Evidence of long-term change in zonal wind in the tropical lower mesosphere: Observations and model simulations

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In recent years, the mesosphere (50 to 85–100 km) has evoked great scientific interest as long-term changes due to global warming can be clearly captured due to the large perturbation amplitudes at these altitudes. In the present study, zonal wind observations between 70 and 80 km over the Indian region provided by rocketsondes (1977–1991), HRDI/UARS (1991–1999), and MST radar (1995–2010) are used to construct a long-term data set from 1977 to 2010. Using this unprecedented data set, a decreasing trend of 2 m/s yr is found, changing from strong eastward winds during the 1970s to weak westward winds in recent years. On the other hand, between 80 and 98 km using medium frequency radar observations during 1993–2009, no perceptible trend is found. Simulations of NCAR TIME-GCM also showed a similar change in the circulation when CO2 in the atmosphere is doubled, suggesting role of anthropogenic changes in the dynamics of the mesosphere.

1. Introduction

In the mesosphere, wave and wave-dissipative processes are important drivers of energetics and dynamics. During the past three to four decades, remarkable advances have been made in our understanding of the dynamics of this region. Both experimental and theoretical works revealed that the dynamics of the mesosphere holds the key to the understanding of the middle atmosphere global circulation system. Evidence of long-term change in zonal wind in the tropical lower mesosphere: Observations and model simulations, Geophys. Res. Lett., 40, 397–401, doi:10.1002/grl.50158.

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and are mainly attributed to the change in the circulation due to tropospheric warming and ozone recovery. To the best of our knowledge, no such systematic study exists in the literature from the low latitudes. Recently, Venkateswara Rao et al. [2012] studied the long-term variability of winds from low latitudes but it is limited to the period 1990–2010 and between 80 and 100 km.

2. Data and Analysis Procedure

[7] Mesospheric zonal winds between 70 and 80 km measured by several techniques in the low-latitude region for nearly 34 years (during 1977–2010) are used in the present study. The observations included data from M-100 rocket-sonde experiment launched every Wednesday from Thumba (8.5°N, 77°E) Equatorial Rocket Launching Station (TERLS) obtained during 1977–1999 (~700 profiles), the High Resolution Doppler Imager (HRDI) onboard UARS data sets during 1991–1999 averaged over the Indian region (8.5°N to 18.5°N and 69°E to 89°E), and the MST radar data from Gadanki (13.5°N, 79.2°E) during 1995–2010. The MST radar observations were obtained with 53 MHz VHF radar during the daylight hours, mainly during the afternoon hours as reliable mesospheric echoes from which winds could be derived are confined to daylight hours only [Woodman and Guillen 1974].

[8] For investigating the long-term trends with the wind data derived from different measurements, it is important to make sure that differences in the observations/techniques do not have any influence on the derived trends. It is found that there is a good consistency between the observations from the rocket and HRDI/UARS in the connecting period and between HRDI/UARS and MST radar during the overlapping period (23 months of observations) [Ratnam et al., 2008]. During the overlapping period, a correlation coefficient of 0.65 at 99% confidence level is found with no systematic bias between the two data sets. Note that Burragge et al. [1996] also reported that the HRDI/UARS winds agree well with those observed by radars, rockets, and the Wind Imaging Interferometer (WINDII) except that the magnitude of the wind speed is smaller from MF radars than from HRDI/UARS. The long-term data sets (1992–2010) from the MF radar at Tirunelveli (8.7°N, 77.8°E), a station in the southern peninsular India, available only in the altitude range 80–98 km for the purpose of present study are utilized. [9] The data between 70 and 80 km where all the different techniques have high accuracy are considered in the present study. Since the vertical resolution varies (1.5–2.4 km) from one instrument to another, the data are interpolated to a uniform resolution of 2.5 km. We applied consensus averaging technique to derive the monthly means which is outlier-resistant. In order to estimate reliable trends, the monthly mean winds between 70 and 75 km and 75 and 80 km have been averaged and taken as representative for 72.5 and 77.5 km, respectively. During the overlap periods, we estimated the average between the available observations. By using the robust fitting method [Holland and Welsch, 1977], we estimated the linear trend in the zonal winds on monthly basis. The robust fitting method used here is iteratively re-weighted least squares fit and is less sensitive for errors in the trend estimation. Here we used bi-square weighting function, and the corresponding tuning constant was 4.685. The tuning constants may be used to adjust the efficiency of the resulting estimators for specific distributions. We chose the maximum iteration limit as 500 although the maximum iterations necessary were 34 (during October for 77.5 km) and the required iterations are eight in many cases.

3. Results

3.1. Observations

[10] Monthly mean zonal winds observed during 1977–2010 for the altitude regions 72.5 and 77.5 km are shown in Figure 1. As mentioned earlier, although the data are from different techniques, they show good agreement in the connecting and the overlapping periods. From the figure, it is clear that the zonal winds in both the altitude regions show a distinct semi-annual oscillation (SAO) during the entire period. In addition to this well-known SAO, there is a decreasing trend of 2–3 m/s/yr on an average in the zonal wind in both the altitude regions. This feature is clear from the annual mean zonal winds superimposed in the respective panels. The composite monthly mean winds derived from the observations from 1977 to 2010

Figure 1. Monthly mean zonal wind (black line) formed by using rocket (1977–1991), HRDI/UARS (1991–1999), and MST radar (1995–2010) at (a) 77.5 km (averaged between 75 and 80 km) and (b) 72.5 km (averaged between 70 and 75 km), respectively. Note that the annual mean zonal wind (red line) from these observations is also superimposed. Composite monthly mean winds of observations along with standard error for (c) 72.5 km and (d) 77.5 km, respectively.
are illustrated in Figures 1c and 1d for 72.5 and 77.5 km, respectively, along with the standard error. In general, westward wind is maximum during equinoxes showing the SAO. 

[11] Figure 2 shows the trend values derived on monthly basis using the 34 year observations. Note that the trend coefficient values with 95% significance level are illustrated with filled circles. The significance levels have been estimated with Fisher’s F test [Lomax, 2007]. In general, the trend coefficient is negative (−2 m/s/yr) at 95% significance level indicating decreasing trend except during the summer months. The coefficients are positive but not significant (at 95% level) during the summer months. The number of iterations carried out during each month and for each altitude level is illustrated in Figure 2c. Note that these iterations refine the trend coefficient and it does not mean that a higher number of iterations increase the significance. For example, the iterations for October at 77.5 km are 34 but the trend coefficient is not significant. For February, the number of iterations is eight at both the altitudes but the trend coefficient is significant.

[12] The trends in both the altitude regions exhibit more or less similar behavior (except in October and also in January) indicating the continuity of the trend (in this altitude region) and this lends further credence to the trend estimates. In general, the negative trends that appear during the winter month indicate the decrease of eastward winds. Note that the eastward wind during the winter months over the study region is the extended tongue of the midlatitude eastward jet, which is due to the Coriolis torque on the meridional circulation [Andrews et al., 1987]. In order to check the influence of solar cycle, we applied twofold (linear and solar cycle trend) regression analyses by taking the solar Lyman alpha radiation as a proxy for the solar cycle. No difference in the trend coefficient is noticed and at the same time the solar signal coefficient is non-significant (figure not shown).

[13] Figure 3a shows the decadal average profiles of zonal wind constructed using the data from 1977 to 2010. One can clearly notice the decrease of eastward wind by the 1980s, changing to weak westward during the 1990s and becoming stronger westward wind in the recent decade. As mentioned earlier, we made use of MF radar observations at Tirunelveli obtained during 1993–2009 to see the trends between 80 and 98 km. Figure 3b shows the decadal change observed in the zonal wind averaged separately during 1993–1999 and 2000–2009. In general, westward wind dominates in both the decades in the altitude region mentioned above. Interestingly, no significant change in the zonal wind is observed between the two decades. However, around 80 km altitude, stronger westward winds can be noticed in the recent decade (2000–2009) when compared to the previous decade (1993–1999) matching well with Figure 3a. Thus juxtaposing the Tirunelveli data (Figure 3b) with the data in the altitude regions.
range between 70 and 80 km (Figure 3a), it can be concluded that significant long-term trends are seen only between 70 and 80 km.

3.2. Model Simulations

[14] To understand the observed long-term trends in the zonal wind, model simulations have been done using the National Center for Atmospheric Research (NCAR) Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM). This model has been discussed in detail in Qian et al. [2011]. Note that for discerning long-term trends in the MLT region, systematic modeling studies are done by Qian et al. [2011]. In brief, “this model uses a base CO2 concentration of 365 ppmv, representative of the year 2000 and doubling it for the year 2100 as projected by the IPCC [2007]. Cooling by CO2 in the mesosphere depends on the collisional excitation rate between the CO2 and O. In the model, the cooling rates employed are $1.56 \times 10^{-12}$ cm$^3$ s$^{-1}$ for $T<260$ K and $1.4 \times 10^{-12}$ cm$^3$ s$^{-1}$ for $T>300$ K with linear interpolation between the two. NO infrared cooling at 5.3 μm which depends on collisional excitation rate between the NO and O is set to $4.2 \times 10^{-11}$ cm$^3$ s$^{-1}$.”

[15] Figure 4 shows the longitude and altitude variation of the zonal wind for the base case (Figure 4a), doubling case (Figure 4b), and the difference in the zonal wind between the doubling of CO2 case and the base case (Figure 4c) for 11.25°N under solar minimum and geomagnetic quiet conditions for 0800UT (December solstice) simulated by the NCAR TIME-GCM. The time 0800 UT has been chosen as most of the data from the MST radar correspond to near local noon (0800 UT = 1330 LT). Note that this figure is similar to Figure 7 of Qian et al. [2011], and as mentioned in that paper, the patterns of semi-diurnal tides are similar for base and doubling case but the amplitudes are different.

[16] In Figure 4, it is interesting to see a clear change in the zonal wind in the order of 10 m/s between 70 and 82 km with nearly no change between 82 and 95 km. At higher altitudes, this change increases to 20 m/s. This change is significant when one considers the zonal wind at these altitudes which is in the order of 50–60 m/s, suggesting that the MLT dynamics will have long-term trend owing to CO2 increase. The long-term trends from observations in the present study are in agreement with these model simulations as far as the direction of the trend is concerned, although not in magnitude which is expected as the model trends are for doubling CO2. Few differences have been noticed in other seasons between the observations and the model simulations particularly during the equinoxes. Note that in the model simulations long-term trends due to O3 and H2O concentrations have not been considered which also could affect significantly the prevailing winds in the MLT region. In the neutral density at mesospheric heights, inclusion of O3 and H2O increases trends according to model simulations by Akmaev et al. [2006].

Figure 4. Longitudinal and altitude variation of the zonal wind for (a) the base case, (b) doubling case, and (c) the difference in the zonal wind between the doubling of CO2 case and the base case at 11.25°N for 0800UT (December solstice) simulated by the NCAR TIME-GCM. Vertical lines in Figure 4c show the longitudes of Indian region.
4. Summary and Discussion

[17] More than three decades of the data set are constructed by combining the observations from different techniques (rocketsonde, HRDI, and MST radar) for the lower mesosphere (70–80 km). Large decreasing trend (2–3 m/s/yr) in the eastward winds except during summer months is noticed which is significant at 95% level. No perceptible trend in the zonal wind is observed during 1993–2009 between 82 and 98 km. No significant solar cycle influence is noticed in between 70 and 80 km. These observations are well captured by the NCAR TIME-GCM model simulations for the low latitudes over Indian region. The change in the zonal wind due to doubling of CO2 is found to be around 10 m/s changing from strong eastward wind to weak westward wind. It is very interesting to see this change between 70 and 80 km but not in between 82 and 90 km in the TIME-GCM simulations exactly as noticed in the observations. Thus, it is prudent to conclude that long-term decreasing trends in the mesospheric zonal winds could be caused to a large extent by an increase of CO2. Observational trends are larger than simulated trends as simulation does not include O3 and H2O which also could contribute to the neutral density.

[18] An increase in the sea surface temperatures (SST) in the Indian Ocean (in the present case) as a result of global warming is expected to lead to more energy available for tropical convection. This can provide more energy to the gravity waves that may develop. However, their formation and intensification do not depend on only the thermodynamic conditions such as SST or moisture but also on dynamic conditions such as shears in the horizontal winds. As noticed in the literature [Ratnam et al., 2008], dynamical changes in the background wind play an important role in determining the wave activity. The differences between the observations and model simulations during equinoxes might indicate the role of dynamics in modulating the trends. Large ozone recovery, due to Montreal protocol implementation at the mid to high latitude regions that is being reported is expected to change the circulation in the tropical latitudes [Hu et al., 2011]. Since the ozone layer is an important component in determining stratospheric and tropospheric-energy balance, the recovery of stratospheric ozone may also have significant impact on tropospheric-stratospheric climate [Hu et al., 2011] and hence on wave activity. As wave activity (gravity wave) plays a pivotal role in the dynamics of the mesosphere, long-term changes in wave activity need to be examined in the context of long-term trends in the mesospheric winds.

[19] As reported by Jacobi et al. [2009] and Laštovička et al. [2008], change in the prevailing wind at mesospheric altitude over midlatitudes, occurred around 1990s. At about the same time several changes have been noticed over the Indian region too. For example, sharp strengthening of the tropical easterly jet around 100 hPa reaching to the level of 1950s has been observed in the warmest decade (2000–2010) around same time (Ratnam et al., 2012, personal communication). Note that the Tropical Easterly Jet is a potential source for gravity wave generation during summer season and strong convection during other seasons over Indian region.

[20] For a better understanding of the mesospheric long-term trends, the relation between SST, upper tropospheric circulation, and wave activity propagating up into stratosphere and mesosphere is to be examined using both observations and general circulation models. It is also needed to examine the long-term trends in the gravity wave forcing that have profound effects on the MLT winds. Effects of O3 and H2O are also expected to play a major role in changing the MLT winds and needed to be considered in future simulations.

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References


