Oscillation of tropical tropopause during passage of atmospheric waves

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Tropopause, the upper boundary of the troposphere, is characterized by the hydrostatic stability and plays key role in stratosphere-troposphere exchange (STE). Variation in the height of the tropopause is one of the mechanisms through which interaction between tropospheric and stratospheric air takes place. In the present paper the height of the tropical tropopause derived from radiosonde observations at Chennai and high range resolution measurements of horizontal winds made using VHF radar at Gadanki, during the period December 1995-April 1996, have been used to study the effect of atmospheric oscillations on tropical tropopause. Results clearly show three prominent oscillations with periodicities (i) 50-70 days (ii) 30-50 days and (iii) 10-20 days in these parameters, with rapid attenuation in the amplitudes for longer periodicities as compared to that of smaller period oscillations. The results provide clear evidence of leakage of energy from troposphere to stratosphere through tropopause.

1 Introduction

Atmospheric waves, considered as perturbations on the steady and slowly changing background atmospheric parameters, are characterized by variations in wind speed, temperature and pressure and thereby in the density. These waves can propagate both in vertical and horizontal directions by carrying energy and momentum from source region to other regions, thus playing very significant role in dynamical coupling process of different regions of the atmosphere. The vertical propagation of these waves may, sometimes, effect the height of stable regions such as tropopause, the upper limit of the troposphere, which is characterized by the hydrostatic stability. This region plays a key role in the stratosphere-troposphere exchange (STE) processes. The mixing of the tropospheric and stratospheric air due to adjustment of the height of the tropopause, which can be expected due to propagation of atmospheric waves, is one of the mechanisms leading to STE. Thus vertical propagation of atmospheric oscillations may influence STE. The attenuation of energy associated with propagation of atmospheric waves to higher altitudes may disturb the stability and structure of stable regions such as tropopause.

The objective of the present paper is to study the effect of passage of long period atmospheric waves on tropical tropopause using high range and time resolution measurements of horizontal winds made by using VHF radar at Gadanki (13.45°N, 79.18°E) and simultaneous measurements of height of the tropopause and temperature made at Chennai (13.1°N, 80.2°E).

2 Observations

The VHF radar at Gadanki is a high power highly sensitive coherent pulsed Doppler system capable of providing high range (~150m) and time (~1 min.) resolution measurements of winds in the troposphere and stratosphere on near continuous basis. The system consted of 32×32, 3-element Yagi antenna array occupying an area of 132 m ×132 m. Each array is fed by individual transmitter with peak power ranging from 120 kW at the central part of the antenna array to 15 kW at the edge of the array. The system is described in detail by Jain et al.¹ and Rao et al.². This system provides Doppler spectrum at each range gate, which is then converted into three low order moments viz. echo power, Doppler shift and width of the Doppler spectrum in off-line. The Doppler shift thus obtained for minimum three non-coplanar beams are then used to derive three components of winds, viz. zonal, meridional and vertical. The off-line data analysis is described in detail by Anandan³.

High range and time resolution measurements of winds have been carried out daily using VHF radar at Gadanki during period December 1995-April 1996 at around 1700 hrs LT. Simultaneous observations of height of the tropopause and height profiles of
temperature are also obtained from nearest radiosonde station at Chennai, which is about 120 km away from radar site. These data sets are utilized to study the effect of long period atmospheric waves on tropical tropopause.

3 Data and method of analysis

Time series of zonal, meridional winds, height of the tropopause and temperature in the upper troposphere and lower stratosphere including tropopause region covering the height region between 10 and 20 km, collected during the period of interest, are used to investigate the effect of atmospheric waves on tropical tropopause. Daily data of winds and temperature collected are scanned for reasonably long sequences with minimum gaps. The data gaps, if any, have been filled by interpolation using Lagrangian formula around the missing point. The resulting data sets are then filtered for oscillations with periodicities less than 5 days using a simple 5-point moving average. Before estimating the power spectra using fast Fourier transform (FFT), the data are reduced to zero mean to eliminate any linear trend. Weights of a Cosine Bell window are applied to first and last 10% of the individual data sets so that the end regions have smooth transitions to the mean of the measured value, which lessen the effects of discontinuities during the spectral estimation. The weights are defined by

\[
w(x) = \begin{cases} 
\frac{1}{2} \left[ 1 - \cos \left( \frac{\pi x}{fL} \right) \right], & 0 \leq x \leq fL \\
1, & fL \leq x \leq L(1-f) \\
\frac{1}{2} \left[ 1 - \cos \left( \frac{\pi - \frac{L-x}{fL}}{fL} \right) \right], & L(1-f) \leq x \leq L
\end{cases}
\]

where, \( L \) is the length of the data and \( f \) is the desires fraction (usually 0.1).

The spectra for time series of wind, temperature and height of the tropopause measurements are then estimated using FFT method that makes use of appending zeros towards the end to bring the number of data points equal to \( 2^k \), where \( k \) is an integer whose magnitude depends on the length of the data series to classify the dominant periodicities in wind, temperature and height of the tropopause. A final smooth estimate is made by further frequency smoothing with Hanning procedure as follows:

\[
G_k = 0.25G_{k-1} + 0.5G_k + 0.25G_{k+1}, \quad k = 1, 2, ..., (m-1)
\]

Here, \( G_k \) represents a smooth estimate at harmonic \( k \) to reduce the error due to truncation.

4 Results

4.1 Time series of height of the tropopause, zonal and meridional winds and temperature

Time series of the height of the tropopause, zonal and meridional winds at different height levels and temperature at standard pressure levels close to the height levels of former parameters are examined for their day-to-day variation. Panel (a) of Fig.1 shows the time series of the height of the tropopause from radiosonde observations at Chennai. The dashed curve in this figure represents the best polynomial fit with seven degrees of freedom for the data series. Oscillation in the height of the tropopause with different periodicities is clearly evident from Fig.1(a), suggesting the presence of different wave components.

Panels (b) and (c) of Fig.1 show time series of radar observed zonal and meridional winds at different height levels in the height range 12-18 km and panel (d) shows time series of temperature at standard pressure levels from radiosonde observations. Variation in all the three parameters with different periodicities revealing the presence of wave activity is clearly evident from these three panels. These oscillations are similar to the oscillations observed in the tropopause. Lines of constant phase are drawn indicating the downward phase propagation, particularly, in the meridional wind and temperature data, which suggests the upward energy propagation. This indicates that the source of these wave activity is in lower troposphere.

4.2 Spectral analysis of wind, temperature and height of the tropopause

To identify more prominent wave components presented in winds, temperature and height of the tropopause, time series of these parameters are subjected to spectral analysis using FFT technique. Spectra of wind and temperature are compared with the spectrum of the height of the tropopause. Spectra of (a) zonal and (b) meridional winds at different
height levels are compared with that of temperature spectra in Fig. 2. The spectrum of tropopause height is also presented in the top panel. It is clearly evident from Fig. 2 that spectra of all parameters show similar features suggesting the presence of similar oscillations. It can also be noted from Fig. 2 that three types of oscillations with periodicities (i) 50-70 days (ii) 30-50 days and (iii) 10-20 days are more prominent. An interesting observation from Fig. 2 is that the amplitudes of oscillations attained a maximum below the tropopause and reduced above the tropopause, suggesting the reduced energy of the wave near and above the tropopause.

4.3 Height profiles of wave amplitude in zonal, meridional winds and temperature

Amplitudes of observed prominent oscillations, representing the energy associated with these oscillations are compared to study the height variation. Panels (a), (b) and (c) of Fig. 3 show comparison of amplitudes of oscillations corresponding to three periodicities for zonal wind, meridional wind and temperature, respectively. Sharp attenuation of amplitude corresponding to zonal and meridional winds for longer period oscillations is clearly evident from these panels. It can also be noticed that amplitudes corresponding to these oscillations are attaining minimum near the height of the tropopause, i.e., at about 16 km. Attenuation is also noted to be much less for smaller period oscillations such as 10-20 day oscillations as compared to that for longer period oscillations. This suggests that although wave perturbations are still there but the same are not able to propagate through the tropopause, as wave energy is severely getting attenuated in the tropopause region. Amplitudes corresponding to similar oscillations in the temperature show an increase with height up to the height of the tropopause in contrast to that observed in winds.

5 Height profiles of energy density

In order to understand the origin and propagation of the observed oscillations, the energy density of
waves is calculated using the height profiles of model
density (p) from the atmospheric model for equatorial
atmosphere, and the wave amplitude from the spectra
for both zonal and meridional wind components. The
wave energy density is expressed as

\[ E = \frac{1}{2} \rho V^2 \]  

where, \( V \) is the resultant amplitude of zonal and
meridional winds corresponding to periodicity of
interest.

The panel (d) of Fig. 3 shows the height profiles of
the energy density for the observed three prominent
oscillations in the troposphere and lower stratosphere.
Sharp attenuation of energy for long period
oscillations compared to that of short period
Fig. 3—Profiles of amplitude of (a) zonal, (b) meridional, (c) temperature and (d) energy density corresponding to three prominent periodicities observed in the spectra.
oscillations, is clearly evident from Fig. 2. This attenuation is as large as 24 dB for longer period oscillations as compared to smaller periodicities which is about 15 dB. This clearly indicates that the part of wave energy density from the troposphere is leaking through the tropopause into the stratosphere.

6 Discussion

Stable regions in the atmosphere, such as tropopause, play significant role in vertical transport of mass and momentum leading to various exchange processes including stratosphere-troposphere exchange. Variation in the height of the tropopause is one of the mechanisms through which tropospheric air mixes with the stratosphere. Such variation could be due to passage of atmospheric waves. The VHF radar observations at Gadanki clearly revealed the multiple stable layer structure of the tropical tropopause. It is noticed that these layers are separated on an average by 600 m (Refs. 5-7).

The vertical propagation of atmospheric waves is one of the mechanisms through which energy is transported from lower levels to higher levels. Passage of such waves with periodicities around 10 days disturbs the structure of the tropopause. More recently Reid and Gage examined the effect of atmospheric waves on tropical tropopause using the database of radiosonde observations. Present observations using high range resolution VHF radar measurements of winds and simultaneous measurements of tropopause height and temperature revealed multiple oscillations with similar features in all parameters under consideration. The spectral analysis of these parameters clearly showed the presence of (i) 50-70 day, (ii) 30-40 day and (iii) 10-20 day oscillations. Rapid attenuation of amplitudes with height is noticed in zonal and meridional winds up to the level of the tropopause, indicating the rapid attenuation of energy for longer periods, i.e. 50-70 day period as compared to that of smaller periodicities, i.e. 10-20 day period. The observed amplitudes are noted to attain minimum just around the level of the tropopause which is consistent with the earlier observations. However, amplitudes corresponding to these oscillations in temperature showed an increase with height up to the tropopause level in contrast to the observed decrease in amplitudes of winds. This suggests that the attenuation of energy associated with the oscillations observed in the wind is getting transformed into the temperature, resulting an increase in amplitude of temperature thereby maintaining the conservation of energy.

Results show that energy associated with the atmospheric oscillations is getting attenuated as they pass through stable regions in the atmosphere such as tropopause and the leakage of energy, which is more prominent for smaller period oscillations, indicates that wave oscillations with different periodicities are contributing to the exchange of air between troposphere and stratosphere. Present study clearly shows the effect of atmospheric oscillations on troposphere and their contribution to STE.

7 Summary and conclusions

The height of the tropical tropopause shows oscillations with multiple periodicities. Such oscillations are also observed in winds and temperature near the tropopause. Spectral analysis of wind, temperature and height of the tropopause clearly show 50-70 day, 30-50 day and 10-20 day oscillations. Amplitudes corresponding to longer period oscillations are observed to be attenuated sparsely as compared to those of smaller period oscillations and these oscillations are attaining minimum at the level of the tropopause. The energy density profiles corresponding to these periodicities show leakage of energy from troposphere to stratosphere through the tropopause. Such leakage is noted to be through the smaller period oscillations. Results thus indicate that wave oscillation of different periods can contribute to the exchange of air mass between troposphere and stratosphere.

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References