Interannual variability of diurnal tide in the tropical mesopause region: A signature of the El Nino-Southern Oscillation (ENSO)

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[1] Long-term MLT radar observations of the diurnal tide at 86 km over Jakarta (6.4°S, 106.7°E) and Tirunelveli (8.7°N, 77.8°E) during the years 1993–1999 are examined in this work. Monthly estimates of tidal amplitudes in the meridional direction over these sites reveal a pronounced interannual variability. The satellite derived Outgoing Longwave Radiation (OLR) is used as a proxy for deep tropical convection in this study. Removal of composite seasonal cycle yields 'anomalies' in the diurnal tide over Jakarta and Tirunelveli that are correlated with the OLR anomalies over the western Pacific region (~120°E). It is suggested that the lower atmospheric large-scale convective systems originating over the western Pacific region in response to the El Nino Southern Oscillation (ENSO) facilitate excitation of nonmigrating tides through latent heat release or large-scale redistribution of water vapor that compete with the dominant migrating tide and possibly induce the observed interannual variability in the diurnal tide. **Citation:** Gurubaran, S., R. Rajaram, T. Nakamura, and T. Tsuda (2005), Interannual variability of diurnal tide in the tropical mesopause region: A signature of the El Nino-Southern Oscillation (ENSO), *Geophys. Res. Lett.*, *32*, L13805, doi:10.1029/2005GL022928.

1. Introduction

[2] Many ground and satellite-based observational studies in the past have indicated that the diurnal tide in the equatorial and low latitude MLT region undergoes large variations as a function of time, height, latitude and longitude [*Hays et al.*, 1994; *McLandress et al.*, 1996; *Vincent et al.*, 1998; *Tsuda et al.*, 1999; *Gurubaran and Rajaram*, 1999; *Talaat and Lieberman*, 1999; *Oberheide and Gusev*, 2002; *Forbes et al.*, 2003]. Model results attribute these variations to the variations in water vapor concentrations and clouds, variations in eddy dissipation, gravity wave interactions with the tide, planetary wave-tide interactions and latent heat release (see *Hagan*, 2000, for a review on the theoretical efforts). Some of these studies revealed the potential role of zonal asymmetries in the thermal excitation of diurnal tide in generating nonmigrating tidal modes that may attain significant amplitudes in the MLT region.

[3] Though single station radar-based studies do not have the advantage of distinguishing various tidal modes, they do provide a wealth of information on the temporal and height behavior of the tidal fields on a continuous basis. Long-term Medium Frequency (MF) radar observations over Kauai (22°N, 160°W), Christmas Island (2°N, 157°W) and Adelaide (35°S, 138°E) brought out the seasonal and interannual variabilities of diurnal tide in the height region 80–100 km over these tropical sites [*Vincent et al.*, 1998]. *Tsuda et al.* [1999] and *Gurubaran and Rajaram* [1999] noted similar interannual variabilities in the diurnal tide over Jakarta (6.4°S, 106.7°E), Indonesia and Tirunelveli (8.7°N, 77.8°E), India, respectively. Both the latter studies made use of nearly five years of radar wind measurements obtained at the respective sites.

[4] The present work focuses on the variability of the diurnal tide at 86 km over Jakarta and Tirunelveli between 1993 and 1999 with nearly seven years of data sets. A meteor wind radar was operating at Jakarta during this period whereas an MF radar has been operating at Tirunelveli since December 1992. In this article we examine the monthly estimates of the meridional component of the diurnal tide at 86 km that has larger amplitudes at both locations when compared to the zonal component. Further, the mean meridional wind speeds are smaller thus placing smaller constraints on the interpretation of the tidal variability.

[5] As noted in the earlier work by *Tsuda et al.* [1999], the diurnal tide in the meridional wind at 86 km over Jakarta shows a pronounced annual cycle with maximum amplitudes during January–February and minimum during June–July. A similar annual cycle is observed over Tirunelveli but the amplitudes are largest during the spring (March–April) [*Gurubaran and Rajaram*, 1999]. During certain years another maximum appears six months later over Tirunelveli. With a longer data base extending up to 1999, we find significant interannual variabilities with smaller amplitudes during 1996 and 1998 and larger amplitudes during 1995, 1997 and 1999.

[6] The present work examines the possible mechanisms responsible for the observed interannual variabilities in diurnal tide over Jakarta and Tirunelveli. Past model results show that the migrating component of the diurnal tide is principally generated by the absorption of solar radiation by water vapor in the middle to upper troposphere. Latent heat release in deep convective clouds is expected to generate nonmigrating tides and those tidal modes that are excited efficiently are capable of reaching MLT heights [*Hagan and Forbes*, 2002]. It is also possible that, under certain conditions to be described below, there arises a large-scale redistribution of water vapor that can generate spatial

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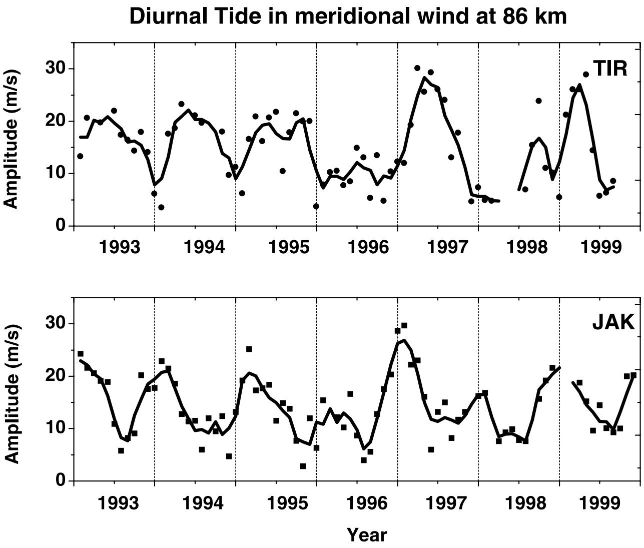

Figure 1. Monthly estimates (filled circles) of the diurnal tide in meridional wind at 86 km over Tirunelveli (TIR) (top) and Jakarta (JAK) (bottom). Continuous curves represent 3-month running means.

inhomogeneities in the solar insolation and thereby account for the excitation of nonmigrating tides [*Lieberman et al.*, 2003].

[7] During the years 1997 and 1998, the lower atmosphere was influenced by the El Nino-Southern Oscillation (ENSO). The ENSO phenomenon has been conceived to involve a large-scale ocean-atmosphere interaction linked to a periodic warming in sea-surface temperatures across the central and east-central equatorial Pacific (see *Wang and Picaut*, 2004, for a recent review on this subject). The atmospheric response to this phenomenon involves movement of active convective systems from the maritime Indonesian continent towards central and east-central equatorial Pacific. With this one can expect a large decrease in the release of latent heat over the western Pacific and an increase in the east-central Pacific. Because the excitation of diurnal tide is intimately linked to the water vapor content [*Lieberman et al.*, 2003] as well as condensational heating [*Hagan and Forbes*, 2002], we have performed a correlative analysis with the tidal winds at 86 km over Jakarta and Tirunelveli and the satellite derived Outgoing Longwave Radiation (OLR). The latter parameter has been used in many studies in the past as an indicator of deep convection in the tropical region [e.g., *Liebmann and Hartmann*, 1982]. While using this parameter, it is implicitly assumed that there arises a diurnal variation in the convective activity as revealed by the position of the clouds that can induce an upward propagating diurnal tide component in atmospheric parameters. It will be shown qualitatively that the temporal variations in the tidal activity in the interannual time scales over the radar sites are related to the corresponding variations in the deep convective activity as reflected in the OLR brightness over the western Pacific region.

2. Results

[8] In Figure 1 we depict the monthly estimates (filled circles) of amplitudes of diurnal tide in meridional wind at 86 km over Tirunelveli (top) and Jakarta (bottom). Thick curves represent 3-month running means over the monthly values. There is a pronounced annual variation in tidal activity over each of the sites as mentioned earlier. During 1996 and 1998, the annual cycle is relatively weaker, clearly indicating an interannual variability in the diurnal tide activity over these tropical sites. For further analysis, the composite climatological monthly values of diurnal tide amplitudes are determined and they are removed from the monthly estimates to yield 'anomalies' in tidal amplitudes. By this means, the pronounced annual variations in tidal amplitudes that are present in the tidal data sets are eliminated leaving enough scope for examining the long-term variations in diurnal tide activity over the two radar sites.

[9] Next we examine the spatial and temporal variations in the satellite derived OLR brightness during the years 1993–1999. Figure 2 shows an initial comparison made between the monthly diurnal tide amplitude at 86 km over

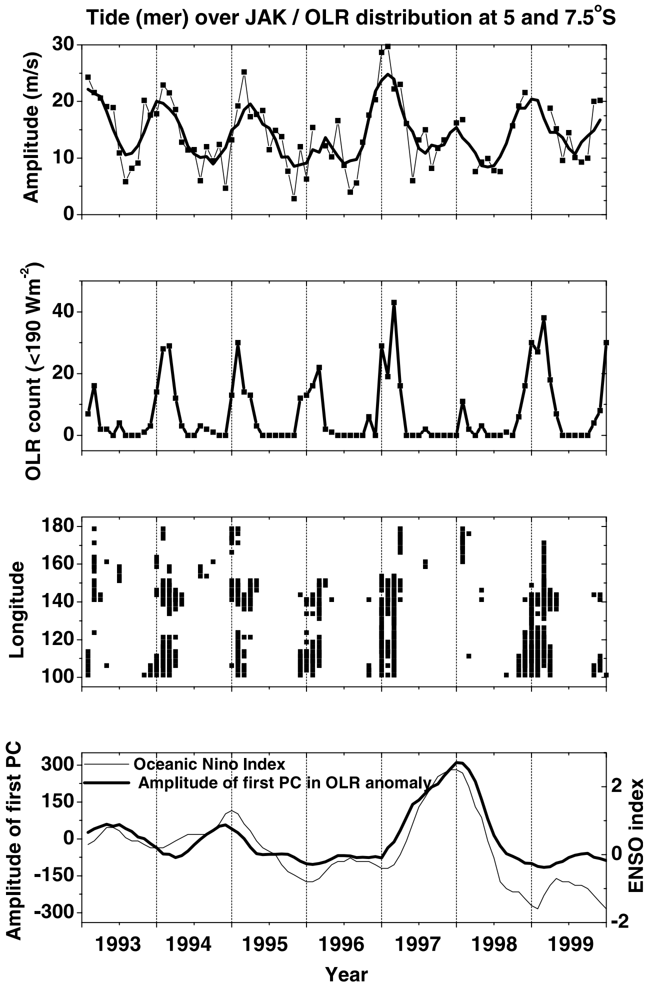

Figure 2. Temporal variation of tidal amplitude at 86 km over Jakarta (top), the OLR count (second plot) representing number of pixels on OLR maps for which the OLR brightness is less than 190 Wm^{-2} and the position of those pixels shown as longitudinal distribution in the range 100-180°E (third plot). The bottom plot depicts the Oceanic Nino Index and the amplitude of the first principal component derived from the OLR anomaly (see text for details).

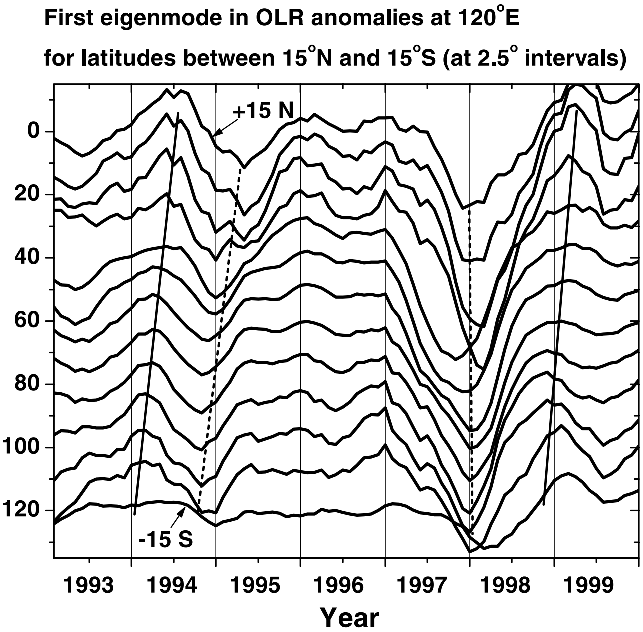

Figure 3. Temporal variation of the reconstructed OLR anomalies for latitudes between 15°N and 15°S at 2.5° intervals.

Jakarta (top plot) and the total number (second plot) and spatial locations (third plot) of those deep convective cells (each of size equal to 2.5° × 2.5° in the latitude-longitude grid) over which the OLR has values less than 190 Wm^{-2} in the longitude region 100–180°E and at latitudes 5°S and 7.5°S. In the bottom panel in Figure 2 the Oceanic Nino index (ONI) (thin curve) is plotted. As expected, deep convective regions in the southern latitudes intensify during the southern summer (refer to second plot). At those times the tidal activity as observed at 86 km over Jakarta gets enhanced. Apart from the seasonal cycle in the tropical convection, the OLR data sets reveal an interannual variation in the deep convective activity and this has been ascribed to the ENSO (refer to the ONI curve in Figure 2) that peaked during December 1997. High and cold cloud tops observed in the southern west Pacific during December 1996 and January–February 1997 are displaced towards the central Pacific during January 1998 (refer to the third plot). At those times when the maritime continent is 'dry' as reflected in high OLR values, the annual cycle in the tidal activity is suppressed. The tidal amplitudes over Jakarta recover a year later when a La Nina is observed across the Pacific during late 1998 and early 1999.

[10] For further analysis, we subject the OLR data sets to the principal component analysis (PCA). PCA is widely used in multivariate analyses for reduction of dimensionality offering a more concise description of the observed data and at the same time extracting significant information from the data [e.g., *Krzanowski*, 2000]. When applied to the OLR data, the method is expected to extract the dominant latitude-longitude patterns of decreasing variance. The more pronounced seasonal cycle in the OLR brightness is first removed by subtracting the 7-year composite climatological OLR monthly values from each of the observed OLR monthly values. The 'anomalies' are then subjected to the PCA.

[11] Results of the PCA analysis (not shown here) of the OLR anomalies provide indications for the first eigenmode to represent the OLR response to the large-scale ENSO phenomenon that introduces significant interannual variation in the OLR. The corresponding eigenvalue is largest at the equator and decreases rapidly beyond ±2.5° on either sides of the equator. The most dominant pattern contributes more than 60% of the variance at the equator. The first two components together contribute 60–80% of the variance to the observed anomaly fields within the latitude region considered herein (15°N–15°S).

[12] The temporal variation of the amplitude of the first PC has an appreciable correlation with the ONI as shown in the bottom panel of Figure 2 (thick curve). This dominant eigenmode captures the El Nino events of 1993, 1994–1995 and 1997–1998 quite well. On the other hand, the La Nina events that occurred during 1995–1996 and 1998–1999 are not well represented in this analysis. It is possible that any of the higher order modes (not shown here) brings out the latter features.

[13] An examination of the spatial structure associated with the first principal component reveals dipole-like patterns with positive anomalies over the western Pacific centered at 120°E and negative anomalies over the eastern Pacific region centered at 210°E as expected for major El Nino events (warm episodes). The OLR anomalies are reconstructed with the first eigenmode and their temporal behavior at 120°E for various latitudes is next examined. In Figure 3 the temporal variation of the reconstructed OLR anomalies at 120°E for each of the latitudes in the range 15°N–15°S at 2.5° intervals is shown. Solid and dashed lines joining the negative and positive peaks reveal that the perturbations have a small eastward tilt (also noticed in the original OLR data sets) and they tend to originate in the southern latitudes (~5°S) and then migrate northwards/southwards and eastwards during the mature phase of warm or cold event. One exception to this feature occurred during the El Nino event of 1997–1998 when the OLR anomaly at 120°E reached its positive peak first over 5°N and later over other latitudes.

[14] Finally, in Figure 4 we compare the temporal variations in tidal and the OLR anomalies at 120°E, recon-

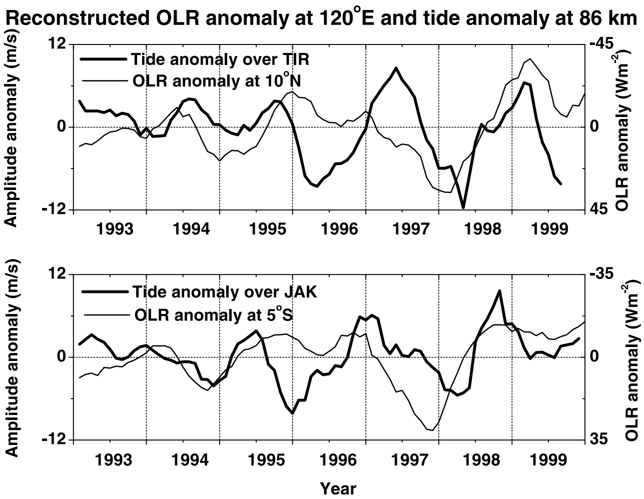

Figure 4. Comparison of tidal and reconstructed OLR anomalies at 120°E for 10°N/Tirunelveli (top) and 5°S/Jakarta (bottom).

structed from the first four principal components, over the respective northern (Tirunelveli, 10°N, top panel) and southern latitudes (Jakarta, 5°S, bottom panel). This longitude, 120°E, is chosen because the OLR response to major ENSO events is greatest around this longitude in the western Pacific region. In these plots the scale for the OLR brightness (shown as thin curves) is reversed in order to facilitate a visual comparison of the temporal variations of the two anomaly fields. Negative OLR anomalies account for periods of deep convective activity and positive OLR anomalies describe 'clear-sky' or 'cloudless' conditions. The thick continuous curves in Figure 4 represent 5-month running means of monthly tidal anomalies. Broadly, the respective anomaly fields have similar variations except during the period 1995–1996 when a large negative anomaly characterized the tidal fields over Tirunelveli and Jakarta. Results from this analysis suggest that the long-term variations in diurnal tide are probably linked to the temporal variation of the deep tropical convection occurring over the western Pacific region in response to the major ENSO events.

3. Discussion

[15] The diurnal tide in meridional wind at 86 km over the tropical sites, Tirunelveli and Jakarta, shows pronounced interannual variabilities during the years 1993–1999. A search for a possible mechanism that can account for these variabilities has been made in the present work. The satellite derived OLR brightness is considered to represent the intensity of deep tropical convection. The results indicate that the processes responsible for the generation of the tides are perhaps linked to the large-scale ENSO phenomenon that influences many of the lower atmospheric parameters in the interannual time scales.

[16] *Vial et al.* [1994] earlier demonstrated an ENSO signature in the surface diurnal pressure variations. The present work demonstrates, for the first time, the effect of the ENSO on the tidal fields at altitudes as high as the mesopause region. There are two sources of tidal excitation that are linked directly to ENSO and could cause such long-term variations: (1) latent heat release in deep convective clouds and (2) longitude variations of water vapor in the troposphere and its global redistribution during the warm and cold episodes of ENSO when the deep tropical convective systems shift across the Pacific. Though *Hagan and Forbes* [2002] brought out the role of latent heat release associated with deep tropical convection in generating non-migrating tides, subsequent modeling efforts of *Lieberman et al.* [2003] showed that the longitudinal inhomogeneities in water vapor could produce heating rates that are 30–90% of the heating rates due to latent heat release in deep convective activity reported earlier.

[17] It is suggested that the observed long-term variations in diurnal tide reported in this work result from significant interference effects between the migrating tide driven by solar insolation and the nonmigrating tide. The latter can result from either latent or radiative heating or both and its temporal variability is expected to be strongly linked to the ENSO phenomenon. The present work has a limitation in that it is considered as a possibility that there is a diurnal variation in convection that induces the observed variability in tidal amplitudes in the monthly time scales. More detailed work on this aspect will be pursued by the authors in the future.

[18] Implications of the results presented in this work can be well recognized considering the fact that the diurnal tide carries momentum and energy from the troposphere into the middle atmosphere and the MLT region as well, providing a dynamical coupling of these distant regions. The consequences of an ENSO modulation of tidal amplitudes for the energy and momentum budgets of the upper mesosphere and lower thermosphere and the regions beyond may now be expected to gather attention during the CAWSES time frame.

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