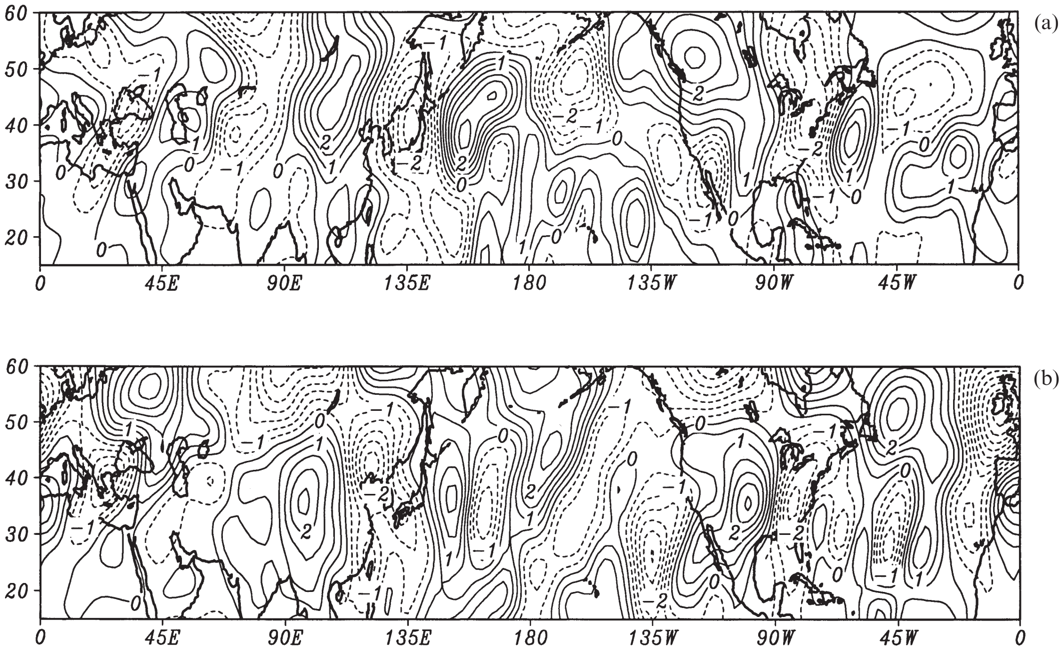

Fig. 7. Meridional wind anomalies of peak monsoon months (July and August) (m s^{-1}) of 200 hPa level for (a) WET and (b) DRY composites. The contour interval is 0.5 m s^{-1}.

of peak ISMR months (July and August) for the composite WET and DRY years are presented. This figure illustrates the presence of the APW in the monsoon season. Since the ITCZ reaches its northernmost position around 30°N in the summer monsoon season and the westerly belt also moves northwards, the APW is found further to the north during this season than during May. The spatial phase is, however, the same during May and the following summer monsoon season.

In order to study the APW-induced anomalies in total ozone in the monsoon season, the total ozone anomalies for WET and DRY composites of peak ISMR months July and August were calculated. In Fig. 8 the total ozone anomaly composites for WET and DRY years are presented. This clearly shows the presence of the APW in total ozone during the summer monsoon season.

7. Summary

The presence of a stationary Rossby wave train in the lower stratosphere was detected during the months of May and the following Indian summer monsoon season, June to September. This wave, prominently seen between 500 and 70 hPa, has a horizontal wave number of 6 or 7 and is confined between 10°N and 70°N. It shows a phase shift of 20° longitude between WET and DRY monsoon years. The amplitude of this wave is maximum around 200 hPa and it decreases both above and below this level. The large-amplitude portion of the wave is thus situated in the tropopause break region, which has a strong meridional gradient in ozone concentration in these levels between the tropics and extratropics, and is found to exchange tropical and extratropical air through the tropopause break. Thus the APW causes meridional mass exchange, which is illustrated using the gridded global TOMS total ozone data. Anomalous northerlies of the APW bring ozone-rich extratropical lower stratospheric air towards the ozone-poor tropical upper troposphere and increase the columnar ozone over this region. On the other hand, anomalous southerlies of the APW bring ozone-poor tropical upper tropospheric air towards the ozone-rich extratropical lower stratosphere and decrease the columnar ozone over this region. This exchange causes total ozone anomal-

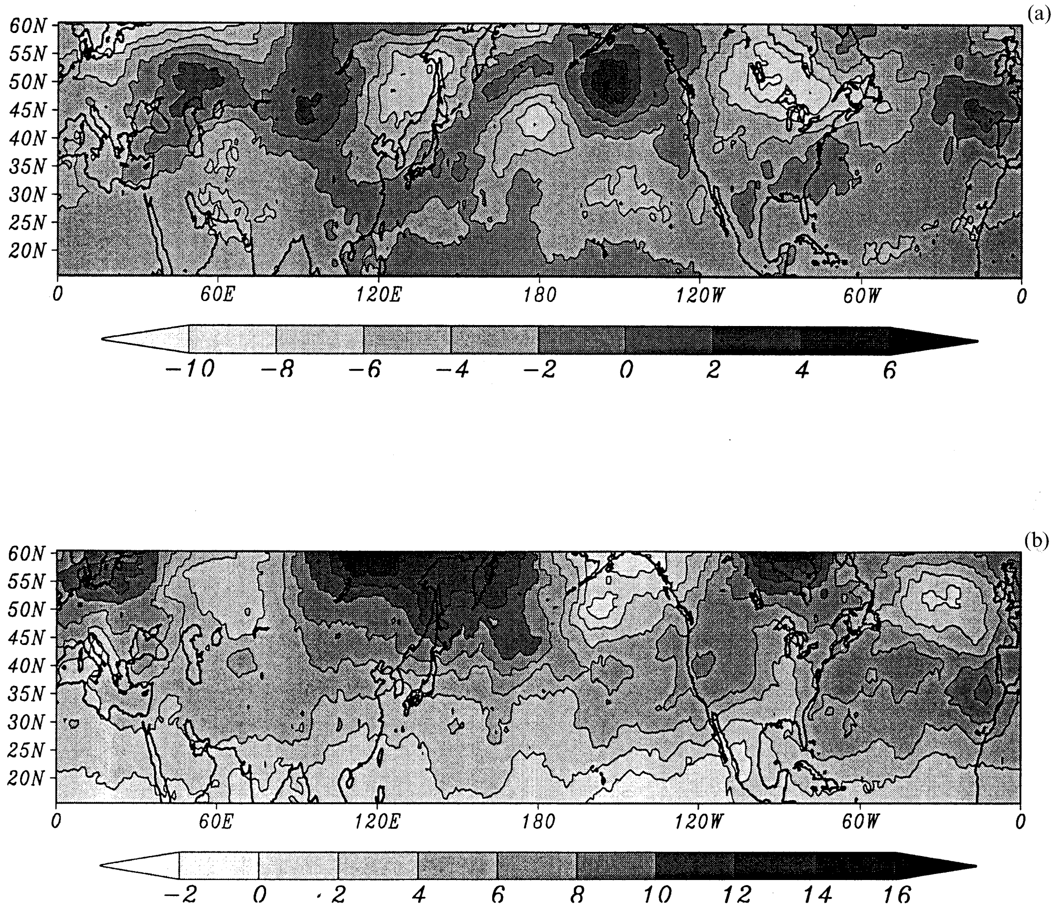

Fig. 8. Total ozone anomalies (DU) of peak monsoon months (July and August) for (a) WET and (b) DRY composites. (The scale is different for each figure.)

ies of the order of 10% covering large areas around the globe during DRY and WET years.

It is well known that a decrease of total ozone increases the amounts of harmful ultraviolet (UV-B) radiation at the earth's surface, which is considered a health hazard (Chanin, 2001; Solomon, 1999; WMO, 1998). Studies have shown that a decrease of total ozone by 10% causes approximately 20% increase in the UV radiation reaching the surface of the earth. During May and the following summer monsoon months, solar radiation is maximum in the Northern Hemisphere, and negative ozone anomalies thus pose health hazards due to increased UV-B radiation.

8. Acknowledgements

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REFERENCES

Bowman, K. P. 1989. Global patterns of the quasi-biennial oscillation in total ozone. *J. Atmos. Sci.* **46**, 3328–3343.

Brasseur, G. and Solomon, S. 1984. *Aeronomy of the middle atmosphere*. D. Reidel Publishing Company, Dordrecht.

Chanin, M.-L. 2001. Stratospheric ozone and its impact on climate change. *WMO Bull.* **50**, 41–45.

Fusco, A. C. and Salby M. L. 1999. Interannual variations of total ozone and their relationship to variations of planetary wave activity. *J. Climate* **12**, 1619–1629.

Hadjinicolaou, P., Pyle, J. A., Chipperfield, M. P. and Kettleborough, J. A. 1997. Effect of interannual meteorological variability on mid-latitude O_3. *Geophys. Res. Lett*. **24**, 2993–2996.

Hamilton, K. 1995. Comment on "Global QBO in circulation and ozone. Part I: Re-examination of observational evidence". *J. Atmos. Sci.* **52**, 1834–1838.

Holton, J. R. 1989. Influence of the annual cycle in meridional transport on the quasi-biennial oscillation in total ozone. *J. Atmos. Sci.* **46**, 1434–1439.

Joseph, P. V. and Srinivasan, J. 1999. Rossby waves in May and the Indian summer monsoon rainfall. *Tellus* **51A**, 854–864.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D. and coauthors. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Met. Soc.* **77**, 437–471.

Logan, J. A. 1985. Tropospheric ozone: seasonal behavior, trends, and anthropogenic influence. *J. Geophys. Res.* **90**, 10,463–10,482.

Logan, J. A. 1994. Trends in the vertical distribution of ozone: an analysis of ozonesonde data. *J. Geophys. Res.* **99**, 25,553–25,585.

McPeters, R. D., Bhartia, P. K., Krueger, A. J., Herman, J. R., Schlesinger, B. M. and coauthors 1996. *Nimbus-7 total ozone mapping spectrometer (TOMS) data products user's guide*. NASA Reference Publication (available in the TOMS Ver-7 Data CD-ROM).

Parthasarathy, B., Munot, A. and Kothawale, D. R. 1994. All-India monthly and seasonal rainfall series: 1871–1993. *Theor. Appl. Climatol.* **49**, 217–224.

Sardeshmukh, P. D and Hoskins, B. J. 1988. The generation of global rotational flow by steady idealized tropical divergence. *J. Atmos. Sci.* **45**, 1228–1251.

Solomon, S 1999. Stratospheric ozone depletion: a review of concepts and history. *Rev. Geophys.* **37**, 275–316.

Trenberth, K. E. 1990. Recent observed interdecadal climate change in the Northern Hemisphere. *Bull. Am. Meteor. Soc.* **71**, 988–993.

Wirth, V. 1993. Quasi-stationary planetary waves in total ozone and their correlation with lower stratospheric temperature. *J. Geophys. Res.* **98**, 8873–8882.

WMO (World Meteorological Organisation), 1998. *Scientific assessment of ozone depletion: 1998*, Global Ozone Research and Monitoring Project, Report No. 44, Vol. I, Geneva.