Effects of Australian Summer Monsoon on Sea Surface Temperature

Diurnal Variation over the Australian North-Western Shelf

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Abstract

Five-year (2010 to 2014) sea surface temperature (SST) data from the Advanced Very High Resolution Radiometer (AVHRR) are used to study the effects of the Australian summer monsoon on SST diurnal variation (DV) over the Australian North-Western shelf (NWS, defined as 105°E-125°E, 25°S-10°S). Strong DV events identified with amplitude of 0.5-2K were observed over the NWS. A double-peak seasonal pattern of DV is obtained, with the strongest DV occurring in February/March and October/November. This seasonal DV pattern over the NWS is largely due to the Australian summer monsoon, which reduces the easterly trade wind during the summer monsoonal period, favouring the development of SST DV. Since the monsoon region is distributed globally in the tropical oceans, in the western and eastern North Pacific, as well as in the southern Indian Ocean, we anticipate that strong SST DV may also exist in these parts of coastal oceans.

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1. Introduction

The Southern Hemisphere trade winds are the easterly to southeasterly winds that affect tropical and subtropical Australia in the austral winter. During the austral summer, the temperature gradient between the landmass in northern Australia and the surrounding oceans generates moist northwesterly wind from the Indian Ocean, which replaces the easterly trade winds. This northwesterly wind over the northern part of western Australia is often referred to as the Australian summer monsoon [e.g., Gentilli, 1971; Suppiah, 1992]. The westerly of Australian summer monsoon, which typically begins in October/November and lasts until March/April each year, has a strong effect on both meteorological conditions and ocean state over the Australian North-Western Shelf (NWS, defined as 105°E-125°E, 25°S-10°S) and along the Australian west coast [e.g., Wyrski, 1962; Godfrey and Ridgway, 1985; Weller et al., 2012; Jourdain et al., 2013].

Both the monsoon and the ocean state in the Australian NWS and west coast may present significant interannual variability due to the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). During La Niña, a strong Leeuwin Current is driven by higher coastal sea level, which advects more warm water southwards. During El Niño, the Leeuwin Current becomes weaker and the water temperature is generally cooler [Feng and Meyers, 2003; Zinke et al., 2014]. In particular, during La Niña in 2010/2011 a strong marine heat wave occurred along the west coast, with the highest sea surface temperature (SST) recorded in the region. This heat wave was caused by the combination of high sea level in the western equatorial Pacific associated with La Niña condition and unusually high air-sea heat flux into the ocean [Pearce and Feng, 2013]. Furthermore, in recent years an increasing trend in SST
in this area has been revealed, which is associated with global warming, and appears to be more significant than that in the Indian Ocean [Caputi et al., 2009; Pearce and Feng, 2007].

SST diurnal variation (DV) is generally defined as the daily temperature variation in the upper few meters of the ocean. A diurnal warm layer typically has a temperature difference relative to the water body below on the order of 0-3K; but in some cases, it can reach values up to 5-8K [e.g., Gentemann et al., 2008; Karagali and Høyrer, 2014]. Past studies on SST DV ranged from the determination and characterization of DV events [e.g., Sverdrup et al., 1942; Soloviev and Lukas, 1997; Clayson and Weitlich, 2005; Kawai and Wada, 2007; Gentemann et al., 2008; Eastwood et al., 2011; Karagali and Høyrer, 2014; and Zhang et al., 2016a], to the roles of DV events in air-sea interaction [e.g., Halpern and Reed, 1976; Li et al., 2001; Clayson and Bogdanoff, 2013; Marullo et al., 2016], and to their impacts on long-term climate patterns [e.g., Masson et al., 2012].

The significance of SST DV has been widely recognized. Many studies indicate that a better understanding of DV events is essential to better represent the air-sea interaction in weather and climate models [e.g., Fairall et al., 1996; Clayson and Bogdanoff, 2013]. Clayson and Bogdanoff [2013] found that excluding SST DV effects can, to different extents in different regions, underestimate the air-sea heat flux. In Brunke et al. [2008], after adding an SST DV scheme, the Community Atmosphere Model (CAM3.1) was better at predicting the diurnal cycle in air temperature and that in precipitation. According to some research, incorporating SST DV signal can enhance the performance of a climate model on long term scale. For instance, Masson et al. [2012] showed that in their general circulation model, the prediction of ENSO amplitude, frequency, and skewness is significantly better if SST DV effects are

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taken into account. Over the Australian NWS region, it is particularly important to study the DV effects given this domain’s role in the tropical climate system and in marine heat wave investigation. The SST DV in this region may also have potential impact on intraseasonal and interannual oscillations such as the Madden-Julian Oscillation (MJO), ENSO evolution, and air temperature prediction over the continent. Finally, the formation of thermal stratification has been accepted as an essential physical condition for the occurrence of phytoplankton bloom in the open waters [e.g., Riley, 1957; Nelson and Smith, 1991; Tett and Walne, 1995; Ruardij et al., 1997] and coastal waters [Azumaya et al., 2001]. As a vast coastal region, the NWS contains shallow waters that are the habitats of temperature sensitive ecosystems such as coral reefs [Zhu et al., 2014]. Therefore, our understanding of SST DV will greatly benefit the studies of the Australian NWS marine ecosystems and their coastal bio-physical dynamics.

In this research, we investigate the effects of the Australian summer monsoon on SST DV over the Australian NWS using a five-year (2010 through 2014) Advanced Very High Resolution Radiometer (AVHRR) SST data set produced by the Australian Bureau of Meteorology (Bureau) and the outputs of the Australian Community Climate and Earth System Simulator-Regional (ACCESS-R) numerical weather prediction model. The organization of the rest of this paper is as follows. In section 2, we give details of the data sets used and a simple physical DV model. In section 3, we present the effects of the Australian monsoon on SST DV. Summary of the study is provided in section 4.

2. Data and Model
Five-year (1st January 2010 to 31st December 2014) AVHRR SST data are used to study the effects of the Australian summer monsoon on SST DV events over the Australian NWS, together with the hourly meteorological data from ACCESS-R 24-hour forecast. A brief description of both data sets and a physical DV model as an example is presented in this section.

2.1. Data sets

2.1.1. SST data

The SST data used in this research are NOAA-19 High-Resolution Picture Transmission AVHRR data version 2 (“fv02”), produced by the Bureau as a contribution to the Integrated Marine Observing System (IMOS; http://www.imos.org.au/). Four types of AVHRR SST products, namely, the Level 2 Pre-processed (L2P), Level 3 Un-collated (L3U), Level 3 Collated (L3C), and Level 3 Super-collated (L3S), have been consistently reprocessed for each satellite platform over the region around Australia (70°E-170°W, 70°S-20°N) from 1992 to 2015 [Beggs et al., 2010, 2013]. IMOS AVHRR SST products are compliant with the Group for High Resolution Sea Surface Temperature (GHRSSST) Data Specification (GDS) 2.0 revision 5 (r5) in the Network Common Data Form (NetCDF) file format [GHRSSST Science Team, 2010]. Gridding the best quality L2P data for each pass generates the L3U data at 0.02° × 0.02° resolution. The L3C products are composed of multiple passes of the same satellite sensor over a fixed time period, typically a single daytime period and a single night-time period. The data set was selected due to its high spatial resolution and SST algorithms designed to minimise day-night SST bias [Zhang et al., 2016b]. The L3U files are
used for validation. For SST DV analyses, to avoid repeated merging of the L3U files within a single daytime or night-time period, daily L3C files are adopted.

The validation results using in-situ data by Zhang et al. [2016b] showed that the AVHRR SST data set is of overall good quality, although the daytime measurements have an average of 0.19K underestimation. Readers are referred to Zhang et al. [2016b] for detailed discussion on the AVHRR SST data quality control method and validation. We also wish to note that since AVHRR SST data are only available under cloud-free conditions, our analysis will unavoidably have this sampling bias, so it may not represent typical SST variation in regions that are frequently obscured by clouds.

2.1.2. Meteorological data

Daily maximum solar shortwave insolation (SSI$_{\text{max}}$), wind speed and direction at 10-m height above sea level are obtained using the ACCESS-R weather prediction model hourly outputs. The original ACCESS climate model is a fully coupled Earth System Model, developed by the Bureau in collaboration with the Commonwealth Scientific and Industrial Research Organisation (CSIRO). In ACCESS, the ocean module, the Modular Ocean Model version 4 (MOM4), and the atmosphere module, the Met Office Unified Model (UM), are coupled via the Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) coupler. The observation processing system uses most routinely available in-situ and remotely sensed data. The frequency of data assimilation is 6-hourly for base times of 00, 06, 12, and 18 UTC using four-dimensional variational algorithms (4dVAR). However, as a transformed and regional version, ACCESS-R weather prediction model is no longer coupled to the ocean module. The SST, which is
used as the boundary condition to ACCESS-R, is derived from observations. ACCESS-R became fully operational since September 2009, and can forecast a variety of surface parameters, including the sensible and latent heat fluxes, shortwave and longwave insolation, and winds [Puri et al., 2013]. The model spatial resolution was increased from 0.375°×0.375° prior to 17th April 2013 to 0.11°×0.11° on 17th April 2013 and kept it so. Preliminary comparison showed an increase in the forecast skill relative to the original coarser resolution model [National Meteorological and Oceanographic Centre Operations Bulletin Number 98, 2013]. Therefore, the higher resolution wind data from the model are used for the period from 17th April 2013 onwards.

The ACCESS-R SSImax and wind speed over the NWS are compared with the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis SSImax data and Cross-Calibrated Multi-Platform (CCMP) sea surface wind data for the same five-year period, respectively (Figure 1). The CCMP data sets are the composite of cross-calibrated satellite winds obtained from the Remote Sensing Systems (RSS) to produce a high-resolution (0.25°×0.25°) gridded analysis [Atlas et al., 2011]. The two sets of data provide high correlations with R = 0.85 and 0.88 for SSImax and wind speed, respectively. The ACCESS-R underestimates both SSImax and wind speed slightly with biases of -27.4 Wm⁻² and -0.33 ms⁻¹, respectively.
2.2. A simple DV model

The process of SST DV is concerned with solar radiation and wind mixing in the surface boundary layer. A number of numerical models are available to understand DV events and predict the variability of the DV process. They range from turbulence closure models [e.g., *Mellor and Yamada*, 1982; *Karagali et al.*, 2017], to statistical models [e.g., *Price et al.*, 1987; *Webster et al.*, 1996; *Gentemann et al.*, 2003], to air-sea coupled models [e.g., *Noh et al.*, 2011], and to physical-empirical hybrid models [e.g., *Gentemann et al.*, 2009; *Weihs and Bourassa*, 2014]. In essence, the balance between the net heat flux and wind-driven turbulent mixing over a daily cycle determines the magnitude of SST DV. As an example, this process can be represented by a simple physical model for a sub-surface boundary layer (under the cool skin layer) [e.g., *Zeng and Beljaars*, 2005; *Takaya et al.*, 2010] in the following equation:

Figure 1. Joint distribution of ACCESS-R and ECMWF/CCMP data for (a) $SSI_{\text{max}}$ and (b) wind speed over the Australian NWS (105°E-125°E, 25°S-10°S) from 2010 to 2014.
\[ \frac{\partial}{\partial t} \int_{-d}^{-\delta} T dz = \frac{Q + R_s - R(-d)}{\rho_w c_w} - K_w \frac{\partial T}{\partial z} \big|_{z=-d} \]  

(1)

where \( T \) is temperature, \( \delta \) is the depth of the cool skin layer, \( d \) is the measurement depth at which the diurnal cycle can be omitted (set as 3 m in this study), \( Q \) is the sum of latent heat, sensible heat, and longwave radiation, \( R_s \) is shortwave radiation, \( \rho_w \) is seawater density, \( c_w \) is seawater heat capacity, and \( K_w \) is turbulent diffusion coefficient. Following Large et al. [1994],

\[ K_w(z) = ku_{sw}(-z)/\phi_t \left( \frac{-z}{L} \right) \]  

(2)

where  \( k = 0.4 \) is the Von Karman constant, \( u_{sw} \) is the surface friction velocity, and \( z \) is negative in the ocean. The stability function is:

\[ \phi_t \left( \frac{d}{L} \right) = \begin{cases} 1 + 5 \frac{d}{L} & \text{for } \frac{d}{L} \geq 0 \\ \left( 1 - 16 \frac{d}{L} \right)^{-0.5} & \text{for } \frac{d}{L} < 0 \end{cases} \]  

(3)

In (3), \( L \) is the Monin-Obukhov length calculated as \( L = \rho_w c_w u_{sw}^3 / (k F_d) \), and \( F_d = g \alpha_w [Q + R_s - R(-d)] \) where \( \alpha_w \) is the thermal expansion coefficient and \( R(-d) \) is shortwave insolation at depth \( d \).

3. Results and Discussion

3.1. SST DV seasonal variability

The SST DV amplitude (also referred to as dSST) in this study is calculated as the daytime SST minus the night-time SST at the same location within the same day (local time). NOAA-19 crosses the local equator at ~14 local solar time (LST) in the day and ~2 LST at night. As
the minimum SST in the daily cycle is observed around dawn (5-7 LST), and the maximum SST, at 14-16 LST [e.g., Gentemann et al., 2003; Karagali et al., 2012; Zhang et al., 2016a], the SST DV amplitude calculated in this study is likely to underestimate the actual maximum DV to some extent. However, it is believed that the general SST DV patterns should be captured, as demonstrated previously by SST DV studies using AVHRR data [e.g., Böhm et al., 1991; Hawkins et al., 1993; Gentemann et al., 2003].

Figure 2 shows the five-year monthly-averaged DV, wind and SSI_{max} over the whole study domain of the NWS. The wind and SSI_{max} averages only include data from days on which DV data are available at that location. The time series of wind vectors over the NWS region shows all-year southerly wind with a strong southeasterly component in the non-monsoon season and a strong southwesterly component in the monsoon season (Figure 2a). A double-peak pattern is revealed for DV over the whole study domain (Figure 2b). The first peak in DV amplitude occurs in February/March, reaching a dSST amplitude of 0.6K. The second peak appears in October/November with a dSST of 0.5K. Both DV peaks coincide with the minimum wind speed and high SSI_{max} in those months. Minimum DV occurs in the austral winter (June/July) when wind speed and SSI_{max} reach maximum and minimum, respectively. Figure 2c shows the five-year monthly- and area-averaged DV but only for the strongest one-third DV events, with collocated wind speed and SSI_{max}. Although not as obvious as in Figure 2b, the double-peak DV pattern can be observed with a maximum amplitude reaching 1.4K in February/March.
Figure 2. (a) Five-year weekly- and area-averaged wind vector; (b) five-year monthly- and area-averaged DV, wind speed, and $\text{SSI}_{\text{max}}$ over the whole study domain of the Australian NWS (105°E-125°E, 25°S-10°S). The wind and $\text{SSI}_{\text{max}}$ averages only include data from days on which DV data are available at that location. (c) Same as (b), except for the strongest one-third DV events with the collocated wind and $\text{SSI}_{\text{max}}$.

3.2. Effects of the Australian summer monsoon on SST DV

Figures 3 and 4 show five-year monthly-averaged wind vector, $d\text{SST}$ and counts of clear days (a proxy for cloud cover) for November, January, March, and August. The former three months represent the beginning, middle, and end of the Australian summer monsoon, respectively, whereas August is a typical non-monsoon season when the SST reaches the coldest of the year. Around October/November, westerly monsoon winds start to develop quickly and largely cancel the easterly trade winds (Figure 3a). At this stage, the resultant winds are very weak ($\sim 1-3$ ms$^{-1}$). Also, the monsoon winds carry a large amount of water vapour; thus, clouds begin to form and the counts of clear days start to decline (Figure 4a). However, despite the decreasing solar radiation due to more frequent cloud cover, the SST
DV can be very large (~1-2K on average), indicating the dominant role of weak wind in determining DV over this region.

Figure 3. Five-year-averaged monthly wind vector and dSST for (a) Nov, (b) Jan, (c) Mar, and (d) Aug.
Figure 4. Spatial distributions of five-year-averaged monthly counts (for Nov, Jan, Mar, and Aug) of the days on which DV data are available, i.e., days on which there are both local daytime and night-time quality controlled SST measurements at the same location.

From January to February, the westerly monsoon winds have replaced the trade winds. Stable westerly winds, which are relatively weak (3-5 ms$^{-1}$), are observed over this region (Figure 3b). More clouds lead to the fewest clear days of the year in January (Figure 4b). Still, the SST DV is relatively strong, mainly due to the weak wind.

The monsoon winds begin to decay in March/April (Figure 3c). Before the easterly trade winds take over, there is another wind speed trough during this period (Figures 2b and c). Clear days are still rarely seen because it takes some time for the clouds to dissipate (Figure
4c). Expectedly, the SST DV sees another peak during this period, with a maximum dSST near the coast on the order of 2K.

The austral winter (May to September) marks the typical non-monsoon climate. Moderate to large easterly trade winds dominate in this period. Figure 3d shows consistent easterly trade winds reaching 5-6 ms\(^{-1}\) in August with a monthly-averaged SST DV close to 0K over the entire NWS region. As expected, most days in August are cloud free, with the counts of clear days on the order of 25 days (Figure 4d).

To further investigate the effects of monsoonal winds on the SST DV, daily-averaged surface turbulent diffusion coefficient \(K_w\) defined by Equation (2) is calculated (Figure 5). The heat fluxes used in the calculation are daily averages, and the depth \(d\) is set to 3 m. Small \(K_w\) represents weak wind mixing and strong stratification due to surface heating, which in turn produces a large SST DV. Due to reduced wind speed in November and March, \(K_w\) is the minimum in the region with a value around 0.1 m\(^2\)s\(^{-1}\). \(K_w\) in January reaches a maximum value of 0.35 m\(^2\)s\(^{-1}\) at the latitude of 24°S, corresponding to a band of strong trade wind deflected to southerly by the monsoon (Figure 3b). In August, persistent southeasterly trade winds produce moderate \(K_w\) over the NWS, despite of low \(K_w\) along the coast of the NWS.

In conclusion, large dSST over the NWS is produced by strong \(\text{SSI}_{\text{max}}\) and weak wind speed at the onset and termination of the Australian summer monsoon season in October/November and February/March, respectively. Two opposing wind systems of easterly trade winds and westerly monsoon winds weaken the wind mixing in the surface boundary layer, ensuring large SST DV events during these months. During the peak of the monsoon season (austral
winter), strong and persistent monsoon (trade) winds of northwesterly (southeasterly) dominate. Large wind mixing events prevent the development of large SST DV. Due to low solar radiation in the austral winter, dSST reaches its minimum in its seasonal variability.

Figure 5. Spatial distributions of the five-year-averaged monthly turbulent diffusion coefficient defined by Equation (2) for Nov, Jan, Mar, and Aug.

4. Summary

Five-year (2010 to 2014) AVHRR SST data produced by the Bureau were used to study the effects of the Australian monsoon on SST DV events over the Australian NWS, together with the hourly meteorological data from the ACCESS-R 24-hour forecast. For the five-year average, strong DV events with amplitude of 0.5-2K show a double-peak seasonal pattern over the NWS, where the strongest DV events occur in February/March and
October/November, and the weakest, in June and July. This strong seasonal DV pattern is largely due to the Australian summer monsoon, which has reduced the easterly trade winds at the beginning and end of the monsoonal period. As a result, the wind speed reaches its minimum in these months, causing large DV events due to the weak wind mixing at the sea surface. The strong DV events are further enhanced by the maximum $\text{SSI}_{\text{max}}$ change from winter to summer at relatively higher latitudes of the NWS. Other factors, such as cloud cover, play a minor role in affecting SST DV of the region.

Since the monsoon region is distributed globally in the tropical oceans of the western and eastern North Pacific, as well as the southern Indian Ocean, the seasonal reversal from easterly trade winds to westerly monsoon winds over these regions can also be observed (e.g., the tropical Asia, West Africa and India in the Northern Hemisphere). Thus, a double-peak seasonal pattern of DV may also exist in these parts of coastal oceans. The effects on SST DV by these regional tropical monsoons may be a subject of our future study.
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