Modulation of Sri Lankan Maha rainfall by the Indian Ocean Dipole

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[1] Investigating the September to December rainy season in Sri Lanka associated with the Maha rice growing season provides insights into the Asian monsoon during the boreal fall. Here, the modulation of the Maha rainfall by the tropical air sea coupled phenomenon referred to as the Indian Ocean Dipole (IOD) is documented. The Maha rainfall has a strong and robust association with the IOD from 1869 to 2000. The anomalously warm sea surface in the western Indian Ocean associated with the positive IOD phase induces large scale convergence in the lower troposphere extending to Sri Lanka leading to the preponderant enhancement of Maha rainfall.

INDEX TERMS: 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 9320 Information Related to Geographic Region: Asia; 9340 Information Related to Geographic Region: Indian Ocean.


1. Introduction

[2] While the boreal summer phase of the Asian monsoon has been well investigated through studies of the Indian summer monsoon rainfall, its behaviour during the other seasons has received less attention [Pant and Rupa Kumar, 1997]. During the fall, the zone of maximum rainfall migrates to southern-most India, Sri Lanka and the neighbouring sea. The rainfall during this period is of immense societal significance as it supports the main cultivation season known as Maha in Sri Lanka and Rabi in India. The Maha season cultivation starts sometime in September depending on the region and the harvest is around March. Water for sowing, transplanting and plant growth is supplied from the September to December rains [Zubair, 2002a]. The January to March period is relatively dry. We shall refer to the September to December rains as the Maha rains in keeping with local usage. The Maha rainfall is a combination of the influences of the monsoon, local thunderstorms from the southwestern passage [Zubair, 2002b] of the inter-tropical convergence zone (ITCZ), depressions and cyclones from the Bay of Bengal and orographic rainfall due to the island's topography.

[3] While the monsoon rainfall during summer in peninsular India usually decreases during El Niño events, quite the opposite happens in Sri Lanka and Southern-most India during the boreal fall [Rasmusson and Carpenter, 1983; Ropelewski and Halpert, 1987]. The October to December Sri Lankan rainfall shows a strong positive correlation with the basin-wide tropical Indian Ocean (IO) sea surface temperature (SST) which in turn was highly correlated with the El Niño/Southern Oscillation (ENSO) phenomenon [Suppiah, 1988].

[4] Recently, an ocean-atmosphere coupled phenomenon referred to as the Indian Ocean Dipole (IOD) has been documented [Saji et al., 1999; Webster et al., 1999]. The IOD is associated with an east-west gradient in the tropical IO SST anomalies. IOD is a seasonally phase-locked phenomenon that initiates in May, peaks in October and wanes by December. The positive phase of the IOD (associated with a warm SST in the West) leads to enhanced rainfall in Eastern Africa and diminished rainfall around Sumatra [Saji et al., 1999; Behera et al., 1999]. The IOD also modulates the relationship between Indian summer monsoon rainfall and ENSO [Ashok et al., 2001].

[5] Sri Lanka lies near the middle of this dipole, and it is not immediately clear what the influence of this dipole mode, if any, will be. Here, we address this question with diagnostic analysis of relationships between the Maha rainfall and SST, sea surface heights (SSH) and velocity potential ($\chi$) fields.

2. Data

[6] The following monthly data sets were used in the analysis; (1) monthly SST reconstructions from 1869 to

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Figure 1. (Left panel) Locations of rain gauges and (right panel) the mean (solid line) and standard deviation (dashed line) of the average rainfall.
2000 [Kaplan et al., 1998] (2) SSH from ocean data assimilation from 1950 to 1999 [Carton et al., 2000] (3) \( T \) = NCEP reanalysis [Kalnay et al., 1996]. These data were band-pass filtered between 5 and 90 months to represent the inter-annual variability clearly.

As customary, the ENSO index of NINO3 is defined as the average SST anomaly in the equatorial Pacific (90°W – 150°W; 5°S – 5°N). The NINO3 index is preferred over the Southern Oscillation Index as it represents the ENSO phenomenon more compactly [Soman and Slingo, 1997]. Saji et al., [1999] have defined an Indian Ocean Dipole Mode Index (IODMI) to characterize the IOD as the difference in the SST anomalies in the tropical western IO (50°E – 70°E; 10°S – 10°N) and the tropical south-eastern IO (90°E – 110°E; 10°S – 0°). In this paper, the index has been slightly modified by shifting the western pole to an overlapping region towards Sri Lanka (60°E – 75°E; 5°N – 15°N). This is because the SST observations before the mid-twentieth century in the south-western IO were sparse compared to that for the shipping lanes leading to Sri Lanka and Sumatra [Kaplan et al., 1998].] The two IODMI indices have a correlation of 0.9 over the last 130 years.

The rainfall data from 1869 to 2000 was obtained from the Sri Lanka Department of Meteorology for 16 stations that have long records (Figure 1) and are distributed in the different climatic zones [Suppiah, 1996; Suppiah, 1997]. A Maha rainfall index was constructed as the average of these measurements from September to December, a period in which the rainfall is fairly evenly distributed [Thambyapillay, 1954].

### 3. Results

The direct relationship of Sri Lankan rainfall with IOD is weaker during summer \( (r = 0.2) \) for JJA than during Maha. The ENSO influence on the Maha rainfall has been noted before. Hence, we shall describe the Maha rainfall-IOD relationship with some commentary on the rainfall-ENSO relationship.

Here, the technique of partial correlations [Fisher, 1925] was used to remove the SST patterns predictable from the contemporaneous ENSO state on the correlation between Maha rainfall and SST fields in a statistical sense. The partial correlation of variable 1 with 2 after the variance predictable from 3 is removed is estimated as

\[
r_{12 | 3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{1 - r_{13}^2}\sqrt{1 - r_{23}^2}},
\]

where \( r_{12} \) refers to the correlation

![Figure 2](image1.png)

**Figure 2.** The partial correlation between Maha rainfall with (a) SST anomalies from 1869 to 2000 and (b) SSH anomalies from 1950 to 1999 with the variance predictable due to NINO3 removed.

![Figure 3](image2.png)

**Figure 3.** The inter-annual variation of the Maha rainfall is shown color-coded as as per the intensity of the IODMI (top) and as per the intensity of NINO3 (bottom). Its standard deviation (\( \sigma \)) is shown as horizontal lines. Weak and strong events are taken to be departures of index exceeding 0.25\( \sigma \) and \( \sigma \) respectively. \( \sigma \) for IODMI and NINO3 is 0.30°C and 0.89°C respectively.

<table>
<thead>
<tr>
<th>Intensity</th>
<th>IOD</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Positive</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Weak Positive</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Neutral</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Weak Negative</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Strong Negative</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Intensity</th>
<th>IOD</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Positive</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Weak Positive</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Neutral</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Weak Negative</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Strong Negative</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

See Figure 3 for classifications of intensity.

### Table 1. Extreme Maha Rainfall Occurrences Classified by its Simultaneous IODMI and NINO3 Intensity. Wet and Dry Years Refers to Maha Rainfall Anomalies That Exceed \( \sigma = 45 \) mm/month

<table>
<thead>
<tr>
<th>Intensity</th>
<th>IOD</th>
<th>ENSO</th>
<th>IOD</th>
<th>ENSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Positive</td>
<td>0</td>
<td>1</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Weak Positive</td>
<td>2</td>
<td>0</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
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<td>7</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Weak Negative</td>
<td>9</td>
<td>8</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Strong Negative</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

See Figure 3 for classifications of intensity.
between 1 and 2. The dipole in partial correlation patterns in the tropical IO points to an IOD influence on the Maha rainfall (Figure 2a). The presence of a dipole structure in the partial correlation between the Maha rainfall and SSH in the tropical IO (Figure 2b) shows that the rainfall anomalies are strongly connected to the air-sea coupling [Rao et al., 2002a, 2002b].

[11] The interannual variation of Maha rainfall anomalies shows the strong relationship between IODMI and rainfall during both wet and dry years (Figure 3). The Maha rainfall preponderantly increases with El Niño and positive IOD phases and declines in the opposite phases. These rules are violated slightly more frequently for ENSO than IOD (Table 1). To establish the relative influence of IOD and ENSO, consider the variability of Maha rainfall when opposing influences from ENSO and IOD are expected. This would happen when one is negative and the other is positive. Of 13 such instances, the IOD influence is dominant preponderantly during 10 occasions (Table 2).

[12] The overall correlation of IODMI with the Maha rain ($r = 0.59$) exceeded the 99% significance level from 1869 to 2000. The correlation of Maha rainfall with the original IODMI index was similar ($r = 0.54$). The relationship held at a decadal scale with slight declines to the 95% level in the 1920s’ and 1980s’ (Figure 4). These declines were during periods of relative inactivity of the IOD phenomenon [S.A. Rao et al., manuscript in preparation, 2002]. The precise cause for this inactivity is not established as yet. The IOD can contribute to skillful probabilistic predictions of the Maha rainfall one season in advance, as the summer IODMI correlates highly ($r = 0.47$) with Maha rainfall, well exceeding the 99% significance level. The IOD influence on the Maha rainfall has exceeded that of ENSO with the exception of 1920s. The Maha rainfall has a 130 year-long correlation with NINO3 ($r = 0.50$) which exceeds the 99% significance level as well. However this relationship declines at the decadal scale in the 1890s’, 1910s’, 1930s’ and after 1950. These observations hold for shorter sliding-window lengths as well.

[13] The correlation between the IODMI and NINO3 from September to December is 0.61. The partial correlation between Maha rainfall and IODMI after removing the NINO3 contribution is 0.42 which exceeds the 99% significance level. The partial correlation between Maha rainfall and NINO3 after removing the IODMI contribution is 0.22 which is at the 95% significance level. This analysis brings out the significant role of IOD in modulating the Maha rainfall.

[14] To understand the dynamics that are involved in the Maha rainfall-IOD relationships, we constructed composite maps of the SST and $\chi$ for the six recent wet Maha’s (Figure 5). These maps bring out features in the tropical IO reminiscent of the canonical IOD structures [Saji et al., 1999] in the SST field (Figure 5a) and in the $\chi$ field (Figure 5b). In response, convection is enhanced over the western IO extending to Sri Lanka and suppressed over the eastern IO (correlation analysis of Maha rainfall with vertical velocity obtained from NCEP reanalyses bears this out). This results in an anomalous Walker-type circulation over

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**Table 2.** The Mean Rainfall Anomaly During Years Where ENSO and IOD Were in Different Phases During Maha is Tabulated

<table>
<thead>
<tr>
<th>ENSO</th>
<th>IOD</th>
<th>Mean Rainfall Anomaly</th>
<th>Years of IOD influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>Negative</td>
<td>-11 mm</td>
<td>6/8</td>
</tr>
<tr>
<td>Negative</td>
<td>Positive</td>
<td>+25 mm</td>
<td>4/5</td>
</tr>
<tr>
<td>Neutral</td>
<td>Positive</td>
<td>+10 mm</td>
<td>4/7</td>
</tr>
<tr>
<td>Neutral</td>
<td>Negative</td>
<td>-10 mm</td>
<td>8/11</td>
</tr>
</tbody>
</table>

The years in which IOD influence prevailed (negative IOD was associated with lower rainfall and positive with higher rainfall) is also tabulated.

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**Figure 5.** Composites of the (a) SST anomalies (°C) (b) $\chi$ anomalies ($\times 10^{-6} m^2 s^{-1}$) at 1000 hPa from September to November for six recent wet Maha seasons (1967, 1972, 1979, 1993, 1994, 1997). The composite rainfall anomalies [Xie and Arkin, 1996] for the four recent wet years are shown as contours in mm/day.

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**Figure 4.** The 31-year windowed sliding correlation of the Maha rainfall with NINO3 (dashed line) and IODMI (solid line).
the tropical IO leading to an increase in the Maha rainfall. The modulation of rainfall due to the IOD is brought out by superimposing the seasonal rainfall anomalies over the composite velocity potential during recent wet years (Figure 5b). During years with IOD but no ENSO, much the same SST and \( \chi \) anomalies prevail. Note, that simulations of the IOD with a coupled general circulation model [Iizuka et al., 2000] also led to a similar anomalous Walker-type circulation in the tropical IO and enhancement of Sri Lanka rainfall in the fall.

4. Conclusions

[15] We have documented the strong modulation of the Maha rainfall by the IOD phenomenon. The Maha rainfall-IOD correlation has exceeded the 99\% significance level and has only diminished to the 95\% level during the 1920s’ and 1980s’. The influence of the IOD on the Maha rainfall exceeded that of ENSO except during the 1920s’ a period of diminished IOD activity. The influences of IOD and ENSO is statistically inter-linked but we have shown that the IOD influence remains highly significant even if the influence of ENSO were removed and that its influence prevails preponderantly over that of ENSO when the two are in competition.

[16] The enhancement of Maha rainfall by positive IOD events is due to the anomalously warm SST’s in the western IO and the associated large-scale convergence extending to Sri Lanka. The convection arising from this convergence leads to enhanced rainfall over Sri Lanka. The opposite mechanism is at work during negative IOD events (not described entirely). These results show the direct influence of the IOD phenomenon on the Asian monsoon during the boreal fall: the season with the strongest IOD intensity. Work is continuing to extend these findings to neighbouring regions, to interrogate coupled global circulation model output along these lines and to develop predictions for the Maha rainfall.

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References


