SUMMARY AND FUTURE PROJECTIONS

7.1 Summary

In the vertical coupling of the Earth’s atmosphere, the role being played by the gravity waves is unanimously concurred by both theoretical, modeling and observational studies. Wind perturbations associated with atmospheric gravity waves dominate the observational variability, and the momentum transported by these waves shapes the observed pattern of the mean zonal wind. Thus, understanding gravity wave sources and their generation mechanisms is crucial in successfully modeling the general circulation of the atmosphere. Thus the study of gravity wave parameters and their possible effects in the dynamics and energetics of the middle atmospheric region is an important subject of current atmospheric research. The major emphasis of the present thesis is to study the propagation characteristics of gravity waves, their seasonal variation and the processes through which they dynamically couple equatorial middle atmosphere. To address the above issues, five year long national program namely MIDAS (2002-2007) was conducted. The wind and temperature data collected in the middle and upper atmospheric region collected under this program was used for the present study. The major results of the present work is summarized as follows

The present thesis work brought out the characteristic features of prominent periodicities of gravity waves and their seasonal variability using temperature measurements (25-60 km) in the middle atmospheric region for more than 2 years using Rayleigh lidar at Gadanki (13.5°N, 79.2°E). Gravity waves of periods in the range 2-4 hour and 0.5-1 hour were found to be prominently present throughout the observational period and showed different propagation characteristics in the stratospheric and mesospheric regions. The vertical wavelength of 2-4 hr periodicities were found to be in the range 5-12 km and that of 0.5-1 hour was found to be in the range 10-15 km. Month to month variation of the gravity wave activity showed equinoctial maximum and
solstitial minimum. The monthly variations in gravity wave activity were attributed to variations in the strength of sources viz., convection and wind shear in the tropospheric region, which are characterized using collocated MST radar measurements. In the case of shorter period gravity waves, strength of wave activity was well correlated with vertical winds in the lower tropospheric region, which is a measure of strength of convection. For gravity waves with longer periods, wave activity was found to be well correlated with horizontal wind shear in the upper tropospheric/lower stratospheric region. The observed mismatch between the wave activity and source strength on some occasions could be due to contributions from sources away from observational site. The results included in this study assume their importance, as there are not many persistent ground-based observations of gravity waves in the tropical middle atmosphere.

Using more than 52 months of Rayleigh lidar temperature observations (1998-2005) over a tropical station, momentum fluxes of gravity waves of prominent periods (0.5 –1 hour and 2-4 hour bands) were estimated in the middle atmospheric region. The method used in the present study could estimate the momentum fluxes of dominant periods of gravity waves from the temperature fluctuations with high temporal resolution, without measuring vertical velocities. The present method assumes its importance as earlier studies of momentum flux estimates applied the same technique to a single profile of horizontal winds and temperature from radiosonde observations without knowing a dominant wave frequency. The seasonal variations in these prominent periods of gravity wave momentum fluxes exhibited semi annual variation with maximum around equinoxes and minimum around solstitial months, which is the first observational result of its kind over this tropical latitude.

The characteristics of the Quasi - Biennial Oscillation (QBO) and its month-to-month acceleration was studied using monthly mean zonal winds from NCEP/NCAR reanalysis data at two pressure levels 10 and 20 hPa. The observed mean flow acceleration was compared with that estimated from the momentum flux divergence of gravity waves, which led to a better insight into the role of gravity waves in driving the QBO through wave-mean flow interactions. The present analysis revealed that the contribution of gravity waves towards the westerly phase of QBO varies from ~10-60%
while that during easterly phase from $\sim$10-30%. Thus the present study is first of its kind over this tropical latitude to quantify the gravity wave forcing towards driving the westerly and easterly phases of QBO.

The present work also quantified the role of gravity waves in driving the tropical Stratospheric Semiannual Oscillation (SSAO). The Rayleigh lidar observations of middle atmospheric temperature over Gadanki were used to estimate the momentum fluxes of prominent periods of gravity waves (0.5–1 hour and 2-4 hour bands) and its momentum flux divergence. Simultaneous wind measurements using rocketsondes over Trivandrum ($8.7^\circ$N, $77.8^\circ$E) were extensively used to study the background wind and the mean flow acceleration in the 30-60 km altitude region. The mean flow acceleration estimated from the divergence of momentum flux of gravity waves was compared with the mean flow acceleration observed using rocket measured zonal winds during three different cycles of SSAO. The behavior of the mean flow acceleration calculated from two different means of measurements (temperature and wind) was in good agreement, which further gives the assurance to the credibility of the various probing techniques of the atmosphere. It was also seen that the gravity wave forcing towards the mean flow acceleration varied significantly from cycle to cycle, which is attributed to the seasonal variations in the strength of gravity wave sources. From the present work, it was noticed that on an average $\sim$30-60% of the forcing to drive the westerly phase and $\sim$50-80% towards the easterly phase of SSAO was contributed by the gravity waves.

The gravity wave momentum fluxes in the Mesosphere Lower Thermosphere (MLT) region were estimated using wind measurements from meteor radar observations over Trivandrum during June 2004-May 2007 using a novel method. The radial velocity variances in the 82-98 km height region, which are mainly caused by gravity waves, measured by the meteor radar are used to determine the gravity wave momentum fluxes. Seasonal variation in the momentum fluxes of short period (less than 2-3 hours) gravity waves showed semiannual variation with equinoctial maximum and solstitial minimum. By using estimated gravity wave momentum fluxes, the contribution of gravity waves in driving the Mesospheric Semi Annual Oscillation (MSAO) is quantified. The mean flow acceleration estimated from the divergence of gravity wave
momentum fluxes was compared with the observed mean flow acceleration computed from monthly mean zonal winds during six MSAO cycles over three years. This comparison revealed that the gravity wave contribution towards the westerly phase of MSAO varies from ~20-60% while that towards the easterly phase varied from ~30-70%. Variations are observed from cycle-to-cycle in the gravity wave forcing towards both phases of MSAO. The significance of the present study lies in estimating the gravity wave momentum fluxes in the MLT region and quantifying their contribution towards the generation of MSAO over the low-latitude for the first time. The present observations gave an excellent opportunity to understand the role of gravity wave forcing in controlling the dynamics of the MLT region.

The significance of the results from above studies lies in quantifying the gravity wave-mean flow interaction during both easterly and westerly phases of QBO, SSAO and MSAO for the first time over this tropical latitude. The complete knowledge of the role of gravity waves in the generation of these longer period oscillations can serve as an important input to the GCMs, which still lacks in quantifying them.

### 7.2 Future Projections

Studies on coupling of different regions of the Earth's atmosphere through wave activities have got momentum in the recent years. In particular gravity waves play a profound role in coupling different regions of the atmosphere. The results presented in this thesis stand as a testimony for such coupling processes. However, at present, there is an incomplete understanding of spatial and temporal variability of dominant gravity wave sources, their phase speeds, and momentum fluxes, as functions of meteorological conditions.

One of the major results reported in the thesis is the seasonal variation of the gravity wave activity in the middle atmospheric region. However, the climatology of the gravity wave activity (such as its energy and momentum fluxes) and gravity wave characteristics are necessary to understand and parameterize these waves in the general circulation models. Long term observations of temperature/wind data in the middle atmospheric region gleaned out using Rayleigh lidar and MST radar over Gadanki would
be helpful in delineating the climatology of the gravity wave activity and wave characteristics such as amplitude, phase speeds and vertical wavelengths in the tropospheric and stratospheric regions.

Apart from this, global measurements from satellites provide vast amount of high resolution data which would be helpful in understanding the three dimensional picture like intensity, seasonal and geographical variations of tropospheric sources of gravity waves, a clear picture of seasonal variation of wave activity and the corresponding sources that excite these waves. These experiments offer an excellent opportunity for gravity wave studies and observation-model comparisons that can resolve issues in the current understanding on stratospheric and mesospheric processes.

Much of the current theoretical focus is on understanding the nature of the vertical wave number spectrum of gravity waves. Observations of horizontal wind fluctuations have generally indicated that the spectra have a similar form regardless of location and atmospheric conditions. A number of different theories have been developed to explain these observations and thus predict essentially the same vertical wave number spectrum, independent of the varying background atmospheric conditions. The last two decades also saw the development of several classes of saturation theories and a number of attempts to distinguish the most relevant dynamics. However, deciding which theories are most realistic has proven difficult, because all yield estimates of spectral amplitude and shape that are arguably consistent with the various measurements available. Long term observations of middle atmospheric temperature data over Gadanki and temperature data from Sounding of the Atmosphere using Broadband Emission Spectrometry (SABER) on board Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite could be used to divulge the climatology of vertical wave number spectra of gravity waves and to validate the saturation theories over the equatorial/low latitude.

Wave-Mean flow interaction and wave-wave interaction are the two major processes through which the gravity waves couple different regions of the atmosphere. Of these, major findings of the present work illustrated the myriad effects of the gravity wave-mean flow interaction. There lies an excellent opportunity to
investigate the interaction of gravity waves with other low frequency variabilities such as tides and planetary waves in the MLT region. Nonlinear interactions among planetary waves, tides, and gravity waves are believed to be responsible for the short term variabilities in the MLT region. However, there are limited observations across the globe on wave-wave interaction in the MLT region to arrive at any general conclusion especially, over low-latitudes. Information on gravity wave momentum fluxes in the MLT region is a crucial parameter to understand the non linear interaction of these waves with tides and planetary waves. Thus the gravity wave momentum fluxes estimated in the present work would be useful in providing a deeper insight into the wave- wave interaction in the MLT region.

The equatorial upper atmosphere is replete with various long term and shorter term phenomena such as Equatorial Electrojet (EEJ), Counter ElectroJet (CEJ) and Equatorial Spread F (ESF). Vertically propagating gravity waves is believed to be one of the causative mechanisms of the aforementioned phenomena. Nevertheless the role of these waves in the generation of these processes is yet to be fully understood. The possible effects may be large because of the significant mean fluxes at lower thermospheric altitudes, the propagation and filtering characteristics of gravity waves. Despite the current qualitative understanding of gravity wave forcing in the lower and middle atmosphere, virtually nothing of its role at thermospheric altitudes is known. As of now, observations and modeling studies that characterize and quantify the gravity wave source characteristics, phase speeds and the wave activity are of high priority, as this information would be helpful to quantify gravity wave influences at higher altitudes also.

In any field of science, there should be a constructive interaction among theory, models and observations. These interactions help to represent the particular process in more realistic manner in numerical models. In the past two decades considerable effort has been made to understand and parameterize gravity-wave drag (GWD) in both climate models and numerical prediction models. The results presented in the thesis in conjunction with climatology of the gravity wave characteristics would be helpful to represent these waves in the GCMs.