The Coupling of Convection, Large-Scale Atmospheric Dynamics, and Sea-Surface Temperature Hot Spots as Characterized by MODIS, TRMM, and ECMWF-Interim Reanalysis Data

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Overarching Motivations

• Understanding ocean-atmosphere interactions over the tropics is paramount to understanding tropical climate and even climate sensitivity.

• Observed has been the relatively narrow SST range over which deep convection occurs, with the onset between 26-28°C, peak convective activity between 29.5°C-30°C [e.g. Waliser and Graham 1993; Kubar et al. (2011); Behrangi and Kubar (2012)], and drop-off beyond these SSTs, the latter related to the formation of SST hot spots (Waliser 1996).

• While Waliser (1996) characterized composites of monthly large-scale circulation, cloud fields, and ocean profile temperatures the month(s) before, during and after hot spots (defined as monthly $10^6\text{km}^2$ regions in which monthly SSTs>29.75°C), less focus was placed on individual hot spot events and the relationships between hot spot intensity, size, and its interplay with large-scale forcing and convective strength.

• We have the advantage of high-temporal resolution multi-sensor satellite data (e.g. MODIS and TRMM) as well as co-located reanalysis data (ERA-Interim), to characterize the horizontal, vertical and temporal evolution of different cloud types, large-scale dynamics/thermodynamics, and precipitation as they relate to hot spots from various time scales (e.g. synoptic to interannual).
Specific Objectives

• Characterize relationships between SSTs, different convective cloud types from MODIS, and large-scale dynamics from ECMWF reanalysis (ERA-Interim)

• Using the Aqua MODIS joint L3 histograms, partition MODIS ice cloud types as a function of visible optical depth $\tau$ as thin cirrus, anvil, and convective core clouds

• Cirrus clouds have $0<\tau<5$, anvil clouds $5<\tau<30$, and convective core clouds $\tau>30$ – thus cirrus clouds have a TOA warming effect, and anvil and convective core clouds a net TOA cooling effect (based on Kubar et al. 2007)

• Perform time-series analyses in domain-averaged 20°longitude x10°latitude boxes, and construct latitudinally-averaged Hovmoller diagrams (between 0-10°S) to quantify the importance of SST hot spot formation on the spawning of deep convection via relationships with upward motion and low-level convergence

• Examine synoptic variability of SSTs, vertical cloud profiles, and large-scale dynamics and moisture profiles vertical profiles over favorable hot spot selection regions

• Investigate the occurrence of a “predator-prey” type of relationship involving convection (predator) and prey (hot spots)
Total Ice Cloud Fraction and $\omega_{500}$ both peak at SSTs ~ 30°C, a slightly higher SST than Waliser and Graham’s (1993) analysis.

Cirrus clouds peak over warmer SSTs and may be a positive feedback with SSTs.

TRMM rain rates peak at 30°C, but then drop off more quickly than cloud fraction, since optically thinner clouds occur over higher SSTs and rain less.
Climatology of SST Hot Spots, Clouds, and Large-Scale Circulation in 20°lon x 10°lat boxes

• Box between 160°-180° and ~0°-10°S generally has just under a 2 month-duration with SSTs>30°C

• Cirrus cloud fraction generally slightly larger with greater areal coverage than anvil clouds

• Generally easterly low-level winds throughout tropics, except near zero mean u-winds over the warm pool, where winds can be easterly or westerly (e.g. during westerly wind bursts)
Time Series of $\omega_{500}$ and Anvil Clouds and SSTs over West & East Selection Regions

160°-180°, 0-10°S (Black: SSTs)

[Graph showing time series of $\omega_{500}$ and Anvil CF with hot spots indicated by black dots.]

180°-200°, 0-10°S (Black: SSTs)

[Graph showing time series of $\omega_{500}$ and Anvil CF with hot spots indicated by black dots.]

- Both $\omega_{500}$ and Anvil CF clouds peak in intensity/coverage just following (~15 days to ~1 month) after peak SST hot spot, usually at the end of each calendar year.

- Moderate El Nino late 2009/10 marked by strongest hot spot of the record, with strongest upward motion and largest anvil cloud coverage just after SST peak.
- Pulses of convective core cloud fraction (e.g. CF>0.1) and corresponding heavy rain rates during the decay stage of hot spots
- Lots of shorter-term convective and precipitation variability as well
- Greatest convective core cloud fraction (top) and rain rates (bottom) just after the SST hot spot peak in late 2009/early 2010
- Other pulses of convective core cloud fraction/rain follow high SSTs (whether or not fully-fledged hot spots)
Summary of Cloud, $\omega$, and Rain Rate Relationships over Primary Hot Spot Region [160°,180°] and Eastern Adjacent Regions

- In both west and east 20°x10° boxes, anvil CF and $\omega_{500}$ are tightly correlated with each other, as are convective core cloud fraction and TRMM rain rates.

- The latter finding is consistent with Kubar et al. (2007) (“Radiative and convective driving of tropical high clouds), but that study used MODIS and AMSR-E and examined regions in the north Pacific ITCZ.
15-Day Hovmoller Diagrams over entire record (2002-2015) of $\omega_{500}$ Anvil CF with Hotspots Superimposed (Dashed Contours: SSTs>30°; Solid: SSTs=29.8°)

- La Ninas (late 2007-2008 and late 2010-2011) – small or no hot spots

Moderate El Nino (late 2009/10): eastward propagation of large and strong hot spots, with large area of strong upward motion and widespread anvil CF
• Moderate El Nino during late 2009-early 2010; eastward-propagating hot spot with SSTs well above 30.2° for a few months → strong upward motion, significant and organized convection, and intense precipitation between 160°-200° during the hotspot decay stage
• While significant synoptic-to-submonthly variability exists of upward motion/convection, more sustained and organized deep ascent follows hot spots
• Shallow to deep transition of convection with time

Convective Core Follows SST Hotspots with a fairly quick response time (days to weeks)

CF Anvil

Strong upward motion following hot spot peak

Sustained period of anvil clouds
- Low-level moistening preceding deep convection, during/after hot spot peak
- Dry mid/upper troposphere (except near tropopause) prior to SST hot spots

Pulses of lower-level westerly winds in association with hot spots; they are associated with low-level convergence (not shown)
Top: Both strong ascent and anvil/convective core clouds increase strongly following hot spot event, with 15-30 day response time.

Lower Right: Convective Core CF and Rain Rates follow a counterclockwise loop – after hot spot peak, convection utilizes, or “preys” on hot spots until hot spot is depleted, after which convection draws down and SSTs eventually rise again.
Quick Summary

• Strong ascent, anvil and convective cloud fraction, and high rain rates are observed in the western and central South Pacific (0-10°S) just after maximum SSTs associated with hot spots.

• In some cases, the strength/duration of the hot spots coincides with the subsequent intensity of convection and precipitation.

• Three independent datasets (MODIS, TRMM and ERA-Interim) are consistent with each other in illustrating these relationships, with anvil clouds and $\omega_{500}$ very strongly linked to each other, as well as convective core cloud fraction and rain rates.

• Hot spots generally move east to west, except during El Nino, when hot spots are larger, more widespread, and longer-lasting.

• The predator-prey relationship between SST and convection is an intuitive concept that illustrates the strongly coupled nature of ocean-atmosphere system.