Chapter 7

Study the modulation of diurnal cycle in the MJO associated intraseasonal events in the TRIO region.

7.1 Introduction

Diurnal cycle is one of the most fundamental modes of variability seen in the upper tropical ocean [e.g., Soloviev and Lukas, 1997; Shinoda and Hendon, 1998] associated with variation in solar forcing and cloud-SST coupling. The Improved Meteorological Instrument (IMET) mooring [Weller and Anderson, 1996] and one-dimensional (1-D) models [Shinoda and Hendon, 1998; Schiller and Godfrey, 2005] showed strong diurnal cycle of sea surface temperature (SST) seen in the western Pacific warm pool associated with the asymmetry of the mixing processes during day and night. IMET observations reported that diurnal cycle increases the amplitude of intraseasonal variability of SST associated with the Madden-Julian oscillation (MJO) [Madden and Julian, 1972] about one-third of its magnitude. There are limited studies related to the modulation of intraseasonal SST over tropical Indian Ocean by diurnal cycle of solar radiation due to lack of high sampling observational systems. Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction program (RAMA) [McPhaden et al., 2009] in the Indian Ocean carrying out a systematic and sustained ocean observation, which revolutionize the understanding of South Western tropical Indian Ocean variability. RAMA, moored buoy at 8$^\circ$S, 67$^\circ$E is deployed in January 2007 during the course of Cirene cruise in the Thermocline ridge of the Indian Ocean (TRIO) [Vialard et al., 2009] and this samples the ocean (mainly incoming short wave radiation and SST in time intervals of less than an hour. Vialard et al. (2009) observed a strong SST diurnal cycle in the TRIO region during the passage of MJO.
TRIO is the breeding center of the modulation of MJO over the tropical Indian Ocean [Izumo et al., 2010] which makes this region unique in the Indian Ocean. Large number of observational [Harrison and Vecchi, 2001, Vialard et al., 2008] and modeling studies [Lloyd and Vecchi 2010, Jayakumar and Gnanaseelan, 2011] which show that large intraseasonal variation of SST in the TRIO region associated with the passage of MJO. Also TRIO region dominated by shallow thermocline and mixed layer especially in the boreal winter (with reference to the Northern Hemisphere) having strong intraseasonal cooling events [Harrison and Vecchi, 2001, Duvel et al., 2004, Saji et al., 2006, Vialard et al., 2008, Vinayachandran and Saji, 2008, Jayakumar and Gnanaseelan, 2011] is associated with the convective-windy phase of the MJO. Jayakumar et al., (2010) using ocean model sensitivity experiments demonstrated that the surface flux (mainly short wave) contribute majority of intraseasonal variability. In this chapter we try to understand the impact of diurnal cycle in the intraseasonal SST modulation in TRIO region. In the case of diurnal model approach towards SST over the tropical Indian Ocean, Schiller and Godfrey (2003) using an OGCM demonstrated that the diurnal cycle significantly increases the amplitude of the SST, but they included non-solar component in the model approach.

In this study, we have designed couple of model sensitivity experiments to quantify the diurnal cycle effects on the amplitude of MJO associated SST over the TRIO region. The impact of the non-solar flux in the upper layers of the bulk model for the events is separated from solar forcing by removing the mixed layer depth (MLD) variation by non–solar components. This makes the study different from the previous approaches corresponds to the modulation of intraseasonal events by the diurnal cycles.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
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<tbody>
<tr>
<td>CTL</td>
<td>Full forcing includes daily averaged short-wave flux</td>
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<tr>
<td>NO_ISO_SW</td>
<td>Low passed filtered shortwave flux and non-solar component keep as CTL</td>
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<tr>
<td>Diurnal_fix</td>
<td>Applied diurnal cycle in short wave flux and non-solar component keep fix as CTL</td>
</tr>
<tr>
<td>Diurnal_relax</td>
<td>Applied diurnal cycle in short wave flux but relaxed non-solar component</td>
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Table 7.1: List of experiments used in this chapter.
7.2 Data and Modeling approach towards diurnal cycle

Data

The interpolated outgoing long wave radiation (OLR) from NOAA is used to detect regions of atmospheric deep convection and Microwave SST product from Level 3 Tropical Rainfall Measuring Mission Microwave Imager (TMI) is used to get SST measurement in cloudy condition. To estimate the air-sea flux associated with the MJO we used latest version of global ocean-surface heat flux products developed by the Objectively Analyzed air-sea Heat Fluxes (OAFlux) project over 1.0°x 1.0°resolution [Yu et al., 2008].

RAMA mooring by NOAAs Pacific Marine Environmental Laboratory (PMEL) located at 8°S, 67°E provide downwelling shortwave data, and SST at daily and 10 minute resolution are used in the present study. Hereafter RAMA in this study represent the moored observation. The Mixed layer depth at this location is calculated from ocean temperature and salinity observed at RAMA. Ocean temperature is measured at 1, 5, 10, 20, 40, 60, 80, 100, 120, 140, 180, 300 and 500m and salinity is measured at 1, 10, 20, 40, 60, 100 and 140 m. Similar density criteria (0.2 kgm$^{-3}$) is applied in both RAMA and model MLD.

Modeling approach

The control experiment (hereafter CTL) is same as discussed in the previous chapters. The upper ocean mixed layer and thermocline zones are well resolved in the OGCM MOM4 with 15 vertical levels within a depth of 155 meters. Vertical mixing is based on the K Profile Parameterization (KPP) scheme [Large et al. 1994] which has significant impact on the diurnal coupling. The daily averaged Large and Yeager short wave flux [LY-SWF, Large and Yeager, 2004] basically derived from International Satellite Cloud Climatology Project (ISCCP) global radiative flux product remapped on the National Centers for Environmental Prediction reanalysis T62 grid [Zhang et al., 2004].

We have performed a sensitivity experiment named as NO_ISO_SW to isolate the effect of short wave heat flux variation by applying low-passed filter on the net short wave radiation at the ocean surface by keeping the full wind stress and the non-solar heat flux (sensible+latent+long wave) forcing as CTL. Model approach toward this experiment is discussed in Jayakumar et al., (2010). In addition, to quantify the impact of diurnal cycle in the TRIO region, we have designed Diurnal_fix by applying diurnal cycle on net short wave radiation at the ocean and keeping the remaining as in NO_ISO_SW. To include the atmospheric feedback, we designed an experiment Diurnal_relax same as Diurnal_fix except relaxing heat flux in the non-solar part. The description of the performed experiment is given in Table 7.1).

The daily anomalies are prepared based on the 1996–2007 climatology. To isolate the signal associated with the MJO, we have used 30-120 day band-pass filtering of daily
7.3: Observed diurnal cycle in a moored buoy over TRIO and Model validation

Observed diurnal cycle in a moored buoy over TRIO and Model validation

anomalies with respect to the mean seasonal cycle. This is similar to the approach followed by Han et al. (2007) and Jayakumar et al., (2010).

Figure 7.1: (a) The diurnal cycle observed at 67°E, 8°S [RAMA] (black solid line) and Model estimated diurnal cycle in shortwave flux at same location (red solid line). (b) Daily averaged short wave flux from RAMA (black solid line), LY (red) and OA Flux (blue). This indicates the most of the high frequency components smoothed out. (c) The RAMA (black dash) and CTL hourly SST (red dash) overlaid in the daily mean SST (black solid line) and the model simulated CTL SST (red solid line). The TMI (blue) satellite observation is overlaid in the same panel. The TMI overestimates the cooling event as it gives the subskin temperature with the high wind condition (observed Dora cyclone). (d) MLD calculated from the RAMA (black solid line) and the model simulated MLD (red solid line). The deepening of MLD to a 35 meter corresponds to the cyclone period (SWF and wind forcing) is simulated in the model also.

7.3 Observed diurnal cycle in a moored buoy over TRIO and Model validation

Figure 7.1(a) shows the observed diurnal cycle in the downward short wave flux from RAMA and the corresponding model derived diurnal cycle (SWF). The model diurnal short wave flux is calculated by converting daily SWF into the energy conserving diurnal cycle by applying sinusoidal wave on daily mean SWF. The diurnal downward short wave
flux in the model \( (Q_{sw}) \) is defined as

\[
Q_{sw} = \pi Q_{sw0} \sin \left( \frac{2\pi (t - 6)}{24} \right), \quad \text{for} \quad 6 < t < 18
\]

\[
0, \quad \text{for} \quad 0 \leq t \leq 6 \quad \& \quad 18 \leq t \leq 24 \quad (7.1)
\]

Figure 7.2: (a) The scattered plot of the NSWR (LY) with NSWR (RAMA) overlay with the regression line (black). (b) NSWR calculated using Shinoda et al., (1998) based on OLR with NSWR (RAMA) (c) Similarly NSWR from OA flux with NSWR (RAMA). The Root Mean Square error (RMS) and correlation (Cor) for LY and OLR derived flux with reference to RAMA is illustrated in the above panels respectively.

after Schiller and Godfrey (2003), where \( t \) is in hour and \( Q_{sw0} \) is the estimated daily mean shortwave radiation. The representative sample in the TRIO region for the period 15th January to 15 February, 2007 resembles to the observed hourly flux albeit with some quantitative difference. This difference can be seen even in the daily averaged LY-SWF which might underestimate the flux effects (trapped in a shallow and more responsive MLD). The OAFlux also shows similar pattern with a difference of \( \sim 50 \text{W m}^{-2} \) from peak to peak mainly in the positive phase. The scattered plot of Figure 7.2a,b,c indicates the relation between the net short wave radiative flux (NSWR) estimated from the LY, OLR based flux, OAFlux and RAMA respectively. OLR based empirical relation was originally developed for the Indo-Pacific warm pool region defined as

\[
Q_{nsw} = Q_{OLR} \times 0.93 - 1.03 \quad (7.2)
\]

after Shinoda et al. [1998], where \( Q_{nsw} \) is the net surface insolation(\( \text{W m}^{-2} \)), and OLR is in \( \text{W m}^{-2} \), which is used to predict NSWR for many of previous Indian Ocean studies [Sengupta and Ravichandran, 2001]. But this relation does not show better result in the moored location (RMSE=56.6Wm\(^{-2}\), Cor=0.5), whereas SWR (LY)
(RMSE=38.2 W m\(^{-2}\), \(\approx\) Cor=0.8) showing a better relation even compared to OA flux (RMSE=43.3 W m\(^{-2}\), \(\approx\) Cor=0.7) also. So LY is considered to be a reliable SW flux for the ocean model experiment over TRIO in high frequency scale.

The strong diurnal cycle is observed even in the model SST from 18–23 January associated with the suppressed MJO phase and is absent in the 23 January–5 February when Dora cyclone passed this mooring site [Vialard et al., 2008]. The variation in the diurnal cycle is seen in the model SST (Fig. 7.1c. The influence of cyclogenesis can be seen as the cooling in the model upper level and the deepening of the model mixed layer up to 35 meter. Once the cyclone effect damped, diurnal cycle is observed (after 5th February) during the intraseasonal cooling period also (though it is not strong as in suppressed phase). The TMI overestimates the cooling event as it gives the subskin temperature during the high wind condition existed in the corresponding period. There was no large SST response associated with the active phase of MJO in the year 2007 as it may be damped by the 2006/07 El Niño- IOD oceanic precondition. Also the length of the MJO associated oceanic wave is smaller compared to the typical MJO associated event in TRIO.

Figure 7.3: a) Composite map of intraseasonal SSTA in CTL

![Composite map of intraseasonal SSTA in CTL](image)

b) Composite map of intraseasonal SSTA in Diurnal-fix

![Composite map of intraseasonal SSTA in Diurnal-fix](image)

Figure 7.3: a) Composite of interseasonal SSTA from (a) CTL and (b) Diurnal_fix. The events are selected based on SSTA (30-120 day band passed) showing value less than 1.5 Standard Deviation. The box indicates the TRIO region used in this study.
The intraseasonal SST response associated with the MJO signal is stronger in the cooling events than the precipitation event [Lloyd and Vecchi, 2010]. So this made us to examine how the diurnal cycle modulates intraseasonal SST in the cooling phase. The cooling events are selected as Lloyd and Vecchi, 2010, where SSTA (30-120 day band passed) is less than 1.5 Standard Deviation (SD). Figure 7.3 shows the composite of intraseasonal cooling events corresponds to CTL and Diurnal fix. The Diurnal fix SST picture gives ~ 18% reduction in the total intraseasonal SST variability in CTL. The reason for the reduction in the cooling is discussed in the next section.

7.4 Quantification of the diurnal cycle modulation

The role of shortwave heat flux in the TRIO displayed interannual variation with its contribution ranging from 59 to 95% (Fig. 4.9) to the intraseasonal variability in SST. The years 2001 (0.75) and 2002 (0.95) showed a large fraction of the shortwave flux to the total heat flux contribution of intraseasonal SST variance. The NO ISO SW experiment gives us to isolate the influence of the intra seasonal short wave flux variation less than 120 days(by considering CTL minus NO ISO SW). This experiment isolates the intraseasonal events largely contributed by SWF (Table 7.1).

By considering the approximation of the negligible role of advection and the dynamic role of entrainment during intraseasonal cooling associated with the MJO active phase [Vialard et al., 2009, Jayakumar et al., 2010] the influence of the diurnal variability in MLD during the events (eg. 2001, 2002, Fig. 7.4) can be quantified by calculating penetrative solar radiation \( F_{-h} \) and entrainment heat flux \( Q_{ent} \) at the base of the mixed layer using the following formulas

\[
Q_{ent} = -(Q_s(1 - F_{-h}) + Q_{ns}) + \rho C_p \partial_t T \tag{7.3}
\]

where \( Q_s \) is the solar components and \( Q_{ns} \) is the non-solar components of the surface heat flux, \( h \) is the mixed layer depth, \( T \) is the mixed layer temperature and \( \rho C_p \) is the volumic heat capacity of seawater. \( F_{-h} \) is the fraction of solar shortwave radiation that penetrates through the base of the mixed layer. This solar transmission parametrization can be calculated on the basis of the Chlorophyll (Chl) in TRIO using a formulation similar to Morel and Antoine (1994) but by neglecting smaller terms (as \( h \gg l_1 \) taken from the eq. given in their appendix).

\[
F_{-h} = v_2 \exp^{h/l_2} \tag{7.4}
\]

where \( l_2 = 17.6m \) and \( v_2 = 0.62 \) following the Chl concentration measured during the Cirene cruise [Vialard et al., 2009]. There is strong role of diurnal cycle in deter-
mining the intraseasonal SST to the penetrative solar radiation which is sensitive to the attenuation depth. This will heat the mixed layer by absorption of this penetrated light.

Figure 7.4a,d shows the mixed layer change in Diurnal\textsubscript{fix} along with the CTL for ISV events associated with MJO. The mixed layer depth variability mainly determines modulation of intraseasonal SST by diurnal cycle especially in the MJOs different phases. The difference can be seen mainly in the active phase of MJO in CTL and the Diurnal\textsubscript{fix}. During the active phase of the MJO, the mixed layer will be deeper in the CTL, whereas it seems to be reduced in the Diurnal\textsubscript{fix}. Figure 7.4c,e shows the amount of heat content change within the mixed layer due to diurnal variation in shortwave flux, by taking normalized MLD in both CTL and Diurnal\textsubscript{fix}. So accounting the diurnal cycle of surface flux concentrated over a thinner mixed layer than in the CTL make the mixed layer warm. This may result in a reduced amplitude of the intraseasonal SST response in cooling event corresponds to MJO active phase (Fig. 7.3). The nocturnal mixed layer is deeper in the CTL and the exchange of under cooled water into the mixed layer. There
7.4: Quantification of the diurnal cycle modulation

may be less temperature gradient at the base of the mixed layer in the Diurnal\_fix which may result in reduced entrainment (in compared to the CTL (Fig. 7.4d,f). Subsequently, Diurnal\_fix experiment enhanced warming in the mixed layer.

The short wave penetration into the upper ocean has a long effect in terms of SST response. Figure 7.5 shows the 30–120 days band passed SST derived from CTL minus NO\_ISO\_SW (black), which gives the idea of short wave flux contribution in the intraseasonal events. Corresponding to this, time series of 30–120 days band passed SST derived from Diurnal\_fix minus CTL (red) will help to isolate the influence of diurnal cycle in a fore mentioned ISV event in the CTL- NO\_ISO\_SW (≈ Cor=0.6). The time series analysis shows that the CTL-Diurnal\_fix will explain ~ 36% variance of the intraseasonal SST due to the short wave flux variability. Interestingly, Diurnal\_fix minus CTL (green) gives a correlation of 0.56 (~ 30.5% variance) with a similar in phase relation with former one. The Diurnal\_relax gives lesser correlation value in comparison to the former which may be due to non-linear interaction by latent heat flux. The mixed layer depth in these two experiments allows us to understand the source of this intraseasonal modulation by diurnal cycle. The MLD changes are mostly associated with the winter intraseasonal events in NO\_ISO\_SW and can be simulated in the Diurnal\_fix experiment where such changes are negligible in the rest of the period. Significant reduction and change in the amplitude of the intraseasonal variability in the sensitivity experiment with the CTL shows the interaction of diurnal cycle with the mixed layer variability.

In short, this section discusses the influence of diurnal cycle in ISV event driven only by shortwave. Analysis demonstrates that ~ 36% variance of the intraseasonal SST due to the diurnal cycle in short wave flux variability.
OGCM sensitivity experiment are used to quantify the modulation of diurnal cycle in the MJO associated event in the South western tropical Indian Ocean. The intensity of the cooling event associated with MJO is reduced by diurnal warming in the shallow mixed layer through applying diurnal cycle. Diurnal cycle explains $\sim 36\%$ variance of the intraseasonal SST due to the short wave flux variability contribution, whereas it is reduced to $\sim 31\%$ variance when the non-solar flux relaxed.

The comparison of the observed diurnal short wave flux between the RAMA in the TRIO region with estimated sinusoidal wave sample for the LY used for forcing the model shows a good match. Also the LY flux in this region is linearly regressed well with the RAMA than the Shinoda et al., (1998) empirical formula derived using OLR in this region. As as further extension to model study by Jayakumar et al., (2010), where strong impact of short wave flux regarding the intraseasonal SST in TRIO region, here we designed a sensitive experiment for modulating the intraseasonal SST (mainly cooling event) by diurnal forcing for the same region. The experiment named Diurnal fix will be isolating the impact of diurnal flux in the mixed layer from the wind stress contribution as the active phase is characterized by the high wind and increased cloud cover.

The sensitive experiment shows that there is a reduction in the amplitude of the intraseasonal SST in the TRIO after taking account of the diurnal cycle in the short wave flux. Mainly the SST variability (intraseasonal time) in this region is determined by the strong intraseasonal cooling event associated with MJO, where it is shallowed by diurnal accounted mixed layer with respect to the CTL run. The increased surface flux accounted by diurnal cycle and reduced entrainment heat flux warm the mixed layer which reduces the intensity of cooling event by some amount. The low passed SWF experiment NO_ISO_SW have a similar phase to phase relation with the Diurnal fix, with a significant modulation in the cooling event period curve inferred same result.

There are limitations in this study due to the coarse resolution though we carried out a new model approach in looking diurnal accounted variability in the Indian Ocean. There is strong dependence of the magnitude of the diurnal cycle of SST on the vertical resolution, with the magnitude increasing rapidly with improved vertical resolution [Shinoda, 2005]. We are using coarse bulk model which may underestimate the strength of the modulation of intraseasonal SST by diurnal cycle. Even though the LY shows better correlation to the RAMA for the full period, the clear sky condition is better as compared to cloudy, this may underestimate the flux effect in the active phase in comparison to the suppressed phase. Also TMI (3 day average) is giving subskin temperature and can overestimate SST value in the short lived episodes of large cooling and warming which creates problem in validating model result with this microwave image.

Diurnal modulated SST results in diurnal warm layer which favors the eastward propagation of MJO in the tropical Indian Ocean during boreal winter [Bellenger and Duvel, 2009]. These diurnal warm layers influence the atmospheric variability from diurnal to
intraseasonal time scales and improve the MJO predictability in a general circulation model [Woolnough et al., 2007]. Hence adding this diurnal layer in the model with high vertical resolution is our future work which will help to quantify the strength of the diurnal cycle better. Also these diurnal modulated SST cycle can influence the biological variability around the phytoplankton rich region in TRIO.