A variable sea surface temperature threshold for tropical convection

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(Manuscript received December 2013, Revised November 2014)

Sea surface temperatures (SSTs) contribute to modulation of deep convection over tropical oceans. Using a threshold value of outgoing long-wave radiation (OLR) as a proxy for deep tropical convection, regional and temporal relationships between SST and deep convection and its variability are examined.

Based on this approach, an SST threshold of 27.5°C for deep convection across the global tropics is identified; this is in agreement with the critical SST of around 27°C for the onset of tropical deep convection identified in previous studies. Monthly and regional variations in the critical SST threshold ($SST_{\text{MON-CRIT}}$) required for the onset of deep tropical convection are also identified. $SST_{\text{MON-CRIT}}$ exhibits interannual and seasonal variations for each of the monsoon regions analysed here. It varies between regions consistent with the mean SST of that region, so is higher in the Pacific than the Atlantic. Further, within a region, the critical SST threshold for convection is cooler in the wet season than the dry. The threshold SST in each region is generally a good proxy for convective activity in the wet season, but this connection breaks down in the dry season. The impact of atmospheric divergence in suppressing convection is much more evident in the dry season. Thus, the applicability of SST as a predictor of convection varies with atmospheric forcing, by region and by season and so we conclude that an absolute SST threshold is not a robust metric for tropical deep convection. Theses results have implications for understanding the distribution of tropical cyclogenesis in varied climate regimes.

Introduction

Tropical deep convection is integral to the global general circulation, transporting moisture and heat away from the tropics (e.g. Malkus 1963; Evans and Jaskiewicz 2001; Zhou and Cui 2006, Hoyos and Webster 2012). Sea surface temperatures (SSTs) play an important role in modulating convection over tropical oceans (e.g. Gadgil et al. 1984; Zhang 1993; McBride and Fraedrich 1995). Graham and Barnett (1987) find that for large (500–1000 km) spatial scales and long (1–2 months) temporal scales, a critical SST of 27.5°C is a necessary but not sufficient condition for deep convection in the tropical Indian and Pacific Oceans. Convection is suppressed in regions of persistent low-level divergence even when the SST exceeds this threshold (e.g. Graham and Barnett 1987; Zhang 1993), so SSTs above a critical threshold value are a necessary but insufficient condition for active deep convection over the tropical oceans. A threshold SST of around 26.5°–27.5°C for tropical cyclone (TC) genesis has long been recognised (e.g. Miller 1958; Gray 1968). The source of this value is best explained by its coincidence to the SST threshold for active convection (e.g. Evans 1993; Dutton et al. 2000; Waters et al. 2012), so insights into the behavior of this SST threshold are helpful when inferring likely variations in TC activity across regions.

Analyses of the links between SST and tropical deep convection provide a context for inferring potential changes in tropical deep convection in a changing base climate. Johnson and Xie (2010) analyse observed secular trends in the mean tropical SST (20°N to 20°S) and SST required for convection over the period 1980–2010. Applying the same analyses to CMIP3 simulations, they suggest that this upward trend will continue. Hoyos and Webster (2012) take this analysis further, analysing trends in tropical SST over the
period 1910–2004 and relating these to changes in the tropical warm pool (defined either as a region exceeding a selected SST threshold, or a region of positive vertically-integrated convective heating). Using these observed relationships to perform corrections to climate model simulations of palaeoclimates (Mid-Holocene and Last Glacial Maximum) and IPCC3 future climate regimes, Hoyos and Webster (2012) infer that the SST threshold for deep convection varies with the underlying base climate. Evans and Waters (2012) analyse a set of transient CO$_2$ simulations from IPCC4 (Randall et al. 2007) that span a wide range of realised warming (a wide range of model climate sensitivity). They demonstrate that the critical SST for tropical deep convection increases as the climate warms, and that the threshold increase is comparable with the mean global surface temperature increase. The findings from both of these studies are consistent with those from an earlier study by Dutton et al. (2000). In all cases, even though the zone of SST exceeding 27°C expands poleward, the spatial coverage of deep convection in the wider tropics (40° S to 40° N) is stable.

Reflecting on the results of these climate change simulations, we see that (1) the Coupled General Circulation Models (CGCMs) are capable of reproducing the climatological relationship between deep convection and underlying SST and (2) that this threshold varies in different base climates. The question arises: how does the SST threshold for deep convection in the present climate vary regionally and seasonally across the global tropics? We explore the interaction of deep convection with the underlying SST by making use of modern, high-resolution datasets.

Table 1. Spatial coverage of the regions analysed (see also Fig. 1).

<table>
<thead>
<tr>
<th>Region</th>
<th>Bounding latitudes/ longitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended tropics and sub tropics</td>
<td>40° N – 40° S</td>
</tr>
<tr>
<td>Global tropics</td>
<td>22° N – 22° S</td>
</tr>
<tr>
<td>Asian Monsoon (North Indian Ocean to South China Sea)</td>
<td>0°–22° N, 50°–125° E</td>
</tr>
<tr>
<td>West Africa</td>
<td>0°–22° N, 50° W–10° E</td>
</tr>
<tr>
<td>Australian Monsoon</td>
<td>22° S–0°, 90°–180° E</td>
</tr>
</tbody>
</table>

Fig. 1. Boundaries of the Asian (red), African (blue) and Australian (purple) monsoon regions used here (Table 1). All points in the 1° x 1° grid (Section 2) with a non-zero land fraction are excluded from these analyses.

Fig. 2. Monthly averaged daily minimum OLR binned by monthly average SST. Data cover all ocean gridpoints (1° resolution) in the tropical domain (22° S–22° N) for every month in the period July 2002 through October 2005. OLR is plotted decreasing upward so ‘high’ values correspond to cold cloud tops and intense convection. The left axis is the population mean OLR (95% confidence interval) for each 0.5°C (crosses), while bin populations (dashed line) are plotted on the right axis.
These analyses provide a contemporary benchmark for projections of changes in tropical convection characteristics in a changing climate.

**Analysis Methodology**

Variations in the intensity, spatial and temporal distribution of deep convection in the tropics and subtropics and its relationship to the underlying SST distribution and structure of the tropical atmosphere are analysed for the period July 2002 through October 2005. We utilise outgoing longwave radiation (OLR) as a proxy for deep convection: lower OLR values correspond to more active convection with deeper vertical extent and cooler cloud tops, while higher values represent low clouds or clear sky.

To infer convection characteristics, we employ satellite-derived OLR from the Terra datasets. These data have global coverage at 1° spatial and three hourly temporal resolution (Wielicki et al. 1996). We use a critical threshold of OLR < 220 W m\(^{-2}\) to diagnose regions of deep convection; this threshold is intermediate between that used by Graham and Barnett (1987) and in other studies of organised convection (e.g. Evans and Shemo 1996; Evans and Jaskiewicz 2001). Sensitivity analyses for the choice of OLR critical threshold were performed using a variety of summary statistics (see below): they confirm that our results are stable across both the range of OLR threshold values used in earlier studies and the choice of reference statistic for identifying the threshold SST. Thus, only results for the 220 W m\(^{-2}\) OLR threshold

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Analyses of the observed SST utilise the NOAA global daily SST database with 0.25° spatial resolution (Reynolds et al. 2007). The daily SST is sub-sampled to the same 1° x 1° grid as the OLR data. Lower- (950 hPa) and upper- (250 hPa) tropospheric environmental divergence is calculated from the ERA-Interim monthly means of daily means; these ERA analyses have global coverage at 1.5° spatial, and monthly temporal, resolution (Dee et al. 2011).

Five domains of interest are examined to characterise the convective activity around the tropics (Fig. 1, Table 1). SST values are for ocean-only data, so all points on the 1° x 1° grid with any land attributed are excluded from the analyses.

To examine the timing (on daily and monthly timescales) of the most active convection in each region, daily-average and daily minimum OLR values are obtained from the three-hourly OLR data and the hour of the minimum OLR is recorded; the monthly-averaged minimum OLR is determined from these daily minima. Collocated OLR and SST pairs are binned by 0.5°C SST increments and summary statistics for the OLR in each bin are calculated: mean (and 95 per cent confidence interval on this mean), median, quartiles, interquartile range (IQR), outliers (more than 3 times IQR from the mean) and population. These statistics are examined for the global tropics over the entire study period (Fig. 2) and at monthly resolution for each monsoon region (e.g. Fig. 3 for the Asian monsoon).

Fig. 4. Time series of the monthly critical SST ($SST_{MON-CRIT}$, symbols) and area mean SST (thin solid line) for the (a) Asian, (b) African and (c) Australian monsoon regions. Wet and dry regimes are denoted by blue circles and red diamonds respectively; + marks the remaining months in which the median OLR < 220 W m$^{-2}$. If the monthly-averaged OLR exceeded the 220 W m$^{-2}$ threshold, data from that month are not plotted.

Fig. 5. Sensitivity of critical SST threshold definition to the averaging period for the Asian monsoon region. The averaging period is varied between (a) 5 days and (e) 25 days at 5 day increments. The cut-off SST for the wet (lowest third, circles) and dry (highest third, diamonds) regimes changes slightly as the averaging period increases but this does not have a significant impact on the regime partitions. Averaging periods in which the median OLR value did not fall below the 220 W m$^{-2}$ OLR threshold are not plotted.

Specifically, we use the GHRSSST Level 4 NCDC AVHRR_AMSR_OI dataset.
For each month of the study and each of the regions (Table 1), the SST at which the median of the daily OLR decreases below the 220 W m\(^{-2}\) OLR threshold is recorded; these SST values are calculated using a weighted linearly interpolated across bins (Fig. 2). The resulting regional time series of ‘monthly critical SST’ (\(SST_{\text{MON-CRIT}}\)) (Fig. 4) tracks variations in the monthly-sampled SST threshold above which deep convection is observed to occur. The monthly sampling period is chosen to emphasise the annual cycle, however consistent results are obtained for sampling periods from five days to one month (e.g. Fig. 5).

Results

Beginning from a tropics-wide perspective (Fig. 2), OLR is relatively constant as SST increases toward 26°C, corresponding to clear skies over cool SST. Convective activity begins to increase (OLR begins to decrease) for SSTs warmer than 26°C, and active deep convection becomes prevalent (OLR < 220 W m\(^{-2}\) threshold) between 28°C and 28.5°C (Fig. 2); the minimum in OLR occurs around 30°C SST. These results are in agreement with previous studies of the global tropics (e.g. Zhang 1993; Hoyos and Webster 2012).

Analyses of \(SST_{\text{MON-CRIT}}\) (Section 2) for the individual monsoon regions (Fig. 1) reveal seasonal (Fig. 3) and regional (e.g. Fig. 4) variability in this threshold. An annual cycle is evident in the regional-mean SST in each of the monsoon regions (Fig. 4, solid lines). For each region of interest, we divide the study period into low, medium and high values of \(SST_{\text{MON-CRIT}}\) corresponding to wet, average and dry precipitation months. This SST-based partition generally captures the wet and dry season rainfall variability across multiple years and regions (e.g. Fig. 3).

The observed SST/OLR relationship is illustrated for a wet month (Fig. 3a, July 2004) and a dry month (Fig. 3b, April 2004) in the Asian monsoon region. \(SST_{\text{MON-CRIT}}\) is 27.5°C for the wet regime and the region is dominated by \(SST > SST_{\text{MON-CRIT}}\) (mode is 29°C; Fig. 3(a)). \(SST_{\text{MON-CRIT}}\) in the dry regime is warmer than the wet, at 30.0°C, consistent with the generally warmer SSTs across the domain (population distribution shifted to the right in Fig. 3b compared to Fig. 3a).

The difference between the regional-mean SST and \(SST_{\text{MON-CRIT}}\) is also generally larger in the dry periods compared to the wet (Fig. 4a). These tendencies are consistent across regions and seasons (Fig. 4): months with lower \(SST_{\text{MON-CRIT}}\) (the wet partition; e.g. Fig. 3a) have a higher fraction of active convection events (OLR < 220 W m\(^{-2}\)). \(SST_{\text{MON-CRIT}}\) is warmer for the dry partition (Fig. 3b) than for the wet (Fig. 3a), while the regional-mean SST is generally cooler in dry periods (Fig. 4). The coincidence in dry periods of cooler mean SST and higher \(SST_{\text{MON-CRIT}}\) for convection leads to constrained areas of intense convective activity over anomalously warmer water. In contrast, regional-mean SST is higher and \(SST_{\text{MON-CRIT}}\) is lower in wet periods compared to dry (Fig. 4), so that the SST threshold for convection is satisfied over a larger proportion of the region.

Composites of the wet and dry partitions for the Asian monsoon region are used here to illustrate the variation of OLR with 950 hPa and 250 hPa divergence and SST (Fig. 6). Active convection (OLR < 220 W m\(^{-2}\), light blue shading through cool colors) is confined to regions of upper-level divergence in both the wet and dry regimes, but convection occurs in far more constrained conditions in the dry regime (left) compared to the wet (right). In the dry regime, convection is confined to areas of increasingly strong 250 hPa divergence and 950 hPa convergence as SST decreases. For example, when SST < 29 °C in the Asian monsoon composites shown here, active convection is only indicated (light blue shading through cool colors) when 250 hPa divergence exceeds 20 x 10\(^{-2}\) s\(^{-1}\) or 950 hPa convergence exceeds 30 x 10\(^{-7}\) s\(^{-1}\). The thin lines in Fig. 6 enclose areas of the data with bin populations exceeding 50 samples, so these tendencies are robust.

Conditions for active convection are more readily achievable in the wet regime—the 220 W m\(^{-2}\) OLR threshold signifying active convection (light blue shading in Fig. 6) occurs at cooler SST. Incidence of deep convection varies with both SST and 250 hPa divergence in the wet regime, but convection is indicated over a much wider range of values for low-level convergence.

Clearly, the atmospheric conditions favorable for active convection are more common in the wet regime compared to the dry.

Discussion

In this study, we derive time series of threshold SST (\(SST_{\text{MON-CRIT}}\)) for the onset of widespread tropical convection (OLR < 220 W m\(^{-2}\)) for the global tropics and for three monsoon regions (Fig. 1). We confirm a tropics-wide SST threshold for widespread active convection around 28°C, consistent with the threshold SST identified as a necessary but not sufficient condition for tropical cyclogenesis in the current climate (e.g. Miller 1958; Gray 1968; Evans 1993). We employ \(SST_{\text{MON-CRIT}}\) to partition the 40 months of the study period into three subsets (wet, average and dry regimes) for each of five regions. \(SST_{\text{MON-CRIT}}\) is found to be lower in the wet regime compared to the dry regime at a given location and SST > \(SST_{\text{MON-CRIT}}\) is satisfied over the majority of each monsoon region in the wet regime but not the dry (Figs. 3–5). Inter-ocean variations in \(SST_{\text{MON-CRIT}}\) are in line with the relative climatological SST distributions between the tropical oceans: the mean SSTs and SST variability are largest in the Asian monsoon zone and the overall SST and its range are lower for the African monsoon region (Fig. 4).

Exploring the relation between SST, divergence and OLR, SST > \(SST_{\text{MON-CRIT}}\) is a good proxy for active convection in the wet regime, with OLR < 200 W m\(^{-2}\) if any upper level divergence is observed and stronger upper level divergence corresponding to even colder cloud tops (Fig. 6). This simple SST/convection relationship is not preserved in the dry regime, where convection varies with low-level
convergence and upper level divergence as well as SST. So we find that SST > \(\text{SST}_{\text{MON-CRIT}}\) is readily satisfied in the wet regimes and is a good marker for widespread deep convection in these periods, but SST is not a good indicator of convection distribution in dry regimes. These results are consistent with the findings of McBride et al. (2003) and others, that variations in rainfall in the Maritime Continent are strongly correlated with ENSO in the dry season but not the wet. The skill of CGCMs in reproducing these regional and seasonal differences in the relationship between the SST and convection should be examined relative to, for example, the model potential for realistically simulating the phases of ENSO: we hypothesise that models in which the wet/dry asymmetry in the SST/convection relationship is not observed will be less likely to realistically represent interannual variability relating to ENSO.

Convection in the African and Australian monsoons exhibits a somewhat weaker dependence on SST than the Asian monsoon region depicted in Fig. 6. Throughout the 2002–2006 period of interest, the Australian monsoon region (indeed, the whole continent) experienced anomalously hot and dry conditions. The relative variations of \(\text{SST}_{\text{MON-CRIT}}\) and mean SST through these years reflect these anomalously dry conditions: the majority of \(\text{SST}_{\text{MON-CRIT}}\) are greater than the regional-mean SST, typical of the dry periods in the other regions (Fig. 4), with most of the wet months identified for the Australian region being due to TC landfall events.

**Conclusion**

The SST threshold of around 27°C for deep convection across the global tropics identified in previous observational (e.g., Graham and Barnett 1987), theoretical (e.g., McBride and Fraedrich 1995) and modeling (e.g., Dutton et al. 2000) studies. The global tropics SST threshold for deep convection of 28°C inferred from the methodology described here is consistent with the results of Hoyos and Webster (2012). The two studies differ in the diagnostic for convective activity, with column-integrated atmospheric heating being employed by Hoyos and Webster (2012) and OLR used here. Both Hoyos and Webster (2012) and our analyses use more modern datasets than were available to the other studies above, raising the possibility that the difference between the earlier 27°C and later 28°C SST thresholds could derive from the observed global warming over the period (e.g., Johnson and Xie 2010; Hoyos and Webster 2012).

We extend this analysis to consider regional and monthly variations in this SST threshold across sub-regions of the...
tropics. We find that the critical SST signifying widespread convection varies temporally and across regions, so that no single threshold value of SST is a good predictor of favorable conditions for convection. Inter-basin variations of SST_{MON-CRIT} are consistent with differences in mean annual SST (i.e., the western Pacific SST_{MON-CRIT} is higher than that in the Atlantic). Further, SST routinely exceeds SST_{MON-CRIT} in the wet regime of a particular region, but SSTs in excess of the critical threshold are relatively rare in the dry regime of that region.

One motivator for this analysis is to provide regionally varying benchmarks for interpreting coupled general circulation models (CGCMs) simulations of changing base climates commonly utilised for projections of past and future climates (e.g. Dutton et al. 2000; Hoyos and Webster 2012; Evans and Waters 2012; Waters et al. 2012). Existing diagnostics of CGCM simulations of warmer climate regimes demonstrate that the tropics-wide SST threshold for deep convection increases as the background climate warms, and that the area of the globe inhabited by deep convection is essentially unchanged in a warmer climate (Dutton et al. 2000; Evans and Waters 2012; Hoyos and Webster 2012). These CGCM-derived results are supported by recent observational studies (Johnson and Xie 2010; Hoyos and Webster 2012) that identify a temporal trend in the SST threshold for tropics-wide incidence of convection in conjunction with the observed global warming. SST provides a good proxy for convection activity in the wet regimes, especially in the Asian monsoon region, but this relationship is not as strong in the dry regimes. This asymmetry in the wet and dry regime SST/convection signatures is reflected in observations that variations in rainfall in the Maritime Continent are strongly correlated with ENSO in the dry season but not the wet (e.g., McBride et al. 2003). Previous studies of links between SST and deep tropical convection in climate model CGCMs have predominantly considered the global tropics (e.g., Dutton et al. 2000; Johnson and Xie 2010; Hoyos and Webster 2012; Evans and Waters 2012). Examination of regional and seasonal analyses of SST and convection variations simulated in CGCMs provides a straightforward test of the model constraints on tropical convection and may also give insight into factors affecting model skill at reproducing ENSO.

Acknowledgments

OLR, SST and ECMWF ERA-Interim data used in this study were obtained from the NASA CERES, NASA JPL and ECMWF data servers respectively. We thank John McBride for many helpful discussions. This research was supported by the National Science Foundation under Grants ATM-0735973 and ATM-1322532, and by an American Meteorological Society fellowship sponsored by NASA Earth Science.

References


Dedication

Jenni Evans dedicates this paper to the memory of Professor Bruce Morton. He was a much loved mentor and friend and I am grateful to have known him.
