Atmos. Chem. Phys. Discuss., 15, 15137–15153, 2015
www.atmos-chem-phys-discuss.net/15/15137/2015/
doi:10.5194/acpd-15-15137-2015

Atmospheric Chemistry and Physics
Discussions
Open Access

Tropical response to extratropical eastward propagating waves

S. Sridharan and M. Sandhya

National Atmospheric Research Laboratory, Gadanki-517 112, Pakala Mandal, Chittoor District, Andhra Pradesh, India

Received: 21 April 2015 – Accepted: 9 May 2015 – Published: 2 June 2015

Correspondence to: S. Sridharan (susridharan@narl.gov.in)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Tropical response to extratropical eastward propagating waves

S. Sridharan and M. Sandhya

Abstract

Space–time spectral analysis of ERA-interim winds and temperature at 200 hPa for December 2012–February 2013 shows the presence of eastward propagating waves with period near 18 days in mid-latitude meridional winds at 200 hPa. The 18 day waves of k = 1–2 are dominantly present at latitudes greater than 80°, whereas the waves of k = 3–4 are dominant at 60° of both Northern and Southern Hemispheres. Though the 18 day wave of smaller zonal wavenumbers (k = 1–2) are confined to high latitudes, there is an equatorward propagation of the 18 day wave of $k = 4$ and 5. The wave amplitude of $k = 5$ is dominant than that of $k = 4$ at tropical latitudes. In the Northern Hemisphere (NH), there is a poleward tilt in the phase of the wave of $k = 5$ at mid-latitudes, as height increases indicating the baroclinic nature of the wave, whereas in the Southern Hemisphere (SH), the wave has barotropic structure as there is no significant phase variation with height. At the NH subtropics, the wave activity is confined to 500–70 hPa with moderate amplitudes. It is reported for the first time that the wave of similar periodicity (18 day) and zonal structure (k = 5) as that of extratropical wave disturbance has been observed in tropical OLR, a proxy for tropical convection. We suggest that the selective response of the tropical wave forcing may be due to the lateral forcing of the eastward propagating extratropical wave of similar periodicity and zonal structure.

1 Introduction

Charney (1963) pointed out that there could be possible forcing of the tropical atmosphere from high latitudes. However, Charney (1969) showed that only Rossby waves with westward phase speed greater than that of the zonal mean westward flow could propagate to low-latitudes. The problem of high-latitude forcing was earlier thought in terms of absorption of these westward propagating waves at critical lines of westward winds. However, Webster and Holton (1982) showed that extratropical Rossby waves

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
15, 15137–15153, 2015

Tropical response to extratropical eastward propagating waves

S. Sridharan and M. Sandhya

could propagate into the tropics in regions of upper tropospheric eastward winds and disperse across the equator into the Southern Hemisphere. These waves play a vital role in directly forcing equatorial waves including Kelvin waves (Lim and Chang, 1981). A number of studies have indicated the role of subtropical Rossby wave trains in the initiation and intensification of the MJO, in addition to the influence of mid-latitude baroclinic systems and cold surges over South China Sea. These waves are associated with the intrusion of high potential vorticity (PV) air into low-latitudes, and they modulate cloudiness, stability, and vertical motion in the vicinity of inter tropical convergence zone (ITCZ). Tomas and Webster (1994) also identified strong PV signals in conjunction with cross-equatorial wave activity during northern winter. The lateral forcing of equatorial perturbations by stationary and mobile forcings were comprehensively studied by Zhang and Webster (1992) and Zhang (1993) respectively. Kiladis (1993) presented strong evidence that the equatorward propagating Rossby wave activity can trigger convection within the ITCZ through the dynamical effects of PV advection into low-latitudes. ITCZ convection is known to be influenced by many disturbances other than those associated with upper-level Rossby waves. In spite of these, Lamb (1973) suggested that the tropics selectively responds to lateral forcing generating equatorial wave disturbances with the wavenumbers and frequencies similar to those of extra-tropical waves and these wave disturbances are further enhanced by the effect of condensational heating. However, the observational evidence for this selective lateral forcing is still lacking. In the present study, we provide an observational evidence for the equatorward propagation of an eastward propagating 18 day wave of zonal wavenumber (k) 5 in the upper troposphere and excitation of a tropical wave of similar characteristics.

ACPD
15, 15137–15153, 2015

2 Data

2.1 ERA Interim data

In this paper, European Center for Medium Range Weather Forecasting (ECMWF) reanalysis (ERA)-Interim winds and temperature for the period December 2012–February 2013, which are available in the website http://apps.ecmwf.int/datasets/data/interim-full-daily/ for different pressure levels and for every $1.5^{\circ} \times 1.5^{\circ}$ latitude–longitude grid are utilized. This is the recent global atmospheric reanalysis of the period 1989 to present, prepared by ECMWF using their variational data assimilation system (Berrisford et al., 2009).

2.2 NOAA-OLR data

Interpolated outgoing Long-wave radiation (OLR) data, obtained from the National Oceanic and Atmospheric Administration and National Centers for Environmental Prediction (NOAA-NCEP) for the period December 2012–February 2013 are used as a proxy for deep tropical convection. The OLR data are indicators of cloud top heights. Very high and cold clouds (low OLR) at tropical latitudes are presumed to be associated with deep convection (Liebmann and Smith, 1996).

3 Results

The two-dimensional spectrum of meridional winds at 200 hPa (Fig. 1) shows the dominant presence of eastward propagating 18 day waves with $k = 3$ at 55° N and with $k = 5$ at 45° N. It may be noted that the presence of the eastward propagating waves are not clearly observed in zonal wind and temperature. The longitude-time cross section of 15–20 day filtered meridional winds at 200 hPa for the latitudes 55 and 45° N shows that the 18 day wave is active around 200° E from day number 20. However, the

ACPD
15, 15137–15153, 2015

wave activity increases from day number 39 and the eastward propagation is clearly observed with large amplitudes.

In order to see the latitudinal structure of the waves, the latitudinal variation of the wave amplitudes in meridional winds at 200 hPa for $k = 1$–5 is plotted in Fig. 2a. Though the 18 day wave of $k = 3$ is dominant at latitudes greater than 50° of both hemispheres, the wave of $k = 5$ is dominant at latitudes 60° N–60° S. The 18 day wave of $k = 1$ and $k = 2$ are dominant only at latitudes greater than 80° of both Northern and Southern hemispheres. The latitudinal variations of the phase of the waves of different k in meridional winds at 200 hPa are shown in Fig. 2b. From the figure, we can infer that the phase shows irregular structure for the waves of $k = 1$–2. The wave phase of $k = 4$ occurs at latter time from high to low-latitudes indicating that the wave propagates towards equator, whereas there is an advancement of the phase of wave of $k = 3$ towards equator indicating the poleward propagation of the wave. The phase of the wave of $k = 5$ remains constant at mid-latitudes and there is a rapid retreating of phase to latter hours around 30° N indicating rapid propagation of the waves toward equator followed by a slow retreat in the latitude region 12–25° N. Hereinafter, the focus of the present study will be on the dominantly present 18 day wave of $k = 5$.

The latitudinal variation of 18 day wave with zonal wavenumber 5 amplitudes in meridional winds is plotted in Fig. 3 for all the pressure levels from 1000 to 1 hPa to study the latitudinal-height cross section of the wave. The wave amplitude appears to increase with height from 1000 hPa at mid-latitudes. In both hemispheres, it reaches the maximum value of 8–9 $\mathrm{m\,s^{-1}}$ at 250 hPa at 45° latitude. Though the wave amplitude in Southern Hemisphere (SH) is larger than that in Northern Hemisphere (NH), the wave signature is present only up to 50 hPa in SH, whereas it persists with smaller amplitudes even above 1 hPa. Moderate amplitude enhancement (4–5 $\mathrm{m\,s^{-1}}$) is also observed around 20° N around 250 hPa. At this latitude, the wave signature is observed only at pressure levels 500–70 hPa. Though similar enhancement in wave amplitude is not there around 20° S, small amplitude of 1 $\mathrm{m\,s^{-1}}$ is observed at 250–175 hPa. Moder-

ACPD
15, 15137–15153, 2015

ate amplitude enhancement (4–5 $m\,s^{-1}$) is also observed around 20° N around 250 hPa. At this latitude, the wave signature is observed only at pressure levels 500–70 hPa.

The latitudinal variations of amplitude and phase of the 18 day wave of zonal wavenumber 5 in zonal and meridional winds and temperature at 200 hPa are shown in Fig. 4. The amplitudes of the wave in zonal wind and temperature are less at 45° latitude. The wave in zonal wind shows large amplitude (6.5 $m\,s^{-1}$) at 30° N, whereas the wave amplitude in meridional wind shows a minimum (2 $m\,s^{-1}$). It also shows a secondary maximum (4 $m\,s^{-1}$) at the latitude of 54° of both hemispheres. The wave in temperature shows maximum amplitude (1.5 K) at 48° latitude of both hemispheres. The phase of the wave in meridional wind is constant from 66 to 36° N. However, it increases as the latitude decreases indicating that the wave propagates towards equator. The phase in zonal wind also increases towards equator from 42° N, though the phase in temperature does not show clearly the equatorward propagation of the wave. Dunkerton et al. (1991) observed that eastward disturbances were confined mostly within the polar vortex, whereas quasi-stationary and westward traveling components propagated to the vortex periphery and beyond, into the tropics. Our observations suggest that though eastward propagating waves of $k = 1$ and $k = 2$ are confined to polar latitudes, the waves of higher zonal wavenumbers propagate towards tropics. Rossby wave energy propagation into the tropics from higher latitudes is well known feature of the general circulation of the atmosphere (Kiladis, 1998). Charney (1969) suggested that only Rossby waves having westward phase speed greater than the zonally averaged westward zonal wind speed could propagate. When extratropical disturbances propagate from mid-latitudes to tropics, the mean flow should possess certain characteristics. Charney (1969) showed that the westward winds could act as an effective barrier for the westward propagating wave disturbances from mid-latitudes into the tropics. Similarly it is expected here that the mean zonal flow over tropics must be westward for the equatorward propagation of the eastward waves. The time-longitude cross section of zonal wind averaged for the latitudes 0–20° N (Fig. 5) shows that the eastward winds are present around 200° E and they become weaker after day number 40. Besides, there are regions (0–25° E during day numbers 25–35 and around 240° E during day numbers 38–42), where westward winds are observed. Through these westward and weak eastward winds, the eastward propagating disturbances could propagate to tropical latitudes. Due to this, there is a convergence of the eastward wave energy flux at tropical upper troposphere. Lamb (1973) suggested that the tropical atmosphere selectively could respond to lateral forcing from mid-latitudes and the generated equatorial wave would have similar characteristics (period and wavenumber) as that of the mid-latitude wave forcing. In order to check this, the OLR data at 15° N, the proxy for tropical convection have been subjected to two-dimensional spectral analysis and the result is shown in Fig. 6a. The spectrum of OLR clearly shows the presence of 18 day wave propagating eastward with zonal wavenumber 3. The 15–20 day filtered OLR (Fig. 6b) shows eastward propagation in the longitude bands 300–360 and 200–260° E from day number 20.

4 Discussion and conclusion

Time-space spectral analysis of ERA-interim winds and temperature at 200 hPa show the presence of an eastward propagating wave with period near 18 days with dominant zonal wavenumber 5 in mid-latitude meridional winds at 200 hPa. The wave maximizes at 250 hPa at the latitude of 45° of both northern and Southern Hemispheres. Unlike the 18 day wave of shorter zonal wavenumbers, which remain confined to polar latitudes, the wave of $k = 5$ propagates towards equator, inferred from the latitudinal variation of the phase of the wave. The 18 day waves of $k = 1$–2 are dominantly present at latitudes greater than 80°, whereas the waves of $k = 3$–4 are dominant at 60° of both hemispheres. Instabilities associated with their relation to the seasonal variation of the mean zonal wind fields have been suggested to be the source for these waves (Hirota, 1976; Shiotani et al., 1993). Previous studies showed that large eastward wave activity with various periods preconditioned the stratospheric circulation prior to the stratospheric warming events and the amplitudes of these waves got reduced imme-

ACPD
15, 15137–15153, 2015

diately prior to the onset of the SSW events (Labitzke, 1981; Limpasuvan et al., 2004; Hoffmann et al., 2007; Pancheva et al., 2008). However, the present study indicates that the wave of $k = 5$ amplifies during and after the SSW event of 2013, which occurs during January 2013 (Nath et al., 2015). Shepherd and Tsuda (2008) observed eastward propagating 10, 16 and 23 day periodicities with $k = 1$ and $k = 2$ in at high latitude Southern Hemisphere (60–75° S). Alexander and Shepherd (2010) noted more eastward wave activity than westward wave activity in both hemispheres, when the stationary wave components were removed. Earlier, Dunkerton et al. (1991) observed that the eastward propagating wave disturbances were confined to polar latitudes and the superposition of traveling and quasi-stationary waves led to constructive interference that was responsible for the SSW events. The present study shows that though eastward propagating 18 day waves of smaller k (1–2, in particular) are confined to high latitudes, there is an equatorward propagation of 18 day wave of zonal wavenumber 5. In the NH, there is a poleward tilt in the phase of the wave at mid-latitudes, as height increases indicating the baroclinic nature of the wave, whereas in the SH, the wave has barotropic structure as there is no significant phase variation with height. At the NH subtropics, the wave activity is confined to 500–70 hPa with moderate amplitudes. It is similar to the characteristics of westward propagating Rossby waves confining themselves to upper troposphere as they approach the tropics under the effect of the easterly dome (Magana and Yanai, 1995). Similarly in the present case, the presence of westerly dome could be the reason for the confinement of the eastward propagating disturbance to upper tropospheric heights. It is interesting to note in the present study that the wave of similar periodicity (18 day) and zonal structure ($k = 5$) as that of extratropical wave disturbance has been observed in OLR, a proxy for tropical convection. We suggest that the selective response of equatorial wave forcing in the tropical convection may be due to the convergence of eastward wave flux at low-latitudes. To the best of our knowledge, only mixed Rossby waves have been reported to be excited over tropics due to the lateral propagation of westward propagating Rossby waves (Mak, 1969; Lamb, 1973; Kiladis, 1998; Hoskins and Yang, 2000). These waves are

ACPD
15, 15137–15153, 2015

associated with the intrusion of high PV air into tropics, where they modulate cloudiness, stability and vertical motion in the vicinity of the ITCZ (Kiladis, 1998).

Probably due to the lateral forcing of wave convergence at low-latitudes, an eastward propagating 18 day wave of zonal wavenumber 5 is selectively generated due to tropical convection as inferred from the space–time spectral analysis of OLR, a proxy for tropical convection. This is the first observational evidence demonstrating the excitation of an eastward propagating wave of similar periodicity and zonal structure as that of extratropical wave disturbance.

Acknowledgements. Interpolated OLR data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA from their Web site at http://www.esrl.noaa.gov/psd/. The ERA-interim data used in the present study were provided by BADC and downloaded from the website http://apps.ecmwf.int/datasets/data/interim-full-daily/.

References

Alexander, S. P. and Shepherd, M. G.: Planetary wave activity in the polar lower stratosphere, Atmos. Chem. Phys., 10, 707–718, doi:10.5194/acp-10-707-2010, 2010.

Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S., Uppala, S.: The ERA-Interim Archive, European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading, Berkshire RG2 9AX, UK, 1–16, 2009.

Charney, J. G.: A further note on large-scale motions in the tropics, J. Atmos. Sci., 26, 182–185, 1969.

Dunkerton, T. J.: LIMS observation of traveling planetary waves and potential vorticity advection in the stratosphere and mesosphere, J. Geophys. Res., 96, 2813–2834, 1991.

Hirota, I.: Seasonal variation of planetary waves in the stratosphere observed by the Nimbus 5 SCR, Q. J. Roy. Meteor. Soc., 102, 757–770, 1976.

Hoffmann, P., Singer, W., Keuer, D., Hocking, W. K., Kunze, M., and Murayama, Y.: Latitudinal and longitudinal variability of mesospheric winds and temperatures during stratospheric warming events, J. Atmos. Sol. Terr. Phys., 69, 2355–2366, 2007.

Hoskins, B. J. and Yang, G.-Y.: The equatorial response to higher-latitude forcing, J. Atmos. Sci., 57, 1197–1213, doi:10.1175/1520-0469(2000)057<1197:TERTHL>2.0.CO;2, 2000.

ACPD
15, 15137–15153, 2015

Kiladis, G. N.: Observations of Rossby waves linked to convection over the Eastern Tropical Pacific, J. Atmos. Sci., 55, 321–339, 1998.
Labitzke, K.: The amplification of height wave 1 in January 1979: A characteristic precondition for the major warming in February, Mon. Weather Rev., 109, 983–989, 1981.
Lamb, V. R.: The response of the tropical atmosphere to middle latitude forcing, PhD thesis, University of California, Los Angels, 151 pp., 1973.
Liebmann, B. and Smith, C. A.: Description of a complete (interpolated) outgoing longwave radiation dataset, B. Am. Meteorol. Soc., 77, 1275–1277, 1996.
Lim, H. and Chang, C. P.: A theory of midlatitude forcing of tropical motions during the winter monsoon, J. Atmos. Sci., 41, 3333–3350, 1981.
Limpasuvan, V., Thompson, D. W. J., and Hartmann, D. L.: The life cycle of the Northern Hemisphere sudden stratospheric warmings, J. Climate, 17, 2584–2596, 2004.
Magana, V. and Yanai, M.: Mixed Rossby-gravity waves triggered by lateral forcing, J. Atmos. Sci., 52, 1473–1486, 1995.
Mak, M. K.: Laterally driven stochastic motions in the tropics, J. Atmos. Sci., 26, 41–64, 1969.
Nath, O., Sridharan, S., and Gadhavi, H.: Equatorial stratospheric thermal structure and ozone variations during the sudden stratospheric warming of 2013, J. Atmos. Sol.-Terr. Phy., 122, 129–137, 2015.
Pancheva, D., Mukhtarov, P., Mitchell, N. J., Merzlyakov, E., Smith, A. K., Andonov, B., Singer, W., Hocking, W., Meek, C., Manson, A., and Murayama, Y.: Planetary waves in coupling the stratosphere and mesosphere during the major stratospheric warming in 2003/2004, J. Geophys. Res., 113, D12105, doi:10.1029/2007JD009011, 2008.
Shepherd, M. G. and Tsuda, T.: Large-scale planetary disturbances in stratospheric temperature at high-latitudes in the southern summer hemisphere, Atmos. Chem. Phys., 8, 7557–7570, doi:10.5194/acp-8-7557-2008, 2008.
Shiotani, M., Shimoda, N., and Hirota, I.: Inter-annual variability of the stratospheric circulation in the Southern Hemisphere, Q. J. Roy. Meteor. Soc., 119, 531–546, 1993.
Tomas, R. A. and Webster, P. J.: Horizontal and vertical structure of cross-equatorial wave propagation, J. Atmos. Sci., 51, 1417–1430, 1994.
Webster, P. J. and Holton, J. R.: Cross-equatorial response to middle-latitude forcing in a zonally varying basic state, J. Atmos. Sci., 39, 722–733, 1982.
Zhang, C.: Laterally forced equatorial perturbations in a linear model. Part II: Mobile forcing, J. Atmos. Sci., 50, 807–821, 1993.

ACPD
15, 15137–15153, 2015

Zhang, C. and Webster, P. J.: Effects of zonal flows on equatorially trapped waves, J. Atmos. Sci., 46, 3632–3652, 1989.

ACPD
15, 15137–15153, 2015

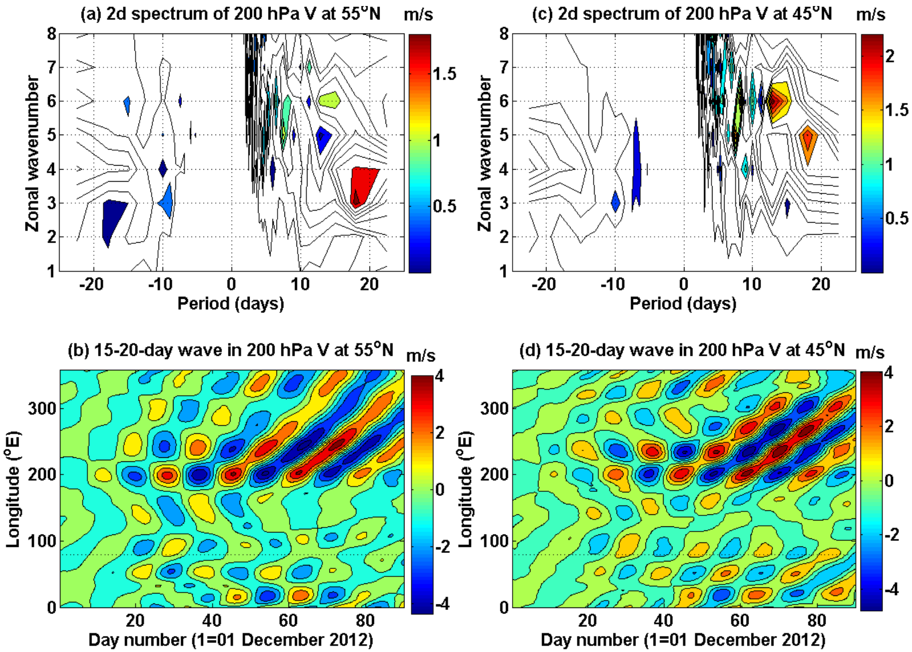

Figure 1. (a) Space–time spectra of ERA-interim meridional winds at 200 hPa at 55 and 45° N and **(b)** 15–20 day filtered ERA-interim meridional winds at 55 and 45° N for the period December 2012–February 2013.

ACPD
15, 15137–15153, 2015

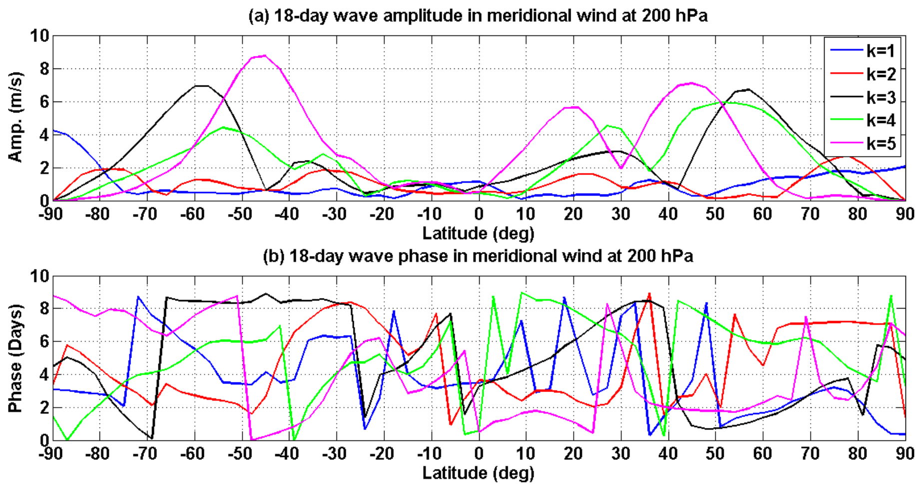

Figure 2. Latitude variation of the 18 day wave amplitudes in ERA-interim meridional winds at 200 hPa for the zonal wavenumbers (k) 1–5 for the period December 2012–February 2013.

ACPD
15, 15137–15153, 2015

S. Sridharan and M. Sandhya

ACPD
15, 15137–15153, 2015

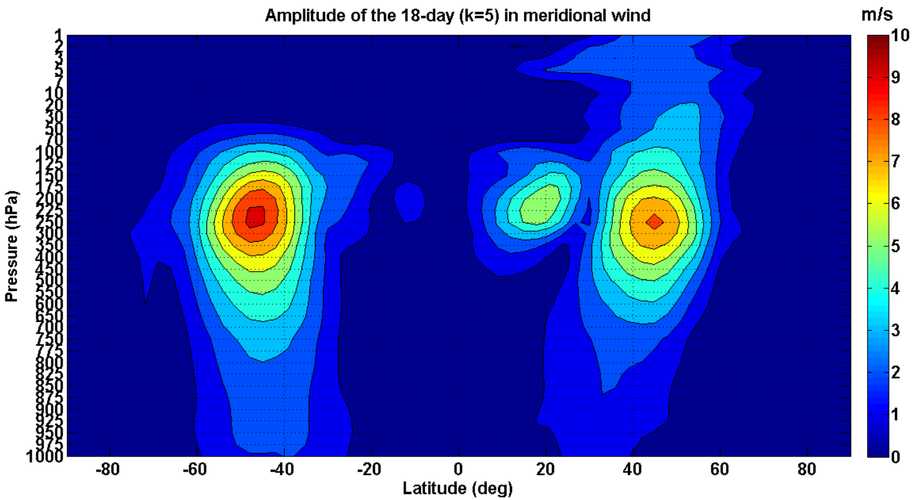

Figure 3. Latitudinal variation of the amplitude of 18 day wave with zonal wavenumber (k) 5 in ERA-interim meridional winds for all the pressure levels from 1000 to 1 hPa.

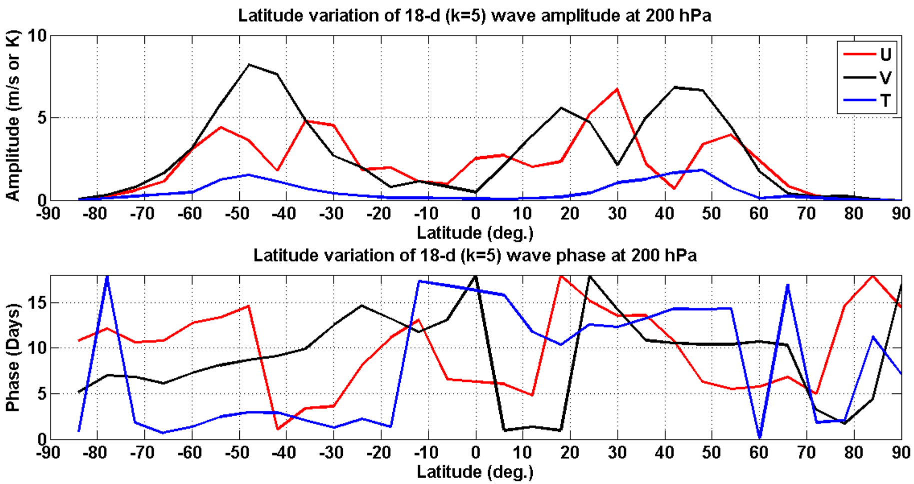

Figure 4. Latitudinal variations of amplitude and phase of the 18 day wave of zonal wavenumber (k) 5 in ERA-interim zonal and meridional winds and temperature at 200 hPa.

ACPD
15, 15137–15153, 2015

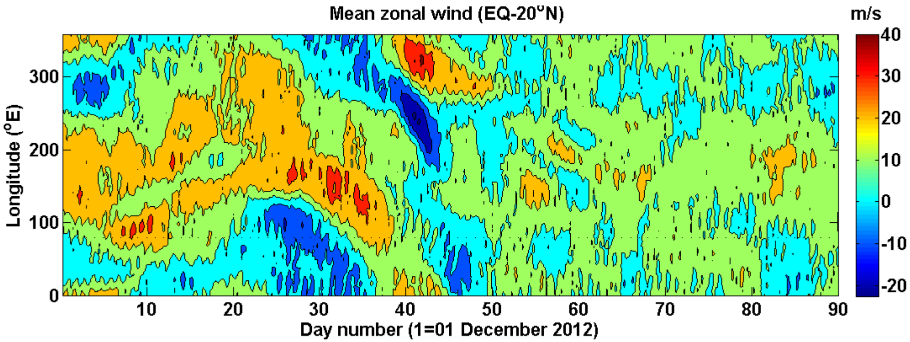

Figure 5. Time–longitude cross section of ERA-interim zonal wind at 200 hPa averaged for the latitudes 0–20° N.

ACPD
15, 15137–15153, 2015

Tropical response to extratropical eastward propagating waves

S. Sridharan and M. Sandhya

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

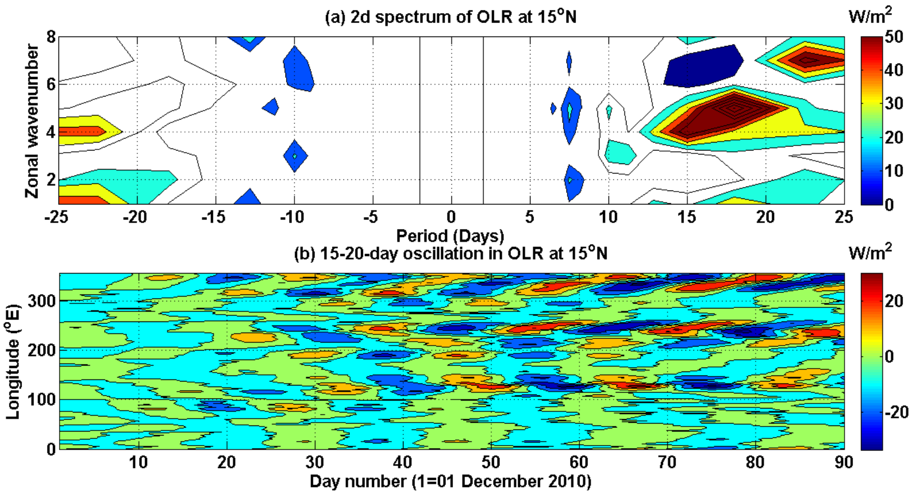

Figure 6. (a) Two-dimensional spectrum of NOAA OLR at 15° N and **(b)** 15–20 day band-pass filtered NOAA OLR at 15° N.

ACPD
15, 15137–15153, 2015

Tropical response to extratropical eastward propagating waves

S. Sridharan and M. Sandhya