Link between convection and meridional gradient of sea surface temperature in the Bay of Bengal

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Running title: ***Convection and SST gradient in Bay of Bengal***

Keywords: ***Southwest monsoon; Indian summer monsoon; Sea surface temperature gradient; ITCZ; Summer Monsoon Current; Southwest Monsoon Current; Tropical Convergence Zone; Indian Ocean.***

Accepted pre-print

May 14, 2007

Abstract

We use daily satellite estimates of sea surface temperature (SST) and rainfall during 1998-2005 to show that onset of convection over the central Bay of Bengal (88–92°E, 14–18°N) during the core summer monsoon (mid-May to September) is linked to the meridional gradient of SST in the bay. The SST gradient was computed between two boxes in the northern (88–92°E, 18–22°N) and southern (82–88°E, 4–8°N) bay; the latter is the area of the cold tongue in the bay linked to the Summer Monsoon Current. Convection over central bay followed the SST difference between the northern and southern bay (ΔT) exceeding 0.75°C in 28 cases. There was no instance of ΔT exceeding this threshold without a burst in convection. There were, however, five instances of convection occurring without this SST gradient. Long rainfall events (events lasting more than a week) were associated with an SST event ($\Delta T \geq 0.75^\circ$C); rainfall events tended to be short when not associated with an SST event. The SST gradient was important for the onset of convection, but not for its persistence: convection often persisted for several days even after the SST gradient weakened. The lag between ΔT exceeding 0.75°C and the onset of convection was 0–18 days, but the lag histogram peaked at one week. In 75% of the 28 cases, convection occurred within a week of ΔT exceeding the threshold of 0.75°C. The northern bay SST, T_N, contributed more to ΔT, but it was a weaker criterion for convection than the SST gradient. A sensitivity analysis showed that the corresponding threshold for T_N was 29°C. We hypothesise that the excess heating ($\sim 1^\circ$C above the threshold for deep convection) required in the northern bay to trigger convection is because this excess in SST is what is required to establish the critical SST gradient.

1 Introduction

Early ideas of the Indian summer monsoon suggested that it was caused by the differential heating between land and sea, making it a gigantic sea breeze (*Halley* 1686). Though differential heating is still held by some to be the primary cause (*Webster* 1987), there is an alternative hypothesis that considers the monsoon to be a manifestation of the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) (*Charney* 1969; *Riehl* 1979; *Gadgil* 2003) in response to the seasonal variation of the latitude of maximum insolation.

The advent of satellites brought about a revolution in our ability to observe facets of the monsoon. Satellite data showed that there are two favourable locations for the cloud bands or ITCZ, one over the equatorial Indian Ocean and the other over the heated Indian subcontinent. *Gadgil* (2003) therefore used the term Tropical Convergence Zone (TCZ) for these bands because convergence in both TCZs cannot be inter-tropical. Prominent in these satellite data are northward propagations of the cloud bands (*Yasunari* 1979) and convection (manifested as satellite-observed maximum cloud zones) (*Sikka and Gadgil* 1980). The seasonal migration of the ITCZ consists of a few such northward propagations during the summer monsoon (June–September), the propagations culminating farther and farther north in the onset phase of the monsoon and farther and farther south in its retreat phase (*Sikka and Gadgil* 1980; *Gadgil* 2003). There are, however, occasions on which no northward propagation is seen.

The TCZ is a manifestation of large-scale convective heating in the atmosphere. Satellite data show that there is a greater propensity for atmospheric convection over the oceans when SST exceeds a critical threshold, which is 27.5–28°C for the Indian Ocean (*Gadgil et al* 1984; *Graham and Barnett* 1987; *Sud et al* 1999). The threshold is a necessary, but not sufficient, condition for convection to occur. In the Bay of Bengal, unlike in the Arabian Sea, SST exceeds 28°C almost throughout the summer monsoon (*Shenoi et al* 2002; *Gadgil* 2003), making the former favourable for convection throughout the summer monsoon. Convection does not, however, occur all the time, resulting in a poor correlation between SST and rainfall over the Indian Ocean (*Gadgil* 2003).

Data from moored buoys (*Premkumar et al* 2000; *Sengupta and Ravichandran* 2001) and microwave-based remote sensing (*Harrison and Vecchi* 2001; *Vecchi and Harrison* 2002) show large-amplitude intraseasonal oscillations in SST in the bay; SST varies by 1–2°C on the basin scale and has been attributed to large-scale changes in surface winds and atmospheric convection (*Sengupta et al* 2001; *Vecchi and Harrison* 2002). Similar changes occur in the structure of the upper ocean during the summer monsoon (*Bhat et al* 2001), with a low-salinity surface mixed layer (due to rainfall and freshwater influx from rivers) playing a role in the SST variations (*Vinayachandran et al* 2002; *Shenoi et al* 2002), leading to a coupling between the ocean and the monsoon (*Gadgil* 2000, 2003; *Shenoi et al* 2002).

Using data from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) satellite, *Vecchi and Harrison* (2002) showed that SST in the northern bay falls about one week preceding a monsoon break (*Ramamurthy* 1969; *Krishnamurti and Bhalme* 1976; *Rao* 1976). Convection and winds decrease with the fall in SST, which then tends to increase, leading to convection. In the southern bay, the SST in a "cold tongue", a region of low SST, is not in phase with the SST in the northern bay (*Joseph et al* 2005). *Vecchi and Harrison* (2002) attributed this low-SST regime to enhanced cooling by westerly monsoon winds, decreased solar radiation owing to the monsoon clouds, and upwelling driven by Ekman suction. Other studies, however, suggested advection of cold waters into the bay (*Rao et al* 2006a,b) by the Summer Monsoon Current (SMC) (*Vinayachandran et al* 1999; *Shankar et al* 2002) as the primary cause of this cooling in the southern bay. Also important is the upwelling forced by Ekman pumping in a "cold dome" off eastern Sri Lanka (*Vinayachandran and Yamagata* 1998).

Vecchi and Harrison (2002) and *Joseph et al* (2005) speculated that convection over the bay could be related to the meridional SST gradient between the warm northern bay and the cooler southern bay. In this paper, we use satellite data for SST and rainfall to show that there exists a strong relationship between convection and the meridional gradient of SST in the bay. We show that convection sets in within a week of the SST difference between the northern and southern bay exceeding 0.75°C. We begin by presenting the data and definitions (Section 2) and the resultant relationship between SST gradient and rainfall (Section 3). Sensitivity of the results to the definitions is discussed in Section 4, followed by a discussion (Section 5) and the conclusions (Section 6).

2 Data and definitions

The data we used are listed in Table 1; all these data are available daily. The main data used are TMI SST (*Wentz* 1998) and GPCP (Global Precipitation Climatology Project) rainfall (*Huffman et al* 2001) during 1998–2005.

To estimate the meridional gradient of SST in the bay, we defined boxes in the northern and southern bay over which SST was averaged (Figure 1). The SST gradient was defined in terms of the SST difference between the northern and southern boxes. The box in the northern bay matches that in which the maximum number of low-pressure systems form (*Rao* 1976; *Mooley and Shukla* 1989; *Shenoi et al* 2002). The box in the southern bay was chosen to cover the region of influence of the SMC. Note that this difference in SST (henceforth referred to as ΔT) is not defined between boxes centred on a meridian: the central longitude of the southern box lies to the west of that of the northern box. Nevertheless, we use the term "meridional gradient" to refer to this north-south SST difference. The Δy in the gradient was dropped for convenience.

The box for averaging rainfall was defined in the central bay just south of the northern box (Figure 1); the meridians bounding this box were the same as those of the northern box.

The averaged data are plotted for May–October during 1998–2005 in Figures 2–9; a corresponding description of the data is given in Tables 2–9. In all eight years, ΔT rose and fell during May–October and there were several bursts in rainfall over the central bay. Our objective was to check if an "SST event" led to a "rainfall event", and whether there were SST events not associated with rainfall events or rainfall events not associated with SST events. For this, we had to define precisely what constitutes an SST event and a rainfall event. The definitions used are as follows.

An SST event was said to occur if the following conditions were satisfied.

1. ΔT, the SST difference between the northern and southern bay, exceeded 0.75°C for at least five days. (For brevity, we use "ΔT exceeded 0.75°C" to mean $\Delta T \geq 0.75^{\circ}$C.)

2. A break of no more than one day in ΔT (i. e., $\Delta T < 0.75^{\circ}$C) was permitted. The SST event ended with the first break exceeding one day. An example of an SST event with a one-day break is Event 1 in 2003 (Table 7 and Figure 7). Event 3 in 2001 (Table 5 and Figure 5) is an example of an SST event that would have lasted longer had it not been for the two-day break during 6–7 September.

3. No break was permitted within the first three days of the event, i. e., $\Delta T \geq 0.75^{\circ}$C was a necessary condition for the first three days of an SST event.

4. Multiple breaks ($\Delta T < 0.75^{\circ}$C) were permitted, provided no break exceeded one day.

5. Multiple SST "events" associated with a single rainfall event (see definition below) were not considered separate SST events. There was only one such case, Event 2 in 1999, with three SST "events" encompassing a single rainfall event. The second and third SST "events" were not considered separate events (Table 3 and Figure 3) because it was not possible to assign multiple start and end dates to a single "event".

A rainfall event was more difficult to define because rainfall is not as continuous as SST: the rainfall graph is more noisy, and rainfall "events", as can be seen in any of the Figures 2–9, tend to include multiple bursts with gaps between them. Hence, a rainfall event was said to occur if the following conditions were satisfied.

1. Rainfall (rate) exceeded 5 mm day^{-1} for at least three days. (As with SST, we use "rainfall R exceeded 5 mm day^{-1}" to mean $R \geq 5$ mm day^{-1}.) In addition, rainfall had to exceed 20 mm day^{-1} on at least one day, or if it did not exceed 20 mm day^{-1}, then it had to exceed

10 mm day^{-1} on at least two days. There are several examples of events in which rainfall exceeded 20 mm day^{-1} on at least one day. Event 4 in 2001 (Table 5 and Figure 5) is an example of an event in which rainfall did not exceed 20 mm day^{-1} on any day. Event # in 2002 (Table 6 and Figure 6) was not considered a rainfall event because it lasted only three days and rainfall exceeded 10 mm day^{-1} on only one day; it did not exceed 20 mm day^{-1}.

2. A break (i. e., $R < 5$ mm day^{-1}) of up to three days was permitted after the first three days. The event ended with the first break exceeding three days. Most rainfall events had such breaks of 1–3 days.

3. No break was permitted within the first three days, i. e., $R \geq 5$ mm day^{-1} was necessary for the first three days. If rainfall exceeded 20 mm day^{-1} on the first or second day, however, then a one-day break was permitted within the first three days. For example, see Event 4 in 1998 (Table 2 and Figure 2): the event was deemed to start on 13 October, not 11 October, because rainfall was below the threshold on 12 October. There are many more such examples. An example of a rainfall event with a one-day break within the first three days is Event 3 in 2000. As with condition 1, this condition ensured that a day of very heavy rainfall (rainfall exceeding 20 mm day^{-1}) was treated equivalent to more than one day of lighter rainfall.

4. After the first break, continuity of the event could be ensured with $R \geq 5$ mm day^{-1}; these subsequent rainfall bursts could last less than three days, provided no intervening break exceeded three days.

5. Multiple rainfall bursts associated with a single SST event were not considered separate rainfall events. For example, consider Event 3 in 2004 (Figure 8); there are three rainfall bursts associated with this SST event, but only the first one is numbered. The other two rainfall "events" are considered to be associated with the same SST event because it is not possible to assign multiple start and end dates to one SST event.

Note that the term "breaks" in the above definitions is not synonymous with the commonly used term "monsoon breaks" (*Ramamurthy* 1969; *Krishnamurti and Bhalme* 1976; *Rao* 1976); it merely represent a fall below the threshold in either ΔT or rainfall.

3 Relationship between SST and rainfall events

The above definitions are precise, but subjective. Sensitivity of the results to a perturbation of the definitions is analysed in Section 4. In this section, we use these definitions to look for a relationship between an SST event and a rainfall event.

The analysis led to three kinds of cases (see Figures 2–9 and Tables 2–9). First, there were cases in which an SST event led a rainfall event (lag greater than 0) or the rainfall event started along with the SST event (lag 0); these cases, in which rainfall events were associated with SST events, are numbered using Arabic numerals. Second, there were cases in which a rainfall event occurred without an SST event; these "isolated rainfall events" are numbered using the Roman alphabet. Third, there were cases in which an SST event occurred without a corresponding rainfall event; thesed "isolated SST events" are tagged with the # symbol.

3.1 Cases during May–October

A total of 53 cases of SST and rainfall events occurred during May–October in 1998–2005 (Table 10). Of these 53 cases, 38 were cases in which an SST event led a rainfall event ($\sim 72\%$); three of these cases were with lag 0, i. e., the SST and rainfall events started on the same day. There were 12 isolated rainfall events ($\sim 23\%$); of these 12 cases, ΔT did exceed the threshold in five cases, but either did so lagging the rain event (Event A in 2003, for example) or was too short to constitute an SST event (Event A in 2002). Seven of these 12 cases occurred in May or October, during the onset or retreat phases of the summer monsoon. There were only three isolated SST events ($\sim 5\%$); all these events occurred in October.

The lag between SST and rainfall events (in the 38 cases observed) varied from 0–27 days (Table 10). There were only seven instances of long lags (lag exceeding, say, 10 days); five of these seven events were associated with either the onset (early May) or the retreat phase (October) of the summer monsoon.

3.2 Cases during core summer monsoon

Since all the isolated SST events, a majority of the isolated rainfall events, and a majority of rainfall events with a long lag occurred during early May and October, we considered separately the "core monsoon period" from mid-May to September. This constraint excludes the pre-onset (early May) and retreat (October) phases of the summer monsoon. The latter half of May was retained because the onset of the summer monsoon can occur during this period.

Considering only the core monsoon period from mid-May to September improved the relation between SST and rainfall events (Table 11). In Tables 2–9, these cases lie within the shorter lines (not covering the last column) in the tables; the cases in early May are listed before the first such short line and the cases in October after the second such short line.

The total number of cases during the core monsoon period was 33. Of these 33 cases, an SST event was followed by a rainfall event (including two cases of lag 0) in 28 cases ($\sim 85\%$). There were five isolated rainfall events ($\sim 15\%$); of these five cases, ΔT did exceed the threshold in one case, but the duration was less than the required five days and hence did not constitute an SST event (Event A in 2002). In the core monsoon period, there was no isolated SST event.

The longest lag between an SST event and the associated rainfall event was 18 days (associated with the late onset in 2002 (*Flatau et al* 2003)); there was one case each with lag 12 (September 2000) and 10 (associated with the onset in 1998). For the events during the core monsoon period, a lag histogram peaked at seven days (Figure 10): of the 28 cases, 21 (75%) had a lag of 0–7 days (Table 11 and Figure 10).

Thus, there was a stronger link between an SST event and a rain event during the core monsoon period than during early May and October.

4 Sensitivity experiments

The definitions used to identify SST and rain events led to a significant relationship between them. The subjectivity of the definitions, however, demands a sensitivity analysis. What happens to this relationship if one or more elements of the definition is perturbed? We carried out a series of "experiments" to test the sensitivity of the relationship between SST and rain events to the definition of these events. The sensitivity analysis was restricted to the core monsoon period. A summary of the results of these sensitivity experiments is given in Table 12; the definitions given in Section 2 defined the control experiment ("C" in the table).

4.1 Sensitivity to ΔT threshold

The most crucial element of the definition of an SST event is the threshold used for ΔT. For the threshold to be useful, ΔT has to rise above and fall below it. Since the northern bay tends to be warmer than the southern bay, setting the threshold too low would result in ΔT exceeding the threshold on most days, making it impossible to define an SST event; a low threshold would also bring ΔT within the range of error in TMI SST (see Section 4.7). Setting the threshold too high would result in a decrease in the number of SST events (and therefore to an increase in the number of isolated rainfall events) or in longer lags. The number of days for which different ΔT critera were fulfilled is listed in Table 13. We tested the sensitivity of the ΔT-rainfall relationship during the core monsoon period to a 0.25°C perturation of the threshold ΔT.

For a 0.5°C threshold (Experiment 1 in Table 12), the total number of events decreased from 33 to 30. There were 25 SST events associated with rainfall events, a decrease of just 1.1% from the control case. The lag increased marginally, with 60% of the events having a lag of a week or less; there were no events, however, with zero lag (Figure 10). There was one isolated SST event.

For a 1°C threshold (Experiment 2 in Table 12), the total number of events increased to 35, but there were only 21 SST events that led a rainfall event (60%), implying a far lower chance that a rainfall event was associated with an SST event. There were far more isolated rainfall events and one isolated SST event.

4.2 Sensitivity to duration of SST event

Would a decrease in the minimum number of days that ΔT had to exceed the threshold (see condition 1 in the definition) improve the relation for the 1°C threshold? We tested this possibility in Experiment 3, in which the minimum duration was lowered to three days. The statistics did not, however, improve much (Table 12).

4.3 Sensitivity to rainfall threshold

In Experiment 4 (Table 12), we tested the sensitivity to an increase in the rainfall threshold to 10 mm day^{-1}. Some of the 3-day breaks for the 5 mm day^{-1} threshold were now longer, leading to an increase in the number of rainfall events. Hence, the percentage of SST events that led a rainfall event decreased to $\sim$ 64, there being a signficant increase in the percentage of isolated SST events.

4.4 Sensitivity to breaks

Conditions 2–4 in the definition of SST and rain events concern breaks, i. e., there are days within an event on which the SST or rainfall falls below the threshold.

The conditions for rainfall breaks were necessary because the rainfall time series is noisy: it does not rain continously during an event and cannot be expected to do so. Even a composite of SST and rainfall events (for a given lag) shows that rainfall occurs in bursts; the corresponding variation in ΔT is much less (Figure 11). When looking at a spatial subset of a physical system like (say) a depression, there can be days on which it does not rain over part of the area covered by the system. Yet, there is a continuity in the physical system that is apparent on the synoptic scale. Permitting "breaks" within an event allows this continuity to manifest even at a sub-synoptic scale like the box considered in our analysis. On the sub-synoptic scale, rainfall may break for one or more days: we allowed a break of up to three successive days (condition 2). Breaks exceeding three days terminated a rain event. The number of such breaks that occurred during 1998–2005 is listed in Table 14. The number of breaks that exceeded three days (implying a multiple event as indicated in condition 5) was very small in comparison to the number of one-day, two-day, and three-day breaks. Hence, a break in rainfall of up to three days turned out to be statistically the most appropriate. A stricter constraint, say not permitting breaks greater than three days, would result in more multiple rainfall events or isolated rainfall events.

SST not only influences rainfall and therefore rain events as shown earlier, but it is also influenced by rainfall. SST tends to decrease when convection occurs. Convection in the central bay is often accompanied by convection in the northern bay, implying that rainfall over the central bay tends to reduce the SST in the northern box and therefore reduce ΔT. Hence, ΔT can drop below the threshold when convection occurs. This response of ΔT to convection necessitated the inclusion of one-day breaks (condition 2) in the definition of an SST event. During 1998–2005, there were eight one-day breaks in SST events, three of them occurring in 2001 and four in 2003. Of these eight one-day breaks, only four (two during Event 4 in 2001 and one each during Event 1 in 2003 and Event 2 in 2004) were critical in the sense that these would not have been classified as SST events if breaks were not permitted. Eliminating one-day breaks from the definition of an SST event did not, however, change the statistics much: the total number of SST and rainfall events increased to 34, the number of SST events leading rainfall events falling to 26. Thus, the percentage of events in which rainfall lagged an SST event fell to 76.5% (down from 84.8% in the control case). During all these eight one-day breaks (and during the two two-day breaks during the multiple events in 1999), ΔT exceeded 0.5°C. Hence, for a ΔT threshold of 0.5°C, the condition on breaks is not needed.

4.5 Does the southern bay SST matter?

A glance at the SST variation (top panel in Figures 2–9) shows that the *intraseasonal* SST variation was much greater in the northern bay than in the southern bay. The northern bay SST varied by as much as 2°C within a few days; for example, note the rapid rise in SST from 27.9°C on 12 July to 30.55°C on 26 July in 1998. In the southern bay, the variation over a similar time scale rarely exceeded 1°C.

The major cooling in the south took place over a longer time scale, during May–July, the period over which the SMC strengthens over the southern bay (*Vinayachandran et al* 1999; *Shankar et al* 2002), but this cooling also showed considerable interannual variation. Examples of gradual cooling were seen in 1998 and 2001. There were years like 1999, however, in which the southern bay was cooler than 29°C in May itself. 2003 presented another pathological case: the SST decreased rapidly in May, but then increased again till mid-June, with another cooling spell lasting till the end of June. This warm southern bay led to 2003 being the year for which ΔT was lowest during the eight-year period (Table 13). Altimeter data show such interannual and intraseasonal variations are to be expected in the SMC (*Shankar et al* 2002).

The northern bay also cooled gradually from May to July, the intraseasonal variations being superimposed on this gradual cooling. SST in the north, however, could recover almost to the values seen in May; this never happened in the southern bay.

So the question is whether the southern bay SST matters? Do we need to invoke the SST difference, or can we link the rainfall events to the warming and cooling events in the northern bay alone?

We tested the sensitivity of the ΔT-rainfall relationship to a switch from the $\Delta T \geq 0.75^{\circ}$C criterion to a criterion based on the northern bay SST, T_N, alone. The rest of the definition — with respect to duration and breaks — remained the same: the five conditions for ΔT were applied to T_N.

Using a threshold of 29°C for T_N (Experiment 5 in Table 12) yielded results similar to that with a ΔT threshold of 0.75°C. The number of events, however, changed. Some rainfall events that were isolated according to the ΔT criterion were associated with SST events defined according to a similar criterion for T_N. An example is Event A in 1999. This led to an increase in the number of events. The larger number of days on which the T_N criterion was fulfilled (Table 13) led to some SST events that were distinct according to the ΔT criterion merging into a single SST event when the T_N criterion was used. For example, T_N exceeded 29°C from 1 May to 29 July; ΔT, however, rose above and fell below the 0.75°C threshold during this period. Hence, with T_N used to define SST events, Events 2 and 3 in Table 6 could not be classified as separate events according to condition 5. This led to a decrease in the number of events.

With T_N as the criterion for defining SST events, the number of events decreased from 33 to 25 (Table 12), but the percentage of SST events that led a rainfall event, or the lag (Figure 10) did not change much. The number of days on which T_N exceeded 29°C was, however, more comparable to the $\Delta T \geq 0.5^\circ$C criterion rather than the $\Delta T \geq 0.75^\circ$C criterion (Table 13).

A T_N threshold of 29.25°C (Experiment 6) was more like a ΔT threshold of 0.75°C with respect to the number of days on which the condition was fulfilled (Table 13), but the T_N-rainfall relation was far worse ($\sim$ 61%) than in Experiment 5.

4.6 Sensitivity to the domain of averaging

The domain of averaging also mattered. Most critical was the box over which the southern bay SST was averaged. It was essential to confine the box to the regime of the SMC. As altimeter data and model simulations show, the SMC shifts westward through the summer monsoon along with the Rossby wave that constitutes its front (McCreary *et al* 1993; *Vinayachandran et al* 1999; *Shankar et al* 2002). Extending the eastern limit eastwards from 88°E to 90°E (Experiment 7 in Table 12) resulted in ΔT decreasing just enough to ensure that Event 4 in 2001 and Events 3 and 7 in 2002 could not be classified as SST events. The percentage of SST events that led a rainfall event fell to $\sim$ 75.

Interannual and intraseasonal variability of the SMC may therefore be important for the intraseasonal variations associated with the Indian summer monsoon, but little is yet known of its intraseasonal dynamics.

4.7 Reliability of the SST observations

Bhat et al (2004) showed that TMI underestimates SST when the winds are strong or when deep convective clouds are present (low OLR). The TMI SST was shown to be almost 0.6°C less than the SST measured by a buoy. How reliable then is the SST difference that has been estimated? We examined each of the cases in Table 10 for the possibility that the ΔT itself was a result of such TMI errors. The wind data used were from QuikSCAT (for 2000–2005) and TMI (for 1998–1999); the OLR data were from NOAA (National Oceanic and Atmospheric Administration) (see Table 1).

The tendency of TMI to underestimate SST is applicable to both the boxes used to define ΔT, but a TMI underestimate of SST in the northern box SST will lead to an underestimate of ΔT, which will not affect the statistics presented for the ΔT-rainfall relationship. The southern box SST, however, is crucial because an increase in the southern SST (to compensate for a potential TMI error) will decrease ΔT: the TMI estimate of ΔT will be greater than the "actual" ΔT, rendering the threshold an artefact of TMI errors and therefore meaningless.

Hence, in checking for the impact of possible errors in TMI, we considered periods when the wind speed exceeded 10 m s^{-1} or OLR fell below 175 W m^{-2}, a threshold for deep convection (*Bhat et al* 2004), in the southern box. We checked each SST event to see if it would fail to qualify as an event if a potential error of 0.5–0.6°C was attributed to the southern bay SST. We retained only those cases in which the winds were strong or OLR was low either over a large fraction of the SST event or, for cases with short lags, at the beginning of the SST event. If the winds were strong or OLR was low over a few days in the middle of the event, then the event was listed only if the SST in the southern bay dropped only during the period of strong winds or low OLR (and maybe for a few days after the winds/OLR peaked). The assumption here was that it was improbable that the impact of TMI errors could be physically random and affect the SST only on some of the days with strong winds or low OLR. Hence, cases wherein the effect of strong winds or low OLR was felt in between an SST event were discarded because the SST event itself then did not owe its existence to an error in TMI SST. This left us with seven cases in which an SST event led a rainfall event (Table 15). In only one of these seven cases (Event 2 in 2000; see Figure 4), however, was there a possibility of the SST event being caused by a possible underestimate of the SST by TMI. In all other cases, the SST difference showed no clear relationship to either winds or OLR. ΔT often increased even after the wind speed fell below the *Bhat et al* (2004) threshold (for example, consider Event 3 in 1998; see remarks column in Table 15 for more such cases) or when the OLR was high (Event 2 in 2005), or showed no clear relation to wind speed (Event 4 in 2002).

Note, however, that SST *is* expected to respond to an increase in wind speed and to the decrease in shortwave radiation due to deep convective clouds (*Rao et al* 1985; *Sanilkumar et al* 1994). What is difficult is the separation between an actual decrease in SST owing to strong winds and deep convective clouds and the TMI tendency to underestimate SST under these conditions. This separation demands a careful study with much more data than was available to *Bhat et al* (2004), which however, is beyond the scope of this paper. Nevertheless, the data presented imply that the relation observed between SST gradient and convection is not due to a possible underestimate of SST by TMI.

5 Discussion

We have shown that a positive meridional gradient of SST in the Bay of Bengal tends to precede a rainfall event in the central bay. The SST gradient was based on the SST difference (ΔT) between two boxes in the northern and southern bay (Figure 1), ΔT having to exceed 0.75°C for five days to constitute an SST event. Rainfall events tended to lag an SST event, with the lag histogram peaking at one week. The greater contribution to ΔT came from the northern bay, which showed intraseasonal temperature variations approaching $\sim 2^{\circ}$C. The box in the southern bay encompassed the "cold-tongue" regime of the SMC (*Shankar et al* 2002; *Joseph et al* 2005; *Rao et al* 2006b).

5.1 Interpretation of the sensitivity experiments

The statistics of the relation between SST and rain events were a function of the period of analysis. In comparison to the period May–October, there was a higher percentage of cases during the core monsoon period in which SST events were followed by rainfall events and there was no case of an SST event occurring in isolation. The lag between an SST event and the rain event following it was also shorter during the core monsoon period. Hence, this relationship between SST gradient and rainfall is more applicable after the seasonal ITCZ is in its "summer monsoon phase", not when it is in the transition phase between the monsoons.

The sensitivity analysis, in which the conditions constituting the definitions of SST and rain events were perturbed, needs to be interpreted carefully. The relation between SST gradient and rainfall *is* sensitive to the definition of SST and rain events. The analysis showed that the control conditions (see Section 2) yielded the best relation between SST and rain events, implying that these definitions picked the physically optimum parameters from the range of possibilities.

5.2 The ΔT and T_N thresholds

The data suggested that the northern bay SST, T_N, could be used as the criterion in lieu of SST difference. The most appropriate T_N threshold (for rainfall events) that emerged from the analysis was 29°C, which is 1–1.5°C higher than the deep-convection SST threshold for tropical oceans (*Gadgil et al* 1984; *Graham and Barnett* 1987; *Sud et al* 1999). Even a threshold of 28.75°C did not yield results comparable to that for the 29°C criterion because the former threshold was exceeded on over 77% of the days during the core monsoon period (Table 13). Since variations in the northern bay SST contributed more to ΔT than did variations in southern bay SST, we hypothesise that the excess heating ($\sim 1^\circ$C above the threshold for deep convection) required in the northern bay to trigger convection is because *this excess in SST* is what is required *to establish the critical SST gradient.* In other words, the $T_N \geq 29^\circ$C threshold is actually a proxy or synonym for the $\Delta T \geq 0.75^\circ$C threshold (but it is not as good).

5.3 Cause or effect?

As noted earlier, the relation between SST and rainfall is two-way: rainfall (or, more precisely, clouds) affects SST as much as SST affects rainfall. It has been shown earlier that SST in the northern bay falls about one week preceding a monsoon break (*Harrison and Vecchi* 2001), the SST (and therefore ΔT) rising again after the rain ceases. Also, a glance at Figures 2–9 reveals that rainfall over the central bay can persist in the absence of an SST gradient: once rainfall occurred, it could persist even if the gradient weakened (fell below threshold) or even became negative at times (as during Event 3 in 2000). Some of the northern-bay convection "spills" over into the central-bay box; if convection persists in the northern bay, it tends to persist in the central bay too. Numerical models suggest that persistence of convection over the northern bay and adjoining land is due to the anchoring of the TCZ in the surface trough and that the duration depends on hydrological processes (*Nanjundiah et al* 1992; *Gadgil* 2003).

A histogram of the lag between the cessation of a rain event and the start of the succeeding SST event is not very different from that for the lag between an SST event and the associated rain event (Figure 10). Hence, a natural question is whether it is the SST gradient that leads a rain event or it is the cessation of a rain event that leads to an increase in T_N and therefore to an SST event. Is the SST gradient the cause of the rain event, or vice versa?

The answer to this question is not easy because SST gradient and rainfall are interdependent and both oscillate through the summer monsoon. Nevertheless, the data show that a rainfall event that lagged an SST event tended to be longer than an isolated rainfall event (Figure 12). Of the five isolated rain events during the core monsoon period, one (Event B in 2003) was 10 days long; the other four events had a duration of 3–5 days. Of the 28 rain events that lagged an SST event, however, 16 ($\sim$ 57%) had a duration exceeding 14 days and only five ($\sim$ 18%) had a duration of a week or less. Since there is no *a priori* reason to expect such a difference, there seems to be a statistical basis for the hypothesis linking a meridional gradient of SST and convection in the bay.

Is there a physical basis for such a relationship? Numerical models suggest that accurate and interactive SST is needed to simulate accurately the slow northward propagations of the TCZ across the Bay of Bengal (*Srinivasan et al* 1993). *Vecchi and Harrison* (2002) invoked the hypothesis that the increase (decrease) in SST in the northern (southern) bay sets up a meridional pressure gradient (with lower pressure in the north), which drives a westerly wind that is in geostrophic balance. This hypothesis is in accordance with that of a geostrophic monsoon advanced by *Xie and Saiki* (1999). Numerical models, however, suggest that the response of the tropical atmosphere to SST gradients is a "heat-low" type of circulation (*Schneider and Lindzen* 1976), in which the circulation occurs within the lower 2–3 km of the troposphere: mid-tropospheric heating due to latent-heat release during deep convection is needed to generate a circulation extending through the troposphere (*Held and Hou* 1980).

Recent research on cumulus parameterisation schemes suggests, however, that shallow convection is a necessary precursor to deep convection in the atmosphere; shallow convection moistens the lower atmosphere, paving the way for deep convection (J. Srinivasan, personal commun ication, 2007). Hence, our hypothesis is that the establishment of a meridonal gradient of SST in the bay, associated with which is a meridional pressure gradient, leads to a geostrophic westerly flow into the central bay. The associated cyclonic vorticity causes shallow convection, which leads to deep convection. The deep convection, in turn, strengthens the westerly flow into the bay (*Joseph and Sijikumar* 2004), creating, in conjunction with hydrological processes (*Nanjundiah et al* 1992), a positive feedback cycle that sustains convection even as SST falls in the northern bay.

5.4 Interannual variability

In spite of the strong relatioan between SST gradient and rainfall over the eight years studied, there ws considerable difference in the variation of SST in the northern and southern bay, and therefore in ΔT, among the eight summer monsoons. The year that was most different from the others was 2002. In 2002, the ΔT and T_N thresholds were exceeded on more days than in other years (Table 13), there were far fewer breaks within rain events (Table 14), and the duration of rain events was the least during the eight years. Rain events tended to occur in shorter bursts in 2002 in comparison to other years, the longest event during mid-May–September 2002 lasting 10 days. The summer monsoon of 2002 recorded one of the lowest rainfalls ever over India (*Gadgil et al* 2002), but an analysis of the possible association of the meridional SST gradient in the bay with this drought is beyond the scope of this paper.

6 Conclusions

The results of this study support the idea that a meridional SST gradient is an important link in the process leading to convection over the bay, which, in turn, seems to be connected to the monsoon's active-break cycles (*Joseph and Sijikumar* 2004). In the absence of such a gradient, rainfall events tend to be short-lived.

Convection bursts over the central bay can be expected to occur within a week of the SST difference ΔT between the northern and southern bay exceeding 0.75°C. Occasionally, these rainfall events occur simultaneously with the SST difference exceeding the threshold (Figure 10), making it difficult to use it as a solitary predictor. It is in such cases that a lower threshold ($\Delta T \geq 0.5^\circ$C) or the northern bay SST ($T_N \geq 29^\circ$C) serve as useful additional criteria. These criteria tend to increase the lag between SST exceeding the threshold and the rainfall event (Figure 10), making prediction more viable.

Hence, in conclusion, a rainfall burst over the central bay can be expected to occur soon after the northern bay SST exceeds 29°C or the SST difference between the northern and southern bay exceeds 0.4°C; the event is extremely likely to occur within a week of the SST difference between the northern and southern bay exceeding 0.75°C, there being a $\sim 85\%$ chance of this based on the percentage of such events during mid-May to September.

The focus of this study has been on SST and convection over the bay, but there is a broader underlying goal. The convection over the bay is often associated with formation of low-pressure systems which subsequently move westward or northwestward from the northern bay, bring precipitation to the Indian subcontinent (*Goswami* 1987; *Mooley and Shukla* 1989). Revival of convection over the bay (and associated formation of low-pressure systems) can therefore be a precursor to precipitation over India (*Gadgil* 2003). ΔT has therefore the potential to evolve into a tool for prediction of behaviour of the monsoon over the Indian subcontinent about a week in advance. Our results reported here therefore suggest a long-term research agenda to evolve a tool for monsoon prediction a week in advance.

Acknowledgements

We thank the referee, G. A. Vecchi, for motivating a formal sensitivity analysis, Sulochana Gadgil and G. S. Bhat for alerting us to the potential impact of TMI errors on the southern bay SST, and J. Srinivasan for pointing to the possibility of SST being the effect of (the end of) a rain event, rather than the SST gradient being the cause of rain events. JS's criticism led to most of Section 5.3. The critical comments of P. N. Vinayachandran and Ravi Nanjundiah and discussions with S. S. C. Shenoi and F. Durand also helped us hone our arguments. Ferret and GMT were used extensively for analysis and plotting the figures; G. S. Michael helped with the figures, and he, Pramila Gawas, and Pallavi Shet put together the data sets used in this paper. This work was supported by the Department of Ocean Development, New Delhi under their INDOMOD programme. This is NIO contribution 4258.

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Tables

Variable	Source	Resolution	URL
SST	TMI	0.25°	ftp://ftp.ssmi.com/tmi/bmaps_v03/
Rainfall	GPCP	1°	ftp://precip.gsfc.nasa.gov/pub/1dd/1DD_doc/
Wind	TMI (1998–1999)	0.25°	ftp://ftp.ssmi.com/tmi/bmaps_v03/
	QuikSCAT (2000–2005)	0.5°	http://airsea.jpl.nasa.gov/DATA/QUIKSCAT/wind/
OLR	NOAA	2.5°	ftp://ftp.cdc.noaa.gov/Datasets/interp_OLR/

Table 1: Data used, their spatial resolutions, and sources on the Internet.

	ΔT_{beg}	ΔT_{end}	R_{beg}	R_{end}	$R > 10$	$R > 20$	Lag	Remarks
A	17 May	18 May	17 May	19 May	17 May	17 May	0	2-day SST, 3-day rain event, but with lag 0.
1	30 May	3 Jul	9 Jun	11 Jul	9 Jun	9 Jun	10	Isolated convection on 1 June (lag 2), but no rain event. Persistent convection in northern and central bay makes rain event long.
2	19 Jul	11 Aug	26 Jul	15 Aug	26 Jul	31 Jul	7	Persistent convection in northern and central bay makes rain event long. Convection over northern bay continues beyond 15 August.
3	19 Aug	26 Aug	23 Aug	16 Sep	24 Aug	25 Aug	4	Repeated bursts of convection with two 3-day breaks during 27–29 August and 3–5 September.
4	16 Sep	20 Oct	13 Oct	19 Oct	13 Oct	—	27	Weak, 1-day convection bursts on 26 September and 8 and 11 October.
B	28 Oct	31 Oct	26 Oct	31 Oct	27 Oct	28 Oct	—	

Table 2: Catalogue of SST and rainfall events during **1998**. Event number is in column 1. Arabic numerals are used when an SST event leads a rainfall event; the Roman alphabet is used when a rainfall event is not associated with an SST event leading it. The symbol # is used when an SST event occurs, but there is no associated rainfall event (see Table 6 for an example). The start and end dates for SST (rainfall) events are in columns 3 (5) and 4 (6). The first date on which rainfall exceeds 10 mm day^{-1} (20 mm day^{-1}) during a rainfall event is listed in column 7 (8). Column 9 contains additional descriptive remarks. The two short lines (not extending into the last column) are used to separate events in early May and October from the core monsoon period; events falling in the core monsoon period are contained between these short lines (see accompanying text in Section 3.2). See Figure 2 for the corresponding plots.

	ΔT_{beg}	ΔT_{end}	R_{beg}	R_{end}	$R > 10$	$R > 20$	Lag	Remarks
1	1 May	21 Jun	18 May	26 Jun	19 May	19 May	17	Isolated convection bursts occur intermittently: 1 May (lag 0) and 9–11 May. Persistent convection in northern and central bay makes rain event long.
A	5 Jul	5 Jul	3 Jul	6 Jul	3 Jul	3 Jul	—	$\Delta T \sim 0.5$–0.6.
2	8 Jul	12 Jul	12 Jul	7 Aug	13 Jul	13 Jul	4	$\Delta T > 0.75$ often till 5 August, but drops each time there is a burst of convection. Persistent convection in northern and central bay makes rain event long.
B	—	—	14 Aug	18 Aug	14 Aug	16 Aug	—	—
3	23 Aug	28 Aug	25 Aug	13 Sep	25 Aug	29 Aug	2	$\Delta T \not> 0.75$ after 28 August owing to repeated bursts of convection. Persistent convection in central bay (repeated bursts in northern bay) makes rain event long.
4	28 Sep	21 Oct	15 Oct	17 Oct	15 Oct	15 Oct	17	—
C	—	—	26 Oct	28 Oct	26 Oct	26 Oct	—	ΔT increases after earlier event (4), but does not cross 0.75. $\Delta T = 0.59$ when convection occurs.

Table 3: As in Table 2, but for **1999**. See Figure 3 for the corresponding plots.

	ΔT_{beg}	ΔT_{end}	R_{beg}	R_{end}	$R > 10$	$R > 20$	Lag	Remarks
1	12 May	20 May	17 May	24 May	17 May	18 May	5	Convection occurs on 13 May, but stops again till 17 May.
2	1 Jun	8 Jun	4 Jun	18 Jun	4 Jun	4 Jun	3	Persistent convection in northern and central bay makes rain event long.
A	—	—	25 Jun	27 Jun	25 Jun	25 Jun	—	ΔT 0.52 on 22 June.
3	27 Jun	17 Jul	6 Jul	26 Jul	6 Jul	6 Jul	9	Persistent convection in northern and central bay makes rain event long.
4	30 Jul	12 Aug	4 Aug	11 Aug	4 Aug	4 Aug	5	—
5	18 Aug	30 Aug	23 Aug	13 Sep	23 Aug	27 Aug	5	Weak convection burst during 16–18 August. Another burst during 10–13 September.
6	16 Sep	27 Oct	28 Sep	1 Oct	28 Sep	28 Sep	12	Two more convection bursts during 10–14 and 24–26 October.

Table 4: As in Table 2, but for **2000**. See Figure 4 for the corresponding plots.

	ΔT_{beg}	ΔT_{end}	R_{beg}	R_{end}	$R > 10$	$R > 20$	Lag	Remarks
A	—	—	11 May	13 May	9 May	13 May	—	$\Delta T \sim 0$.
1	16 May	12 Jun	22 May	2 Jun	24 May	24 May	6	Strong convection during 8 June to 18 July in northern and central bay. ΔT drops after 11 June as convection picks up, increasing (but not reaching 1) between bursts. $\Delta T < 0$ often during this period. The rain spell from 8 June to 18 July is continuous; there is a break from 3–7 June separating these two events.
2	29 Jul	21 Aug	1 Aug	19 Aug	1 Aug	2 Aug	3	Persistent convection in northern and central bay makes rain event long.
3	26 Aug	5 Sep	26 Aug	29 Aug	26 Aug	27 Aug	0	ΔT does not drop below 0.54 after previous event. ΔT = 0.60 on 1 September, but exceeds 1 again during 2–5 September. High ΔT persists till 16 September.
4	8 Sep	16 Sep	15 Sep	19 Sep	15 Sep	—	7	This appears as a continuation of the earlier event (3).
5	21 Sep	25 Oct	26 Sep	29 Sep	29 Sep	29 Sep	5	Several convection bursts, the last one following the ΔT fall below 1 on 24 October.

Table 5: As in Table 2, but for **2001**. See Figure 5 for the corresponding plots.

	ΔT_{beg}	ΔT_{end}	R_{beg}	R_{end}	$R > 10$	$R > 20$	Lag	Remarks
1	11 May	24 May	11 May	18 May	11 May	11 May	0	—
2	31 May	27 Jun	18 Jun	25 Jun	18 Jun	18 Jun	18	Aborted convection bursts during 5–6 June (lag 5) and 14–15 June (lag 14).
3	4 Jul	9 Jul	7 Jul	16 Jul	7 Jul	7 Jul	3	Short gap between events 3 and 4.
4	13 Jul	22 Jul	22 Jul	30 Jul	23 Jul	23 Jul	9	—
5	28 Jul	15 Aug	4 Aug	15 Aug	4 Aug	11 Aug	7	Aborted 2-day convection burst during 29–30 July (lag 1).
A	20 Aug	22 Aug	20 Aug	22 Aug	20 Aug	21 Aug	0	3-day event in ΔT and rainfall (lag 0).
6	4 Sep	10 Sep	5 Sep	10 Sep	4 Sep	4 Sep	1	—
7	15 Sep	27 Sep	17 Sep	26 Sep	18 Sep	18 Sep	2	Another convection burst during 23–27 September.
8	6 Oct	14 Oct	7 Oct	15 Oct	9 Oct	13 Oct	1	—
#	21 Oct	26 Oct	—	—	24 Oct	—	—	Rain exceeds 10 mm day^{-1} only on one of three days; hence, this is not considered a rain event. $\Delta T > 1$ only on 22–23 October.

Table 6: As in Table 2, but for **2002**. See Figure 6 for the corresponding plots.

	ΔT_{beg}	ΔT_{end}	R_{beg}	R_{end}	$R > 10$	$R > 20$	Lag	Remarks
A	11 May	6 Jun	10 May	19 May	12 May	12 May	—	ΔT 0.51 on 10 May, crosses 0.75 only on 11 May, a day after convection occurs. Another convection burst occurs during 2–6 June.
B	—	—	15 Jun	24 Jun	16 Jun	16 Jun	—	$\Delta T < 0.5$; warm SMC (southern) box.
1	13 Jul	25 Jul	13 Jul	7 Aug	13 Jul	13 Jul	0	$\Delta T > 0.75$ during 13–15 July, 17 July, and during 19–25 July. There are two 1-day breaks in this ΔT event during 16 and 18 July. $\Delta T > 1$ only during 15 July and 22–25 July. Several convection bursts during this event. Persistent convection in northern and central bay makes rain event long.
2	16 Aug	27 Aug	20 Aug	15 Sep	21 Aug	21 Aug	4	Convection weakens and picks up often during 20 August to 5 September. Bursts during 20–28 August and 3–5 September.
3	14 Sep	8 Oct	5 Oct	8 Oct	6 Oct	7 Oct	21	Earlier convection event (2) lasts till this ΔT event. Large lag owing to "overlap" with earlier event.
C	—	—	14 Oct	17 Oct	14 Oct	14 Oct	—	Convection revives after a break following previous burst (3) triggered by high ΔT.
#	21 Oct	26 Oct	—	—	—	—	—	Weak rain even on 27 October. $\Delta T > 1$ only on 22 October.

Table 7: As in Table 2, but for **2003**. See Figure 7 for the corresponding plots.

	ΔT_{beg}	ΔT_{end}	R_{beg}	R_{end}	$R > 10$	$R > 20$	Lag	Remarks
1	7 May	18 May	14 May	19 May	14 May	15 May	7	—
2	24 May	12 Jun	31 May	2 Jun	1 Jun	1 Jun	7	Big convection burst during 10–20 June.
3	27 Jun	28 Jul	29 Jun	3 Jul	29 Jun	30 Jun	2	ΔT high throughout July, leading to repeated bursts of convection: 11–15 July and 20 July to 23 August. Persistent convection in northern and central bay makes rain event long.
4	31 Aug	11 Sep	7 Sep	18 Sep	8 Sep	9 Sep	7	—
5	26 Sep	6 Oct	1 Oct	4 Oct	1 Oct	2 Oct	5	—
A	13 Oct	14 Oct	12 Oct	17 Oct	12 Oct	12 Oct	—	ΔT high (> 0.7) from 11 October, reaches 0.81 on 13 October, but collapses owing to convection burst.

Table 8: As in Table 2, but for **2004**. See Figure 8 for the corresponding plots.

	ΔT_{beg}	ΔT_{end}	R_{beg}	R_{end}	$R > 10$	$R > 20$	Lag	Remarks
1	12 May	27 Jun	31 May	19 Jun	31 May	1 Jun	19	Isolated convection bursts on 13 and 25 May. 4-day break in convection during 20–23 June, followed by another burst during 30 June to 8 July. $\Delta T < 0.75$ after 27 June. High winds and low OLR in the northern bay. Persistent convection in northern and central bay makes rain event long.
2	12 Jul	29 Jul	21 Jul	19 Aug	21 Jul	21 Jul	9	Repeated bursts of convection. There is a break in convection during 11–16 August, but weak convection occurs on 12 and 14 August; hence, this is considered a single event. Persistent convection in northern and central bay makes rain event long.
3	31 Aug	18 Sep	8 Sep	19 Sep	8 Sep	8 Sep	8	—
#	5 Oct	31 Oct	—	—	11 Oct	27 Oct	—	No sustained convection, but three 2-day bursts.

Table 9: As in Table 2, but for **2005**. See Figure 9 for the corresponding plots.

Lag	1998	1999	2000	2001	2002	2003	2004	2005	Total	Remarks
0	—	—	—	1	1	1	—	—	3	1 in May
1	—	—	—	—	2	—	—	—	2	Sep, Oct
2	—	1	—	—	1	—	1	—	3	1 in Sep
3	—	—	1	1	1	—	—	—	3	—
4	1	1	—	—	—	1	—	—	3	—
5	—	—	3	1	—	—	1	—	5	1 in May, 1 in Sep
6	—	—	—	1	—	—	—	—	1	May–Jun
7	1	—	—	1	1	—	3	—	6	1 each in May, Sep
8	—	—	—	—	—	—	—	1	1	—
9	—	—	1	—	1	—	—	1	3	—
10	1	—	—	—	—	—	—	—	1	—
12	—	—	1	—	—	—	—	—	1	Sep
17	—	2	—	—	—	—	—	—	2	Early May, early Oct
18	—	—	—	—	1	—	—	—	1	End May (onset)
19	—	—	—	—	—	—	—	1	1	May
21	—	—	—	—	—	1	—	—	1	Late Sep, early Oct
27	1	—	—	—	—	—	—	—	1	Sep–Oct
Total	4	4	6	5	8	3	5	3	**38**	$\mathbf{\frac{38}{53}} \sim \mathbf{72}\%$
A	2	3	1	1	1	3	1	—	**12**	Rain event without SST event. 3 events in May (1998, 2001, and 2003) and 4 in October (1998, 1999, 2003, and 2004). 2 events have lag 0. $\mathbf{\frac{12}{53}} \sim \mathbf{23}\%$.
#	—	—	—	—	1	1	—	1	**3**	SST event, but no rain event. All events in Oct. $\mathbf{\frac{3}{53}} \sim \mathbf{5}\%$.
Total	6	7	7	6	10	7	6	4	**53**	

Table 10: Summary of SST and rainfall events during May–October. The events are tabulated by year as function of lag (SST leading). Column 1 contains the lag. The "A" after the horizontal rule represents isolated rainfall events. The symbol # represents isolated SST events. The numbers in columns 2–9 (for 1998–2005) list the number of events in each year corresponding to each value of lag; a "—" indicates no event with the given lag occurring in that year. Column 10 contains the number of events during 1998–2005 for each lag. Column 11 contains some descriptive remarks. The total for each year is listed twice. The first total is for the SST events leading a rainfall event. The second total is for all events during the year. A total of 53 events were observed during May–October, of which 38 (∼72%) were SST events leading rainfall events, 12 (∼23%) were isolated rainfall events, and 3 (∼5%) were isolated SST events.

Lag	1998	1999	2000	2001	2002	2003	2004	2005	Total	Remarks
0	—	—	—	1	—	1	—	—	2	—
1	—	—	—	—	1	—	—	—	1	Sep
2	—	1	—	—	1	—	1	—	3	1 in Sep
3	—	—	1	1	1	—	—	—	3	—
4	1	1	—	—	—	1	—	—	3	—
5	—	—	2	1	—	—	—	—	3	1 in Sep
6	—	—	—	1	—	—	—	—	1	May–Jun
7	1	—	—	1	1	—	2	—	5	1 in Sep
8	—	—	—	—	—	—	—	1	1	Sep
9	—	—	1	—	1	—	—	1	3	
10	1	—	—	—	—	—	—	—	1	Onset
12	—	—	1	—	—	—	—	—	1	Sep
18	—	—	—	—	1	—	—	—	1	Onset
Total	3	2	5	5	6	2	3	2	**28**	$\mathbf{\frac{28}{33}} \sim \mathbf{85\%}$
A	—	2	1	—	1	1	—	—	**5**	Rain event without SST event. 1 event has lag 0. $\mathbf{\frac{5}{33}} \sim \mathbf{15\%}$.
#	—	—	—	—	—	—	—	—	**0**	SST event, but no rain event.
Total	3	4	6	5	7	3	3	2	**33**	—

Table 11: As in Table 10, but for the core monsoon period (mid-May to September; see Section 3.2); events in the first half of May and in October are not considered. A total of 33 events were observed during May–October, of which 28 (∼85%) were SST events leading rainfall events and 5 (∼15%) were isaolated rainfall events; there was no isolated SST during the core monsoon period.

Exp	Experiment description	1	1(%)	A	A(%)	#	#(%)	Total
C	ΔT threshold 0.75°C (Control: definition of event as in Section 2)	28	84.4	5	15.2	0	0.0	33
1	ΔT threshold 0.5°C instead of 0.75°C	25	83.3	4	13.3	1	3.3	30
2	ΔT threshold 1°C instead of 0.75°C	21	60.0	13	37.1	1	2.9	35
3	ΔT threshold 1°C, but duration 3 days instead of 5	23	63.9	11	30.6	2	5.5	36
4	Rain threshold 10 mm day^{-1} instead of 5 mm day^{-1}	25	64.1	10	25.6	4	10.3	39
5	T_N threshold of 29°C used instead of ΔT threshold of 0.75°C	20	80.0	5	20.0	0	0.0	25
6	T_N threshold 29.25°C instead of 29°C	16	61.5	10	38.5	0	0.0	26
7	Definition as in control, but eastern edge of SMC box at 90°E instead of 88°E	25	75.8	8	24.2	0	0.0	33

Table 12: Sensitivity experiments. The definition of SST and rain events was perturbed to test the sensitivity of the conclusions to the definitions. The definition given in Section 2 was the control experiment (C). Column 1 lists the Experiment number. Column 2 contains a description of the experiment; except for the change stated in this column, all other elements of the definition were as in the control experiment. The number and percentages of events in which an SST event led a rainfall event (events tagged with Arabic numerals) are listed in columns 3 and 4, that of isolated rainfall events (events tagged with Roman alphabet) in columns 5 and 6, and that of isolated SST events (tagged with the # symbol) are in columns 7 and 8. The last column lists the total number of events for each sensitivity experiment.

Criterion	Min (Year)	Max (Year)	Average (%)
$\Delta T \geq 0.75^{\circ}$C	60 (2003)	96 (2002)	$\sim$ 78 (56.5)
$\Delta T \geq 1^{\circ}$C	45 (2003)	75 (2005)	$\sim$ 63 (45.7)
$\Delta T \geq 0.5^{\circ}$C	72 (2003)	116 (2002)	94 (68.1)
$T_N \geq 29^{\circ}$C	71 (1999)	111 (2002)	93 (67.4)
$T_N \geq 29.25^{\circ}$C	41 (1999)	93 (1998)	$\sim$ 76 (54.9)
$T_N \geq 28.75^{\circ}$C	83 (1999)	126 (2002)	$\sim$ 106 (77.0)

Table 13: Number of days on which the criterion listed in Column 1 was fulfilled during the core monsoon period. The minimum and maximum over the eight years are listed in Columns 2 and 3, and the average is in Column 4. The core monsoon period consists of 138 days.

Year	1	2	3	4	> 4	Total
1998	6	1	3	0	0	10
1999	6	3	1	0	0	10
2000	4	1	1	0	0	6
2001	5	1	2	0	1	9
2002	2	2	1	0	0	5
2003	3	3	2	0	0	8
2004	2	2	0	1	2	7
2005	6	2	1	1	0	10
Total	34	15	11	2	3	65
%	52.3	23.1	16.9	3.1	4.6	100

Table 14: Breaks in rain events. Column 1 lists the year and columns 2–4 the number of one-day, two-day, and three-day breaks ($R < 5$ mm day^{-1}) within rain events. The number of four-day and longer breaks are listed in columns 5 and 6. In column 6 is the total number of such breaks within rain events for a given year.

Table 15: Catalogue of events that might have been influenced by errors in TMI SST. Column 1 lists the year and column 2 the event in that year. Column 3 (4) lists the start (end) of the SST event. Column 4 (5) lists the start and end of a wind event (wind speed exceeding 10 m s^{-1}). Column 5 (6) lists the start (end) of an OLR event (OLR below 175 W m^{-2}). Column 7 contains additional descriptive remarks.

Year	Event	ΔT_{beg}	ΔT_{end}	V_{beg}	V_{end}	$\mathrm{OLR}_{\mathrm{beg}}$	$\mathrm{OLR}_{\mathrm{end}}$	Remarks
1998	3	19 Aug	26 Aug	—	—	18 Aug	22 Aug	ΔT exceeds 2°C; it drops only when convection starts in northern bay on 25 August.
2000	2	1 Jun	8 Jun	1 Jun	5 Jun	29 May	2 Jun	Wind and OLR events in southern bay, OLR event in northern bay (3–7 June) make this a complicated case. ΔT, however, exceeds threshold beyond wind and OLR events.
	5	18 Aug	30 Aug	19 Aug	24 Aug	—	—	Wind speed exceeds 11 m s^{-1} during 20–23 August; maximum in ΔT is after the wind speed drops below 10 m s^{-1}.

continued on next page

Table 15: *continued*

Year	Event	ΔT_{beg}	ΔT_{end}	V_{beg}	V_{end}	OLR_{beg}	OLR_{end}	Remarks
2002	5	28 Jul	15 Aug	30 Jul	5 Aug	31 Jul	2 Aug	Wind speed hardly changes when over 10 m s^{-1}, but ΔT changes by $\sim$ 1°C during this period.
2004	3	27 Jun	28 Jul	27 Jun	3 Jul	—	—	$\Delta T > 0.75$ even after wind event ceases in southern bay.
2005	2	12 Jul	29 Jul	—	—	12 Jul	14 Jul	ΔT continues to increase after OLR over southern bay increases above 175 W m^{-2}.
	3	31 Aug	18 Sep	2 Sep	7 Sep	31 Aug	5 Sep	ΔT continues to increase after OLR over southern bay increases above 175 W m^{-2}.

Figure captions

Figure 1: The panel on the left shows TMI SST (colour, $^{\circ}$C) and the panel on the right shows GPCP rainfall (colour, mm day^{-1}). Superimposed on both panels are QuikSCAT wind vectors (m s^{-1}); the vector scale is at the bottom right corner of the right panel. The data are plotted here for 1 August 2003. Boxes are shown defining the regions over which SST and rainfall are averaged. In the northern bay, SST is averaged over 88°–92°E and 18°–22°N; in the southern bay, SST is averaged over 82°–88°E and 4°–8°N, the regime of the SMC. Rainfall is averaged in the central bay over 88°–92°E and 14°–18°N.

Figure 2: SST, SST difference, and rainfall for 1998. The first panel shows TMI SST ($^{\circ}$C) in the northern (red circles) and southern (blue squares) boxes. The second panel shows the SST difference (ΔT) between the northern and southern boxes; black symbols are used for $\Delta T < 0.75^{\circ}$C, blue for $0.75^{\circ}\mathrm{C} \leq \Delta T < 1^{\circ}$C, and red for $\Delta T \geq 1^{\circ}$C. The third panel shows rainfall (R, mm day^{-1}); black symbols are used for $R < 5$, blue for $5 \leq R < 10$, red for $10 \leq R < 20$, and light blue for $R \geq 20$. In panels 2 (ΔT) and 3 (rainfall), the duration of an event is shown by a line. Events in which SST leads rainfall are in red, and isolated rainfall (SST) events are in blue (magenta). The event number precedes the line showing its duration. Lines segments without a preceding event number indicate continuation of the previous event (see condition 5 in the definition of SST and rainfall events). See Table 2 for a description of the events.

Figure 3: As in Figure 2, but for 1999. See Table 3 for a description of the events.

Figure 4: The first three panels are as in Figure 2, but for 2000. See Table 4 for a description of the events. The fourth (fifth) panel shows QuikSCAT wind speed (m s^{-1}) (OLR (W m^{-2})) in the northern (circles) and southern (squares) boxes. Wind speed ≥ 10 m s^{-1} is in red (blue) for the northern (southern) box. OLR ≤ 175 W m^{-2} is in red (blue) for the northern (southern) box. For a more detailed explanation of panels 4 and 5, see Table 15 and Section 4.7.

Figure 5: As in Figure 2, but for 2001. See Table 5 for a description of the events.

Figure 6: As in Figure 2, but for 2002. See Table 6 for a description of the events.

Figure 7: As in Figure 2, but for 2003. See Table 7 for a description of the events.

Figure 8: As in Figure 2, but for 2004. See Table 8 for a description of the events.

Figure 9: As in Figure 2, but for 2005. See Table 9 for a description of the events.

Figure 10: Lag histogram for the core monsoon period; the lag (in days) is on the abscissa. The figure shows the frequency distribution for different lags. (a) For SST events, defined on the basis of a $\Delta T \geq 0.75^{\circ}$C criterion, leading a rainfall event during the core monsoon period (Experiment C in Table 12); see Table 11 for a summary of these events. (b) For SST events, defined on the basis of a $\Delta T \geq 0.5^{\circ}$C criterion (Experiment 2 in Table 12). (c) For SST events, defined on the basis of a $T_N \geq 29^{\circ}$C criterion (Experiment 5 in Table 12), leading a rainfall event during the core monsoon period. The number of events depends on the criterion used to define them. (d) Histogram (during the core monsoon period) for the lag between the ending of a rain event and the start of the succeeding SST event based on the $\Delta T \geq 0.75^{\circ}$C criterion. This histogram is complementary to that in (a).

Figure 11: ΔT (top panel) and rainfall for a composite of events with four-day lag (SST leading rainfall). The three events with a four-day lag are Event 3 in 1998 (Figure 2 and Table 2), Event 2 in 1999 (Figure 3 and Table 3), and Event 2 in 2003 (Figure 7 and Table 7). The abscissa is in days, with Day 5 marking the start of the individual and composite SST events. The arrows mark the start of the composite (and individual) SST and rain events. The composite of the events is shown by the solid line and filled circles in both panels. Black circles are used for $\Delta T < 0.75^{\circ}$C, blue for $0.75^{\circ}\text{C} \leq \Delta T < 1^{\circ}$C, and red for $\Delta T \geq 1^{\circ}$C. Black circles are used for $R < 5$, blue for $5 \leq R < 10$, red for $10 \leq R < 20$, and light blue for $R \geq 20$. The individual events are shown by coloured asterisks (dark red for 1998, green for 1999, and magenta for 2003).

Figure 12: Histogram showing the frequency distribution of duration of SST and rain events. (a) SST events for the $\Delta T \geq 0.75^{\circ}$C criterion. Event 6 in 2000 was longer than 35 days, but has been clubbed with 35-day events. (b) Rain events that lag an SST event are shown as dark gray bars (total 28 events) and isolated rain events are shown as light gray bars (total 5 events). This histogram is for the $\Delta T \geq 0.75^{\circ}$C criterion. In the case of three events (Event 1 in 2001 and Events 2 and 3 in 2004), the duration shown excludes the multiple rain bursts associated with the SST event. Including the multiple bursts increases the duration to 58, 21, and 56 days from 12, 3, and 5 days for the three events. Note that the duration of SST events is less than that of associated rain events.

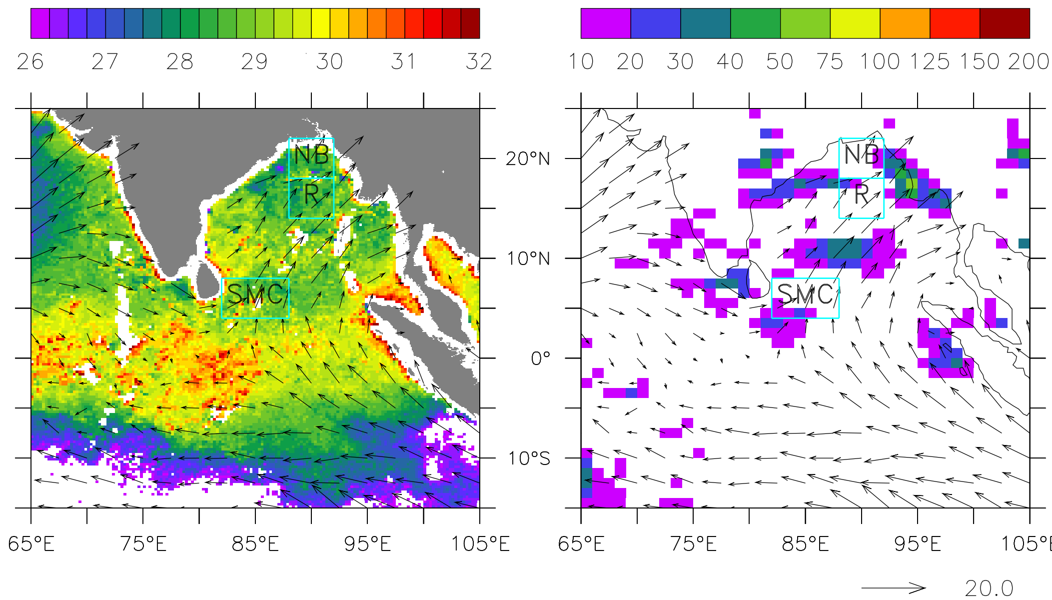

26 27 28 29 30 31 32
10 20 30 40 50 75 100 125 150 200
NB
R
SMC
20°N
10°N
0°
10°S
65°E 75°E 85°E 95°E 105°E
20.0

Figure 1

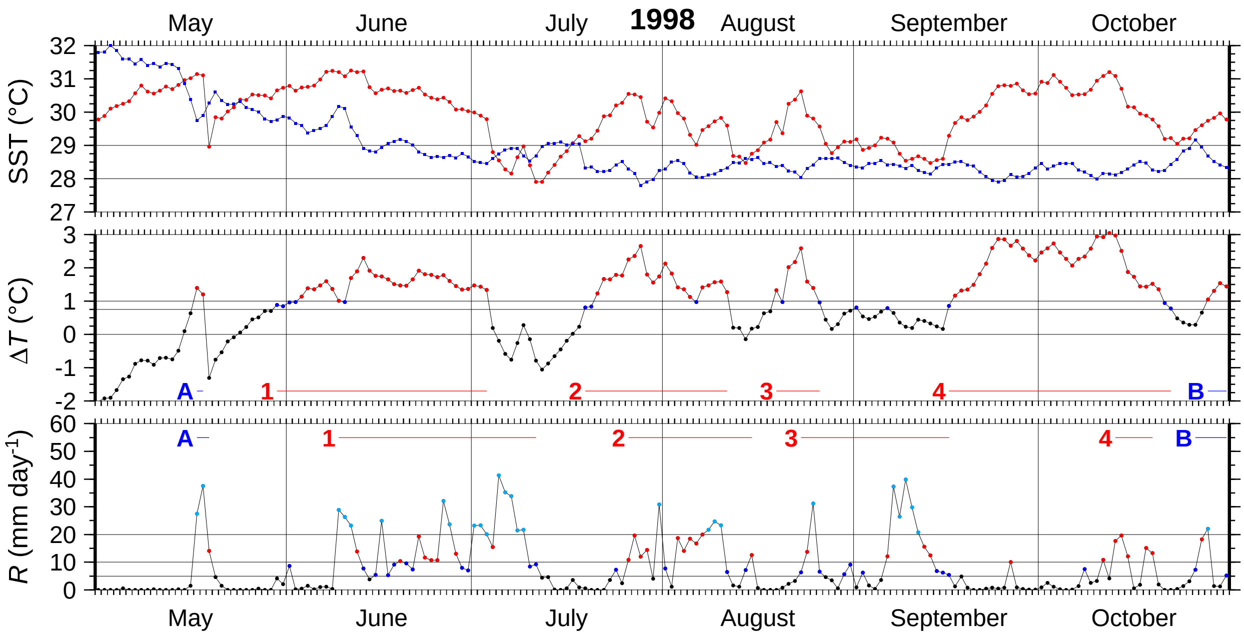

1998
May
June
July
August
September
October
SST (°C)
ΔT (°C)
R (mm day-1)
A
B
1
2
3
4

Figure 2

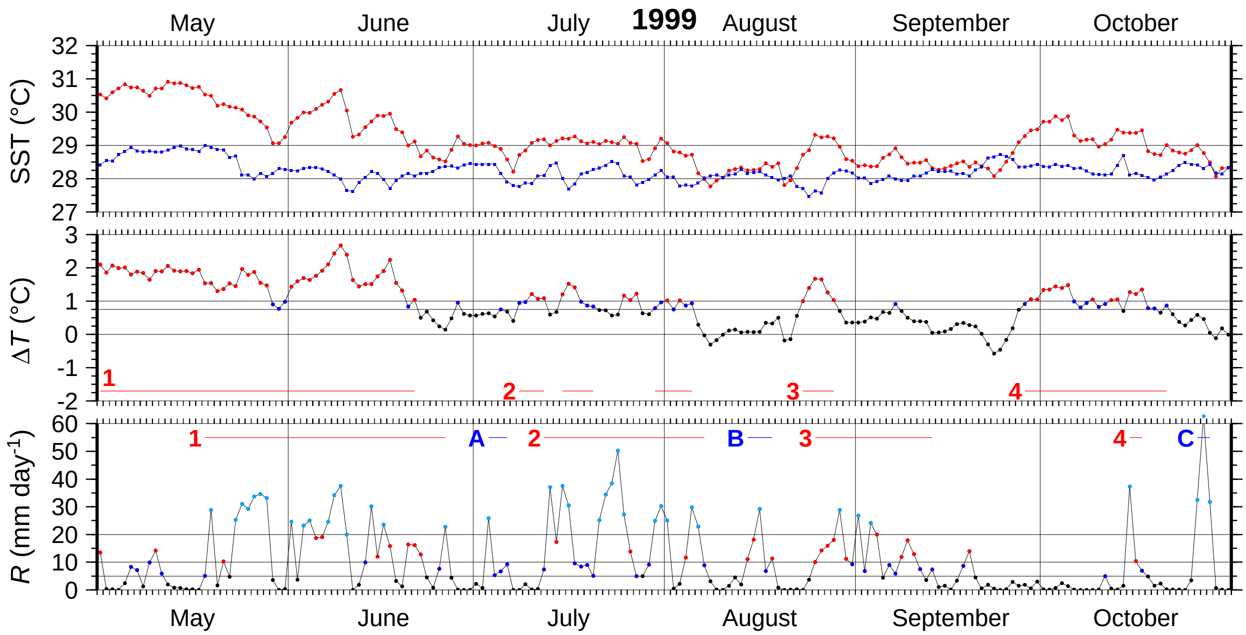

1999
May
June
July
August
September
October
SST (°C)
ΔT (°C)
R (mm day-1)
1
2
3
4
A
B
C

Figure 3

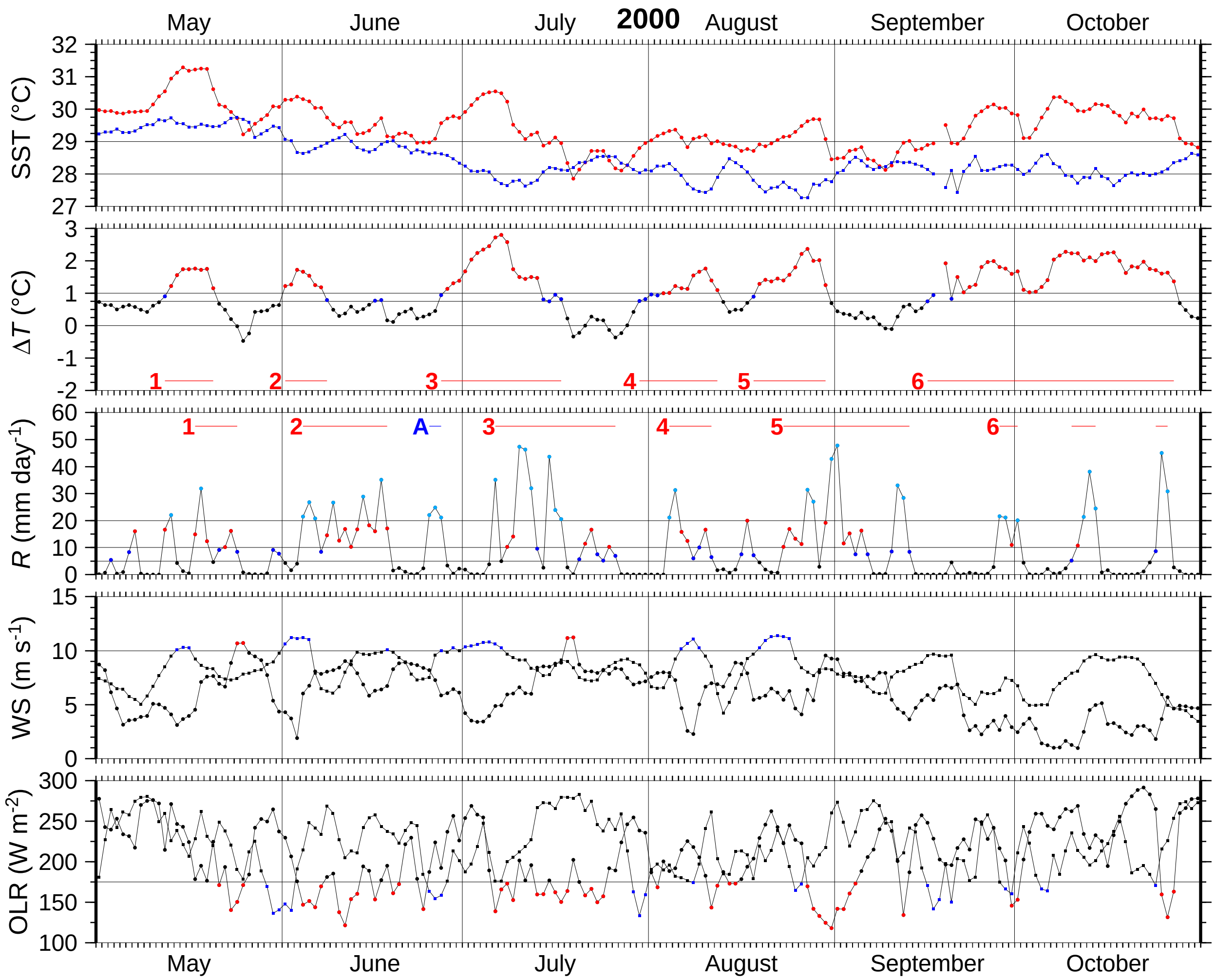

2000
May
June
July
August
September
October
SST (°C)
ΔT (°C)
R (mm day-1)
WS (m s-1)
OLR (W m-2)
1
2
3
4
5
6
A

Figure 4

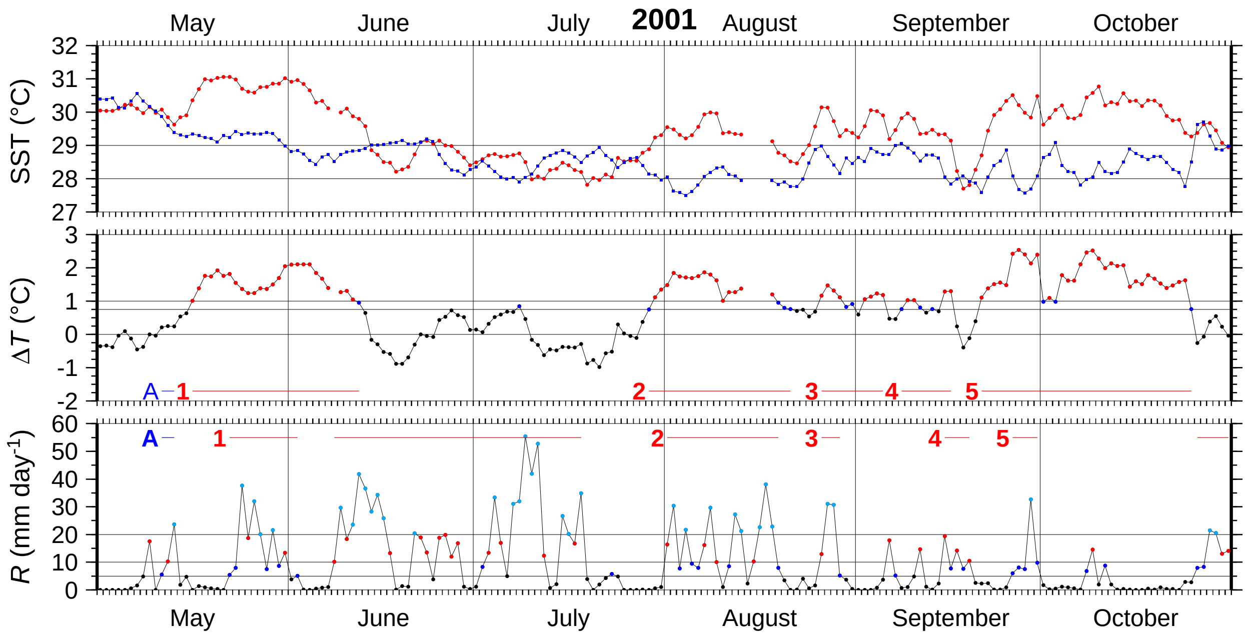
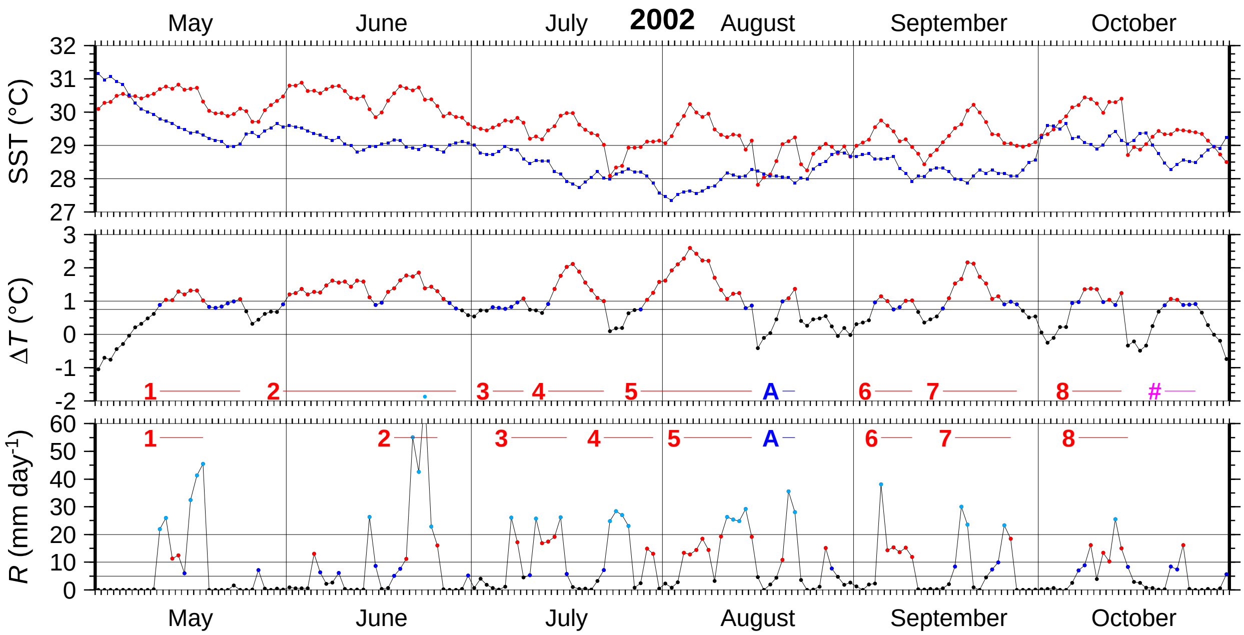

2001
May
June
July
August
September
October
SST (°C)
ΔT (°C)
R (mm day-1)
A
1
2
3
4
5

Figure 5



2002
May
June
July
August
September
October
SST (°C)
ΔT (°C)
R (mm day-1)
1
2
3
4
5
A
6
7
8
#

Figure 6

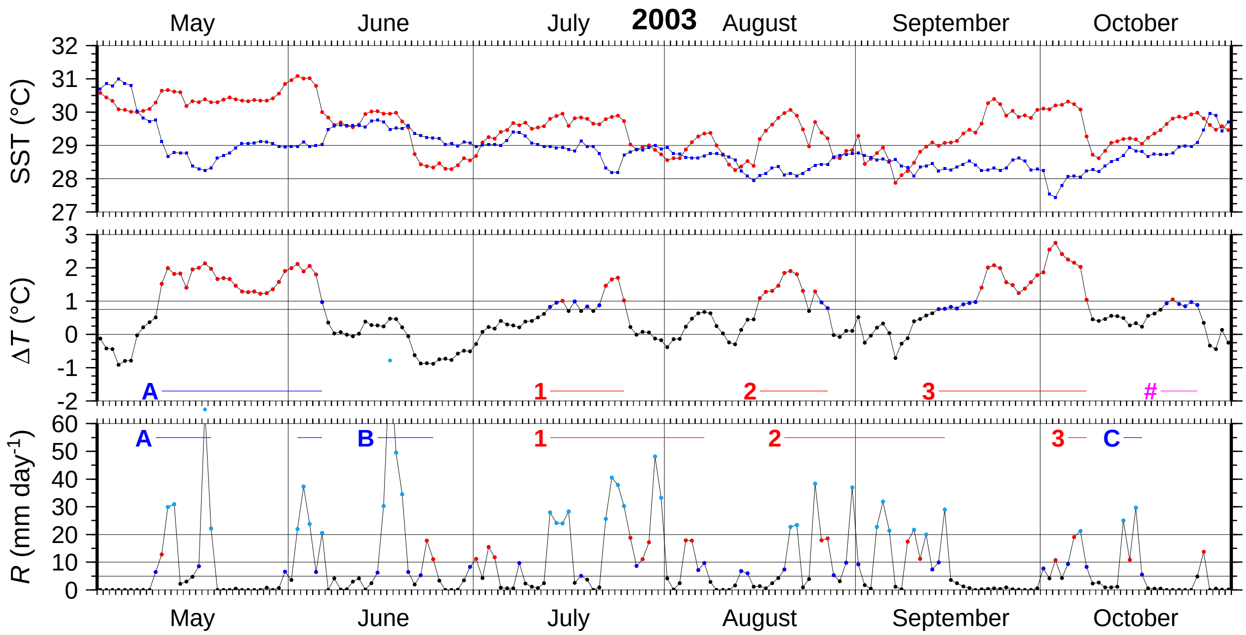

2003
May
June
July
August
September
October
SST (°C)
ΔT (°C)
R (mm day-1)
A
B
C
1
2
3
#

Figure 7

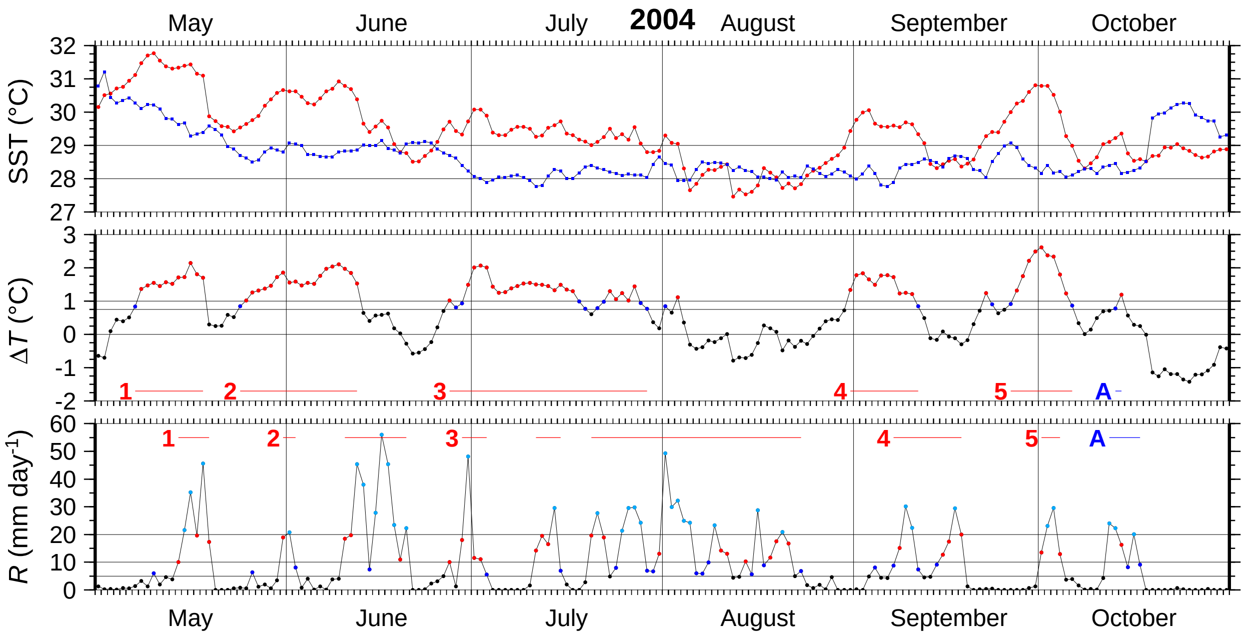

2004
May
June
July
August
September
October
SST (°C)
32
31
30
29
28
27
ΔT (°C)
3
2
1
0
-1
-2
1
2
3
4
5
A
R (mm day-1)
60
50
40
30
20
10
0
1
2
3
4
5
A
May
June
July
August
September
October

Figure 8

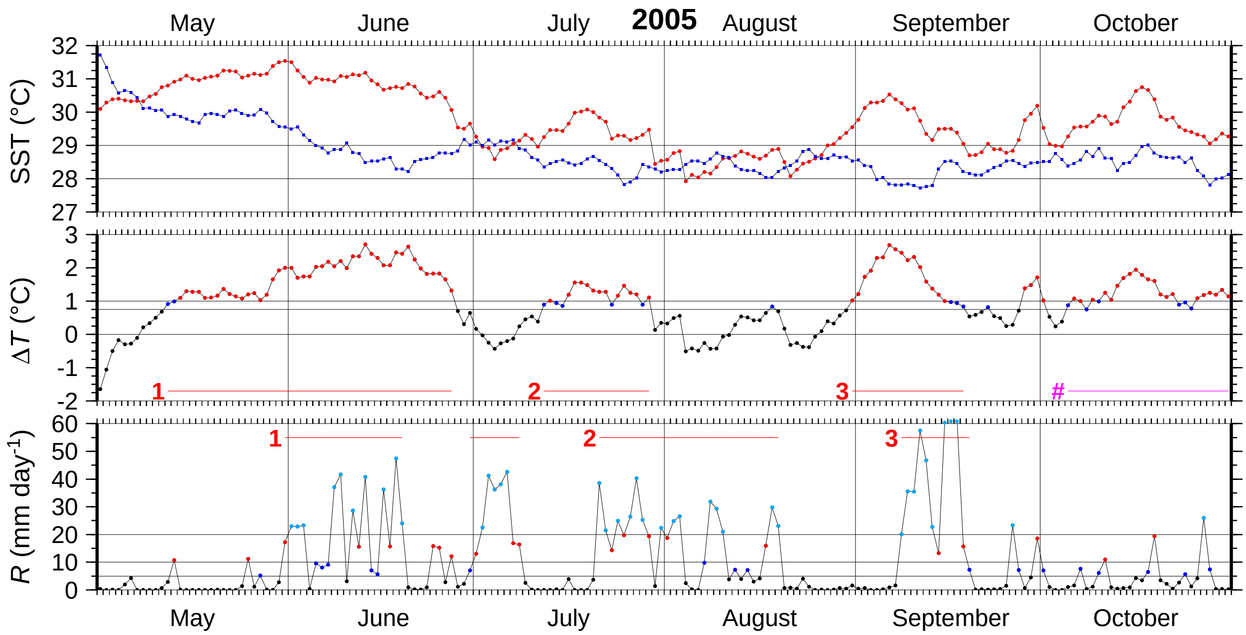

2005
May
June
July
August
September
October
SST (°C)
ΔT (°C)
R (mm day-1)
1
2
3
#

Figure 9

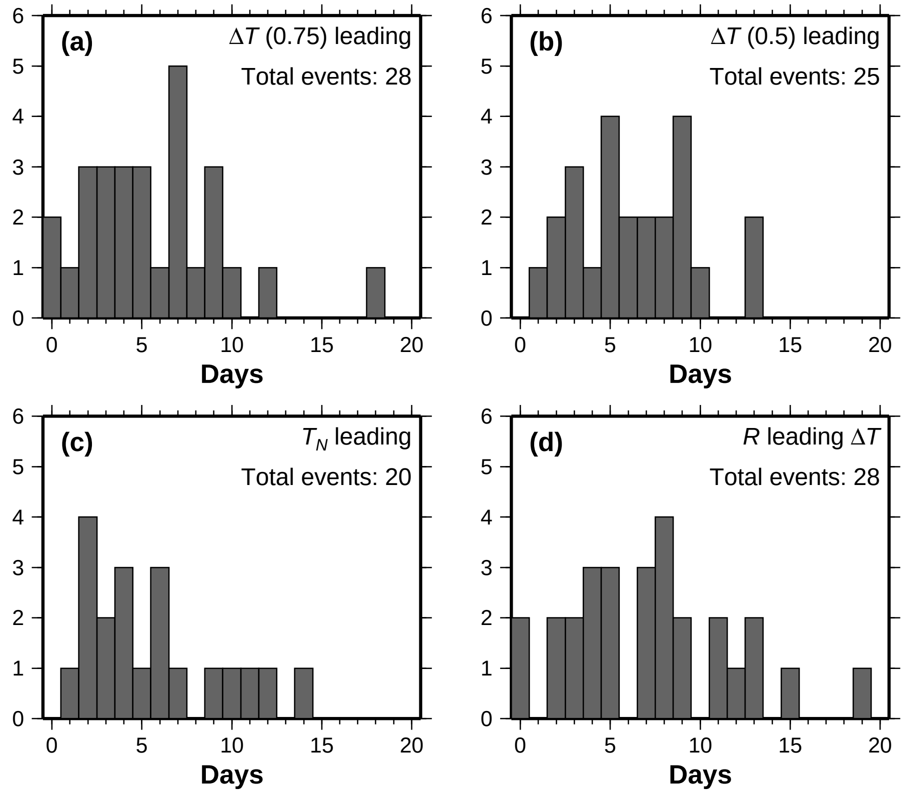

(a)
ΔT (0.75) leading
Total events: 28
(b)
ΔT (0.5) leading
Total events: 25
(c)
T_N leading
Total events: 20
(d)
R leading ΔT
Total events: 28
Days
0 5 10 15 20
0 1 2 3 4 5 6

Figure 10

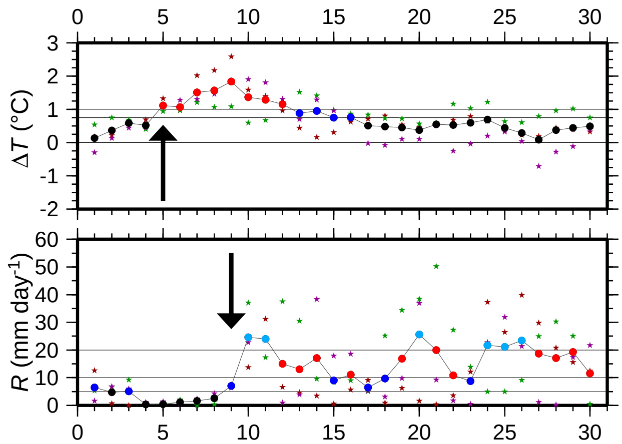


Figure 11

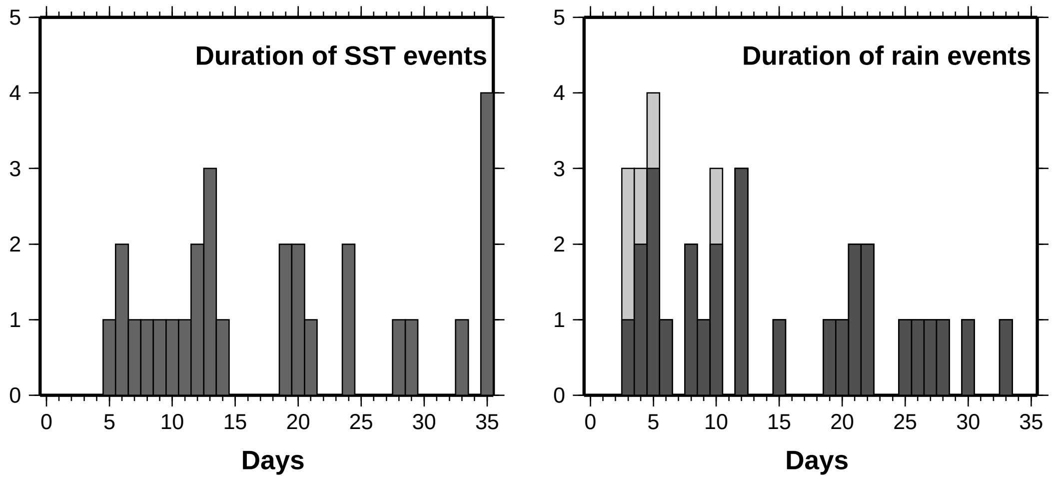


Figure 12