CHAPTER-3

OBSERVATIONS OF LARGE-SCALE WAVE STRUCTURES OF EARTH’S LOWER ATMOSPHERE MEASURED WITH GPS RADIO OCCULTATION TECHNIQUES
3.1 Introduction

Raw data collected from geosynchronous satellites serve as fundamental information for any climate monitoring system globally. In good olden days, these data were mainly used to gauge the existing state of the atmosphere thereby providing preliminary information for weather forecast models used to monitor short term changes in climate (now-casting). Monitoring an operant such as large scale wave structures, especially different wave activities, of Earth’s lower atmosphere is a prerequisite to understand atmospheric stability under two aspects in view of major concerns and their impacts on climate change. First, how Kelvin waves respond to various phase transitions of QBO. Second, the relation between temperature anomalies and various phase transitions of ENSO. These well-meant intentions can be resolved by effective utilization of existing instrumentation and monitoring technologies followed by observational analysis of large scale planetary wave structures. Continuous monitoring of atmosphere on vertical and horizontal scales over a long period of time allows us to perform analysis and accurate calibration. For example, observed temperature profiles using radio occultation (RO) technique can be compared with radiosonde temperature profiles over a long period to identify anomalies leading to unusual or modified climatic conditions that includes catastrophic events.

Generally, the variability of Kelvin waves is mainly due to the disturbances in convective heating processes in the tropical troposphere. These disturbances can be evaluated in terms of east ward propagating waves that can settle around the equator with a decrease in their density levels away from the equatorial region. Diabetic heating by organized tropical convection rouse atmospheric waves near the equatorial region. Propagation of these atmospheric equatorial waves leads to the generation of convective storms exhibiting its impact over large longitudinal distances thereby influencing remote responses to localized heat sources. In addition to that, inducive interaction of these atmospheric equatorial waves with low-level moisture convergence controls spatial and temporal distribution of convective heating. This enthused many researchers to conduct various studies using different methods of measurement to identify relative lateral displacements as well as vertical propagation of large scale wave structures (Scherllin-Pirscher, 2012; Stephens et al., 2003; Trenberth et al., 2006; J.Li et al., 1993). Yeared back, changes in large scale wave structures are identified by individual observations made from radiosondes, rawinsondes, RADARs and satellites although the data provided by them have contributed to the define physical parameters but unable to resolve the complete structure of tropical environmental hazards over large scales. This can be attributed to the data assimilation models and observational systems that do not meet decision rules related to consistency over the entire globe because of the fact that that atmosphere never
remains stable due to continuous adjustment of variance due to mass and wind fields in the course of production and propagation of phenomenal waves which necessitates development of improved tracking, retrieval algorithm, data processing and assimilation methods.

This chapter infers about observational advancements made since 1995 in atmospheric dynamics about large scale wave structures of Earth’s lower atmosphere using COSMIC GPS RO technique along with discussion on advantages and assessment accuracy of the observational methods employed during this progress in identifying Kelvin waves and their variance due to induced ambient effects as well as their relation with other climate change parameter such as ENSO.

This chapter was arranged in the following sequence: In section 3.1, we present a brief literature survey on observations of large-scale wave structures of Earth’s lower atmosphere measured with GPS-RO techniques and in section 3.2, we discuss in detail about the different identification procedures of Kelvin waves using RO techniques along with their advantages and extra features revealed by adopting this technique. In section 3.3, we present the characteristic and observed features of ENSO and QBO from large scale wave motions derived from COSMIC retrieved temperature profiles, followed by discussion and summary in section 3.5.

3.2 Literature survey

The history of understanding the atmosphere leaps forward from Aristotle who identified three distinct climate zones and wind patterns that changed seasonally in the 18th century. A review of research publications in the light of available literature that used different methodologies and analytical observational studies using a wide variety of satellite missions, radiosondes and rawinsondes to understand planetary-scale wave structures of Earth’s atmosphere based on the atmospheric parameters are discussed. The following is a list of research works carried out by different researchers and scientists throughout the globe in advancing atmospheric research incorporating science and technological tools as well as several identification procedures, data retrieval and analysis methods along with the results based on their conducted studies for the benefaction of societal needs within the line of our research work. Here the literature review has been presented in the format of year wise achievements towards concerned title abstract right from 1971-2014 to understand the progress and importance of this work.

The probing of planetary atmospheres by RO started in early 1960’s with Mariners 3 and 4 passing behind Mars and viewed from Earth. Although RO has explored planetary and interplanetary atmospheres, its application on planet Earth was prolonged due to the requirement of continuous, synoptic and comprehensive measurements which can be accomplished by making use of
transmitter-receiver pairs outside the Earth’s atmosphere in tandem to attain hourly dense sampled data of global atmosphere. Fjeldbo et al., (1971) proposed an occultation technique that remained idle for a long time until it had been experimentally proved by GPS Meteorology (GPS-MET) project utilizing GPS satellites for Earth’s atmospheric studies.

A notable study made by Holton and Lindzen (1968) reveals the scope for strong excitation of atmospheric Kelvin wave based on the data analyses made by Wallace and Kousky (1968) on vertically propagating oscillations in the zonal wind of the tropical stratosphere between 80mb and 20mb for 12-15 days and a vertical wavelength of ~10 kilometres. Later, Holton and Lindzen (1972) arrived at a conclusion that large-scale Kelvin and Rossby-gravity waves are thought to play an important role in driving the eastward phase of QBO by the zonal winds of equatorial stratosphere.

Salby et al., (1984) utilized the datasets from Nimbus-7 satellite launched in 1978 that carried Limb Infrared Monitor of the Stratosphere (LIMS), specifically intended for monitoring the Earth’s stratosphere in addition to Earth’s oceans as well as water bodies and contributed enormously to understand the Kelvin wave modes in stratospheric altitudes by revealing Kelvin wave variability that lies within a range of zonal wave numbers 1-3.

Garcia and Salby (1987) by using stochastic near field behaviour of disturbances excited by randomly evolving tropical heating inferred that deep convection is a principal source of wave variability in the tropical atmosphere as the associated vertical circulation effectively promotes or suppresses convection there by modulating short-term heating variability. Together with the onset and collapse of the monsoon, this would be expected to lead to significant heating power at very low frequencies. Further, these authors had found quasi-stationary wave structures near tropopause (17 kilometres) for six consecutive months and a regular eastward propagating wave at 19 kilometres with variance dominated by the Kelvin mode that captures an appreciable fraction of the overall tropical power even at the tropopause.

Hitchman and Leovy (1988) found several interesting bulk properties of Kelvin waves from LIMS record to document three dimensional structure of Kelvin waves on a daily basis to reckon quantitative forcing of the mean state by these waves in the altitudinal range of ~16-70 kilometres which showed that slower gravity waves might be absorbed in the equatorial lower stratosphere thereby strengthening their flow and influencing QBO. Further in 1990’s, UCAR (University Corporation for Atmospheric Research) along with JPL successfully tested economical geodetical surface based receiver that can hover in space to receive occultation data and validated estimation accuracy of atmospheric refractive index using Doppler shift in rays by inevitable refractive bending.
Using Radiosonde instruments, Tsuda et al., (1994) has shown that Kelvin waves can significantly influence the tropopause structure by observing temperature fluctuations determined in periodogram analysis with a fixed period of 20 days. Further, they have also identified sinusoidal variation of temperature fluctuations coinciding with Kelvin wave period and intermittent shift in tropopause while performing their analysis with respect to time-height structure during observation period there by suggesting that upward flux of vapor transported from tropospheric top into equatorial stratosphere can be modulated by the activity of Kelvin waves.

During the same time, Canziani et al., (1994) observed Kelvin wave activity from the data collected by Microwave Limb Sounder (MLS) during first two solstices of Upper Atmospheric Research Satellite (UARS) mission. MLS measurements demonstrated strong evidence supporting the presence of Kelvin wave activity in zonal wave numbers 1 - 2, when two subsequent interims of Kelvin wave activities are compared during different stages of QBO. Despite the vertical resolution limitations of MLS, Canziani et al., (1994) had noticed some interesting results such as displacement of the wave peak off the equator thereby resembling equatorial asymmetry as a response to latitudinal shear of mean zonal flow.

Pires et al., (1997) studied equatorial synoptic waves existing in the western and central Pacific region using Coupled Ocean–Atmosphere Response Experiment (COARE) during the whole Intensive observational period (IOP) focussing on interim locations of equatorial modes had revealed that Kelvin or Rossby- gravity waves are most important equatorial wave modes that gavage tropical troposphere by convective processes while Shiotani et al., (1997) investigated Space-time variations of atmospheric temperature in the equatorial lower stratosphere using temperature data derived from cryogenic limb array etalon spectrometer(CLAES) instrument on-board the UARS mission for January 1992 to May 1993 and observed clear evidence of eastward progression of zonal wavenumber 1 temperature anomalies giving rise to a conclusion that the temperature variation seen in the equatorial lower stratosphere is mainly due to slow Kelvin waves. In addition to this, Dunkerton, (1997) carried out two dimensional numerical model studies on role of vertical gravity momentum transport during QBO which revealed a minimum sufficient condition to attain QBO by relating total wave flux with observed large scale Kelvin waves with respect to realistic Brewer-Dobson upwelling.

Alexander and Holton, (1997) adopted two dimensional non hydrostatic cloud-resolving numerical model with slight alteration to Alexander et al. (1995) to study gravity waves generated by tropical squall line simulations to understand their underplay in influencing QBO by zonal winds in the
equatorial stratosphere and observed excitation of mesoscale gravity waves away from the equator which played significant role in influencing QBO.

Fujiwara et al., (1998) made an intensive observation to investigate ozone enhancement phenomenon using ozonesondes and rawinsondes from Indonesia in May-June, 1995 showing that the downward motion associated with the Kelvin wave had carried stratospheric ozone into the troposphere and mixing of air due to Kelvin wave breaking at tropopause also led to stratosphere-troposphere exchange of ozone while Canziani and Holton, 1998 had derived a method to evaluate role of Kelvin wave in vertical flux of westerly momentum of equatorial stratosphere with respect to temperature and geopotential perturbations using CLAES temperature data set during the first part of UARS mission and analyzed zonal wind data from High Resolution Doppler Imager (HRDI) as well as correlative assimilation data set from United Kingdom Meteorological Office (UKILOMETRESO) which suggested that Kelvin waves are ineffectual in dropping westerly phase of the QBO.

Further, Huang et al., (1998) proposed an efficient new adaptive empirical mode decomposition method for analysing complicated solitary wave data set by disintegrating into a small number of finite intrinsic mode functions so that instantaneous functions of energy-frequency-time distribution can be obtained to identify imbedded structures of Kelvin waves.

Wheeler and Kiladis, (1999) performed wavenumber-frequency spectrum analysis to extract disturbances due to accouplement in the time-longitude domain by filtering outgoing long wave radiation (OLR) dataset retrieved from satellites for specific zonal wavenumbers and frequencies which reveals variance in convective driven propagating waves over geographical distribution thereby indicating testimony of the spectral peaks that corresponds to particular equatorial wave modes giving rise to explicate cumulus parameterization problem as well as excitative equatorial waves in the lower stratosphere plus extended-range forecasting in the tropics.

Wickert et al., (2001), studied nearly 3000 recorded RO measurements from CHAMP (CHAllenging Minisatellite Payload) satellite by means of GPS signals to collate global weather analyses, which indicated a temperature weft ~1K on upper tropopause and less than 0.5K in an altitudinal range of 12-20kilometres at latitudes greater than 30 with profiling cover of last kilometre above the Earth’s surface while Fujiwara et al., 2001 noticed that equatorial Kelvin heave at tropopause acting as a dessication pump for the stratosphere by observing retroversion phase of a Kelvin wave, dry and ozone-rich stratospheric air carryoff tropospheric top while during uprise phase, higher specific humidity air thrust tropopause region thereby cooling the air to confine vapor entering the stratosphere in addition to contribution of wave breaking towards irreversible transport of ozone.
across the tropopause giving rise to a notion that Kelvin waves might prelude in maintaining the dryness of tropical lower stratosphere.

Sasi and Deepa, (2001), estimated the seasonal variation of vertical flux of the horizontal momentum associable equatorial Kelvin wave using wind measurement data from Indian MST RADAR located at Gadanki (13.5°N, 79.2°E) from September 1995 - August 1996 in tropopause region which showed larger momentum flux values during equinox seasons than solstices.

Mote et al. (2002), observed three-dimensional structure of stratospheric Kelvin waves from MLS during July 1992 - April 1993 concentrated around the equator and identified four Kelvin wave modes, two for each zonal wave numbers 1 and 2 based on extended empirical orthogonal functions which are in agreement with linear theory appeasing dispersion relation for Kelvin waves with periods ranging from 4.5-10 days across state boundary of fast and slow Kelvin waves according to canziani et al., (1988) thereby revealing “pancake structures” associated with inertial instability.

Smith et al., (2002), utilized CRISTA (Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere) carrying limb-scanning spectrometers to measure temperature and trace species amid atmosphere at high spatial resolution operating aboard Shuttle Pallet Satellite (SPAS) can fetch information simultaneously from triplet telescope whose viewing angles are offset by 18° so that it became possible to retrieve tropical perturbational characteristics of Kelvin waves recognized by measured temperature data from two terrain flights revealing appearance of wave signals in several stratospheric trace species thereby confirming accountability of vertical velocity for perturbations in addition to exhibition of relative phase shift in view of changes in photochemical processes with increasing height while ozone at stratospheric top correlates negatively with temperature due to destruction of ozone by temperature dependent reaction rates.

Lindzen (2003), examined the hypothesis that low-level convergence of waves having predefined pattern on a given scale due to perturbation when converges with convection due to evaporation influences the existing patterns of convection at large scales by assuming associable pattern with time scale independent of wave scale or amplitude so that phase proportionality of semidiurnal component of observable daily variations in precipitation, equivalent depths as well as vertical structures of tropical waves can be analysed in accordance with Wheeler and Kiladis (1999); Straub and Kiladis (2003) so that time scale for patterning will be longer than deterioration and regeneration of waterspout approaching spatiotemporal coherence of mesoscale cloud complexes suggesting that pattern might be influencing complexes rather than clouds to show consistency in wave properties with a continuous spectrum.
Randel et al. (2003), studied mean homogeneity of cold point temperatures (CPT) in the tropical upper troposphere and lower stratosphere (UTLS) (~10-30 kilometres) based on GPS/MET data observables from April 1995-February 1997 and observed that sub-seasonal variability in CPT and height vestige that swell like Kelvin waves as well as exhibiting accountable correlations with GPS/MET retrieved temperature data quantifying linearity between large-scale tropical temperature and momentary convection thereby disclosing coherent wave-like variations over ~ 12-18 kilometres across hemisphere in longitude with a further evidence of stratospheric QBO in temperatures at altitudes ~16-40 kilometres.

Hajj et al. (2004), evaluated atmospheric temperature, pressure and moisture by comparing RO profiles from nearby CHAMP and SAC-C (Satellite de Aplicaciones Cientificas- C) missions, operating from 2000 and examined one lakh thirty thousand profiles out of which two hundred and twelve pairs occurring within 30min at a distance of 200 kilometres between them are taken into consideration at sixty eight percent assurance range within 0.1k mean between 5 and 15 kilometres height level by eliminating expected variability to understand changes in climate by studying three central claims such as instrumental bias and drift in GPS data retrievals, accuracy of temperature data profiles to less than 0.5K for 5-20 Kilometres range and accuracy of average profiles for analyses to be less than 0.1K. Their study had noticed that the N-bias problem prevalent in GPS/MET is also present in CHAMP and SAC-C whose prospects lie in implementation of OL tracking by subsequent missions.

Randel and Wu, (2005) studied variability of Kelvin waves that hover equatorial tropopause for 2001-2002 term from temperature data profiles retrieved from above mentioned satellite missions and identified that Kelvin waves with planetary zonal wavenumbers 1-2 represented its characteristic phase change with altitude having vertical wavelengths of 6-8 Kilometres in-between December-January durancy while shorter vertical wavelengths of 4-5 Kilometres in-between May-September durancy in addition to variation in Kelvin wave temperatures with maximum displacements of 2-4 K approaching 10 K for profiles with quasi stationary wave structures near tropopause that are east ward propagative in the lower stratosphere across tropopause having periods of nearly 20 days for May-September 2002 durancy revealing consistency between GPS and radiosonde measurements.

Sridharan et al., (2006) made radiosonde observations of winds and temperature over several sites in Southeast Asia for one month campaign study i.e. 10th April - 9th May 2004 on Coupling Processes in the Equatorial Atmosphere (CPEA) have shown a revelation of seven day Kelvin wave characteristics around tropopause with an amplitude peak at altitudes of 20-21 kilometres.
Ratnam et al. (2006), studied vertical and temporal heaving of Kelvin waves and associable effects on tropical tropopause. They have considered identified Kelvin wave variation of 10-15 days with vertical wavelengths of 5-8 kilometres showing eastward phase propagation in longitude-time plot having a tilt with respect to height in altitude Vs longitude, exhibiting their characteristic nature for analysis. Their study had validated the interaction between Kelvin wave and QBO in and around tropopause by analyzing amplitudes of Kelvin wave activities with different phases of QBO with respect to temperature and their influence on tropopause sway.

Tindall et al. (2006a), quantitatively estimated equatorial wave activity of tropical lower stratosphere by combining wavenumber-frequency spectral analysis and linear wave theory in a novel method which revealed signals consistent with idealized Kelvin waves at wavenumbers and frequencies in agreement with earlier studies when averaged over 12 year period (1981-1993) resembling $1 \ K^2$ of temperature variance on the equator at 100 hPa for Kelvin wave whereas Tindall et al. (2006b), investigated variedness of idealized, linear, equatorial waves in the lower stratosphere using temperature as well as velocity fields using European Centre for Medium range Forecasts (ECMWF) 15 year reanalysis dataset and identified peak Kelvin wave activity occurring during solstice seasons at 100hpa, during December-February at 70hpa and in the easterly to westerly QBO phase transition at 50hpa. These waves with $n=1$ are correlated with the QBO at 50hpa, which revealed that strongest acceleration appears to be provided by the Kelvin wave.

Anthes et al., (2008) presented a summary on early results of COSMIC mission, a constellation of six microsatellites, was successfully placed in five hundred and twelve kilometres orbit at 0140 UTC on 15 April 2006 and individual satellites wean into their final orbits at 800 kilometres elapsing 17 months from initial date of launch thereby providing a powerful demonstration of RO by retrieving two thousand fine retrievals of globalized data on daily basis to worldwide data monitoring centres proximate to test their impact on weather forecasts. By the end of March 2013, reports show that COSMIC provided 1500 RO data profiles per day with 0.05°C precision of individual profiles to support regular indifferent preciseness in observations.

Alexander et al., (2008), studied potential energy associable with equatorial gravity waves of 7 Kilometres vertical wavelength and their coevolution with QBO using temperature profiles derived from COSMIC RO data can be wedged into grids of size 20º in longitude and 5º in latitude that surmise equatorially trapped Kelvin waves zonally with wavenumber(s) $\leq 9$ using bandpass filtration of wavenumber-frequency temperature continuum by means of propagative spatio-temporal vertical structures as well as wave-mean flow interactions with respect to reference mean flow and comparing COSMIC derived equatorial wave RO data with OLR for discrimination.
Ern et al., (2008), carried out analysis on excitable planetary scale Kelvin waves due to convective progression in troposphere as well as stratosphere using temperature data derivatives of Atmosphere using Broadband Emission Radiometry (SABER) instrument and ECMWF and observed overreckoning of Kelvin wave components while a case study conducted by them using aircraft measurement campaign, Stratospheric-Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere (SCOUT-03) at Darwin/Australia in November-December of 2005 regarding the same issue is in agreement with ECMWF studies for lower stratosphere.

Ao et al., (2009), described atmospheric Doppler and delay model use in SAC-C and COSMIC OL tracking program by discussing test execution on SAC-C along with examples of OL processing and their data accuracy improvement (80%) in lower part of the tropical atmosphere (<2Kilometres) whereas it is 50% with CL tracking.

Rao et al., (2009), studied observations from campaign that was conducted at a tropical site, Gadanki (13.48°N, 79.18°E), India during July 2006 to March 2007 by comparing with COSMIC RO data to validate meteorological parameters such as density, refractivity, temperature and vapor profiling of neutral atmosphere while Nd-YAG Rayleigh LIDAR was utilized to validate temperatures in the height range of 30-40kilometres and identified large difference in temperature of about 8k thereby arriving at conclusion that pressure plays a key role than temperature in determining the refractivity.

Brahmanandam et al., (2010), analysed temperature data for September 2006 - February 2008 period derived from COSMIC GPS RO datasets which showed the presence of Kelvin waves with wave period afar 10 days and higher zonal wave numbers in the tropopause region revealing vertical wavelengths that fall within the range of 5-12 kilometres exhibiting predominance in altitudinal stretch 15-28 kilometres centred on tropical tropopause. Appellative to that their descent suggests that their derivatives are progressing upward from instant of its identification at lower altitudes by tropical convection and compared with the zonal wind radiosonde data over Singapore (1°N, 104°E) for the same period that showed ~24 - 26 months periodicity in Stratosphere along with zonal wind characteristics of QBO for March 2006 – May 2007 and June 2007 - July 2008 durancy respectively for eastward and westward zonal winds. Their Observation related to enhanced characteristics of Kelvin waves during their interaction with QBO at different phases are identified to be in line with previous results.

Anthes (2011), summarized apposition results of RO missions and their observational analysis for prediction accuracy in atmospheric research right from initiated GPS/MET mission in 1995 proving proving RO repertoire.
Zhang et al., (2011), made a comparative study using temperature profiling from both CHAMP (May 2001-October 2008) as well as COSMIC (July 2006 - December 2009) and data from thirty eight Radiosonde stations in Australia which showed results that are in accord with each other.

Additionally, Steiner et al., (2011), presented analytical review based on RO data for climate studies across whole tropical tropopause with a discussion related to RO physiognomy towards understanding climate change indication characteristics and associable parameters.

Scherllin-Pirscher et al. (2012), investigated spatio-vertical composition of atmospheric ENSO signal using RO data for August 2006-December 2010 durancy as they apposite to study 3-d structural ENSO episode across UTLS due to its global echelon and found variations in temperature anomalies with respect to zonal, mean and eddy components during warm phase of ENSO.

Mannucci et al., (2012), presented the potential of COSMIC-2/FORMOSAT-7 (C-2/FS-7) as an Earth and Space science mission that describes systems engineering considerations to maximize science return targeted to yield improved forecasts that promises to be more than a robust provider of data similar to its predecessor COSMIC/FORMOSAT-3.

Yang and Hoskins (2013), investigated and refound thermodynamical impact of ENSO on atmospherical Kelvin waves along with associable tropical convection by means of ECMWF Re-Analysis, National Oceanic and Atmospheric Administration (NOAA) OLR and YHS methodology (Yang and Hoskins methodology – Yang et al 2003 with a special focus on equatorial central-eastern Pacific.

Anisetty et al.,(2014), presented a study on planetary-scale equatorially trapped Kelvin waves derived from temperature profiles using COSMIC satellites during 2006- 2009 and their interactions with background atmospheric conditions which showed that the Kelvin waves are associated with wave periods of higher than 10 days (slow Kelvin waves) with higher zonal wave numbers (either 1 or 2) in addition to possession of downward phase progression giving evidences that the source region of them are located at lower altitudes thereby indicating that the Kelvin waves are driven by convective activity. Further their study has also shown the relationship between Kelvin waves and QBO during different phases of ENSO.

A review of the literature yielded information from publications that used various observational methodologies to study planetary scale wave structures associated with the dynamics of atmospheric processes. Autognosis of ideal ambience and data incapacity are ascribable restrictions to comprehend climate change by building realistic climate models. From above literature review one can clearly understand that the variability in the atmospheric processes due to variance in
physical parameters within troposphere leads to modification of different planetary scale wave structures in the upper atmosphere generating curiosity to demystify the reality.

3.3 Different Identification procedures of Kelvin waves

In general atmospherical waves are generated by turbulent eviction due to perturbation on an initially balanced flow. To eliminate this perturbation, restoring force overacts leading to the generation of oscillating wave structures. In view of this, diagnosing restoring force responsible for ripple structure is important to understand their development pattern as well as characteristic nature of their sign structure, although it is neither necessary nor possible to interpret individual waves using trigonometry. An example of this kind is a topographical gravity wave produced by wetness passing over a ridge under atmospheric equilibrium.

Kelvin waves were first identified in the nineteenth century by William Thomson (Lord Kelvin). Kelvin waves are large scale waves whose structure is in such a way that gets trapped so that they propagate along a physical boundary such as coastline in the ocean or a mountain range in the atmosphere. In tropical atmosphere, each hemisphere act as the barrier for a Kelvin wave with its adjacent hemisphere resulting in equatorially trapped Kelvin waves, one of the critical wave motion in response to the tropical atmospheric circulation from a near source. When an imposed heating centred on the Equator is entered at some initial time, Kelvin waves tends to move rapidly eastward, thereby creating easterly trade winds in that region and forming a Walker cell with a rising motion over the heat source region and sinking motion towards east. Internal equatorial Kelvin waves traveling with typical phase speeds of 20–80ms⁻¹ are an effective means by which the equatorial atmosphere becomes homogenized in the zonal direction. The easterly winds are in geostrophic equilibrium producing a trough along the Equator, with the winds along the Equator flowing directly down the pressure gradient.

Although there were several methods that had been proposed earlier to identify Kelvin waves and their characteristics making use of GPS RO missions, they have employed closed loop (CL) tracking mode in which the receiver uses a phase-locked-loop (PLL) which often fails in the presence of low signal to noise ratio (SNR) and high signal dynamics. In view of this, we have taken advantage of OL tracking method that has been implemented on COSMIC satellites while retrieving atmospheric profiles (further details on the same has been presented by Ao et al. ,(2009) to retrieve atmospheric temperature profiles. along with OLR analysis and a Fast Fourier Transform (FFT) method has been adopted to identify Kelvin wave characteristics followed by Hilbert Huang Transform (HHT) method to study influence of ENSO on Kelvin waves.
Before discussing the available observational results of this study, it should be appropriate to discuss about the validity of COSMIC RO retrieved temperature profiles as the accuracy and precision of any observation system that measures atmospheric constituents should be confirmed with well-established ground based experimentations. In view of this, we have made a few comparative studies between COSMIC retrieved vertical temperature profiles and near-by radiosonde measurements at two important equatorial stations in the following manner.

**Figure 3.3.1** Vertical profiles of temperatures over Maldives (0.4°S, 73°E) measured with radiosonde (thin lines) and nearby GPS retrievals (thick blue lines) on (a) 8 January 2007 and (b) 9th January 2004 and over Singapore (1°N,104°E) on (c) 18th October 2006 and (d) 1st Jan’ 2007.

Figure 3.3.1 shows a typical comparison of vertical profiles of temperature provided by radiosondes represented by thin black line with nearby COSMIC GPS RO measurements represented by thick blue line over Gan/Maldives (0.4°S, 73°E) on 08th January (Figure 3.3.1a) and 09th January 2007 (Figure 3.3.1b), whereas Figures 3.3.1c and 3.3.1d show the comparison over Singapore (1°S, 104°E) on 18th October 2006 and 01st January 2007. Here, it should be noted that ‘dt’ and ‘dx’ in all figures indicate the differences in time and location between radiosonde and GPS RO measurements.
Further, it is clearly evident from these figures that the vertical temperature profiles covenanted with these two measurements thereby providing confidence in using COSMIC RO retrieved temperatures in atmospheric dynamics studies.

Studies conducted earlier at different longitude sectors have also found good correspondence between GPS RO retrieved and radiosonde measured temperatures. As an example, a validation study performed at Gadanki (13.48° N, 79.2° E), a tropical station in Indian longitudinal zone by Rao et al., 2009 has revealed little variance in mean ~1k amongst 10 – 27 kilometres was found amid COSMIC and radiosonde temperatures. In addition to this, Kishore et al., 2009 rendered justification study using stratospheric analyses that includes NCEP, Japanese 25 year Reanalysis (JRA-25) and UKILOMETRESO datasets which showed good agreement between the COSMIC and reanalysis outputs taken into consideration with differences in global mean and height (8-30 Kilometres) being not as much of than 1k.

Spatially, altitude-wise principal digression were observed over polar latitudes around tropical tropopause with differences being 2–4 K. Collocated global atmospheric temperature profiles from radiosondes and from COSMIC GPS RO satellites have been compared for April 2008 to October 2009 by Sun et al., 2010 and found that in troposphere, the temperature standard deviations errors are 0.35 K per 3 h durancy and 0.42 K per 100 kilometres. Comparative studies made by Zhang et al. (2011) between GPS-RO and radiosonde retrieved data have shown a very good agreement between the two datasets which showed average temperature difference between them to be 0.39° C (CHAMP Vs Radiosonde) and 0.37° C between radiosonde and COSMIC satellites.

As most of the Kelvin waves are concentrated around the equator (Mote et al. 2002), we have adopted COSMIC GPS RO retrieved temperature profiles between ±5° latitudes around the equator starting from September 2006 to August 2009 by following a simple procedure to extract Kelvin characteristics in the temperature profiles. In the first step, the retrieved temperature data have been interpolated to 500 m. It should be emphasized that the primal COSMIC data occult at 100 m vertical resolution and efficacious vertical resolution follow 500 m or above in the UTLS. Due to their high inclination that is 72° orbit of COSMIC satellites, the temperature profile data occurrence rates around the equator are rather sparse and hence an interpolation (cubic) method in longitude has been applied on the temperature profile data to fill-in the missing data starting from 5 to 30 kilometres altitudes as shown in Figure 3.3.2.
Figure 3.3.2 shows the longitudinal temperature profile represented with blue stars at 17 kilometres on 2nd September 2006 over the entire equatorial region that is 5°S - 5°N and cubic interpolation data (T) represented with blue solid line along with 3rd order polynomial fit represented by red solid line. In the second step, we use a 3rd order polynomial (T₀) to best fit to the interpolated data that can be considered as background temperature variation. It should be noted that the third order polynomial fit has been applied on time series at each individual height separately from 5 to 30 kilometres. Then background values were removed from each temperature profile corresponding to each altitude and the resulting fluctuation, that is T’ = T - T₀ data have been utilized to identify the Kelvin wave features.

Moreover, fluctuation data for every three month period are put together as ensembles to show the seasonal variation of Kelvin wave activity during September equinox (SON: September-October-November) followed by December solstice (DJF: December-January-February), March equinox (MAM: March-April-May) and June solstice (JJA: June-July-August) seasons of different years. Figure 3.3.3a shows interpolated data for fall 2006 between 5 - 30 kilometres altitudes which indicate tropopause location around 17 kilometres with ~-75° C (198°K) throughout the globe while Figure 3.3.3b shows the cubic interpolation data during same period for the entire globe at 17 kilometres.
Finally, we have applied FFT on large scale temperature fluctuation components and the subsequent application of incoherent integration on output of the FFT to identify typical characteristics of Kelvin waves including wave number, wave period in days, phase speed and vertical wavelength followed by a comparative study made between the observed characteristics of Kelvin waves with theoretical ones and presented them in Table 3.3.1 as shown below.

<table>
<thead>
<tr>
<th>Season and Year</th>
<th>Wavenumber (s)</th>
<th>Wave Period in days (T)</th>
<th>Phase Speed in Km/hr (Cx)</th>
<th>Vertical Wavelength in Km (Lz)</th>
<th>Theoretical Lz in Km</th>
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<td>September Equinox/2006</td>
<td>1</td>
<td>15</td>
<td>75.6</td>
<td>5-6</td>
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<td>December Solstice/2006</td>
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<td>17</td>
<td>92.6</td>
<td>6-8</td>
<td>5.45</td>
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<tr>
<td>March Equinox/2007</td>
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<td>10</td>
<td>83.3</td>
<td>5-8</td>
<td>4.8</td>
</tr>
<tr>
<td>June Solstice/2007</td>
<td>1</td>
<td>17</td>
<td>87.5</td>
<td>6-12</td>
<td>7.3</td>
</tr>
<tr>
<td>September Equinox/2007</td>
<td>2</td>
<td>9.5</td>
<td>77.5</td>
<td>6-10</td>
<td>9.2</td>
</tr>
<tr>
<td>December Solstice/2007</td>
<td>1</td>
<td>15</td>
<td>86.8</td>
<td>6-7</td>
<td>12</td>
</tr>
<tr>
<td>March Equinox/2008</td>
<td>2</td>
<td>12</td>
<td>77.2</td>
<td>9</td>
<td>7.9</td>
</tr>
<tr>
<td>June Solstice/2008</td>
<td>1</td>
<td>13</td>
<td>76.8</td>
<td>8-9</td>
<td>9.9</td>
</tr>
<tr>
<td>September Equinox/2008</td>
<td>1</td>
<td>14</td>
<td>85.2</td>
<td>6-7</td>
<td>8.5</td>
</tr>
<tr>
<td>December Solstice/2008</td>
<td>2</td>
<td>9</td>
<td>70.2</td>
<td>10</td>
<td>8.6</td>
</tr>
</tbody>
</table>
Table 3.3.1 clearly shows that most of the observational values are in close comparison with theoretical values indicating the ability of the present methodology that we have adopted to carry out this study.

### 3.3.1 Advantage of RO techniques in analysis of Kelvin Waves

There were several advantages of GPS RO products like unprecedented global high vertical denouement in all weather conditions. Although Earth’s atmosphere has been monitored with RO techniques using mono satellite missions including GPS/MET, CHAMP and SAC-C, due to their sampling bias one can study either seasonal or multiyear phenomena of equatorial waves [Melbourne et al., (1994); Wickert et.al, (2001); and Hajj et al., (2004)]. Further, six COSMIC satellite takeoff provided a boon to the scientific community delivering enhanced number of GPSRO profiles [Anthes et al.,(2008)], a follow-through project for space weather, climate monitoring, research and geodesic knowledge. Estimations shows that COSMIC satellites provide frequent global snapshots that covers 12 times higher database than earlier RO missions with an average profiles ranging in between 1500-2000 during a day, although planned for 4000 soundings around the globe as stated by Brahmanandam et al., (2010); Anthes (2000); Anthes,(2011). Therefore, it is expected that the COSMIC constellation can provide additional detailed analysis of wave structures with higher wavenumbers in lower atmosphere [Alexander et al., (2008); Brahmanandam et al., (2010)].

Most of earlier GPS-RO techniques like GPS/MET and CHAMP have suffered with the inability to transcribe rising occultations and failed to perforate 2kilometres in tropical troposphere due to usage of traditional phase-locked loop (PLL) in their LEO satellite receivers, as close-loop (CL) tracking approach of PLL in LEO receiver was unsuccessful to lock on signals associated with high dynamics present in atmospheric boundary layer (Ao et al., 2009). where PLL adjusts the preferred frequency response on the based on of preceding calibrations instead of considering the original signal and hence CL approach works well where sufficient signal to noise (SNR) as well as signal dynamics are not above prescribed limit which may not be the case particularly in and around the atmospheric boundary layer. But in order to study atmospheric convective parameters that are too temperature and moisture sentient, the atmospheric profiles below 5kilometres would be necessary. COSMIC satellites can overcome this problem as they have been implemented with an open-loop (OL) tracking approach which is model based and works on real time navigation solution
where there is a provision to guess the reference signal based on the knowledge of orbits, receiver
clock drift and atmospheric Doppler shift and delay estimation so that more than 90% of COSMIC
soundings penetrate below 1kilometres and planetary boundary layer [Ao et al., (2009)] that enable
us to retrieve rising GPS signals there by doubling the number of occultation’s compared to LEO and
improves the ability to calculate atmospheric convective indices.

3.3.2 Important features as revealed by COSMIC GPS RO

Periodical low temperature fluctuations from November 2006 to February 2007 had been observed
at 16, 17 and 18 kilometres that are characterized by the predefined climatology of squat
temperatures at longitudes of ~90°-200°E which are associable to maximum convection so that
overall patterns remains quasi-stationary over Indonesia as stated by Highwood and Hoskins, (1998),
fluctuations at 19 and 20 kilometres showed zonal wavenumber-1 composition to be usual eastward
propagative while these observational results are consistent with earlier reported results including
retrievals have found quasi stationary wave structures near the tropopause at 17 kilometres for six
months starting from October 2001 to March 2002 and regular eastward propagating waves at 19
kilometres with the data gridded in-between 10°N–10°S at each height above sea level in longitude
Vs time.

Since from long time, detection of chosen spatiotemporal planetary scale zonal propagation in deep
tropical convection has been carried out by applying spectral analysis approaches on satellite
derived outgoing long wavelength radiation as stated by wheeler and Kiladis, (1999), Randel and
Wu,(2005), precise and profound convection is a principal basis for wave variance in the tropical
atmosphere as observed by Salby and Garcia, (1987), Wheeler and Kiladis, (1999) and remained as
an interesting study to understand the relationship between large-scale Kelvin waves and deep
convection. We have analysed OLR database to understand the relation among Kelvin waves with
deep convective activities by considering OLR as a stand-in for deep convection. Following Figure 4
show longitude-time grid of OLR information averaged in 5°N - 5°S from January 2006 to January
2013.

From Figure 3.3.2.1, observations clearly shows that three regions including ~10 - 30°E, ~60 - 170°E,
and ~280 - 310°E are characterized by relatively low OLR values reaching less than 180Wm⁻²
particularly over ~60 - 170°E compared to rest of the globe indicating deep convective activities
often present at ~60- 180°E longitude sectors and it has been found that significant convective
activities are found to be present during northern winter months of all years with eastward propagating features.

Figure 3.3.2.1 OLR averaged between 5°N-5°S between January 2006 and January 2013

As the deep cold temperatures were also seen approximately around ~80-190°E longitude sectors at 16, 17 and 18kilometres as shown in following figure's 3.3.2.2 b,3.3.2.2 c, 3.3.2.2d and figure's 3.3.2.3a, 3.3.2.3b, 3.3.2.3c and 3.3.2.3d, we can believe that these cold temperatures are excited by those deep convective activities.

Figure 3.3.2.2 Temperature fluctuations in longitude vs. months over 5°S - 5°N during September 2006 to February 2007. (b) at 16 km (c) at 17 km (d) 18 km.
Figure 3.3.2.3 Temperature fluctuations in longitude vs. months over $5^\circ$S- $5^\circ$N during March 2007 to August 2007 a) at 15 km b) at 16 km c) at 17 km d) 18 km.
From the above mentioned observational results and previous studies, it is conceivable that the tropical convection generated over Indonesia region during November 2006 to February 2007 could be the plausible source mechanism for Kelvin waves as stated by Salby and Garcia, (1987), Wheeler and Kiladis, (1999). Further, observations clearly shows that phase speed of travelling OLR pattern is slower compared to Kelvin waves in this present study indicating that the observed Kelvin waves are feebly coupled to convection. Most probable observandrum is consistent with free mode exsufflation across convective variability spectra i.e. active Indonesian region in accord Randel and Wu, (2005) and Ratnam et al., (2006).

Figure 3.3.2.4 Kelvin waves in temperature fluctuations during eastward phase [(a), (b)] and westward phase [(c), (d)] of QBO.

Figure 3.3.2.4 shows vertical waves of temperature fluctuation components to identify Kelvin wave activity in both phases of QBO for four following days:

(1) 13/14 October 2006 (Fig. 3.3.2.4 a: eastward phase),
(2) 15/16 May 2007 (Fig. 3.3.2.4 b: eastward phase),
(3) 27/28 August 2007 (Fig.3.3.2.4 c: westward phase), and
(4) 19/20 February 2008 (Fig. 3.3.2.4 d: westward phase)
Obviously, its unique eastward phase inclination characteristic of Kelvin wave along with vertical coherence structure is evident in all figures i.e. from ~11 - 27 kilometres having peak amplitudes impend over tropical tropopause while vertical wavelengths in figures 3.3.2.4 a and 3.3.2.4 b are found to be ~10 and 12 kilometres with phase lines of temperature waves in figures 3.3.2.4 c and 3.3.2.4 d extending into the upper troposphere exhibiting upright behaviour of longer vertical wavelengths around 13 and 14 kilometres. Moreover, the Kelvin wave event shown in Figure 3.3.2.4 d is relatively stronger than its counterpart events. Earlier, the relationship between associated Kelvin waves and wind cognizance is mainly due to thermal damping proposed by Shiotani and Horinouchi in (1993).

![Image of Kelvin wave amplitude variations](image)

Figure 3.3.2.5 Time-height variations of Kelvin wave amplitudes observed at equatorial latitudes (±10°) using COSMIC GPS RO satellites during September 2006-September 2008.

Similar analysis had been carried out from 10-30 kilometres time series entirety between September (2006-2008) as shown in figure 3.3.2.5, which represents averaged time-height variations of amplitudes for wavenumbers 1 and 2. An increased tendency in wave amplitudes is seen particularly above 18 kilometres during westward phase and a decreased tendency during eastward of QBO between September 2007 and September 2008 while in general, it has been reported that Kelvin waves do not exist above 20kilometres altitude except during a strong westward QBO-phase or during a strong eastward-shear as stated by Ratnam et al., (2006). Therefore, we are confident with our observations as the results are obeying the research findings of Ratnam et al., (2006). In addition to this, Ratnam et al, (2006) have clearly discussed how Kelvin wave activity at near tropopause with enhanced features could increase the height of the tropical tropopause and observation of resonant Kelvin wave amplitude around tropopause altitude irrespective of QBO phase as shown in figure 3.4.1.
3.4 ENSO and their features revealed with COSMIC GPS RO

“El Niño and southern oscillation” (ENSO), is an intrinsic accouplement of Earth’s atmospherical dynamic system that balances our climatic structure by means of interstate rolling (warming and cooling) for every four or five years. Variation in microclimate components in our acclimate system (e.g.autogenouse forcing’s) cause the climate to be altered due to dynamic convection of internal energy exchanges. In general, an event related to ENSO accrues with united interactions in between atmosphere and ocean centred over tropical Pacific. Although it originates in tropical pacific, ENSO puts a thump on climature change and regional weather in the course of different mechanisms such as low-frequency teleconnections, tropical forcing and ambient flows as stated by Wallace and Gutzler, (1981), Barnston and Livezey, (1987), Kushnir and Wallace, (1989), Zhang et al.(1996), Wang et al., (2000), Kawamura et al., (2001), Trenberth et al., (2002), Chou et al., (2003), Sakai and Kawamura (2009).

Theories related to ENSO emphasize the role and importance of wave dynamics on the initiation of ENSO that involves both oceanic and atmospheric Kelvin waves while changes due to ENSO in the ambient flow and thermal forcing would have significant impact on equatorial waves in the atmosphere since frequent geodesical studies displayed that zonal flow and convective forcing can influence their behaviour as stated by Yang et al.,(2007a), (2011), (2012) in addition to the modelling study of Maury et al., (2012) indicating that the ENSO signal has a substantial effect on stratospheric equatorial Kelvin waves. However, there is a limited understanding of ENSO impact on equatorial Kelvin waves in the atmosphere due to less number of observational studies as of today.
Figure 3.4.1 Temperature fluctuations in longitude vs. months over 5° S- 5° N during September 2006 to February 2007 a) at 15 km b) at 16 km c) at 17 km d) 18 km e) 19 km, and f) at 20 km.
In view of this we have verified how temperature anomalies will respond during different phases of ENSO using COSMIC retrieved temperature profiles and presented them at different altitudes so that temporal variations of ENSO can be studied using a known index during January 2005-January 2012 which shows retroactive warm ENSO (El Nino) in 2006-2007 and 2009-2010 as well as cold ENSO (La Nina) events in 2007-2008 and year-end 2010.

Figure 3.4.1 depicts pictorial longitude-time isochor fluctuations at 15 and 16 kilometres represented by 3.4.1a and 3.4.1b, at 17 and 18 kilometres represented by 3.4.1c and 3.4.1d and at 19 and 20 kilometres by 3.4.1e and 3.4.1f during September 2006-February 2007 which coincide with warm ENSO phase revealed that the temperature anomalies have associated with negative values at 16, 17 and 18 kilometres while positive values appeared at 19 and 20 kilometres at most of the places with a transition from negative to positive occurring at tropopause altitude obeying the earlier research results stated by Scherllin-Pirscher et al., (2012).
Temperature fluctuations in longitude vs. months over 5°S- 5°N during March 2007 to August 2007 a) at 15 km b) at 16 km c) at 17 km d) 18 km e) 19 km, and f) at 20 km.

Figure 3.4.2 shows pictorial longitude-time isochor fluctuations at 15 kilometres and 16 kilometres represented by figure’s 3.4.2 a and 3.4.2 b, at 17 kilometres and 18 kilometres by figure’s 3.4.2 c and 3.4.2 d while at 19 kilometres and 20 kilometres by 3.4.2 e and 3.4.2 f from March 2007 to August 2007 that coincides with cool ENSO phase. It has been observed that, although the temperature anomalies have associated with negative values at 15, 16, 17 and 18 kilometres in line with the trends observed during El-Nino phase (Figure 3.4.1a-d), the anomaly trends at 19 and 20 kilometres have not associated with higher positive values when compared with their counterpart values observed during El-Nino phase (3.4.1e-f) obeying the research findings of Yang and Hoskings, (2013).

First of all, we have applied Multivariate ENSO index (MEI) proposed by Randel et al., (2009) to identify temporal variations in ENSO during 2005-2011 study periods before presenting ENSO features observed from COSMIC temperature profiles. The MEI resource http://www.esrl.noaa.gov/psd/enso/mei/mei.html provides trans-pacific-brim index generated from numerous physiographic variables including sea surface temperature, outgoing long-wave radiation and pressure gradient across far-off locations of Pacific Ocean with atmospherical parameteric lag by approximately two months as stated by Randel et al., (2009).
Figure 3.4.3 Time series of ENSO MEI index from January 2005 to January 2012. The horizontal black dashed lines represent 1σ standard deviation.

Figure 3.3.3 shows MEI indicant for January (2005-2012) period, wherein the positive deviation from mean resemble warm event (El-Nino) while negative deviation resemble cold event (La-Nina), and together known as ENSO. The flat dashed lines denote 1σ variance which indicates intensity of warm or cold ENSO epics. From this figure 3.3.3, it is clear that the warm ENSO (El-Nina) is present between August-December 2006 and November- March 2010, while cold ENSO (La-Nina) is present between January-May 2008 and again between July 2010 and June 2011, respectively.

We have eliminated the annual mean of temperatures in order to get the temperature anomalies before applying the powerful HHT thereby applying the multi-dimensional ensemble empirical mode decomposition (MEED) method suggested by Wu et al., 2009 to extract intrinsic mode function (IMF). Although the resultant IMFs has shown irregular patterns, the fifth IMF (C5) have clearly showed the presence of ENSO and QBO features in temperature anomalies.
Figure 3.4.4 shows HHT-MEED decomposed IMF C5 component representing ENSO cold phase (La Nina) during March 2008 from near Western Pacific (~100° E) to eastern Pacific (150° W) in agreement with MEI index shown in Figure 3.4.3 while a weak warm phase of ENSO (El-Nina) is observed between August 2006 and January 2007 from Indonesian sector (~80°E) to western Pacific (160°E), whereas a strong El-Nina is present around February 2010 from 80°E to 180°E which is also in agreement with MEI index shown in Figure 3.4.3. Further, as stated by Scherllin-Pirscher et al., (2012), ENSO features in temperature anomalies could not be revealed beyond 16 kilometres altitude range due to strong confounding effects of QBO.

Figure 3.4.5 HHT –MEED decomposed C5 components of temperature anomalies showing QBO at 24 km during 2006-2010.

Figure 3.4.5 shows HHT-MEED decomposed IMF C5 component representing QBO features at 24 kilometres wherein easterly phase of QBO is found between February 2006 and November 2006 and again between December 2007 and September 2008 whereas Westerly phase of QBO is found between December 2006 and November 2007 as well as between October 2008 and March 2010 obeying QBO in zonal winds over Singapore (1°N, 100°E) in addition to one to one correspondence with the results provided by steiner et al., (2011).

3.5 Discussion and summary

The fact that enhancement of Kelvin wave-related convection due to El Niño event and wind itself as well as suppression of them due to La Niña event has not been revealed in previous observational studies. The impact of ENSO on convectively coupled propagative Kelvin waves in lower stratosphere is also a new finding. Further, the results found in this study revealed a potential link between ENSO and QBO as the Kelvin wave is the main forcing of the QBO westerly winds.
Also, it is evident that the Kelvin wave-related convection varies with ENSO phases and hemispheres, both for winter and summer. In La Niña years, Kelvin wave-related convective signal a fortiori in eastern hemisphere than western hemisphere similar to climatological mean state with convection being stronger over the eastern hemisphere’s warm water region. However, in El Niño years, Kelvin wave-related convective signal beef up in western hemisphere than eastern hemisphere. The ENSO related difference is clearer in the western hemisphere, with the Kelvin wave-related power being much stronger in El Niño than in La Niña while in eastern hemisphere, the power shows an opposite tendency to that in the western hemisphere but the ENSO related difference is small. Due to the dominant difference in the western hemisphere, power spectra obtained from the entire tropical domain still indicate a stronger signal in El Niño year than La Niña year in contradiction to Wheeler et al.,1999, who indicated improper modification of OLR spectra by ENSO phases. Different power intensities shown in the composite field is also present in each case with the Kelvin wave signal being stronger in El Niño than in La Niña (not shown) which indicates that the difference of Kelvin wave-related convection between ENSO phases is robust.