Studies on the Characteristics of Vertical Circulation and Equatorial Waves using Indian MST Radar

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in partial fulfilment of the requirement for the Degree of

DOCTOR OF PHILOSOPHY
in
ATMOSPHERIC SCIENCE

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JUNE 2000

to my beloved parents

CERTIFICATE

This is to certify that the thesis entitled ***'Studies on the Characteristics of Vertical Circulation and Equatorial Waves using Indian MST Radar'*** *is a bona fide record of the research work done by* ***Mr. V. H. Annes, M.Sc.***, *in the Department of Atmospheric Sciences, Cochin University of Science and Technology. He carried out the study reported in this thesis, independently under my supervision. I also certify that the subject matter of the thesis has not formed the basis for the award of any Degree or Diploma of any University or Institution.*

Certified that ***Mr. V. H. Annes*** *has passed the Ph.D. qualifying examination conducted by the Cochin University of Science and Technology in August, 1996.*

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Supervising Teacher

DECLARATION

I hereby declare that this thesis entitled ***'Studies on the Characteristics of Vertical Circulation and Equatorial Waves using Indian MST Radar'*** is a genuine record of research work carried out by me and no part of this thesis has been submitted to any University or Institution for the award of any Degree or Diploma.

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Preface

The dynamical processes in tropics are quite distinct from those at middle and high latitudes. An understanding of the characteristics of tropical waves and the vertical circulation are, therefore, important as they are playing a prominent role in the general circulation of the tropical lower and middle atmosphere. The aim of the present study is to understand the characteristics and properties of different wave modes and the vertical circulation pattern in the troposphere and lower stratosphere over Indian region using data obtained from the Indian Mesosphere-Stratosphere-Troposphere (MST) radar, National Center for Environmental Prediction/National Centres of Atmospheric Research (NCEP/NCAR) reanalysed data and radiosonde observations.

The doctoral thesis consists of seven chapters. In Chapter 1, a general introduction on the topic of study, various atmospheric phenomena observed in the middle atmosphere, different techniques used in atmospheric probing including a brief account on Indian MST radar, and national and international scientific programs are included.

Based on published works in various scientific journals, books and reports a review on the literature is given in Chapter 2. Chapter 3 contains detailed description of the data and methodologies used in the thesis.

In Chapter 4, results obtained from the studies on the characteristics of various wave modes present over the tropics, using high resolution zonal (u), meridional (v) and vertical (w) velocity components from the Indian MST radar at Gadanki (13.5° N, 79.2° E) at different levels in the troposphere and lower stratosphere are presented. It is noted that during winter season various types of modes including equatorial Kelvin (10-day) and mid-latitude Rossby (15-day and 22-day) waves are present with an out-of-phase relationship between u and w in the case of 15-day and 22-day waves.

Studies on the vertical motion in monsoon Hadley circulation are carried out and the results are discussed in Chapter 5. From the analysis of MST radar data, an overall picture of vertical motion of air over Indian region is explained and noted that there exists sinking motion both during winter and summer. Besides, the study shows that there is an anomalous northerly wind in the troposphere over the southern peninsular region during southwest monsoon season.

The outcome of the study on intrusion of mid-latitude upper tropospheric trough and associated synoptic-scale vertical velocity over the tropical Indian latitudes are reported and discussed in Chapter 6. It shows that there is interaction between north Indian latitudes and tropical easterly region, when there is an eastward movement of Western Disturbance across the country. It explains the strengthening of westerlies and a change of winter westerlies into easterlies in the tropical troposphere and lower stratosphere. The divergence field computed over the MST radar station shows intensification in the downward motion in association with the synoptic systems of the northwest Indian region.

In Chapter 7, a summary and conclusion of the research work carried out in the present thesis work is presented. References mentioned in the texts are listed at the end of the thesis in alphabetical order.

Chapter 1

Introduction

1.1 Relevance of the topic

Solar radiation controls the entire structure and the energetics of the earth's atmosphere and has a dominant influence on the chemical and dynamical processes taking place in it. The middle and lower atmosphere are linked dynamically, radiatively and chemically. While dynamical processes in the atmosphere are generally considered as being driven by thermal process, waves can also be a means of transport of energy, momentum and trace constituents in the atmosphere. The large differences in the levels of energy absorbed in different regions of the atmosphere makes transport of energy from one region to another. Significant part of the transport takes place through waves and hence coupling processes have become important subjects of study.

It has been known for many years that large-scale equatorial waves propagate vertically and zonally through the middle atmosphere. These wave modes are capable of changing the mean flow through wave-mean flow interaction processes. The interaction process of the equatorial waves with the mean flow is through wave dissipation. During the process, the waves transport momentum from the tropospheric source region into the middle atmosphere. The most significant features of the equatorial middle atmosphere are the quasi-biennial oscillation (QBO) and the semi-annual oscillation (SAO) produced by these waves. Clearly, a systematic programme of observations in tropics are required to measure the eddy fluxes due to the equatorial wave modes and then to determine the validity of the models for the QBO and SAO. The Indian MST Radar can perhaps meet the requirements of the database.

1.2 Justification of the study

The capability of MST Radars in measuring vertical velocity has great significance in realising many dynamical processes such as stratosphere-troposphere exchange, vertical transport of heat, momentum and energy by waves and so forth. It is the vertical velocity, which determines the weather over a particular area and hence play a decisive role in short and long-term weather forecasting. The couplings between different layers of the atmosphere are due to the manifestations of vertical velocity, which controls the transport of trace constituents. Besides, knowledge of the vertical motion is essential for a better understanding of the meridional circulation. Availability of vertical velocity in the Indian tropical region would be useful in evaluating the physical processes taking place during monsoon season. The unique feature of the tropical atmosphere involving the vertical circulation associated with the inter-tropical convergence zone (ITCZ) and the Hadley circulation may also be examined in addition to the circulation features associated with the monsoons of the Indian region.

The dynamical processes in the tropics are quite distinct from those at middle and high latitudes. It is now generally accepted that the Kelvin and Mixed Rossby-gravity (MRG) waves are the dominant wave modes which controls the dynamics of the middle atmosphere of the tropics. They are believed to be generated by cumulus convection which is active in the tropical atmosphere. Theoretical and modelling studies highlighted the important role played by Kelvin and MRG waves in generating the QBO observed in the equatorial lower stratosphere and SAO observed in the upper stratosphere and mesosphere (Holton and Lindzen, 1972; Holton, 1975; Mahlman and Umscheid, 1984; Plumb, 1982). Holton and Lindzen (1972) argued that QBO is an internal oscillation which results from the wave mean flow interaction that occur when vertically propagating MRG and Kelvin waves are radiatively or mechanically damped in the lower stratosphere. The descending easterly and westerly phase of the QBO are due to the momentum flux convergence as the Kelvin or MRG waves propagate into the shear zones.

Most of the studies using Indian MST Radar data were carried out on the basis of the assumption that the data is comparable with conventional radiosonde or rawinsonde observation. For this Madras (13.00° N, 80.18° E) radiosonde data and rawinsonde data from SHAR Centre (13.7° N, 80.2° E) were used and inter-comparisons have been made to validate the Indian MST Radar measurements (Jain, *et al.*, 1994; Kishore *et al.*, 1994). In the present study the radar data is compared with both radiosonde observations at Madras and the global National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysed data (Kalney *et al.*, 1996). Comparisons are made through studying the seasonal reversal of the Hadley circulation during winter and summer. A detailed analysis of various equatorial wave modes for different seasons from the MST Radar data have not yet been done despite some efforts by Iyer *et al.* (1994), Jivrajani *et al.* (1997) and Sasi *et al.* (1999). The Indian MST Radar should offer an excellent opportunity for the study of the dynamics of the tropical middle atmosphere by virtue of its unique location. The data being continuous with excellent altitude and time resolution should enable the delineation and detailed study of all the wave motions in the equatorial atmosphere having periods ranging from a few hours through tides, planetary scale waves and longer period SAO, annual oscillations (AO) and QBO and the products of the interactions among the waves and with mean flow.

1.3 Observational Techniques

Systematic observation of stratosphere commences from the International Geophysical year (IGY) of 1957-1958. Following IGY, knowledge regarding the temperature, wind and composition of the middle atmosphere has dramatically increased. The main goal of the lower atmospheric (troposphere and lower stratosphere) research is to understand the 3-dimensional structure of the atmosphere on different scales. The wind, temperature and relative humidity informations are necessary to provide satisfactory representation of the circulation, stability and moisture distribution of the atmosphere. Newly developed wind profilers has given novel insights into the behaviour of the atmosphere.

Observational techniques are of two types: remote sensing and *in situ* observations. Balloons, aircraft and rockets carry *in situ* sensors to obtain the wind, temperature, and humidity profiles in the different layers of the atmosphere. Remote sensors may be also aboard aircraft or satellite.

1.3.1 *In situ* or direct observations

(a) Radiosonde

To measure atmospheric parameters such as wind, temperature, humidity and pressure upto 30 km, radiosonde is generally used. The instrument is carried aloft by a hydrogen/helium filled balloon. The elevation and the azimuth angles are determined by tracking the balloon at the ground using a receiver. The elevation is obtained from the recorded pressure. Because the balloon's position is known at all times, its drift with the wind is used to measure the wind speed and direction. The signals are transmitted by different sensors, which are received by the receiver at the ground. The sensors are thermistors, hygristors and aneroids to measure temperature, humidity and pressure, respectively.

(b) Rawinsonde

The ascending balloon is carried along horizontally by the wind at its level and the tracking is usually carried out by means of radar so that a series of observations of its position enable to measure the average wind over the layers traversed between successive observations. The tracking depends upon the reflection of radio waves transmitted from the ground station for which a reflector made up of metal or metalised nylon mesh is suspended from the balloon. This method is not impeded by the presence of cloud or precipitation. Radar can be used to measure wind in addition to temperature and humidity using a balloon carrying both radar reflector and radiosonde apparatus.

(c) Meteorological Rockets

The meteorological rockets involve a rocketsonde that is lowered by parachute after the rocket reaches the altitude of 80-90 km range. Rocketsonde is capable to measure temperature and pressure and also wind by the measuring their horizontal drift. The drift of alkaline metal vapours that scatter sunlight at twilight can be used to measure winds in the upper atmosphere. Besides, cloud chaff dipoles ejected by rockets upto 80-90 km are also used to measure wind by tracking the chaff particles using radar.

Rocketsonde provides good vertical profiles of meteorological parameters like temperature in the mesosphere. Although large quantities of data are available, they are restricted mostly to land areas of the Northern Hemisphere. Rocket observations are useful to calibrate and verify satellite-derived data and to formulate the climatology of the middle atmosphere over certain regions of the globe. But the number of sounding is limited by the cost of the launch and the equipment.

1.3.2 Remote Sensing or Indirect Observations

Remote sensing techniques such as Sodar, Lidar, Radar and Satellites use quite similar sounding techniques. But the nature of the transmitted waves differs according to the instruments. In the case of Sodar it transmits acoustic waves into the atmosphere. Electromagnetic waves in various frequency ranges are used for other instruments.

(a) Lidar (Light Detection And Ranging)

Lidar techniques are widely used to study the structure and dynamics of the middle atmosphere. Lidar operate as optical frequency radars in which short, intense laser pulses are transmitted into the atmosphere and the back scattered signals are analysed to derive information about atmosphere using receivers. They use radiation in the form of visible or infra-red laser beams and detect scatterers. The laser properties, which makes lidars useful for the exploration of the atmosphere, are their possibility to emit short pulses which allows to perform remote sounding without disturbing the medium with high vertical resolution. Besides, the monochromaticity of laser emissions allows the use of very sharp spectral widths. By using a variety of scattering and absorbing processes it is possible to obtain a great deal of information about the atmosphere, its constituents and their changes in both time and space. According to the process to be used the back scattering occur at the same wavelength (Rayleigh and Mie scattering) or at a different wavelengths (Raman fluorescence).

(i) Doppler Lidar

The coherent Doppler lidar operates at optical and infrared wavelengths, from 0.3 to 100μ. At these wavelengths, the scatters are mainly particles, which move with background wind. The Rayleigh scattering applies to spherical particles with diameters smaller than a wavelength. When the concentrations are very large, the aerosols scatter and attenuate the signal. The coherent lidar is limited to boundary layer research. But stratospheric aerosols from mount Pinatubo's eruption enhanced the back-scattered signal considerably and permit measurements into the lower stratosphere (Ralph and Neiman, 1997).

The coherent Doppler lidar uses different scanning mode with one or two lidars (Rothermel *et al.*, 1985). Their horizontal ranges varies from 10-20 km. Coherent Doppler lidar observations are very useful in boundary layer projects that do not involve clouds or precipitating weather systems. The susceptibility of the lidar beam to attenuation by water vapour and thick clouds remains a serious disadvantage.

Besides the coherent Doppler lidar, the incoherent Doppler lidar at 532 nm permits to obtain the vertical profile of the horizontal wind from 10 to 40 km. It works in a fixed direction and uses high resolution spectroscopy (Chanin *et al.*, 1989; Gonzalez *et al.*, 1994)

(ii) Rayleigh Lidar

Rayleigh lidars operate to receive only Rayleigh scattering (i.e., at altitudes greater than 30 km). It provides the vertical density and temperature distribution of the atmosphere. The scattering of the laser beam is due to the presence of air molecules irrespective of their nature and occurs at every altitude. The possibility to derive a density (and then temperature) measurement by Rayleigh Lidar is limited near the lower altitudes due to the presence of aerosols. Rayleigh lidar offers a powerful ground based method to measure temperature profile in the altitude region between 30 and 80 km with adequate height and time resolution to study atmospheric dynamics.

(iii) Mie Lidar

To obtain the number density information of aerosols Mie scattering is the sole method. The intensity of the scattering varies inversely as the fourth power of the probing wavelength in the case of Rayleigh scattering (whereas in Mie scattering, the dependence is less stronger) which is based on the size of the scatterers (aerosols).

(iv) Raman Lidar

Raman scattering results from the excitation of the vibrational or rotational transitions of molecules. This process involves the exchange of energy between the incident photons and the scattering constituents, resulting in a frequency shift between the incident and the scattered photons. This method has been successfully used to obtain temperature profile from N_2 and O_2 densities. In the first few kilometres of the atmosphere, it is used for measuring the water vapour contents. Raman lidar does not require a tuneable laser is one of its advantages.

(b) Meteorological satellites

Major advantages have been realised in atmospheric studies with the advent of satellites. Satellites are classified into two, namely, polar orbiting and geo-stationary satellites. Polar orbiting satellites orbit around the poles, while geo-stationary satellites remain fixed over a spot on the equator.

Satellite's data, representing an average over a given horizontal distance and vertical depth, requires some smoothing is a disadvantage. In terms of resolution satellite data have relatively low resolution in horizontal and vertical directions. The advantage of satellites over other observing techniques is that they can monitor atmospheric conditions worldwide in a spatially continuous manner. The following are some important advantages that satellites have over other conventional observational techniques.

(a) Satellites provide spatially continuous data, contrasting strongly with those obtained from network of stations.

(b) Some satellites are capable of giving higher temporal frequency of observations than conventional systems.

(c) *Certain parameters like radiation are affected by in situ measurements which does not occur in satellite measurements.*

(d) *Satellites can investigate the distribution of selected elements more homogeneously than in situ observing networks, which utilise different packages of instruments.*

(e) *Satellite systems can provide a complete global coverage of data.*

(f) *The satellite data facilitates a global viewing of the atmosphere on almost real time basis. These unique advantages have given rise to a phenomenal growth in satellite technology as applied to atmospheric studies over conventional systems.*

The Upper Atmosphere Research Satellite (UARS) launched on September 12, 1991 is carrying out the first systematic comprehensive study of the earth's stratosphere and mesosphere. It can take measurements to 80° latitude north and south covering over 98 % of the earth's surface.

(c) Radars

The acronym RADAR stands for Radio Detection And Ranging. Radar systems have been designed and are in use for a very broad spectrum of applications. One of the major applications of the Radar system is in the atmospheric research, because of their simplicity, reliability and virtue of the fact a radar system provides a means of sampling the atmosphere at a rapid rate in a cost effective way. The Radar techniques make use of the fundamental properties of an electromagnetic (radio) wave. They are frequency, phase, amplitude and polarisation. Atmospheric radars derive information on the dynamical atmospheric phenomena by making use of the variations on the above four parameters of radio waves which are transmitted from the radar system, backscattered by the atmosphere and received by the radar system again. The tracer elements for the study of atmospheric dynamics using microwave radar are the hydrometeors (rain, snow, hail, etc.) and have the wavelength of a few centimetres.

(i) Meteor wind radar

The 80-110 km altitude region of the atmosphere (meteor region) is not accessible for study using balloon and meteorological rockets. *In situ* measurements in this region using satellites also are not possible, because the atmospheric density at these levels is large enough so that satellites with orbits at these heights can not sustain for long periods. The meteor wind radar is the only means of measuring winds in the upper mesosphere and the lower thermosphere. It provides data on more or less a continuous basis for detailed studies, and understanding of the dynamics of the above region on temporal scales extending from a few hours to several days and months.

The meteor trails in the meteor zone are good targets for very high frequency (VHF) radars and strong echoes are obtained when the radar beam is perpendicular to the trail axis. Significant number of meteor trails that can be observed by VHF radars are formed over the altitude range of 75-110 km and maximum number of meteor trails are observed at around 95 km altitude. The radial velocity of the meteor trail can be measured using the rate of change of phase of the echo pulses by phase coherent detection with the transmitted frequency as reference. The phase coherent radar systems that are developed for meteor observation are basically of two forms: the bistatic continuous wave (CW) and the monostatic pulsed radar.

A state of the art sophisticated meteor wind radar system was developed in Space Physics Laboratory (SPL), VSSC, Thiruvananthapuram, India, in 1984. It is a coherent detection type of radar operating at a frequency of 54.95 MHz with height resolution of ± 2 km. Another meteor wind radar is established in Waltair, Andhra Pradesh.

(ii) Doppler Radar

A new generation of pulse Doppler radar systems has emerged which are probing the atmosphere and studying the dynamics of the atmosphere using the back scattered signals from clear air turbulence (CAT). The tracer elements for such radar system are the variations in the atmospheric refractive index. Such radars have come to be known popularly as MST, the ST and the T radars depending on the height coverage of the radar corresponding to the three regions of the atmosphere viz. Mesosphere, Stratosphere and Troposphere. Because of the scale sizes of the refractive index variations, these radars operate at wavelengths of the order of a fraction of a meter to a few meters.

Pulse Doppler radar operates in a coherent mode. Coherent mode of operations means that the transmitted frequency and therefore the received frequency are having a common phase reference which is in general a very stable oscillator known as *stalo* (stabilised local oscillator).

Fig. 1.1 depicts a simplified block diagram of pulse coherent Doppler radar. Using pulse Doppler radar measurements of the target, radial velocity as well as the target range and target amplitude fluctuations can be made. In this context of atmospheric radars, the targets being either hydrometeors or packets of refractive index variations.

(iii) MST Radar

A major advance has been made in the radar probing of the atmosphere with the realisation in early seventies by Woodman and Guillen (1974) that it is possible to explore atmospheric dynamics upto a height of about 100 km by means of a high power VHF backscatter radar. It led to the concepts of MST (Mesosphere-Stratosphere-Troposphere) radar and this class of radars have come to dominate the atmospheric radar scene over the past two decades. Fig. 1.2 shows a global distribution of such radars including medium frequency (MF), meteor and

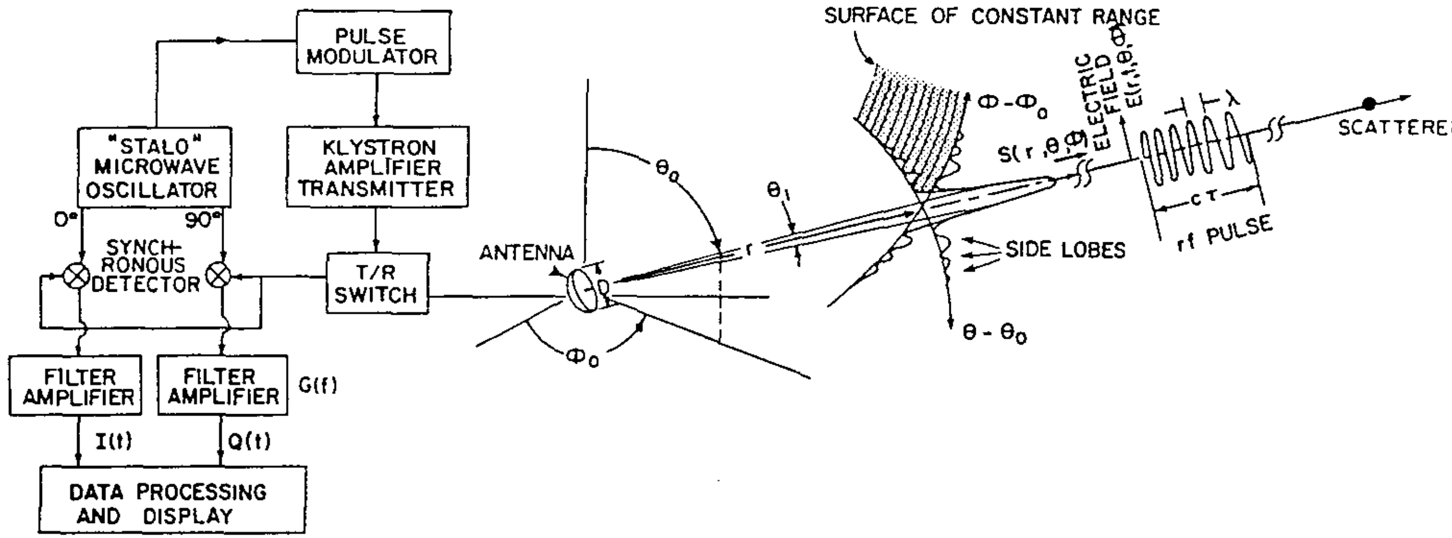

Fig. 1.1 Simplified block diagram of pulse coherent Doppler radar

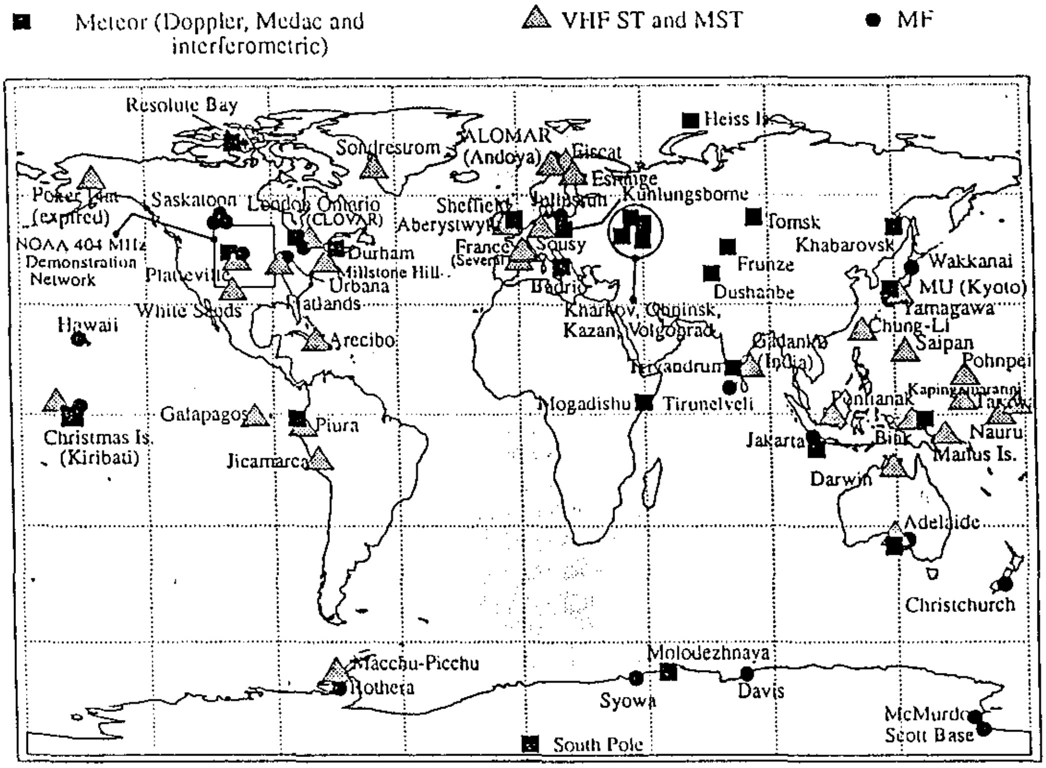

Fig. 1.2 Global distribution of MF, meteor and VHF radar

VHF radars. These instruments vary from large systems to more compact systems. The radar planned for Indonesia is designed to be essentially the most powerful and versatile MST instruments in the world.

MST Radar is a highly sensitive high resolution pulse coded phase coherent radar operating in the lower VHF band, typically around 50 MHz, with average power aperture product exceeding about $5x10^7$ Wm^2. Radar operating in the higher frequencies or having smaller average power aperture products are termed ST (Stratosphere-Troposphere) radars.

The MST Radar technique offers a great deal of promise in advancing our understanding of the dynamics of the atmosphere. This techniques uses ultra sensitive VHF and ultra high frequency (UHF) radars to study the weak back scattering arising from refractive index fluctuations in the neutral atmosphere and the lower ionosphere. Analyses of the scattered signals enable measurements of the dynamical properties of the atmospheric wind, waves, turbulence and atmospheric stability throughout the atmosphere. The high spatial and temporal resolution of the data on a continuous basis is one advantage of this technique. One of most important parameters, which this radar can give, is the vertical wind component not directly available by any other technique and is a necessary requirement for operational weather forecast purposes (Sienkiewicz and Gal-Chen, 1989; Larsen *et al.*, 1989).

The index of refraction is a measure of the speed at which electromagnetic waves propagate through a medium. Atmosphere is the medium for wind profiling. A spatial variation in this index encountered by a radio wave causes a minute amount of energy to be scattered in all directions. Most of the energy incident on the refractive index irregularity propagates through it without being scattered.

In the atmosphere minor irregularities in the index of refraction exist over a wide range of sizes. In troposphere and stratosphere, the index of refraction depends primarily on temperature, pressure and humidity of the air. The atmosphere is in a constant stage of agitation, which produces irregular, small scale variation in temperature and moisture over relatively short distances. The wind as it varies in direction and speed produces turbulent eddies. Irregular heating of the ground by the sun associated with different surface conditions provides another mechanism for the formation of eddies. Turbulent eddies are created over a spectrum of size ranging from many tens of meters down to centimetres or even millimetres. An eddy once created is unstable and tends to break up into smaller eddies, which in turn break up into small eddies and so on.

This eddies produce small and irregular variations in the index of refraction of the air that initiate scattering. Radio frequency electromagnetic pulses propagating through the air lose part of their energy to scattering from these refractive index irregularities. A small portion of this scattered energy is returned to the radar site, where it can be received and analysed. Back scattering (scattering of energy towards its point of origination) occurs from irregularities of a size of about one half of the wavelength of the probing radio waves. Since these irregularities are carried by wind, they prove to be good tracers of wind.

Power aperture product and its significance

The product of mean pulse power and its effective antenna is defined as the power aperture product. For most of the MST and ST radars the power aperture product is one of the most important parameter. It indicates the figure merit for the radar. The sensitivity of MST Radar depends on power aperture products. Higher the product, higher would be the system sensitivity. The power aperture product enhances the radar signal to noise ratio considerably. Signal to noise ratio (SNR) is the ratio of peak echo power to noise power.

The volume reflectivities of the air parcel from different layers of the atmosphere vary from 10^{-12} to 10^{-19}. Thus typically the power aperture values of the order of 10^{8} to 10^{10} are required for the radar to be suitable for MST operation whereas radars with power aperture product less than 10^{8} would qualify themselves as ST radar.

Pulse compression technique

The weak radar reflectivity of the turbulent scatter coupled with requirement of a few tens of meters of range resolution has called for the application of a pulse compression technique for the radar probing of the MST structure and dynamics.

In a pulsed radar system, SNR depends upon the pulse width. Because, the bandwidth of the receiver is indirectly proportional to the pulse width, SNR is better for a wider pulse. On the hand range resolution (the capability of the radar system to resolve two contiguous targets) is limited by the pulse width. Good range resolution requires narrower pulses. The range resolution and signal to noise are conflicting requirements.

Pulse compression is a technique employed in pulsed radar to improve range resolution with out sacrificing SNR ratio by the use of special modulation within radar pulse. In many cases pulsed radars are peak power limited and have good average power capacity. Pulse compression exploits this feature for getting good range resolution. To observe certain atmospheric phenomenon, typical range resolution required is 150 m, which corresponds to a pulse width of 1 μsec.

Wind information from MST Radar

There are two basic techniques to extract the vector wind information from the MST Radar returns. They are:

(1) *Doppler beam swinging method* (DBS) and

(2) *Spaced antenna drift* (SAD) method.

(1) DBS method

In this technique a narrow beam pointed in vertical and off vertical directions measure the Doppler shift of echo scattered from refractive index irregularities. A beam in the zenith direction and at least two more off vertical in orthogonal directions are used to measure the radial velocities in each beam position. Estimation of vertical and horizontal velocities is done from the radar return through signal processing.

The DBS method uses a narrow beam at an angle θ and measures the Doppler shift, which is a measure of the radial velocity. For a preset condition of Doppler resolution and maximum Doppler shift, the percentage error in velocity determination decreases with increasing velocity.

(2) SAD method

This method uses three or more spaced antennas and the received signals are cross-correlated to determine the horizontal velocity components. In this method the transmitter beam is pointed vertically while the signal is received at three (or more) spaced antennas (receivers) and the horizontal velocity is obtained from the time delays as the signal pattern drifts past the spaced antennas. The vertical velocity can be determined either from the phase information or from the Doppler shift.

Apparently it appears that the two techniques are different but they are closely related and the difference is only in the experimental sense. The DBS method uses a narrow beam at an angle θ and measures the Doppler shift, which is a measure of the radial velocity. The SAD method on the other hand receives energy returned over a range of angles around zenith and measures the movement of the amplitude pattern over the ground which moves at velocity twice that of the scatters.

1.4 Network of radars

A recent major thrust in MST application has been the developments of various types of radar networks (Hocking, 1997). Networks can contribute valuable data for many studies of the atmosphere. One such field of study is in the area of stratospheric-tropospheric exchange. MST Radars can play a very important role in the study of vertical propagation of extratropical waves, tides, gravity waves and equatorial waves. A meridional chain of MST Radars in the tropics could study the Hadley circulation and zonal chain could study the Walker circulation since they are believed to exchange air masses between stratosphere and troposphere. A network of VHF-ST radars has been developed across the equatorial Pacific Ocean region (Gage *et al.*, 1991; 1996). Its primary purpose was to study tropospheric circulation in the Pacific region, like studies on El-Nino and Walker circulation (Gage *et al.*, 1991) and studies on equatorial phenomena including QBO and Kelvin waves.

The radar networks can be useful in the field of weather nowcasting and forecasting. Radar networks potentially could be used to follow the organisation of severe weather in clear air. A properly conceived radar networks could sense the entire life cycle of mesoscale events occurring within such a network. In addition a planned system of radars, built with a common design is currently under development by METEO-France. The objective is to incorporate these instruments into forecasting tool.

MST networks are required to measure important wave parameters such as horizontal wavelength and phase velocity of gravity waves. Since general circulation is a global scale phenomena, a global MST Radar networks would be required to study the general circulation. Even smaller networks have been built to examine motions on scales of a few hundred kilometres. Systems that have been developed include a small group of VHF radar in France (Ecklund *et al.*, 1985) and a triangle of three MF radars developed by Manson *et al.* (1993).

Experience with the Colorado-Profiling Network has illustrated some of the practical difficulties that are encountered with MST Radar Network. These include frequency allocation problems, altitude limitation on data acquisition, radio interference problems, site selection and slow data processing procedures.

1.5 Indian MST Radar

A major MST Radar has been established as a national facility for atmospheric research in India based on the recommendations of Indian National Committee on Space Research (INCOSPAR). The scientific requirements dictated that the location of the Indian MST Radar should be preferably below 15° N latitude. After considering various constraints regarding the siting of a powerful radar system operating in VHF band, and short listing of all possible sites, a site at Gadanki Village (13.47° N, 79.18° E) near Tirupati in the Chittoor district of Andhra Pradesh State was located. The radar site for the National MST Radar Facility (NMRF) is located in a very picturesque valley in the Panapakam range of the Eastern Ghats.

The Indian MST Radar a is highly sensitive, high resolution, pulse coded, coherent VHF phased array radar with an operating frequency of 53 MHz and an average power aperture product of 7×10^8 Wm^2. Based on the inertial subrange atmospheric height and the frequency clearance available in the Indian subcontinent, a carrier frequency of 53 MHz with an operating bandwidth 2 MHz was chosen. With an average power aperture product of 7×10^8 Wm^2, the Indian MST Radar is in league with the largest MST Radars in the world. Table 1.1 summarises the system design specifications and Fig. 1.3 shows a functional block

SYSTEM

Operating Frequency	:	53 MHz
Peak power aperture product	:	3×10^{10} W. m^2
Height range	:	5 to 100 kms
Spatial Resolution		
Range	:	150 m (pulse width)
Angle	:	3° (Beam width)
Velocity resolution	:	0.1 ms^{-1}
Time resolution	:	0.5 minute
Wave form	:	Selectable pulse widths & PRF's Including pulse compression
Pulse compression	:	Psuedo random coding (Complementary BPSK code sequence of Baud length = 1 μs)
Signal Processing	:	Real time Digital (FFT based)
SUBSYSTEMS		
Antenna	**:**	Phased array with 1024 crossed Yagi Elements
Gain	:	36 db (nominal)
Beam width	:	3°
Beam positions	:	Zenith, 20° off zenith in EW & NS Directions
Side lobe	:	-20 db
Size	:	130 m x 130 m
Transmitter	:	Coherent; modular with variable Pulse width & PRF
Peak Power	:	2.5 MW
Duty Ratio	:	2.5%
Pulse width	:	Selectable 1 to 32 μs
Receiver	:	2 channel (I & Q) coherent
Overall gain	:	110 db
Dynamic range	:	70 db
Coho stability	:	1×10^{-10} (short term)
Data acquisition & Signal processing	:	Real time, computor controled
Data resolution	:	12 bits (Bipolar)
Sampling rate	:	1 MHz per channel
No. of range gates	:	upto 256
No. of points for spectral estimation	:	64 to 512
Velocity resolution	:	0.1 ms^{-1}
Signal enhancement by coherent integration	:	20 db (nominal)
Spectrum integration period	:	Selectable from 5 s to 10 min. in steps
System computer	:	32 bit (MASSCOMP 5600)
Operating system	:	Real Time Unix (RTU)
Online memory	:	8 M Bytes (expandable)
Storage	:	Hard disk, Floppy & Mag. Tape
Display	:	CRT with colour graphics
Hard copy	:	Printer, Plotter

Table 1.1. Summary of system specification of the Indian MST radar

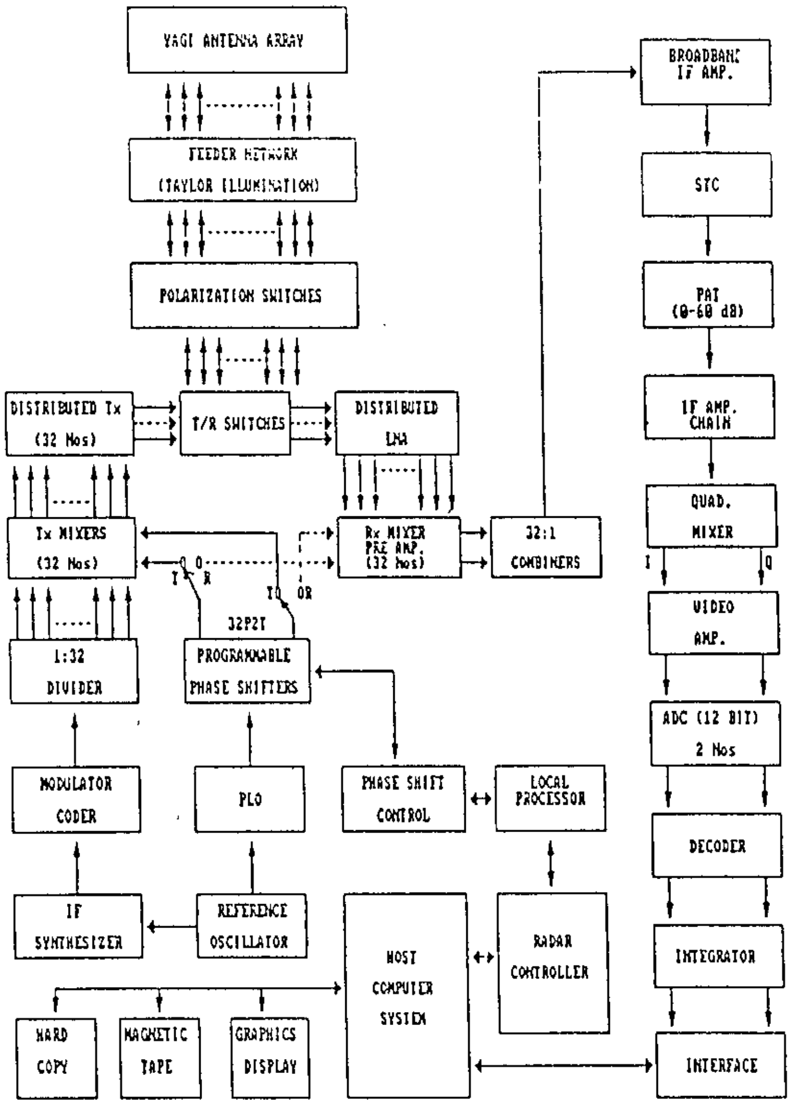

Fig. 1.3 A functional block diagram of the Indian MST radar

diagram of the radar system. The details of Indian MST Radar system configuration and other features have been explained elsewhere (Rao *et al.*, 1994; Rao *et al.*, 1995).

The Indian MST Radar has an array of 1024 (32 x 32) crossed three-element Yagi-Uda antennas and 32 units of high power transmitters, each unit feeding one subarray of 32 Yagis. It covers an area of 130 m x 130 m arranged in the form of a 32 x 32 matrix. The radar operates under instruction from a radar controller, which executes an experiment specification file (ESF). The on-line data processing carries out the Fast Fourier Transform (FFT) and incoherent integration of the Doppler spectra. The off-line data processing involves the estimation of three low order spectral moments which provides total signal power, radial wind velocity and its spread for each range bin. For obtaining the three moments the spectral signature of the received back scatter signal for various range bins is tracked using an adaptive algorithm which takes into account the SNR, Doppler range of the signal and the maximum vertical shear of the horizontal wind.

The Indian MST Radar makes use of the Doppler Beam Swinging (DBS) Technique for measuring wind field. This method for measuring the three components of the wind vector requires spectral measurements at a minimum of three non-coplanar beam positions. The radar uses normally five beams to determine the wind components in a least square sense as described by Sato (1989).

The radar beam can be positioned at any look angle but is currently programmed to sequence automatically any combination of the following seven look angles.

- Zenith in X polarization
- Zenith in Y polarization

- $\pm 20°$ off zenith in North, South, East, West
- $14.8°$ due north to look transverse to the magnetic field for ionospheric studies

Considering the uses of such a radar for upper atmospheric and ionospheric research and with out prejudice to the measurement for neutral atmospheric studies, the array is aligned along the geomagnetic meridian to enable the radar beam to be transverse to the Earth's magnetic field. After careful calculations using geomagnetic models, the antenna is oriented $2°$ due west with reference to the geographic meridian. The MST mode radar with full aperture and 32 transmitters generating a peak power of 2.5 MW was established in March, 1993.

1.6 International Scientific Activities

Major international programs in which MST Radar system will be playing an active part are (1) Solar Terrestrial Energy Program (STEP) (2) STEP-Results, Applications and Modelling Phase (S-RAMP) (3) International Geosphere-Biosphere Program (IGBP) (4) Stratospheric Processes And their Role in Climate (SPARC), etc.

1.6.1 Solar Terrestrial Energy Program (STEP)

To advance the quantitative understanding of the physical processes responsible for the transfer of energy and mass from one region of the solar-terrestrial system to another was the scientific aim of the STEP. Its practical goal was to improve the predictability of the effects of the variable component of the solar energy and disturbance on the terrestrial environment, on technological systems in space and on earth and on the biosphere. The integration of space and ground-based observation was a particularly important objective.

STEP took a global look at the solar-terrestrial system with ground-based, aircraft, balloon, rocket and satellite experiments. It offered an unparalleled opportunity to scientist from all countries to unravel the mysteries of the solar-terrestrial environment. Integral to the success of the STEP is the set of solar-terrestrial spacecraft missions approved by the Inter Agency Consultative Group (IACG). Of fundamental importance was the close co-ordination of all the ground-based, balloon and rocket experiments with spacecraft measurements.

1.6.2 STEP - Results, Applications and Modelling Phase (S-RAMP)

STEP - Results, Applications and Modelling Phase (S-RAMP) is a five year program organised by the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) which will extend over the period 1998-2002. The major objectives of S-RAMP are:

(1) To facilitate and enable the detailed study of the STEP data base so as to increase our understanding of the physical mechanism responsible for coupling the various regions of the sun-earth system.

(2) To facilitate and enable the effective transfer of data and information among S-RAMP researchers and to encourage feedback among the experimental, theoretical and computer modelling communities.

(3) To demonstrate the scientific finding and their societal benefits to funding agencies, the media and the general public so as to generate support for future scientific programs, cross-disciplinary studies and practical applications of knowledge of the sun-earth system.

1.6.3 International Geosphere-Biosphere Program (IGBP)

International Geosphere-Biosphere Program (IGBP) is the largest and most ambitious multidisciplinary international scientific programme ever attempted by the International Council of Scientific Unions (ICSU) in view of the growing concern for the large scale changes in the earth systems caused by human and anthropogenic activities. Its aim is to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system and the manner in which they are influenced by the human activities. The main emphasis of IGBP is on processes that affect the biosphere and that are most susceptible to human perturbations. IGBP is closely co-ordinated with the World Climate Research Programme (WCRP), which focuses on the physical aspect of climate change.

1.6.3.1 IGBP in the Indian context

India, with its diverse environmental conditions and ecosystems and with economy closely linked with the monsoon performance, has several urgent problems that are need to be addressed. The problems such as drought/desertification, floods, deforestation, pest and land degradation are closely linked with weather and climate changes on one hand and the environmental and ecological effects and interaction on the other. It is thus obvious that there are a number of important problems that have an environmental impact. The MST Radar progress will thus provide the necessary inputs in the study of the various dynamical processes in the atmosphere including the monsoons and the cyclonic storms over the Bay of Bengal.

1.6.4 Middle Atmospheric Program (MAP)

MAP was formulated as an international endeavour in scientific research for investigation of the physical and chemical processes and phenomena taking place in the 10-100 km region. It was undertaken during 1982-1988 period through MAP Steering Committee constituted by the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) under ICSU. The main objectives of MAP are :

(i) *determine thermal structures and compositions of the middle atmosphere, specially in regard to important minor species and ions*

(ii) *determine the interaction of radiation from the sun, the earth and the atmosphere with the middle atmosphere*

(iii) *investigate the motions of the middle atmosphere on all scales, including the interactions with the troposphere and magnetosphere, and to monitor these motions on a continuing basis.*

Indian Middle Atmospheric Program (IMAP) was carried out as multi-institutional and multi-agency funded activity for scientific investigations of the atmospheric phenomena and processes between 10 and 100 km region of the atmosphere. About 200 scientists were participated in this programme during 1982-1989. Original integral proposal for IMAP contained the setting up of Indian MST Radar at a location away from the equator but below 15° N, which could provide information on winds, waves and turbulence in the middle atmosphere. While IMAP was implemented, a parallel project on the development and installation of MST Radar was taken up with multi-agency funding. In conjunction with the results obtained under IMAP and further investigations, MST Radar is expected to enhance our knowledge of interconnections between the troposphere and thermosphere with the middle atmosphere.

1.6.5 Stratospheric Processes And their Role in Climate (SPARC)

In March 1992, WCRP established the SPARC project. The basic reasons why the stratospheric studies are important in the overall investigation of global change are the influence of stratospheric processes on climate and indirectly on the biosphere. SPARC seeks to understand present stratospheric interactions with the climate and to predict the influences that the future states of the stratosphere will have on the climate of the troposphere-stratosphere system. Changes in stratospheric ozone could alter the climate of the troposphere as a result of alteration in the incoming and outgoing radiation fluxes. There is also the possibility that ozone changes in the stratosphere would lead to changes in the stratospheric distribution of temperature and wind and thus affect the dynamical interaction between the troposphere and stratosphere.

The four principal themes of the SPARC are

(i) *the influence of the stratosphere on climate*

(ii) *physics and chemistry associated with stratospheric ozone change*

(iii) *stratospheric variability and monitoring*

(iv) *stratospheric change and radiation including UV-B penetration*

The implementation of SPARC involves co-ordinated observation, modelling and analysis to understand the effect of stratospheric changes on climate.

1.7 Major dynamical phenomena observed in the middle Atmosphere

It is realised that stratospheric physical and chemical processes may be helpful in understanding the dynamics of the lower atmosphere and provide a tool for long range forecasting of weather. Propagation of wave disturbances, oscillations like the semi-annual, and quasi-biennial form the major part the middle atmospheric circulation, dynamics and variability which are important in the dynamics of the stratosphere and mesosphere.

1.7.1 Equatorial waves

The transport of energy in the equatorial region is mainly through large period wave motions that propagate vertically as internal gravity waves and the energy they transport from their source region, the troposphere, is upward while the phase propagation is vertically downward. Detailed theoretical studies show that in the tropics there are two major forced oscillations propagating eastward (westerly mode) and westward (easterly mode). The westerly mode is known as the Kelvin wave (10-20 day period) and the easterly wave is known as the Mixed Rossby-Gravity (MRG) wave (4-5 day period). Both the wave modes are latitudinally trapped and confined to about $\pm 15^{\circ}$ latitude.

Wallace and Kousky (1968) and Yanai and Maruyama (1966) discovered the Kelvin and the MRG waves, respectively. Both the waves are able to transport wave energy and westerly momentum flux upward. Maruyama (1969) studied the long-term behaviour of these waves and computed the westerly momentum fluxes from station data at different stages of the QBO using horizontal wind and temperature. These calculations were indirect, because they lacked the vertical velocity of the station. Since MST Radars can provide vertical velocity it can be used to determine the presence of these waves as well as the momentum flux at upper levels. Table 1.2 shows the observed characteristics of the Kelvin and MRG waves.

1.7.2 Quasi-Biennial Oscillation (QBO)

The alternating pattern of westerly and easterly wind regimes in the equatorial lower stratosphere with period varying from 22 to 32 months with an average period of about 26 months is called quasi-biennial oscillation (QBO). Fig. 1.4 shows zonal wind averaged over equatorial stations as a function of time and height. Veryard and Ebdon (1961) the alternation of easterly and westerly winds in the equatorial stratosphere with an average period of 27 months. The QBO is symmetric about the equator and is confined to latitudes of less than about 15° (Salby, 1996) with maximum amplitude near the equator (Asnani, 1993). A detailed mathematical discussion of the properties of tropical planetary waves as well as of the driving mechanism can be found in Andrews *et al.* (1987). Lindzen (1987) gives a review of the development of the theory of the QBO.

Sl. No.	Characteristics	Kelvin waves	mixed Rossby-gravity waves
1.	Zonal wave number	1 - 2	4
2.	Period (days)	10 - 20	4 - 5
3.	Phase speed (ms^{-1})	25	- 23
4.	Direction of propagation	Westerly	Easterly
5.	Horizontal wavelength (km)	30,000	10,000
6.	Latitudinal wavelength (km)	1,000	1,000
7.	Vertical wavelength (km)	6 - 10	4 - 8
8.	Amplitude		
	(a) Zonal wind **u** (ms^{-1})	8	2 - 3
	(b) Meridional wind **v** (ms^{-1})	0	2 - 3
	(c) vertical wind **w** (cms^{-1})	15	15
	(d) Geopotential height **Z** (km)	4	30
	(e) Temperature **T** (°K)	2 - 3	1
9.	Symmetry about the equator		
	(a) Zonal wind	even	odd
	(b) Meridional wind	—	even
	(c) Geopotential height	even	odd
10.	Phase relation between the perturbation quantities		
	(a) Pressure **p** and **u**	out of phase	in phase
	(b) pressure **p** and **T**	**T** leads **p** by 90°	**T** leads **p** by 90°
	(c) Pressure **p** and **v**	—	**p** leads **v** by 90°
	(d) **u** and **w**	in phase	in phase

Table 1.2 Typical characteristics of Kelvin and mixed Rossby-gravity waves

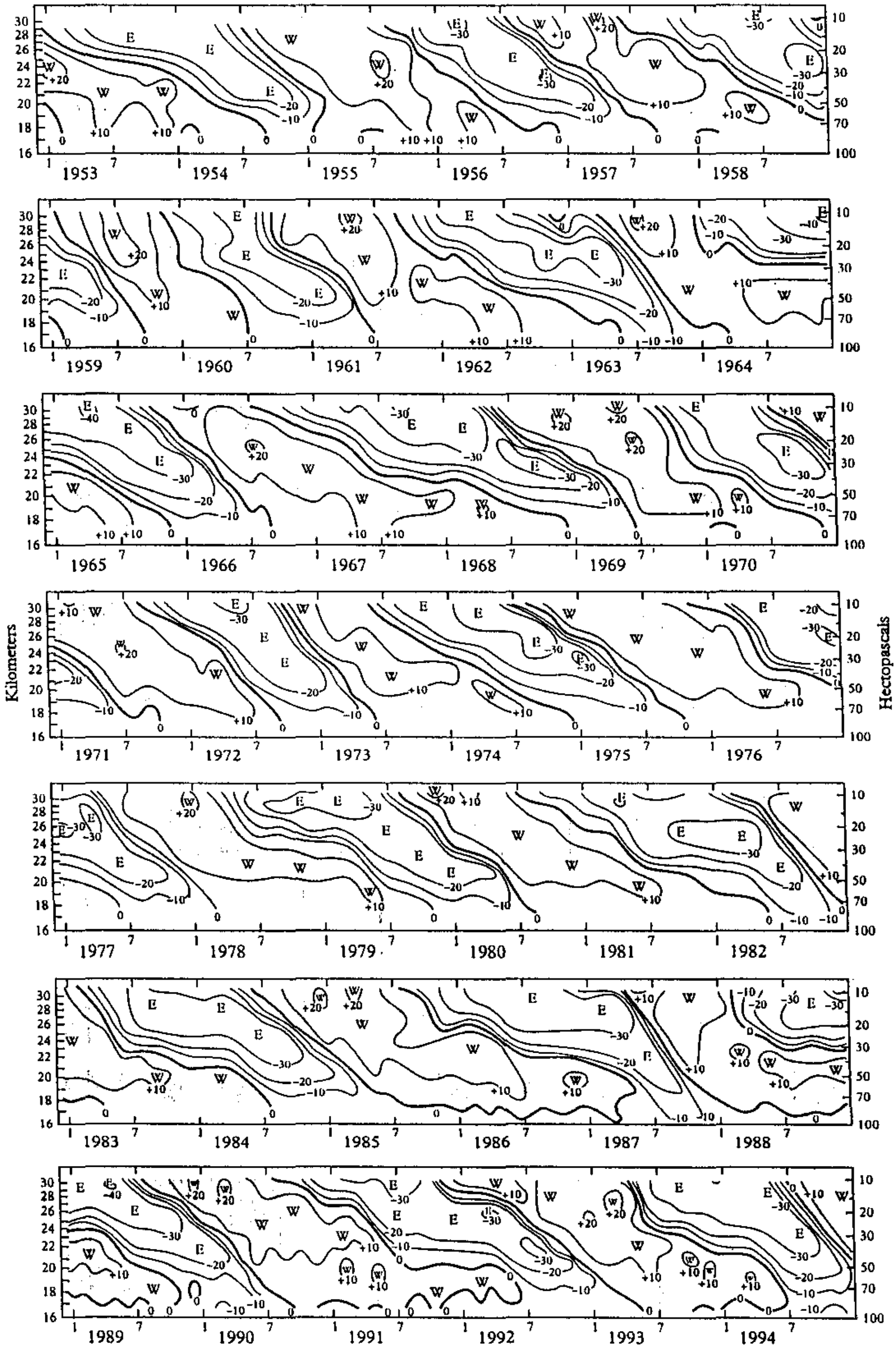

Fig. 1.4. Monthly mean zonal winds in the stratosphere at equatorial stations (ms^{-1})

It was reported that the westerly acceleration appears first at the equator and then spreads to north and south. The easterly accelerations are more uniform in latitudes and the westerly accelerations are more intense on the average than the easterly acceleration that is consistent with the more rapid descent of the westerly shear zone. The wind regimes propagate downward at an average rate of 1 km/month. Holton and Lindzen (1972) proposed that the interaction between the equatorial Kelvin and MRG waves with the mean flow through wave dissipation give rise to alternating winds. These waves transport momentum and energy upward. The eastward propagating Kelvin waves carry westerly momentum and the westward propagating MRG waves easterly momentum, which explains the downward propagation of alternating westerly and easterly wind regimes.

The period of the QBO cycle depends on the rate of deposition of the eddy momentum fluxes by the equatorial waves. It is a coincidence that the available fluxes are such that the QBO period turns out to be about two years. The waves proposed by Holton and Lindzen (1972) do not seem to sufficiently account for all the required QBO forcing. Other waves are probably involved; recent observational and numerical studies suggest that tropical gravity waves may be the missing source of forcing. Just which waves contribute what amount of forcing still needs to be determined. The observed variability of individual QBO cycles is a question to be answered apart from the phase-locking of the QBO easterlies to the annual cycles. Of special interest in regard to the circulation in the stratosphere is a possible link between the QBO and the dynamics of the arctic polar vortex during winter-specifically, the occurrence of the sudden midwinter warmings (Holton and Tan, 1980).

1.7.3 Annual Oscillation (AO)

The observed annual oscillation of the global atmosphere is mainly due to two factors (a) the march of the sun from one hemisphere to the other with seasons and (b) the differential heating of the surface due to the presence of land

and oceans. It is the annual oscillation (AO) which is the most prominent of all oscillations having other periods like diurnal, semidiurnal, quasi-biennial etc. Broadly speaking the wind is easterly in the summer hemisphere and westerly in the winter hemisphere in the stratosphere and mesosphere. The maximum amplitudes of the summer easterlies and the winter westerlies are observed near the solstices.

The circulation reverses from summer to winter and winter to summer over most of the strato-mesosphere during equinoctial period. The equinoctial conditions, therefore, manifest relatively weak zonal winds in both the hemispheres as revealed by Hopkins (1975). The amplitude of the annual oscillation in the zonal wind shows a minimum in the tropics above 30 km (Belmont, 1985). Generally the amplitude of AO is similar in the northern and southern hemispheres. Studies of Barnett *et al.* (1985) shows that the amplitude of the annual oscillation is minimum at the equator and maximum at the poles with large amplitude at 80° S than at 80° N.

1.7.4 Semi-Annual Oscillation (SAO)

One of the very significant features of the low latitude upper stratosphere is the semi-annual oscillation (SAO) of the zonal winds (Meyer, 1970). The SAO in the zonal wind is quite strong in the equatorial stratosphere and mesosphere. In common with the QBO, it is characterised by the appearance of alternating regimes of eastward and westward winds, the former appearing near the equinoxes and the later at the solstices. Hopkins (1975) indicated that the westerly accelerations of the SAO are confined to the equatorial region and are very uniform from season to season, but the easterly accelerations are quite irregular with seasons. The eastward regime of the SAO appears to be driven by planetary-scale Kelvin waves and smaller-scale gravity waves; westward regime is thought to be driven by the transport of westward momentum from the summer hemisphere by the mean meridional circulation. The conspicuous features that the

SAO is confined to tropics with its phase decreasing with height in a manner similar to QBO suggest that the westerly phase of SAO should be due to the westerly momentum deposition at the relevant altitudes by Kelvin waves.

The very rapid dissipation with height of the long period Kelvin waves producing the westerly phase of the QBO implies that the long period Kelvin modes would not be available to transport energy and momentum to the mesospheric levels. However, the shorter period Kelvin waves are not absorbed significantly in the lower stratosphere and these waves with very small amplitudes carry large enough westerly momentum for the westerly phase of the SAO. The mesopause SAO which is out of phase with the stratopause SAO may be due to selective transmission of Kelvin and gravity waves propagating through the stratopause SAO (Dunkerton, 1982).

Chapter 2

Review of Literature

2.1 Literature survey

The last few years have seen many significant advances in the field of middle atmospheric research using VHF radar techniques. Application for these instruments quickly developed, and a large and successful community has been built up around them. Several successful international workshops have discussed scientific and technical aspects of the so-called MST techniques and have been summarised in MAP and STEP handbooks.

For the past few decades, the parameter C_n^2, known as refractivity turbulence structure constant, has been the focus of many radar measurements. It is recognised as the most appropriate parameter to specify the intensity of the refractivity turbulence. The vertical profile of the received power can be converted into a vertical structure constant C_n^2 and also the eddy dissipation rate ε, which is a measure of intensity of turbulence. Doppler radars are used to observe clear-air turbulence with coherent techniques. Breaking of gravity waves, believed to be generated in the troposphere, are sources of turbulence in the atmosphere. These waves transport energy and momentum between different layers of the atmosphere and are major sources of turbulence. Observations of upward flux of horizontal momentum are useful to study such effects. Vincent and Reid (1983) measured the vertical flux of horizontal momentum using dual complementary coplanar Doppler beams using the Adelaide MF radar. Since then several studies using VHF radar data explored application of this method for momentum flux computations. Jain *et al.* (1995) and Rao *et al.* (1997) carried out studies on C_n^2, ε and vertical momentum flux using Indian MST radar.

Sudden changes in troposphere structure on time scales less than a few hours or so have been detected by MST radar (Rastogi and Rottger, 1982; Nastrom *et al.*, 1989) and documented as tropopause break/folding. With the advent of clear-air Doppler radar it has become possible to continuously monitor the tropopause under all weather conditions. Yamanaka *et al.* (1996) found layered structure in the subtropics due to turbulence triggered by inertio-gravity waves. Jaya Rao *et al.* (1994) observed multiple layered structure near the tropopause in the tropical atmosphere using the Indian MST radar. MST radars have successfully been used in detecting tropopause. The tropopause is associated with a large positive vertical gradient of signal-to-noise-ratio (SNR) (Gage *et al.*, 1986; Nastrom *et al.*, 1989). Recently, Mandal *et al.* (1998) determined multiple layered structure near the tropopause and its "weakening". Their study emphasised more on the aspect of mass exchange between stratosphere and troposphere during weakening of tropopause.

However, new techniques and applications of the VHF radars have found application in many regions of the atmosphere from the troposphere into stratosphere and mesosphere. MF radar at Adelaide, Australia, with a narrow beam has performed experiments in regard to aspect sensitivity (Hocking, 1979; Lesicar *et al.*, 1994), gravity wave motions and momentum fluxes, turbulence measurements, long-term wind data, tidal and planetary wave studies. The observations of VHF radar are able to provide valuable information on tidal winds in the mesosphere and the lower stratosphere due to their very good height and time resolution. VHF radars are also being used in the field of lower ionospheric and the D region studies. The EISCAT radar operating at 224 MHz has been used in studies of the polar mesospheric summer echo and studies of D region turbulence (Rottger *et al.*, 1990; Collis *et al.*, 1992). Another area of application is in the field of equatorial spread of F region (ESF) using coherent and incoherent mode of operation.

Several more diverse applications of VHF radars have arisen in recent years (Caccia and Cammas, 1998; Nastrom, *et al.*, 1998; Gossard, *et al.*, 1998). These include measurements of rainfall, frequency and spatial domain interferometry, rain drop size distribution and radio acoustic sounding system (RASS). First observations of rain echoes at VHF were presented by Fukao *et al.* (1985c). Precipitation studies using radar which are normally considered to be clear-air instruments have also to be proved quite interesting (Ralph, *et al.*, 1996) apart from cloud detection studies (Kobayashi, *et al.*, 1999). Methods for using radar data to determine absolute precipitation rates and studies of the drop size distribution have become areas of research (Sato *et al.*, 1990; Rajopadhyaya *et al.*, 1993; Maguire and Avery, 1995). Chilson *et al.* (1993) performed experiments to study precipitation at Arecibo. They found that the rainfall fall speeds and drop size distributions are unreliable in a turbulent environment. Many studies have been carried out on lee waves and mountain waves using VHF radar measurements (Prichard, *et al.*, 1995; Caccia, *et al.*, 1997; 1998; Rechou, *et al.*, 1999; Worthington, 1999).

Rottger *et al.* (1995) have reported several observation of lightning including location and duration and generation of infrasound proving that VHF radar can be effectively used in the area of lightning research. Special equipment modifications are needed in order to obtain sufficient temporal resolution to make these studies. Another application is to use RASS to VHF studies. This technique is used to transmit sound waves into the atmosphere to create artificial irregularities, which cause strong backscatter of radio signals. Then the speed of these artificial periodic inhomogenities are measured to determine the speed of sound using the radar which is used to find the temperature of the atmosphere at the heights of the radio wave scatter. Many notable works have been carried out in this field (Peters *et al.*, 1985; May *et al.*, 1990, 1996; Yamamoto *et al.*, 1996).

Some other experiments computed the temperature of the troposphere, stratosphere and mesosphere, even though the techniques differ in each regime, without using additional equipment like RASS. Gage and Green (1982a, b) used measurements of backscattered power to deduce temperature profile in the troposphere. Revathy *et al.* (1996) used measurements of vertical velocity spectra from Indian MST radar to identify the vertical profile of Brunt-Vaisala frequency in order to compute the temperature profile with good accuracy.

The troposphere is the portion of the neutral atmosphere that is more likely to be convectively unstable than other altitude region. It is the convection process that induces vertical transport between different layers of the atmosphere. The vertical transport due to convection is very pronounced in the tropical region, which drives the mean global circulation. As shown by Reiter (1975), vertical flow pattern changes consistently with latitude and season. The organised large-scale horizontal and vertical motions expressed by the mean meridional circulation is a major process responsible for mass transfer between troposphere and stratosphere. Reiter (1975) estimated that about 40% of the vertical transport are due to the Hadley cell circulation in the tropics. Since VHF radars exhibit a unique capability to measure vertical velocities, a continuous operation of a chain of VHF radars along a meridian would be suitable contribution to monitor the mean vertical transport, tropical Hadley circulation and also the meridional motion.

Massive amounts of heat and moisture are carried with the air that moves in the cellular Hadley circulation. In the rising limbs of the Hadley cells heat and moisture are carried into the upper parts of the atmosphere (McGregor and Nieuwolt, 1998). The transport of moisture represents an energy transfer as when moisture condenses latent heat is produced. Other forms of energy transported by the Hadley circulation are kinetic energy and angular momentum. The northern Hadley cell is more important for the transport of kinetic energy in its stationary eddy form. Piexoto and Oort (1992) have documented the cross-sections of vertical velocities (the vertical equivalence of horizontal wind speed) and the meridional wind for a range of latitudinal bands in the atmosphere for annual, summer and winter seasons. A global view of the vertical motions in the lower and mid-troposphere during northern hemisphere summer season (June-August) shows strong ascending motion centred on 5° N while the low latitude of the southern hemisphere become dominated by sinking motions.

The zonally averaged symmetric Hadley cells reverses from winter to summer as shown by Oort and Rasmusson (1971). In India the summer season (June, July, August and September) is known as southwest monsoon. During the southwest monsoon season a reverse Hadley cell exists over Indian region which is different from the usual Hadley cell over the rest of the tropics (Schulman, 1973). Kuo's (1956) meridional circulation stream function can be used to interpret the vertical motion over monsoon region as explained by Keshavamurty and Sankar Rao (1992). It is essential to understand the vertical motion during monsoon season that helps in studying the physics of the symmetric and asymmetric monsoons. The direct measurements of vertical velocity from the Indian MST radar may help in diagnosing the nature of the Hadley circulation during both winter and summer over Indian region. Particularly, it could be used to study the nature of the vertical motions and the Hadley circulation during southwest monsoon season.

The present meteorological analysis schemes are based on inferences of large-scale vertical motion. Although an abundant literature has been developed dealing with methods to estimate the vertical motions associated with the large-scale flow from radiosonde data, there is still no consensus on the best method to estimate vertical motions (Barnes, 1986; Durran and Snellman, 1987; Portis and Lamb, 1988; Doswell, 1989; Van den Dool, 1990). With the development of wind profiling radar technology by Woodman and Guillen (1974) and Green *et al.* (1975), the first measurements of the vertical velocity with a time resolution of the order of minute became possible. Temporal averages of vertical motions from MST radar can aid in diagnosis of atmospheric process if the conditions under which they represent the large-scale flow are understood. Many studies were carried out on vertical motions of large-scale system (Nastrom *et al.*, 1985; Larsen *et al.*, 1988; Sato, 1990). Results from case studies of vertical motions reveals that synoptic or subsynoptic scale vertical motions can be observed using VHF radars (Nastrom *et al.*, 1994, Warnock *et al.*, 1994). Recent studies on vertical velocities addressed several problems and found new techniques from VHF/MST radar observations (Nastrom and VanZandt, 1996; Cifelli *et al.*, 1996; Nastrom *et al.*, 1998).

Earlier, indirect computations of vertical motions during winter and summer over Indian tropical middle atmosphere were made using the thermodynamic equations (Mukherjee and Ramana Murty, 1973; Mukherjee *et al.*, 1984). Mukherjee *et al.* (1984) showed that the vertical velocity is downward in the stratosphere during summer and winter over the tropical Indian atmosphere. Studies on the long-term variations in the vertical motion in the lower and upper atmosphere over the tropical Indian regions have been very few. Recently, Rao *et al.* (1997) studied the monthly vertical motion field using the Indian MST radar data but that could not provide any possible explanations for the observed vertical motions.

It is well known that disturbances which move from west to east in winter across Iran, Afghanistan, Pakistan and extreme northwest India, called western disturbances (WD) produce small but important precipitation over northwest India. Pisharoty and Desai (1956) defined WD as *eastward moving upper air troughs in the subtropical westerlies which extend down to the lower troposphere of the north Indian latitudes in winter months*. The rainfall is very important for winter crops of the northwest India. The WD influence the weather of northwest India from middle of December (Veeraraghavan and Nath, 1989). Based on ten years of satellite cloud pictures Agnihotri and Sing (1982) studied WD approaching northwest India during November to March from the movement of overcast cloud masses. Sing (1979) discussed the relationship between the approach of a developing upper level trough from the west and the consequent formation of two WD, one in the southeast sector and the other in northeast of the trough. He suggested that the appearance of WD over India was mostly in this from and the southern one was generally stronger than the other. Sharma and Subramaniam (1983) in their case study presented the interaction between the WD and the tropics during winter. They showed the linkage between a low in the lower tropospheric easterlies in the Arabian Sea off west coast of India. The analyses proved that the intensification of the western disturbance is linked with the low in the Arabian Sea.

The tropical easterly flow in the low levels is insulated from mid-latitudes by the sub-tropical high pressure belt. North of the sub-tropical anticyclone is westerlies. Many studies have highlighted the intensification of the upper air trough in the mid-latitude westerlies. Passage of large amplitude troughs in the westerlies can alter the tropical circulation and even the tropical weather systems. The mobile cloud systems associated with short waves on the subtropical jet (STJ) amplify the long wave troughs. This trough may extend into the tropical atmosphere leading to sway of mid-latitude westerlies over tropics.

Interaction of tropics and mid-latitudes are frequent during all seasons of the year in India and neighbourhood. During winter, the interaction between the tropics and mid-latitudes leads to the intensification of WD. Earlier studies reported that during winter relatively strong tropical and extratropical disturbances when approach the same longitude, they get linked mutually and intensify. In such cases upward motion (Pisharoty and Desai, 1956) east of the southern disturbance destroys the normal subsidence and brings rain and bad weather in the eastern portion of the two systems. As Holton (1992) explained the vertical motion will be upward to the west and east of a trough. Since the vertical motion field is easily available from the Indian MST radar, which is located in the tropics, the interaction of an extended trough in the mid-latitude westerlies deep into the tropics and the associated horizontal and vertical circulation can be addressed. Kalsi and Halder (1992) discussed the intensification of WD and the extension of trough in the mid-latitude westerlies into tropical atmosphere, their eastward movement and the northward movement of cloud bands formed ahead of the trough over tropics. The clouds, as they showed in their case study, owes its existence to trough in the westerlies in the middle and the upper troposphere which also induce the extension of low level hot and moist tropical easterly flow northward where it meats the westerly flow of the mid-latitudes. Recently, Wu and Chan (1997) studied the upper-level features associated with winter monsoon surges over south China. The analyses suggest that the eastward passage of short wave trough and the polar jet have strong influence on the winter monsoon of China.

It is well known that in the equatorial region there are certain waves with longitudinal scales of over thousand kilometers and wave periods ranging from a few to a few tens of days. The large solar heat input received in the equatorial atmosphere generates various atmospheric waves and different types of wave disturbances are found over the tropical atmosphere. Rocketsonde and radiosonde measurements and satellite data have elucidated their existence and other characteristics. Because an inertial period rapidly increases near the equator, an intrinsic frequency range of waves that could propagate upward without vertical trapping becomes increasingly wider as well. Over the past several years substantial efforts have been made to delineate the numerous wave modes prevailing over the tropical latitudes using various data records.

Matsuno (1966) derived a dispersion relation for the wave solutions of the shallow water equations on an equatorial β-plane. Lindzen (1967) and Holton and Lindzen (1968) extended the theory to an isothermal atmosphere. The tropospheric disturbances exhibit a higher degree of complexity, and difficulties were encountered in analysing them with spectrum analysis technique. No dominant scales were clearly marked and identification and separation of wave modes are difficult although extensive studies were carried out on Kelvin and mixed Rossby-gravity waves in the stratosphere using single station's data. Early theoretical models of equatorial waves did not provide clues as to what physical mechanisms are responsible for their generation in the atmosphere and for the dominance of particular mode or another. Yanai and Hayashi (1969) suggested a tropospheric origin of the stratospheric equatorial waves by computing the upward flux of wave energy at the tropopause level associated with mixed Rossby-gravity wave. The model by Holton (1972b, 1973) provides good evidence that the diabatic heat sources in the tropical troposphere are able to generate equatorial waves in the stratosphere. Recent studies suggested that topography and strong cumulus convection could trigger equatorial waves.

Observational evidence indicates that, of various theoretically possible equatorially trapped wave modes, the Kelvin and mixed Rossby-Gravity (MRG) waves are of sufficient amplitude to be important for the large-scale dynamics of the equatorial stratosphere. These wave modes are of planetary scale in the zonal direction, but are trapped in within about 15° north and south of the equator. The Kelvin and the MRG waves have been extensively studied for many years since their initial discovery by Wallace and Kousky (1968) and Yanai and Maruyama (1966), respectively, among other various tropical wave studies (Wallace, 1973; Zangvil and Yanai, 1980; Salby *et al.*, 1984; Devarajan *et al.*, 1985; Cornish and Larsen, 1985; Krisna Murthy *et al.*, 1986). Theoretical studies highlighted the important role played by Kelvin and MRG waves in generating the QBO in the equatorial lower stratosphere (Reed *et al.*, 1961; Veryard and Ebdon, 1961) and the SAO observed in the upper stratosphere and mesosphere (Holton and Lindzen, 1972; Holton, 1975; Dunkerton, 1979; Holton and Wehrbein, 1980; Dunkerton, 1982; Hamilton, 1982; Plumb, 1982; Mahlman and Umscheid, 1984; Hitchman and Leovy, 1986; Vincent, 1993; Eluszkiewicz *et al.*, 1996). Hitchman and Leovy (1986) suggested that planetary-scale Kelvin waves account for about 30%-70% of the total forcing around the stratopause level.

Recent modelling study by Sassi and Garcia (1997) shows that intermediate-scale and planetary-scale Kelvin waves account for most of the force required to drive the westerly and easterly phases of the SAO. These large-scale motions are driven by equatorial wave forcing through wave mean flow interaction rather than by thermal forcing. The study suggests that the excitation of the intermediate-scale equatorial waves depends on the diurnal variation of convection and these waves play an important role in the forcing of the tropical SAO. It was found that intermediate-scale Kelvin and inertia-gravity waves provide between 25% and 50% of the forcing necessary to drive the westerly phase of the SAO near the stratopause, while the reminder is supplied by the planetary-scale Kelvin waves.

Several authors have expedited the theory of equatorial waves (Matsuno, 1966; Lindzen, 1967; Holton and Lindzen, 1968) and many experimental and modelling studies (Coy and Hitchman, 1984; Salby and Garcia, 1987; Garcia and Salby, 1987; Itoh and Ghil, 1988) revealed their source, generation and existence. There have been several theoretical studies of Kelvin waves like that of Chang and Lim (1988). They studied the theory of Kelvin wave-CISK modes on the equatorial β-plane to explain the Madden-Julian Oscillation (MJO). Recent observational studies of equatorial waves using OLR data and wavenumber-frequency spectrum analysis identified a number of convectively coupled equatorial Kelvin and MRG waves (Wheeler and Kiladis, 1999) and more detailed analysis on dynamical fields associated with convectively coupled equatorial waves were carried out by Wheeler *et al.*, 2000). Pires *et al.* (1997) studied the equatorial wave systems and their relationship with convective activity in the western and central Pacific. Recent observational and model studies enriched the existing knowledge of the tropical Kelvin and MRG waves and helped in understanding their link to the tropical middle atmospheric general circulation (Maruyama, 1991; Randel, 1992; Dunkerton, 1993; Takayabu and Nitta, 1993; Shimizu and Tsuda, 1997; Sato and Dunkerton, 1997; Ortland, 1997; Dunkerton, 1997; Riggin *et al.*, 1997; Shiotani *et al.*, 1997; Lieberman and Riggin, 1997; Srikanth and Ortland, 1998; Canziani and Holton, 1998).

Numerous studies were carried out to identify the characteristics of MRG waves in the troposphere and stratosphere (Maruyama and Yanai, 1967; Maruyama, 1967, 1969, 1979; Yanai *et al.*, 1968; Yanai and Murakami, 1970a,b; Nitta, 1972). These studies have shown that MRG waves in the lower stratosphere have wavenumber-4 longitudinal scale with westward phase propagation and periods in the range of 3-5 days (Andrews, *et al.*, 1987). Theoretical, observational and modelling studies suggest that these waves have a tropospheric origin (Mak, 1969; Hayashi, 1970; Nitta, 1970; Hayashi and Golder, 1978; Zangvil and Yanai, 1980, 1981; Yanai and Lu, 1983; Itoh and Ghil, 1988; Hendon and Liebmann, 1991; Goswami and Goswami, 1991; Emanuel, 1993; Dunkerton and Baldwin, 1995; Magana and Yanai, 1995). Seasonal variation in the MRG wave activity in the troposphere and lower stratosphere were detected by Wikle *et al.* (1997) with peaks occurring in late winter-spring and in late summer-fall.

Observed Kelvin waves have large amplitudes in the zonal wind component (u') with small meridional wind component (v'). Maximum amplitudes are found near the equator with period in the range of 10-20 days, moving eastward and downward with a phase speed of 25-30 ms^{-1} relative to the ground. Mixed Rossby-gravity waves, however, have lower periods, of the order of 4-5 days, and propagate westward and downward with a phase speed of 20 ms^{-1}. MRG waves have fluctuations in the zonal as well as meridional wind components. Both the waves exhibit amplitudes of the order of 1.5×10^{-3} ms^{-1} in the vertical velocity component (Wallace, 1973).

The Kelvin wave plays a unique and important role in the equatorial stratosphere dynamics because it is apparently the only oscillation which can transport westerly momentum upward and hence produce westerly mean zonal wind accelerations in the equatorial stratosphere. A number of climatological studies (Wallace and Kousky, 1968b; Maruyama, 1969; Kousky and Wallace, 1971; Angell *et al.*, 1973) have shown that the Kelvin waves reach maximum amplitude during the easterly phase of the QBO in the lower stratosphere. Kousky and Wallace (1971) showed that the Kelvin waves are rapidly damped as they propagate into a westerly shear zone and that the resulting momentum flux convergence is sufficiently large to account for the observed westerly accelerations associated with the descending westerly phase of the quasi-biennial oscillation.

The MRG waves, on the other hand, have their greatest amplitudes during the easterly phases of the QBO. Theoretically it is shown that this mode should be able, at least partially, to account for the easterly accelerations associated with the descending easterly phase of the QBO. However, there is another possible source of easterly accelerations in the equatorial stratosphere, namely, the divergence of the northward horizontal eddy momentum flux associated with quasi-stationary planetary waves of the winter hemisphere (Tucker, 1965; Wallace and Newell, 1966; Hirota and Sato, 1970).

Of special significance for equatorial dynamics is the vertical structure of these waves. Both Kelvin and MRG waves transport wave energy and westerly momentum flux upward. However, unlike the Kelvin wave, the mixed Rossby-gravity wave does not provide a net source of westerly momentum for the stratospheric mean flow. The net eddy forcing of the mean flow depends not only on the direct vertical flux of momentum (u'w'), but on the indirect forcing due to the lateral eddy heat flux as well. Like the amplitude distributions, the maximum fluxes are to be observed at the equator for Kelvin waves and at several degree latitudes of both hemispheres for MRG waves. It has been suggested that in the equatorial area the upper troposphere might supply the stratosphere with wave energy (Lindzen and Matsuno, 1968; Maruyama, 1968b; Yanai *et al.*, 1968). Maruyama (1969) studied the long-term behaviour of these waves and their westerly momentum transport in the different stages of the quasi-biennial oscillation. He calculated the vertical momentum fluxes (u'w') due to these waves using co-spectrum analysis between zonal wind and temperature by assuming adiabatic processes and neglecting terms of horizontal advection. Yanai and Hayashi (1969) calculated the vertical energy fluxes of the equatorial waves using co-spectrum analysis of horizontal wind and temperature data. These calculations were indirect, because they lacked the direct measurement of vertical velocity (w).

But (MST) radars provide direct measurement of the station's vertical velocity (w) in the lower and the middle atmosphere. A cross-spectrum analysis between zonal and vertical velocity will give the vertical momentum fluxes of the Kelvin and mixed Rossby-gravity waves present in the tropical atmosphere. Recently, Sasi *et al* (1999) computed the momentum fluxes of equatorial waves from the Indian MST radar wind data.

Madden and Julian (1971, 1972) identified a larger period wave (40-50 days) mainly in the zonal component, propagating eastward in the tropical troposphere. Madden and Julian (1994) has given a review of this tropical oscillation. Many studies indicated that the oscillation appear both in the mid-latitudes as well as in the tropics (Knutson *et al.*, 1986; Lau and Chan, 1986; Lau and Phillips, 1986; Madden 1986; Chen, 1987; Hartmann and Gross, 1988). This may be true even for some period range (10-20 days) conventionally believed to be Kelvin waves, particularly during winter months when large westerlies prevail over the tropics and modes with substantial meridional velocity components are noticed. Studies manifest that these large scale waves may be due to the penetration from mid latitudes through the "westerly duct" in the equatorial troposphere or stratosphere (Wesbster and Chang, 1988; Raghavarao *et al.*, 1990; Nagpal and Raghavarao, 1991).

For mid-latitude disturbances to propagate into the tropics, the mean zonal flow must posses certain characteristics. Charney (1969) showed that the easterlies act as an effective barrier for wave propagation from mid-latitudes into the tropics. Webster and Holton (1982), on the other hand proposed that the region of equatorial westerlies, the so-called "westerly duct", act as an effective corridor for mid-latitude disturbances to propagate into the deep tropics. Zang and Webster (1989) have shown that the existence of equatorial westerlies in the eastern Pacific leads into a larger meridional extension of equatorial Rossby and MRG waves in the region, allowing a closer interaction between mid-latitude disturbances and these equatorial modes. The excitation mechanism by lateral forcing was originally proposed by Mak (1969) and later refined by Lamb (1973), Wilson and Mak (1984), Zhang and Webster (1992) and Zhang (1993). This theory involves the effect of extratropical disturbances on those in the tropics. Magana and Yanai (1995) showed that MRG waves are excited by the effect of mid-latitude disturbances propagating into the region of equatorial westerlies.

Chapter 3

Data and Methodology

3.1 General

Data obtained from Indian MST radar, radiosonde and National Center for Environmental Prediction/National Centres of Atmospheric Research (NCEP/NACR) Reanalysis Project have been used for the present work. The Indian MST radar provides information on wind data in the mesosphere, stratosphere and troposphere with very good resolution. As far as radiosonde data is concerned, data from Madras station is used for comparing the circulation features observed in the radar data. Although MST radars are invariably used in the field of middle atmosphere research, it provides data at a single station. This is a major drawback of studies that use VHF radar data. The present study attempts to understand the atmospheric phenomena and processes involved in the middle atmosphere of the Indian latitude that requires a regional coverage of the circulation features. In order to get a spatial coverage, data from NCEP/NCAR Reanalysis Project is widely used.

3.2 Data from the Indian MST Radar

Daily wind data for the period December 1995 to February 1996, June to August 1996 (JJA) and December 1997 to January 1998 from National MST Radar Facility (NMRF) at Gadanki (13.47° N, 79.18° E) have been used in the present study. The zonal (u), meridional (v) and vertical (w) velocities between 3.6 km to 30 km, with 150 m height resolution, extracted from the Doppler spectrum obtained daily at 1700 Indian Standard Time are used in the analysis. The spectral data are collected by the radar using 6-beam positions (east, west, zenith-X, zenith-Y, north, south) with 16 μs coded pulse and 1000 μs inter-pulse period (IPP).

3.3 NCEP/NCAR Reanalysis Data/Radiosonde Data

Monthly zonal and meridional wind during January-February 1996 and June-August 1996 from 1000 hPa to 100 hPa levels apart from daily data, from the NCEP/NCAR reanalysis are utilised in the study. From the monthly data winter and summer wind data between 30° S and 30° N are obtained by averaging the 2.5° x 2.5° gridded data over different longitudinal bands. Averaging in space for three longitudinal bands, *viz.*, 50° E - 65° E, 72.5° E - 82.5° E and 85° E - 95° E during summer and for 72.5° E -82.5° E during winter, have been carried out to understand the seasonal changes of the meridional circulation over Gadanki (MST radar) region in the troposphere and lower stratosphere. To study the circulation over Indian region, wind vector and contour analyses between 50° E and 100° E longitudes are used.

Daily zonal and meridional wind data from January 1 to March 18, 1996 are incorporated in the analysis to explain the synoptic features. Streamline analysis at 850 hPa, 500 hPa and 200 hPa from 60^0 to 100^0 E and equator to 40^0 N have been carried out using the NCEP/NCAR reanalysis data. Contour analysis of daily zonal wind data at 200 hPa from January 1 to March 18, 1996 between equator and 30° N is carried out to understand the wind in the upper troposphere. NCEP/NCAR wind data at 1200 GMT are used in the present study. The details of the NCEP/NCAR Reanalysis Project are given in Kalnay *et al.* (1996). Daily upper air wind data from the Madras radiosonde station during January 1996 is also included in the study to compare the wind and circulation features of the MST radar station.

3.4 Method of Analyses

3.4.1 Computation of u, v and w from MST Radar Doppler Spectrum

The Indian MST radar use Doppler Beam Swinging (DBS) method to determine the three wind components, *viz.*, u, v and w. The spectral data are collected by the radar using multiple beam positions (east, west, zenith-X, zenith-Y, north and south) with 16 μs coded pulse and 1000 μs IPP. The complex time series of the decoded and integrated signal samples are subjected to the process of Fast Fourier Transform (FFT) for on-line computation of the Doppler power spectra for each range bin of the selected range window. The off-line data processing for parameterisation of the Doppler spectrum involves five steps, namely (1) the removal of dc, (2) estimation of the average noise level, (3) the removal of interference, if any, (4) incoherent integration and (5) computation of the three low-order (0^{th}, 1^{st} and 2^{nd}) moments.

The flow chart (Fig. 3.1) shows the steps involved in the estimation of the atmospheric parameters. The dc contributions are eliminated by notching out the zero frequency and averaging the two adjacent Doppler bins to interpolate for a new zero frequency value. Hilderband and Sekhon's (1974) objective method is adopted for estimating the average noise level. The noise level is subtracted from the received power for each Doppler bin. Any interference band appearing in the entire range windows is subtracted out by estimating in a range bin where it dominates the real signal. If required, to improve the signal detectability, incoherent integration is implemented. The total range is then divided into specified number of window and following criteria are set up for each window for adaptive tracking of the signal for range bin to range bin: (a) Doppler window (b) SNR threshold and (c) maximum wind shear. Within the specified Doppler window, five potential spectral peaks are selected for each range bin and in the first scan (spectrum obtained using any one of the beam), the prominent peak in each range bin is checked against the SNR threshold and accepted if the criterion

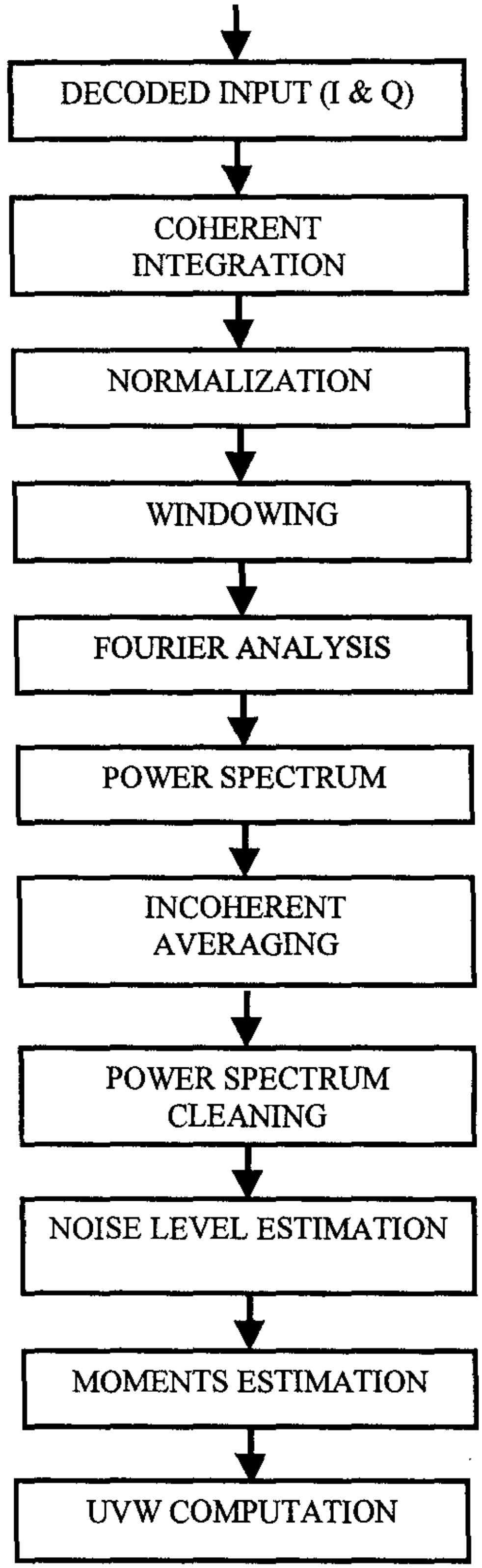

Fig. 3.1. Processing steps to estimate the atmospheric parameters from the radar spectrum

is satisfied. If the SNR criterion is not met, the most prominent candidate signal that meets the wind shear criterion is taken to represent the signal. The range bins that still remain unrepresented are filled in through interpolation of the spectral moments computed for the closest range bin. The parameters used for the three criteria are adjusted to provide the best Doppler profiles as judged by visual inspection. Then the three spectral moments are computed using the expression given by Woodman and Guillen (1985). The three moments are signal strength, weighted mean Doppler shift and half-width parameters of the spectrum, respectively.

The first moment give the Doppler shift (v_d) which provides a direct measurement of the radial velocity of scattering irregularities. After computing the radial velocity for different beam positions, the absolute velocity (u, v and w) can be calculated. To compute u, v and w, at least three non-coplanar beam radial velocity data are required. Since more than three beams are used the wind components are determined in a least square sense as described by Sato (1989). Here we need to make an assumption that the velocity field is uniform in the space over the volume, which contains the range cells used to compute a velocity vector. Then the height corresponding to off-vertical beams is converted into the true height. Details of the algorithm used to determine the three velocity components from the National MST Radar Facility (NMRF) Doppler spectra are given in the *Atmospheric Data Processor, Technical and user Reference Manual*, NMRF, Gadanki.

3.4.2 Cubic Spline Interpolation

In the study missing of data are encountered due to several reasons and they are interpolated using the Cubic Spline interpolation technique. One must use 'stiffer' interpolation provided by a so-called spline function in situation where continuity of derivatives is a concern. A spline is a polynomial between each pair of table points, but one whose coefficients are determined slightly non-locally.

The nonlocality is designed to guarantee global smoothness in the interpolated function upto some order of derivative. Most popular techniques are Cubic Splines. They produce an interpolated function that is continuous through the second derivative. Splines tend to be stabler than polynomials, with less possibility of wild oscillation between the tabulated points.

The number of points (minus one) used in an interpolation scheme is called the order of the interpolation. Increasing the order does not necessarily increase the accuracy, especially in polynomial interpolation. If the added points are distant from the point of interest x, the resulting higher-order polynomial with its additional constrained points tends to oscillate wildly between the tabulated values. The oscillation may have no relation at all to the behaviour of the true function. Of course, adding points close to the desired point usually does help, but a finer mesh implies a larger table of values, not always available.

Given a tabulated function $y_i = y\,(x_i\,)$, $i = 1, \ldots\ldots N$, focus attention on one particular interval, between x_j and $x_{j=1}$. Linear interpolation in that interval gives the interpolation formula.

$$y = A y_j + B y_{j+1} \qquad \ldots(3.1)$$

where

$$A \equiv \frac{x_{j+1} - x}{x_{j+1} - x_j}; \quad B \equiv \frac{x - x_j}{x_{j+1} - x_j} \qquad \ldots(3.2)$$

Equations (3.1) and (3.2) are the special case of the general Langrange interpolation formula.

Since it is (piece-wise) linear, equation (3.1) has zero second derivative in the interior of each interval, and an undefined or infinite, second derivative at the abscissa x_j. The goal of Cubic spline interpolation is to get an interpolation formula that is smooth in the first derivative and continuous in the second derivative, both within an interval and at its boundaries.

3.4.3 Discrete Fourier Transform

Any well-behaved continuous function can be described by an infinite Fourier series, *namely*, the sum of an infinite number of sine and cosine terms. In the case of a discrete time series with a finite number of points we are required to have only a finite number of points, only a finite number of sine and cosine terms are required to fit our points exactly.

Using Euler's formula,

$$e^{ix} = \cos x + i \sin x, \quad \text{where, } i = \sqrt{-1} \qquad \ldots(3.3)$$

Inverse Transform:

$$A(k) = \sum_{n=0}^{N-1} F_A(n)\, e^{i2\pi nk/N} \qquad \ldots(3.4a)$$

where n is the frequency and $F_A(n)$ is the discrete Fourier transform. A time series with N data points (indexed from k = 0 through N-1) needs no more than N different frequencies to describe it. *n* can be expressed in number of cycles (per time period, $\mathbb{P} = N\Delta t$, where Δt is the time increment of successive observation).

A frequency of zero (n=0) denotes a mean value. The *fundamental frequency*, where n = 1, means that exactly one wave fills the whole time period, ℙ. Higher frequencies correspond *to harmonics* of the fundamental frequency.

$F_A(n)$ is complex number, where the real part represents the amplitude of the cosine waves and the imaginary part is the sine wave amplitude. It is a function of frequency because the waves of different frequencies must be multiplied by different amplitudes to reconstruct the original time series. If the original time series A(k) is known, then these coefficients can be found from:
Froward Transform:

$$F_A(n) = \sum_{k=0}^{N-1} \left[\frac{A(k)}{N} \right] e^{-i2\pi nk/N} \qquad \ldots(3.4b)$$

Equations (3.4a) and (3.5b) are called *Fourier transform pairs*. The second equation performs the *forward transform*, creating a representation of the signal in *phase space* (another name for the frequency or spectral domain). This process is known as *Fourier decomposition*. The first equation performs the *inverse transform*, converting from frequencies back into *physical space*.

The sine and cosine form of equation (3.4b) is:

$$F_A(n) = \frac{1}{N} \sum_{k=0}^{N-1} A(k) \cos(2\pi nk/N) - \frac{i}{N} \sum_{k=0}^{N-1} A(k) \sin(2\pi nk/N) \qquad \ldots(3.5)$$

For n = 0, all of the cosines of zero are unity and all of the sines are zero. This leaves:

$$F_A(0) = \frac{1}{N} \sum_{k=0}^{N-1} A(k) \qquad \ldots(3.6)$$

Which is just the mean of A.

Aliasing and other hazards: A basic rule of discrete data analysis is that at least two data points are required per period or wavelength in order to resolve a wave. Since Fourier analysis involves splitting arbitrary signals into waves, the two data point requirement also holds for our arbitrary signals. For example, if there is a total of N data points, then the highest frequency that can be resolved in Fourier transform is $n_f = n/2$, which is called *Nyquist frequency*. These requirements apply to measurements; *namely*, if a wave period as small as 0.1 s must be measured while flying in an aircraft, then the physical signal must be digitised at least once every 0.05 s. Similarly, if a wavelength as small as 1 m must be measured, then the physical signal must be digitised at least once every 0.5 m.

What happens when there is a physical signal of high frequency that is not sampled or digitised frequently enough to resolve the signal? The answer is that the true high-frequency signal is *folded* or *aliased* into a lower frequency, creating an erroneous and deceiving Fourier transform. In other words, if n_h represents a frequency higher than the Nyquist frequency, then the signal or amplitude of that wave will be folded down to a frequency of $n = N - n_h$, where it will be added to any true amplitude that already exists at n. This folding or reflection occurs around the Nyquist frequency and hence it is known as *the folding frequency*. Any nonzero wave amplitude and spectral energies in the true signal at frequencies higher than the Nyquist frequency are folded back and added to the energies of the true signal at the lower frequencies, yielding an aliased (and erroneous) spectrum.

Data window: If we examine only a finite size record of data, the Fourier analysis implicitly assumes that the data is periodic and thus repeats itself both before and after the limited period of measurement. A Fourier analysis can indeed describe series such as saw-tooth or square wave patterns, but a wide range of frequencies are required to get the sum of all the sines and cosines to make the sharp bends at the points of the teeth. These spurious frequencies are called *red* *noise* by analogy to visible light because they appear at the low frequency end of the spectrum. To avoid red noise the data series are *detrended* by subtracting the straight line best-fit from the data segment, leaving a modified time series. In general, any very low frequency that has a period longer than the sampling period will also generates the noise. If we know a-priori the period of this frequency, such as diurnal or annual, then a least-square fit of this frequency to the time series is performed and subtracts the result from the series. Otherwise, a simple polynomial curve is fitted to the data and subtracts it to both detrend it and remove these low frequencies.

Even after detrending, the sharp edges of the data window cause what is known as *leakage*, where spectral estimates from any one frequency are contaminated with some spectral amplitude leaking in from neighbouring frequencies. To reduce leakage, a modified data window with smoother edges is recommended. Although a variety of smoothers can be used, a common one utilises sine or cosine squared terms near the beginning and ending, such as 10% of the period of record, and is known as a *bell taper*.

$$W(k) = \begin{cases} \sin^2(5\pi k/N) & \text{for } 0 \leq k \leq 0.1N \\ 1 & \text{elsewhere} \\ \sin^2(5\pi k/N) & \text{for } 0.9N \leq k \leq N \end{cases} \qquad \ldots(3.7)$$

When this window weight W(k) is multiplied by the time series A(k), the result yields a modified time series with fluctuations that decrease in amplitude at the beginning and end of the series. The Fourier transform can then be performed in this modified time series. The bell taper data window is not without its problems. Although the tapered ends reduced the leakage, they also reduce our ability to resolve spectral amplitude differences between small changes in frequencies.

Also, the tapered window reduces high-frequency noise at the expense of introducing low-frequency noise.

The process of detrending, despiking (removing erroneous data points), filtering and bell tapering is known as *conditioning* the data. Conditioning should be used with caution because it may introduce biases or errors in the data and the best recommendation is to do as little conditioning as is necessary based on data quality.

3.4.3.1 Discrete Energy Spectrum

The square of the norm of the complex Fourier transform for any frequency n is:

$$|F_A(n)|^2 = \left[F_{\text{real part}}(n)\right]^2 + \left[F_{\text{imag. part}}(n)\right]^2 \qquad \ldots(3.8a)$$

When $|F_A(n)|^2$ is summed over frequencies n = 1 to N-1, the result equals the total biased variance of the original time series:

$$\sigma_A{}^2 = \frac{1}{N}\sum_{k=0}^{N-1}(A_k - \overline{A})^2 = \sum_{n=1}^{N-1}|F_A(n)|^2 \qquad \ldots(3.8b)$$

Thus, $|F_A(n)|^2$ is the portion of variance explained by waves of frequency n.

The *discrete spectral intensity (or energy)*, $E_A(n)$, is defined as $E_A(n) = 2\cdot|F_A(n)|^2$ for $n = 1$ to n_f, with N = odd. For N = even, $E_A(n) = 2\cdot|F_A(n)|^2$ is used for frequencies from $n = 1$ to $(n_f - 1)$, along with $E_A(n) = |F_A(n)|^2$ at the Nyquist frequency. This is called *the discrete variance (or energy) spectrum*.

3.4.4 Spectra of Two Variables

3.4.4.1 Cross Spectra

Define $G_A = |F_A(n)|^2$ as the unfolded spectral energy for variable A and frequency n. Then $G_A = F_A^* \cdot F_A$, where F_A^* is the complex conjugate of F_A, and where the dependence of n is still simplified. Let $F_A = F_{Ar} + i \cdot F_{Ai}$, where subscripts r and i denote real and imaginary parts respectively. Now, the expression for the spectral energy can be written as,

$$\begin{aligned} G_A &= F_A^* \cdot F_A \\ &= (F_{Ar} - iF_{Ai}) \cdot (F_{Ar} + iF_{Ai}) \\ &= F_{Ar}^2 + iF_{Ai}F_{Ar} - iF_{Ai}F_{Ar} - i^2 F_{Ai}^2 \\ &= F_{Ar}^2 + F_{Ai}^2 \\ &= |F_A(n)|^2 \end{aligned} \qquad \ldots(3.9)$$

Similarly, the spectral intensity $G_B = F_B^* \cdot F_B$, for another variable B. The *cross spectrum* between A and B is defined as,

$$\begin{aligned} G_{AB} &= F_A^* \cdot F_B \qquad \ldots(3.10a) \\ &= F_{Ar}\, F_{Br} + i\, F_{Ar}\, F_{Bi} - i\, F_{Ai}\, F_{Br} - i^2\, F_{Ai}\, F_{Bi} \end{aligned}$$

Upon collecting the real and the imaginary parts, the real part is defined as the *cospectrum, Co,* and the imaginary part is called the *quadrature spectrum, Q*:

$$G_{AB} = Co - iQ \qquad \ldots(3.10b)$$

where

$$Co = F_{Ar}\, F_{Br} + F_{Ai}\, F_{Bi} \qquad \ldots(3.10c)$$

and

$$Q \quad = \quad F_{Ai}\,F_{Br} - F_{Ar}\,F_{Bi} \tag{3.10d}$$

Where F_A and F_B are functions of frequency n, making both Co and Q functions of n too: Co (n) and Q (n).

From the quadrature and co-spectra an *amplitude spectrum* can be defined as

$$\begin{aligned} Am &= G_{AB}^{*} \times G_{AB} \\ &= Q^2 + Co^2 \end{aligned} \qquad \ldots(3.10e)$$

A large amplitude at any frequency n implies that A is very strongly correlated to B at that frequency, regardless of phase differences between A and B. Also if the amplitude is small for any frequency n, then coherence and phase spectra are not significant for that frequency.

The coherence spectrum, Coh, is defined by,

$$Coh^2 = \frac{G_{AB}^{*}\,G_{AB}}{G_A\,G_B} = \frac{Q^2 + Co^2}{G_A\,G_B} \qquad \ldots(3.10f)$$

This is essentially a normalised amplitude and is a real number in the range 0 to 1 and it is not a function of phase shift.

Finally, a phase spectrum, ϕ, can be defined as,

$$\tan\phi = Q / Co \qquad \ldots(3.10g)$$

This can be interpreted as the phase difference between the two time series A and B that yielded the greatest correlation for any frequency n.

The cospectrum is frequently used in meteorology, because the sum over frequency of all cospectral amplitude, Co, equals the covariance between A and B (Stull, 1988). The quadrature spectrum is usually not used directly but it too has a physical interpretation. It is equal to the spectrum of the product of b' times a phase shifted a', where a' is phase shifted a quarter period of n. In other words, the amount of time lag applied to a' depends on the frequency, n, such that the phase shift is always 90° for each n.

Chapter 4

Studies on the characteristics of tropical waves during winter

4.1 Introduction

It is well known that in the equatorial region there are certain waves with longitudinal scales of over thousand kilometres and wave periods ranging from a few to a few tens of days. The large solar heat input received in the equatorial atmosphere generates various atmospheric waves and different types of wave disturbances are found over the tropical atmosphere. Rocketsonde and radiosonde measurements and satellite data have elucidated their existence and other characteristics. Because an inertial period rapidly increases near the equator, an intrinsic frequency range of waves that could propagate upward without vertical trapping becomes increasingly wider as well. Thus substantial efforts have been made over the past several years to delineate the numerous wave modes prevailing over the tropical latitudes using various data records.

Observational evidence indicates that, among various theoretically possible equatorially trapped wave modes, the Kelvin and mixed Rossby-gravity (MRG) waves are important for the large-scale dynamics of the tropical stratosphere. These wave modes are of planetary scale in the zonal direction, but are trapped in within about 15° north and south of the equator. The Kelvin and the mixed Rossby-gravity (MRG) waves have been extensively studied for many years since their initial discovery by Wallace and Kousky (1968) and Yanai and Maruyama (1966), respectively, among other various tropical waves (Maruyama, 1969; Wallace, 1973; Zangvil and Yanai, 1980; Salby *et al.*, 1984; Devarajan *et al.*, 1985; Cornish and Larsen, 1985; Krisna Murthy *et al.*, 1986). Kelvin waves (period in the range of 10-20 days) propagate eastward and downward while MRG waves (periods of the order of 4-5 days) propagate westward and downward. Many studies highlighted the role played by these waves in generating the quasi-biennial oscillation (QBO) in the equatorial lower stratosphere and the semi-annual oscillation (SAO) in the upper stratosphere and mesosphere (Holton and Lindzen, 1972; Plumb, 1982; Mahlman and Umscheid, 1984).

Recently, interest in the equatorially trapped waves in the troposphere and lower stratosphere has been revived (Randel, 1992; Takayabu and Nitta, 1993; Tsuda *et al.*, 1994). Several authors have expedited the theory of equatorial waves (Matsuno, 1966; Lindzen, 1967; Holton and Lindzen, 1968) and many experimental and modelling studies (Coy and Hitchman, 1984; Salby and Garcia, 1987; Garcia and Salby, 1987; Itoh and Ghil, 1988) revealed their source, generation and existence. Holton's model (1973) provides clear evidence that the diabatic heat source in the tropical troposphere is able to generate equatorial waves in the stratosphere.

Observed Kelvin waves have large amplitudes in the zonal wind component (u') with small meridional wind component (v'). Maximum amplitudes are found near the equator with period in the range of 10-20 days, moving eastward and downward with a phase speed of 25-30 ms^{-1} relative to the ground. Mixed Rossby-gravity waves, however, have lower periods, of the order of 4-5 days, and propagate westward and downward with a phase speed of 20 ms^{-1}. Mixed Rossby-gravity waves have fluctuations in the zonal as well as meridional wind components. Both the waves exhibits amplitudes of the order of 1.5×10^{-3} ms^{-1} in the vertical velocity component (Wallace, 1973).

The Kelvin wave plays a unique and important role in the equatorial stratosphere dynamics because it is apparently the only oscillation which can transport westerly momentum upward and hence produce westerly mean zonal wind accelerations in the equatorial stratosphere. A number of climatological studies (Wallace and Kousky, 1968b; Maruyama, 1969; Kousky and Wallace, 1971) have shown that the Kelvin waves reach maximum amplitude during the easterly phase of the QBO in the lower stratosphere. Kousky and Wallace (1971) showed that the

Kelvin waves are rapidly damped as they propagate into a westerly shear zone and that the resulting momentum flux convergence is sufficiently large to account for the observed westerly accelerations associated with the descending westerly phase of the quasi-biennial oscillation.

The mixed Rossby-gravity waves, on the other hand, have their greatest amplitudes during the easterly phases of the quasi-biennial oscillation. Theoretically it is shown that this mode should be able at least partially to account for the easterly accelerations associated with the descending easterly phase of the quasi-biennial oscillation. However, there is another possible source of easterly accelerations in the equatorial stratosphere, namely, the divergence of the northward horizontal eddy momentum flux associated with quasi-stationary planetary waves of the winter hemisphere (Tucker, 1965; Wallace and Newell, 1966; Hirota and Sato, 1970)

Of special significance for equatorial dynamics is the vertical structure of these waves. Both Kelvin and mixed Rossby-gravity waves transport wave energy and westerly momentum flux upward. However, unlike the Kelvin wave, the mixed Rossby-gravity wave does not in fact provide a net source of westerly momentum for the stratospheric mean flow. The net eddy forcing of the mean flow depends not only on the direct vertical flux of momentum (u'w'), but on the indirect forcing due to the lateral eddy heat flux as well. Like the amplitude distributions, the maximum fluxes are to be observed at the equator for Kelvin waves and at several degree latitudes of both hemispheres for mixed Rossby-gravity waves. It has been suggested that in the equatorial area the upper troposphere might supply the stratosphere with wave energy (Lindzen and Matsuno, 1968; Maruyama, 1968b; Yanai *et al.*, 1968). Maruyama (1969) studied the long term behaviour of these waves and their westerly momentum transport in the different stages of the quasi-biennial oscillation. He calculated the vertical momentum fluxes (u'w') due to these waves using co-spectrum analysis between zonal wind and temperature by assuming adiabatic processes and neglecting terms of horizontal advection. Yanai and Hayashi (1969) calculated the vertical energy fluxes of the equatorial waves using co-spectrum analysis of horizontal wind and temperature data. These calculations were indirect, because they lacked the direct measurement of vertical velocity (w). But Mesosphere-Stratosphere-Troposphere (MST) radars provide direct measurement of the station's vertical velocity (w) in the lower and the middle atmosphere. A cross-spectrum analysis between zonal and vertical velocity will give the vertical momentum fluxes of the Kelvin and mixed Rossby-gravity waves present in the tropical atmosphere. Recently, Sasi *et al* (1999) computed the momentum fluxes of equatorial waves using cross-spectrum analysis using the Indian MST radar data.

Furthermore, Madden and Julian (1971, 1972) identified a larger period wave (40-50 days) mainly in the zonal component, propagating eastward in the tropical troposphere. Many studies indicated that these waves appear both in the midlatitudes as well as in the tropics (Knutson *et al.*, 1986; Lau and Chan, 1986; Lau and Phillips, 1986; Madden 1986; Chen, 1987; Hartmann and Gross, 1988). This may be true even for some period range (10-20 days) conventionally believed to be Kelvin waves, particularly during winter months when large westerlies prevail over the tropics and modes with substantial meridional velocity components are noticed. Studies manifest that these large scale waves may be due to the penetration from mid latitudes through the "westerly duct" in the equatorial troposphere or stratosphere (Wesbster and Chang, 1988; Raghavarao *et al.*, 1990; Nagpal and Raghavarao, 1991).

For mid-latitude disturbances to propagate into the tropics, the mean zonal flow must posses certain characteristics. Charney (1969) showed that the easterlies act as an effective barrier for wave propagation from mid-latitudes into the tropics. Webster and Holton (1982) proposed that the region of equatorial westerlies, the so called "westerly duct", act as an effective corridor for mid-latitude disturbances to propagate into the deep tropics. Zang and Webster (1989) have shown that the existence of equatorial westerlies in the eastern Pacific leads into a larger meridional extension of equatorial Rossby and mixed Rossby-gravity waves in the region, allowing a closer interaction between mid-latitude disturbances and these equatorial modes. Recently, interest in the equatorially trapped waves in the troposphere and lower stratosphere has been revived (Maruyama, 1991; Randel, 1992; Dunkerton, 1993; Takayabu and Nitta, 1993). Magana and Yanai (1995) showed that mixed Rossby-gravity waves are excited by the effect of mid-latitude disturbances propagating into the region of equatorial westerlies. The excitation mechanism by lateral forcing was originally proposed by Mak (1969) and later refined by Wilson and Mak (1984), Zhang and Webster (1992) and Zhang (1993). This theory involves the effect of extratropical disturbances on those in the tropics.

The main objective of the present study is to identify various types of waves present over a tropical station and their characteristics during winter season (December-February). Data from the Indian MST radar at Gadanki (13.47° N, 79.18° E) during 1995-96 winter have been used for the purpose.

4.2 Data

Daily observations of zonal (u), meridional (v) and vertical (w) velocity components with 150 m height resolution from December 1, 1995 to March 18, 1996 taken at 1200 GMT have been collected from the MST Radar. Considering the location of the radar station (13.5° N, 79.2° E), daily zonal wind at 1200 GMT and at 200 hPa along 80° E longitude from the NCEP/NCAR reanalysis project (Kalnay *et al.*, 1996) during January-March, 1996, is used to assess the mean wind to the north and south of the radar station. Gaps in the radar derived wind data are interpolated using the cubic-spline method.

As the Signal-to-Noise Ratio (SNR) is found to be low at upper levels, the MST radar data analysis has been carried out upto 22 km. The radar wind components are block averaged in height for every 1.05 km (7 altitude levels of 150 m resolution) using running mean, thereby reduce analysis to 18 levels. Since the aim is to resolve wave characteristics during winter season, data used in the spectrum analysis is limited from December 1995 to February 1996 (90 days), representing the winter season.

To understand the wave characteristics, Discrete Fourier Transform (DFT) in u and v components and cross-spectrum analysis between u and w components were carried out. All the three wind components are *detrended* to remove presence of any long-term trend and tapered on both ends of the data to reduce leakage of the spectral amplitude from neighbouring frequencies. The Fourier spectrum extracts the variances of the zonal (u'^2) and meridional (v'^2) winds while the cross-spectrum estimate co-spectrum (u'w'), quadrature spectrum and coherence squared (Coh^2) values.

4.3 Results and discussion

4.3.1 *Mean wind and wave structure at Gadanki during winter 1995-96*

Figure 4.1 shows the monthly mean vertical profiles of zonal wind (u) during winter season (December-February). Zonal wind in December between 4 and 22 km is westerly and the maximum wind speed is noted in the 8-13 km region with a speed of about 12 ms^{-1}. In the month of January the zonal wind has become weak compared to that of December with almost uniform speed in the troposphere and

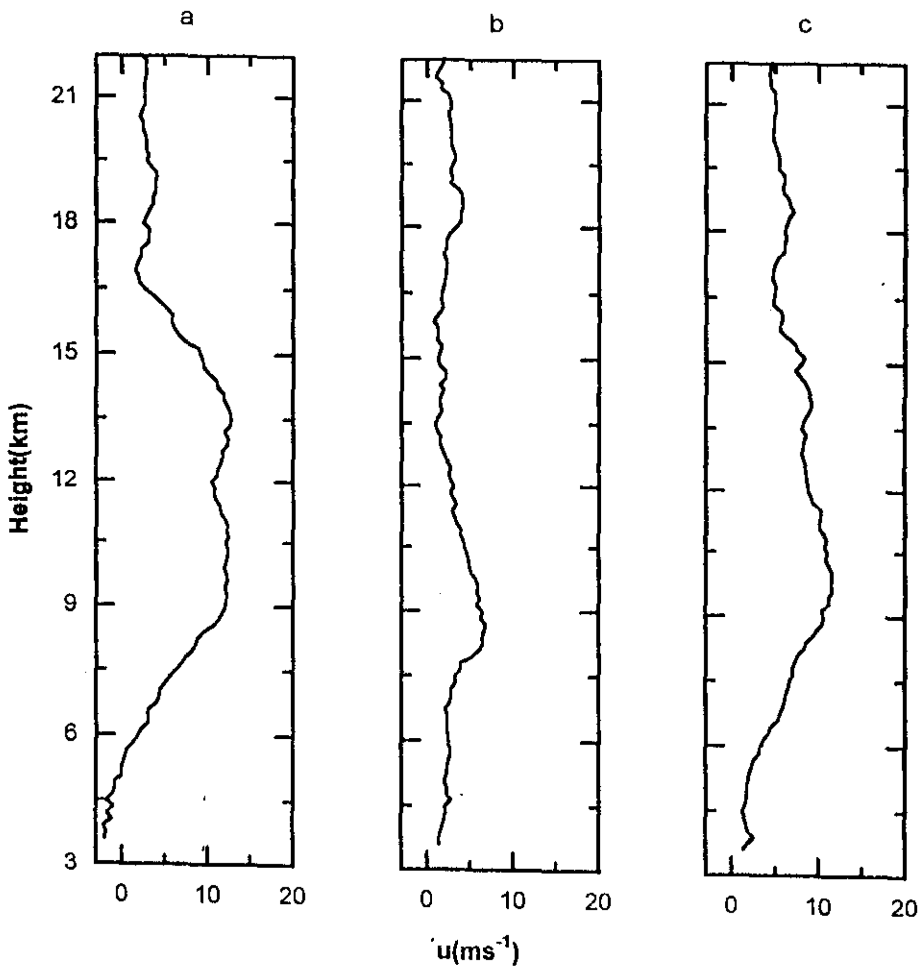

Fig. 4.1. Monthly mean vertical profiles of zonal wind (u) during winter 1995-96 at Gadanki

lower stratosphere. During February, the winter westerlies regain their strength in the entire troposphere and lower stratosphere.

Strong wave activities can be noticed with different time and vertical scales in the zonal wind component (Fig. 4.2(a)) with long period waves dominating at all levels, especially in the middle and upper troposphere, where oscillations with a period of about 22-day is prominent. A wave with a period around 10-12 days can be traced from troposphere into the lower stratosphere with phase lines tilting eastward and downward. Even though the u component shows short scale variations, their periods are not clearly discernible as in the case of long period waves. Fig. 4.2(b) explains the oscillations present in the meridional wind component and shows much of the variance in the low frequency modes. In the upper troposphere long period oscillations are more dominating. Periodic oscillations with a period of 22 days are present in the v component. Although large variances are noticed, their periodicities differ from the zonal component and not clearly seen from the mere time-height plots.

4.3.2 *Spectrum of zonal (u) and meridional (v) winds*

Figure 4.3 shows the variance at different levels in u and v components at three selected levels, representing mid-troposphere (8.25 km), upper troposphere (13.50 km), and lower stratosphere (18.75 km). Logarithm of period is plotted along the ordinate against variance along the abscissa. In mid-troposphere and lower stratosphere the 22-day oscillation is conspicuous, whereas in the upper troposphere 40-50 day oscillation is prominent in the zonal wind. Another oscillations with a period of 10-15 days are also present in the zonal wind component in the troposphere and lower stratosphere. Waves with 22-day period are strong in the meridional wind in middle and upper troposphere and weak in the lower stratosphere. In the upper troposphere and lower stratosphere, the presence of 40-50 day oscillation is very weak with some variance in the mid-troposphere.

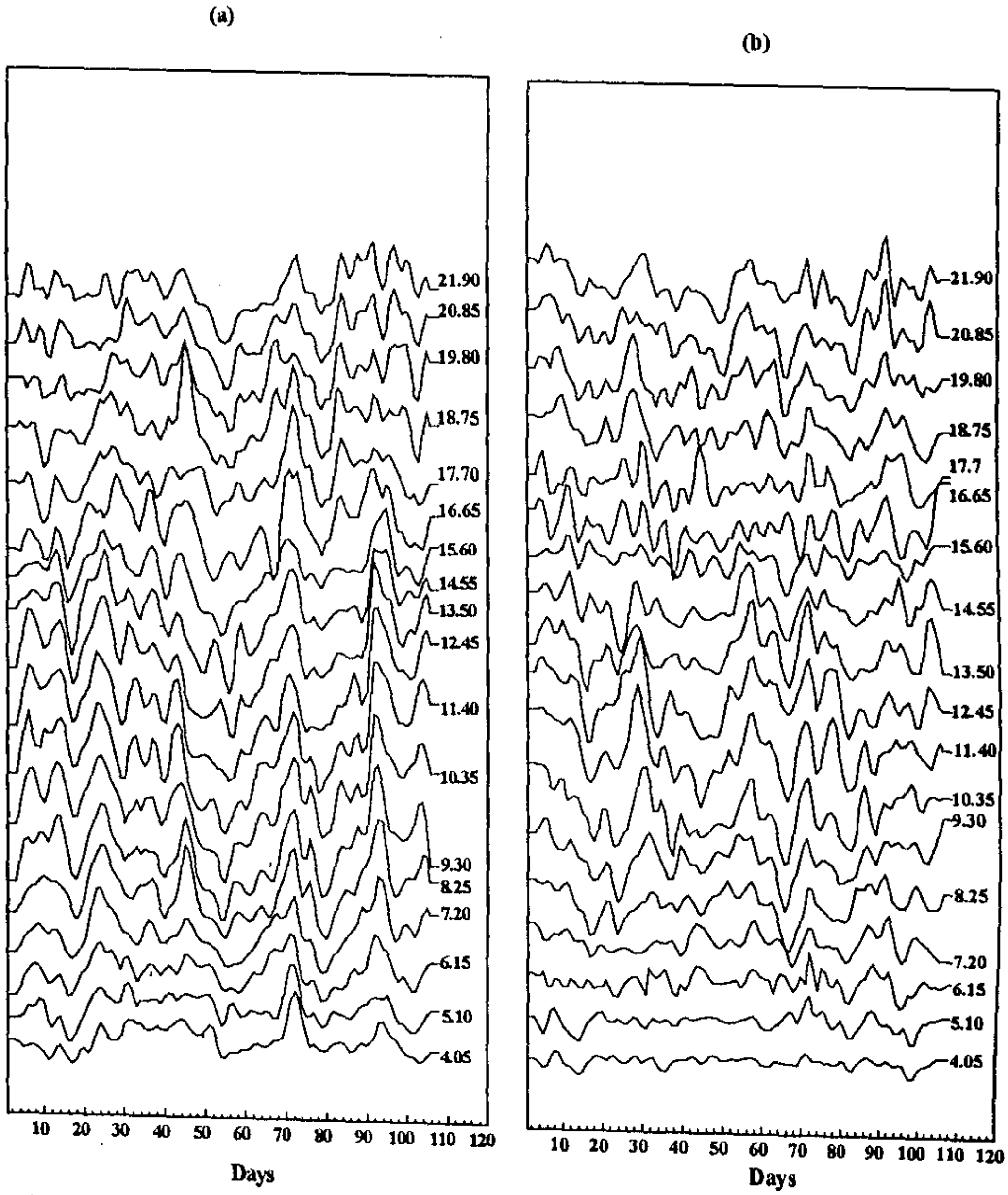

Fig. 4.2. Zonal (a) and meridional (b) wind at different levels (levels in km are noted to the right side) from December 1, 1995 to March 18, 1996

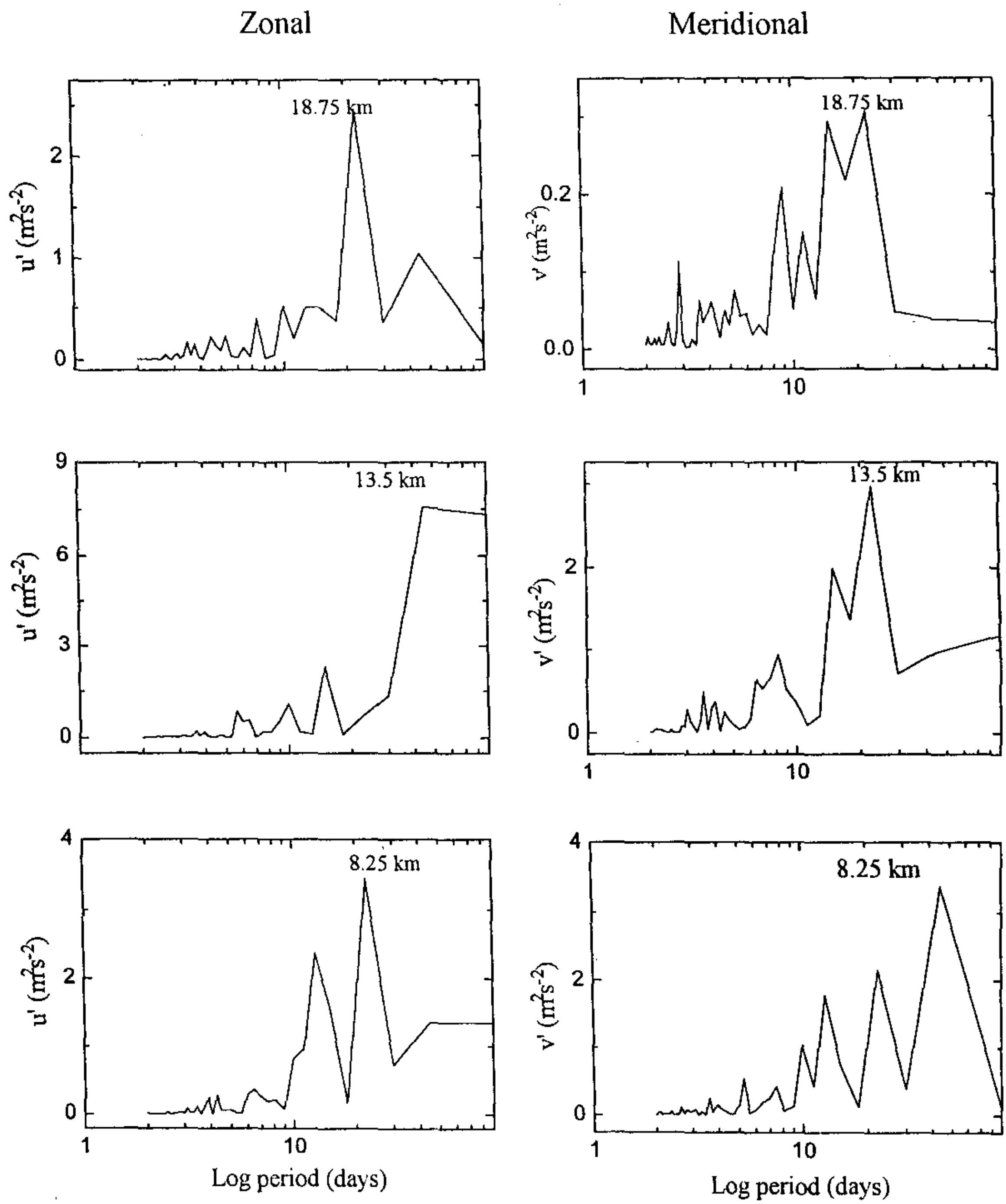

Fig. 4.3. Fourier spectra of zonal and meridional wind at different levels during winter 1995-96

Figures 4.4 (a) and 4.4(b) represent the frequency-height plots of u'^2 and v'^2, respectively. The periods are represented in frequency (number of cycles/90 days). It is seen that the variance in 22-day wave is large in the middle troposphere, while it is the maximum around 40-50 day period in the upper troposphere. Large meridional variance is noted near 22-day period in the middle and upper troposphere. The 15-day and 10-day period waves are also noted in both the zonal and meridional wind components.

To understand the behaviour of these periods (10, 15, 22 and 45 day) in the troposphere and lower stratosphere, u'^2 and v'^2 values are plotted against altitude as shown in Figs. 4.5(a)-(d). A common feature noted is that the variances are large in the middle and upper troposphere. In the case of 10-day oscillation both zonal and meridional components show maximum variance at 11 km, in which the zonal variance is relatively higher than that of the meridional component, characteristic similar to that of Kelvin waves (see Fig. 4.5(a)). They show maximum variance in the upper troposphere since the middle atmosphere is believed to be the source region of equatorial waves (Andrews *et al.*, 1987). In the case of 15-day wave it exhibit two peaks in the troposphere, the first is observed at 9 km altitude and the second around 13-14 km height. In between these two altitudes the u'^2 is minimum where the meridional component exhibits the peak variance (Fig. 4.5(b)). Figure 4.5 (c) illustrates that u'^2 attains the maximum and v'^2 registers the minimum around 7 km in the case of 22-day oscillation. But, v'^2 increases with height and reaches the maximum around 12 km and decreases thereafter. Thus it is clear that 15-day and 22-day waves are present both in u and v components, which are characteristics of Rossby type waves. The zonal component shows largest variance in the upper troposphere (centred around 13-14 km) in the case of 45-day oscillation (see Fig. 4.5(d)) with less variance in v component as reported by Madden and Julian (1971,

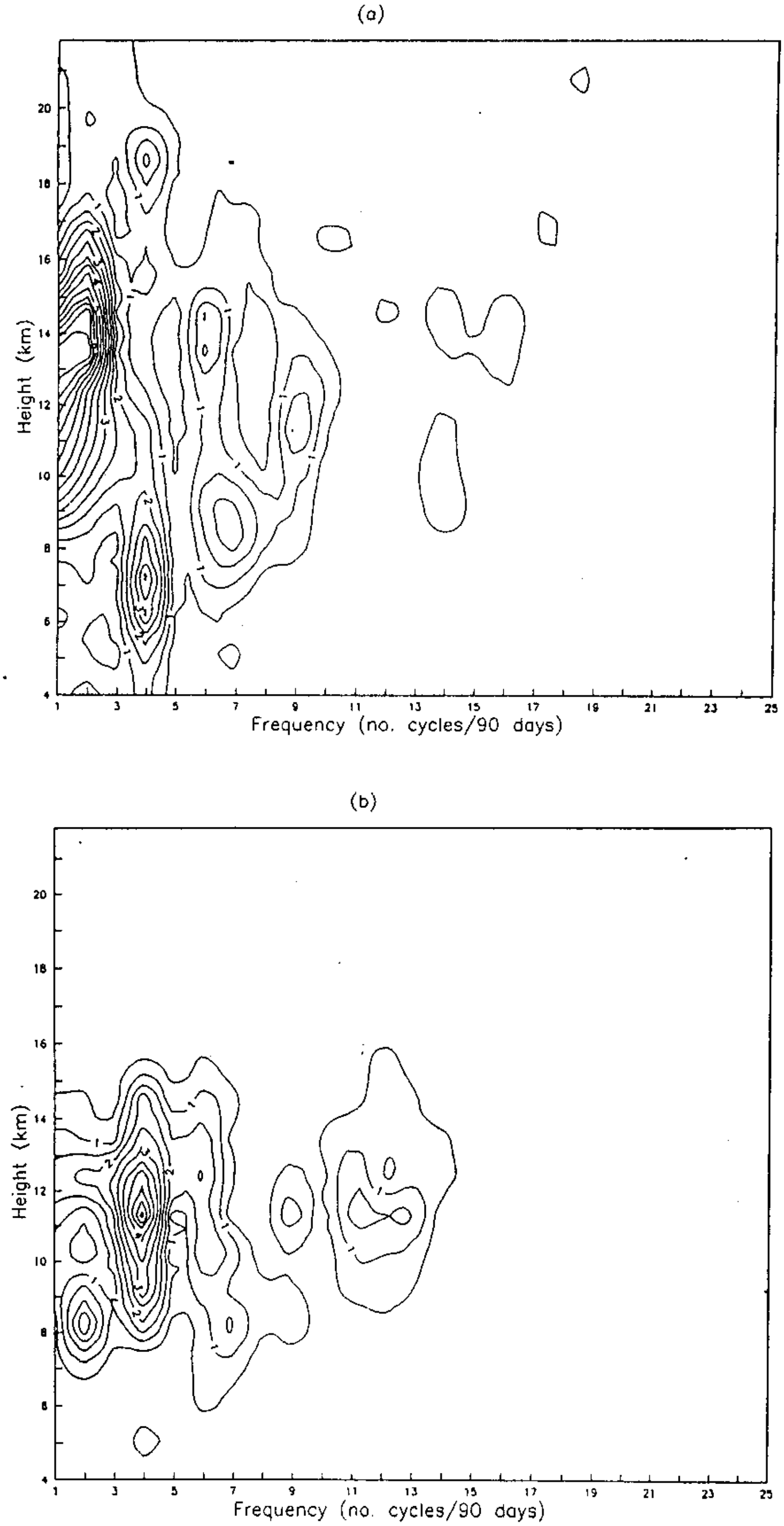

Fig. 4.4. Frequency-height plots of variance in the zonal (a) and meridional (b) winds

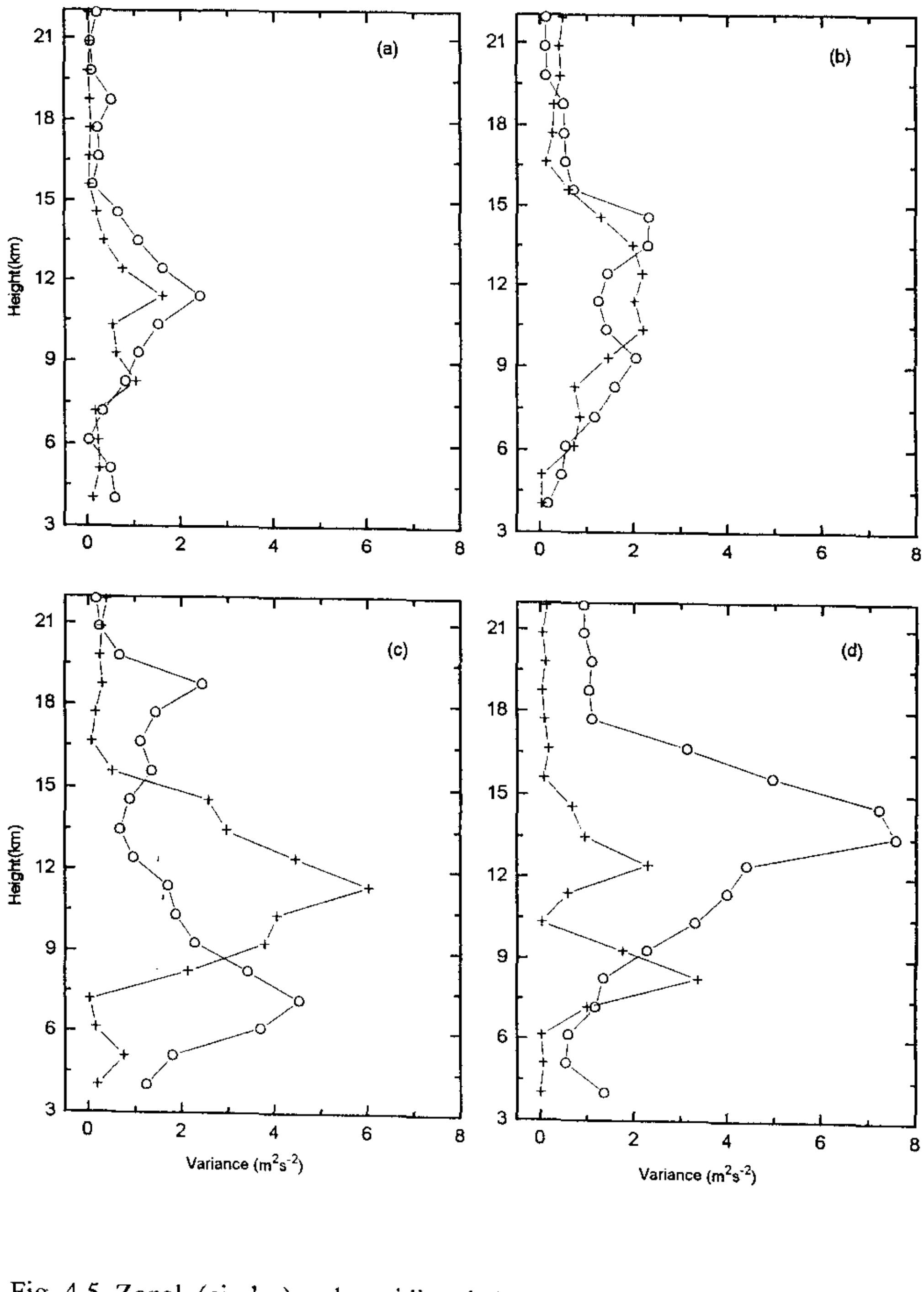

Fig. 4.5. Zonal (circles) and meridional (crosses) wind variance for 10 (a), 15 (b), 22 (c) and 45 (d) day oscillations

1972). Kumar and Jain (1994) observed presence of a 30-70 day oscillation in both the zonal and meridional winds over Indian tropical middle atmosphere. In the present study, the observed variance in the zonal component for the 45-day oscillation is very large, compared to that in the meridional wind.

Vertical variation of u'w' and Coh^2 for 10-, 15-, and 22-day waves are illustrated in Figs. 4.6(a) - 6(c), respectively. Fig. 6(a) shows that above 11 km u'w' is positive and is highly coherent, whereas in the lower levels (i.e., below 10 km) negative values (u'w') are noted. As suggested by Holton (1992), the u' and w' have positive correlation so that u'w' > 0 in the case of Kelvin waves and carries momentum upward. From Fig. 4.6(a) it is evident that the wave with period of 10 days propagate from the troposphere to the lower stratosphere and indicate that they are of tropospheric origin. An eastward tilt of 10-12 day waves is also seen in Fig. 2(a), confirms the existence of Kelvin wave. Yanai and Hayashi (1969) computed indirectly the vertical transport of wave energy by equatorial waves from horizontal wind and the temperature, since observed vertical velocity was not available then. Maruyama (1969) indirectly estimated transport of westerly momentum flux by the equatorial Kelvin and MRG waves using wind and temperature. However, MST radars can provide accurate measurements of vertical velocity (w) at different levels with high resolution and thus provide information on the westerly momentum fluxes transporting to the upper atmosphere. Sasi *et al.* (1999) identified a slow Kelvin wave (12-day) transporting westerly momentum upward in the upper troposphere.

The co-spectrum (covariance), u'w', for 15-day wave is negative in most of the levels with high coherence as seen in Fig. 4.6(b). The positive values are having small Coh^2 compared to that of negative u'w'. From Fig. 4.6(c), it is seen that u'w' of 15-day wave is large and negative at almost all levels, except at some heights ranges, with high Coh^2 values. The phase-altitude profile of zonal wind for 22-, 15-, and 10-day

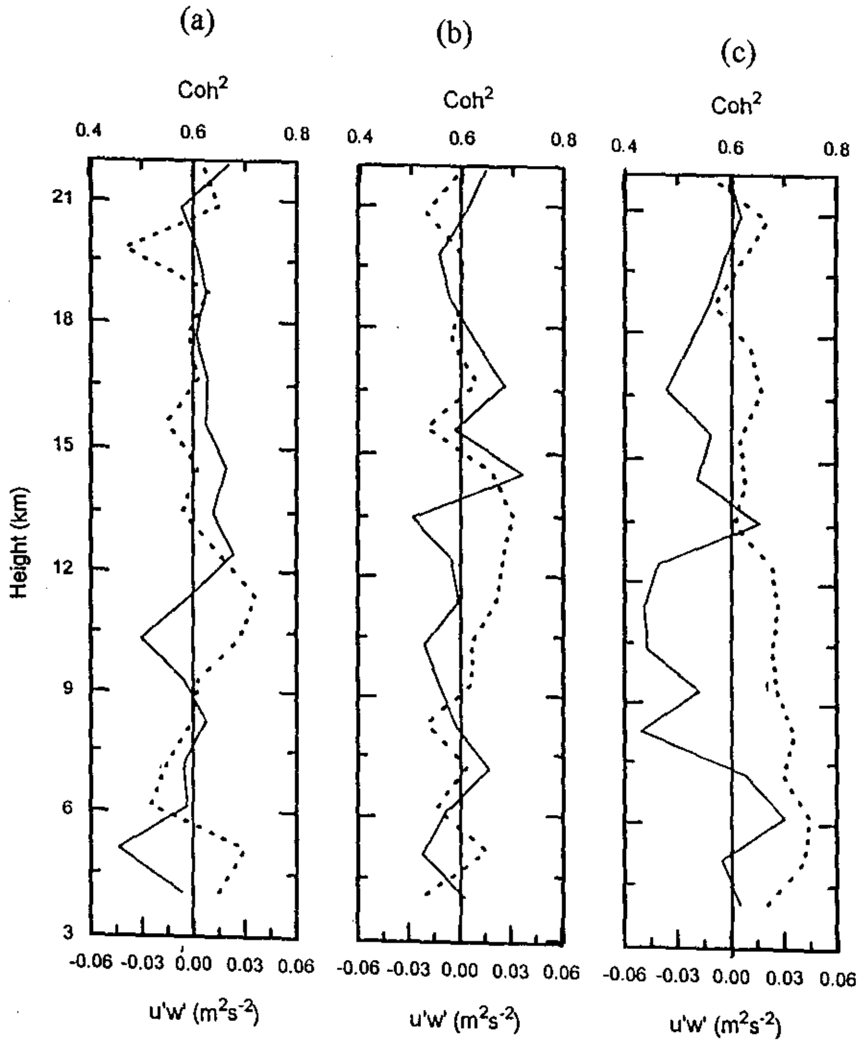

Fig. 4.6. Co-spectrum (u'w') between u and w and Coh^2 values (dotted line) for 10 (a), 15 (b) and 22 (c) day waves. Lower scale is for u'w' and upper scale for Coh^2

waves are shown in Figs. 4.7(a)-(c), respectively. It is noted that the 22-day wave shows downward phase propagation with height, whereas in the case of 15-day wave downward phase propagation is seen below 13.5 km region. From Fig. 4.7(c), downward propagation is found for the 10-day wave that may be a convectively activated type as reported by earlier studies (Holton, 1972; Dhaka *et a l.*, 1993).

Wave modes other than Kelvin and mixed Rossby-gravity waves can exist in the tropical troposphere as reported by many studies (Madden, 1986; Lau and Phillips, 1986; Chen, 1987; Raghavarao *et al.*, 1990). As the *westerly duct* during winter season acts as an effective corridor for large-scale waves, their penetration from mid-latitudes into the tropics is possible (Nagpal and Raghavarao, 1991). Fig. 4.8 shows the monthly mean zonal wind at 80° E during January-March, 1996 between equator and 30° N at 200 hPa (upper troposphere). It can be noticed that strong westerlies prevail north of Gadanki and extend upto 8° N equatorward. From the zonal wind at Gadanki and the upper tropospheric wind at other latitudes, it is seen that the condition is favourable for propagation of mid-latitude disturbances equatorward (Webster and Holton, 1982). Dhaka *et al.* (1993) using rocketsonde data at different stations over Indian region identified a Rossby mode with 18-day period when there exists westerly wind over the region. The 15-day and 22-day waves in the present study show large variances in the zonal and meridional winds. Further, positive correlation between u and w is absent as would be in Kelvin waves, these waves may possibly be Rossby modes penetrating from the mid-latitudes through the *westerly duct* or may be originating in the vicinity.

4.4 Conclusion

From the present analysis, it is seen that during winter season the waves passing through the tropical station, Gadanki, consist of both equatorial modes and

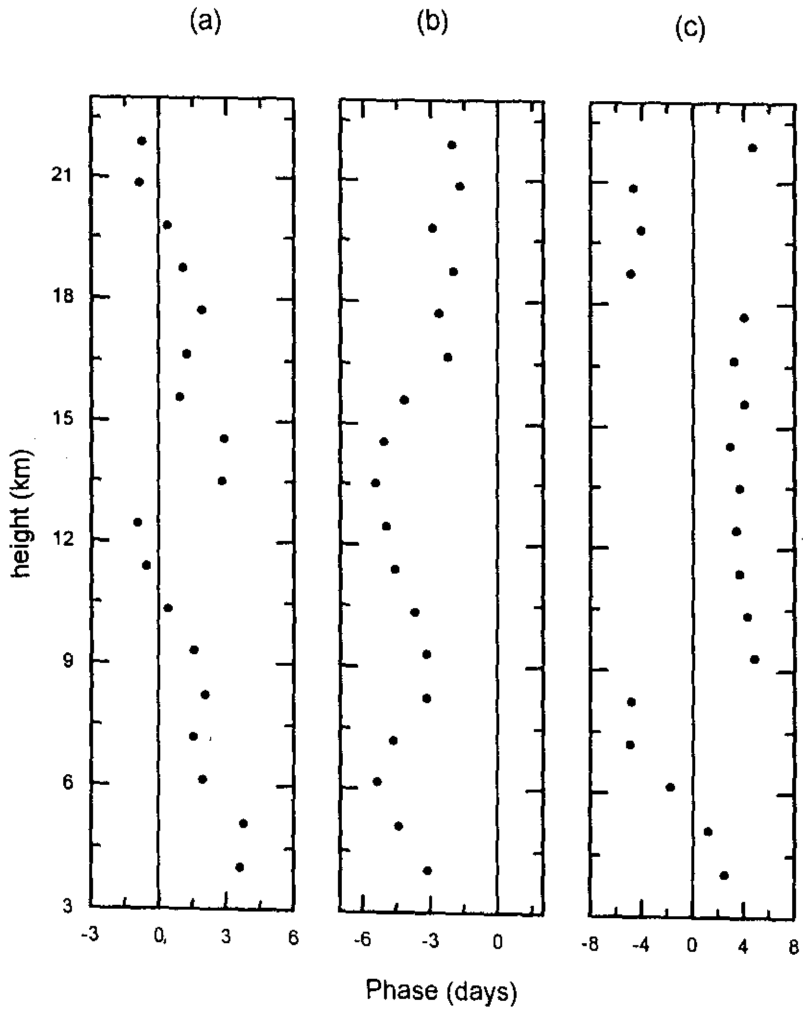

Fig. 4.7. Variation of phase (time of maximum) with altitude for 22 (a), 15 (b) and 10 (c) day waves

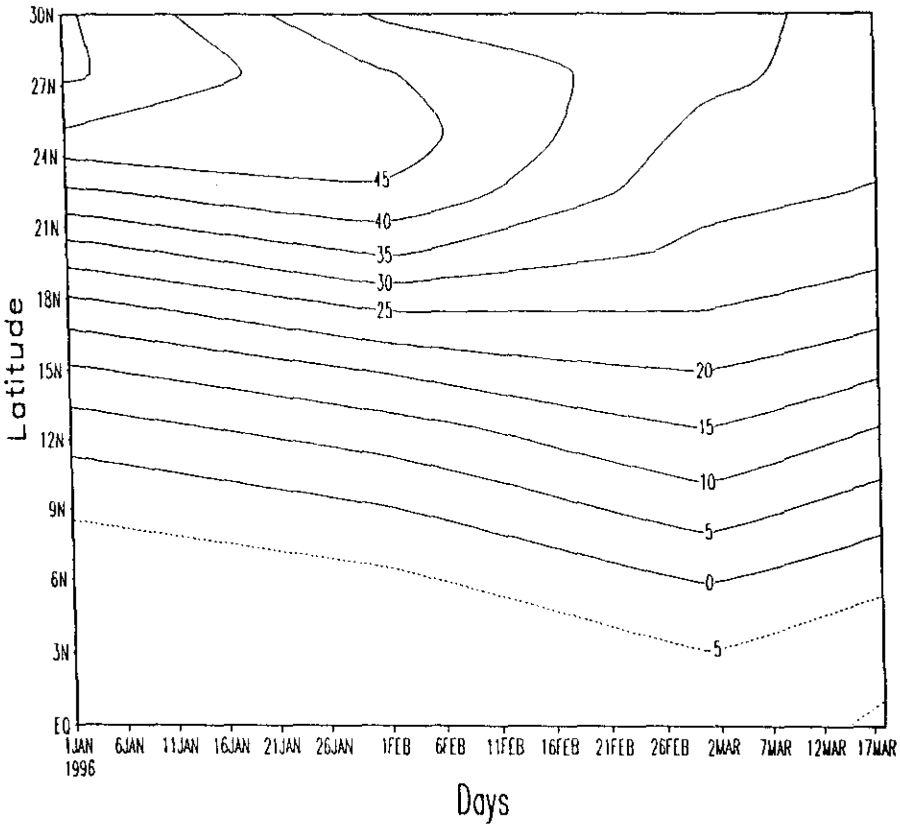

Fig. 4.8. Time-latitude distribution of daily zonal wind (u) at 200 hPa along 80° E longitude

long period Rossby modes penetrating equatorward through the *westerly duct* or originating in the vicinity. As the NCEP/NCAR reanalysis data illustrated the presence of westerlies (*westerly duct*) between 8° N and 30° N, it act as a corridor for the propagation of large scale disturbances originating in the mid-latitudes. Large zonal and meridional variances found in 15-day and 22-day wave show that they are Rossby type waves. The covariance between u and w is observed to be highly coherent and generally negative for the 15-day and 22-day waves. It is noted that the zonal variance of 10-day wave is relatively large compared to the meridional variance and shows downward phase propagation. Further, these waves are found to be transporting westerly momentum to upper levels, denotes the presence of Kelvin waves.

Chapter 5

Vertical motion in monsoon Hadley circulation over India

5.1 Introduction

In order to study the meridional circulation and for assessing vertical and horizontal transport processes, knowledge of vertical motion is essential. Transport of heat, moisture and momentum and natural and anthropogenic materials is the manner by which the vertical motion provides linkage between the lower and upper atmospheres. Direct measurements of vertical velocity using VHF radars enable the computation of vertical momentum fluxes due to different types of short and long period atmospheric waves (Vincent and Reid, 1983, Sasi *et al.*, 1999). Moreover, dynamical, chemical and radiative coupling between the stratosphere and troposphere are among the many important manifestations of the vertical motion. Anthropogenic chemical substances transported from the troposphere into the stratosphere are responsible for the stratospheric ozone depletion (WMO, 1995). Downward transport from the stratosphere not only constitutes the main removal mechanism for many stratospheric constituents, including those involved in ozone depletion, but also represents a major input of ozone and other reactants into the tropospheric chemical system (Levy *et al.*, 1980). Thus an understanding of vertical circulation is a very important aspect in the stratosphere-troposphere exchange processes.

Earlier workers (Craig and Lateef, 1962; Finger and Teweles, 1964; Quiroz, 1969; Newson, 1974; McInturff, 1978; Weisman and Olivero, 1979) have carried out computation of vertical velocity for different seasons and latitudes using indirect methods. Recently MST radars operating in VHF band have become a reliable technique to measure the three dimensional wind field in the Mesosphere-Stratosphere-Troposphere (MST) region of the atmosphere over the station (Woodman and Guillan, 1974; Green *et al.*, 1975) with good spatial and temporal resolution. One such radar operating at 53 MHz frequency has been established in 1993 at Gadanki (13.4° N, 79.18° E) India. Many studies were carried out using MST radar on vertical velocities and also its variation due to meteorological effects (Nastrom *et al.*, 1985; Ecklund *et al.*, 1985; Larsen *et al.*, 1988; Sato, 1990). Much longer time-scale, like mesoscale and synoptic-scale, vertical motions are important because they are useful to meteorological forecasting and dynamic processes. Clark *et al.*, (1993) and Nastrom *et al.*, (1994) have shown downward mean motions of several cm s^{-1} in the middle and upper troposphere at mid-latitudes and have discussed many possible causes for descent in the troposphere. Fukao *et al.*, (1991) and Nastrom *et al.*, (1994) also observed such downward motions at different sites. Warnock *et al.*, (1994) and Nastrom *et al.*, (1994) showed that synoptic-scale vertical velocity could be measured by wind-profiling radars with useful precision.

Seasonal mean vertical velocity studies were carried out using the Poker Flat MST radar at Alaska by Nastrom and Gage (1984) and noted downward motions as also by Nastrom and VanZandt (1994). Variations of seasonal vertical velocities were carried out by Nastrom and Eaton (1995) using four years of data from White Sands Missile Range (WSMR), New Mexico, MST Radar and reported negative values during all seasons with a small region of upward motions in the lower stratosphere. Theoretical studies (Nastrom and VanZandt, 1994) shows that mean vertical velocity will be proportional to vertical velocity variance and studies on seasonal vertical variance were done by Nastrom *et al.*, (1996) and found some relationship between vertical velocity and their variance.

Earlier studies on vertical motions in Indian regions were based on rocketsonde data form which indirect calculations were performed using thermodynamic equations with geostropic assumptions. Mukherjee and Ramana Murty (1973) and Mukherjee *et al.*, (1984) calculated seasonal vertical velocity for different seasons in the stratosphere and mesosphere of the Indian tropical atmosphere using weekly rocketsonde data. Their studies reported downward motion in the middle atmosphere but did not provide possible causes of the descent of the middle atmospheric air. Rao *et al.*, (1997) using the x- and y-polarization beams carried out studies on seasonal mean vertical motions using Indian MST radar still without any possible causes for the observed vertical velocity characteristics.

In India, the summer season is when the southwest monsoon (June-September) occurs. Winter season is December to February. Over India the meridional vertical circulation has a reversal in direction from winter to summer. During monsoon season, the symmetric Hadley cell of the Northern Hemisphere (NH) is replaced by an asymmetric circulation over the monsoon region. The usual Hadley cell exists over two-thirds of the tropics but over the monsoon region a reverse Hadley cell, the upper limb of which extending even up to 35° N, exists (Oort and Rasmusson, 1971; Schulman, 1973). Such a reverse Hadley cell introduces rising motion at about 25° N - 35° N that would result in sinking motions over the south Indian region and further south. The heating contrast of the Asian continent with respect to the Indian Ocean and the latent heat release in the monsoon trough region sets up a vertical Hadley type circulation with southerlies in the lower levels and northerlies in the upper levels. The Hadley circulation during winter season has upward motions in the Inter Tropical Convergence Zone (ITCZ) of the Southern Hemisphere (SH) and sinking motion over the entire Indian region. Thus during most parts of the year, except for brief periods when ITCZ is present close-by, Gadanki experiences downward vertical motion.

The vertical velocity observed from the Indian MST radar (Rao *et al.*, 1995) is compared with other studies carried out over the Indian tropical atmosphere during different seasons. Also from the observed three-dimensional velocities during 1995-96 the change in the meridional circulation and the associated vertical circulation are documented.

5.2 Data

Daily wind data from the Indian MST Radar is used to study the vertical motion field in winter and summer for the period from December 1995 to February 1996 (DJF), and June to August 1996 (JJA). The zonal (u), meridional (v) and vertical (w) velocities between 3.6 km to 22.0 km extracted from the Doppler spectrum obtained daily at 1200 GMT are used in the analysis. NCEP/NCAR reanalysed monthly zonal and meridional wind during January-February 1996 and June-August 1996 for different levels is also utilised (Kalnay *et al.*, 1996). Winter (1996) and summer (1996) wind data between 30° S and 30° N are obtained by averaging the 2.5° x 2.5° gridded data over different longitudinal bands. To study the circulation over the region between 50° E and 100° E, wind vector and contour plots are used. Averaging in space for three longitudinal bands, *viz.*, 50° E - 65° E, 72.5° E - 82.5° E and 85° E - 95° E during summer and for 72.5° E - 82.5° E during winter, is done to understand the seasonal change of the Hadley circulation and the anomalous southwest monsoon flow observed over the Gadanki region in the lower troposphere. Missing in the radar data are interpolated using the cubic-spline technique.

5.3 Results

5.3.1 Hadley Cell (Circulation)

The tropical regions of the earth are the area between the tropic of Cancer and the tropic of Capricorn, the parallels at latitudes at 23.5° N and S. As a large part of the solar radiation reaching the earth is received in the tropics, the tropical belt plays an important role in the general circulation of the atmosphere. The tropics are major sources of heat, moisture and angular momentum. These regions are receiving more energy from the sun than they radiate back and the large oceanic region stores a good part of this energy. Massive amounts of heat and moisture are carried with the air that moves in the Hadley circulation. Heat and moisture are carried into the upper parts of the atmosphere through the rising limbs of the Hadley cells and in the upper troposphere these are turned poleward. The poleward transport of moisture is a heat source for the atmosphere, which is redistributed to higher latitudes by the upper branches of the Hadley cells (McGregor and Nieuwolt, 1998). Thus, the general circulation over the tropics is geared to the requirement of transporting the excess heat of the tropics to the higher latitudes, by atmosphere and ocean. The observed Hadley circulation is however confined to the tropics (Holton, 1992). In the tropics, the Hadley cell serves as the basic mechanism for transporting heat poleward and reducing the tropical north–south temperature gradient. India lies mostly within the tropics.

5.3.2 Vertical circulation during winter 1995-'96 (DJF)

Winter (December, January and February) mean zonal (u), meridional (v) and vertical (w) wind components over Gadanki are plotted with height as illustrated in Fig. 5.1. From Fig. 5.1, it is seen that zonal winds (u) during winter over Gadanki are westerlies between about 4 km and lower stratosphere. Maximum westerly wind of about 10 ms^{-1} is noted at 9 km. The mean meridional wind (v) is northerly below about 10 km, which changes to southerlies at upper levels. Southerly winds above 16 km are very weak. Strong southerlies are noted in the upper troposphere with a maximum of about 6 ms^{-1} near 12 km. The observed vertical velocity (w) over the station is downward above 4 km and in the lower stratosphere. The vertical component shows strong descending motion with a maximum value of about 0.1 ms^{-1} at all the levels except a rising motion of 0.1 ms^{-1} near 14 km region.

It is well known that during the winter season the ITCZ is situated in the south Indian Ocean (Asnani, 1993). Thus the rising limb of the Hadley cell is in the SH

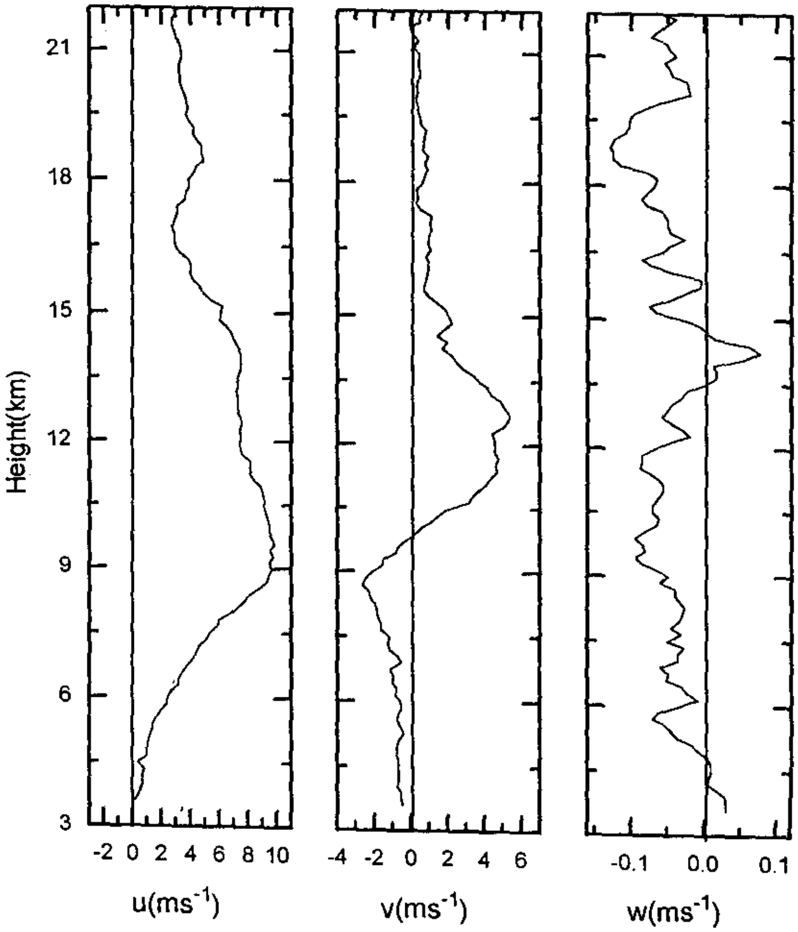

Fig. 5.1. Mean zonal (u), meridional (v) and vertical (w) winds during winter (DJF) 1995-96 from MST radar observations

which flows poleward at upper levels and on crossing the equator turns to become westerlies. The air descends in the NH and the return southward flow completes the Hadley circulation. This is well represented by the u, v and w components of the MST radar data at Gadanki.

The meridional wind averaged over 72.5° E to 82.5° E during January-February 1996 (representing the winter season) using the NCEP/NCAR reanalysed data is shown in Fig. 5.2. The data extends from 1000 hPa to 100 hPa. This figure clearly shows the Hadley circulation. The associated vertical motion during winter can be inferred. Northerly wind (equatorward limb of the Hadley cell) with speeds ranging from 1 to 4 ms^{-1} is observed between 5° S to 13° N and extends upto about 700 hPa. Above 300 hPa the meridional wind is southerly (poleward limb of the Hadley circulation) and extends from 14° S to 27° N. The inferred upward motion is near 15° S and sinking motion north of 10° N. Therefore during winter season the horizontal and the vertical velocity plots of MST radar station fits in well with the Hadley circulation obtained from the NCEP/NCAR data.

5.3.3 Vertical circulation during summer 1996 (JJA)

During the summer season (June, July and August) the mean zonal wind is westerly below about 7 km and turns to easterly at upper levels (Fig. 5.3). Easterly winds increase with height and attain maximum speed of 25 ms^{-1} near 16 km (Tropical Easterly Jetstream) and thereafter it is found to be decreasing. Meridional winds during summer are weaker compared to that during winter. Northerlies are present in the layer 12-16 km. There are two more layers of northerlies in the height range 4 km to about 9 km. The vertical velocity profile during summer shows that downward motion persists over the station, which is very strong in the troposphere and lower stratosphere.

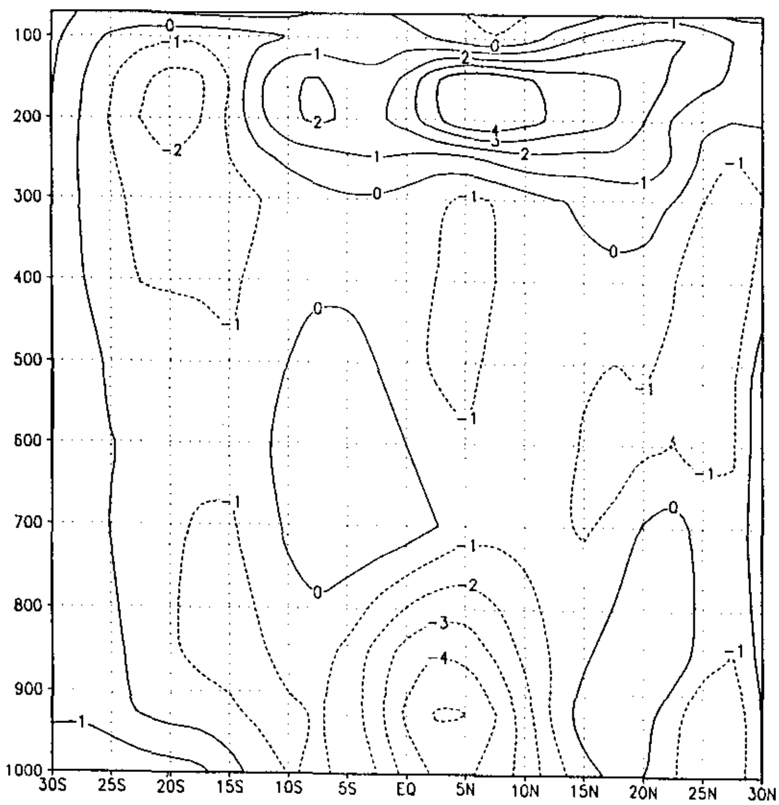

Fig. 5.2. Meridional wind from 1000 to 100 hPa averaged between 72.5° E and 82.5° E over 30° S-30° N during January-February 1996 using NCEP/NCAR reanalysed data

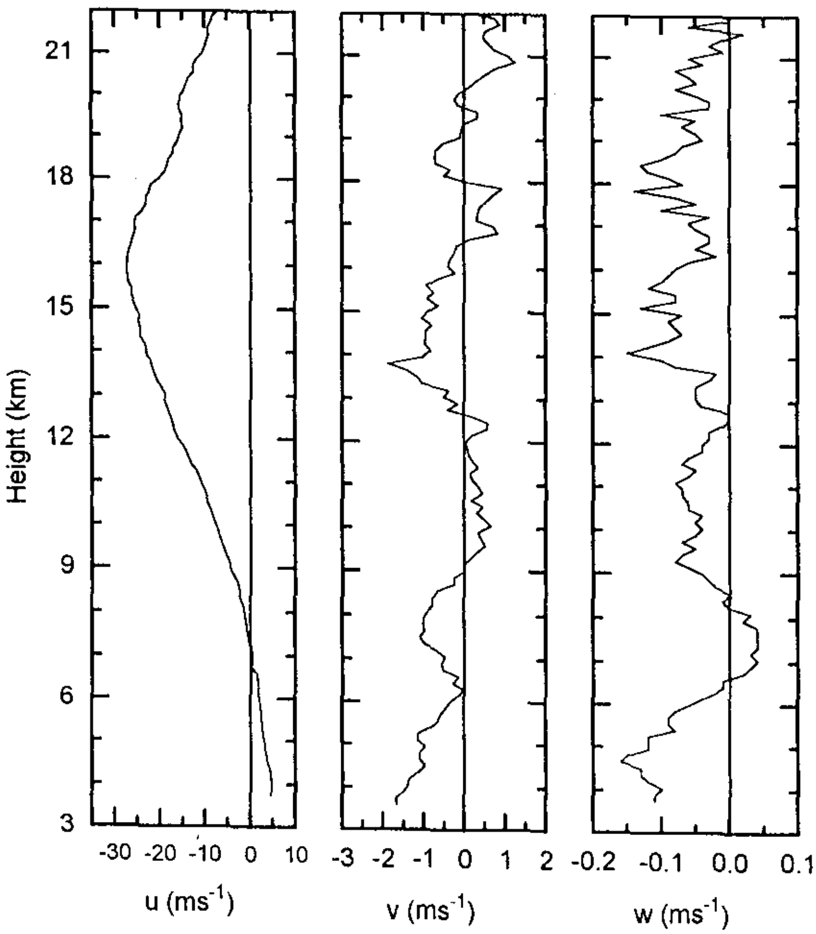

Fig. 5.3. Mean zonal (u), meridional (v) and vertical (w) winds during summer (JJA) 1996 from MST radar observations

In the Indian region, summer season is roughly the period of southwest monsoon (June-September) and the meridional circulation over the region is known as reverse (monsoon) Hadley circulation (Koteswaram, 1960; Schulman, 1973; Rao, 1976). The implication of the reverse Hadley circulation during monsoon is that, southerlies in the lower levels turns to monsoon westerlies (southwesterlies) and northerlies in the upper levels into the well known Tropical Easterly Jet Streams (TEJ) due to the Coriolis effect.

During the summer season the meridional winds are northerlies at lower levels. In the reverse (monsoon) Hadley cell, the low-level return flow should be poleward (southerlies). Comparing the observed plot with the Hadley cell, the reverse circulation does not seem to be fitting during summer season at Gadanki. The zonal and meridional winds at lower levels suggest that, the region around Gadanki experience a northwesterly flow instead of monsoon southwesterlies. However, the upper level wind is the strong TEJ observed over the southern parts during southwest monsoon season (Koteswaram, 1958). The strong vertical velocity at Gadanki (13.5° N) again shows that during summer also, there is sinking motion over the region.

Climatologically, the lower tropospheric wind over southern peninsular region (where the MST radar is situated) shows an anomalous pattern during the summer monsoon season compared to that observed in the Arabian Sea and the Bay of Bengal regions where southwesterlies exist during summer. This is clearly seen from the horizontal charts plotted at different levels over the Indian region using the NCEP/NCAR data.

Figure 5.4 shows the circulation prevailing in the longitudinal region between 50° E to 100° E at 1000, 850, 700 and 500 hPa levels during the season June-August 1996. Over the Arabian Sea and the Bay of Bengal region, the surface (1000 hPa) to

500 hPa wind is southwesterly. The flow turns clockwise over the Arabian Sea and flows with a southward component over peninsular India. After crossing the southern peninsular region, the circulation gets cyclonic curvature and moves towards north-east in the Bay of Bengal. Northerly flow is observed over the Arabian Sea below 500 hPa level and the flow extends towards the equator with height.

The ascending limb of the Hadley cell during monsoon season is over the Monsoon Trough (MT) and generally it is seen from 25° N - 35° N. The rising air flow turns equatorward (northerlies) at upper levels, sinks, and flows poleward (southerlies) at lower levels. But the observed low level meridional wind at the MST radar station is northerlies instead of southerlies. From Fig. 5.4, it is seen that the mean wind is southwesterly over Arabian Sea and Bay of Bengal, but it is northwesterly near peninsular India.

This is again illustrated using the NCEP meridional wind plot for different longitudinal bands during June-August 1996 (Fig. 5.5(a)-(c)). From Fig. 5.5(a) (flow averaged over longitudinal band 50° E - 65° E) it is found that the wind is strong southerlies between 20° S and 25° N from surface to about 700 hPa. The continental northerly air flow above this layer peaks at 600 hPa. This flow extends southward upto 5° N. Strong northerlies are seen above 400 hPa in the SH. Fig. 5.5(b) shows the meridional wind averaged between 72.5° E and 82.5° E. The meridional wind is northerly at upper levels of the NH as in Fig. 5.5(a). It becomes stronger as it flows toward SH and at 10° S the speed of the northerly wind is of the order of 10 ms^{-1} at 200 hPa. The return flow is towards north at lower levels. However, an anomalous flow over peninsular India is seen from 30° N to equator between 1000 and 600 hPa. It can be inferred that the vertical upward motion is around 20° N - 30° N.

Figure 5.5(c) shows the flow over Bay of Bengal region (flow averaged over longitudinal bands 85° E - 95° E). Southerly wind is strong over the Indian latitudes

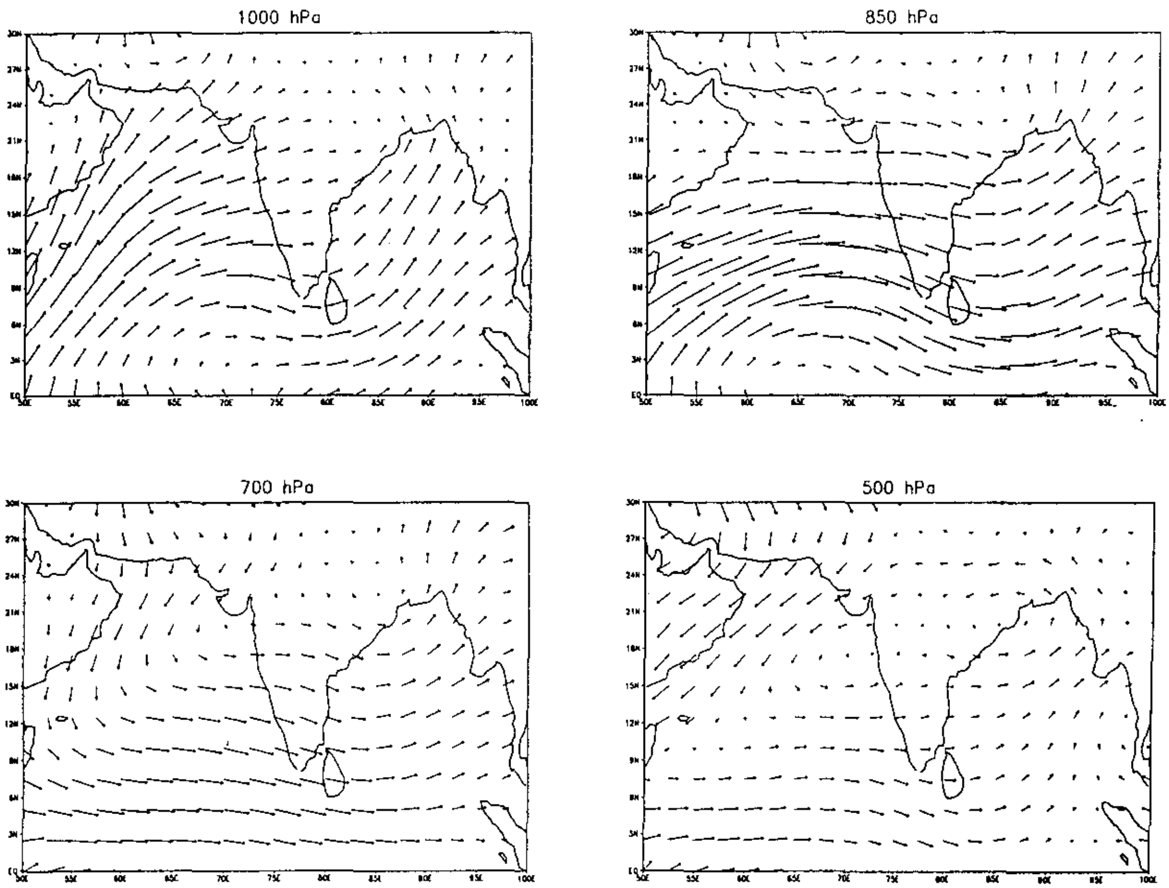

Fig. 5.4. Wind vector over 0°-30° N and 50° E-100° E at 1000, 850, 700 and 500 hPa levels during JJA 1996 (NCEP/NCAR reanalysed data)

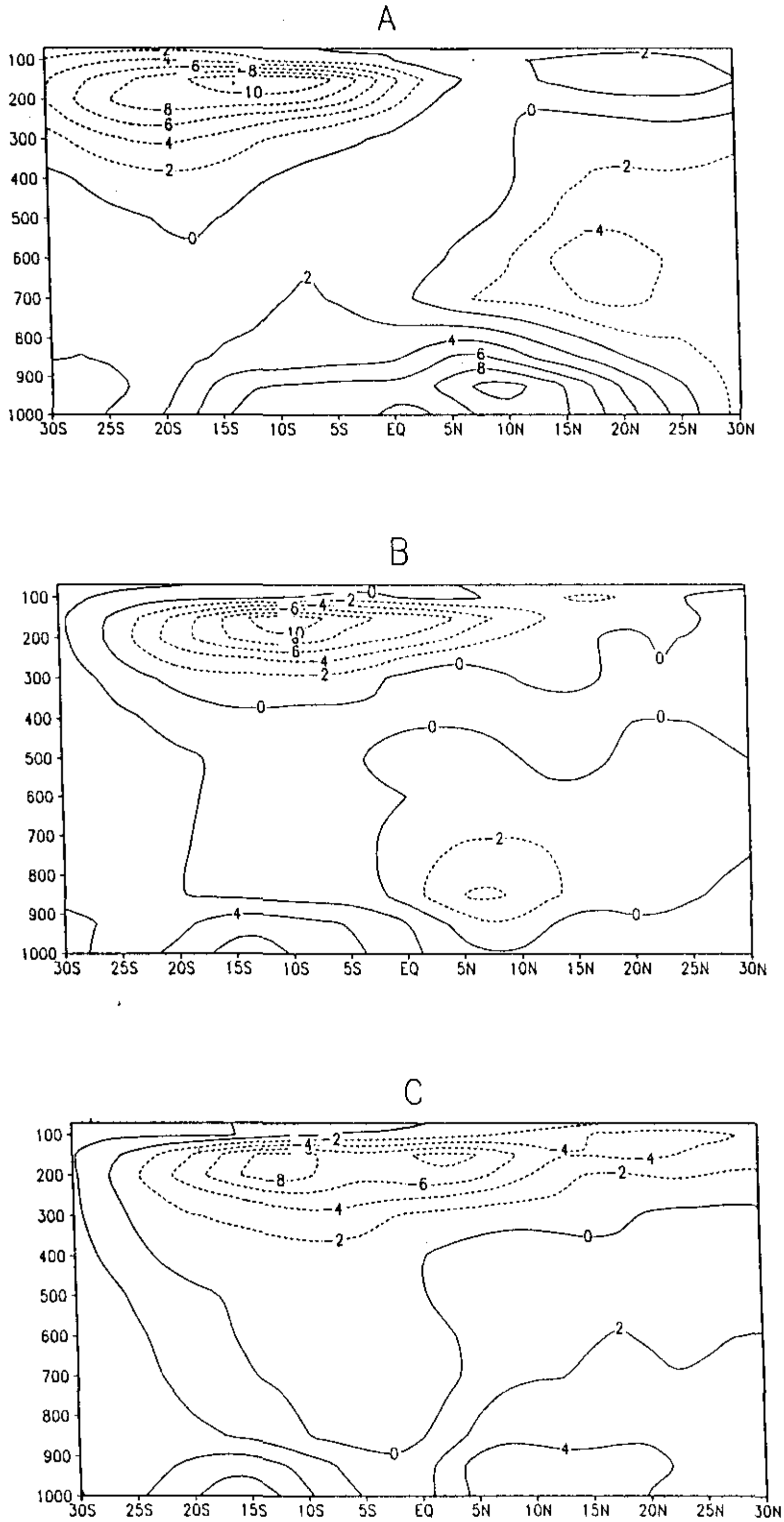

Fig. 5.5. Meridional wind from 1000 to 100 hPa averaged between 50° E and 65° E (A), 72.5° E - 82.5° E (B) and 85° E - 95° E (C) over 30° S - 30° N during summer (JJA) 1996 using NCEP/NCAR reanalysed data

upto 400 hPa and seen in the SH as well. An interesting feature noted from this figure is the presence of shallow northerly wind near the equatorial region, which may be due to sinking motion (Asnani, 1993). Fig. 5(b) is comparable with Fig. 5.3 in the case of meridional wind of Gadanki. From Fig. 5(a)-(c) it is clear that the anomalous wind is very prominent over the southern peninsular region and absent in the Arabian Sea and Bay of Bengal. Thus the observation using Indian MST radar data match well with the NCEP/NCAR data during summer also.

5.4 Discussion

Using MST radar it is possible to directly measure the vertical velocity over the radar station. Many studies on vertical velocity in the middle atmosphere have been carried out using indirect methods (Newson, 1974; McInturff, 1978). Mukherjee *et al.*, (1984) computed vertical velocity using wind and temperature data from rocketsonde observations and reported downward motion in the tropical middle atmosphere at Thumba (8° 32' N, 76° 52' E), India, during both winter and summer. The vertical velocity profiles of DJF season show strong ascending motion in the SH over the mean position of ITCZ and strong subsidence dominate the latitudes between 10° N and 30° N (Piexoto and Oort, 1992). In the present analysis, zonal, meridional and vertical velocity during winter is studied and we found strong subsidence at Gadanki (13.5° N). The measurements of wind at Gadanki provide a clear picture of the Hadley type circulation based on the observed vertical velocity profile and it fits in well with the Hadley cell circulation during winter obtained from other studies using indirect methods. Earlier studies compared the Indian MST radar data with radiosonde data at Madras (13.04° N, 80.7° E), near to the radar station (Kishore *et al.*, 1994; Jivrajani *et al.*, 1997). Using NCEP reanalysed data the meridional wind averaged over 72.5° E - 82.5° E showed that the MST radar observation is comparable in winter season. How far the downward motion of air extends in the meridional direction over Indian region will be clear only if vertical velocity profiles for stations beyond 13.5° N is available.

India is mostly within the tropics and well known for monsoons. The meridional circulation over Indian region reverses direction from winter to summer. During summer, the monsoon trough (MT) is generally observed around 25° N - 35° N and it is a region of strong ascending motion. The equatorward flow at upper levels gives rise to Tropical Easterly Jet Stream (TEJ) near tropopause over South India. The return flow at lower levels should be southerly (Schulman, 1973). But the observed meridional wind is northerly at lower levels over the radar station. This anomaly is confirmed using the NCEP/NCAR reanalysed data between 30° S and 30° N in the longitudinal belt of Gadanki during June-August 1996. Such an anomaly is not present over Arabian Sea and Bay of Bengal. However, in the Arabian Sea, there is a northerly anomalous flow for a different reason (the monsoon trough shifts southward faster with height over the Arabian Sea and the Arabian Desert air flow towards south).

A recent study by Rodwell and Hoskins (1995) examined the potential vorticity (PV) of the low-level monsoon air flow and found that the sharp anticyclonic turning of the low level monsoon flow (Low Level Jet) away from Africa into the Arabian Sea was due to the rapid decrease in depth as the PV conserving flow encountered the east African highlands. The authors further suggested the vertical distribution of diabatic heating, whether it is centered above or below the low-level monsoon air flow over the Arabian sea, determines whether the south westerlies continue eastward or turns southwards. Their study presents a possible reason for the observed wind anomaly over south India. Holton has discussed in a simplified application of potential vorticity concept, the lee side trough formation (Holton, 1992). According to this, the westerly flow ascending over a large-scale mountain will acquire anticyclonic curvature conserving PV and move southward. The north-south mountain range (Western Ghats) along the west coast of India can thus force the westerly wind to turn anticyclonically equatorward. Gadgil (1977) applied a quasi-geostropic model for a homogeneous fluid on a β-plane and showed that a quasi-persistent trough forms in the monsoon westerlies as a Rossby wave response forced by the north-south mountain range along the west coast of peninsular India.

Strong downward vertical velocity is observed at the station both during winter and summer. But the extent of this downward limb of the Hadley cell is unknown due to the lack of vertical velocity profiles at other latitudes of Indian region. During monsoon season large amounts of heat and moisture are transported over the Indian region. The lower stratospheric vertical motion is downward during winter and summer, thus affecting the troposphere-stratosphere exchange processes over India.

5.5 Conclusion

The Hadley circulation is the process by which large amount of moisture, heat and momentum are transported from the surplus to the deficit region horizontally and the vertical motion links the troposphere and stratosphere through the exchange processes between these two layers of the atmosphere. In the present analysis the Hadley circulation during summer and winter seasons over Indian region is studied using the Indian MST radar data at Gadanki (13.47° N, 79.18° E) and NCEP/NCAR reanalysed data. It is found that during winter the zonal and meridional wind components observed using the radar fits in well with the Hadley circulation over the Gadanki region inferred from NCEP/NCAR reanalysed data. The Hadley circulation over the Indian region suggests that the vertical velocity should be downward in winter, which is confirmed from the observed vertical velocity at Gadanki.

During the southwest monsoon season, the reverse Hadley cell theory (Koteswaram, 1960; Schulman, 1973) over Indian latitudes requires upward motion over the monsoon trough (MT) with southerly flow at lower levels. However, the low-level wind over Gadanki region is northerly. This anomalous wind over the peninsular Indian region is seen in the NCEP/NCAR data also. Such flows are absent in the Arabian Sea and Bay of Bengal. The observed reverse Hadley circulation and the negative vertical velocity values at Gadanki conclude that downward limb of the Hadley cell exists north of the equator during summer.

Chapter 6

Intrusion of mid-latitude upper tropospheric trough and associated synoptic-scale vertical velocity over tropics

6.1 Introduction

The interaction between tropics and mid-latitude is frequent during anomalous and disturbed weather epochs in all seasons of the year in India and neighbourhood. Several authors (Singh, 1963; 1979; Dutta and Gupta, 1967) have brought out the intimate connection of the upper air westerly troughs with the intensification and movements of western disturbances over Indo-Pakistan region. Western disturbances are defined as eastward moving upper air troughs in the subtropical westerlies, often extending down to the lower troposphere of the north Indian latitudes during the winter months (Pisharoty and Desai, 1956). These upper tropospheric troughs often give rise to closed cyclonic circulation on the surface or cut-off lows in the mid-tropospheric levels over Iran, Afghanistan, Pakistan, and adjoining north India and they are responsible for rain/snowfall over those areas.

Midlatitude-tropics interaction often leads to intensification of western disturbances, outbreak of convection, oscillation of monsoon trough and deformation of circulation including cyclonic storms. As a result of the extension of westerly troughs in lower and subtropical latitudes, the low-level circulation changes. The easterlies in the tropical atmosphere extend northward and come under the sway of middle and upper level westerlies in the non-monsoon months (Kalsi and Halder, 1992).

The vertical velocity is intimately linked with the dynamics of the atmosphere and synoptic-scale vertical motions are important for meteorological forecasting. MST radars are now used to study various aspects of the dynamics of lower and upper atmosphere (Vincent and Reid, 1983; Fritts and Vincent, 1987; Reid and Vincent, 1987; Fritts, 1989; Fritts *et al.*, 1992; Fritts and VanZandt, 1993; Pauley, *et al.*, 1994; Warnock, *et al.*, 1994; Nastrom and Eaton, 1995; Nastrom and VanZandt, 1996). Many researchers have used MST radar data to outline mesoscale and synoptic scale features at different regions (Larsen and Rottger, 1982; Nastrom *et al.*, 1989; Crochet *et al.*, 1990; Nastrom *et al.*, 1994). Warnock *et al.*, (1994) using radar data found that synoptic-scale fluctuations are detectable by VHF radars. A unique feature of the MST radar is that it can measure the vertical velocity component Nastrom *et al.*, 1996).

The anomalous circulation pattern observed during 1995/96 winter season has been studied in the present work using the Indian MST radar wind data. It is observed that change from westerlies into easterlies during the period is connected with the north-south oscillation of the anticyclones normally seen over Indian region during the passage of an intense western disturbance. The extension of the westerly trough during the passage of the western disturbance brings out synoptic-scale variations in the vertical velocity. The synoptic variations observed in the radar vertical velocity are compared with the computed horizontal divergence using the NCEP/NCAR reanalysis wind data. The north-south oscillation of the anticyclones seen over the Indian tropical region during winter season is also explained.

6.2 Data

Daily observations of horizontal and vertical velocity components from December 1, 1995 to February 28, 1996, and December 1, 1997 to January 31, 1998 at 1200 GMT from the Indian MST radar are used in the study. Radiosonde data from Madras (13.00° N, 80.18° E) at 1200 GMT during January 1996 are utilised to compare the anomalous winds and synoptic features observed from the 1995-96 radar data.

NCEP/NCAR zonal and meridional wind data during January 1996 is incorporated in the analysis to explain the synoptic features. Streamline analysis at

850 hPa, 500 hPa, 200 hPa and 100 hPa from 60^0 E to 100^0 E and equator to 40^0 N at every grid points ($2.5^\circ \times 2.5^\circ$) has been carried out using the NCEP/NCAR reanalysed data to determine the synoptic features and the circulation characteristics over the Indian latitudes during winter season.

Divergence at 200 hPa for selected days during January 1996 is computed from the zonal and meridional wind components between equator and 40^0 N and 60^0 E and 100^0 E from the NCEP/NCAR reanalysis data sets. Missing in the radar and radiosonde wind data are filled in by interpolation using the cubic-spline interpolation method.

6.3 Results and discussion

(a) Anomalous wind observed from the MST radar data

The monthly mean zonal (u), meridional (v) and vertical (w) velocities observed using Indian MST radar during December 1995, January-March 1996 from 3.6 km to 21 km are plotted as shown in Fig.6.1. Zonal wind is westerly in the entire altitude range during all months. Westerly wind is increasing with height in the lower troposphere, attain the peak of about 12 $m.s^{-1}$ at 9 km region during December and February, whereas in March the strength increase further to about 25 ms^{-1} at about 12 km. During this season the westerly wind becomes weak near the tropopause and in the lower stratosphere. The meridional wind below 9 km is generally from north, which changes to southerly above 10 km. During winter months (December-February) southerly wind speed attains maximum around 12 km and decreases upward. In March weak northerly wind is seen below 7 km with strong southerly wind of about 8 ms^{-1} at 10 km which is decreasing with height.

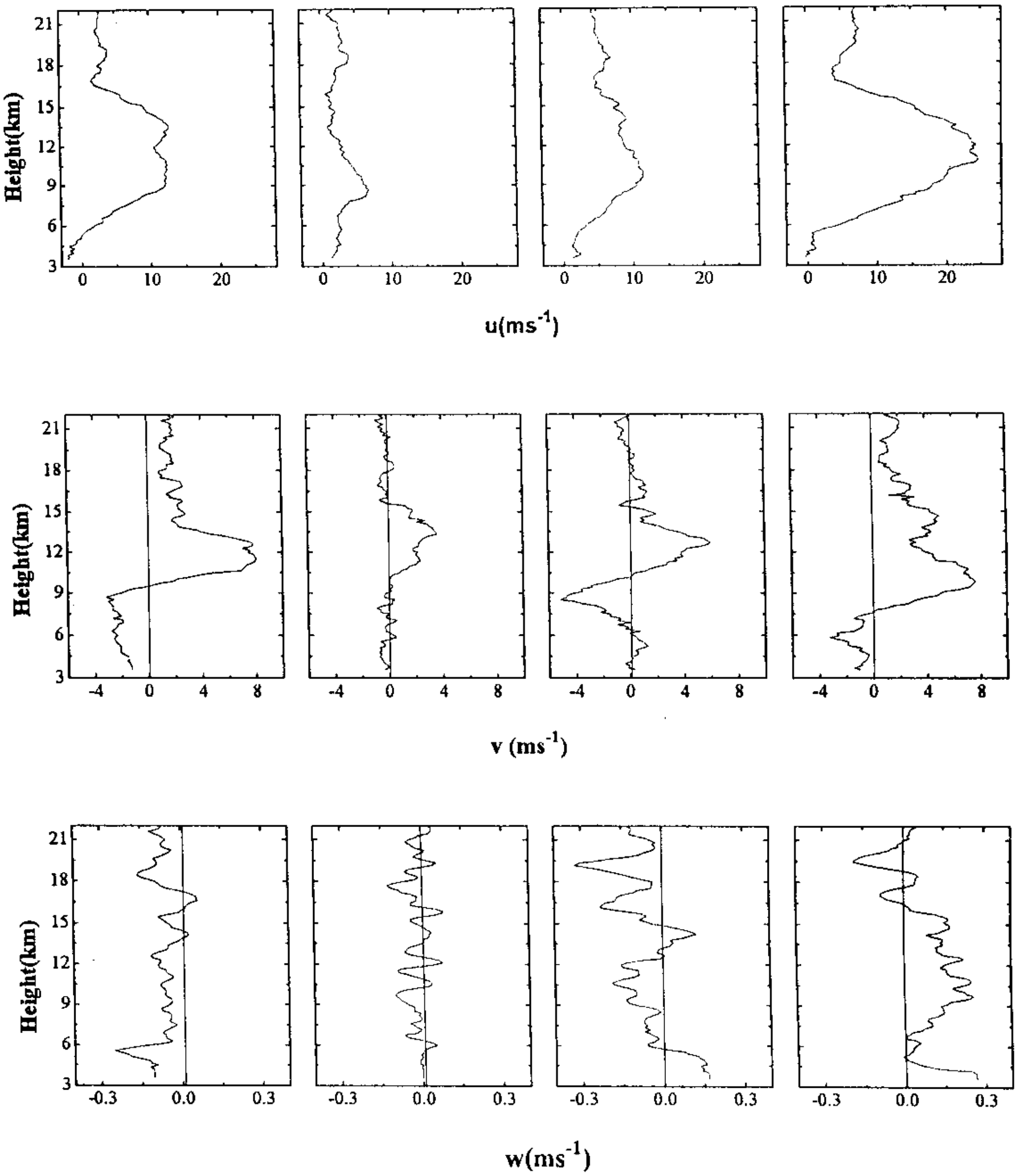

Fig. 6.1. Monthly mean zonal (u), meridional (v) and vertical (w) velocities during December 1995-March 1996

The mean vertical velocity (w) has been smoothened with a three point running mean at all levels to remove random variations. It is generally downward throughout the layer with large negative values. Between 3-6 km the vertical motion is upward in the month of February and a change in the vertical motion is noted below 15 km altitude. However, in March the vertical motion is upward with strong positive values in the upper troposphere and downward in the lower stratosphere.

Fig. 6.2 shows the monthly mean u, v and w during December 1997-January 1998 between 3.6 km to 21 km. It is seen that the height of maximum westerly wind is at 16 km in December and at 14 km during January with a peak of 13.5 ms^{-1}. Southerly wind is noted at all levels with a maximum of about 4 ms^{-1} at 13 km in December. The meridional wind in January do not show any regular pattern but with alternate southerlies and northerlies. The vertical velocity is generally downward during December in the upper troposphere and lower stratosphere except a positive velocity between 4-7 km altitude range. In the month of January the upward motion is centred at some regions in the lower and upper troposphere with a general descending motion. From the figure it is seen that the wind do not indicate any variability as noted in the year 1995-96.

A general feature noted in all the three wind components during January 1996 is that there is some variability in their characteristics (Fig. 6.1). From the Fig. 6.1, it is clear that monthly mean u and v have been decelerated in the region of their maximum values, whereas mean w shows random variations.

To demonstrate this the time-section of zonal wind at the MST Radar station during January is plotted in Fig. 6.3. It shows that the zonal wind in January exhibits two maxima in the mid-troposphere and lower stratosphere in the first half of the month. An interesting feature noted over the radar station during January is the change of zonal wind from westerlies into easterlies in the second half of January,

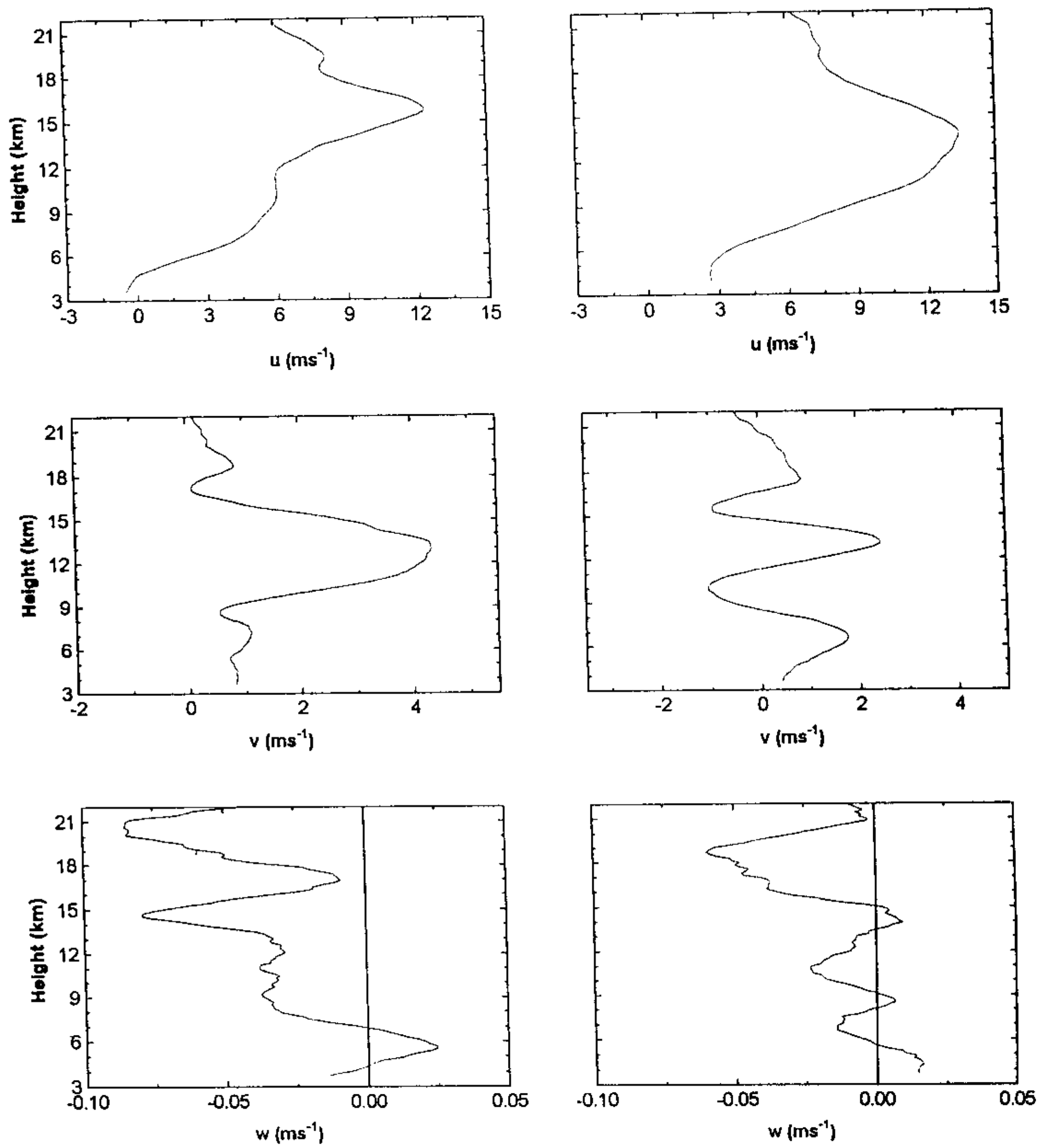

Fig. 6.2. Monthly mean zonal (u), meridional (v) and vertical (w) velocities during December 1997-Janury 1998

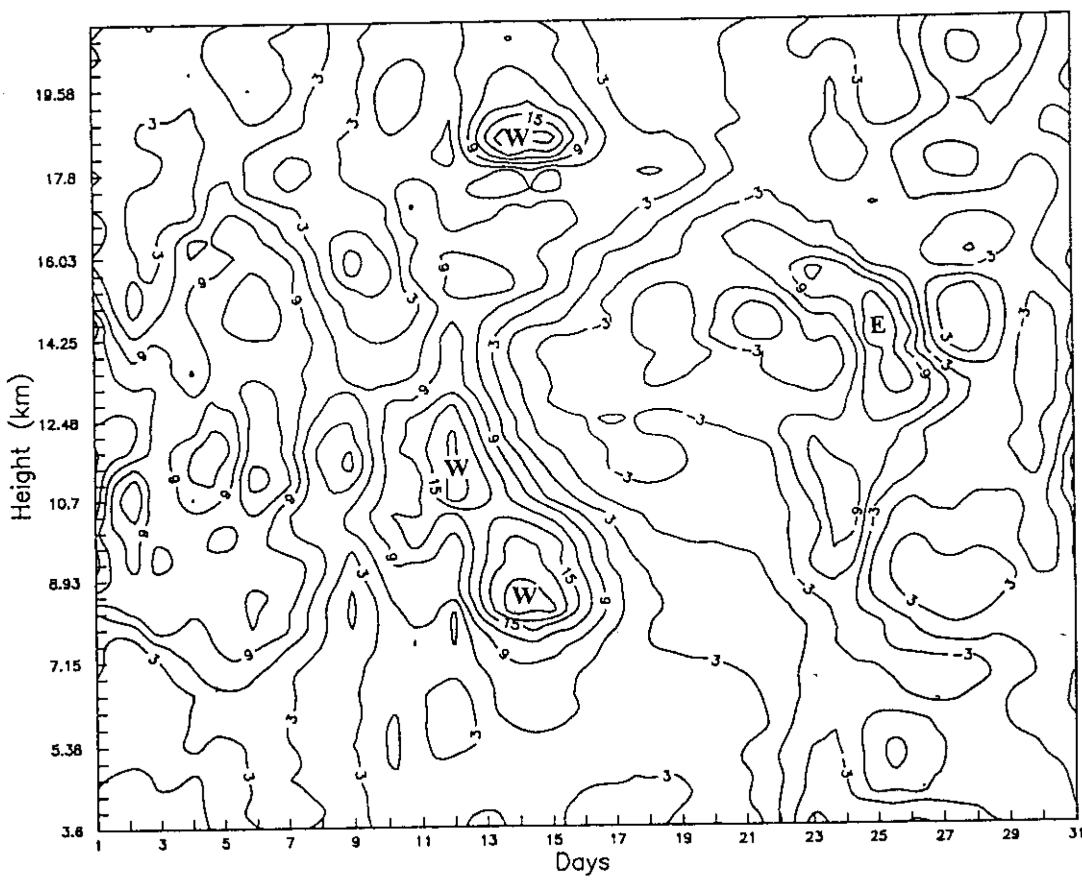

Fig. 6.3. Time-height profile of u from MST radar data at Gadanki in January 1996

which starts from about 14 km altitude and propagates downward. On January 15, the zonal wind is easterly at 14 km, whereas it is westerly below and above. It is noted that the westerly wind becomes as high as 21 ms^{-1} in the mid-troposphere and lower stratosphere and shows similar variations prior to the changes occurring at 14 km altitude. The westerly wind regime strengthened in the mid-troposphere and lower stratosphere during the middle of January.

The radiosonde data is used to compare the circulation of the radar station. Fig. 6.4 shows the time-section of zonal wind at Madras between 0.1 km and 13 km, which is nearest to the radar station. The radiosonde data is not reliable in this particular data sets above 13 km, which limits the comparison upto 13 km level. From the figure, the zone of westerly wind maximum is seen near 9 km on January 15. The change of zonal wind from westerly to easterly is also observed near 12 km as seen in the radar data. Earlier studies (Kishore *et al.*, 1994; Jivrajani *et al.*, 1997) used radiosonde data at Madras to compare MST radar data and found good agreement between the two observations. From Fig. 6.3 and Fig. 6.4 one can deduce that the change in zonal wind direction at the MST Radar station is a true signal since the radiosonde data also exhibit similar features.

(b) Synoptic features observed during January 1996

Since the variation in wind field noted from MST Radar data during January is absent in the other two winter months of December 1995 and February 1996 and of December-January 1997-98, the reason for the anomalous circulation features cannot be elucidated from mere MST radar data. Rather, the wintertime synoptic conditions influencing the circulation of Indian latitudes, during winter 1995-96 can better illustrate the features and associated circulation patterns of the Radar station. Hence, a detailed analysis is attempted to understand the possible association between the observed anomaly in the troposphere and the lower stratosphere and the synoptic

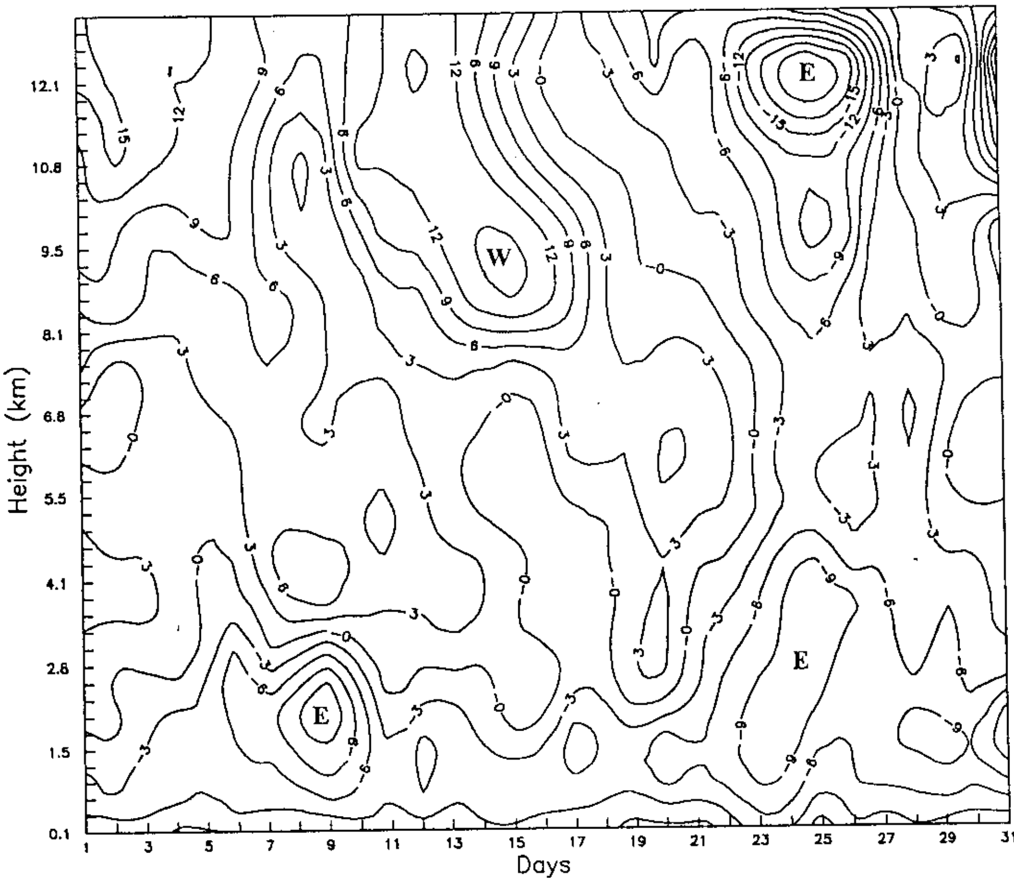

Fig. 6.4. Time-height profile of u from Madras radiosonde data

features during January 1996. Daily NCEP/NCAR zonal and meridional wind data analysed during January 1996 explains the circulation characteristics, which prevailed over the Indian peninsular region. The following are the synoptic features observed from the streamline analysis at 850 hPa, 500 hPa and 200 hPa between latitudes equator to 40° N and longitudes 60° E - 100° E at 1200 GMT.

During January 1996, six western disturbances moved across the Northwest Indian region in which the most intense western disturbance is reported during 14 to 17 January. Details of these synoptic features during the month are given elsewhere (De *et al.*, 1997). The remarks made regarding the intense western disturbance, which moved, across the country during January 14 to 17 is noteworthy. This system may be responsible for causing the observed anomalous circulation in the troposphere and the lower stratosphere as noted from MST radar. To understand the association between the anomalous circulation pattern in the troposphere and the lower stratosphere and the synoptic features, three days are selected; (i) *before the appearance of the western disturbance (January 11)*, (ii) *during the active phase of the western disturbance (January 15)* and (iii) *after the disappearance of the western disturbance (January 19)*. Streamline analysis at 850, 500 and 200 hPa levels during the above three representative days are plotted and are illustrated in Figs. 6.5, 6.6 and 6.7 respectively.

In Fig. 6.5, intense anticyclonic flow is noted at 850 hPa over the MST Radar station at Tirupati. As seen at different levels, the axis of anticyclones is found to be tilted southward with height. At 850 hPa the centre of the anticyclone is over 16° N while the position is over about 7^0 N at 200 hPa. North of the northern half of the anticyclone, westerly wind prevails and increases with latitude and height.

Signal of western disturbances over Northwest Indian region is clearly seen on January 15 as evidenced from the closed cyclonic circulation (Fig. 6.6). As a result of

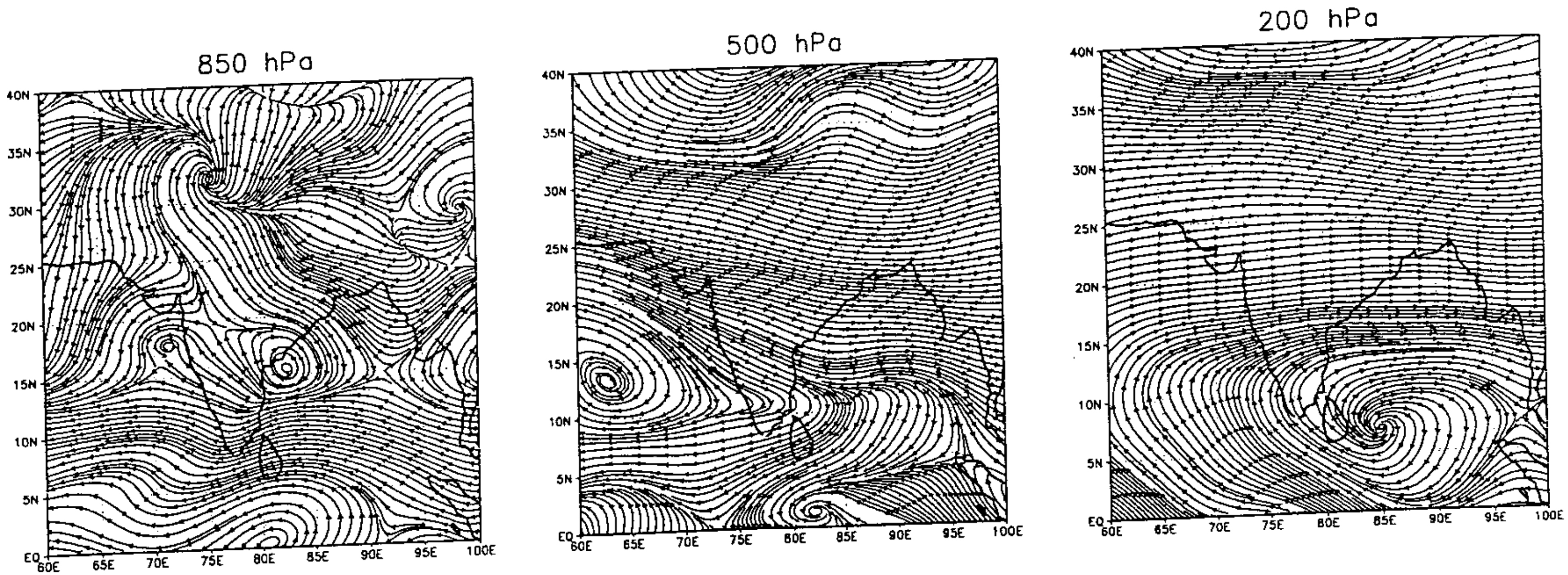

Fig. 6.5. Streamline plots for 850, 500 and 200 hPa levels before the appearance of the western disturbance (January 11, 1996)

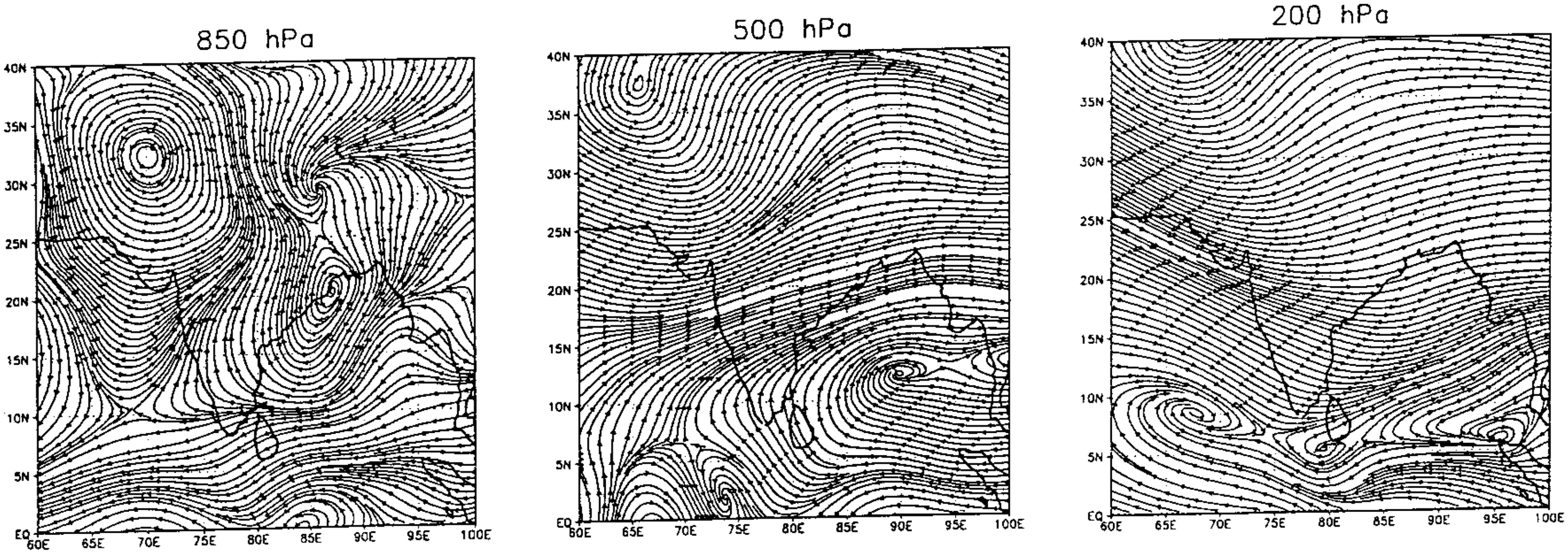

Fig. 6.6. Streamline plots for 850, 500 and 200 hPa levels during the active phase of the western disturbance (January 15, 1996)

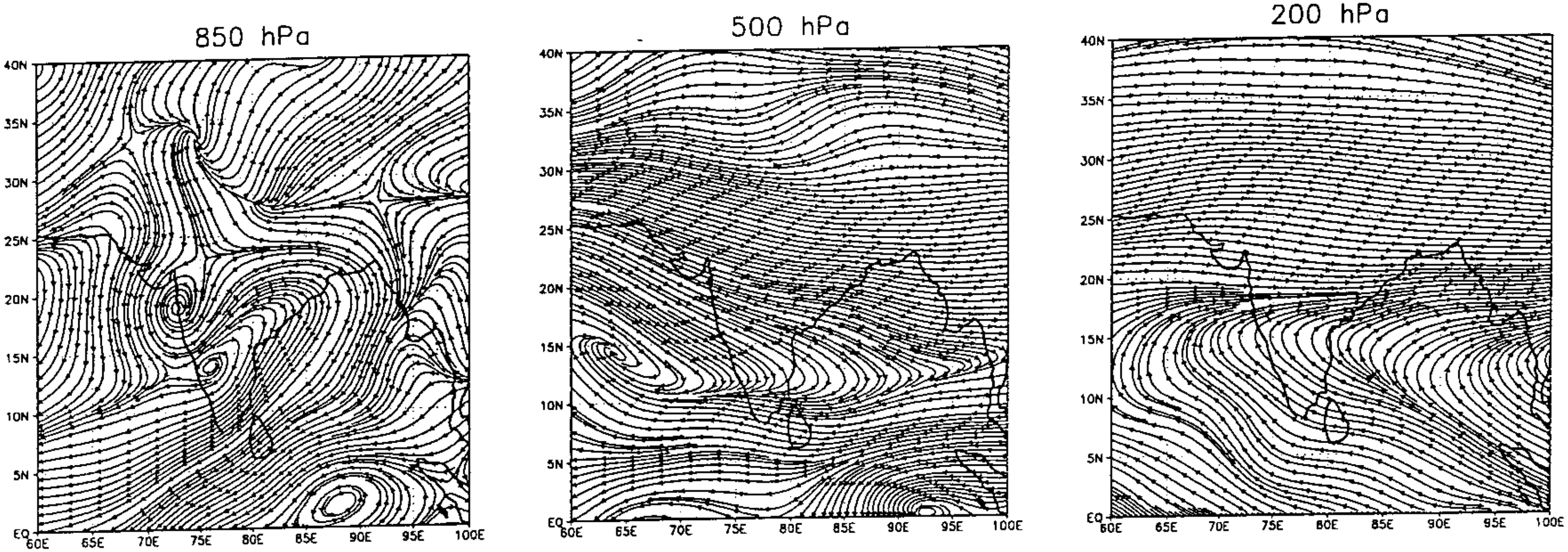

Fig. 6.7. Streamline plots for 850, 500 and 200 hPa levels after the disappearance of the western disturbance (January 19, 1996)

the movement of the western disturbances, westerly trough is found to be intruding into the tropics and extends upto 10^0 N. The westerly trough is also seen at 200 hPa. This intrusion of the trough is observed as the strong westerly wind regime on January 15 in the radar and the radiosonde data. Case studies have shown that the intensification of western disturbances is connected with the upper air westerly troughs over Indo-Pakistan region (Sing, 1963; 1979; Dutta and Gupta, 1967). Troughs associated with mid-tropospheric westerlies can extend southward during winter (Sharma and Subramanian, 1983) which is clearly seen in the present work. The intrusion of the trough pushed the 200 hPa anticyclone further south. At 200 hPa the anticyclone is centred at 5^0 N. Thus the wind over the radar station (13.5° N) is westerly at upper levels as revealed from the stream line plots. However, the structure of the circulation pattern and the position of centre of the anticyclones suggest that during the passage of western disturbances, the anticyclones over the region may experience some sort of north – south movements at different levels.

From Fig. 6.7 it is seen that the anticyclone circulation at 200 hPa has moved back to north so that the flow south of 15^0 N is easterly instead of westerly which prevailed on January 15. This change of westerlies into easterlies is evident from the radar and radiosonde data (Figs. 6.3 & 6.4). Kalsi and Halder (1992) have mentioned that extension of easterlies towards north could alter the tropospheric westerlies to easterlies at upper levels.

From Fig. 6.1 it seen that the movement of western disturbance influenced u, v and w over northern Indian region. To understand the effect of the western disturbances on the horizontal and vertical circulation wind values are plotted for the three selected days. Fig. 6.8 shows the variation of u, v and w in the troposphere and lower stratosphere during January 11, 15 and 19. It is noted from Fig. 6.8 that on January 11, u component is from the west in the troposphere and lower stratosphere

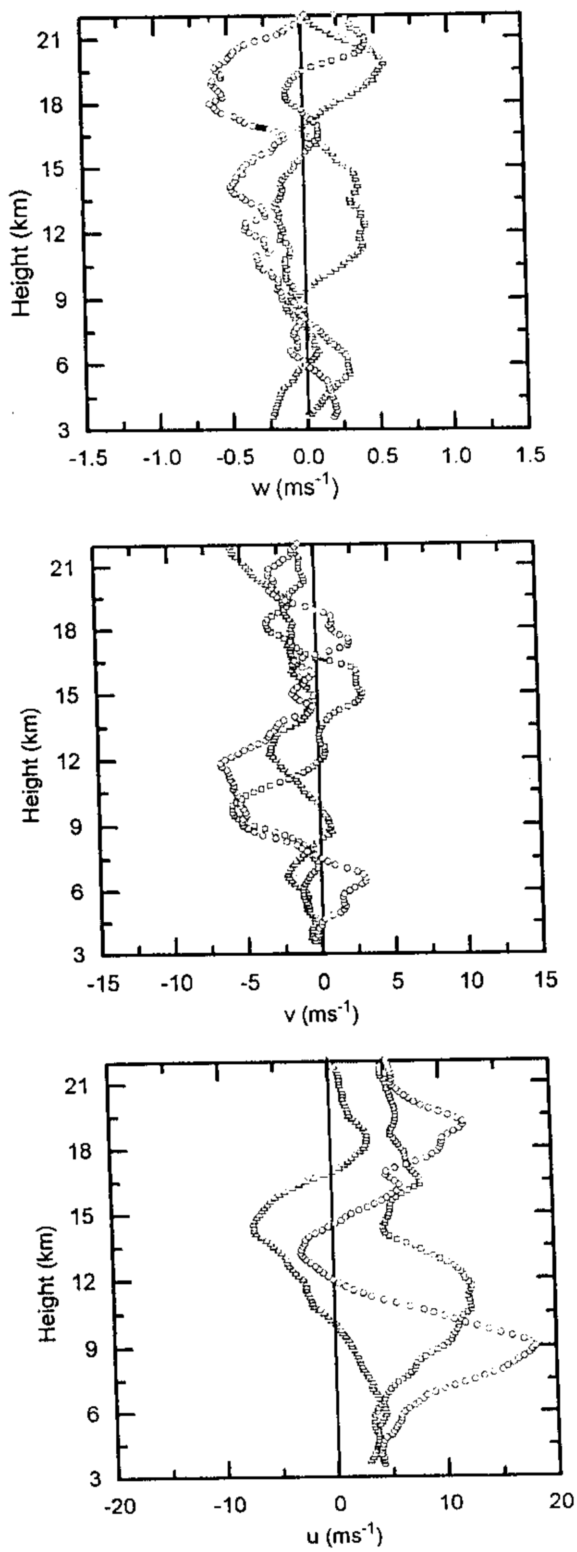

Fig. 6.8. Variation of u, v and w in the troposphere and lower stratosphere during January 11 (squares), 15 (circles) and 19 (triangles), 1996

with peak around 12 km. On January 15, the westerly wind becomes easterly in the upper troposphere and this is extending upward and downward on January 19 with a deceleration in the strength of the westerlies. The westerlies in the mid-troposphere and lower stratosphere have been strengthened on January 15. The meridional wind is northerly at lower levels and southerly at upper levels on January 11 as seen from Fig. 6.8. However, on January 15 the upper level southerly wind changed into northerly and extended in the region of maximum northerlies and these northerlies decelerated between 10 and 14 km on January 19.

It is clear from Fig. 6.8 that the general downward motion noted in the monthly mean w over the station is again seen on January 11 with upward motion in the lower stratosphere. The sinking motion has further strengthened on January 15 with large negative values in the troposphere and lower stratosphere. After the disappearance of the western disturbance w is upward between about 9 and 21 km with strong upward motion between 11 and 15 km.

(c) *Intrusion of trough into the tropics and the synoptic-scale vertical velocity*

The influence of a strong mid-latitude weather system like the one discussed here and its effect on the vertical motion over tropics may provide some clues for operational weather forecasting. To determine such synoptic-scale interaction a time-section plot of w during January 1996 is given in Fig. 6.9. It shows that before the appearance of the western disturbance, vertical velocity was weak and not organised. In the lower levels it is alternate upward and downward motions. But on January 15, it is seen that the vertical velocity is strong and downward between 8 and 22 km. Thus it is clear that the synoptic-scale system in the northern Indian latitudes influence not only the horizontal circulation but the vertical motion of the tropical atmosphere also.

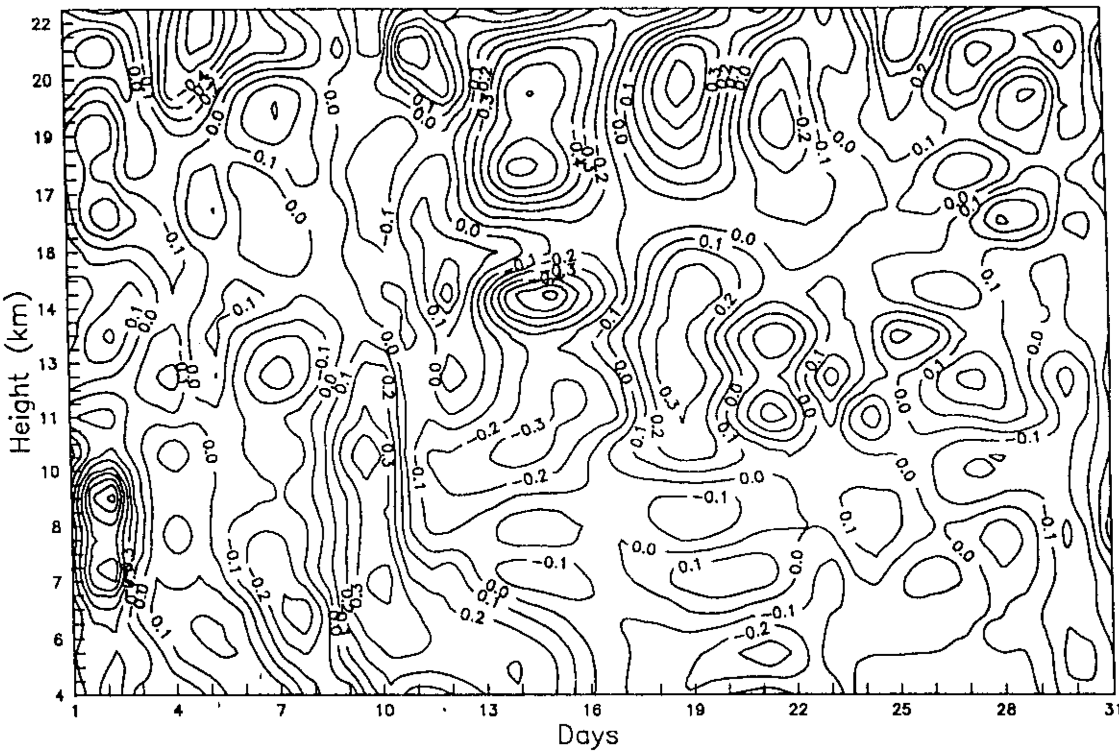

Fig. 6.9. Time-section analysis of vertical velocity during January 1996

It is well known that upper air trough region is a zone of convergence where the vertical velocity will be downward (Holton, 1992) and on either side of the trough is divergence where ascending motion of air takes place. In Fig. 6.10 horizontal divergence between equator to 40° N and 60° E to 100° E for the three selected days (January 11, 15 and 19, respectively) are depicted. The values are plotted for 200 hPa level at which the extension of the mid-latitude trough is seen as far equatorward as 6° N (Fig. 6.6). It is seen from Fig. 6.10(a) that before the appearance of the western disturbance (ahead portion of the trough) there exist weak convergence (weak downward motion) over the radar station (around January 11). This is clearly seen from the time-section plot of vertical velocity at the radar station. On January 15, due to the intrusion of the trough in the mid-latitude westerlies deep into the tropics there is a zone of strong convergence (Fig. 6.10(b)) at the apex of the trough. On January 19 (Fig. 6.10(c)), the area around the MST radar station shows divergence or upward motion (rear portion of the trough, around January 19) that is observed from the MST radar vertical velocity (Fig.6.9). From the foregoing discussions it is apparent that the Indian MST radar vertical velocity is useful to extract information on synoptic-scale signals that are caused by mid-latitudes weather systems.

6.4 Conclusion

A process of mid-latitude-tropics interaction during winter is outlined based on MST radar, radiosonde and NCEP/NCAR reanalysis data. The zonal wind over Tirupati completely changes from westerlies to easterlies in the troposphere and lower stratosphere during January 1996. It is found to be associated with the appearance of an active western disturbance during this period. Similar changes in the zonal wind are observed in the mid-troposphere and lower stratosphere. The interaction between the mid-latitude and the tropics is further evidenced from the strong westerly wind regime in the radar and radiosonde data. During the passage of

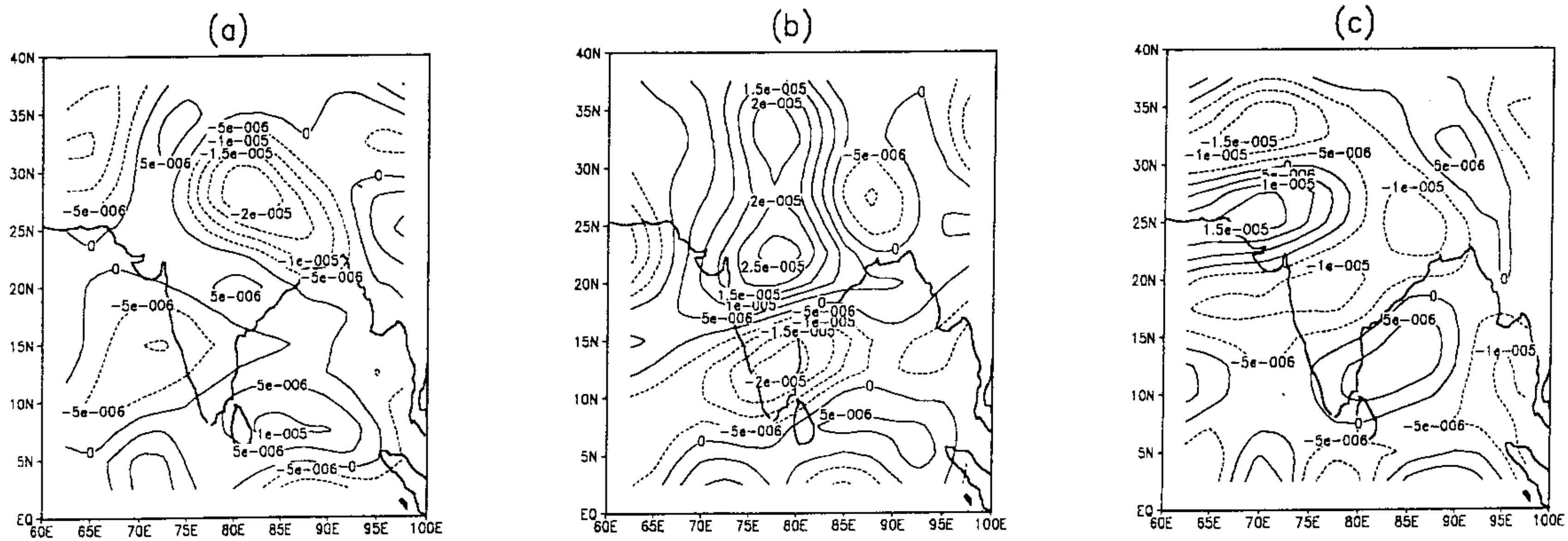

Fig. 6.10. Horizontal divergence between equator to 40° N and 60° E to 100° E for the three selected days (January 11, 15 and 19, respectively) are depicted.

western disturbance, the trough in the mid-latitude has intruded into the tropics and is reflected as strong westerlies in the mid-troposphere. The divergence field computed over the radar station shows that the observed intensification of the downward motion is in association with the synoptic system of the northwest Indian region. Divergence is seen on either side of the trough intruded into the tropics. Winter-time vertical velocity will be strong downward over the radar station when there is an intense upper air trough in the mid-latitude westerlies.

Chapter 7

Summary and conclusion

7.1 Summary and conclusion

The characteristics of the vertical circulation and that of the equatorial waves have been studied using MST Radar, radiosonde and NCEP/NCAR reanalysis data over the Indian region and the results are discussed in the present thesis. Major outcomes of the study are presented as follows.

The tropical circulation is characterised by the presence of the Hadley Cell, which is a major means of meridional and vertical transport of moisture, energy and momentum in the tropical atmosphere. In the present work, the MST Radar derived vertical wind is compared with the NCEP/NCAR reanalysis global data and studied the seasonal reversal of vertical and meridional circulation pattern. It is noted that during winter, the zonal and meridional wind components as observed from Indian MST radar agree well with the Hadley circulation over Gadanki region inferred from NCEP/NCAR reanalysis data. The Hadley circulation over south Indian region suggests that the vertical velocity should be downward during winter, which is confirmed from the observed vertical velocity at Gadanki during the winter season.

During the southwest monsoon season, the reverse Hadley cell theory (Koteswaram, 1960; Schulman, 1973) over Indian latitudes requires upward motion over the monsoon trough (MT) with southerly flow at lower levels. However, the low-level wind over Gadanki region is northerly. This anomalous wind over the peninsular Indian region is also seen in the NCEP/NCAR data. Such flows are absent in the Arabian Sea and Bay of Bengal. From the seasonal vertical velocity profile it is found that the long-term vertical motion is downward during summer season over the radar station (Gadanki). The observed reverse Hadley circulation and the negative vertical velocity values conclude that downward limb of the Hadley cell exists north of the equator during summer over Indian region.

Studies on the characteristics, of equatorial waves, show that during winter season the waves passing across the Indian MST radar station (Gadanki), consist of both equatorial modes and long period Rossby modes penetrating equatorward through the *westerly duct* or originating in the vicinity. As the NCEP/NCAR reanalysis data illustrated the presence of westerlies (*westerly duct*) between 8° N and 30° N, which act as a corridor for the propagation of large scale disturbances originating in the mid-latitudes. Large variances zonal and meridional components found in 15-day and 22-day wave show that they are Rossby type waves. From the vertical velocity data the covariance for different wave modes in the troposphere and lower stratosphere are computed. The covariance between u and w is observed to be highly coherent and generally negative for the 15-day and 22-day waves and positive for the 10-day wave. It is noted that the zonal variance of 10-day wave is relatively large compared to the meridional variance and shows downward phase propagation and is found to be transporting westerly momentum to upper levels as Kelvin wave.

Based on MST radar, radiosonde and NCEP/NCAR reanalysis data a process of mid-latitude-tropics interaction over Indian latitudes during winter is outlined. It is noted that disturbances (trough) in the mid-latitude westerlies would affect the tropical atmospheric circulation. From the study it is seen that the zonal wind over the Indian MST radar station change its flow from westerlies to easterlies in the troposphere and lower stratosphere during January 1996. It is found to be associated with the appearance of an active western disturbance (WD) during this period. The atmospheric flow noted from the radar data has been confirmed from the radiosonde data from Madras. Similar changes in the zonal wind are observed in the mid-troposphere and lower stratosphere. This observed interaction processes between the mid-latitude and the tropics are further evidenced from the strong westerly wind regime in the radar and radiosonde data. During the passage of the western disturbance, the trough in the mid-latitude has intruded into the tropics and is reflected as strong westerly winds in the mid-troposphere. Intensification of the vertical motion in the troposphere and lower stratosphere during the passage of the western disturbance is compared using the horizontal divergence determined from the NCEP/NCAR reanalysis data. The divergence field computed over the radar station shows that the intensification of the downward motion is in association with the synoptic system of the northwest Indian region. Divergence is seen on either side of the trough that has been intruded into the tropical atmosphere. It shows that the vertical velocity during winter will be strong and downward over the radar station when there is an intense upper air trough in the mid-latitude westerlies.

7.2 Scope for future studies

The seasonal changes and the vertical motion observed in the Hadley circulation using the Indian MST radar data combined with the NCEP/NCAR reanalysis data can be extended to study the inter-annual variability of the intensity of the Hadley cell. These studies may reveal the connection between the Hadley circulation and the inter-annual variability of the southwest monsoon. The outcome of these studies will be significant in understanding the performance of the Indian summer monsoon.

Another area of future study using the Indian MST radar is the movement of the Inter Tropical Convergence Zone (ITCZ) over Indian region during the monsoon season. The 30-50 day oscillation and its connection with the Indian summer monsoon are well known. Its relationship with the observed vertical velocity over Indian region can be studied in detail using the vertical velocity data from the Indian MST radar. The inter-annual variability in the momentum transport by the equatorial waves is another area of research. This will help in understanding the variability in the period of the equatorial quasi-biennial oscillation (QBO) and its possible association with the tropospheric weather systems.

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List of publications

1. **Annes, V. H., and K. Mohankumar:** A comparative study on the variabilities and trend in total ozone in the northern and southern hemispheres, *Indian J. Rad. Space Phys.*, 26, 249-255,1997.

2. **Annes, V. H., and K. Mohankumar:** Variability and trends in total ozone in tropics – *abstract presented in the National Space Science Symposium (NSS – 96)* held at Osmania University, Hyderabad, February 6-10, 1996

3. **Annes, V. H., and K. Mohankumar:** A study on the latitudinal variability of Quasi-biennial oscillation in total ozone–*paper presented in the National Seminar on Climate Variability and Predictability* held at Cochin University of Sci. & Tech., Cochin, September 18-19, 1996

4. **Annes, V. H., and K. Mohankumar:** A comparative study on the variabilities and trend in total ozone in the northern and southern hemisphere – *paper accepted for presentation at First SPARC General Assembly,* held in Melbourne, Australia, December 2-6, 1996

5. **Annes, V. H., and K. Mohankumar:** A study on winter circulation changes using MST radar observations – *abstract presented at the 8th International Workshop on Technical & Scientific Aspects of MST radar* -mst8- held at Bangalore, December 15-20, 1997

6. **Annes, V. H., and K. Mohankumar:** Variability in vertical flux of horizontal momentum during winter 1995-96 - *paper presented at the 8th International Workshop on Technical & Scientific Aspects of MST radar* -mst8- held at Bangalore, December 15-20, 1997

7. **Annes, V. H., and K. Mohankumar:** Midlatitude-tropics and stratosphere-troposphere interaction over India during winter – *paper accepted for presentation in the Seminar on Stratosphere-troposphere interactions* held at the Department of Atmospheric Sciences, Cochin University of Sci. & Tech., Cochin, November 24-26, 1998

8. **Annes, V. H., S. Sijikumar and K. Mohankumar:** Changes in the troposphere and lower and stratosphere circulation pattern over Indian region associated with the movement of Western Disturbances - paper accepted for presentation *at the 9th*

International Workshop on Technical & Scientific Aspects of MST radar -mst9- held at Toulouse, France, March 13-17, 2000

9. **Annes, V. H., K. Mohankumar and P. V. Joseph:** A study on the characteristics of monsoon Hadley circulation over Indian region using MST radar and NCEP/NCAR reanalysed data - paper accepted for presentation *at the 9th International Workshop on Technical & Scientific Aspects of MST radar* -mst9- held at Toulouse, France, March 13-17, 2000

10. **Annes, V. H., S. Sijikumar and K. Mohankumar:** Midlatitude-tropics interactions as seen from MST radar observations at Gadanki (13.5° N, 79.2° E) during winter - paper accepted for publication in the Special issue of the *Indian J. Rad. Space Phys.*, August, 2000

11. **Annes, V. H., K. Mohankumar and P. V. Joseph:** Vertical motion in monsoon Hadley circulation over India as monitored by MST radar at Gadanki (13.5^{O} N, 79.2^{O} E) - paper communicated for publication in the *International Journal of Climatology, UK*

12. **Annes, V. H., and K. Mohankumar:** Studies on the characteristics of tropical waves using MST radar observations atGadanki (13.47° N, 79.18° E), India, during winter - paper communicated for publication in the *Annales Geophysica*, UK