SEA SURFACE TEMPERATURE VARIABILITY AS A PREDICTOR OF INDIAN MONSOON ACTIVITY

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This paper represents my own work in accordance with University regulations,

Abstract

The monsoons in the Bay of Bengal impact millions of people living in South Asia, altering weather patterns, rainfall, flooding, agriculture, and the safety of the inhabitants. Understanding the active and break periods of monsoons will ultimately improve our ability to predict these changes in activity. This paper revisits a 2002 paper by Gabriel Vecchi and D. E. Harrison which found a strong correlation between sea surface temperature fluctuations and monsoon activity but was based on only three years of data. Using the satellite data on sea surface temperatures (SST) and outgoing longwave radiation (OLR), this paper replicates the findings and calculation of the monsoon break index described in the Vecchi and Harrison paper. In applying these methods to new data from the last 20 years, it is expected to see the same strong statistical correlation between SST and monsoon breaks. After replicating the procedures of Vecchi and Harrison, the correlation between SST changes and monsoon activity is consistent in this larger dataset, producing a lagged correlation of 0.61 at -7 days.

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Introduction

The monsoons in the Bay of Bengal drive the weather patterns of the region and are responsible for nearly 90% of the annual rainfall in the subcontinent of India (Xie and Arkin, 1996). Monsoons, however, are not characterized by constant heavy downpours, but instead contain active periods of rain and break periods. The duration and timing of these breaks and active periods can greatly impact the lives of the inhabitants, especially farmers and their crops. As such, being able to predict these variations in activity in of great importance to the region.

A coupled atmospheric-oceanic relationship has been thought to be important in variability of monsoon activity (Krishnamurti et al. 1988; Webster et al.1998) however a thorough investigation was limited by technology. Infrared satellite imaging is not effective during times of intense cloud cover, and buoys provide only sparse data. With the advent of new microwave imaging technology on the Tropical Rainfall Measuring Mission in 1997, it is now possible to observe the surface of the Earth via satellite even through cloud coverage. With this new instrument, large scale, basin-wide variation in sea surface temperature (SST) have been observed, motivating Gabriel Vecchi and D. E. Harrison's to take a closer look at the ocean's role in Indian southwest monsoon activity (Vecchi and Harrison 2002). Large-scale SST variability has previously been studied in relation to El Niño, the Indian Ocean dipole, and seasonal cycle of SST on time scales of seasons, years, or decades. With the new satellite data, it is now possible to investigate large-scale, basin-wide variability on shorter, subseasonal time scales.

The 2002 Vecchi and Harrison paper found a strong correlation between SST and monsoon activity, in which the cooling of SST led breaks in the monsoon which then preceded rises in SST. Their paper also included atmospheric analysis of the wind and convection which led them to develop a conclusion that monsoon activity was consistent with an atmosphere-ocean coupled system. In Figure 1, a Hovmoller/time-latitude contour plot and its accompanying caption from their paper illustrates one aspect of the coupling between atmosphere and ocean.

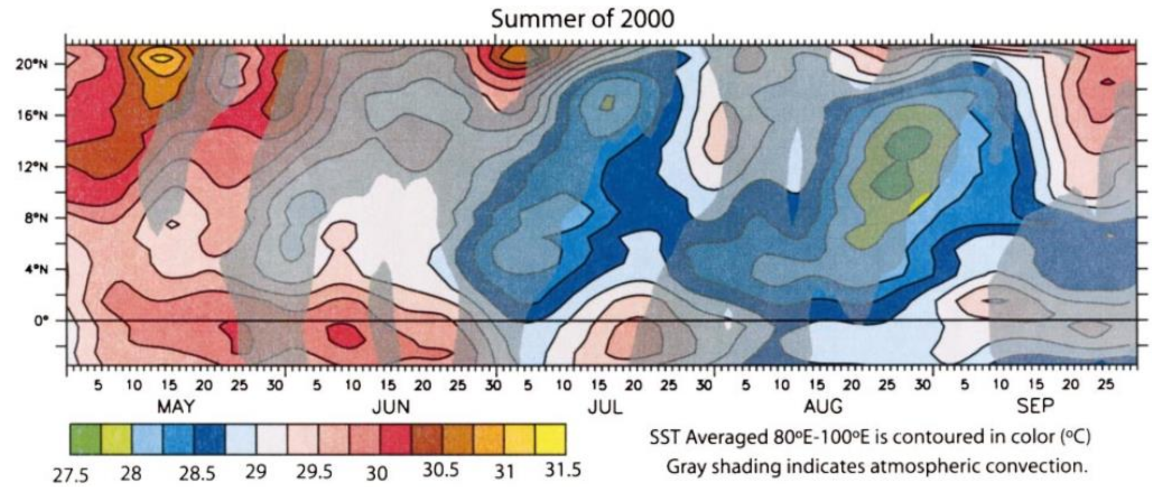


Fig 1. Time–latitude plots of SST and ''atmospheric convection'' averaged 80°–100°E, over the summer of 2000. Color shading and contours indicates zonally averaged, 7-day boxcar-smoothed TMI SST. Gray overshading indicated areas where zonally averaged 7-day boxcar-smoothed OLR is less than 210 W m^{-2}. Contour interval for SST is 0.25°C.

This figure shows the propagating nature of the SST and atmospheric changes. After atmospheric convection in the northern part of the bay (May-Jun), the SST begins to cool. Once it has cooled the convection weakens. After the active convection (around mid-July), the surface warms again and more convection follows. The active atmospheric convection represents times of increased cloudiness and wind speeds, which cause the water to cool. Once the water cools, there is less evaporation and cloud coverage. Finally, with less cloud coverage and wind the SST can rise again which triggers more evaporation and cloud cover, starting the cycle over.

This behavior is also seen in Figure 2 (also directly from Vecchi and Harrison 2002) where a monsoon break index—explained in greater detail later—is used to quantify monsoon activity. Active periods are expressed as negative indexes and breaks are represented as positive indexes.

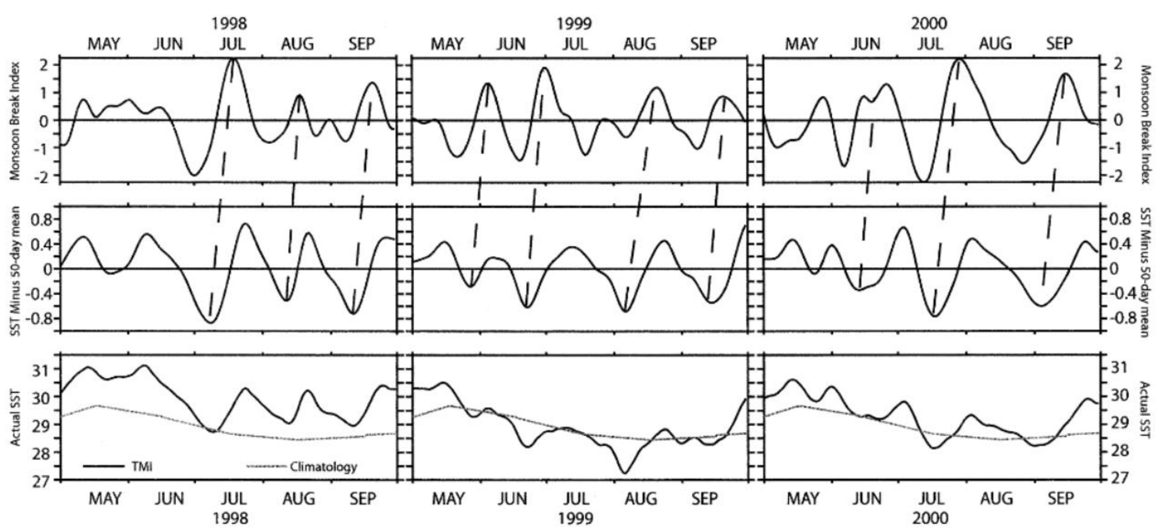


Figure 2. The subseasonal SST events correlate strongly with monsoon variability; plots of weekly smoothed: (a)–(c) OLR-based monsoon break index (positive values indicate a monsoon break), (d)–(f) TMI SST averaged 15°–22°N in the BoB minus its 50-day centered mean, and (g)–(i) TMI SST (black line) and COADS climatological SST (red line) averaged 15°–22°N in the BoB, for each of the southwest monsoons 1998–2000.

Figure 2 shows peaks in the monsoon activity seem to correspond to extrema in the SST, with cooler SST values preceding breaks in monsoon activity. This relationship is further explored using statistical analysis. To determine if this apparent phase shift relationship was real and significant, they compute lag correlations, finding a maximum positive lag correlation of ~0.7 at 7 days apart—where a positive monsoon break index led a positive SST anomaly—and a maximum negative lag correlation of ~0.67 at 10 days apart—where negative SST anomalies led a positive monsoon break index (Vecchi and Harrison, 2002). Based on these results, they find that monitoring SST can be an effective means of predicting monsoon activity, where dips in SST in the northern part of the BoB signal breaks in the monsoon activity by about a week. However, they are unable to definitively corroborate the coupled air-sea dynamic without vertical depth profiles of the ocean at those times.

The findings of the Vecchi and Harrison paper while exciting are based solely on three years of data. This paper seeks to replicate the methods and procedures of their paper, applying new data from the last two decades to determine whether their findings remain consistent over time, across a larger dataset. It is expected to observe a similar correlation between SST and monsoon activity, further corroborating the conclusion of Vecchi and Harrison that an air-sea coupling is responsible for and can be used to predict changes in monsoon activity.

Methods

This paper relies on sea surface temperature and outgoing longwave radiation data. The sea surface temperature readings (Remote Sensing Systems) were taken using the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), satellite launched in 1997 (Vecchi and Harrison, 2002). The advent of this satellite was particularly revolutionary as it has the capability to pierce through cloud cover, in contrast to infrared satellite observations. This made it possible to observe SST in the Bay of Bengal even during active monsoon periods with intense cloud cover. The data itself is Level 3 gridded data taken daily with "both ascending (daytime) and descending (daytime) gridded orbital passes on packaged into the same daily file" (PODAAC) (available at https://podaac.jpl.nasa.gov/dataset/REMSS-L2P_GRIDDED_25-TMI) with 0.5 degree Celsius precision in rain-free conditions (Wentz 1998).

The outgoing longwave radiation data (Liebmann B. and C.A. Smith 1996) was downloaded in November of 2019 from the NCAR archives (provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website https://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html), ranging from 1998 to 2018, and it came from three different satellites, NOAA 14, 16, 18. The satellites recorded Level 3 gridded data of the OLR twice a day (during day and night) with a spatial coverage of 2.5 degree latitude x 2.5 degree longitude global grid (144x73). Because of drifting the satellites did not always achieve the same number of crossing times (with the goal being 1430 times). There are also some gaps in the data that were filled in using interpolation.

This paper replicates the figures made in the 2002 Vecchi and Harrison paper and repeats the methods on newer data from the last two decades. It produces climatologies of the region by averaging SST for the summer months of the monsoon season. To observe propagating features, Hovmoller diagrams (or time-latitude contour plots) are produced for each year. To investigate the sea surface temperature variability and monsoon break correlation, I calculate the monsoon break index using the method described below from the Vecchi and Harrison paper:

"We define as our monsoon break index the difference between normalized 7-day boxcar-smoothed OLR anomalies averaged (108–308N, 658–858E) and (108S–58N, 758–958E), minus its 50-day centered mean (to focus on subseasonal variability). The index is positive (negative) for monsoon breaks (active periods), and is consistent with pentad precipitation anomalies in the Indian subcontinent from the NOAA Merged Analysis of Precipitation (Xie and Arkin 1996; provided by the NOAA–CIRES Climate Diagnostics Center, available online at http://www.cdc.noaa.gov/.)" (Vecchi and Harrison 2002)

Finally, I calculated the lag correlations between the SST and monsoon break index time series using a fast-Fourier transform method.

Results

To create a climatology for each month, each year's summer month SST values were averaged. Figure 3 shows the average sea surface temperatures in the Bay of Bengal during the summer months or monsoon season.

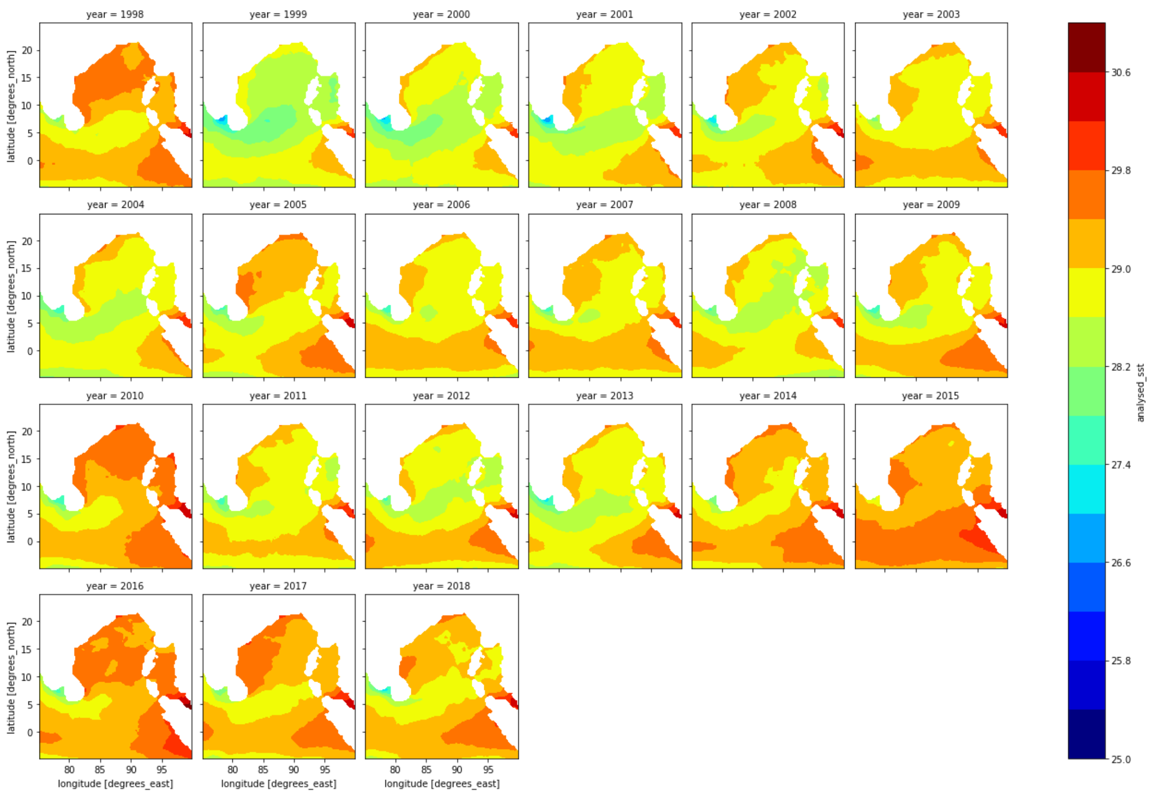


Fig. 3: Average SST (in degrees Celsius) in the Bay of Bengal from 1998 to 2018

Notice the stretch of cool water (generally 28 degrees Celsius or lower) across the south part of the Bay surrounded by relatively similar temperature waters (around 29 degrees Celsius or higher) on either side. The stretch sometimes completely covers the opening of the BoB and in other years (2003, 2005-2007, 2011, and 2015) just barely juts out across the bay.

Across two decades there will obviously years that are warmer or cooler than others. To visualize these differences, the SST anomalies were calculated by subtracting the average SST for all years from the average SST for each year, shown in Figure 4. The benefit of computing this spatially across the bay is that we can also see where the temperature differences are. For instance, most years the entire bay is cooler or warmer than usual, but in some years (2003, 2005, 2006, 2007, 2009, 2012) there are large differences in temperature across the bay, with some areas warmer than usual while others are cooler.

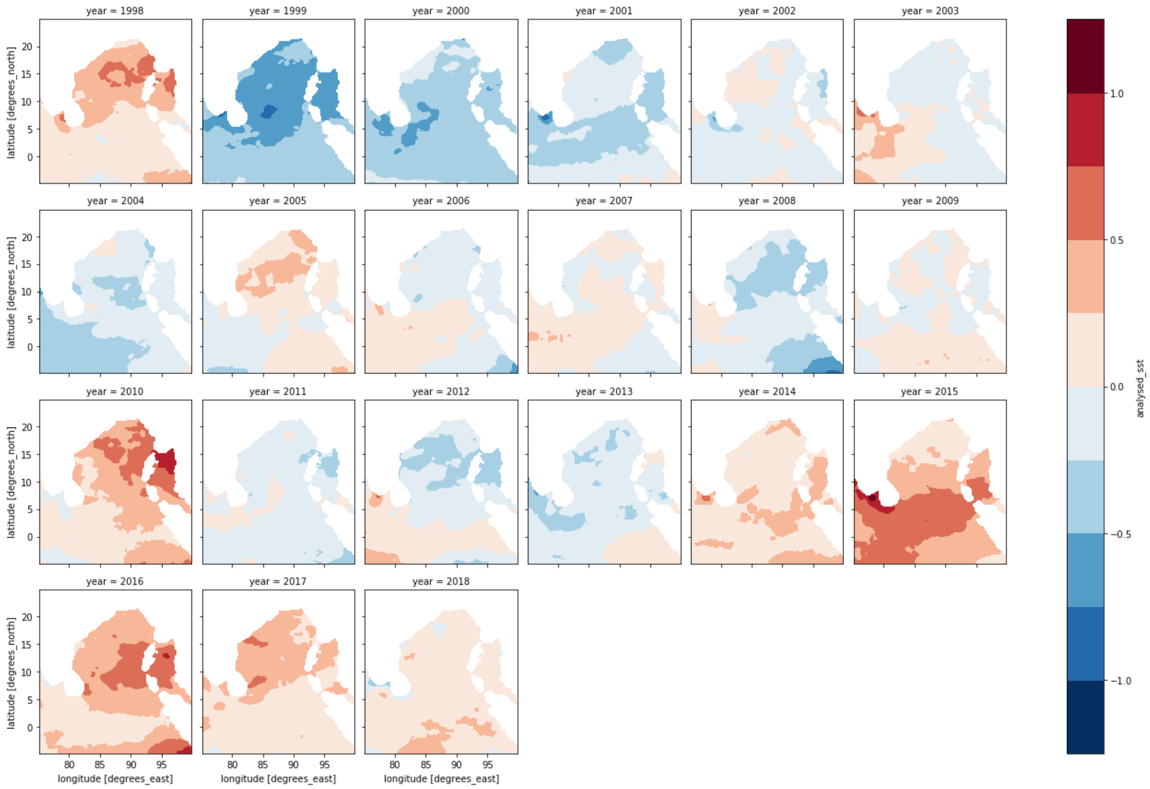


Fig 4: SST anomalies in degrees Celsius in the Bay of Bengal calculated by subtracting the average SST across all 20 years from the average summer temperatures for each year.

Figure 5 shows an example of a subseasonal monsoon event. It illustrates what is physically happening during monsoon breaks and active periods. On Jun-22, the bay is generally consistent in temperature, around 28.5°C (also with calm wind speeds according to Vecchi and Harrison's version of this figure). From Jun-28 to Jul-04 the "tongue" of cool water strengthens across the bay's mouth. From Jul-16 through Jul-22 the bay undergoes a cooling to about 28°C. You can observe the cool "tip" of water spreading eastward around the corner and into the Bay of Bengal cooling all of it. Then by Aug-03 the bay has shifted to have a warm northern bay above 29°C and a cool tongue of 27.5°C.

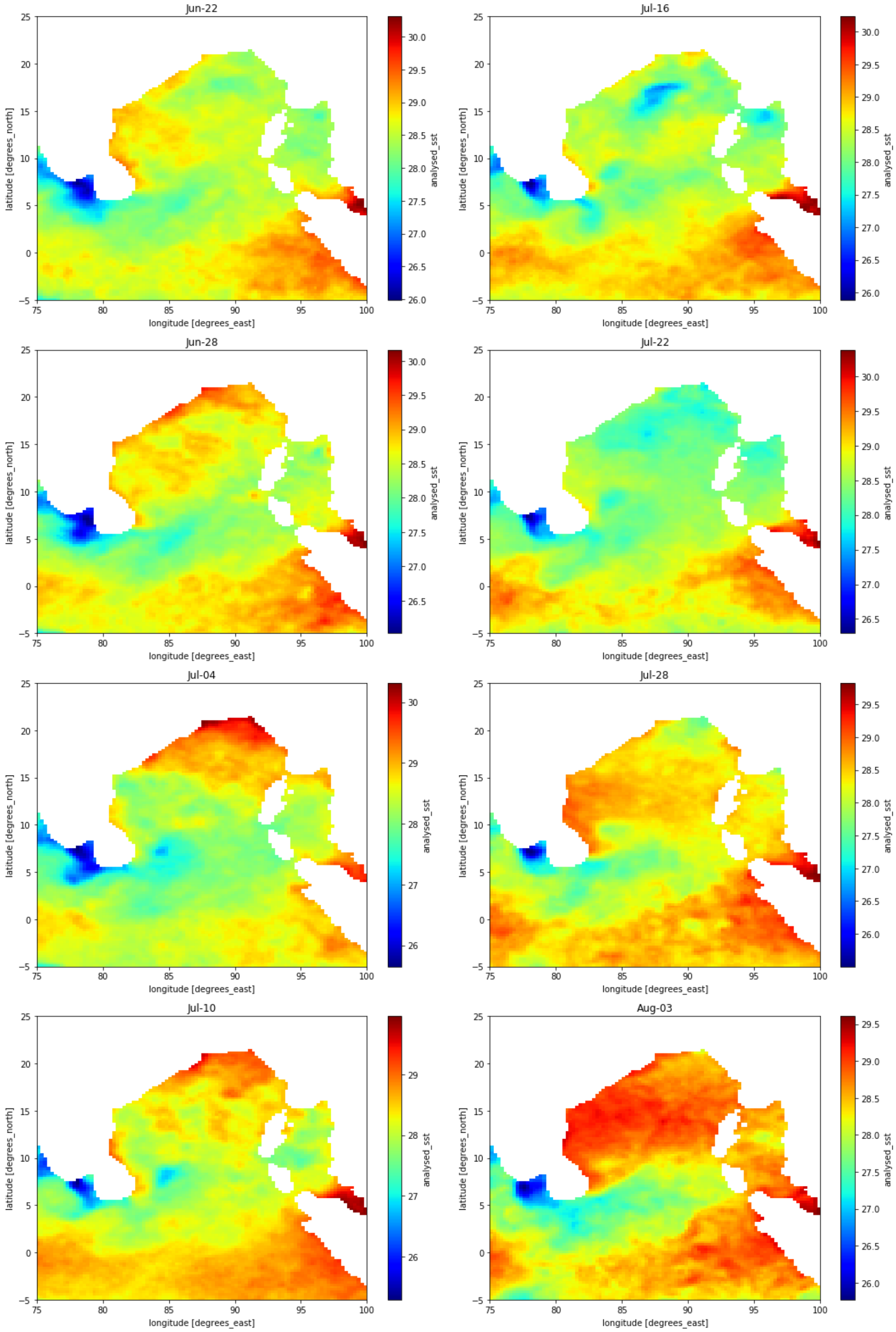
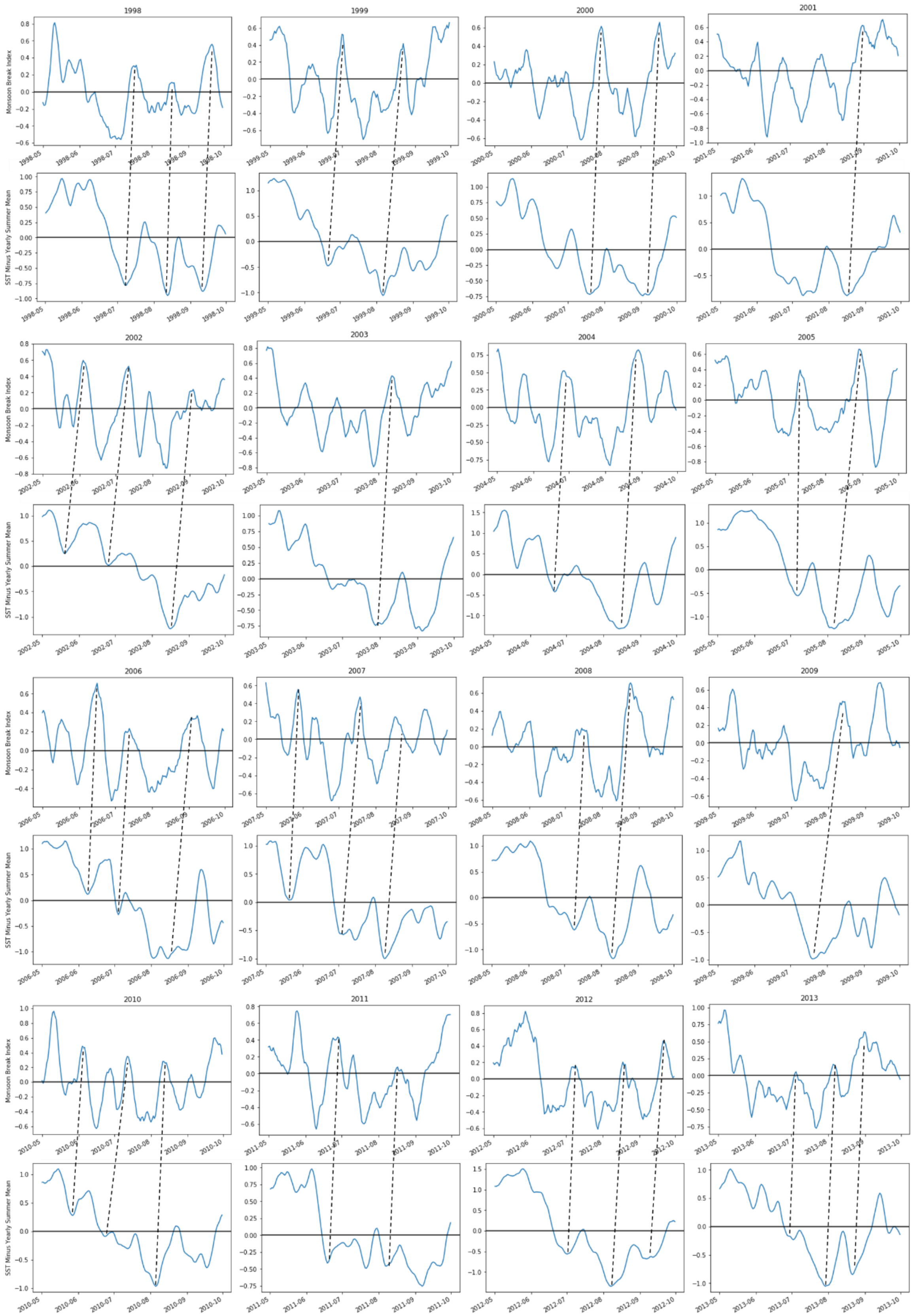


Fig 5: A subseasonal monsoon event in 2000, read from (5a) top left or Jun-22 down to (5d) Jul-10 then (5e) Jul-16 down to (5h) Aug-03.


1998
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Monsoon Break Index
SST Minus Yearly Summer Mean

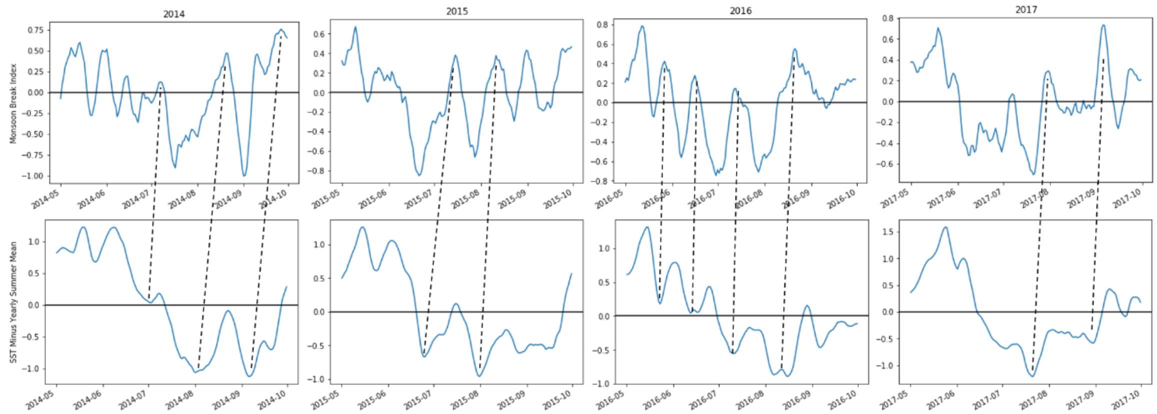

Fig 6: Time series of the SST anomalies compared to the monsoon break index for years 1998-2018

Figure 6 shows the calculated monsoon break index for years 1998-2018 compared to the SST anomalies for the same time period. The dotted lines are to highlight the paired maximums and minimums in the SST and MBI. Computing the time-lag correlations for each year produced an average maximum negative correlation of 0.61 at 7 days.

Discussion

Figure 3 serves as a control for observing subseasonal variabilities. It illustrates the climatologies of the bay for each year to serve as a comparison for the status of the water during a monsoon event. The “tongue” of cold water that sticks out across the bay is due to the westerly winds coming off the mainland. These winds are caused by a large difference in air surface pressure between the land—which is warmed greatly during the summer months leading to lower air pressure—and the bay, which has comparatively higher pressure (Vecchi and Harrison, 2002). This is the environment characteristic of the Bay of Bengal during monsoon season. This is the landscape that changes during monsoon breaks and active periods.

In examining a time series over two decades, it is expected that there will be variability from year to year. In Figure 4, we see most years the bay is slightly warmer or cooler than average across the board. In these instances, we would expect to see normal monsoon behavior, as what drives the atmospheric convection and winds is the spatial temperature gradient. However, there are some years (2003, 2005, 2006, 2007, 2009, 2012) with large differences in SST spatially and the steeper contrast between the northern bay and the mouth could lead to stronger monsoon behavior.

Figure 5 illustrates the SST variability during a monsoon event. Based on Figure 1, we know what the Bay of Bengal should look like on average. We see this represented in the 5a (Jun-22). As the cool tongue moves across the bay, it is transitioning from a break to active period. As the tongue spreads into the bay, there is a massive cooling, during which time clouds are overhead and wind speeds increase in the midst of an active period. After the cloud coverage and wind have cooled the bay, evaporation slows leading to dissipating clouds (Jul-28 shows this transition period), and by Aug-03 the bay has returned to a break period due to the lack of clouds and weaker winds with a strong SST gradient—a warm northern Bay and a cool tongue.

Just as Vecchi and Harrison found in 2002, there does seem to be a lagged relationship between SST and monsoon activity. There is a particularly good example in 2016, seen below.

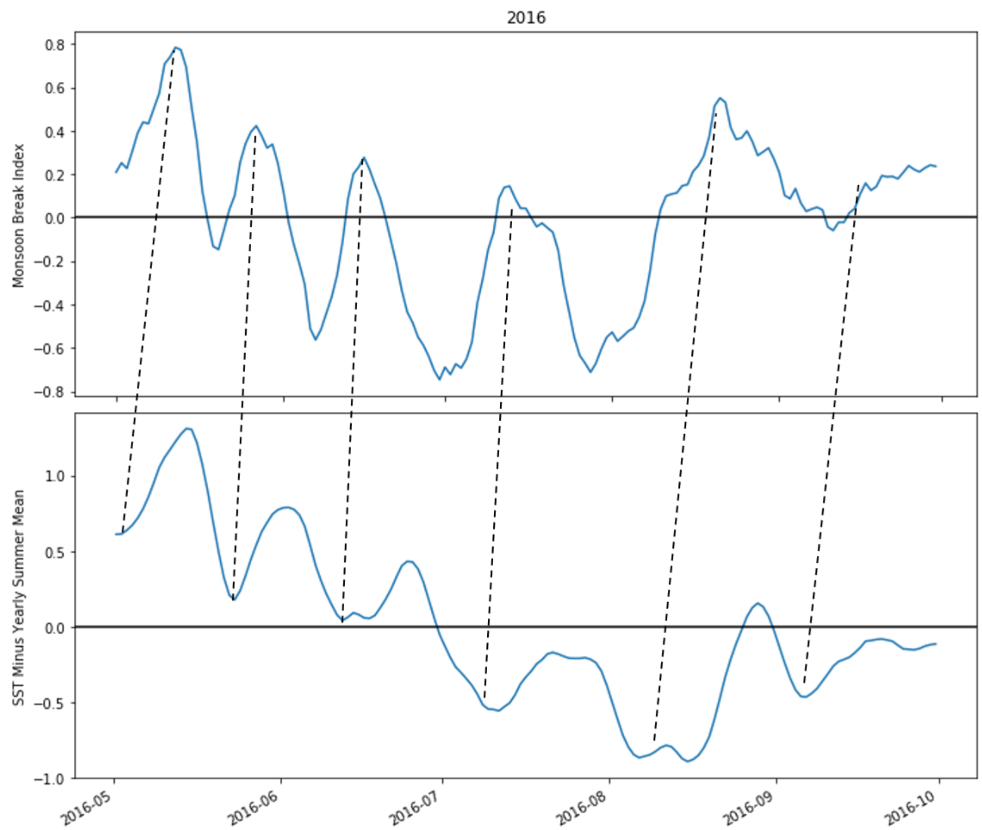

Figure 7: The SST anomalies and Monsoon Break Indices calculated for the year of 2016.

In Figure 7, we can clearly see the similar behavior of the MBI and the SST anomalies. From a simple glance, we can see that the dips in SST precede spikes in the MBI, just as Vecchi and Harrison found in 2002.

Computing the lagged correlations revealed an average maximum correlation of 0.61 at -7 days. In other words, the minimum SST events led maximum MBIs. This result aligns with Vecchi and Harrison which found the largest negative lagged correlation to be 0.67 at 10 days for the years 1998-2000. It is reasonable then to predict breaks in the monsoon to occur 7-10 days after a significant SST cooling.

Conclusions

The purpose of this paper was to assess the validity of a previous conclusion drawn by Vecchi and Harrison back in 2002. They found evidence to suggest a coupled air-sea dynamic played a key role in regulating the activity of monsoons. Their findings however, were based on only three years of data. This study replicated their methods to determine whether these conclusions held true in a larger sample of data. As demonstrated and discussed in the Results and Discussion section, this study found similar results to that of Vecchi and Harrison, showing (in Fig 6) the pattern of cooling SST preceding maximums in the MBI, or monsoon breaks and further verified this relationship with a time lag correlation of 0.61 separated by 7 days.

Further investigation into the behavior of the ocean could be done by analyzing temperature (and salinity) depth profiles of the Bay of Bengal. This would demonstrate how far down the temperature variations occur or whether separate temperature gradients below the surface also influence the coupled air-sea oscillations. Nevertheless, this study agrees with the initial hypothesis, suggesting there is in fact a reasonably strong correlation between SST and monsoon activity, and this relationship can be used to predict short-term changes in monsoon activity—a helpful tool for residents of the bay.

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