The cold pool of the Bay of Bengal and its association with the break phase of the Indian summer monsoon

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ABSTRACT
During the summer monsoon season, strong coastal upwelling occurs along the southwest coast of India and at the southern tip of India, which cools the surface temperature of the waters around these regions. The summer monsoon current carries the upwelled cold waters into the Bay of Bengal and forms the 'cold pool of the Bay of Bengal', with its core south of Sri Lanka and over the south-central Bay of Bengal. The present study focuses on the intrusion of these cold waters into the south of the Bay of Bengal, its interannual variability, and its association with the surface wind during the break phase of the summer monsoon, when strong westerly surface winds flow south of 10°N. The authors hypothesize that the enhanced cooling in the cold pool region during monsoon spells is associated with the strong westerly wind stress there during the break spells of the monsoon. Seven cases of long break monsoon spells that occurred during the nine years from 2001 to 2009 are analyzed, and the results confirm our hypothesis.

1. Introduction
The strong monsoonal winds over the Indian Ocean play a major role in driving the surface currents of the region, thus influencing the sea surface temperature (SST) in the Indian Ocean (Schott and McCreary 2001; Shankar, Vinayachandran, and Unnikrishnan 2002; Schott, Xie, and McCreary 2009). The surface winds over the southwest coast of India cause divergence of the near-surface waters and play a role in bringing upwelled colder subsurface waters to the surface, causing a cooling of SST (Shetye 1984; McCreary and Chao 1985; Johannessen, Subbaraju, and Blindheim 1987; Shetye et al. 1990; Luis and Kawamura 2002; Shankar et al. 2005). There is also strong cooling of surface waters at the southern tip of India during this season due to near-surface divergence off the coast in this region (Rao et al. 2006a,b). During June to September, the summer monsoon current (SMC) flows eastwards around the southern part of India and Sri Lanka into the Bay of Bengal (Vinayachandran et al. 1999, 2004). This current carries the cold upwelled waters into the Bay of Bengal. Joseph et al. (2005) established the existence of the 'cold pool of the Bay of Bengal' between 3°N and 10°N during the summer monsoon season. Subsequently, Das, Vinayachandran, and Behara (2015) studied the formation mechanisms of this cold pool during the pre-monsoon season and at the onset of the monsoon in 2009. They concluded that atmospheric conditions also play a role in the formation of the cold pool.

During the summer monsoon, strong cross-equatorial winds flow in the lower levels of the atmosphere over the Indian Ocean, called the low-level jet stream (LLJ), the existence of which was established by Joseph and Raman (1966) and Findlater (1969), and the core of which is at around 850 hPa (at a height of about 1.5 km). Findlater (1971) suggested the jet splits into two branches during the summer monsoon, but Joseph and Sijikumar (2004) showed that there is no such splitting; rather, a north-south shift in the axis of the LLJ occurs, closely associated with the active–break cycle of the monsoon. They used the winds from NCEP–NCAR data to study the intraseasonal variability of the LLJ. The active phase of the monsoon is associated with increased convection and rainfall over India, the eastern Arabian Sea, and the Bay of Bengal, when the core of the LLJ passes over the Indian peninsular
region between 12.5°N and 17.5°N. Whereas, during the break phase, the LLJ turns clockwise over the Arabian Sea, bypasses India and flows south of India with its core between 2.5°N and 7.5°N (Joseph and Sijikumar 2004). During break periods, which last from a few days to more than two weeks, the wind stress increases south of latitude 10°N in the Bay of Bengal. We hypothesize that the increase in wind stress during break monsoon periods over the low latitudes of the Bay of Bengal cause enhanced SST cooling in the cold pool region.

In order to test our hypothesis, we study the year-to-year variations in the SST of the cold pool, as well as the role of break monsoon spells in the SST fluctuations that occur within the cold pool region, using SST data from satellite observations. Section 2 briefly describes the datasets and methods used in the study. The results are presented and discussed in Section 3, followed by a summary and conclusions in Section 4.

2. Datasets

2.1. Satellite SST data

Tropical Rainfall Measuring Mission Microwave Imager (TMI) data provide a three-day composite of SST globally, with an accuracy of 0.5 °C (Wentz et al. 1998). The data with a 1° resolution are used for the present study. They are also used to verify the intraseasonal and interannual variability of SST in the cold pool region. The data from 2001 to 2010 are used for the present analysis.

2.2. Ocean current data

The Ocean Surface Current Analysis Real-time (OSCAR) data-set provides ocean surface velocities (units: m s⁻¹), making use of surface parameters derived from different satellite missions (https://www.esr.org/oscar_index.html). The data for the Indian Ocean region for the study period (2001–2010) are obtained from NASA’s Physical Oceanography Distributed Active Archive Center (https://podaac.jpl.nasa.gov/). The surface currents, at five-day intervals and a spatial resolution of 1/3°, are provided by the data center. The surface current data are used to show the characteristics of the SMC, which flows into the Bay of Bengal.

2.3. Rainfall data

The rainfall data over the Indian subcontinent are from the National Data Centre, Indian Meteorological Department, as gridded rainfall data. The data cover the rainfall over the Indian land area. The data-set is mainly used to identify the active–break cycles of the Indian summer monsoon, following the criteria used by Rajeevan et al. (2006), which is described in Section 3.3.

2.4. ERA-Interim winds

For wind analysis over the study region, we use the surface winds at a height of 10 m from ERA-Interim. These global reanalysis data from ECMWF provide atmospheric products, including the wind at 10 m from January 1989 onwards (Dee et al. 2011). The data-set contains winds at six-hour intervals and at a spatial resolution of 0.5°. The surface winds are used to verify the shift in the LLJ between the active–break phases of the summer monsoon.

3. Results and discussion

3.1. Cold pool development as observed in TMI SST data

Multi-year (2001–2010) averages of TMI SST over the cold pool and surrounding regions (southwest coast of India, south of Sri Lanka, and south-central Bay of Bengal) for the months of June, July, August, and September, are presented in Figure 1 (top panel). The box in Figure 1 (2°–9°N, 75°–90°E) marks the cold pool region that we discuss in the present paper. During June, upwelled cold waters reduce the SST along the southwest coast of India (Shetye 1984; Johannessen, Subbaraju, and Blindheim 1987; Shetye et al. 1990). Due to a lack of data along the coast, the upwelling along the southwest coast in June is not visible in Figure 1(a), but the presence of upwelling off the southern tip of India (Rao et al. 2006a,b) is observed as a decrease in SST during June, indicated by the green color (Figure 1(a)). By July, the upwelling along the coast and off the southern tip of India (Luis and Kawamura 2002; Rao et al. 2006b) intensifies (Figure 1(b)) and continues to persist further into August (Figure 1(c)). Surface ocean currents for the same periods are presented in the bottom panel of Figure 1. Multi-year (2001–2010) averages of surface ocean currents from OSCAR data show the SMC, which strengthens (speeds above 0.4 m s⁻¹) during July–August (Shankar, Vinayachandran, and Unnikrishnan 2002), flows towards the Bay of Bengal (Vinayachandran et al. 1999), and carries the cold upwelled waters into the south-central part of the bay (Figure 1(e)–(h)).

These cold waters, which form a pool of cold SST in the Bay of Bengal, are referred to as the ‘cold pool of the Bay of Bengal’ (Joseph et al. 2005; Joseph and Sabin 2008). By September — the end of the summer monsoon (Figure 1(d)) — the upwelling ceases along the southwest coast of India (Shetye 1984; Johannessen, Subbaraju, and Blindheim 1987; Haugen, Johannessen, and Evensen 2002; Jayaram et al. 2010), weakening the cold pool. The
SMC weakens (Figure 1(h)) and later reverses its direction (Schott and McCreary 2001; Shankar, Vinayachandran, and Unnikrishnan 2002), and SSTs start to gradually increase (Chatterjee et al. 2012). The formation and progress of the cold pool is clearly observed in the TMI satellite SST measurements. During the months of July–September (Figure 1(b)–(d)), enhanced cooling is observed within the cold pool region, towards the south of the peninsula as well as the east of Sri Lanka. A detailed analysis of the cold pool and its intrusion into the Bay of Bengal, as seen in the TMI observations, is carried out in the following sections.

3.2. Interannual variability of the cold pool

The upwelling along the southwest coast of India and the associated cold pool in the Bay of Bengal is a regular phenomenon during the summer monsoon season. Nevertheless, there is significant interannual variability associated with this phenomenon. Figure 2 shows the monthly mean SST of the cold pool during June–September, as obtained from the TMI data-set. Monthly averages of SST, for the months of June to September, are plotted for all the 10 years from 2001 to 2010 (Figure 2). Cold water intrusion into the Bay of Bengal occurs during these months, with the coldest SST occurring mostly in the months of July and August. It is noticeable that, in these 10 years, the coldest SST in the cold pool is during the monsoons of 2002, 2004, and 2009. According to the Oceanic Niño Index (three-month running mean of ERSST.v4 SST anomalies in the Niño3.4 region (5°N–5°S, 120°–170°W)), the period from June to September of these years fall within the El Niño year criteria (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

One of the characteristics of El Niño years is the occurrence of long break monsoon spells in the Indian summer monsoon (Joseph 2014). During break monsoon spells, there is a shift in the axis of the LLJ, which causes strong positive wind stress curl in the cold pool region, as discussed in the following Sections 3.3–3.5.

3.3. The active–break cycle of the summer monsoon

Intraseasonal variability of the summer monsoon is observed in the wind, convection, and rainfall mainly associated with the active–break cycles of the Indian summer monsoon (Goswami 2005; Joseph and Sabin 2008). The active spells are associated with high rainfall and strong low-level winds over India, and break periods are accompanied by decreased winds and subdued monsoon rainfall over India. The large-scale rainfall over India is interrupted for several days during break periods. Rajeevan et al. (2006) suggested a criterion to identify these active–break spells during the summer monsoon, based on gridded rainfall data. For our analysis, we follow their criteria to define active and break spells (Section 2.3).

From the 1° x 1° gridded rainfall data (Rajeevan et al. 2006), the normalized daily rainfall is calculated for the area over India (21°–27°N, 72°–85°E) during June–September for the years 2001 to 2010 (Figure 3(a)). Prolonged break phases, especially those with normalized rainfall below -1.0 for seven consecutive days or more, are marked with

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**Figure 1.** (a–d) Multi-year (2001–2010) averages of SST (units: °C) from TMI for the months of (a) June to (d) September. The SST of 28.5 °C is contoured in black. (e–h) Multi-year (2001–2010) averages of ocean surface currents (vectors; units: m s⁻¹) and their magnitudes (shaded; units: m s⁻¹) from OSCAR (Ocean Surface Current Analysis Real-time) data for the months of (e) June to (h) September. Note: The box in the figures marks the cold pool region discussed in the study.
Figure 2. Monthly averages of SST (units: °C) from TMI, from 2001 to 2010 during the months of June–September.
In the El Niño year of 2002, there was a very long break spell of 16 days from 26 August to 10 September (Figure 3(a)). The year 2005 featured comparatively higher rainfall over India during June and July. In August, however, yellow color; and the active phases, with normalized rainfall above +1.0 for six consecutive days or more, are marked in green (Figure 3(a)). These break days for the seven cases are listed in Table 1. The periods selected for calculating the composites of active monsoon are: (1) 7 August to 15 August 2004; (2) 28 June to 5 July 2005; and (3) 26 August to 31 August 2006 (marked in green in Figure 3(a)).

The El Niño year of 2002 featured unusually low rainfall over India during the monsoon season (19% below the long-term average) (Gadgil 2003), and there were two break spells in July 2002 (Figure 3(a); 2002). The year 2003 featured normal rainfall (Gadgil 2003) with no significant break spells during the summer monsoon. In the El Niño year of 2004, there was a very long break spell of 16 days from 26 August to 10 September (Figure 3(a)). The year 2005 featured comparatively higher rainfall over India (Figure 3(a)) during June and July. In August, however,
there were two break spells (Figure 3(a)). In 2006, a break spell is apparent in July (Figure 3(a)), followed by a short active phase during September (Figure 3(a)). The following two years (2007 and 2008) did not have long break phases. The year 2009 was an El Niño year, with severe Indian monsoon drought (Neena, Suhas, and Goswami 2011) and an anomalous cooling observed in the Bay of Bengal (Chacko et al. 2012). Figure 3(a) shows the long break spell in 2009, from 28 July to 10 August.

Studying the break periods in the Indian summer monsoon and the daily SST evolution in the cold pool region (figure not shown) for the years from 2001 to 2009, it is apparent that a close relationship exists between the enhanced cooling that occurs within the cold pool region and break periods during the summer monsoon. We further analyze this relationship in the following Section 3.4.

3.4. Break periods and enhanced cooling within the cold pool

The composite of ocean surface temperatures for the abovementioned break and active spells of the summer monsoon, based on TMI SST data, are presented in Figure 3(b). The SST pattern during the break period shows a southward spread of the cold pool, as well as enhanced cooling (SST < 28.5 °C) within the cold pool region. There is a marked difference between the SST patterns during break and active phases of the summer monsoon. The mean difference between the two phases (break minus active) is also presented in the figure. The mean difference reaches more than 1 °C inside the cold pool region, especially towards the southern parts of India. It is particularly clear from Figure 3(b) that, during the composite of break spells, the cold pool SST is colder compared to the composite of active spells. It is also apparent that there is a cold region north of 15°N in the Bay of Bengal in the active monsoon composite, which is due to the location of the LLJ around 15°N during active monsoon spells (Joseph and Sijikumar 2004).

3.5. Surface winds during break and active phases of the monsoon

The surface wind at 10 m over the region for the composites of break spells and active periods are presented in Figure 3(c). The strength of the winds over the Bay of Bengal, south of 4°N, is enhanced during the break spells (Figure 3(c)) compared to the active period. The strong winds in these two periods also show a difference in their distributional pattern. During the break period, stronger winds blow south of India, and the maximum wind speeds lie within the cold pool region. However, during active periods, there is a shift in the axis of the surface winds (Joseph and Sijikumar 2004) and the winds get stronger over the northern Bay of Bengal. The differences in surface wind between the two phases of the monsoon are shown in Figure 3(c).

4. Summary and conclusions

The cold pool in the Bay of Bengal, which occurs during the summer monsoon season (June to September), is studied using observational data from TMI. There is prominent intraseasonal and interannual variability associated with the cold pool. The upwelled waters from the southwest coast of India are advected into areas south of Sri Lanka and further into the south-central Bay of Bengal by the SMC. There is also advection of the upwelled waters from the southern tip of India into this region.

A detailed analysis of the rainfall pattern over India, which depicts the active–break cycles of the Indian summer monsoon, shows that there is a close relationship between the enhanced cooling that occurs within the cold pool region and the break phases of the summer monsoon. During the break spells in most of the years studied, an intensification of cooling within the cold pool region is apparent, especially during July–September. To substantiate the hypothesis that a link exists between the intensified cooling within the cold pool region and the break periods of the Indian summer monsoon, seven cases of long break spells and three active spells are selected for analysis.

There are significant differences between the SST patterns during break and active periods of the summer monsoon. Intense cooling in the cold pool region is found during break periods. Also observed is a southward extension of these cold waters towards the equator. Whereas, during active periods, the enhanced cooling is absent in the cold pool region. The surface winds show a shift towards the south of India during break periods, while in the active monsoon period the axis of the wind is over mainland India. The winds are stronger south of 6°N during break spells, as compared to active periods.

In conclusion, the results from the present study confirm that enhanced cooling exists in the cold pool region during break periods of the summer monsoon. It is shown that this enhanced cooling is due to increased wind stress that happens over the region during break phases of the summer monsoon, thus confirming our hypothesis.

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