Effects of Diurnal Variations of Outgoing Longwave Radiation Over the Tropical Oceans

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Introduction

Several current problems in atmospheric radiation over the tropical oceans may have at least partial solutions as effects of diurnal variations of outgoing longwave radiation (OLR). At issue are explanations for the following: a) excessively large amplitudes (in relation to theory) of the diurnal thermal tides over the tropical oceans (Braswell and Lindzen 1998); b) reported observations of excessively large direct atmospheric absorption of incident broadband solar radiation, which conflict with prior work and concurrent, collocated narrowband measurements centered in the visible spectrum (Cess et al. 1998); and c) the observed morning intensity maximum of the deepest, most intense tropical convective systems (Hall and Vonder Haar 1999; Gray and Jacobson 1977). The present lack of diurnally resolved broadband satellite OLR observations of sufficient accuracy and temporal resolution has been a restraint on our approach to these issues. Nevertheless, beginning with the morning maxim of intense tropical convection, we discuss each of these problems and show evidence of common links to OLR-related processes.

Data

Diurnally resolved surface pressure (SLP) data were obtained from the archives at the National Center for Atmospheric Research (NCAR) for various island locations in the Tropical Western Pacific (TWP) including Kwajalein (8.7N, 176.7E) and Koror (7.3N, 134.5E). Monthly rainfall and sounding data were also obtained from NCAR. Various results for the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) program were obtained from the TOGA data archive maintained at Colorado State University (CSU) by P. Ciesielski. In general, the data were used as received with only minimal interpolation to patch a few missing data points. Notable trends in both the SLP and atmospheric moisture profile data were left in the data and their possible effects are noted below where appropriate.

The Morning Maximum of Deep Convection

The well-known morning maximum of intense deep convection over the tropical oceans has numerous manifestations. These range from the concentrated incidence of very heavy rainfall near sunrise (Gray and Jacobson 1977) to roughly concurrent maxima of vertical (subsiding) motion (Gage et al. 1992) to the morning maximum incidence of very cold cloud top infrared (IR) brightness temperatures (BTs) colder than -65 °C (Hall and Vonder Haar 1999). One of several explanations (see Hall and Vonder Haar 1999 for a review) of the timing of this maximum is based on effects due to increased rates of net OLR cooling in the expansive area of clear/broken-cloud conditions between large clusters of deep convection. This concept is illustrated in Figure l. In the absence of direct solar heating of the atmosphere (at night), the ongoing net radiative cooling (IR heat loss) increases in these areas of continuous net atmospheric subsidence. The associated subsidence tends to reduce the relative humidity of the sinking air, typically reducing net cloudiness and increasing net column IR cooling and, thereby, further enhancing subsidence. Thus, increased rates of net IR cooling at night are associated with a positive feedback process whereby areas of broken cloudiness tend to become systematically clearer and other dryer and with gradually increasing OLR rates during the night. Prior work (Sheaffer and Gray 1996) illustrates this effect as a morning maximum of IR BT values (i.e., pixel counts) warmer than +15 °C, which occurs roughly concurrently with the morning maximum of intense convection and BT values colder than -65 °C in cloudiness data for the TWP; the total morning increase of the warm BT area typically being more than 50 times greater than the increase of the very cold cloud top area.

As implied by Figure 1, one effect of nocturnal clearing and increasing rates of OLR and subsidence is the convergence of mass to the mid and low levels of these clearing areas. This convergence has the potential to increase pressure locally but is also is available to accommodate mass divergence to adjacent areas of established deep convection, thereby allowing said convection to increase and intensify during the night, attaining the observed morning maximum. Note the distinction wherein it is suggested that the subsidence effects act to “accommodate” the convergent mass needs for intensification of ongoing, established convection nearby; we avoid the suggestion that the nocturnal cooling either initiates or forces the intensification of the convection. The latter then diminishes the requirement for the sharp positive nocturnal pressure gradients between clear and convective areas and long-range mass transport mechanisms to accomplish the effect. Indeed, this “accommodation” perspective suggests that smaller diurnal pressure enhancements will occur in subsidence areas when intensifying broad-scale convection extracts mass from the subsidence areas; we return to this point in the discussion below.

Satellite Estimates of Diurnal OLR

Diurnally resolved geostationary satellite measurements of broadband OLR appropriate for studying this issue do not presently exist. Broadband OLR observations from polar orbiter systems are widely dispersed in time such that the important spatial differences in the transient interactions suggested in Figure 1 are lost in the averaging of multiple observation sequences taken over periods of many weeks. The only approach to estimating details of diurnal OLR variability currently available is to apply regression based adjustment algorithms to correct various water vapor window (e.g., 11 micron) BT data and/or similar multispectral narrow band data to estimates of equivalent black body BTs (Ellingson et al. 1994). The results of a window brightness temperature conversion to estimated broadband OLR is shown in Figure 2a for two brief “suppressed” periods (Sui et al. 1997) versus the entire 120-day TOGA-COARE Intensive Operational Period (IOP). The amplitudes of these diurnal harmonics of the estimated OLR are likely underestimates as the brightness values in the available TOGA data are linear spatial averages whereas the actual radiance from these areas varies as the fourth power of the individual pixel BT values. Clearly, increased IR radiance from the greatly expanded morning warm BT areas must cause this increase. Similar data are shown in Figure 2b but where we present a time

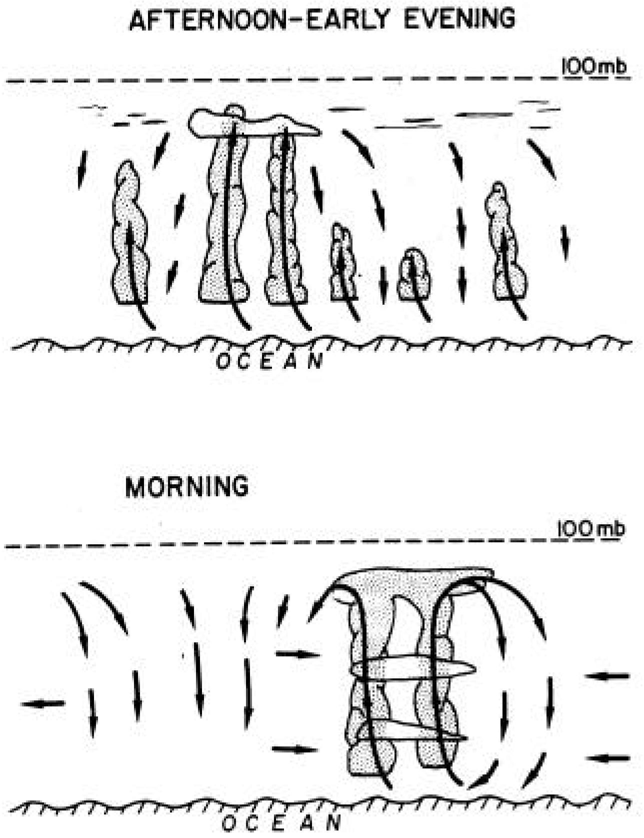

Figure 1. Conceptual illustration of the overnight trend in the cloudiness properties of interest over the tropical oceans. Extensive afternoon cloud cover dissipates, forming the comparatively clear morning subsidence areas enveloping concentrations of intense, deep convection.

series of estimated morning-minus-prior-evening (generally positive) changes of OLR for a large area the tropical Pacific extending from 0 N to 20 N and from 150 E to 180 E. Exercising only minimal selectivity, much larger diurnal amplitude OLR cycles with similar phasing can typically be raised from day-to-day Geostationary Meteorological Satellite (GMS) BT data for appreciable portions of the TWP region.

Thermal (Air) Tides

Classical tidal theory characterizes the air tides as westward migrating thermal oscillations depicted by sets of sinusoidal (Hough) functions, which represent multiple modes of response to solar heating for highly idealized atmospheric conditions. These conditions are reasonably well met by the deep and comparatively uniform ozone heating processes represented by second (12-hour) or semidiurnal harmonic response [S2(P)]. However, such is often not the case for the diurnal 24-hour [S1(P)] tide, which originates in the troposphere and is influenced by variable moisture and clouds and by surface

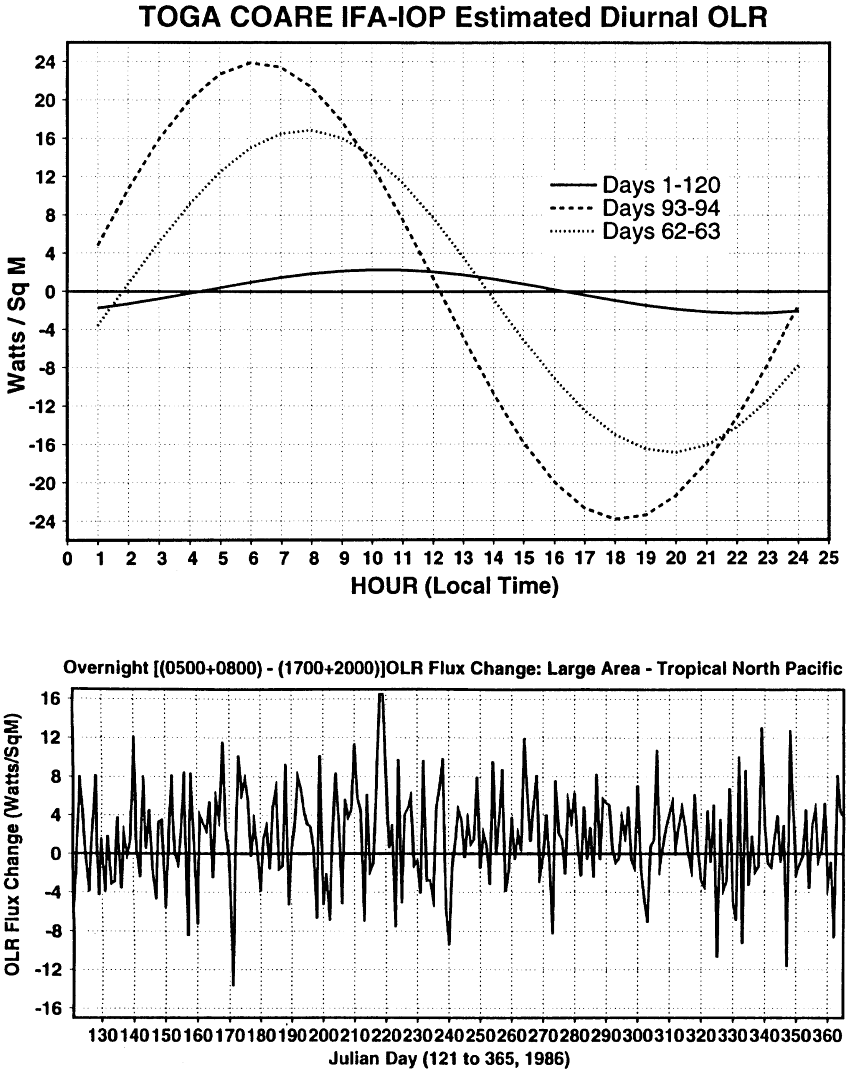

Figure 2. (a) First diurnal harmonics of OLR over the TOGA-COARE Intensive Flux Array during two suppressed periods January 1-2 and February 2-3, 1993, and for the entire 120-day IOP. (b) 244-day time series of overnight change (morning-minus-prior-evening) of OLR during 1986 for the tropical Pacific between 0 N to 20 N, 150 E to 180 E.

heating effects over large land areas. The basic qualities of the diurnal tide are shown in Figure 3. Owing to its comparatively shallow vertical wavelength scale (28 km), components of S1(P) excited in the stratosphere and thermosphere are strongly attenuated by destructive interference and, consequently, surface values of S1(P) are dominated by tropospheric heating effects.

A long standing issue regarding theoretical descriptions of the forcing of the diurnal air tide is the fact that observed values tend to be much larger than predicted by theory. This is especially so for the

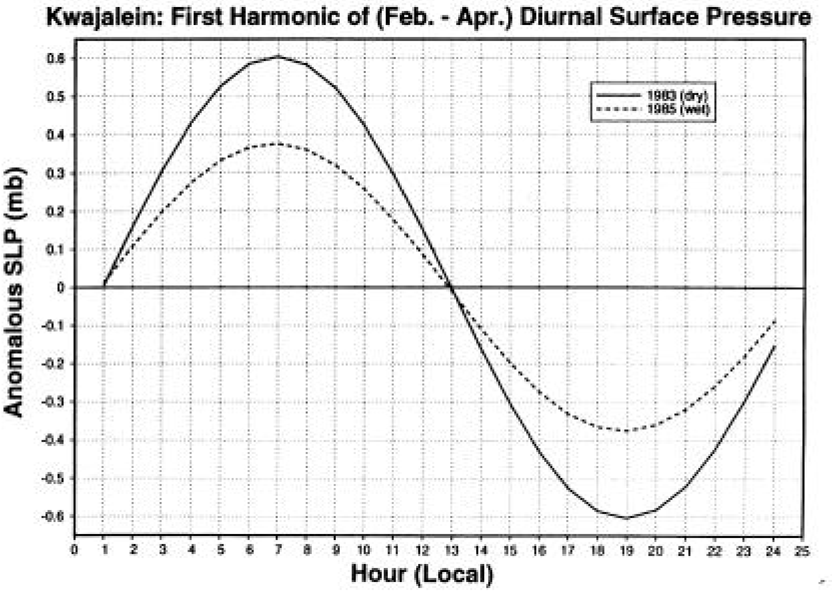

Figure 3. Comparison of the first diurnal harmonics of surface pressure at Kwajalein for comparatively wet and dry periods.

tropical oceans where observed values of S1(P) are typically on the order of 0.4 mb to 0.7 mb, whereas theory predicts values of approximately 0.2 mb to 0.35 mb. Over large land areas, thermal boundary layer disturbances due to strong surface (sensible) heating is an obvious source of enhanced forcing of the diurnal tide. However, these effects are not a proper part of the pure migrating thermal tide addressed by classical theory, being instead regarded as "non-migrating" components. Nevertheless, S1(P) values over small islands in the open ocean (with essentially no diurnal cycle of surface sensible heat flux) are often much larger than can be explained as an oscillatory response to diurnal atmospheric heating via known rates of absorption of solar radiation by clouds and water vapor. Note, however, that these classical theory-based calculations of the tides assume that OLR cooling rates are diurnally invariant.

Some recent studies of the absorption of solar radiation by the troposphere (thought to be about 30 W/m^2 to 50 W/m^2) have suggested than the actual broadband absorption is appreciably greater; these new estimates ranging from approximately 60 W/m^2 to 80 W/m^2 for clear air and 150 W/m^2 or more for heavy overcast (Cess et al. 1998). This issue remains unresolved with questions regarding effects due to water vapor, clouds, and various ancillary aerosol factors as possibly being implicated. Braswell and Lindzen (1998) consider the prospect that the amount of "enhanced" solar absorption being suggested in these new data might account for the missing forcing in calculated versus observed tropical S1(P) values. However, another possible source of forcing for a portion of the large S1(P) values may lie in enhanced nocturnal OLR cooling effects coupling with daytime solar heating to create an enhanced net diurnal heating/cooling pulse, resulting in a larger diurnal thermal tidal response. Our advocacy of the latter OLR driven process stems in part from the implications of prior work concerning the nature of the prominent morning maximum of intense convection (Gray and Jacobson 1977).

The basic result for this study is illustrated in Figure 3 wherein contrasting mean diurnal cycles of S1(P) at Kwajalein are compared for anomalously wet versus dry February to April periods; the distinctly stronger tides being typical for anomalously dry conditions. A more general expression of this same result is shown in Figure 4 as the annual cycle of linear correlation between S1(P) at Koror versus mixing ratio (q) at various levels of the atmosphere. Note that the negative correlation values tend to be stronger for higher atmospheric levels. [Both S1(P) and 900 mb q values at Koror show distinct upward secular trends throughout the 30 years of data considered in this study, whereas q at levels above about 700 mb show little if any trend. Close inspection of the year-to-year variations of 900 mb q versus S1(P) reveals these two series to be strongly out of phase on inter-annual time scales. Hence, it is likely that the latter two effects (i.e., co-linear long-term trends versus inverse inter-annual tendencies) tend to offset each other, resulting in the apparent lack of correlation of q and S1(P) at low levels evident in Figure 4.] Additional information on these relationships appears in the scatter plot of anomalous monthly rainfall versus S1(P) at Kwajalein, in Figure 5. The results again suggest a general decline in the amplitude of S1(P) with greater atmospheric moisture, in this case rainfall, but note that the values of S1(P) appear to trend asymptotically toward a minimum value for very large rainfall anomalies; in this case, an S1(P) value of about 0.32 mb, which is the approximate value for this latitude obtained from theory using the currently recognized solar heating rates without the additional anomalous solar absorption factors suggested by Braswell and Lindzen (1998).

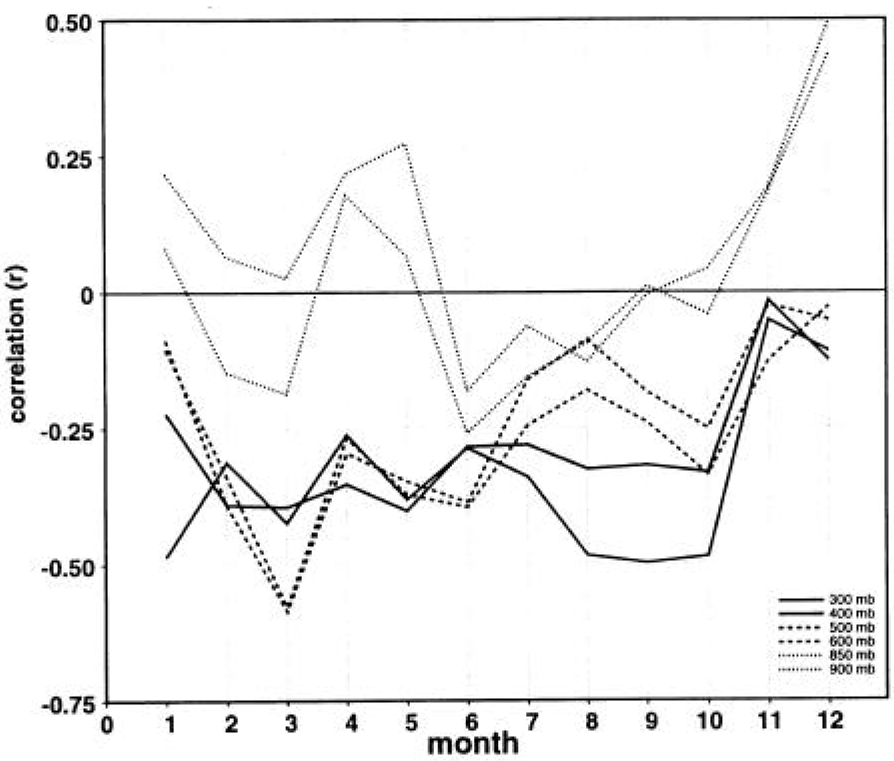

Figure 4. Annual cycles of the linear correlation between S1(P) and water vapor mixing ratio for various levels at Koror. Data represent 1970 through 1993.

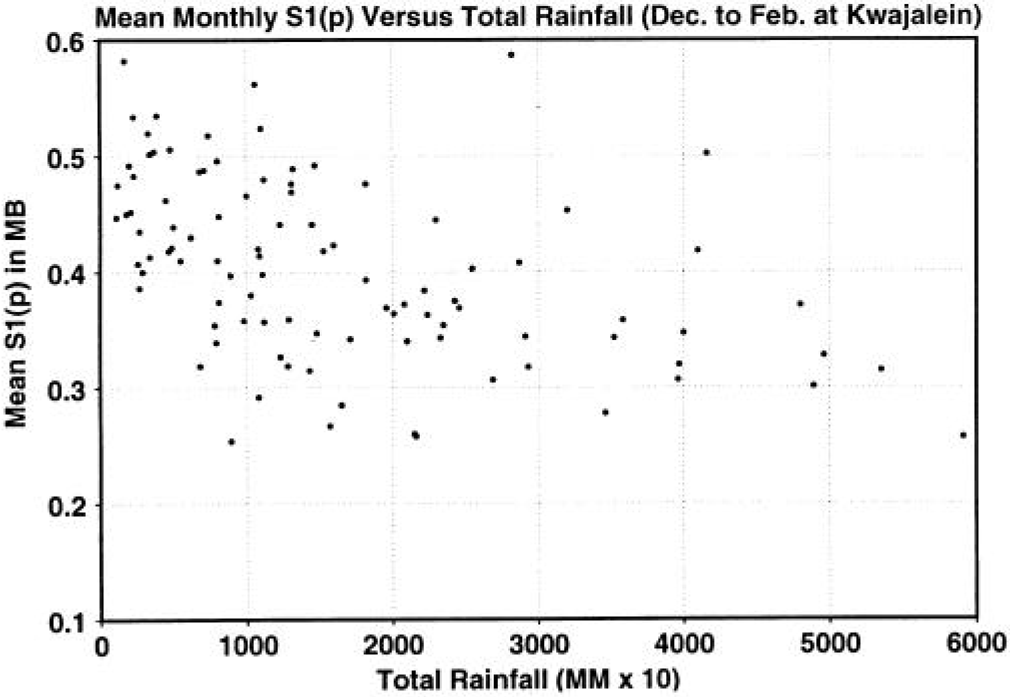

Figure 5. Scatter plot showing the distribution of anomalous monthly values of S1(P) in mb versus monthly rainfall totals (mm x 10) at Kwajalein in data for 1962 through 1993.

Summary

We have reiterated old arguments whereby enhanced nocturnal OLR cooling of the tropical atmosphere may contribute to the well known morning maximum of intense convective systems. We extended the discussion of these same effects to interpret the discrepancy between various estimates of direct solar forcing of the diurnal S1(P) tide over the tropical oceans versus observations. The expected effects of recently proposed larger than heretofore observed solar absorptivity by clouds and water vapor are inconsistent with the results shown here; all of which indicate that the solar diurnal tide is systematically smaller for comparatively moist atmospheric conditions, including anomalous rainfall, large upper level mixing ratios and presumably, greater cloudiness. Dry conditions are not conducive to significantly greater sensible heat flux from the ocean surface whereas dry conditions in the upper troposphere are conducive to more efficient nocturnal OLR cooling. Thus, the latter effect may couple with direct daytime solar heating to enhance the total radiative forcing of the diurnal tide. In addition, for periods of heaviest rainfall, the systematically smaller diurnal tidal values appear to converge to values predicted by classical theory using established rates of direct solar forcing of clear air and clouds. The latter trend toward weaker tides is then likely due to diminished nocturnal OLR cooling, which is strongly inhibited by anomalously moist conditions at upper levels.

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