CHAPTER 5

Low latitude temperature change in the stratosphere and mesosphere relation to Sudden Stratospheric Warming (SSW)

5.1 Introduction

To understand middle atmosphere dynamics, the basic thermal structure needs to be studied in addition to the background wind. Note that middle atmosphere temperature and winds are strongly modulated by various kinds of waves from short period gravity waves to planetary scale waves. It is very important to study temperature structures from ground to upper atmosphere at various parts of the globe, which play significant role in understanding the coupling between different regions of the atmosphere. In recent years, the importance of a systematic monitoring of the temperature structure and dynamics of the middle atmosphere has been demonstrated by several of middle atmospheric program (MAP) campaigns. Thermal structure over mid and high latitudes is extensively studied while observations from low latitude are sparse. It is well known that thermal structure over low latitude is significantly different from the mid and high latitude due to vertical motion at various levels associated with the meridional circulations.

The middle atmospheric thermal structure, including the stratospheric warming signature and its effects have been studied in the mid and high latitude and a very few observational evidences are devoted in the tropical region using ground based and space-borne observations.
Recent observations and global circulation models predict the increasing emissions of greenhouse gases that are likely to have an impact on the thermal structure of the middle atmosphere [Beig et al. 2003].

In the past, rocketsondes and falling spheres were used to characterize the middle atmospheric temperature with poor vertical resolution and accuracy due to uncertain radiative and aerodynamic heating corrections [Beig et al. 2003]. During the last three decades, Rayleigh lidar [Hauchecorne and Chanin, 1980; Chanin et al, 1985, and references therein; Nee et al, 2002; Sivakumar et al. 2003] and resonance fluorescence lidar [States and Gardner, 2000] operating over different latitudes on the globe have been used for obtaining the middle atmospheric thermal structure. Rayleigh lidar provides continuous measurements of temperature (or density) with height and temporal resolutions in the altitude range of 30–80 km. The resonance fluorescence lidar provides information in the altitude range of 80–105 km. However, lidar operation is restricted to cloud free nights only. Very few studies have been carried out during daytime by making special modifications to the lidar systems [States and Gardner, 2000].

In the lower stratosphere the coldest region (about 190K) is near the tropical tropopause at about 16 km. The warmest regions (about 240 K) are found in summer at high latitudes and in winter the mid latitudes are warmer than both the low latitude and the polar region. It is to be noted that the net radiative heating is a maximum in the cold low latitudes and the horizontal heat flow is not generally in the same direction as the horizontal temperature gradient. The tropical tropopause is highest and coldest in January. This may be associated with the overall activity of the troposphere’s Hadley cells which is a maximum at that time.
Sivakumar et al. [2001, 2004], Ratnam et al. [2003], Shepherd et al. [2007] and thus have examined the stratosphere and mesosphere temperature structure, mesospheric inversion layer, double stratopause and stratospheric warming effects using ground based lidar and space borne measurements such as SABER and HALOE. Mukherjee et al. [1987] examined the dynamics of the tropical stratosphere and mesosphere in the winter of 1984-85 employing weekly rocket temperature profiles and radar winds from Thumba (9°N). The period was marked by a minor stratospheric warming followed by a major warming event registered at high latitudes. In the tropical lower mesosphere, deep cold and warm anomalies were observed prior to major stratospheric warming, which was observed by about two weeks later, accompanied by cold anomalies in the mesosphere.

Sivakumar et al. [2004] examined the stratospheric warming effects at low latitude using Rayleigh lidar observations from Gadanki (13.5°N, 79.2°E). They reported a stratospheric warming event at low latitude about a week after a major warming was registered at high latitudes, with a temperature increase of 18K above the tropical winter mean values at 45 km height.

An extensive study of the low latitude (5-15°N) stratosphere and mesosphere temperature variability during sudden stratospheric warming has been reported by Shepherd et al. [2007]. They have observed the mesospheric cooling at the time of stratospheric warming in the tropics correlative with stratospheric warming events at middle and high latitude. In addition, Planetary waves m=1 with period of 4-5,6-8,10 and 12-18 days are found to be dominated during
this period. Recently, Pancheva et al. [2008] examined the planetary wave variability during 2003/2004 winter using the TIMED/SABER measurements and compared with UKMO temperature results. They have observed the planetary waves, their spatial structure and their temporal evolution during stratospheric warming.

It is well known that the lidar observations are confined to cloud free nights only. Until now the nocturnal averaged lidar temperature profiles are taken as representative of the day due to the above limitation. Hence, this chapter is mainly focused to delineate the characteristics of low latitude middle atmospheric temperature (20-90 km) structure during normal winter and disturbed winter periods using Rayleigh lidar located at Gadanki and SABER/TIMED sounding for the winter periods from 2004-2008. In addition, UK Met Office assimilated data are also used for the period from 2003-2008. The UKMO temperature at all available heights from lower stratosphere to the mesosphere is compared with SABER temperatures. The space-time analysis was applied to the UKMO temperature data at high and low latitude region and the results are used to examine the planetary wave variability during stratospheric warming events.

5.2. Thermal structure observed using Lidar and Rocket observations

Temperature measurements made by Soviet Meteorological M-100 rocketsondes from Thumba Equatorial Rocket Launching Station (TERLS) available during the period of 1970-1991 are utilized. After March 1978, revised M-100 (M-100B) rockets have been used for the observations. These rocketsondes have been launched once a week, every Wednesday from TERLS, Thumba. Composite monthly mean temperature profiles was obtained from more than
800 (700) rocket soundings attaining altitude of 65 km (attaining more than 65 km) over Thumba for the period 1970-1991.

Figure 5.1 (a) Composite monthly mean temperatures observed by Gadanki Rayleigh lidar during 1998-2007. (b) Total number of nights sorted according to the month during 1998-2007. (c and d) same as (a and b) but for the M-100 rocket observations during 1978-1991.

Figures 5.1a and 5.1c show the composite monthly mean temperature over the height region of 30-80 km derived from lidar and rocket observations over Gadanki and Thumba respectively. This is the average seasonal behavior presented in the contour from using twenty years (1971-1989) of temperature data from Thumba and averaged period (1998-2007) of temperature data from Gadanki. Number of days of data set used in each month for lidar and rocket is also depicted in Figures 5.1 b and 5.1d. Note that in figure 5.1b, the lidar data during nighttime in monsoon season (June-October) are considerably less number of nights of observations than
those in other seasons. However, this limitation is not there for rocket observations. The composite monthly mean values of both lidar and rocket observations show similar features but with some difference in magnitude. The difference between lidar and rocket observations could be due to several reasons: different period of observations used, difference in techniques involved and also to some extent the difference in locations.

Figure 5.1(a, c) reveals clear temperature variations with peak temperature of ~265 K during February-April and September-October around stratopause heights (40-50km) and temperatures during March-April and September-October around 70-80 km showing clear semiannual oscillation. The thermal structure of the tropical middle atmosphere was known to reveal significant annual and semiannual variations because of the variations in convective activity and solar flux [Lambeth and Callis, 1994; Mohankumar, 1994, Gobbi et al. 1995].

5.3. The winter stratosphere and mesosphere at 5-15°N

An SSW event was observed at high and mid latitudes when the stratospheric temperatures increased by 25 K during February 1993 reported by Whiteway and Carswell [1994]. Walterscheid et al. [2000] observed that in the mesosphere the effect of the SSW was expressed as a cooling trend at high latitudes with a maximum cooling of 25 K on 13-14 February 1993 about a week before a warming trend was observed in the high latitude stratosphere as seen in the Eureka (80°N) Lidar observations.

Cho et al. [2004] have observed the mesosphere and lower thermosphere (MLT) cooling using Spectral Airglow Temperature Imager (SATI) during 2001/2002 winter over Resolute Bay
(74°N). They have compared their results with UKMO stratospheric assimilated data for the Resolute bay location and for zonally averaged at 75°N, at two pressure levels 3.16 hPa and 0.316 hPa. The MLT cooling was observed and it coincides with stratospheric warming from zonally averaged temperature at 3.1 hPa.

*Siskind et al.* [2005] also observed the mesosphere cooling associated with high latitude stratospheric warming using TIMED/SABER observations during February 2002, August 2002 and February 2003. Moreover, mesospheric temperatures between 0.7 and 0.01 hPa show significant anticorrelation with stratospheric temperatures. *Manney et al.* [2008] have examined the spatial and temporal evolution of polar stratosphere and mesosphere throughout the life cycle of major sudden stratospheric warming during 2005/2006 winter using MLS and SABER temperature. They have noticed a drop of 20-30 km in polar stratopause altitude during the SSW event and cooling after the peak of the SSW. They show that over a three-week period following the major warming there is a complete disappearance of the warm stratopause followed by reformation of a cooler stratopause near 75 km that warms and descends to the original pre-warming altitude.

No previous observational studies have focused specifically on the effect of SSW events on low latitude middle atmosphere thermal structure and gravity wave propagation. In this chapter the temperature variability from stratosphere to mesosphere and lower thermosphere is studied using TIMED/SABER and stratosphere and mesosphere temperature data obtained by lidar over Gadanki. The data cover the time interval from 01 December to 28 February. The results to be presented in this chapter begin with an investigation of the TIMED/SABER daily
temperature over the latitude range of 5-15°N and longitude of 60-85°E in the stratosphere and lower mesosphere for the time interval of 01 December to 28 February.

5.3.1 December 2003-February 2004

The effect of SSW on the low latitude mesosphere and stratosphere was examined employing temperature data from the Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) experiment on the TIMED satellite providing daily temperatures with good quality and resolution since January 2002. The time-height cross section of daily temperature averaged for the latitudes 5-15°N and longitudes 60-85°E for time interval of 01 December 2003-28 February 2004 is presented in Figure 5.2. The top panel of Figure 5.2 represents mesosphere and lower thermosphere and bottom panel represents the stratosphere and lower mesosphere. The stratopause near 45-55 km is clearly evident in the bottom panel and an increasing warm stratopause with more than 270K during February 2004 was observed. A cold temperature of about 220 K was noticed in the middle stratosphere (~35 km) between day numbers 25 and 35. This cooling was extended up to 45 km on day number between 25 and 35.
After day number 35, the cold condition was replaced by normal winter state. Fall in temperature can be linked with the commencement of high latitude stratospheric warming events. The association of cooling in the tropical latitude was first observed by Fritz and Soules [1970] in NIMBUS satellite measurements. In the tropical mesosphere (70-90 km) height, the temperature field exhibits significant variability with height over time as it can be seen in top panel of Figure 5.2. There were two warming pulses of 230 K noticed in the lower mesosphere region of 70-78 km on day number 25 and other one is around 31 and it was extended on day
number 40 (01-January-10 January 2004). The temperature perturbations taking place during the stratospheric warming were not confined to the upper stratosphere but extended up to the mesosphere. The time of these warm temperatures correlate well with the SSW registered at middle and high latitudes, out of which, the one at the beginning of January 2004 is a major warming event. At higher altitudes above 80 km, warm temperature was replaced by cold temperature of 180 K from end of December to early January 2004. Mukherjee et al. [1987] observed the pattern of cooling and warming of the mesosphere before the cold temperature corresponding to the SSW sets in.

5.3.2 December 2004-February 2005

The mean state of this winter was described in chapter 3. Figure 5.3 is same as Figure 5.2 except for the period from 01 December 2004 to 28 February 2005. During this winter, stratosphere was cold and the polar vortex was relatively strong in the entire period and has no disturbance occurring in the high latitude stratosphere. In the mesosphere, warming and cooling were noticed in the month of December 2004. Above 70 km, moderate cooling was noticed after January 2005 and continued till the end of February 2005.
Figure 5.3 Same as Figure 5.2, but the time interval from 01 December 2004 to 28 February 2005.

5.3.3 December 2005-February 2006

Figure 5.4 is the same as Figure 5.2 except for time interval from 01 December 2005 to 28 February 2006. One of the strongest, most prolonged SSWs on record began in January 2006. There were series of warming events, which can be inferred from the high latitude stratosphere during this winter. Though there were three successive warming events, only the third event was a major warming, as it was accompanied by the reversal of zonal wind at high latitude stratosphere.
There was a cooling of ~10 K on day numbers between 40 and 60 in the altitude region of 30-35 km high latitude stratosphere warming. An increasing warm stratopause with more than 270K during February 2006 was found in the bottom panel of Figure 5.4 and it maintained even after day number 65 when the major warming even ends at high latitude. The lower mesosphere (70-80 km) region experiences significant warming of nearly ~10 K on day number ~28 and day number 50 (20 January 2006). Earlier model results of Lindzen [1981], Holton [1983], Dunkerton and Butchart [1984] suggest that the inhibition of upward propagation of gravity waves lead to a cooling toward radiative equilibrium in the mesosphere. At higher altitudes above 80 km the warm temperature changes into cold temperature during December 2005-January 2006. After middle of February 2006 the cold temperature extended into lower mesosphere below 75 km.
Figure 5.4 Same as Figure 5.2, but the time interval from 01 December 2005 to 28 February 2006.

5.3.4 December 2006-February 2007

Figure 5.5 is the same as Figure 5.2 except for the period from 01 December 2006 to 28 February 2007. The winter of 2006/2007 was typical as colder than average in November-January by Free University of Berlin (FUB) as colder than average in November-January, and with a major SSW in February. There were three disturbances registered at 10hPa at 60°N near
2nd January (day number 33), 5th (day number 35) and 24th February (day number 86). For the disturbance of 2nd January 2007, the mid stratosphere showed a clear response with cooling on day number ~34 and this cooling trend was seen up to upper stratosphere. Two warm temperatures noticed on day number on 63 and 82 were linked with disturbances observed in the high latitude stratosphere. In the mesosphere, first disturbance showed clear response with warming on day number between 30 and 35 in the height region of 70-74 km. There was no short term mesospheric thermal response to the minor SSW observed near 5 February 2007.

Figure 5.5. Same as Figure 5.2, but for the time interval from 01 December 2006 to 28 February 2007.
5.3.5 December 2007-February 2008

Figure 5.6 is the same as Figure 5.2 except for the period from 01 December 2007 to 28 February 2008. At high latitude stratosphere has disturbed during January and February 2008. There were two minor warming followed by a major warming was noticed during 22 January 2008, 15 February 2008 and major warming is on 23 February 2008. In the stratosphere, the lowest temperature of 220 K noticed during day numbers between 22 and 25 at 30 km region was associated with high latitude stratosphere disturbances. The warm temperature was noticed at about 275 K at 48 km on day numbers 22 and 31 January 2008.

In the mesosphere, weak warming signature was associated with high latitude mesospheric cooling in the height region of 70-75 km. At higher altitude above 80 km, warm temperature was replaced by cold during January 2008 and the lower mesospheric temperature showed clear opposite tendency with the middle stratosphere during the period between day number 25 and 30. This reveals the clear evidence of high and low latitude coupling during sudden stratospheric warming events.
Figure 5.6. Same as Figure 5.2, but for the time interval from 01 December 2007 to 28 February 2008

5.3.6 December 2008- February 2009

Figure 5.7 is the same as Figure 5.2 except the period from 01 December 2008 to 28 February 2009. The 2006 SSW, along with a similar event in 2004 was the strongest and long-lasting on record. During this winter, January 2009 SSW surpassed that in 2006 and had a more profound and lasting effects in the stratosphere and mesosphere. As can be seen in Figure 5.7 (bottom panel), there was strong cold temperature of 215K observed on day numbers between 55
and 65 at 32 km. The observed cooling was associated with high latitude stratosphere warming. The increasing temperature was observed after February 2009 and also the stratopause height is clearly evident at the height region between 45 and 50 km. In the mesosphere, there were two warm temperatures observed on day numbers 47 and 60 in which the first one was weaker than the second one. By day number ~60, warm temperature of about 230K was noticed at the height gates of 70-75 km, this warm pulse was linked with high latitude mesosphere cooling.

Figure 5.7. Same as Figure 5.2, but for the time interval from 01 December 2008 to 28 February 2009
At higher altitudes say about 80km, the cold temperature reached in to 75 km during middle of December 2008 and cooling of about less than 180K was noticed in the higher altitudes on day number around 43. This short term reversal was seen only two days after that it was replaced into normal winter temperature condition. The stratosphere cooling and mesospheric warming were observed during sudden stratospheric warming events in the tropical region which is more pronounced in this winter compared to other winters.

5.4 Thermal structures of Lidar and UKMO observations during January 2006 warming event

Rayleigh lidar, installed at Gadanki under Indo-Japanese collaboration, has been operated during night time under cloud free conditions since March 1998. The lidar employs a Nd:YAG laser, which operates at the second harmonic wavelength of 532 nm. The pulse energy is 550 mJ and pulse width is 7 ns. The lidar is operated with an altitude resolution of 300m and pulse repetition frequency of 20 Hz. The system provides backscattered signals, which are integrated over 5000 transmitted pulses corresponding to a temporal averaging of 250 s. The temperature information is retrieved from the received photon counts using the method adopted by Hauchecorne and Chanin [1980]. There have been quite a number of results reported from this site (Bhavani Kumar et al, 2000; Parameswaran et al., 2000; Sivakumar et al. 2001, to state a few). Though the highest altitude is taken as 90 km and from which temperature is derived using downward integration, the standard error in the estimation of temperature information above 75 km is larger and hence the data for the heights 30 and 75 km are only presented. The lidar operation limits to nighttime and cloud free conditions and hence the data for each night also
varies. The Rayleigh lidar observations have been carried out in almost all the nights during January–February 2006.

As the major stratospheric warming event occurred at high latitudes during end of January 2006, the temperature observations over Gadanki provide us the opportunity to examine the thermal structure at low latitudes prior to, during and after the major stratospheric warming event occurring at high latitudes. The thermal structure of low-latitude middle atmosphere preceding, during and after the major stratospheric warming period is investigated. Figure 5.8 shows daily averaged Rayleigh lidar temperature measurements over Gadanki (13.5°N, 79.2°E). There is a sudden increase of temperature at stratopause heights on day number 21, coinciding with the major warming event occurring at high latitude. The difference between mean temperature of day numbers 5–15 and 25–35 is 5–10°K in the height region 45–50 km.

Figure 5.8. Daily averaged Rayleigh lidar temperature over Gadanki (13.5°N, 79.2°E).
The maximum temperature in the daily averaged temperature profile on day number 20 is 267K and is increased to 280K on day number 25 and nearly maintains a temperature of 275K until the end of the observation period. The increased temperature maintains even after day number 33, when the major warming event ends at high latitude. The lower mesosphere (70–75 km) region experiences significant cooling of nearly 20°K. Changes in wind speed and direction during a sudden stratospheric warming will inhibit the upward propagation of gravity waves and lead to a cooling towards radiative equilibrium in the mesosphere \[\text{Lindzen, 1981; Holton, 1983; Dunkerton and Butchart, 1984}.\] Whiteway and Carswell [1994] observed mesospheric cooling at high latitude site Eureka (80°N, 86°W) during the sudden stratospheric warming event.

In order to investigate the gravity wave activity prior to and during sudden stratospheric warming events using temperature information from Gadanki, the temperature profiles derived for every half an hour and the temperature perturbations are used. The background temperature profile \(T_0(z)\) are extracted from the half an-hour averaged profiles. The background temperature profile \(T_0(z)\) is obtained by averaging the temperature profile for the entire night and smoothed vertically by 5 km. The root-mean-square (rms) perturbation and available potential energy per unit mass are used to infer whether there was dissipation of energy. At a given altitude, the variance of temperature perturbation from the estimated background state was computed from the series of half-hour average temperature profiles obtained on a given night. The noise variance due to statistical uncertainty in the photon counting process is subtracted to obtain real atmospheric temperature fluctuations, which at a given altitude is given by
\[
\left( \frac{T'(z)}{T_0(z)} \right)_r^2 = \frac{1}{N_P} \sum_{i=1}^{N_P} \left( \frac{T'(z)}{T_0(z)} \right)_{i}^2 - \frac{1}{N_P} \sum_{i=1}^{N_P} \left( \frac{\delta T(z)}{T_0(z)} \right)_{i}^2
\]

where \( \delta T(z) \) is the uncertainty in the temperature measurement at height \( z \) due to statistical fluctuations in the photon counting process. The real variance is then used to determine a profile of rms perturbation and the average available potential energy per unit mass is calculated from

\[
E_p(z) = \frac{1}{2} \left( \frac{g}{N(z)} \right)^2 \left( \frac{T'(z)}{T_0(z)} \right)^2
\]

where \( N(z) \) is the brunt-vaisala frequency and \( g \) is acceleration due to gravity. The temperature derivative is used to obtain \( N(z) \), which is computed by using three adjacent points.

Figure 5.9. Time series of potential energy per unit mass in the 30-40 km, 40-50 km and 50-60 km region computed from Rayleigh lidar temperature fluctuations over Gadanki.
Figure 5.9 shows the time variation of potential energy per unit mass averaged over the heights 50–60 km (top panel), 40–50 km (middle panel) and 30–40 km (bottom panel). Before the onset of warming vents, the Ep values are larger at all heights. The values decrease drastically just before the onset of the event. The Ep values for the heights 30–40 km and 50–60 km show similar time variation during the day numbers 1–25. The Ep values are larger (50–70 J/kg) on day number 16 and they decrease drastically to 71.2 J/kg on day number 21. However, Ep values for the height region 40–50 km show a sudden increase (~40 J/kg) two days prior to the onset of the warming event at high latitudes, but decrease drastically to ~7 J/kg in two days. The variation of Ep values seems to show modulation at periods in the range of 7–25 days. It could probably be due to the interaction of planetary waves with gravity waves.

In order to see the latitudinal structure of temperature and winds, UKMO zonal mean temperature and zonal winds are considered. Figure 5.10 shows the daily variation of UKMO zonal mean temperature difference between the latitudes 60°N and 90°N, zonal mean zonal wind at 60° N, zonal mean temperature and zonal mean zonal wind at 10° N. The three warming events can also be inferred from UKMO data sets. All three warming events persist almost entirely in the stratosphere. The third event, which is a major warming event, is accompanied by the reversal of zonal mean zonal wind at 60° N. The reversal first begins at mesospheric heights and slowly descends down to stratosphere. At 10° N, the zonal mean zonal wind shows eastward winds at stratospheric heights throughout January–February 2006.
Figure 5.10. UKMO data (top left) Daily variation of zonal mean temperature difference (90°N-60°N), (bottom left) zonal mean zonal wind at 60°N, (top right) zonal mean temperature and (bottom right) zonal mean zonal wind at 10°N.

However, at mesospheric heights, westward winds are observed prior to the onset of major warming events and they decelerate slowly, after the onset of a major warming event at high latitudes. Above the major warming event, with the onset at day number 21, the zonal mean temperature difference is reversed at high latitude and the reversed temperature difference persists in the region around 1 hPa even during the end of February. Coinciding with this cooling episode at high latitudes, warming episode occurs at low latitudes and is consistent with the Rayleigh lidar observations over Gadanki.
5.5 Planetary wave signature in the stratosphere and mesosphere temperature

The dynamics of the middle atmosphere in winter are known to be dominated by planetary waves of large amplitudes. The most important are quasi stationary Rossby waves, which propagate upward from the troposphere and are very strong but quite variable during winter. The interaction of the planetary waves and the zonal mean flow is known to be major driver of winter stratospheric dynamics. Several sudden stratospheric warmings (SSW) events occurred during the Arctic winters of 2003-2009. Herein we utilize temperature measurements from the SABER instrument onboard the TIMED spacecraft collected from 01 December to 28 February in an effort to elucidate the planetary wave dynamics prior, during and post to the stratospheric warming. In order to investigate the temporal variation of planetary wave activity in the stratosphere to mesosphere over tropical region, daily temperature averaged for the latitudes 5°N-15°N and longitudes 60°E-85°E are subjected to wavelet analysis. The Morlet wavelet was selected because of its simplicity and convenience in investigating wave like events observed in the temperature of stratosphere and mesosphere.

5.5.1 December 2004-February 2005

Figure 5.11 depicts the normalized wavelet spectra of temperature in the stratosphere at two height gates of 34 (bottom column) and 46 (top column) km for 1-90 days starting from 01 December 2004 to 28 February 2005 which is shown in the left panel and right side shows the wavelet spectra of mesosphere temperature at 78 km (bottom column) and 90 km (top column) respectively.
The planetary wave with periods of between 2 and 20 day are discussed in detail. As it can be seen in left panel of Figure 5.11, it shows the 8-14 days are quite dominant. Their energies increase in time period less than 10 days. Another strong wave activity of periods of 5-8 day wave periods was appeared in the middle of February 2005 at upper stratosphere and it continued up to end of February 2005. The peak amplitude of ~5 K was noticed in the upper stratosphere and less amplitude observed in the middle stratosphere (34 km). During this winter, no midwinter warming was observed in the high latitude stratosphere.

Figure 5.11 Wavelet spectra of stratosphere temperature (34 km and 46 km) at 5-15°N (left panel) and mesosphere temperature (78 km and 90 km) (right panel) from SABER for the time period from 01 December 2004 to 28 February 2005.

There were two dominant periods noticed in the mesosphere that 11-14 days and ~8 day. The 11-14 day wave periods were appeared in the end of December 2004 and it lasted up to middle of
January 2005. At 78 km, no such kind of wave activity was observed during entire course of the events. The ~8 day wave period was noticed in the end of December 2004 and peak amplitude of 5K at 90 km. Another ~8 day wave period with moderate peak of 3K was noticed in the end of February 2005 at 90 km. An intense 12-16 day wave period was noticed in the middle of December 2004 at 90 km and it persisted until beginning of January 2005 at 90 km. In mesospause, 12-16 day planetary wave noticed one week earlier to that seen in the stratopause.

5.5.2 December 2005-February 2006

Figure 5.12 is same as Figure 5.11 but the period from 01 December 2005 to 28 February 2006.

Figure 5.12 is same as Figure 5.11 but the period from 01 December 2005 to 28 February 2006. As it can be seen in left column of the Figure 5.12, there was weak wave period of 11 day
period observed in the upper stratosphere in the course of the events. The ~8 day wave period was observed with weak amplitude in the prior to the warming events. There was significant reduction in wave amplitudes during and several days after the SSW event. In the mesosphere, the wavelet spectrum shows the wave period of 14-20 days were dominant before the onset of SSW wave events. This wave event was not present after the onset of SSW events. The strong ~6 day wave period was observed at the end of February 2006 and reduction in the PW energies is observed during onset of SSW warming events. Pancheva et al. [2008] noted an opposite relationship between the variability of the MLT zonal wind at high and low latitudes and indicated the presence of zonally symmetric waves in the MLT zonal wind. This suggests that PW variabilities in stratosphere and mesosphere regions are significantly influenced by the major SSW events.

5.5.3 December 2006- February 2007

Figure 5.13. Same as Figure 5.11, time period was taken from 01 December 2006 to 28 February 2007.
Figure 5.13 is same as Figure 5.11 but for the period from 01 December 2006 to 28 February 2007. In the stratosphere, wavelet spectrum of temperature shows three dominant periods of \(\sim 14\)-17 days and \(\sim 5\)-8 days that were noticed in all two height gates in the left column of Figure 5.13. The 14-17 day wave period was noticed with peak amplitude of 3 K in the middle of December 2006 and it continued up to the end of January 2007 in the middle stratosphere (34 km) and strong 5-8 day wave period was noticed in the beginning of December 2007 at 34 km. At stratopause height (say at 46 km), strong 17-20 day wave period was noticed in the entire time period and it was significant and another wave period of 5-8 day wave was observed with significant amplitude of \(\sim 4\) K at the end of January 2007. During this winter, there was no major mid winter warming occurred in the high latitude stratosphere as per World Meteorological Organization (WMO). Earlier, during winter 2005/06 was observed that there was a significant reduction in the PW energies but here we have noted an increase in the wave energies during winter 2006/2007. The wavelet spectrum of mesosphere temperature shows three dominant periods of 17-20 days, 9-11 days and \(\sim 5\)-7 days noted during this winter. There was strong 17-20 day wave period with peak amplitude of 4 K is noticed in the middle of January 2007 in the height of 78 km. At 90 km, an enhanced 11 day wave period of 4K is noticed in the end of December 2006 and 17-20 day wave period of 3K is also observed during the beginning of January 2007. During middle February 2007, enhanced 9-11 day wave period of \(\sim 3\) K was observed and weak 5 day wave also appeared in the beginning of February 2007. The 5 day oscillation is noticed in the beginning of December 2006 at 78 km and also observed in the similar period in the middle stratosphere at 34 km.
5.5.4 December 2008-February 2009

Figure 5.14. Same as Figure 5.11, for the time period was considered from 01 December 2008 to 28 February 2009.

Figure 5.14 is same as Figure 5.11 but for the period from 01 December 2008 to 28 February 2009. As it can be seen in the left column of Figure 11 that there are significant wave energies is reduced in the stratosphere heights gates 34 and 46 km respectively. There are only two wave period of ~8 day and ~11 day was observed with weak amplitude of 2K in the middle and upper stratosphere.

At 46 km, no wave activity was found during entire course of the events which clearly reveals reduced wave activity in the stratosphere. According to WMO, in this winter the
stratosphere was considered as a major warming event in the high latitude. Moreover, this event was the strongest and long lasting in record. Earlier 2006 event was considered as the strongest event but the event of 2009 surpassed the event of 2006. In the mesopause region at 90 km, PW activity with periods of 5-8 day waves and 17-20 day wave periods were dominant before the onset of the stratospheric warming event and the peak amplitude is noticed at about 3 K. At 78 km, increased 17-20 day oscillation with peak amplitude of ~3 K was noticed in the middle December 2008 and it lasted in to middle of January 2009. The 5-8 day wave periods were found in the beginning of December 2008 and similar periods were noticed in the middle stratosphere (34 km) as well. Our results reveal that PW variabilities in stratosphere and mesosphere regions are significantly influenced by the major SSW events.

The other two winters namely 2003-2004 and 2007-2008 were not shown here because of the large data gap during these winter periods. Shepherd et al (2007) have discussed extensively the 2003-2004 winter events thoroughly using TIMED/SABER in the tropical latitude and they have observed strong 7 day wave activity in the mesosphere at the beginning of January 2004 and these are seen after following the enhancement of stratosphere temperature at the beginning of January 2004. In addition, 9-12 waves were observed during the end of January and it extended to early February 2004. They have seen these waves and observed them at 50 and 86 km as identical.
5.6 Discussion

Observations of stratosphere and mesosphere temperatures from TIMED/SABER, Lidar, rocket observations and UKMO were presented in this chapter for the winter years from 2003-2009. Lidar temperature with SABER has shown good agreement at the altitude of 35 km and 74 km. The tropical stratosphere is found to be highly stable, whereas considerable variability is noted in the mesosphere. Kishorekumar et al. [2008] has observed that the diurnal and nocturnal averaged monthly mean from SABER show similar features with slight difference in temperature indicating that there will not be much difference in temperatures either obtained by nocturnal average or diurnal average. But, there is slight difference both in height and temperature between different techniques used in the present study. Large difference between SABER and lidar observations during monsoon (June-October) months suggests that background thermal structure deduced from lidar measurements alone may not represent true background conditions. Moreover, they have noted the stratopause and mesopause lie in the height region of 47-49 km and 97-99 km with peak temperature of 265 K and 170 K.

The dynamics of the winter middle atmosphere is marked by considerable gravity wave activity and events of SSW, which in turn are coupled with planetary wave in the upper stratosphere and lower mesosphere, appear as warm temperature. In this chapter, we have considered three major mid winter warming events and two non warming events. In all three major mid winter warming cases show the cooling in the lower stratosphere on the onset date of SSW is registered at high latitudes. The stratopause temperature suddenly increases over Gadanki (13.5°N, 79.2°E) during onset of SSW. Earlier Sivakumar et al. [2004] presented an
increase in stratopause temperature by 18 K with respect to the winter mean temperature profile derived from lidar data collected during March 1998 to July 2001. Because of the data gaps, they could identify the warming events two weeks after the onset of major warming event at high latitude. The present result reports the enhancement of stratopause temperature simultaneously with the warming event at high latitude lower stratosphere. Mukherjee et al. [1990a] has studied the sudden stratospheric warming effects in the low latitude region using rocket M-100 observations for two major mid winter warming and three minor warmings. They suggest that the commencement of high latitude stratospheric warming was concurrently accompanied by a simultaneous cooling in the stratosphere and the warming in the mesosphere over low latitude concurrently in association with the high latitude stratospheric warmings. Their concepts is in confirm with the results of theoretical work that high latitude stratospheric warming is associated with the mesospheric cooling which in turn is associated with the mesospheric warming at low latitudes. The increasing temperature is not sufficient to explain as that observed during the events [Sivakumar et al. 2001]. In addition gravity wave activity has shown the wave activity to be maximum during winter for high latitudes and during equinoctial periods for low latitudes [Fritts, 1984]

Mukherjee, et al. [1990b] have studied the effects of minor warming events during 1985-86 using rocket M-100 experiments conducted under Indo-Soviet collaborative program. The rocket observations were from Thumba (8.5°N, 76.9°E) and Balasore (21.5°N, 86.9°E) in the Indian region and Heiss Island (81°N, 53°E) and Volgograd (49°N, 44°E) in the Russian region. They have observed two minor warming during mid January and mid February in the winter of 1985-86. During mid January warming were observed in the stratosphere both at Heiss Island
and Volgograd, which were concurrently associated with cooling over Thumba. There is no significant change observed over Thumba during mid February event. This effect clearly demonstrates a strong latitudinal coupling of the thermodynamic processes in the upper stratosphere during major stratospheric warming event. An association between high latitude stratosphere warming and the tropical and even equatorial summer hemisphere cooling was revealed by the Nimbus III satellite data [Fritz and Soules, 1970]. The out of phase relationship in the stratosphere temperature at high and low latitudes was evident only in the radiances when averaged around latitude circles.

The TIMED/ SABER mesosphere temperature shows abrupt increase of 15 K in the height region of 70-75 km over low latitude region which is prior to the onset of SSW event occurred in the high latitude. Upper mesosphere (above 80 km) showed that there is a strong cooling accompanying the SSW, which was also observed in the high latitude mesosphere. As was first described by Matsuno [1971] and further elaborated on and described by Liu and Roble [2002], the key mechanism for the generation of SSW is the growth of upward propagating planetary waves from the troposphere and the interaction between the transient wave and the mean flow. Matsuno’s [1971] model also showed that mesospheric cooling accompanying the SSW, which was also experimentally observed. The interaction decelerates and/or reverses the westerly winter stratospheric jet and induces a downward circulation in the stratosphere and upward circulation in the mesosphere, which in turn leads to adiabatic warming/cooling in the stratosphere and mesosphere respectively.
The mesospheric warming may be due to planetary wave activity which may be another
dynamical source for this warming. Earlier observation and model studies were focused on the
wave propagation and changes in the thermal structure in the high latitude winter stratosphere
during SSW events. *Lindzen* [1981] anticipated that during SSW events, when westward winds
may develop in the stratosphere, the upward propagation of quasi stationary gravity waves would
be inhibited. *Whiteway and Carswell* [1994] noted cool mesosphere in their high-latitude
Rayleigh lidar observations and substantially greater dissipation of gravity wave energy within
the upper stratospheric warming in comparison with preceding and following periods. They
suggested referring to earlier model results of *Lindzen* [1981] *Holton* [1983] and *Dunkerton and
Butchart* [1984] that the inhibition of upward propagation of gravity waves leading to a cooling
toward radiative equilibrium in the mesosphere.

Air glow observations also show changes in the thermal structure at mesospheric altitudes
in relation to the SSW events. *Walterscheid* et al. [2000] observed mesospheric cooling over
Eureka, at high latitude (80°N) site in Canada. Their comparative model simulation indicated
alternating regions of cooling and warming above the main warming in the lower stratosphere.
The low latitude observations also show alternate cooling and warming regions. Recently,
*Vineeth et al. [2009]* noted amplified wave signatures of 16-day period, during the course of an
SSW event, in the daytime multi wavelength dayglow photometer measurements of the OH (8-3)
airglow intensity of rotational lines at 731.6 and 740.2 nm over Trivandrum (8.5°N, 76.5°E).
They proposed that during SSW year, the westward propagating waves, including the quasi-16
day wave could propagate upward through the prevailing eastward lower stratospheric
circulation and get dissipated over the MLT region. There is always a heating tendency at higher
latitudes and cooling at lower, as a result of flux divergence. Thus, the low latitude warming cannot be a direct result of planetary wave enhancement. The poleward heating effects force zonal mean in an upward motion at higher latitudes and downward motion at lower latitudes. The forced vertical motions diminish above the critical level because the heat transport vanishes there. Then there must be flow from higher to lower latitudes near the critical level for the continuity of mass flux.

The TIMED/SABER temperature at 5-15°N is used to investigate the PW activities in the stratosphere and mesosphere during four winter periods are considered (2004-05, 2005-06, 2006-07 and 2008-2009) when there are two major SSW warming occurred and the other two are normal winter years. The present analysis found in both the cases (2005-06 and 2008-09), the PW wave is enhanced in the mesosphere heights several days before the onset of SSW events and is considerably reduced when the warming event is onset. The other two winters (2004-05 and 2006-07) shows the increased planetary wave activity whereas no midwinter major warming during the course of the events. Similarly in the stratosphere also the planetary wave activity was reduced during warming periods and increased activity during the non warming winter years. A detailed of observations of this planetary wave forcing in the stratosphere and mesosphere are demonstrated in the following sections.