CHAPTER 4

BIENNIAL VARIABILITY OF ATMOSPHERIC AEROSOLS
AND ITS RELATION WITH QBO

4.1. Introduction

The Quasi-Biennial Oscillation (QBO) in the zonal winds is a well known primary mode of interannual variability in the tropical lower stratosphere. These equatorially symmetric easterly and westerly wind regimes alternate regularly with a mean period of 24-30 months (Lindzen and Holton, 1968; Baldwin et al., 2001; Mohanakumar, 2008). Along with these oscillations warm and cold stratospheric temperature anomalies accompany these wind regimes as they propagate lower into the atmosphere (Gray et al., 1992). The driving force for the QBO is the vertical transfer of momentum from troposphere to stratosphere by the vertically propagating gravity waves, such as Kelvin waves, mixed-Rossby gravity waves and inertia-gravity waves (Holton and Lindzen, 1972; Dunkerton, 1997). There is considerable variability of the QBO period and amplitude, easterly phase being stronger than the westerly phase.

The QBO circulation requires a westerly shear zone with a warm temperature anomaly created by anticyclonic vorticity anomalies in the tropical upper troposphere, subsidence and warming at the equator. This temperature anomaly is accompanied by a meridional circulation pattern in which a horizontal component of this circulation having an equatorward motion aloft and poleward motion at the lower levels, thus completing the circulation cell. The reverse scenario occurs during the easterly phase. The wave driving the QBO provides the necessary energy required for this thermodynamic circulation. Therefore, this circulation which
maintains the QBO induced temperature anomaly have a direct effect on atmospheric constituents in the tropics.

Reid and Gage (1985), has found a significant dependence on the phase of the QBO in zonal winds of the tropical stratosphere and tropical tropopause height based on radiosonde data obtained from nine tropical stations. Later studies (Huesmann and Hitchman, 2001; Ribera et al., 2008) has reported the correlation between the stratospheric phenomenon such as QBO and the evolution of the pressure and temperature at the tropical tropopause. A warming (cooling) of the tropical tropopause occurs during QBO positive (negative) phase for which the radiosonde data has shown that tropopause height will be lower (higher). The relationship between the QBO, tropopause height, temperature and pressure are studied extensively (Angell and Korshover, 1964; Randel et al., 2000). Their results showed a good agreement with all these parameters and are either in-phase or out of phase with respect to the equatorial QBO. From all these reported studies we can infer that these stratospheric oscillations affect the dynamics of most of the tropospheric variables.

Using in situ measurements, Saha and Moorthy (2005) noted that AOD over peninsular India shows enhancements from climatological mean for every alternate years and suggested that large scale atmospheric dynamics to be one of the possible reasons for this varying magnitudes. A similar variation in monthly mean AOD has been reported by Beegum et al., (2009) over four tropical stations in Asia and Africa. It has been postulated by Kane (1992) that winds at 50 hPa are responsible for the periodicities in the concentration of trace elements and surface aerosols in the range of 2-4 years. Moreover, numerous studies indicate that QBO plays an important role in the distribution of aerosols and chemical constituents such as ozone, water vapour and methane (Trepte and Hitchman, 1992; Hitchman et al., 1994; Cordero et al., 1997; O’Sullivan and Dunkerton, 1997; Randel et al., 1998).
It is interesting to note that how much a stratospheric phenomenon like QBO influences aerosol concentrations which is predominantly confined to troposphere. There are not many studies done on the relation between QBO and atmospheric aerosol concentrations. Therefore our study focuses on how much the changes in QBO phase influences the prevalence of atmospheric aerosols in the northern Indian region where most of the earlier studies (Guttikunda et al., 2003; Dey et al., 2004; Tripathi et al., 2006; Nair et al., 2007) have reported large amount of aerosols in the region. Such a study is relevant in a region where a majority of the people in the billion population of India resides.

4.2. Data and analysis

Monthly mean MODIS (MODe rate resolution Imaging Spectroradiometer) data onboard 
*Terra* and *Aqua* satellite is used to determine the aerosol properties for the years 2000 to 2009 (10 years) over the chosen location. MODIS monthly data is available in 36 spectral bands from visible to thermal infrared (29 spectral bands with 1km, 5 spectral bands with 500 m, and 2 spectral bands with 250 m, nadir pixel dimensions). The *Terra* and *Aqua* spacecrafts has an equatorial crossing time of 10:30 and 13:30 (local time) respectively. Due to its larger swath widths and instrument-scanning angle of 110° a nearly global image is produced (Levy et al., 2003). This sensor measures the land aerosol characteristics using the algorithm based on ‘dark target’ approach (Kaufman and Sendra, 1988; Kaufman et al., 1997; Remer et al., 2006), therefore does not retrieve over bright surfaces such as snow, ice and deserts. The aerosol properties are derived by the inversion of the MODIS-observed reflectance using pre-computed radiative transfer look-up tables based on aerosol models (Remer et al., 2005; Levy et al., 2007). The initial versions of the MODIS algorithms have been under continued development and have recently received an improved aerosol determination, *via* processing to Collection 5 (C005) Level 3 products (Levy et al., 2007).
The C005 Level 3 (spatial resolution 1°×1°) MODIS products are obtained from Giovanni website (http://giovanni.gsfc.nasa.gov/). MODIS retrieves the column aerosol concentration (in cloud free, solar glint free) conditions that is represented as aerosol optical depth (AOD). Overall, the uncertainty of the MODIS-derived AOD is ±0.05 ± 0.2 AOD over the land (Kaufman et al., 1997a; Chu et al., 2002). The MODIS-derived AOD are validated against the in situ AOD observed at AERONET stations, which shows that AOD retrievals in the visible wavelengths are generally within the pre-launch uncertainty (Jethva et al., 2007; Remer et al., 2008). An intercomparison of MODIS derived AOD with AERONET observations over India are found to be in reasonably good agreement with the ground-based sun photometer observations of AOD over the Gangetic plain (Jethva et al., 2005; Aloysius et al., 2008).

The tropopause temperature and pressure are obtained from the Atmospheric InfraRed Sounder (AIRS) onboard MODIS Aqua sensor. The AIRS sounding suite is the most advanced atmospheric sounding system to date, with measurement accuracies far surpassing those of current weather satellites. The AIRS is an infrared grating spectrometer that operates in the thermal infrared portion of the spectrum, from 3.7 μm to 15.4 μm. From its sun synchronous polar orbit, the AIRS system provides more than 300,000 all-weather soundings covering more than 90% of the globe every 24 hours. This system measures upwelling thermal radiation emitted from the atmosphere and the surface. By analyzing an observed spectrum it is possible to infer the vertical distribution of temperature and water vapor. This is accomplished by inverting the radiative transfer equation (RTE), which models the spectral intensity for a given distribution of the geophysical parameters.

The AIRS and Advanced Microwave Sounding Unit (AMSU) form an integrated temperature and humidity sounding system for numerical weather prediction and climate studies. Due to its hyper spectral nature, AIRS can provide near-radiosonde-
quality atmospheric temperature and moisture profiles with the ability to resolve some small-scale vertical features (Aumann et al., 2003). It retrieves temperature profiles with a vertical resolution of 1 km in the troposphere at an accuracy of 1K, and water vapor profiles with a vertical resolution of 2 km in the troposphere at an accuracy of 15%. In addition to temperature, profiles of ozone, CO and other minor gases are also produced. The dataset available for this study ranges for the period from October 2002 to December 2009.

The QBO of zonal winds at 50 hPa and 30 hPa are used to determine the phase change of zonal winds at these levels. High resolution radiosonde data of zonal wind in the lower stratosphere from an equatorial station where the QBO is a maximum is used for this study. It is made possible by using the Singapore wind data obtained from the Monthly Climatic Data of the world published by National Climatic Data Center, Asheville, USA.

4.3. Results and discussions

The monthly mean zonal winds averaged over the two altitude levels, viz., 50 and 30 hPa levels representing stratospheric QBO and the monthly mean AOD for the period ranging from March 2000 to December 2009 are depicted in Fig 4.1. The figure shows that the aerosol concentration undergoes a biennial variation with peak values for every alternate years. Analysis of this behaviour of aerosols in relation to QBO shows that aerosol concentration is more during westerly phase (positive phase) of QBO, and lesser values during the easterly phase (negative phase) of QBO. It is observed that the AOD attains a maximum value in the month of July during almost all the years. Starting from 2000, the peak values of AOD are observed for the even years 2002, 2004, 2006 and 2008 for the month of July. While, for the odd years lower values are observed. In the drought years of 2002 and
2004, dry conditions are favourable for enhanced aerosol concentration resulting in very high values during those years.

The QBO winds were in the westerly phase during the years 2002, 2004, 2006 and 2008. The westerly phase has maximum duration in the year 2008 which extended till the pre-monsoon season of 2009. The amplitude of the westerly phase shows a maximum in the year 2002. The AOD shows a decreasing pattern with the weakening of the zonal wind amplitude. It is seen that the amplitude of the easterly phase is about twice as strong compared to the westerly phase. The easterly phase has the maximum duration in the year 2001 and maximum amplitudes in the years 2005 and 2008. It can be seen that during both phases of QBO, higher values of AOD coincides with maximum amplitude of QBO zonal winds and declines with weakening amplitudes.
4.3.1. Meridional Circulations

The maximum values of monthly mean AOD has a periodicity of 24 months and the duration between a maximum and minimum AOD has a periodicity of about 12 months. A close evaluation suggests that the monthly mean AOD has a correspondence with the QBO. Stratospheric QBO, which is driven by vertically propagating Kelvin waves, contribute a westerly force, and Rossby gravity waves, that contribute an easterly force. These waves, which is the main driving mechanism of the QBO has maximum amplitude at the equator (Holton and Lindzen, 1972). The QBO’s secondary meridional circulation (SMC) which is superimposed upon the Brewer Dobson Circulation consists of an increase of the upwelling in the easterly shear phase and a suppression of the upwelling in the westerly phase (Plumb and Bell, 1982).

According to Trepte (1993), divergence of the SMC occurs in the easterly jet, above the easterly shear and below the westerly shear, and convergence occurs in the westerly jet (see Fig 4.2). As a result, during the westerly phase of QBO, the divergence from the equatorial troposphere would enhance the aerosol loading, thereby increasing the AOD to higher values. Moreover, it is also seen that the QBO westerly phase lasts longer than the easterly phase. During this prolonged duration of westerly phase, the aerosols in the upper troposphere gets transported to lower levels in the atmosphere resulting in a build up of aerosols.

But, during the easterly phase the intrusion of tropospheric air into the lower stratosphere, may result in a much less aerosol content and thereby a decrease in AOD. The lower aerosol content may be possibly because the easterly phase induces anomalous motion that leads to a cooler, higher tropopause near the equator (Gray et al., 1992). Therefore these aerosols undergo mixing to a greater extent thereby reducing their concentration in the atmosphere. But during the westerly phase the
lower tropopause confines these aerosols to the shorter extent thereby increasing their concentrations in the atmosphere.

Fig. 4.2. Schematic representation of the mean meridional circulation driven by the QBO, after Trepte (1993). Dashed contours indicate isopleths of zonal velocity; solid contours represent anomaly isotherms. The thick, gray lines represent the tropopause. (a) Warm anomaly during descending zonal mean westerly shear; (b) cold anomaly during descending zonal mean easterly shear (Adapted from Collimore et al. 2003).

The QBO modulates the transport of aerosols in two distinct ways. The QBO modulates diabatic transport. There is local meridional diabatic circulation in the tropics and subtropics associated with the equatorial QBO winds (Plumb and Bell, 1982). In periods with westerly QBO shear, there is equatorward motion at upper levels, relative downwelling at the equator at the level of maximum shear and
poleward motion at lower levels. At the peak of the westerly circulation, the QBO secondary circulation is convergent with wind flowing towards the equator. In periods with ascending easterly QBO shear, the pattern of the meridional circulation is reversed with relative upwelling at the equator.

These patterns of meridional circulation induce corresponding QBO associated patterns in aerosol distribution. This flow reverses at peak of the easterly circulation. The aerosols in the tropical regions are rapidly transported zonally with mean stratospheric winds while, meridional transport is determined by large scale stirring and mixing (Plumb, 1996). Secondly, it is suggested that the QBO winds modulates isentropic mixing through their influence on extratropical planetary wave propagation and breaking. The large scale transport and isentropic mixing of aerosol, coupled with the process of particle condensational growth, coagulation and sedimentation is more effective during the westerly phase than in the easterly phase of QBO.

4.3.2. Vertical Distribution of Aerosols

Gautam et al (2009) has reported a increased concentration of aerosols during the pre-monsoon and summer seasons at elevated altitudes. During the westerly phase aerosols originating from the Thar Desert contribute to aerosol loading in the vertical levels. Higher deplorisation suggests the presence of large concentrations of dust and other anthropogenic aerosols in the 5 km levels. Together with pre-monsoon westerly winds and enhanced convection, these aerosols move aloft from the Desert regions towards the Gangetic region. High deplorisation values across the elevated dust transport levels (3-5 km) validates this analysis. This signifies the increased aerosol concentration during the westerly phase of QBO. The sulphuric acid or water droplets that compose the majority of the stratospheric aerosol can also act as condensation nuclei as they enter the upper troposphere, thereby affecting cloud formation and precipitation patterns (Twomey, 1991). During winter and spring, synoptic disturbances, traveling the lower stratospheric westerlies, transport
aerosol into the tropical troposphere. Large aerosol loading occurring in the premonsoon season during westerly phase is concurrent with a quasi-horizontal advection, diffusion and gravitational sedimentation over the tropical regions increasing the AOD.

4.3.3. Tropopause Characteristics

Horizontal and seasonal variations in tropical tropopause temperature and thermodynamic properties are broadly associated with the distribution of convection and large scale vertical motion. The effect of the QBO in zonal wind on tropopause pressure level, height and temperature are presented in Fig 4.3. In the figure, anomalies in tropical tropopause pressure, height and temperature over the chosen location for the years 2002 to 2009 are illustrated. It is seen that the elevation of the tropopause level (positive anomalies of pressure) is associated with negative phase of QBO. During the positive phase of QBO, the tropopause is characterized by less than normal pressure levels which represent a higher tropopause. The height of the tropopause reflects the temperature of the underlying troposphere, and it decreases with decreasing atmospheric stability, suggesting an indirect response to convection.

The analysis of temperature anomalies at tropopause level together with the analysis of its QBO served to identify positive (negative) tropopause temperature anomalies during westerly (easterly) phase of QBO. It can be seen from Fig 4.3. that positive temperature and pressure anomalies are seen during the westerly phase of QBO. The present study is in agreement with those results obtained by Heusmann and Hitchman (2001), in which a positive correlation between the QBO and temperature at the tropopause level was detected using data from the NCEP reanalysis. During QBO easterly phase, strong negative tropopause temperature anomalies are observed in the months of January to May, which indicates a warming of the tropical troposphere.
Fig 4.3. Anomalies of tropical tropopause (a) pressure (b) height (c) temperature respectively for the years 2002 to 2009. The anomalies are averaged from 22°N to 29°N and 69°E to 89°E.
Ribera et al., (2008) has reported that at tropics the QBO induces a secondary circulation that modulated the height and pressure of the tropopause. This may be the possible cause of the variations in tropopause characteristics with the changes in stratospheric zonal winds.

The modulation of QBO mean meridional circulation of the stratosphere induces changes in pressure and temperature of the tropopause (Salby and Callaghan, 2004). They showed that the changes in the Brewer-Dobson circulation generate anomalies in the tropopause temperature and height. During the westerly QBO phase, anticlockwise circulation anomalies are found in the low tropical stratosphere. These anomalies lead to downwelling and warming the tropical stratosphere region. In westerly shear zones due to sinking motion and the associated adiabatic warming implies a maximum temperature at the equator. The opposite holds in easterly shear zones. The variations in tropopause temperature and pressure anomalies bring about changes in troposphere height. Therefore, as mentioned above, during the downwelling of this positive phase, an increase in tropopause temperature and pressure and a decrease in tropopause height are seen. As a result the AOD increases.

But, during the easterly phase of QBO, cyclonic circulations create an upwelling in the tropical tropopause so that a negative temperature and pressure anomalies persist at tropical tropopause. Therefore, the tropopause height increases and the AOD decreases. The warming of the tropical tropopause layer would push the tropopause layer to higher latitudes and thereby to lower pressures. As the troposphere warms, the free troposphere or the upper troposphere gets warmer by a larger amount than the surface (Santer et al., 2005). Using global models, Gettelman et al., (2009) has established this theory and reported that warming of the troposphere results in a heating of the tropopause. The resulting increase in convection causes the effective mixing of the constituents in the troposphere (eg. aerosols) and lowering its concentration.
Since more than 90% of the total volume of aerosols lies in the troposphere the dilution in its concentration reduces the AOD values in the atmosphere. But, when tropical tropopause layer cools the tropopause shrinks to lower altitudes (higher pressures) so that atmospheric aerosols are confined to a smaller area in troposphere. As a result, the aerosol concentrations increases which is indicated by high AOD values in the atmosphere. As mentioned above, this occurs during the westerly (positive) phase of the QBO. It can be noted that increasing concentrations can be observed during the months when the prevailing winds in the tropopause are westerlies. These winds are capable of bringing dust aerosols from the arid regions (eg. Arabian Peninsula, Mediterranean and Thar Desert) to the study location and thereby increasing the surface concentration.

Therefore, the variations in AOD have an association with the waxing and waning of the tropical tropopause. Stratospheric QBO in zonal winds is one of the primary mechanisms for this variation in tropical tropopause layer as a result of which AOD undergoes a biennial variability in response to positive and negative phases of the QBO. It is suggested that positive temperature anomalies in response to QBO are the resultant of a complex forcing due to aerosols and greenhouse gases.

4.4. Conclusions

The time series of monthly mean AOD over the Indian region shows a biennial variability which is seen to be associated with the positive and negative phases of QBO in stratospheric zonal winds. Further analysis reveals that QBO modulates the tropical tropopause layer by which the tropopause undergoes an oscillation in tropopause characteristics (height, pressure and temperature). The warming (cooling) of the troposphere during the positive (negative) phase of QBO enables intense convection thereby resulting in an increase (decrease) in concentration of atmospheric aerosols. Equatorial QBO, which is predominantly a stratospheric phenomenon, induces changes in the tropospheric characteristics that in turn modify
the distribution of tropospheric constituents including concentrations of atmospheric aerosols. Moreover, the increasing concentrations are observed when the winds are westerlies suggesting the transport of dust aerosols from the arid regions of Arabian Peninsula and Thar Desert.

Therefore it is evident from Chapter 3 and Chapter 4 that North Indian region which comprises of IGP is influenced by significant loading of aerosols as a result of the complex interactions between meteorological parameters and tropopause dynamics. The aerosols reaching the location by means of zonal, meridional and vertical transport accumulates due to the typical characteristics of the region. This enhanced piling up of aerosols in significant quantities during the non-monsoon months has a potential role in modifying cloud processes and consequent rainfall distribution in the region.