Variability of precipitation/ convection over tropical oceans

OSICON-13
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Why is it important to understand the variability of organized convection/rainfall over the tropical oceans, even if one is interested primarily in the monsoon rainfall over the Indian region?
The CTCZ is maintained by genesis of cloud systems over the surrounding ocean and subsequent propagation onto the monsoon zone.
CTCZ is maintained partly by synoptic systems generated over the Bay which propagate onto the monsoon zone. The genesis of several of these can be traced to the West Pacific, which suggests a link of monsoon variability to the West Pacific as well.
Daily variation of latitudinal belts with low OLR along 70°, 80°, and 90°E during May-September, 2007
Teleconnections of the monsoon-interannual scale

Correlation coefficient between ISMR and OLR

June-September 1982-2012

Equatorial Indian Ocean Oscillation (EQUINOO)

El Nino & Southern Oscillation (ENSO)
Thus monsoon variability on the interannual scale is linked to the variability over the equatorial Indian Ocean, and the tropical Pacific as well as the Arabian Sea and large parts of the Bay.

Understanding the variability of convection/precipitation over these oceanic regions is, therefore, important.
• Variability of organized convection over these tropical oceans can depend on local as well as remote oceanic and/or atmospheric factors.

• Amongst the local factors, the sea surface temperature (SST) is the most popular candidate for understanding/explaining the variation of organized precipitation/convection over the tropical oceans, since the saturated vapour pressure at the surface varies nonlinearly with SST.
• It is important to note that it has also been suggested that the most important variable for determining the transition to strong convection over the tropics is the column water vapour, PWAT (Neelin et. al 2009, JAS).

• I shall discuss the relationship of the variability of precipitation and PWAT, at the end, if time permits.
Fig. 1. (a) Pickup of ensemble average precipitation $\langle P \rangle$, conditionally averaged by 0.3-mm bins of column water vapor $w$ for 1-K bins of the vertically averaged tropospheric temperature $\hat{T}$, for the eastern Pacific. Lines show power-law fits above the critical point of the form (2). (b) As in (a), but for 2-mm bins of the lower-troposphere integrated saturation value $\overline{q_{\text{sat}}}^{\text{LT}}$ for the eastern Pacific. Inset: As in (a), but for 5-mm bins of the vertically integrated saturation value $\overline{q_{\text{sat}}}$. 

Fig. 2. (a) Eastern Pacific ensemble average precipitation $\langle P \rangle$ ($w/w_c$) showing the collapse of the curves for all $\hat{T}$ when column water vapor is rescaled by the critical value $w_c$ for each $\hat{T}$. Inset: Log–log plot of $\langle P \rangle$ vs $(w - w_c)/w_c$ (for $w > w_c$), offset vertically for clarity; straight lines show the fit of (2) for $\beta = 0.23$. (b) As in (a) but for the Atlantic. Higher scatter because of fewer data counts at high $w$, but otherwise the curves conform closely to a single log–log form. Similar plots for the Atlantic.
Relationship of tropical convection/precipitation, with SST

- Half a century ago, Palmen suggested that SST has to be above a threshold of 26.5°C for tropical disturbances to intensify to tropical cyclones or hurricanes.
- In a pioneering study, Bjerknes* (1969) showed that the variation of monthly rainfall over Canton island in the central equatorial Pacific could be attributed to variations of SST.
Note that, generally the monthly rainfall is less than 10cm. However, there were periods when the monthly rainfall was sustained at a high level i.e., well over 10-50cm or several months, when the SST was above 28°C.
Systematic investigation of the variation of convection and its relationship with SST became possible only after the availability of satellite data.

In the first such study*, the relationship between monthly cloudiness intensity (determined from cloudiness index derived from satellite images) over the equatorial Indian Ocean, Bay of Bengal and Arabian Sea and the SST was investigated.

Relationship of cloudiness intensity and SST

- The following data for 1966-72 were analyzed by Gadgil et al. 1984
- (i) daily values of a cloudiness index (ranging from 1 to 9) each 2.5 degree squares over the tropics based on operational nephanalysis prepared by NESS, NOAA and compiled by Sadler and associates, and henceforth called Sadler index
(ii) monthly SST over oceanic regions between 40°-100°E north of 10°S, for 5 degree latitude-longitude grids, compiled by Joseph and Pillai* from voluntary observational fleet of over 40 maritime nations and stored at the National Data Centre of the India Met. Dept.

* Joseph P.V. and Pillai, P.V. 1984: Air-sea interaction on a seasonal scale over North Indian Ocean - Part I: Inter-annual variations of sea Surface Temperature and Indian summer monsoon rainfall, Mausam, 35,3,323-330.
A comparison of the daily distribution of Sadler index with the hemispheric mosaics analyzed by Sikka and Gadgil (1980) showed that synoptic and large-scale convection (such as the TCZ) is associated with Sadler index of 6 or larger. Hence in this study, the cloudiness intensity (henceforth CI) at any grid point for any month was calculated as the sum of the Sadler index for the days on which it was 6 or larger.
At each grid point for each month of the summer monsoon season (June-September) a pair of values for the Cloudiness intensity (CI) and SST were available for the seven seasons 1966-72.

There are 58 grids (each of 5° latitude-longitude) in the study area. Thus there are more than 1600 pairs of values of CI and SST.

The most straightforward way of depicting the relationship between CI and SST is a scatter plot (next slide) with the frequency of the points in each SST-CI bin indicated.
Note (i) most points to the right of AB, BC
(ii) A given CI occurs only for sufficiently high SST
(iii) For SST below about 27.5°C, there is a well defined value for the maximum CI, which increases linearly with SST, whereas above 27.5°C, there is a very large scatter. Thus SST above about 27.5°C is a necessary but not sufficient condition for high values of CI (above about 100)
Frequency distribution of cloudiness intensity for different SST ranges over the Indian Ocean, after Gadgil et. al. 1984

Note the shift of the mode across 27.5 °C
The probability of different values of CI for given SST ranges (next slide) also shows a marked change across 27.5°C.

Whereas the most probable CI (the mode) is zero for SST below 27.5°C, it shifts to about 40 units above this SST.

Gadgil et. al. concluded that SST of 27.5 or 28°C is a threshold for active generation of organized convection.

The propensity of convection is high for SST above the threshold and for SST below the threshold, the convection tends to get suppressed.
SST-OLR relationship

- Graham and Barnett’s (1987) analysis of a better data set on convection, viz. OLR, showed that this nonlinear relationship, first discovered by analysis of data over the Indian Ocean, is a basic feature of organized deep convection over the tropics.
- They used $5^0$ by $5^0$ averages of OLR for 5 day periods which were filtered to remove the 40-60 day (Madden-Julian) oscillation.
Scatter plot indicating the # of grid points with SST-OLR values in each bin based on co-located SST and OLR at 20 sites in tropical Indian and Pacific oceans

- Note the discontinuity at 27.5°C associated with OLR threshold of 240w/m²
- Note the large scatter in OLR values for SST above 27.5°C

Below $T_c$ the chance of OLR<240wm$^{-2}$ is negligible; above $T_c$, OLR could be between 280 to <200 wm$^{-2}$. 

Graham and Barnett 1987
Indian Ocean

For July 1982-98

Relationship is nonlinear and there is a large variation in OLR (from no convection to intense convection) for SST>27.5°C
Major results:

1. high propensity for organized convection over warm oceans with SST above about 27.5 or 28\(^\circ\) C, called the threshold, \(T_c\).

2. When the SST is above \(T_c\), the cloudiness intensity/OLR varies over a large range from almost no convection to intense deep convection.

3. The relationship is nonlinear as also seen in the variation of the mean OLR with SST.

Results also valid for precipitation
Observed relationship between rainfall and SST for June, July, August during 1979-2009 for the Indian Ocean (IO, a, b, c), NINO3.4 (d, e, f), and West Pacific Ocean (WPO, g, h, i).

From Rajendran et. al 2012
Understanding the mean seasonal rainfall patterns
Correlation of the rainfall with local SST

• Given the non-linear nature of the SST-convection/precipitation relationship, it has been suggested that a linear measure such as the correlation coefficient is not appropriate.

• In fact, Gadgil et. al (1984) have shown that the correlation of the cloudiness intensity with SST depends on the SST range, and is negligible for SSTs above $T_c$ (next slide).
Table 1  Correlation between SST and degree of cloudiness over Indian Ocean

<table>
<thead>
<tr>
<th>SST greater than (°C)</th>
<th>No. of data points</th>
<th>Correlation coefficient (±95% confidence limits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.5</td>
<td>1,602</td>
<td>0.564 ± 0.034</td>
</tr>
<tr>
<td>25.0</td>
<td>1,568</td>
<td>0.548 ± 0.035</td>
</tr>
<tr>
<td>25.5</td>
<td>1,502</td>
<td>0.517 ± 0.037</td>
</tr>
<tr>
<td>26</td>
<td>1,418</td>
<td>0.468 ± 0.041</td>
</tr>
<tr>
<td>26.5</td>
<td>1,340</td>
<td>0.418 ± 0.045</td>
</tr>
<tr>
<td>27</td>
<td>1,212</td>
<td>0.364 ± 0.050</td>
</tr>
<tr>
<td>27.5</td>
<td>1,064</td>
<td>0.282 ± 0.056</td>
</tr>
<tr>
<td>28</td>
<td>823</td>
<td>0.183 ± 0.067</td>
</tr>
<tr>
<td>28.5</td>
<td>468</td>
<td>0.094 ± 0.092</td>
</tr>
<tr>
<td>29</td>
<td>190</td>
<td>0.01</td>
</tr>
</tbody>
</table>

From Gadgil et. al 1984
A: 90° E, 5° N
SST is always maintained above the threshold. The OLR is independent of SST

C: 50° E, 15° S
The SST varies from 24°C to above the threshold. OLR is above 240 Wm⁻² when the SST is below the threshold but varies between 210 Wm⁻² to 260 Wm⁻² similar when it is above the threshold.

Graham and Barnett 1987
Graham and Barnett (1987) have pointed out that “One might be tempted to fit a sharp looking curve to the distribution which suggests a strong dependence of convection on SST. However, associations between SSTs and OLR for SSTs above 28°C at applicable locations suggest that the dependence of the level of convection in this temperature range is usually slight.”

They further suggested that when the SST is maintained above the threshold, convection is determined by the low level convergence. Thus above the threshold the SST is no longer the limiting resource but dynamics can be.
**Fig. 6.** Mean OLR values (contoured at 5 W m$^{-2}$ intervals) for 0.5°C SST bins (vertical axis) and 10 × 10$^{-7}$ sec$^{-1}$ surface wind divergence bins (horizontal axis, negative values indicate convergent surface flow) for locations used to prepare Figs. 2 and 5. OLR values in less than 240 W m$^{-2}$ are shaded. Note the increasingly close relation between divergence and convection when SSTs are above 28°C.
Observations: monthly scale

GPCP and HadSST ERA 40 reanalysis 1979-2002
SST < 27.5°C

(i) BoB
γ = 0.21

(ii) NINO3.4
γ = 0.84

Conv. at 850 hPa (x10^3)

γ = 0.07

γ = 0.45

Rainfall (mm/day)

γ = 0.54

γ = 0.60

SST < 27.5°C

blue dots
• The analysis I have considered so far has been of the variability of the rainfall and local SST for monthly scales and of association i.e. relationship at zero lag.

• Roxy (2013)* has suggested that considering monthly time-scales with no lead/lag are major lacunae and has considered variation on daily time-scale and with lead/lag between SST and precipitation.

• *’Sensitivity of precipitation to sea surface temperature over the tropical summer monsoon region—and its quantification’, Mathew Roxy

‘Based on this assessment’ (i.e. of Gadgil et. al and Graham and Barnett that if SST is maintained above the threshold, the dependence of the level of convection on the local SST in this SST range is slight) ‘it has often been presumed that, since the mean SSTs over the Asian monsoon basins (Indian Ocean and north-west Pacific) are mostly above the threshold, SST does not play an active role on the summer monsoon variability. It also implies that increasing SSTs due to a changing climate need not result in increasing monsoon precipitation.’
• Note that the earlier studies only discuss the relationship of convection over such ocean basins to local SST and not of the summer monsoon rainfall over land with the SST over the surrounding seas.
• I believe (and will discuss later in the talk, why) that the implications for the impact of increasing SST associated with changing climate on the monsoon rainfall cannot be derived by merely considering relationship of convection/rainfall with local SST in the present climate.
‘The current study using a novel perspective, points out the illogicality behind it (earlier approach), and draws out a new figure for the SST-precipitation relationship. The study, taking into account the appropriate lead/lags between SST and precipitation at each monsoon basin, shows that precipitation increases throughout the range of observed SSTs over these basins (26–31 C) and that there is no upper threshold for such a relationship -- the current study quantifies the relationship—a 2 mm/day increase in rainfall for every 1°C rise in SST, consistent across all the monsoon basins, both for the observations and the model simulations.’ Roxy 2013 I consider next these claims.
‘Instead of using monthly data, daily data with appropriate lead-lags, for each basin, are utilized to re-examine the co-variability between SST and precipitation. This is based on the realization that the SST-precipitation relationship has a lag, that too with a spatial variability, over the monsoon basins.’

‘The implications with respect to the above mentioned hypothesis (i.e. hypothesis of Gadgil et al., Graham & Barnett etc.) are critical for the Asian summer monsoon since the SSTs over the monsoon basins (e.g.: Indian Ocean, west Pacific) during summer is mostly above such a threshold. ’

I focus here on the Bay of Bengal for which the SST during summer is mostly above such a threshold.
It should be noted that while the earlier studies generally considered the relationship of convection/precipitation with the local SST (i.e. over regions of a grid scale ranging from 250km to 500km), Roxy (2013) considers averages over much larger regions.
SST-rainfall association for different spatio-temporal scales

Average over BOB  Monthly  2.5° grids of BOB

Ave BoB (85-95°E; 5°S-20°N) JJAS

Rainfall (mm/day)

SST (°C)

Grid BoB (85-95°E; 5°S-20°N) JJAS

Rainfall (mm/day)

SST (°C)
SST-rainfall association for different spatio-temporal scales

### Monthly

- **Ave BoB (85-95E; 5-20N): JJAS (1998-2013)**
  - TRMM
  - $\gamma = 0.18$

### Average over BOB

### Daily

- **Ave BoB (85-95E; 5-20N): JJAS (1998-2013)**
  - TRMM
  - $\gamma = -0.06$
The perception of the relationship completely changes when the inherent lag is considered for examining the co-variability.

The lags at maximum regression coefficient are 5, 10 and 12 days in observations, for AS, BoB and SCS, respectively.

Arabian Sea (AS, 63–73E), Bay of Bengal (BoB, 85–95E) and the South China Sea (SCS, 110–120E) over 5-20N; period:1998-2011.
Correlation between SST and rainfall

Note: the maximum mag. of the correlation coeff. when SST leads Prec. for unfilt and one fil. case is about 0.2 (and one fil. case is 0.3). Thus only 4% of the variance is explained by this relnship.

10-90 Bandpass filter (Roxy et al 2012)
20-100 day bandpass filter (as suggested by CLIVAR MJO diagnostics of Waliser et al 2009 and used by Arun Kumar et al 2013, Wu et al 2008, COLA report)
Change in pattern of AS
Another look at daily scale variation

Counts with 0.25 °C bins
Bay of Bengal (BoB) 85-95E; 5-20N

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std Dev</th>
<th>Corr Coeff</th>
<th>Slope (mm/day/C)</th>
<th>Unexp Variance (%)</th>
<th>RMSE mm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST leads P</td>
<td>8.40</td>
<td>4.68</td>
<td>+ 0.08</td>
<td>+ 0.6</td>
<td>98.55</td>
<td>4.66</td>
</tr>
<tr>
<td>10 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SST leads P</td>
<td>8.46</td>
<td>4.76</td>
<td>- 0.06</td>
<td>- 0.7</td>
<td>98.59</td>
<td>4.75</td>
</tr>
<tr>
<td>0 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Note that only about 1.4 % of the variance is explained by the line fit in each case.
• The slope of the fitted line is \(-0.7\text{mm/day}/^\circ\text{C}\) for zero lag and \(+0.6\text{ mm/day}/^\circ\text{C}\) for 10 day lag, whereas the root mean square errors of the linear fit is 4.75 and 4.66 mm/day respectively, because the scatter is so large.
• Hence the linear fit is not representative of the SST-rainfall relationship in either of the two cases.
Same holds for AS as well

<table>
<thead>
<tr>
<th></th>
<th>Mean (mm/day)</th>
<th>Std Dev (mm/day)</th>
<th>Corr Coeff.</th>
<th>Slope (mm/day/C)</th>
<th>Unexp Variance (%)</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST leads P 5 days</td>
<td>3.47</td>
<td>3.88</td>
<td>+ 0.37</td>
<td>+ 2.4</td>
<td>84.09</td>
<td>3.69</td>
</tr>
<tr>
<td>SST leads P 0 days</td>
<td>3.69</td>
<td>4.23</td>
<td>- 0.34</td>
<td>+ 2.6</td>
<td>87.04</td>
<td>3.99</td>
</tr>
</tbody>
</table>
Another such example

The linear fit to the plot has a slope (-0.26 mm/day/°C). The rms error of the linear fit is 0.11 mm/day, close to the rms of the precipitation variance, 0.12 mm/day. Hence, the linear fit is not representative of the relationship between precipitation and SST anomalies. The linear correlation coefficient between the CMAP precipitation and SST anomalies is 0.38.

Su and Neelin, 2003, *The Scatter in Tropical Average Precipitation Anomalies, J. Climate*
Thus considering lead-lags on the daily scale has not in any way changed the SST-rainfall relationship from that of association i.e. no lead or lag.

The large scatter around any fitted line/s implies that the SST-rainfall relationship is extremely weak, whether there is lag or not.
Impact of SST increase associated with global warming

- Roxy concludes (on the basis of the slope of the fitted line of 2mm/day/°C for the SST-rainfall relationship) that
- ‘Though recent studies suggest a weakening of the monsoon circulation over the last few decades, results here suggest an increased precipitation over the tropical monsoon regions, in a global warming environment with increased SSTs.’
Impact of cold SST bias

AR4 AGCM and CGCM

Rajendran et. al 2012
High-resolution models suggest that the related sea surface temperature threshold for tropical cyclones rises in a warming climate. From an analysis of 30 years of satellite data, Johnson and Xie (2010)* show that there is nearly perfect correspondence between changes in tropical mean SST and SST threshold for convection which suggests that the fractional area of the tropical oceans that is convectively active may change little, despite the projection of a substantial increase in boundary-layer moisture in a warmer climate.
The variability of the tropical SST threshold for convection is robust and clearly detectable in both observations and in global climate models. Thus it is not clear that impact of increase of SST due to global change can be derived by considering the SST-rainfall relationship in the present climate.

* Johnson and Xie, ‘Changes in the sea surface temperature threshold for tropical convection’ NATURE GEOSCIENCE VOL 3 DECEMBER 2010
Acknowlegdements

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Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) Datasets

Datasets: Sea Surface Temperatures and Rain Rates as average of 3 days ending on and including file date

Coverage: Global region extending from 40S to 40N

Resolution: Pixel resolution of 0.25 deg (~25 km)

Period: 1998-2013
Season: JJAS
Ref: Wentz et al 2000
SST bins: 0.25C