Chapter 6

Summary and Scope for Future Work

6.1 Summary and Conclusions

The major objectives of this thesis were to investigate various interactions of the Earth's upper atmosphere using ground- and satellite-based observations to understand the scientific objective that were set in Chapter 1. These goals were accomplished by studying the waves and oscillations present in the MLT region, solar and atmospheric influences in the MLT region, wave dynamical coupling of atmospheres, mesospheric wave dynamics during cyclones, mesospheric temperature inversion and their possible causes, and latitudinal coupling of the atmosphere during SSW events. Nightglow emission intensities at multiple wavelengths, which emanate from different altitudes of the Earth's upper atmosphere and OH and O_2 derived mesospheric temperatures along with some supplementary data have been used to address the scientific objectives used in this thesis.

As discussed in Chapter 1, the Earths atmosphere is capable of sustaining various timescales atmospheric waves. These atmospheric waves are generated through disturbances in the lower atmosphere e.g., convection, orography, or thunderstorm and while propagating upwards to the upper atmosphere they carry energy with them. They mostly break in the MLT region, deposit their momentum, which causes changes in the winds and temperatures that can induce large-scale circulations at those altitudes. Measurement of airglow emission intensities is an important tool to understand the dynamical process in the Earths atmosphere since they respond to the density of the reactants involved in the photochemical processes which in turn is affected by these atmospheric waves. In addition to these waves, the Earths upper atmosphere is also influenced by the incoming solar radiation. In this thesis, the effect of these two forcing on the upper atmosphere, in general, and MLT region, in particular has been studied under varying geophysical conditions. This Chapter summarizes the main findings of the present thesis work that has been achieved using ground- and satellite-based observations.

The present work has added new long-term and high cadence measurements on the multi-wavelength nightglow emission intensities and temperatures using in-house built spectrograph (NIRIS) and photometer (CMAP). NIRIS provides spectral images of OH(6-2) Meinel and O_2 atmospheric bands simultaneously, from which nocturnal variation in nightglow emission intensities and temperatures corresponding to 87 and 94 km altitudes are derived. CMAP provides nocturnal variation of nightglow emission intensities of Na (589.0 and 589.6 nm), OI 557.7 nm, and OI 630.0 nm emission emanating from peak altitudes of about 92, 100, and 250 km. The details of NIRIS and CMAP and procedure for retrieval of nightglow emission intensities and temperatures are described in Chapter 2. In addition to these ground-based measurements, mesospheric temperatures from SABER, SOFIE, and OSIRIS, OLR from Kalpana-1, and stratospheric temperatures and winds from MERRA have been used in this study.

The important findings that have emerged based on the scientific objectives set in Chapter 1 (section 1.11) is summarized below:

6.1.1 Atmospheric Waves and Coupling in the Earths Upper Atmosphere

The results dealing with the vertical coupling of the atmospheres are discussed in Chapter 3 and Chapter 4. Some of the main results that emerged from these studies are:

1. In Chapter 3, we have seen that OH(6-2) and O_2(0-1) band intensities and corresponding temperatures shows presence of short-timescale (of gravity wave regime) variations. These GW periodicities have been obtained from the nocturnal variations of these parameters for all the individual nights for three years (2013-2015) of NIRIS observations from Gurushikhar, Mount Abu. There are total of 437 nights of observation from which GW periods ranging from 10 min to 3 hours are obtained. These periods showed significantly different behaviour in intensities and temperatures. In intensities it has been observed that GWs show the presence of the 2 h and 15 to 20 min of periodicities in over 23% and 10% of nights, respectively. However, temperatures show 2 h and 20 to 60 min periodicities for over 18% and 12% of nights, and do not show significant number of periodicities smaller than 15 min. These GW periodicities neither show any seasonal dependence nor any solar activity dependence in their occurrence rate or in the time periods [*Singh and Pallamraju* (2017b)].

2. In Chapter 4, we have addressed the question related to the vertical coupling of the atmosphere during cyclone Nilofar which developed in the Arabian sea during 25–31 October 2014. In this study, data obtained from NIRIS, CMAP, and Kalpana-1 satellite have been used. Using these multiple data sets obtained for 26 October 2014, not only was it demonstrated that the Earths atmosphere is coupled through gravity waves that were generated due to the cyclone Nilofar but also different

gravity wave parameters that can be present during cyclonic storms (τ, c_h, λ_h, c_z, λ_z, and θ_v) were derived [*Singh and Pallamraju* (2016)].

6.1.2 Solar Influences in the MLT Nightglow Emissions and Temperatures

From the production mechanisms that give rise to the O_2 and OH band emissions in the mesosphere (Chapter 1) it was reported that the O_2 and OH nightglow emission intensities are related to the concentrations of atomic oxygen and ozone and hence, to the ultra-violet (UV) solar energy input that is responsible for their photochemical production. Therefore, these emissions are expected to show variations with the UV solar energy input and hence, with solar activity. From the NIRIS derived nightglow emission intensities and temperatures from over three years (2013-2015) of observations we have seen presence of waves and oscillations of both the origins i.e., atmospheric and solar. Spectral analyses of these O_2 and OH intensities and the corresponding temperatures showed statistically significant periodicities of around 150, 195, 270, and 420 days. The solar variations in this duration (F10.7 cm solar flux and SSN) also displayed some of the periodicities (150, 190, 245, 380, and 410 days) that are present in atmospheric oscillations as well thereby revealing a clear evidence of influence of solar activity on the mesospheric airglow emissions and temperatures. In addition to these common periods, the O_2 and OH intensities also showed periods around 84, 95, and 122 days which are due to the seasonal variations [*Singh and Pallamraju* (2017b)].

6.1.3 Mesospheric Temperature Inversions and their Possible Sources

NIRIS observations of around one year (2013) show that, in general, T(O_2) is lower than T(OH) which is the synoptic behaviour of Earth's atmospheric mesospheric temperature structure. However, it was also observed that there are several occasions when $T(O_2)$ is greater than T(OH) indicating the formation of mesospheric temperature inversion layers. Based on the statistical study, some preliminary results were discussed in Chapter 4, which indicate that such formation of MTIs could be more probable due to chemical heating in the mesosphere [*Singh and Pallamraju* (2017a)].

6.1.4 Global Mesospheric Temperatures During SSW Events

In Chapter 5, we have shown how mesospheric temperatures varies latitudinally during SSW events. NIRIS derived mesospheric temperatures from Gurushikhar showed enhanced temperatures (compared to their monthly mean values) during the SSW event of January 2013. This led to a wider investigation to understand mesospheric temperature changes over various latitudes and to characterize the behaviour of mesospheric temperature variation as a function of geographic latitude during SSW periods with respect to the stratospheric (at 10 hPa pressure level) temperatures over high-latitude (60^o–90^oN). In this work, SABER, SOFIE, and OSIRIS derived mesospheric temperatures have been considered. Detailed analyses revealed that there exists mesospheric heating over tropical- to mid- latitudes, more so in the NH, during major SSW events. All the major SSW events studied showed well-known mesospheric cooling over NH high-latitudes. Closer to the equatorial-latitudes the mesospheric heating turns into cooling and again turns to heating over mid-latitudes in the SH before turning to cooling over the SH high-latitude regions. The "double-humped" structure in the mesospheric to stratospheric temperature ratios ($\Delta T_M/\Delta T_S$) vs latitude is very clear during major SSW events with two crests over tropical- to mid-latitudes and a trough over the geographic equator. Mesospheric temperatures during minor events do not show formation of such "double-humped" structure. It is also found that the CIRA-86 derived mesospheric temperatures overestimate the values in the NH and underestimate them in the SH as compared to the SABER measured temperatures, which is more prominent at the higher latitudes. These results strongly support the existence of stratospheric-mesospheric coupling and high- to low-latitude coupling of mesosphere lower thermosphere region, especially during SSW events [*Singh and Pallamraju* (2015)].

6.1.5 Techniques to Measure MLT Nightglow Emission Intensities and Temperatures

1. **NIRIS:** In order to derive nocturnal variations in nightglow emission intensities and corresponding temperatures representing the emission altitudes of 87 and 94 km, spectrographic technique is used. Using this technique a grating spectrograph called NIRIS, Near InfraRed Imaging Spectrograph, is developed which uses 1200 lines mm^{-1} grating as the dispersing element, a 1024×1024 pixels thermoelectrically cooled CCD camera and has a large field-of-view (FOV) of 80^{o} along the slit orientation [*Singh and Pallamraju* (2017a)]. The details of NIRIS are given in Chapter 2. Most of the results obtained in this thesis work have been obtained using data obtained from NIRIS that has been operating since 2013 in an automated mode from PRL's optical aeronomy observatory at Gurushikhar, Mount Abu.

2. **CMAP:** A CCD-based Multi-wavelength Airglow Photometer (CMAP) is developed in-house to study the nightglow emission intensities which emanate from mesosphere lower thermosphere (MLT) region of the Earth's upper atmosphere. In contrast to NIRIS, CMAP works on the photometric technique, which uses narrow bandwidth interference filters having full width at half maxima of 0.3 nm and these are mounted in a temperature stabilized filter wheel. The temperature controlled filter wheel can house five filters at a time enabling near-simultaneous measurements at five different airglow emissions. A Software is developed in-house to control

various operations of CMAP such as, CCD and filter wheel operations in a pre-defined mode, filter wheel temperature monitoring, which is programmed in such a way to provide CCD images in FITS format [*Phadke et al.* (2014)]. The details of CMAP which deals with the optical design, fabrication of different components, and derivation of nightglow emission intensities from CMAP is discussed in Chapter 2.

6.2 Scope for Future Work

This work provided significant contribution in the understanding of the vertical and latitudinal couplings in the MLT region under varying atmospheric conditions. The results presented in this thesis have underlined some promising areas especially those related to the MLT region and raised the numerous issues for further investigations. This opens up further scope for interesting scientific and technical studies some of them are ongoing and some can be followed in the future.

1. Understanding the mesospheric temperature inversions and their possible causes is very important in order to comprehensively model the atmospheric dynamics. From the existing NIRIS data, work is ongoing to understand these aspects.

2. We have described in Chapter 2 that how by making use of large FOV information of NIRIS the meridional scale sizes are derived. Similar method can be adopted to derive the zonal scale sizes by orienting NIRIS in the east-west direction. From the existing data, studies are ongoing to understand the observed variations in the scale sizes at two altitudes and to understand their behaviour in different seasons and solar activity levels.

3. The characteristics of vertical wave propagation during strong convective storms has been presented in this thesis. However, the vertical propa-

gation characteristics of waves during normal conditions is still not well known experimentally. These kind of continuous observations with good temporal and spatial resolution as presented in this thesis will help to address these scientific issues.

4. A detailed investigation of tidal and planetary waves in the MLT region is being studied, which will enhance our understanding of the coupling processes in those time scales.

5. NIRIS provides simultaneous measurement of nightglow emission intensities and temperatures using OH(6-2) Meinel and O_2(0–1) atmospheric band spectra. The brightest emission of OH nightglow occurring in between 1.4 μm to 1.8 μm which includes OH(2-0), OH(3-1), and OH(4-2) vibrational rotational transitions. Historically the observation of these brighter emissions are sparse and more difficult since they require the use of InGaAs potodiode arrays. However, with the commercially available InGaAs arrays now it is becoming possible to make instruments which can provide observation of these vibrational bands with required resolution and efficiency. We are in the process to develop such an instrument which will provide OH(3-1) rotational line spectra to derive nightglow emission intensities and temperatures. The OH(3-1) band is around 70 times brighter than the OH(6-2) band and is less affected by the water vapour absorption. Also at these longer wavelengths as the scattering is less in comparison to near infrared with such an instrument it should also be possible to obtain data during even full-moon nights (when the moon is not directly in the instruments FOV).

6. Since OH rotational temperatures can be derived using different methods. Different simulation exercises are planned to assess the differences between various methods of mesospheric temperature determination.

7. Although the mesospheric emission intensities show a clear solar activity

dependence, the effect of solar activity on to the mesospheric temperatures are ambiguous on short time scales. This needs further investigation with respect to the wave amplitudes versus viscous drag effects that may prevent its presence in temperatures.

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