Disentangling the Impact of ENSO and Indian Ocean Variability on the Regional Climate of Bangladesh: Implications for Cholera Risk

BENJAMIN A. CASH
Center for Ocean–Land–Atmosphere Studies, Calverton, Maryland

XAVIER RODÓ
Catalan Institute of Climate Sciences, Barcelona, Catalunya, Spain

JAMES L. KINTER III
Center for Ocean–Land–Atmosphere Studies, Calverton, Maryland

MD. YUNUS
International Center for Diarrheal Disease Research, Dhaka, Bangladesh

(Manuscript received 6 March 2008, in final form 5 October 2009)

ABSTRACT

Recent studies arising from both statistical analysis and dynamical disease models indicate that there is a link between the incidence of cholera, a paradigmatic waterborne bacterial illness endemic to Bangladesh, and the El Niño–Southern Oscillation (ENSO). Cholera incidence typically increases following boreal winter El Niño events for the period 1973–2001. Observational and model analyses find that Bangladesh summer rainfall is enhanced following winter El Niño events, providing a plausible physical link between El Niño and cholera incidence. However, rainfall and cholera incidence do not increase following every winter El Niño event. Substantial variations in Bangladesh precipitation also occur in simulations in which identical sea surface temperature (SST) anomalies are prescribed in the central and eastern tropical Pacific. Bangladesh summer precipitation is thus not uniquely determined by forcing from the tropical Pacific, with significant implications for predictions of cholera risk.

Nonparametric statistical analysis is used to identify regions of SST anomalies associated with variations in Bangladesh rainfall in an ensemble of pacemaker simulations. The authors find that differences in the response of Bangladesh summer precipitation to winter El Niño events are strongly associated with the persistence of warm SST anomalies in the central Pacific. Also there are significant differences in the SST patterns associated with positive and negative Bangladesh rainfall anomalies, indicating that the response is not fully linear. SST anomalies in the Indian Ocean also modulate the influence of the tropical Pacific, with colder Indian Ocean SST tending to enhance Bangladesh precipitation relative to warm Indian Ocean SST for identical conditions in the central and eastern tropical Pacific. This influence is not fully linear. Forecasts of Bangladesh rainfall and cholera risk may thus be improved by considering the Niño-3 and Niño-4 indices separately, rather than the Niño-3.4 index alone. Additional skill may also be gained by incorporating information on the southeast Indian Ocean and by updating the forecast with information on the evolution of the SST anomalies into spring.

1. Introduction

Cholera is a waterborne disease endemic to the Bangladesh region. Infection results from ingesting water contaminated with the bacteria vibrio cholerae. While cholera is endemic to the Bangladesh region, it has also been responsible for numerous worldwide pandemics throughout history and the modern era (Said and Drasar 1996; Parry et al. 2007). Left untreated, mortality rates as high as 50% are common; however, with proper treatment mortality rates can be reduced to less than 1%, even in severe cases (Cook 1996). Because infection results from ingesting contaminated water, cholera epidemics typically occur in regions with a limited or damaged infrastructure.
Consequently, it is not always possible to provide adequate treatment in a timely fashion once an epidemic has begun. The ability to forecast cholera risk would thus be of great benefit to society, allowing for critical medical resources to be readied in advance.

Cholera incidence in Bangladesh typically reaches a maximum during boreal fall after the abatement of the summer monsoon rains (Glass et al. 1982). A secondary maximum occurs in boreal spring prior to the arrival of the monsoon, suggesting a relationship between cholera incidence and rainfall. More generally, the hypothesis that environmental factors (such as water temperature, salinity, and pH) influence *Vibrio cholerae* concentrations, and hence disease risk, is supported by numerous studies (e.g., Colwell 1996; Franco et al. 1997; Pascual et al. 2000, 2002; Rodó et al. 2002; Koelle and Pascual 2004; Koelle et al. 2005b; Pascual et al. 2008) although the exact mechanism is still a matter of debate.

One potentially significant relationship between cholera and the environment, in terms of forecasting cholera risk, is the observed correlation between fall cholera incidence in Bangladesh and winter El Niño–Southern Oscillation events (e.g., Pascual et al. 2000; Koelle et al. 2005b; Pascual et al. 2008; Cash et al. 2008a, hereafter CRK08). Cholera incidence has been shown to increase following winter [December–February (DJF)] El Niño events, representing a possible basis for improving cholera risk forecasts (Pascual et al. 2008). The physical basis for this relationship is explored in CRK08 and Cash et al. (2009, hereafter CRK09), using a “pacemaker” model, in which SST is prescribed in a limited portion of the domain and determined by an ocean model elsewhere (e.g., Alexander 1992a,b; Alexander et al. 2002; Bladé 1997, 1999; Lau and Nath 2000, 2003; Rodé 2001; Shinoda et al. 2004; Wu and Kirtman 2004a,b). Taken together, CRK08 and CRK09 demonstrate that SST anomalies in the central and eastern tropical Pacific are the primary drivers of the global ENSO response, including increased cholera incidence, while anomalies in the western Pacific arise as a response. These studies also find that Bangladesh summer rainfall increases as a response to warm winter SST anomalies in the central and eastern tropical Pacific, providing a plausible physical link between winter El Niño events and cholera incidence in Bangladesh through increased flooding and breakdowns in sanitation (A. Dobson 2008, personal communication).

Increased Bangladesh summer rainfall occurs for warm–cold ENSO composites in all members of the CRK08 ensemble, as well as in the Chen et al. (2002) rainfall product, indicating that this is a robust response of the system. However, rainfall does not increase following every winter El Niño event in either the model or observations (e.g., Chowdhury 2003; Kumar et al. 2006)—with important implications for the use of ENSO in cholera forecasts (Pascual et al. 2008). Understanding which ENSO events are likely to impact cholera risk, as well as the influence of non-ENSO variability, will be crucial to providing useful and accurate forecasts of cholera risk.

The factors that modulate the response of the Bangladesh and Indian Ocean regional climate to ENSO are still not fully understood. Kumar et al. (2006) examines variations in the response of Indian monsoon rainfall to El Niño events during June–September (JJAS). El Niño events associated with drought conditions over India tend to be characterized by warmer SST in the central tropical Pacific and colder SST in the eastern tropical Pacific relative to El Niño events in nondrought years. The study also finds that rainfall increases over Bangladesh during these same Indian drought years (see their Fig. 2b), suggesting that central tropical Pacific SST represents an additional source of potential predictability for Bangladesh rainfall, and hence cholera risk. However, while idealized numerical experiments, presented in Kumar et al. (2006), support the hypothesis that central tropical Pacific SST anomalies influence Indian rainfall through shifts in the tropical Walker circulation, their experiments do not reproduce the observed increase in Bangladesh rainfall (see their Fig. 4b). It is thus not clear from their experiments if enhanced Bangladesh rainfall arises from the same mechanism.

In addition to differences in the structure of the SST anomalies in the tropical Pacific, the Indian Ocean may also affect the variability of Bangladesh rainfall. Anomalously warm temperatures in the southeast Indian Ocean (SEIO) (Terray et al. 2003, 2005, 2007) and central Indian Ocean (Yang et al. 2007) are associated with increased rainfall over India in both the observations and idealized numerical experiments. However, as with the influence of the central tropical Pacific, the effect on Bangladesh rainfall is ambiguous. Warm SEIO SST anomalies are clearly associated with reduced precipitation over Bangladesh in some simulations (Terray et al. 2007, their Fig. 8), while there is relatively little sensitivity of Bangladesh rainfall to warm Indian Ocean SST anomalies in others (e.g., Yang et al. 2007, their Fig. 5b).

One factor that complicates efforts to determine the influence of the Indian and tropical Pacific Oceans on Bangladesh rainfall and cholera is the potential for interaction between the two. Does the impact of the Indian Ocean depend on the current state and evolution of ENSO? Are model errors or Indian Ocean SST responsible for the differences between the modeled and observed response of Bangladesh rainfall to central tropical Pacific SST in Kumar et al. (2006)?

To help address these questions, particularly the effect of variations between El Niño events and how El Niño variability may be modulated by SST variations
elsewhere, we use the CRK08 pacemaker experiments to compare, in detail, differences in Bangladesh regional climate variations between different El Niño events and between the same event in different ensemble members. We make particular use of a unique feature of pacemaker ensembles, namely, that each ensemble member includes identical SST anomalies in the central and eastern tropical Pacific and freely varying SST elsewhere. Thus, differences between ensemble members are independent, by construction, of variations in SST in this critical region. This property allows us to determine, in part, which variations in the Bangladesh regional climate are attributable to variations in the forcing from the tropical Pacific, chaotic atmospheric variations, SST anomalies outside of the tropical Pacific, or a combination of all three.

The paper is organized as follows: The pacemaker model and analysis methodology are described in detail in section 2. Results and comparisons to observations and previous results are presented in section 3. Section 4 summarizes these results and discusses the implications for cholera risk and prediction.

2. Data and methodology

a. Pacemaker experiments

The model used in this study is described in detail in CRK08 and, hence, only briefly here. We use a regionally coupled, or pacemaker, model in which SST is prescribed in a limited portion of the ocean domain. Outside of the prescribed region a simple 50-m slab thermodynamic mixed layer model determines ocean temperatures. The atmospheric model consists of the Center for Ocean–Land–Atmosphere Studies (COLA) version 3.1 atmospheric general circulation model (AGCM) with 28 vertical levels and T62 horizontal resolution. This version of the AGCM is similar to the version 3.2 model described in detail in Misra et al. (2006).

We prescribe the observed record of monthly-mean SST from the Hadley Centre Global Sea Ice and Sea Surface Temperature version 1 (HadISST1) (Rayner et al. 2003) dataset in the central and eastern tropical Pacific (see Fig. 1). The transition between the prescribed and mixed layer domains is handled through a “blending region” in which the total SST is calculated from a weighted average of the prescribed and predicted SST. To prevent the model SST from drifting away from climatology we also prescribe an implied ocean heat flux, or $q$ flux, at all mixed layer points (including those within the blending region). This $q$-flux field is calculated from a separate 20-yr integration using prescribed climatological SST in the pacemaker region and a 60 W m$^{-2}$ K$^{-1}$ relaxation toward climatology in the mixed layer region. The annual cycle of monthly-mean restoring tendencies from the relaxation term is

![Fig. 1. Prescribed and blending regions used in pacemaker experiments. Shading denotes weighting of prescribed, observed SST from the HadISST dataset. Weighting is set to 1 in the tropical central and eastern Pacific and polar region.](image-url)
calculated for each grid point and introduced as an additional term in the pacemaker mixed layer temperature tendency equation, along with a much weaker $(10 \text{ W m}^{-2} \text{ K}^{-1})$ relaxation to climatology. It should be emphasized that the $q$-flux field has a fixed annual cycle and thus does not act to suppress variability in the simulated SST. Each experiment consists of an eight-member ensemble integrated from 1950 to 2002. Initial conditions for individual integrations are taken from a separate model run in which monthly SST from 1949 is prescribed perpetually in the pacemaker region. Each member of the ensemble is then initiated from a different December taken from this run.

b. Intraevent and intraensemble comparisons

While identifying a specific and repeatable response of Bangladesh rainfall and cholera to tropical SST anomalies would be of the greatest use in improving forecasts of cholera risk, this type of deterministic relationship is not the only one of potential value for cholera prediction. Improved understanding of shifts in the probability density function of rainfall and cholera risk associated with variations in SST would also be of use.

As noted in the introduction, a unique feature of ensembles of pacemaker integrations is that SST in the forcing region is identical for each member of the ensemble and is determined independently by an ocean model elsewhere. This is in contrast to both fully prescribed models, in which SST at a given point is identical for all members, and to fully coupled models, in which SST will differ between ensemble members for all points. Thus, because each member of a pacemaker ensemble experiences identical SST in the forcing region, any differences between ensemble members cannot be attributed directly to the influence of the forcing region. Differences between ensemble members at a given time must, instead, arise from (i) atmospheric noise or (ii) differences in boundary conditions outside of the forcing region. It is important to note that (ii) can include differences in SST in, for example, the Indian Ocean or North Pacific, despite the fact that the pacemaker model does not include a dynamical ocean model. These differences arise initially through chaotic atmospheric variability and may be reinforced by local air–sea interactions. It is also important to note that the influence of the forcing region may be modulated by both (i) and (ii), and thus contribute indirectly to differences in ensemble members.

Owing to this unique feature of the pacemaker methodology, analyzing differences between ensemble members has the potential to identify regions that modulate the impact of ENSO on Bangladesh, as well as regions that affect Bangladesh independently. These associations between difference fields can be quantified using a non-parametric paired-characteristics test (Kraft and van Eden 1968), as described below. Formally, let

$$P_{Bi} = P_{Bi} - \bar{P}_{Bi}^{ac}$$

$$\text{SST}'_{i} = \text{SST}_{i} - \bar{\text{SST}}_{i}^{ac},$$

where $P_{Bi}$ and SST$_i$ denote Bangladesh mean precipitation and SST in the $i$th member of the ensemble; superscript “$ac$” denotes the time-mean annual cycle (calculated separately for each ensemble member as the mean value for each month for 1950–2002). For convenience we drop the primes denoting anomalies in the following discussion.

For a given pair of variables (e.g., $P_{Bi}$ and SST$_i$) we determine whether certain characteristics, such as the sign and magnitude of anomalies, occur independently between the two variables. This test can be expressed through a table (see Table 1) where cell values denote the number of months in which the listed conditions are satisfied. If the rows and columns are independent, we expect the individual cell values to be approximately equal. The significance of any deviations from equality can be tested on a chi-squared distribution as

$$\chi^2 = \sum_{i} \sum_{j} \frac{[n_{i,j} - (n_{i} \bar{n}/N)]^2}{n_{i} \bar{n}/N}$$

where $n_{i,j}$ denotes the number of months in which the listed characteristics are satisfied.
TABLE 2. El Niño and La Niña years used in this study. Events are based on DJF values of the Niño-3.4 region index and are taken from the Climate Prediction Center (available online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). Years listed below are for January and February; event definitions include December values from the previous year.

<table>
<thead>
<tr>
<th>El Niño</th>
<th>La Niña</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958</td>
<td>1951</td>
</tr>
<tr>
<td>1964</td>
<td>1955</td>
</tr>
<tr>
<td>1966</td>
<td>1956</td>
</tr>
<tr>
<td>1969</td>
<td>1957</td>
</tr>
<tr>
<td>1970</td>
<td>1962</td>
</tr>
<tr>
<td>1973</td>
<td>1965</td>
</tr>
<tr>
<td>1977</td>
<td>1971</td>
</tr>
<tr>
<td>1978</td>
<td>1972</td>
</tr>
<tr>
<td>1983</td>
<td>1974</td>
</tr>
<tr>
<td>1987</td>
<td>1975</td>
</tr>
<tr>
<td>1988</td>
<td>1976</td>
</tr>
<tr>
<td>1992</td>
<td>1984</td>
</tr>
<tr>
<td>1995</td>
<td>1985</td>
</tr>
<tr>
<td>1998</td>
<td>1989</td>
</tr>
<tr>
<td></td>
<td>1996</td>
</tr>
<tr>
<td></td>
<td>1999</td>
</tr>
<tr>
<td></td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>2001</td>
</tr>
</tbody>
</table>

(see Table 2 for the list of events considered here). All results presented are significant at the 95% confidence level.

In the following discussion, this test will be used to address two specific questions.

1) **WHAT SST PATTERNS ARE ASSOCIATED WITH DIFFERENCES IN BANGLADESH RAINFALL BETWEEN EL NIÑO EVENTS?**

Previous results (CRK08) show that, in the ensemble mean, Bangladesh summer rainfall increases following winter El Niño events. However, the response to any given El Niño event is not necessarily increased rainfall (see Fig. 4a). Determining why the rainfall response differs between El Niño events is of great interest (e.g., Kumar et al. 2006). Following the discussion above, let

\[
P_{Bikl} = P_{Bi}(k) - P_{Bi}(l)
\]

\[
SST_{ikl} = SST_i(k) - SST_i(l),
\]

where \(i\) denotes the ensemble member, \(k\) and \(l\) are labels for the 14 individual DJF El Niño events from 1950 to 2002, and anomalies are calculated for all \(k < l\). For example, \(P_{B112}\) represents the difference in Bangladesh mean rainfall between the first and second El Niño events for the first member of the ensemble. As the differences in (3) are calculated between El Niño events, rather than between ensemble members, SST anomalies in the forcing region will not be zero. The paired-characteristics test is used in this case to identify differences between El Niño events that are significantly associated with variations in Bangladesh rainfall.

2) **WHAT SST PATTERNS ARE ASSOCIATED WITH DIFFERENCES IN BANGLADESH RAINFALL FOR IDENTICAL ENSO EVENTS?**

In addition to differences in the response of Bangladesh rainfall to different El Niño events, the response to a given El Niño or La Niña is not necessarily consistent across all members of the ensemble (see Fig. 6). This raises the question of whether these variations between ensemble members are purely chaotic or if they are attributable to differences in SST outside of the forcing region, such as in the Indian Ocean (e.g., Terray et al. 2007; Yang et al. 2007). Let

\[
P_{Bij} = P_{Bi} - P_{Bj}
\]

\[
SST_{ij} = SST_i - SST_j,
\]

where \(i\) and \(j\) range over the eight ensemble members, and paired differences \(ij\) are calculated for all \(i < j\). As noted previously, because differences are calculated for pairs of ensemble members, \(SST_{ij}\) is zero by construction in the pacemaker region. Thus, \(P_{Bij}\) is independent of the direct influence of SST in the highly influential central and eastern tropical Pacific. If the anomalies \(P_{Bij}\) are due entirely to chaotic atmospheric processes, then we expect to find no significant relationship between \(P_{Bij}\) and \(SST_{ij}\) as determined by (2). In contrast, if SST anomalies outside of the central and eastern tropical Pacific influence Bangladesh rainfall, then we expect to find regions for which we can reject the null hypothesis of no association between \(P_{Bij}\) and \(SST_{ij}\).

3. Results

a. **Observed and simulated rainfall**

It should be noted that there are significant disagreements between the published rainfall products in the Bangladesh region (Cash et al. 2008b). As a result, defining a “ground truth” rainfall for Bangladesh is not a trivial problem, and results may depend in part on the choice of rainfall product. Results presented here are from the Chen et al. (2002) product, which includes rain gauge observations within Bangladesh itself and agrees well with the densely observed Indian rainfall reported by the Indian Meteorology Department (Rajeevan et al. 2005).

There is considerable decadal variability in the observed response of June–August (JJA) Bangladesh rainfall to winter ENSO events. Composite anomalies (defined here as the mean difference in response between
warm and cold ENSO events) for the period 1976–2002 (Fig. 2a) are positive for Bangladesh and in excess of 1 mm day$^{-1}$. In contrast, Bangladesh anomalies are weaker in amplitude and opposite in sign for the period 1950–75 (Fig. 2b). It is unclear whether these changes arise entirely from chance or if they are related to the change in the ENSO–monsoon relationship known to have occurred in the mid-1970s (e.g., Kinter et al. 2002). This shift significantly complicates analysis of the ENSO–monsoon relationship by requiring either a reduction in the number of events considered or the inclusion of events with distinctly different characteristics.

In the case of linking climate to cholera we are additionally constrained to focus on the recent period in the observations, when the El Tor strain of cholera replaced “the Classical” strain in the environment during the mid-1970s, so the two strains may respond differently to environmental drivers (Koelle et al. 2005a).

As with the observed rainfall for the recent period (Fig. 2a), the model ensemble-mean composite precipitation anomalies in the Bangladesh region show a clear increase in rainfall throughout JJA over Bangladesh (Fig. 3) for the same period (Fig. 3a). The model does not reproduce the observed increase along the west coast of India, which is likely related to the poor representation of the Western Ghats in the model topography. In contrast to the
observations, the anomaly patterns for the 1976–2002 (Fig. 3a) and 1950–75 (Fig. 3b) periods are similar, although the amplitude of the 1950–75 anomaly is only ~50% of that found for the more recent era. Thus, the pattern of the precipitation anomalies in the model is relatively stationary over the entire period but the amplitude increases after 1975. Given that results for the pacemaker model are relatively similar in the two eras and that those results are consistent with the observations for our period of interest (1976–2002), in the remainder of this work we present results from the entire period 1950–2002.

It is not clear why the pacemaker model fails to reproduce the observed decadal variability in the ENSO–monsoon relationship, but it is perhaps not surprising. The pacemaker model includes information from the observations only in the central and eastern tropical Pacific. As a result, if the ENSO–monsoon relationship is affected by trends in SST outside of this region, it will not be reflected in the model. This difficulty in capturing the mid-1970s ENSO–monsoon transition has also been noted in other pacemaker studies (E. Jin 2008, personal communication).

Although the composite Bangladesh precipitation anomaly is positive for each member of the ensemble (see Fig. 6 of CRK08), there is considerable event-to-event variability. Bangladesh rainfall decreases following some El Niño events (Fig. 4a) and increases following some La Niña events (Fig. 4b). The ensemble-mean JJA precipitation anomaly over Bangladesh is thus not uniquely determined by the state of the tropical Pacific. In this the model is consistent with the observed rainfall anomalies, which do not have a one-to-one relationship with Pacific SST (e.g., Chowdhury 2003; Kumar et al. 2006).

b. Variations in rainfall between El Niño events

Given the sensitivity of the monsoon circulation to the distribution of SST anomalies associated with El Niño (Kumar et al. 2006), variations in SST in the central and eastern tropical Pacific likely contribute to the anomalous precipitation responses shown in Fig. 4. We test this hypothesis by applying the paired-characteristic test [section 2b(1)] to Bangladesh rainfall and SST ($P_{Bi}$ SST) for the 14 El Niño events in Table 2. We find that strongly enhanced Bangladesh rainfall (relative to other El Niño events) is significantly associated with strongly reduced SST in the SEIO and western Pacific and enhanced SST in the central tropical Pacific (Fig. 5a). These relationships generally hold true for March–May (MAM) SST and JJA Bangladesh rainfall as well (Fig. 5c), although the extent of the significant area is considerably reduced.

In contrast, reduced Bangladesh JJA rainfall following an El Niño event is associated primarily with strongly reduced JJA SST in the central and eastern tropical Pacific and is more weakly associated with the Indian Ocean (Fig. 5b). The same general region of the tropical Pacific, although again reduced in extent, is significantly associated with strongly reduced JJA Bangladesh rainfall during MAM (Fig. 5d). The region of SST significantly associated with strongly enhanced Bangladesh JJA rainfall is centered near 160°W, as opposed to 120°–140°W for reduced rainfall. Strongly enhanced JJA Bangladesh rainfall thus appears to be associated with greater persistence of warm SST anomalies in the central tropical Pacific into the summer months, while reduced rainfall is associated with a more rapid waning of the El Niño.
event in the eastern tropical Pacific. Differences in DJF SST between El Niño events are not significantly associated with JJA Bangladesh rainfall (not shown), indicating that the differentiation in the impact of winter El Niño events on Bangladesh rainfall comes from the evolution of the event, not the initial anomalies. Similar association patterns are obtained when weakly enhanced or reduced SST and rainfall are considered, although the strength of the association is greatly reduced (not shown).

Interestingly, the influence of the tropical Pacific on Bangladesh JJA rainfall is not limited to following winter El Niño events. We find the same association between the state of the central tropical Pacific and Bangladesh rainfall described in Fig. 5 (not shown) when we perform the same paired characteristics analysis for all model years, rather than limiting the analysis to summer months following winter El Niño events.

Taken together, the results of the paired characteristics tests are consistent with Kumar et al. (2006) in finding that the state of the central tropical Pacific during JJA plays a critical role in determining the response of the monsoon system, including Bangladesh rainfall, to El Niño. In addition, we have identified nonlinear aspects (differences in SST patterns associated with enhanced and reduced rainfall) and lagged relationships not noted previously. The lagged relationships with MAM SST identified in Figs. 5c and 5d are of particular interest, as they represent additional sources of potential predictability for Bangladesh rainfall and cholera risk.

c. Variations in rainfall between ensemble members

Following winter El Niño events, the majority of the ensemble members in the pacemaker model produce positive JJA Bangladesh precipitation anomalies (1969 is shown as an example in Fig. 6). However, it is also common for at least one member (see Fig. 6c) to produce large negative anomalies. Thus, even in the case where SST anomalies in the central and eastern tropical Pacific are identical, JJA Bangladesh precipitation can differ dramatically. It is clear that not all variations in

![Figure 5](image_url)
the simulated Bangladesh precipitation can be accounted for by the differences in tropical Pacific forcing described in section 3b.

Applying the paired characteristics test to differences between ensemble members for the same ENSO event (rather than between El Niño events as in section 3b), we find the region of strongest association between JJA Bangladesh precipitation and SST in the Indian Ocean (Fig. 7). Strongly enhanced precipitation is significantly associated with strongly reduced SST in the Indian Ocean and Bay of Bengal (Fig. 7a) and strongly reduced precipitation with strongly enhanced SST (Fig. 7b). The association patterns for enhanced and reduced JJA precipitation are near opposites, suggesting that the Indian Ocean has a more linear impact when isolated from the influence of the tropical Pacific (cf. to Figs. 5a and 5b). Differences in the location of the strongest centers of association between JJA rainfall and MAM SST are larger (Figs. 7c and 7d), indicating that the relationship is not fully linear. The area of significant association is reduced in MAM relative to JJA, with the absence of the Bay of Bengal suggesting that changes in this region arise as a response to the differences in the strength of the monsoon. The association between JJA Bangladesh precipitation and MAM SST in the SEIO indicates that this region, along with the central tropical Pacific, represents an additional source of potential predictability for Bangladesh rainfall and cholera risk over DJF Niño-3.4 values alone.

To test whether the SEIO influences JJA monsoon rainfall purely by modulating the influence of ENSO, rather than by altering the monsoon circulation directly, the paired characteristics analysis was repeated for a selection of ENSO-neutral years (not shown). When strong and weak anomalies are considered together, the patterns of association between Bangladesh rainfall and SST for these events were similar to those found following winter ENSO events (Fig. 7), consistent with an independent influence of the Indian Ocean on the monsoon (e.g., Ashok et al. 2004; Terray et al. 2003, 2005, 2007; Yang et al. 2007). However, the strongly enhanced and reduced association patterns are not identical in the ENSO and ENSO-neutral cases, and these differences will be explored in future work.

d. Dynamical analysis and discussion

While the patterns identified by the paired characteristics tests are indicative of a relationship between tropical SST and Bangladesh rainfall, they do not directly demonstrate an underlying dynamical mechanism. In addition, it is not obvious how to compare the association patterns with the results from previous modeling and observational studies (e.g., Kumar et al. 2006; Terray et al. 2003, 2005, 2007; Yang et al. 2007) that make use of the more common composite analysis.

To elucidate the dynamical links between the central tropical Pacific and Bangladesh rainfall suggested by the paired characteristics analysis (Fig. 5), we follow Kumar et al. (2006) in calculating composite velocity potential anomalies at 200 hPa for enhanced and reduced Bangladesh rainfall (Fig. 8). The composite is calculated using the same comparison of paired El Niño events described in section 2b(1) but without scaling the amplitude.
by the standard deviation. We find that three main centers of action dominate the velocity potential in the tropical belt, with positive anomalies to the west of India and negative anomalies centered over the region of enhanced SST identified in the tropical central Pacific by the paired characteristics analysis (Figs. 5a,c).

The pattern of velocity potential anomalies is remarkably similar in pattern and opposite in sign to that calculated by Kumar et al. (2006, see their Fig. 2b). Based on the similarity in rainfall, SST, and velocity potential, it is evident that similar dynamical mechanisms are operating in both the pacemaker model and the observations. Namely, anomalously warm SST in the central tropical Pacific drives changes in the tropical Walker circulation that act to suppress rainfall over India and enhance rainfall over Bangladesh [enhanced rainfall over Bangladesh is clearly evident in the Kumar et al. (2006) rainfall composite]. Composites and paired characteristics tests using an index of Indian rainfall confirm that the inverse relationship between Bangladesh and Indian rainfall holds in the CRK08 model as well (not shown).

Turning to the role of the Indian Ocean, observational studies and idealized CGCM experiments indicate that warm SST anomalies in the SEIO and central Indian Ocean during spring and summer are linked to enhanced Indian summer monsoon rains (e.g., Terray et al. 2007; Yang et al. 2007) through changes in the monsoon circulation.

To assess the dynamical impact of the Indian Ocean SST patterns identified by the paired characteristics test (Fig. 7), we calculate composite SST anomalies for the 32 ENSO events in Table 2 (the results are not sensitive to limiting the selection to El Niño events only). The composites are calculated by taking the difference in SST (and other fields of interest) between the ensemble members with maximum and minimum Bangladesh rainfall for each event. For SST (Fig. 9a), this produces
a well-defined cold SST anomaly across much of the Indian Ocean, very similar to the pattern from the paired characteristics analysis (cf. to Figs. 7a,b). The cold SST anomaly is associated with a region of high sea level pressure across much of the Indian Ocean, and high (low) pressure anomalies are found over India (Bangladesh) (Fig. 9b). These anomalies alter the 850-mb circulation (Fig. 9b) in such a way as to enhance moisture convergence over Bangladesh (not shown) and hence rainfall. This circulation pattern is generally opposite that found by Yang et al. (2007) for warm Indian Ocean SST anomalies (see their Fig. 5b), again indicating that the insights gained from the paired characteristics analysis of the pacemaker simulations are dynamically consistent with previous analysis of the observed links between tropical SST and rainfall over India and Bangladesh.

4. Summary and implications for cholera

In previous studies (CRK08; CRK09), we link variations in Bangladesh summer rainfall to ENSO events in the preceding winter, providing a physical basis for the observed correlation between cholera incidence and ENSO (e.g., Pascual et al. 2000; Rodó et al. 2002) and establishing a physical justification for the use of the Niño-3.4 index in forecasts of cholera risk (Pascual et al. 2008). However, although the mean observed and simulated response of Bangladesh rainfall to El Niño is positive for the period 1975–2002, the sign and magnitude of this response varies from event to event. Given that the response of Indian summer rainfall to ENSO is generally opposite in sign and likewise variable (e.g., Kumar et al. 2006), these variations in the response to ENSO hold significant implications for the entire Indian Ocean region. These variations also demonstrate that the relationship between tropical SST anomalies and the monsoon cannot be fully characterized solely by the sign and magnitude of the Niño-3.4 index.

In the work presented here we further develop the relationship between the regional climate of Bangladesh and tropical SST anomalies. Through paired characteristics analysis of the CRK08 pacemaker simulations, we find that Bangladesh summer precipitation is generally higher following winter El Niño events when the warm SST anomalies in the central tropical Pacific persist through the summer months. These results are consistent with the observation analysis of Kumar et al. (2006), who found that anomalously warm JJA SST in the central tropical Pacific leads to shifts in the tropical Walker circulation that reduce precipitation over India and enhance precipitation over Bangladesh. We also find that reduced Bangladesh rainfall is generally associated with a more rapid cooling of the eastern tropical Pacific, indicating that the response of the monsoon rainfall to SST is nonlinear.

Analysis of the pacemaker ensemble also identifies the southeastern Indian Ocean as a source of potential predictability for Bangladesh rainfall and cholera risk. As noted in the introduction, differences between ensemble members in a pacemaker model are, by construction, independent of the direct influence of SST anomalies in the influential central and eastern tropical Pacific region. This simplifies interpretation of our results significantly, as variations in the pattern and magnitude of tropical Pacific SST anomalies are a constant confounding factor in the comparison of ENSO events. Enhanced SST in the SEIO is associated with decreased rainfall over Bangladesh and increased rainfall over India. As with SST anomalies in the tropical Pacific, statistically significant associations between Bangladesh
FIG. 9. Composite (a) SST anomalies and (b) circulation (vectors) and sea level pressure (shading) for enhanced minus reduced JJA Bangladesh rainfall: shading interval is (a) 0.1° K and (b) 0.1 hPa.
summer rainfall are identified with spring SEIO SST anomalies, providing additional predictability for rainfall and cholera risk during the summer and fall, respectively.

The importance of the SEIO in determining cholera risk is further supported by lagged-rank correlation (see CRK08 for a detailed description of this technique) between the September cholera peak and May SST (Fig. 10). The SEIO is clearly identifiable as a region of statistically significant negative correlation between cholera and SST. Since rainfall provides a substantial part of the link between cholera and SST, this correlation is consistent with the SST association patterns (Figs. 7c,d) and composite SST anomalies (Fig. 9a). The lagged correlation is also consistent with the physical model presented here and elsewhere (e.g., Terray et al. 2007; Yang et al. 2007), namely, that colder SST in this region is associated with changes in the low-level monsoon circulation, leading to reduced monsoon rainfall over India and increased monsoon rainfall over Bangladesh.

The existence of sources of potential predictability for Bangladesh rainfall beyond El Niño has important implications for the modeling and forecasting of cholera risk. Given that local rainfall is a key mediator of the effect of ENSO on cholera, it seems likely that forecasts of cholera risk will be improved by considering the Niño-3 and Niño-4 indices separately, rather than focusing on the Niño-3.4 index alone. These indices more directly represent the critical central and eastern tropical Pacific regions (see Fig. 5). Our results also suggest that, while an initial cholera risk forecast can be made based on the state of ENSO during the winter months, the forecast should be updated in the spring based on the observed duration and intensity of the event in the tropical Pacific, as well as the state of the Indian Ocean. Given that there are significant associations between SST and the climate of Bangladesh throughout the summer months, a reasonable forecasting strategy would involve continuously incorporating information on the state of Pacific and Indian Ocean SST until forecast lag for the fall cholera peak is too short to be of practical value. However, it should be noted that initial efforts (Rajeevan and Pai 2007) to improve forecasts of Indian summer mean rainfall (ISMR) using an index of central tropical Pacific SST were generally unsuccessful, and the utility of these indices in forecasting cholera risk is the subject of ongoing research.

Acknowledgments. Support from NSF Grant EF-0429520 and NOAA Grant NA04OAR4600194 is gratefully acknowledged. XR also received funds from the Spanish MEC Project PANDORACGL-63053. We wish
to express our thanks to the three reviewers whose comments substantially improved the initial manuscript. All model calculations were performed on the Lightning compute cluster at NCAR.

REFERENCES


Kinter, J. L., III, K. Miyakoda, and S. Yang, 2002: Recent change in the connection from the Asian monsoon to ENSO. *J. Climate*, 15, 1203–1215.


Terray, P., P. Delecluse, S. Labattu, and L. Terray, 2003: Sea surface temperature associations with the late Indian summer


