Utilization of Satellite-Derived Salinity for Indian Monsoon Studies

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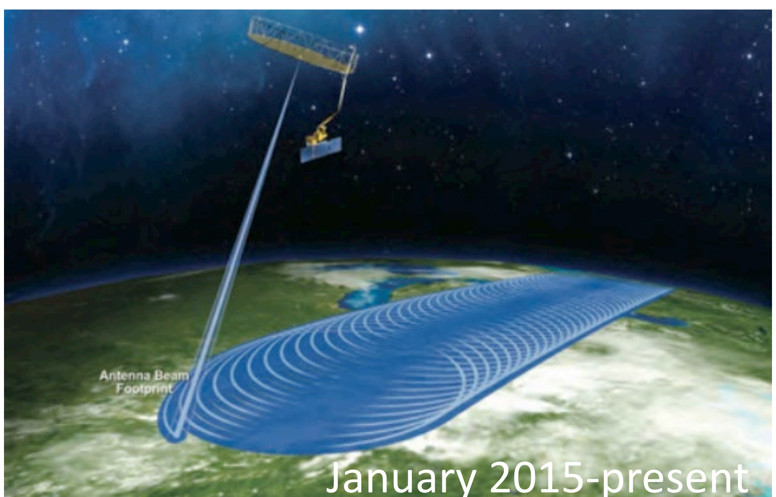
University of South Carolina — College of Arts and Sciences | School of the Earth, Ocean and Environment

Office of Naval Research — Science & Technology

Sea Surface Salinity Satellites

Soil Moisture & Ocean Salinity (SMOS) Mission
by European Space Agency
L-band radiometer

Aquarius/SAC-D Mission
by NASA & CONAE
L-band radiometer + radar



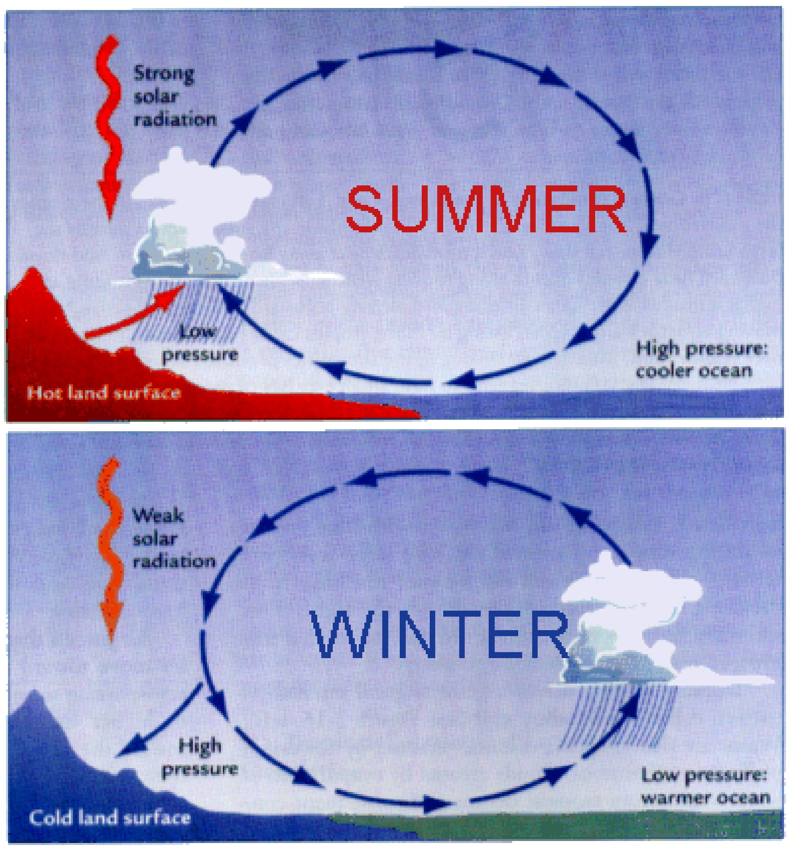
NASA's Soil Moisture Active-Passive (SMAP)
L-band radiometer + radar

Overview

- Salinity in the northern Indian Ocean has a unique influence on the development and modulation of the Indian monsoon
  - Development of barrier layer fuels monsoon onset vortex
- The air-sea coupling in this region directly impacts annual rainfall rates for over a billion people
- Wet and dry periods are modulated by intraseasonal oscillations (ISOs)
- A big challenge for coupled Atmospheric-Ocean models is generation of these ISOs
  - Opportunity to integrate satellite-derived salinity
- Three major periods: 30-90 days (Madden Julian Oscillation), 10-20 days (quasi-biweekly oscillation), 3-7 days (synoptic variability)

Indian Monsoon Season

- Two monsoon seasons: summer or Southwest Monsoon (June-Sept) and winter or Northeast Monsoon (Nov-Feb)
- Synoptic systems in the summer monsoon lead to heavy seasonal rainfall over southern Asia
- Extremely important, but highly variable and difficult to predict



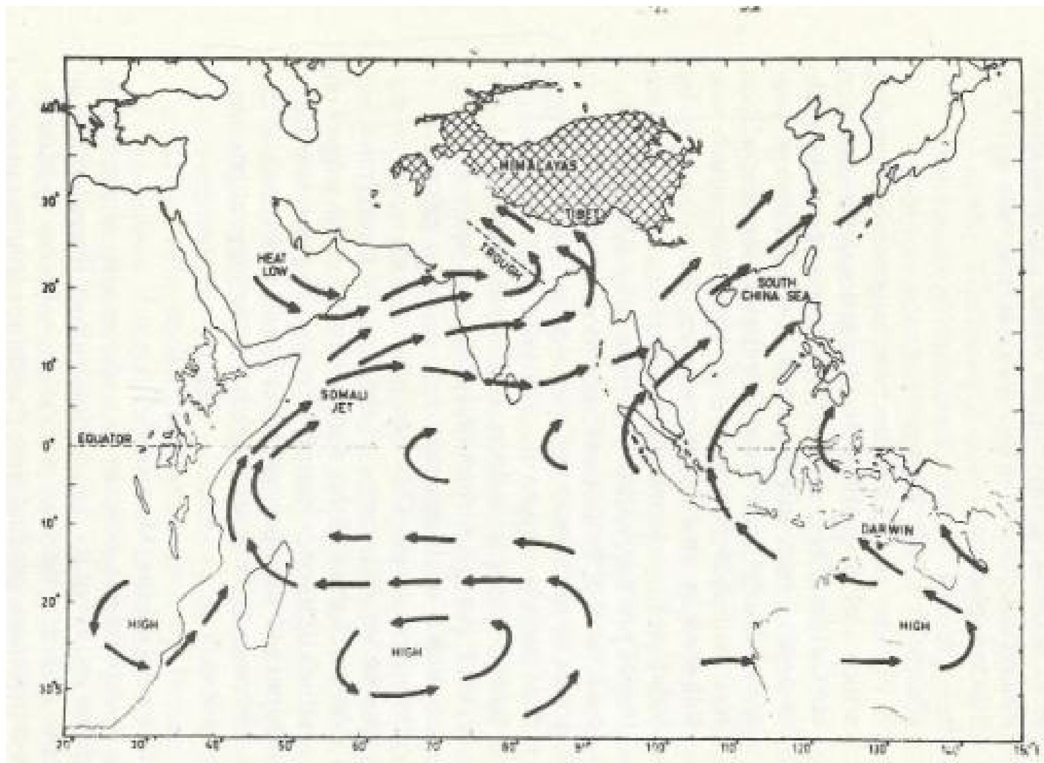


Figure 2.6. The Summer Monsoon. Low level winds.

Left: Seasonal monsoonal circulation (from globe.gov)
Right: From "The Monsoons" by Dr. P.K. Das

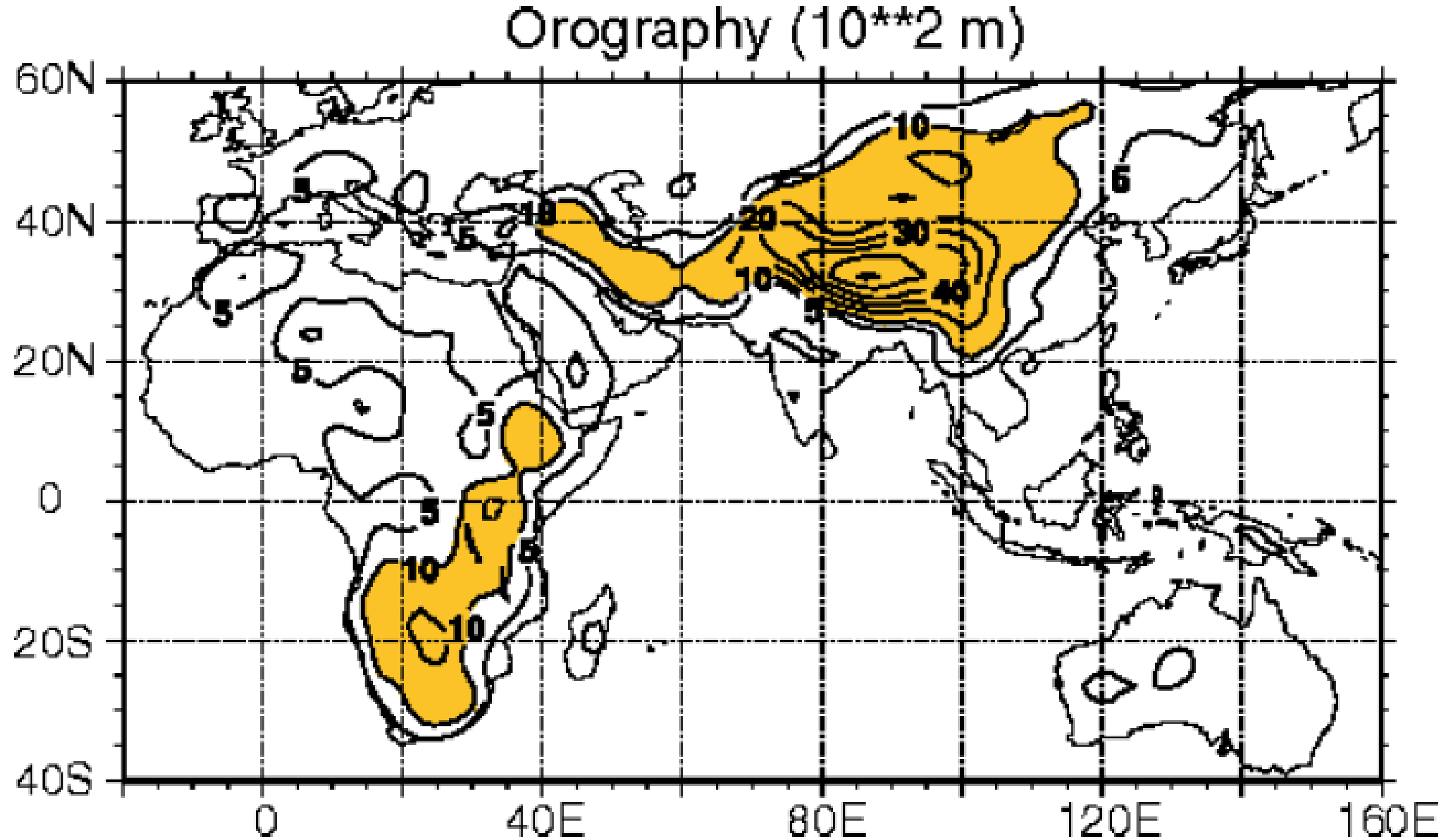
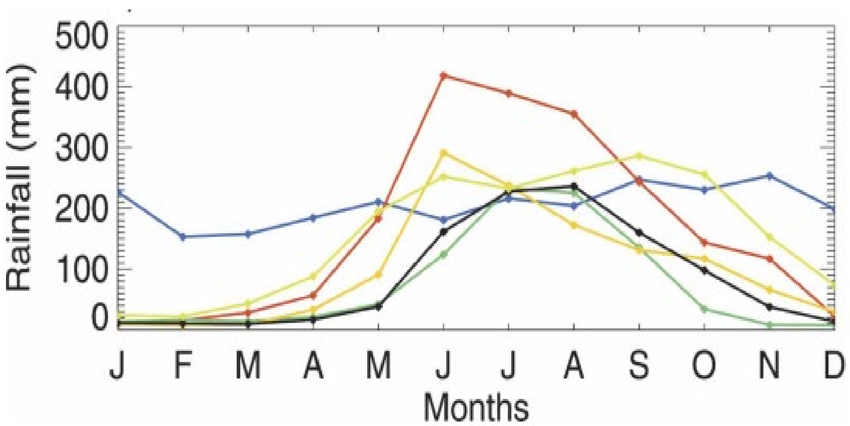


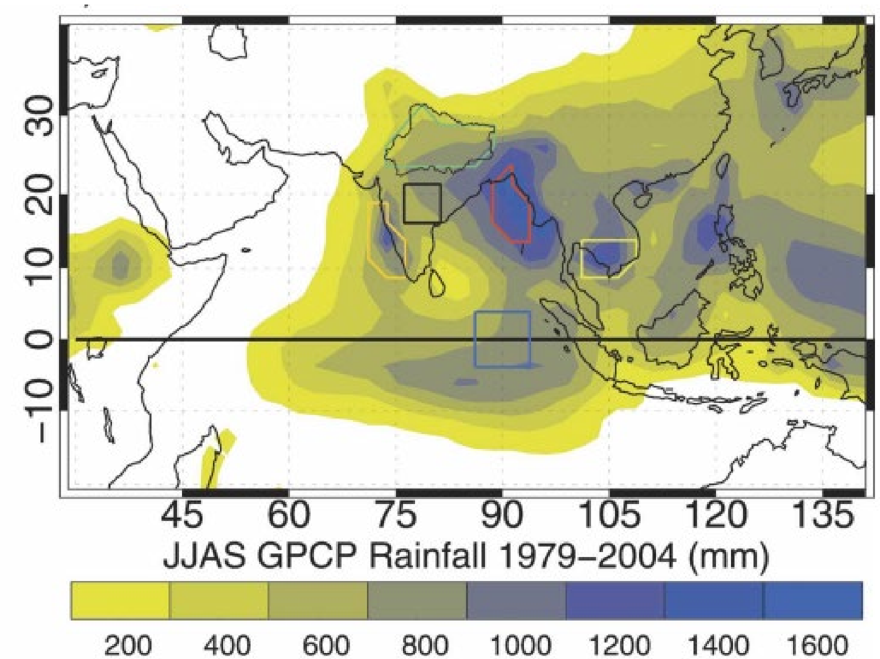
Figure 11a.(a) Orography and the south Asian summer monsoon. Orographic structure of the eastern hemisphere (units are 102 m). The Indian Ocean is surrounded by the East African Highlands to the west and the Himalayan Mountains to the north. Australia, on the other hand, is devoid of major orography. Orography with elevations >1 km are shaded. .

(Webster et al., 1998)

Indian Summer Monsoon

- India receives 78% of its annual rainfall June-September (>90% in some regions)
  - Population: ~1.3 billion people
- Drives agriculture, infrastructure, daily life, etc.
  - Highly consequential and requires improved prediction





Top: Floods in Agartala, the capital of Tripura State in India (New York Times, August 2017)
Bottom: Hoyos and Webster, 2007

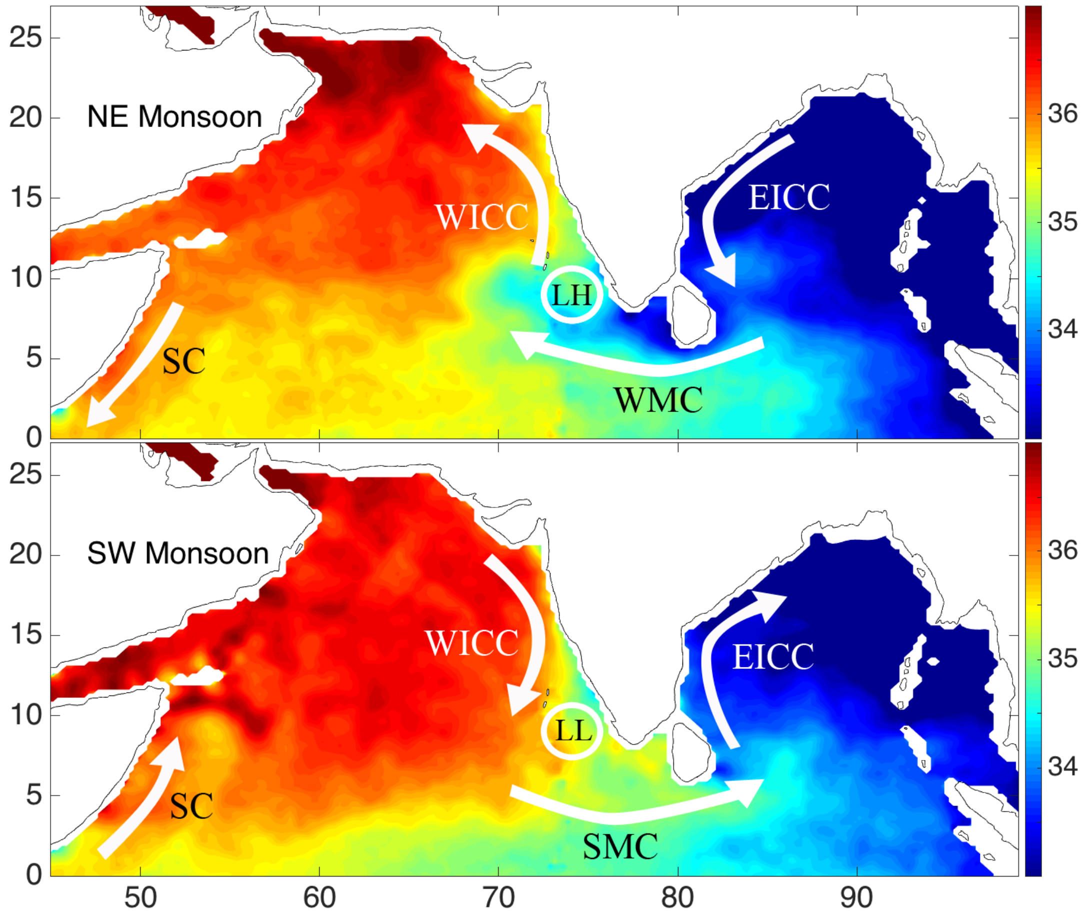
Annual Circulation

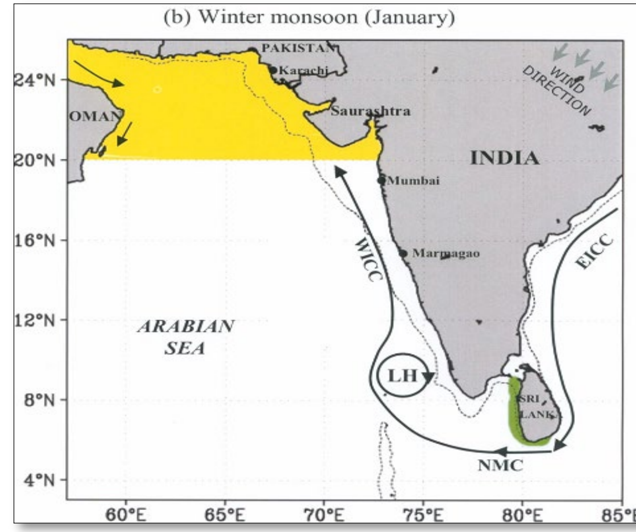
- Wind-induced complete reversal of surface currents
- Highly variable
  - Essential to quantify variability of fluxes on a seasonal and interannual timescale, which is currently lacking
  - Influences stratification, particularly in the southeastern Arabian Sea

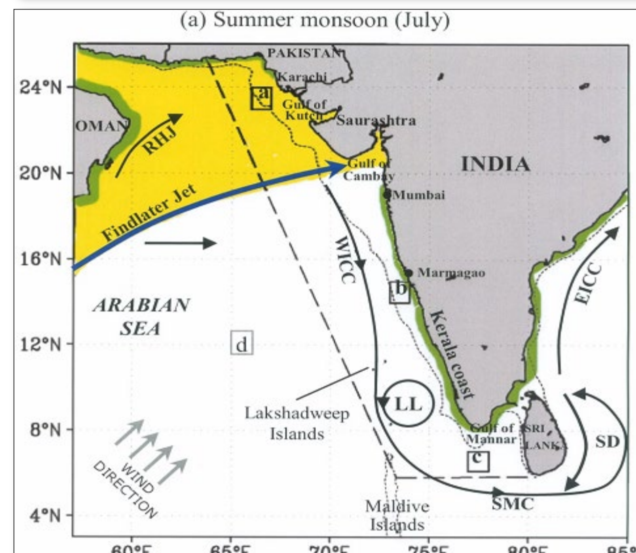
HYCOM tracers in the Arabian Sea and Bay of Bengal (courtesy of Tommy Jensen)

Freshwater Intrusion

- Seasonal exchange of salt water and fresh water between basins



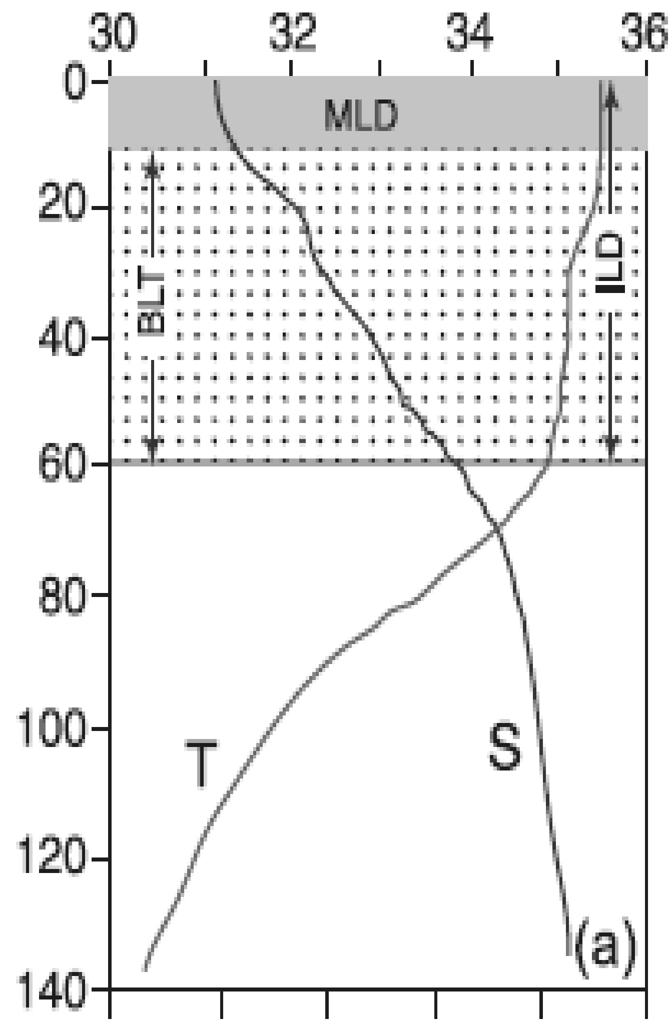




Left: SMAP salinity during the 2016 winter and summer monsoons
Right: Luis and Kawamura, 2004

Barrier Layer

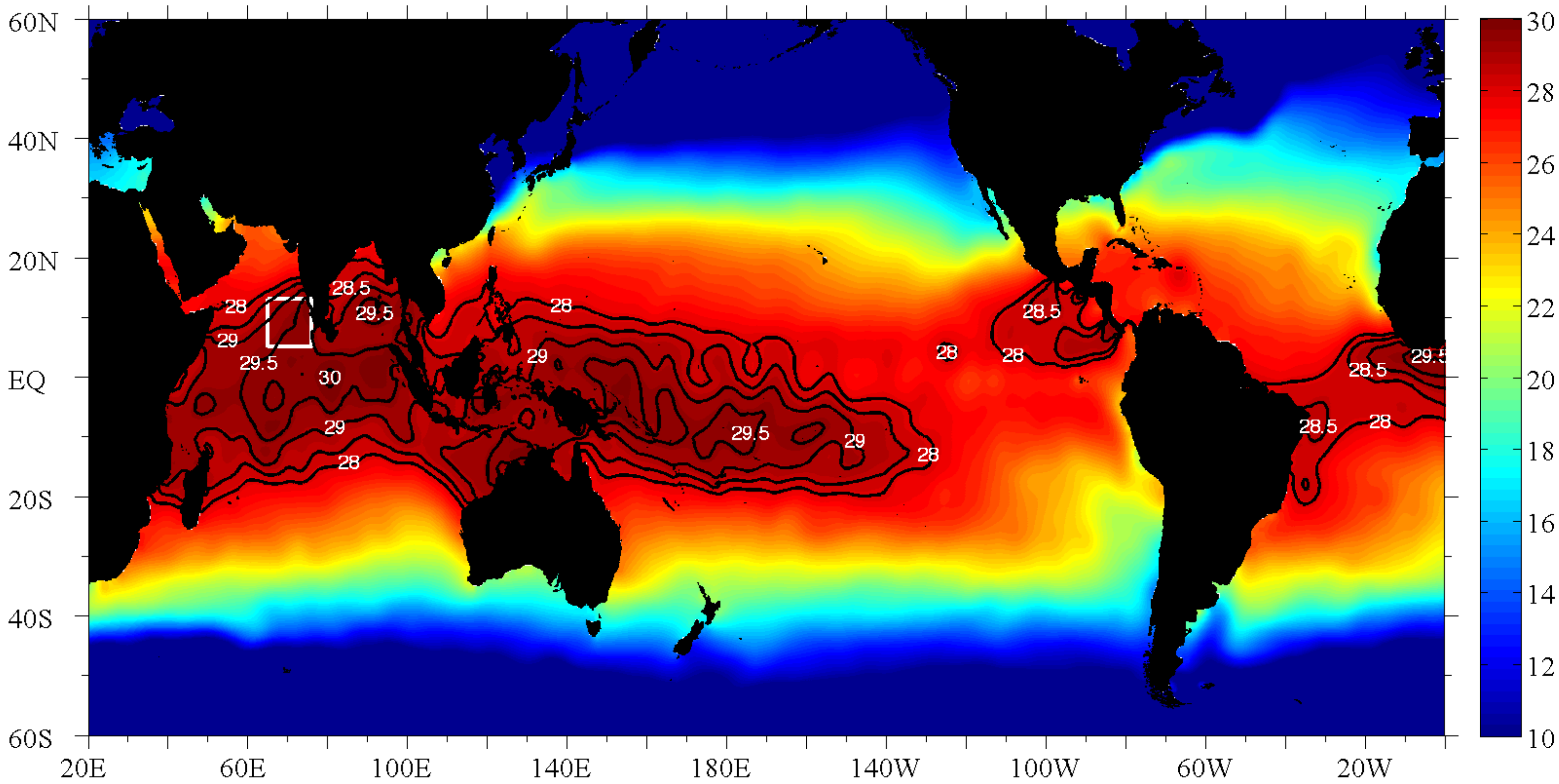
- Barrier Layer results from surface haline stratification
- Mixed Layer much thinner than Isothermal Layer, resulting in a very deep Barrier Layer
- Inhibits entrainment cooling
- Favors the warming of mixed layer and increased SSTs



Thadathil et al., 2007

Arabian Sea Warm Pool

Mean SST for March-April from Argo

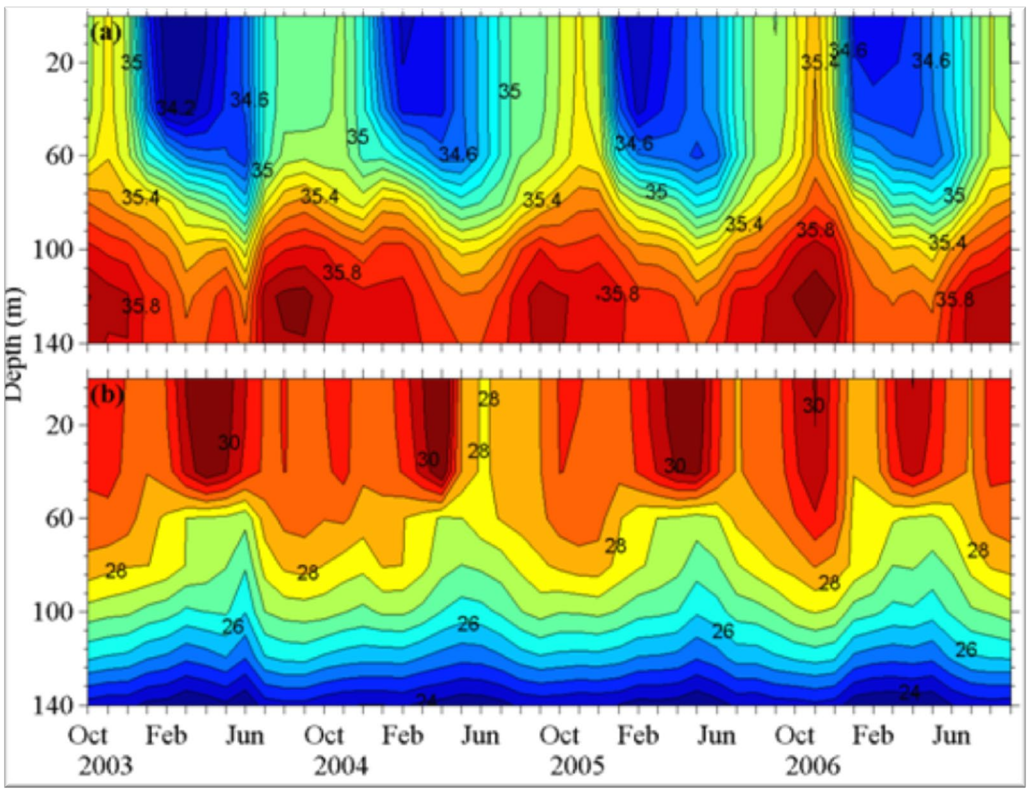


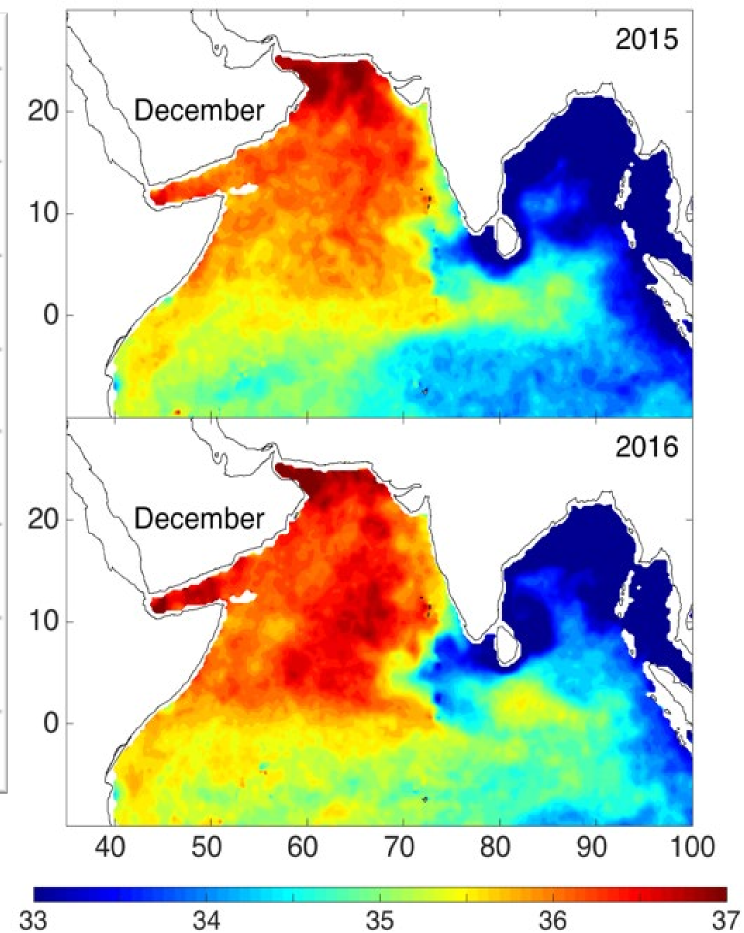
- Arabian Sea Mini-Warm Pool is a part of the larger Indo-Pacific Warm Pool

(Nyadjro et al., 2012)

Freshwater Pool

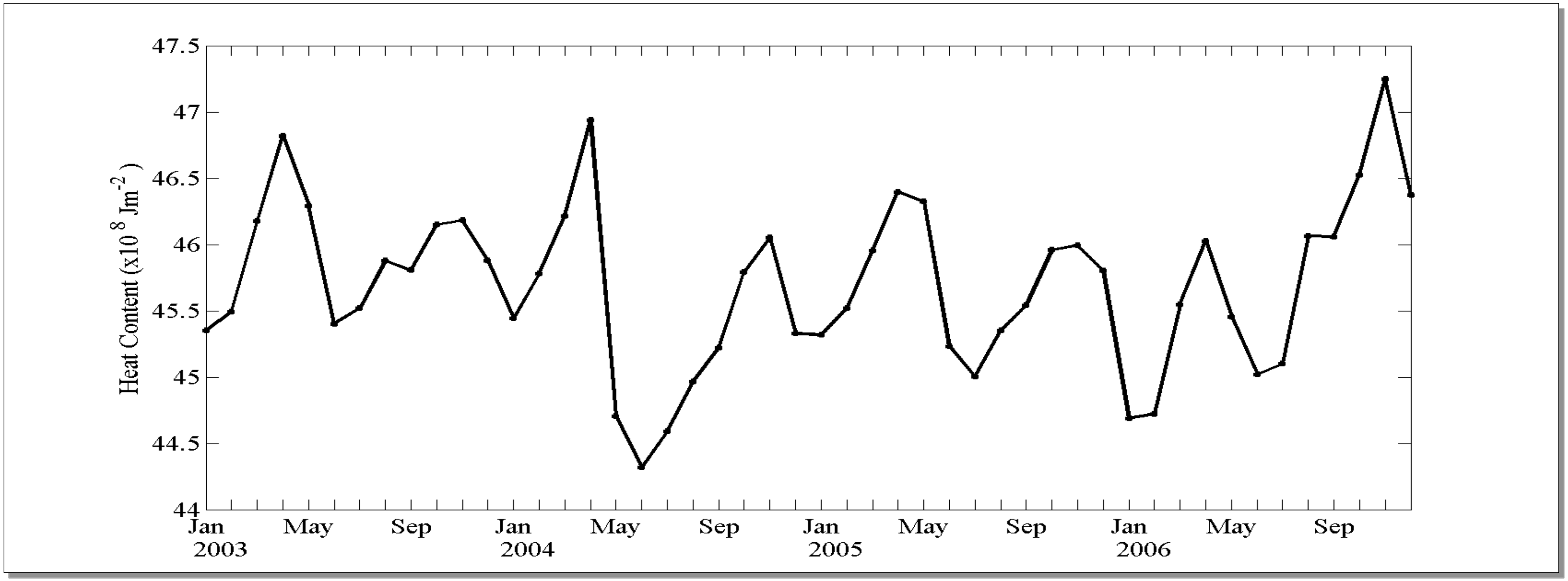
- Low salinity (<34 psu) water in top 60 m during December – June and higher salinity (>36) water below 70 m between July-November
- Well-observed event, but there is insufficient knowledge of its variability (and subsequent impacts on the summer monsoon)





Left: Depth-time of HYCOM (a) salinity and (b) temperature in SEAS region (Nyadjro et al., 2012)
Right: SMAP SSS for December 2015 and 2016

Heat Content



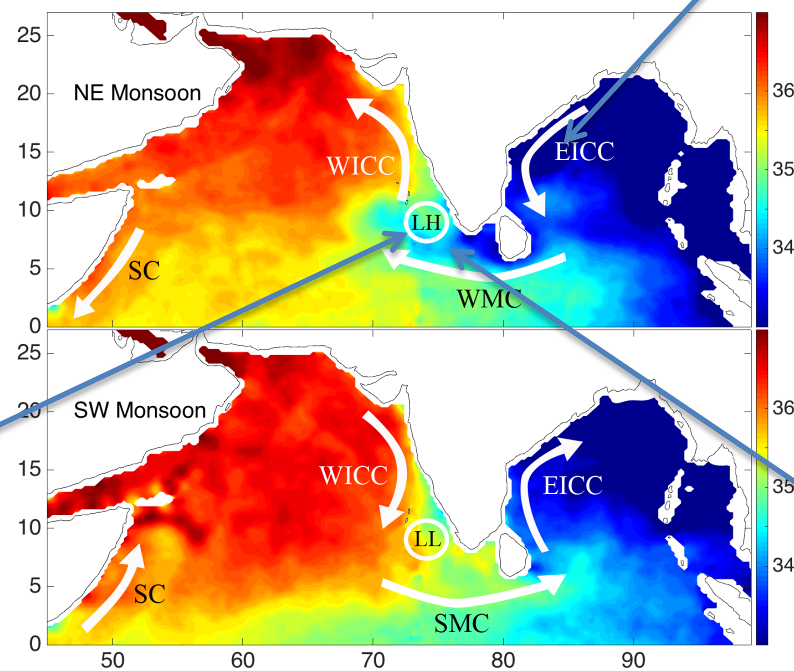
- High heat content from January to April in 2004 and contributed to the monsoon onset vortex in May 2004
- After monsoon vortex, heat drops drastically
- Low heat content in break monsoon years
- High value in Nov 2006; early arrival of low salinity waters due to IOD in 2006

Oceanic Conditions for Monsoon Onset

5. ITCZ moves over the SST high by end of May, increasing both SST and large-scale moisture convergence. Genesis of the monsoon onset vortex!

1. Southwest monsoon collapses in October and the northeast monsoon strengthens, triggering EICC and westward flow

4. High April SSTs trigger pre-monsoon rainfall (not sufficient moisture for full onset)

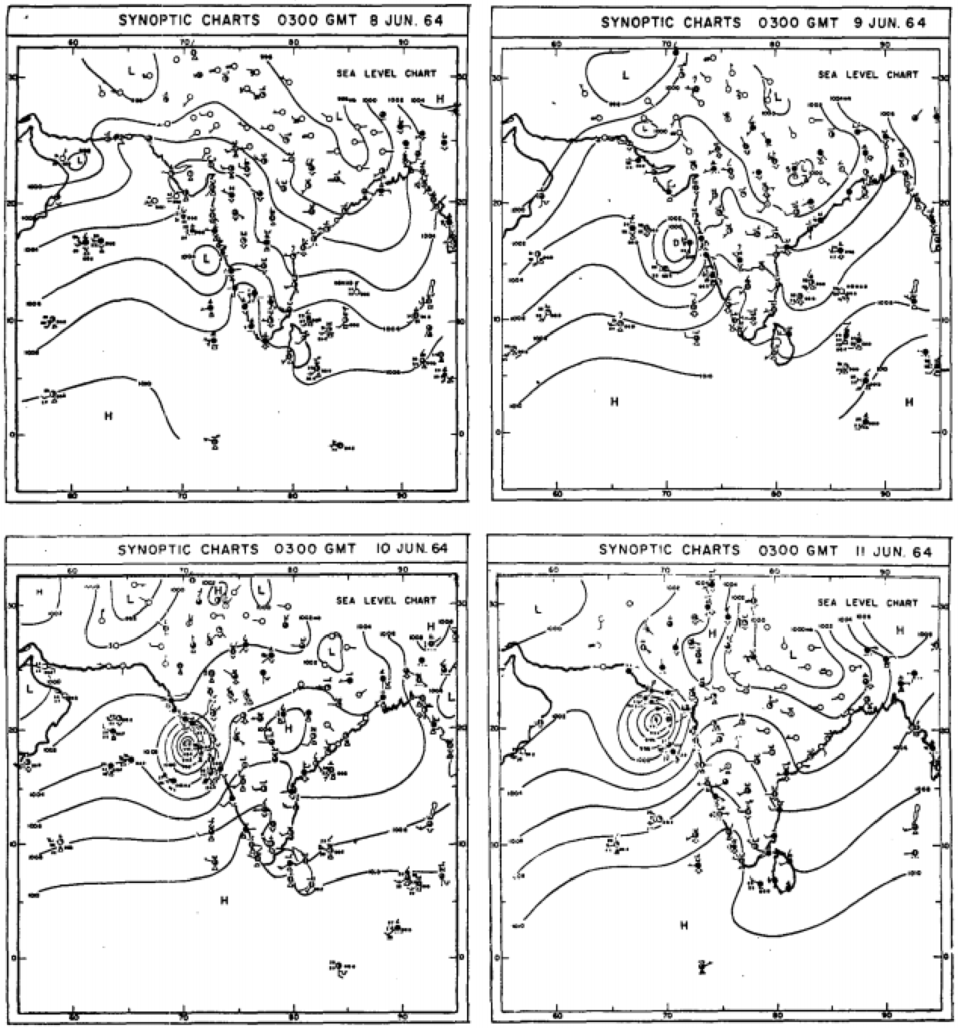


3. Stable stratification & downwelling provide conditions favorable to surface warming, leading to higher SSTs by March

2. By January, a region of high sea level and low SSS forms in Lakshadweep Sea

Shenoi et al. (1999)

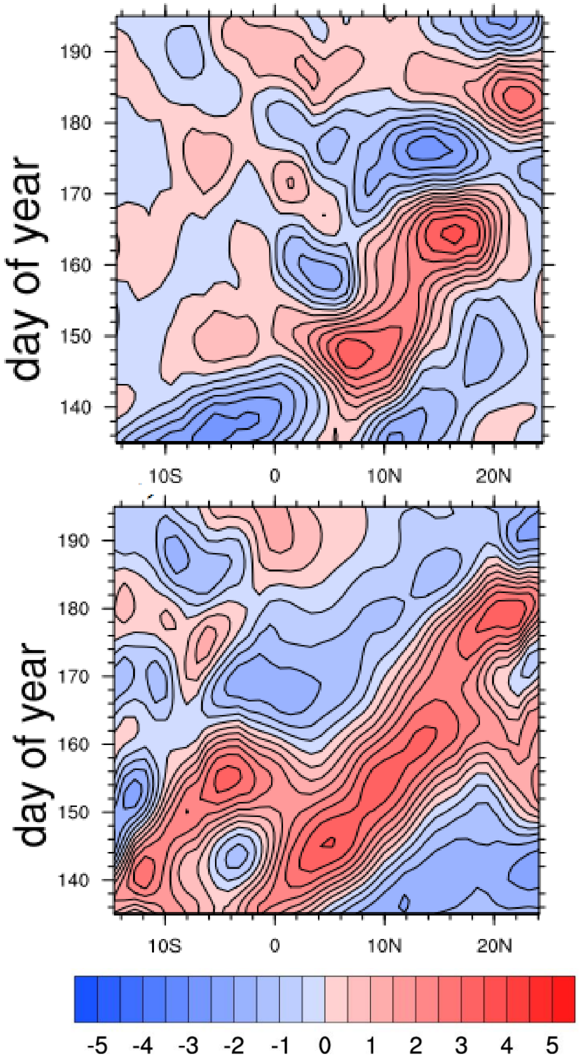
Monsoon Onset Vortex



- Beginning of the summer monsoon is called the "onset," typically in early June or late May (climatological date is June 1st)
  - First rainfall over the southwestern state of Kerala
- Associated with a low-pressure system (onset vortex) in the southeastern Arabian Sea
  - Moves northward as the monsoon advances along the west coast of India, accelerated by its intense cyclonic circulation
    - Also due to a variety of intraseasonal oscillations
  - Followed by commencement of monsoon rains

A sequence of surface pressure charts illustrating the onset vortex during 1964, based on Philip et al. (1973)

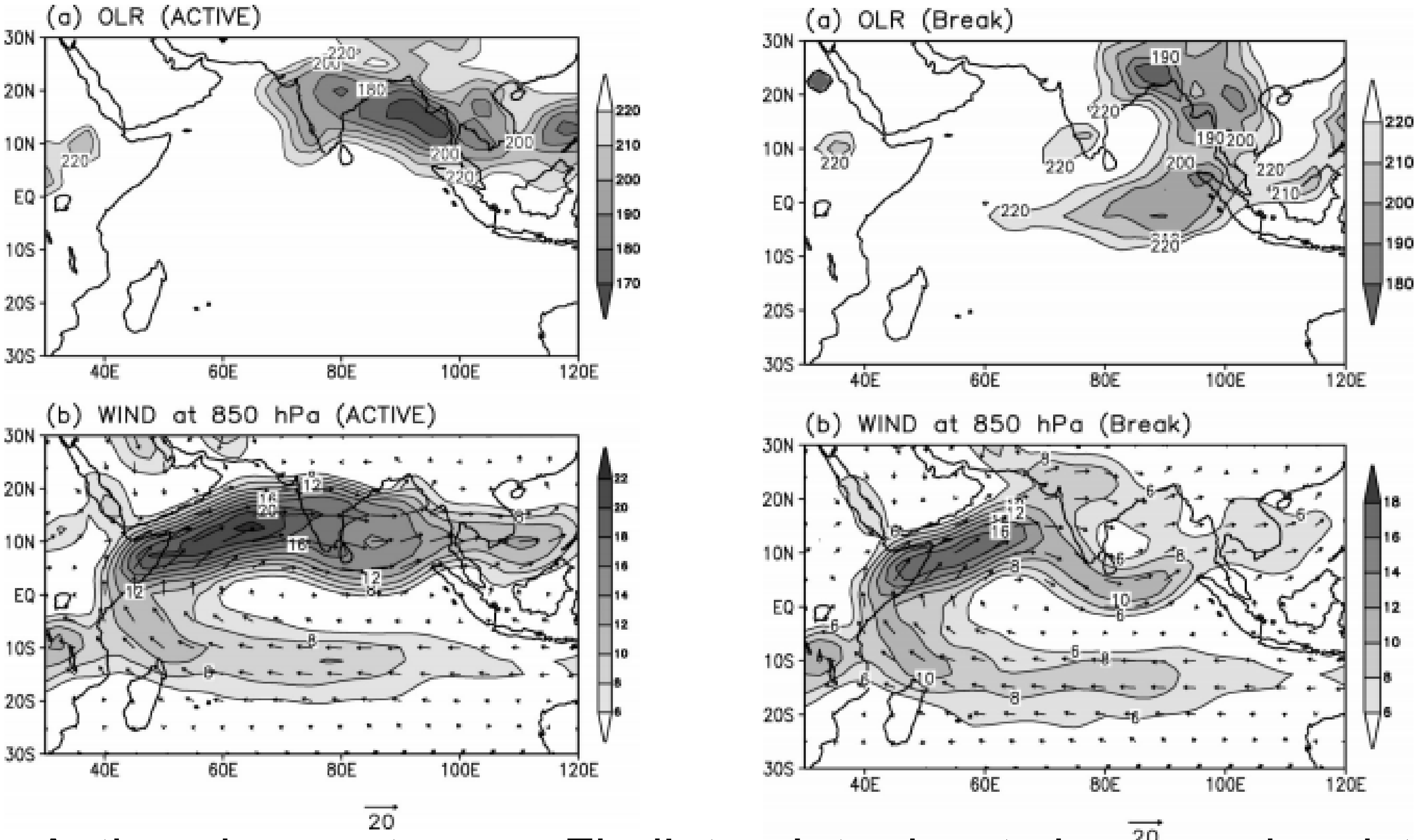
Monsoon Onset



- Northward propagation of ISOs directly impacts the strength of the monsoon onset
- Results in increased moist, unstable air from the tropical Indian Ocean over the Indian subcontinent
- Further investigation of the dynamics of ISOs and how they relate to monsoonal wet and dry conditions will improve accuracy of monsoon onset prediction

Figure: Northward-propagating track of climatological intraseasonal oscillations using observations (top) and CFS (bottom) for May 15th-June 15th over 1997-2008 (mm/day; Pradhan et al., 2017)

Active & Break Conditions

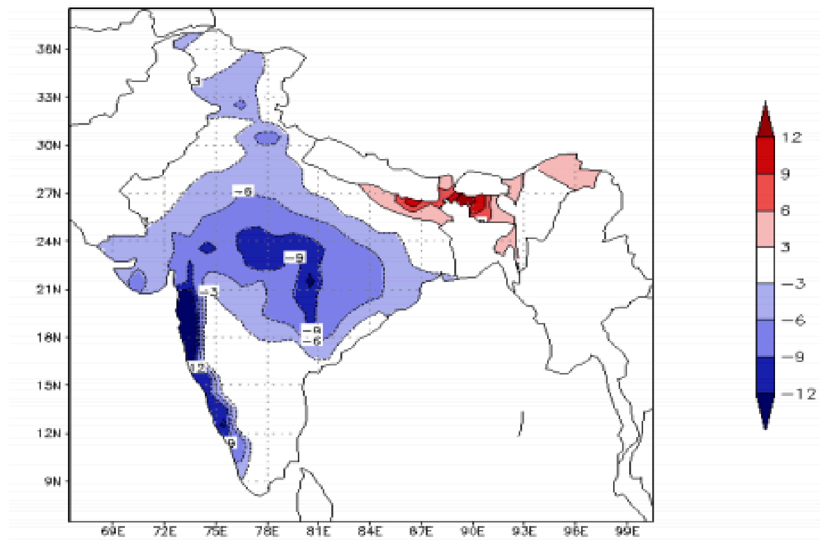


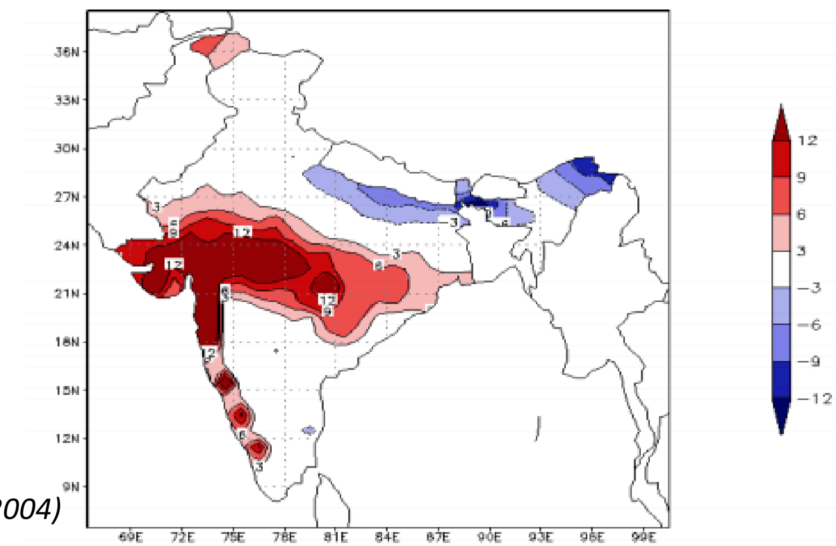
- Active phase: stronger Findlater Jet advects increased moisture and momentum over India; wetter conditions
- Break phase: weaker Findlater Jet; drier conditions

Joseph and Sijikumar (2004)

Active & Break Conditions

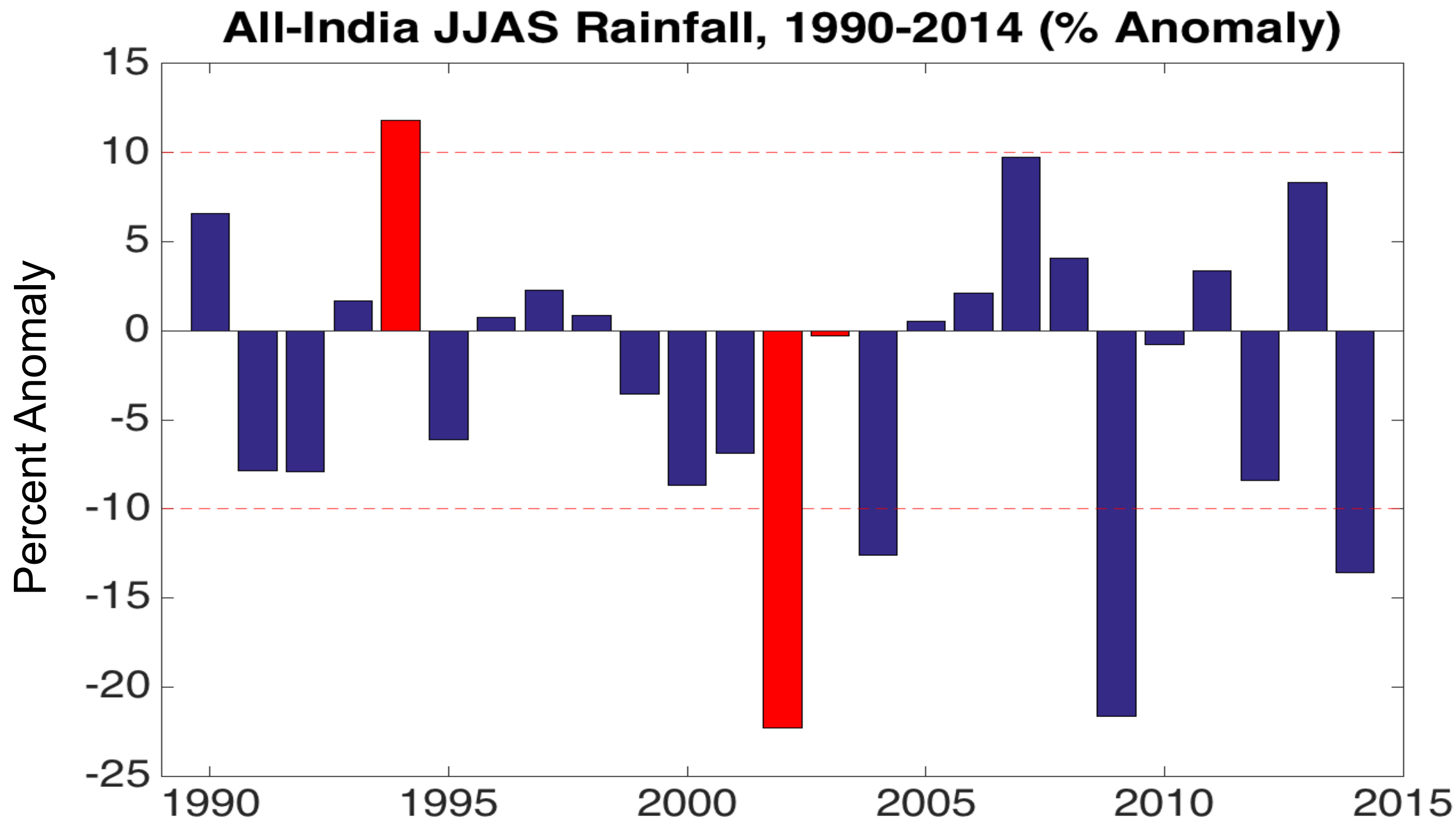
- Stark contrast in rainfall between active and break conditions
  - Phases last 3-7 days
- End of break events attributed to northward propagation of convective clouds
- Too many break days can lead to drought conditions and too many active days can lead to flood conditions
- Improved prediction of monsoonal rainfall relies on understanding ocean-atmosphere interactions and intraseasonal oscillations





Top: composite rainfall anomaly (mm/day) map for the break days (1951-2004)
Bottom: composite rainfall anomaly (mm/day) map for the active spells (1951-2004)
Figure courtesy of Rajeevan et al., 2008

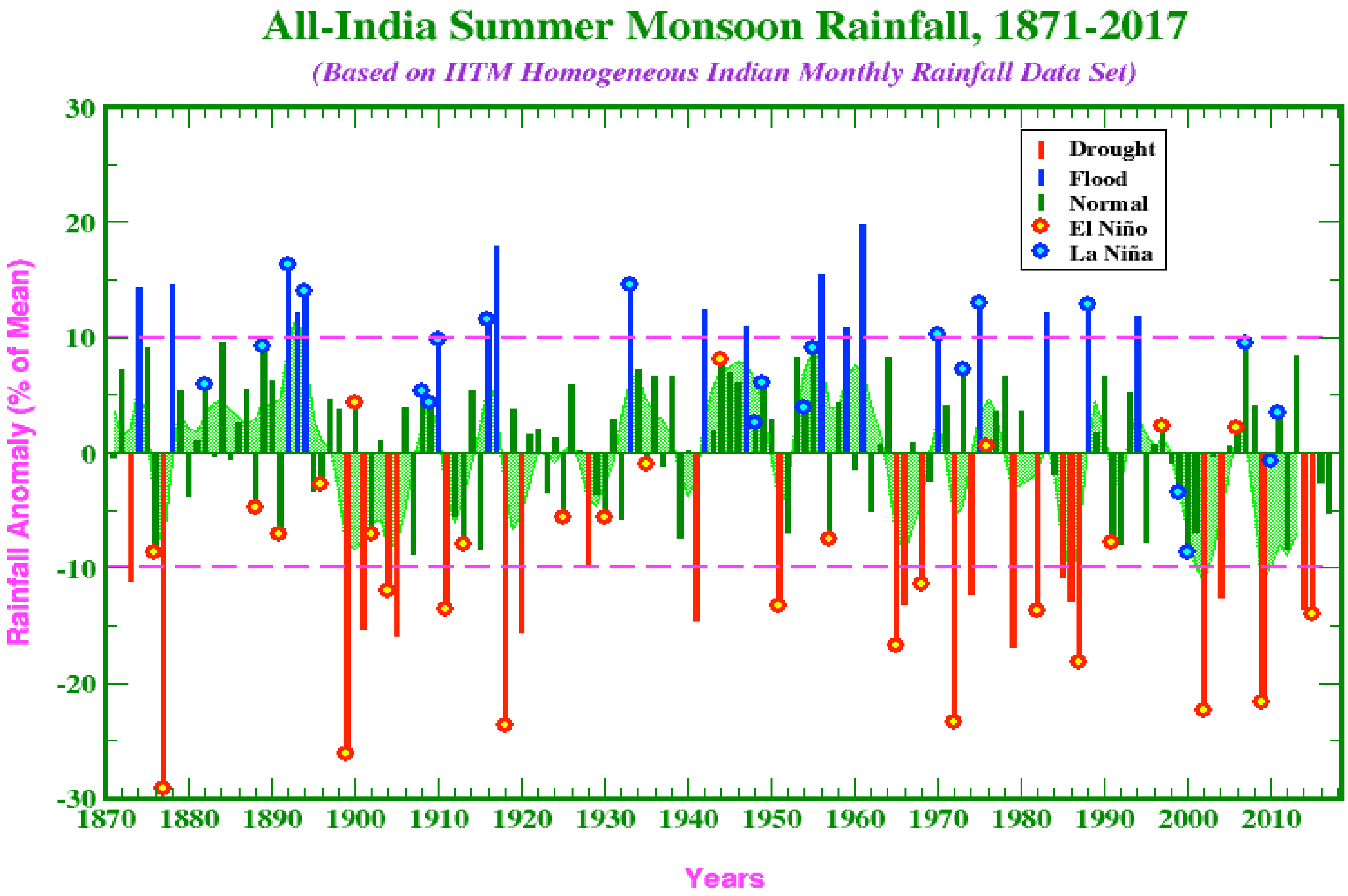
Indian Summer Monsoon Rainfall



- Right: All-India Rainfall (June-September). The percent anomalies are in reference to the long-term seasonal mean of 85.2 cm.
- Red bars indicate the 3 years with the highest (1994, +11.8%), lowest (2002, -22.3%), and smallest (2003, -0.3%) rainfall anomalies.

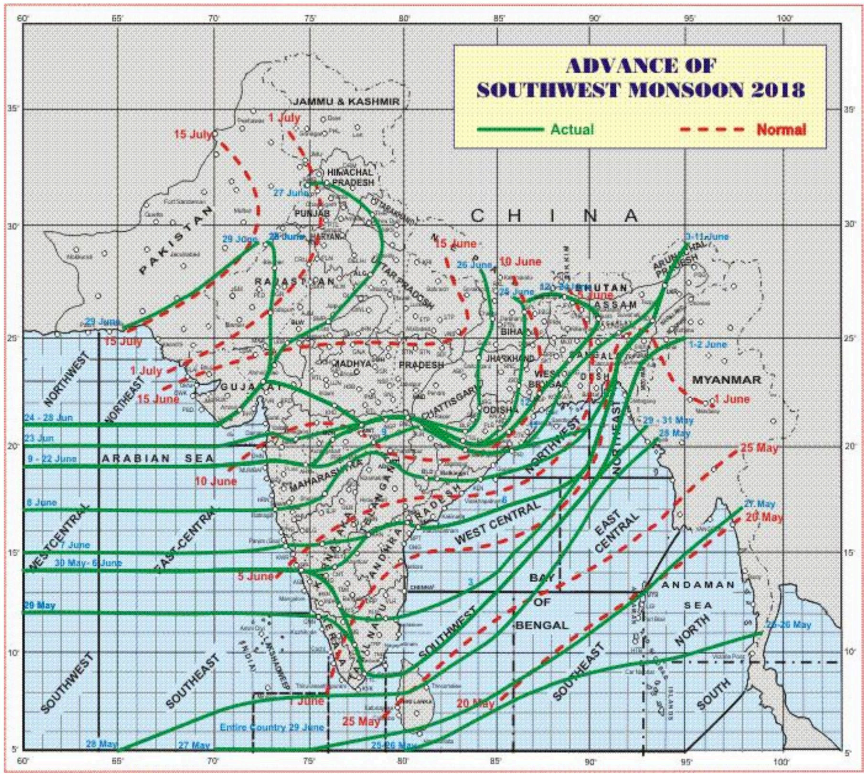
Trott et al. (2017)

Indian Summer Monsoon Rainfall



Monsoon Onset

IMD, 2018



Daily GPM precipitation (mm/day)

2018 values are:

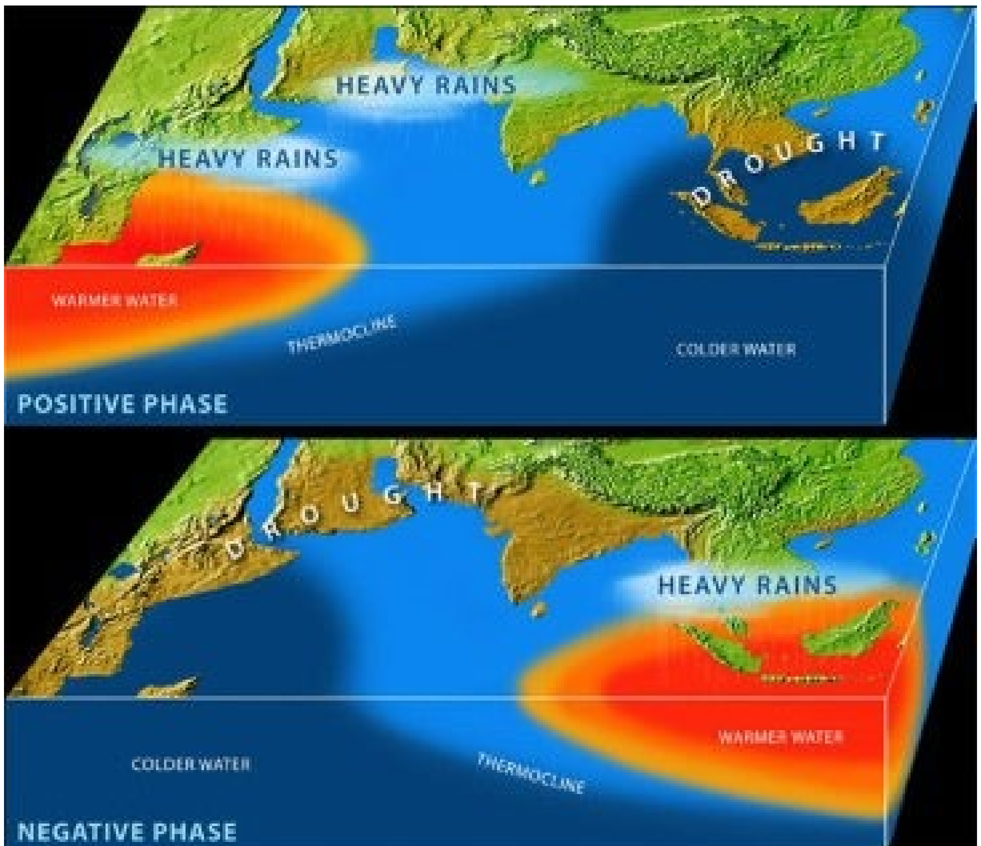
Actual: 804.0 mm Normal: 887.5 mm Departure from Normal: -9.4 %

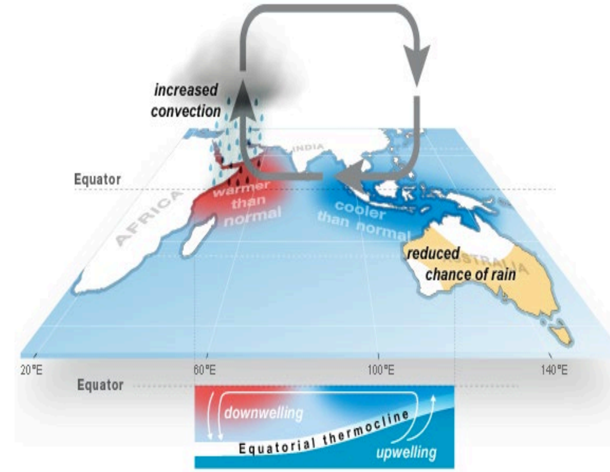
(It does not come under drought as the deficiency is less than 10%.)

2018 Summer monsoon advances from June 1. The green lines are the long-term mean path of the monsoon front. The redlines are the path of monsoon 2018.

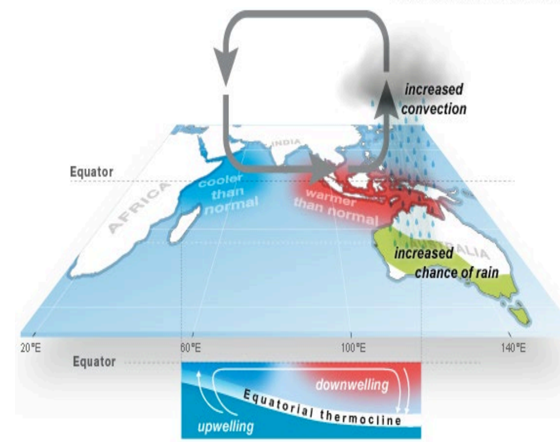
Indian Ocean Dipole

- Indian Ocean Dipole (IOD)
  - Defined by a temperature differential between the eastern and western Indian Ocean
    - Alters circulation and regions of convection





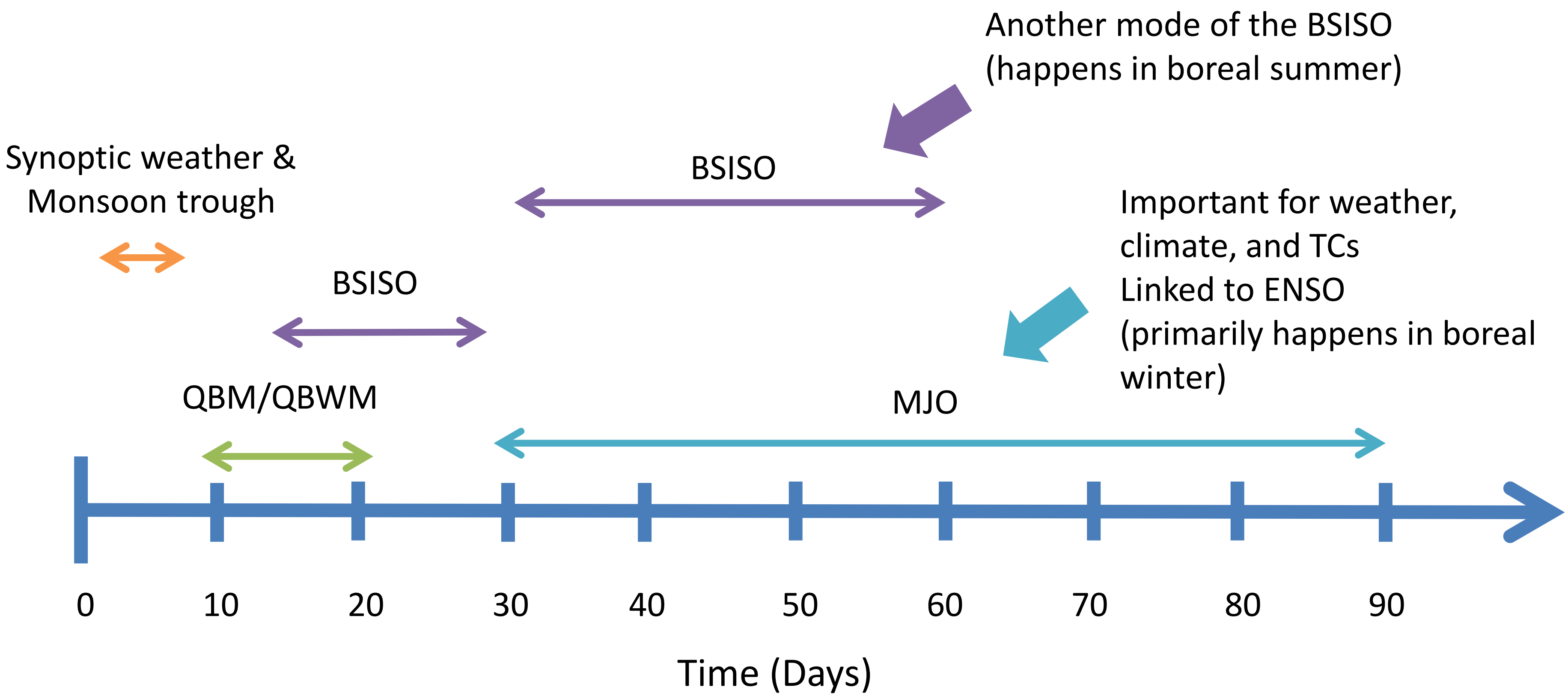
Indian Ocean Dipole (IOD): **Positive phase**



Indian Ocean Dipole (IOD): **Negative phase**

Left: Paul Oberlander, WHOI; Right: http://www.bom.gov.au/climate/iod/

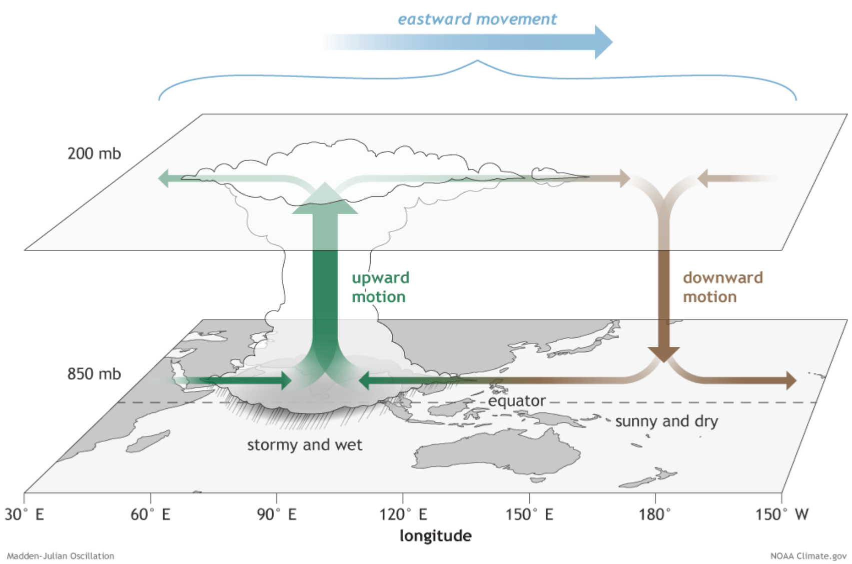
Intraseasonal Oscillations

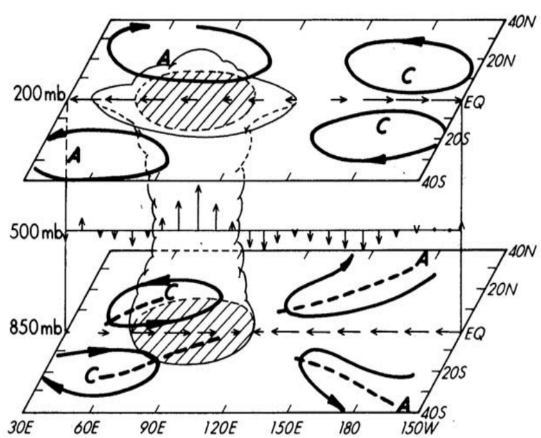


Legend

BSISO = Boreal Summer ISO (15-30 & 30-60)
MJO = Madden-Julian Oscillation (30-90)
QBM/QBWM = Quasi-biweekly mode (10-20)
ENSO = El Niño-Southern Oscillation

Madden Julian Oscillations (MJO)



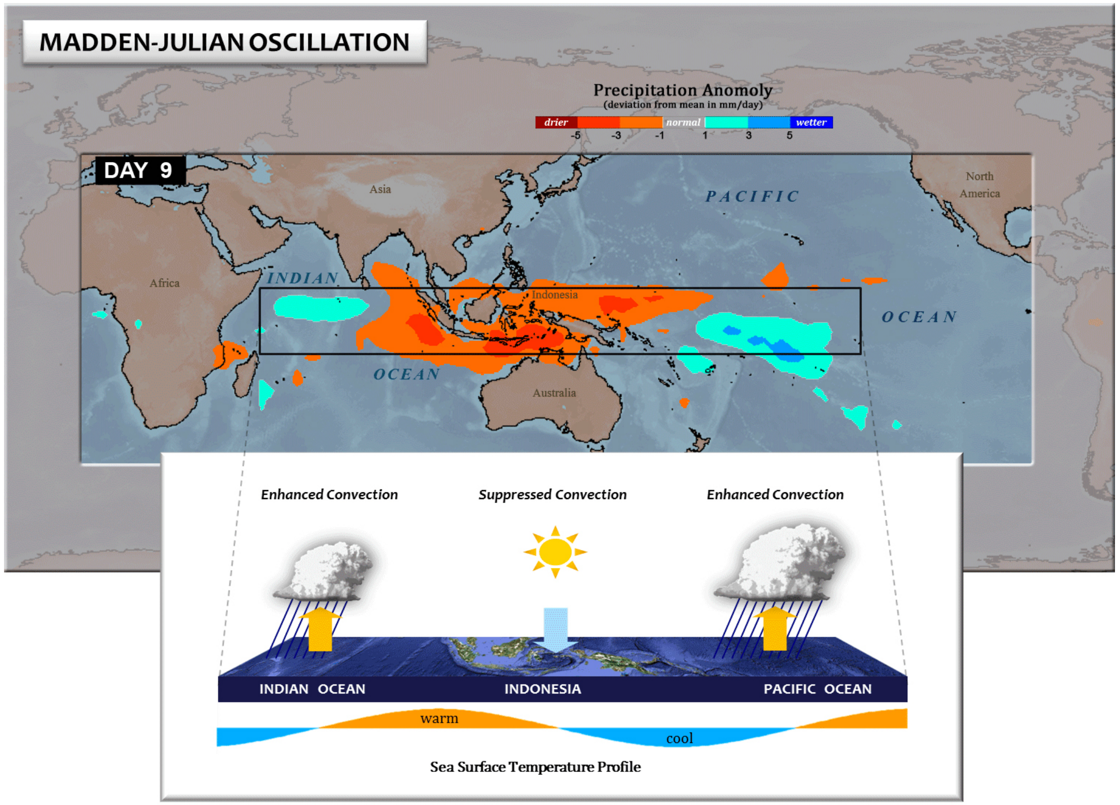


- Madden Julian Oscillation (MJO)
  - Originally noted as a 40-50 day oscillation
  - Commonly defined as 30-90 days, consistent with spectral peaks in precipitation and low-level winds
  - Eastward propagating at ~5 m/s
- Wavelength of 10,000 km
- The dominant tropical ISO → global impacts, TCs, etc.
- 8 phases, most often represented in RMM index/Wheeler and Hendon

Figure 5. Schematic depiction of the large-scale wind structure of the MJO. The cloud symbol indicates the convective center. Arrows represent anomalous winds at 850 and 200 hPa and the vertical motions at 500 hPa. "A" and "C" mark the anticyclonic and cyclonic circulation centers, respectively. Dashed lines mark troughs and ridges. From *Rui and Wang* [1990].

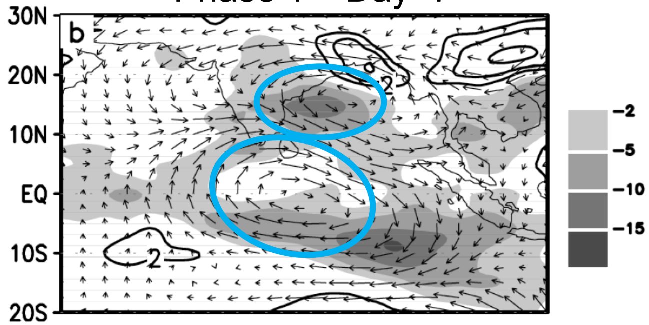
Madden-Julian Oscillation

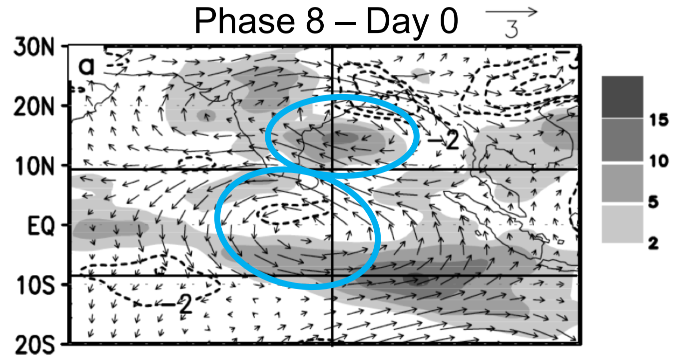
- 30-90 day oscillation
  Reduced cloud-cover.
  Enhanced convection.
- Equatorially trapped.
- Travels eastward and northward over the BoB during SW monsoon
- Strong air-sea coupling.
- Propagates at a rate of 3-5 ms^{-1} and gradually weakens when it reaches the central Pacific.



This illustration shows a moment in the evolution of the Madden-Julian Oscillation, a complex process involving sea surface temperatures and their influence on atmospheric processes. (©UCAR. Illustration by Lex Ivey, based on data from Adrian Matthews.)

10-20 Day Oscillation





10-20 day mode quick facts:

- First characterized by Murakami (1976) as a mesocyclone over the BoB
- One of the main controls on active/break cycles of monsoon rainfall
- Propagation speed 4.5-6 m/s
- Dominant wavelength: 6000 km
- Dominant westward propagating mode for wavenumbers 3-6

- 10-20 day mode consists of a double-cell structure of either lows or highs around ~the equator and 15-20°N, (Figure; Chatterjee and Goswami 2004). → **vortex double-cell**
- Structure propagates W, where the northernmost cell propagates along the monsoon trough → Rossby Waves

- Vertical structure has local Hadley circulation connecting 2 cells; does not change phase in troposphere → TCZ
- Significant rainfall in northern cell (BoB)→ most monsoon precipitation modulated by the 10-20 and 30-60 day oscillations

(Krishnamurti and Ardanuy 1980; Chen and Chen 1993; Goswami et al. 1998; Chatterjee and Goswami 2004)

3-7 Day Synoptic Variability

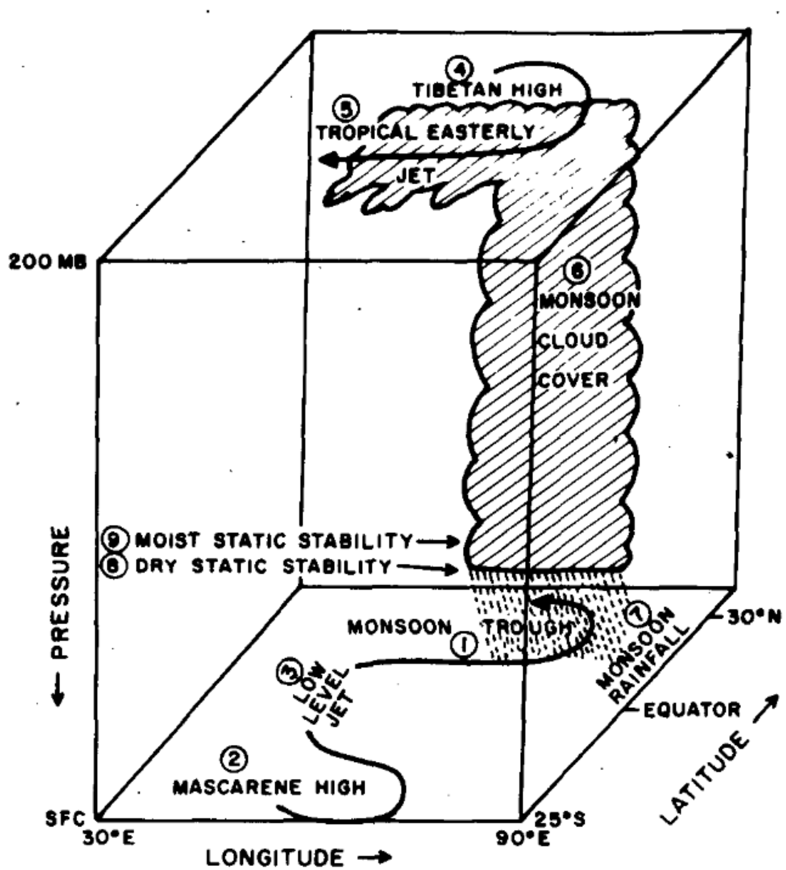


FIG. 1. Schematic diagram of the nine elements of the monsoon system considered in this study.

- 3-7 day oscillation = oscillations in the monsoon trough and synoptic scale weather events
- Wavelength of 2000 km
- TCZ = ascending branch of local Hadley circulation of monsoon
  - During NH summer located around 25°N over India
- TCZ and 3-7 day mode both likely modulated by other ISOs and interannual variability
  - Spatial/temporal structure of TCZ consistent with 30-60 day mode
  - Variations in trough → variations in rainfall

From Krishnamurti and Bhalme (1976)

(Krishnamurti and Bhalme1976; Gadgil and Asha1992; Goswami et al. 1998; Goswami et al. 2003)

Satellite Data

- Aquarius/SAC-D SSS version 5.0
  - Launched June 10, 2011, ended June 7, 2015
  - 1.0° grid spacing with accuracy within 0.2 psu
  - Obtained from JPL/PO.DAAC

- SMOS SSS version 3.0
  - Launched November 2, 2009 (still active mission)
  - 0.25° grid spacing with accuracy within 0.2-0.5 psu (depends on coastal proximity)
  - Obtained from LOCEAN CATDS (Centre Aval de Traitement des Données SMOS)

- SMAP SSS version 4.0
  - Launched January 31, 2015 (still active mission)
  - 0.25° grid spacing with accuracy within 0.26 psu
  - Obtained from JPL/PO.DAAC

Model Simulations

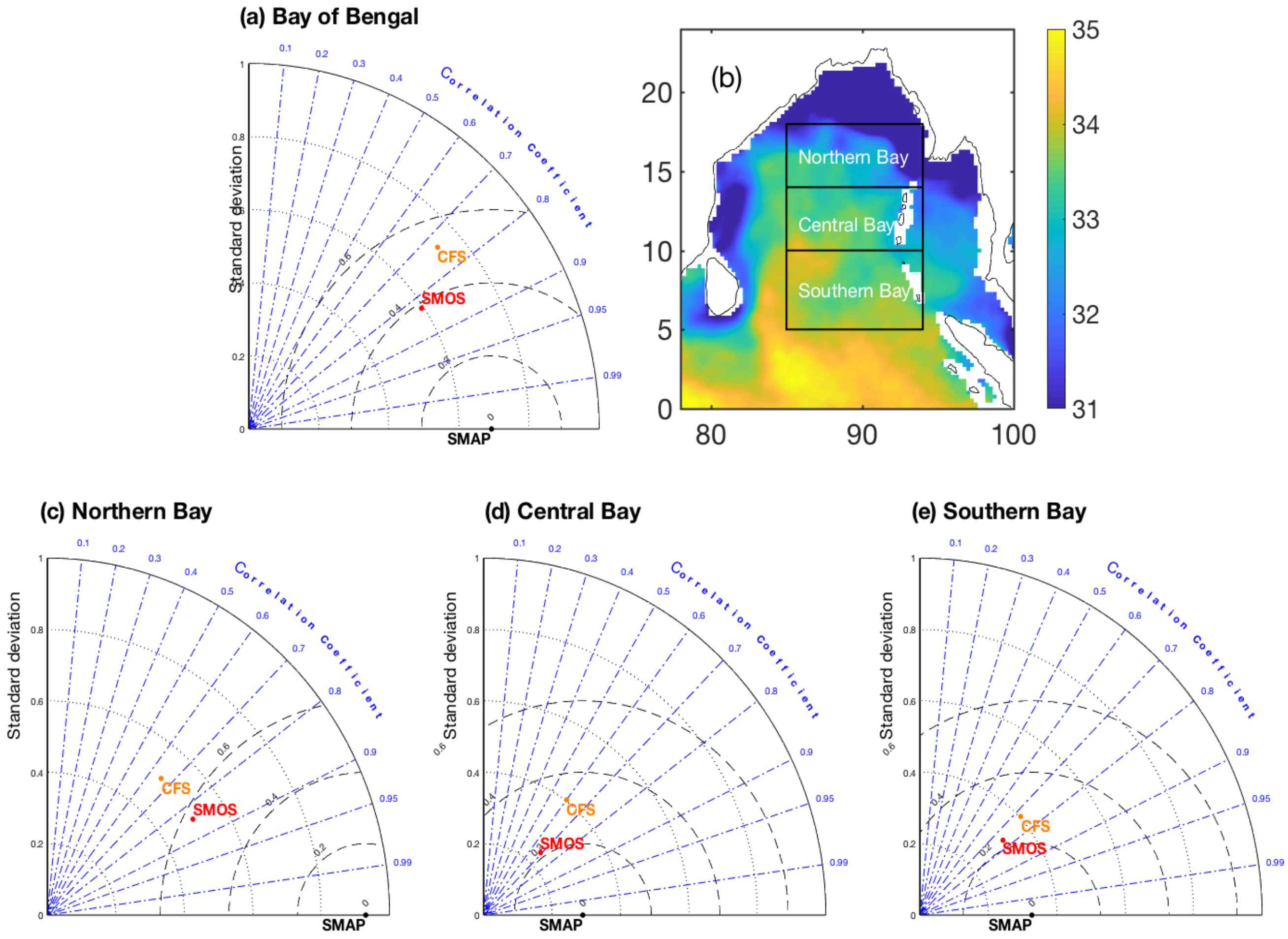
- HYbrid Coordinate Ocean Model (HYCOM)
  - Salinity, temperature, density, layer thickness, sea surface height, currents, density, mixed layer thickness
  - Equatorial resolution of 0.08°, 41 depth layers
  - Daily data from 1993-present
  - Ocean model (not coupled)
  - Hybrid Coordinates:
    - Isopycnal (density tracking – best for stratified ocean)
    - Levels of equal pressure (best used in mixed layer and unstratified ocean)
    - Sigma coordinates (terrain-following – best choice in shallow waters)

  - HYCOM is the most state-of-the-art ocean model, but to fully understand monsoonal processes (including air-sea feedbacks), one must use a coupled model.

Model Simulations

- Climate Forecast System version 2.0 (CFSv2.0)
  - NOAA-NCEP product
  - Atmosphere-land-ocean coupled model
  - Resolution of 0.25° at six-hourly intervals from 2011-present (CFS Reanalysis is from 1979-2011) with 40 vertical layers
    - Useful for upper- and lower-level processes
  - Simulates Indian monsoon circulation well
    - Accurate climatology and annual variability
    - Depicts the important components of the summer monsoon (Chaduhari et al., 2012):
      1. Monsoon trough
      2. Low-level cross-equatorial flow
      3. Upper-level Tibetan high
      4. Upper tropospheric tropical easterly jet

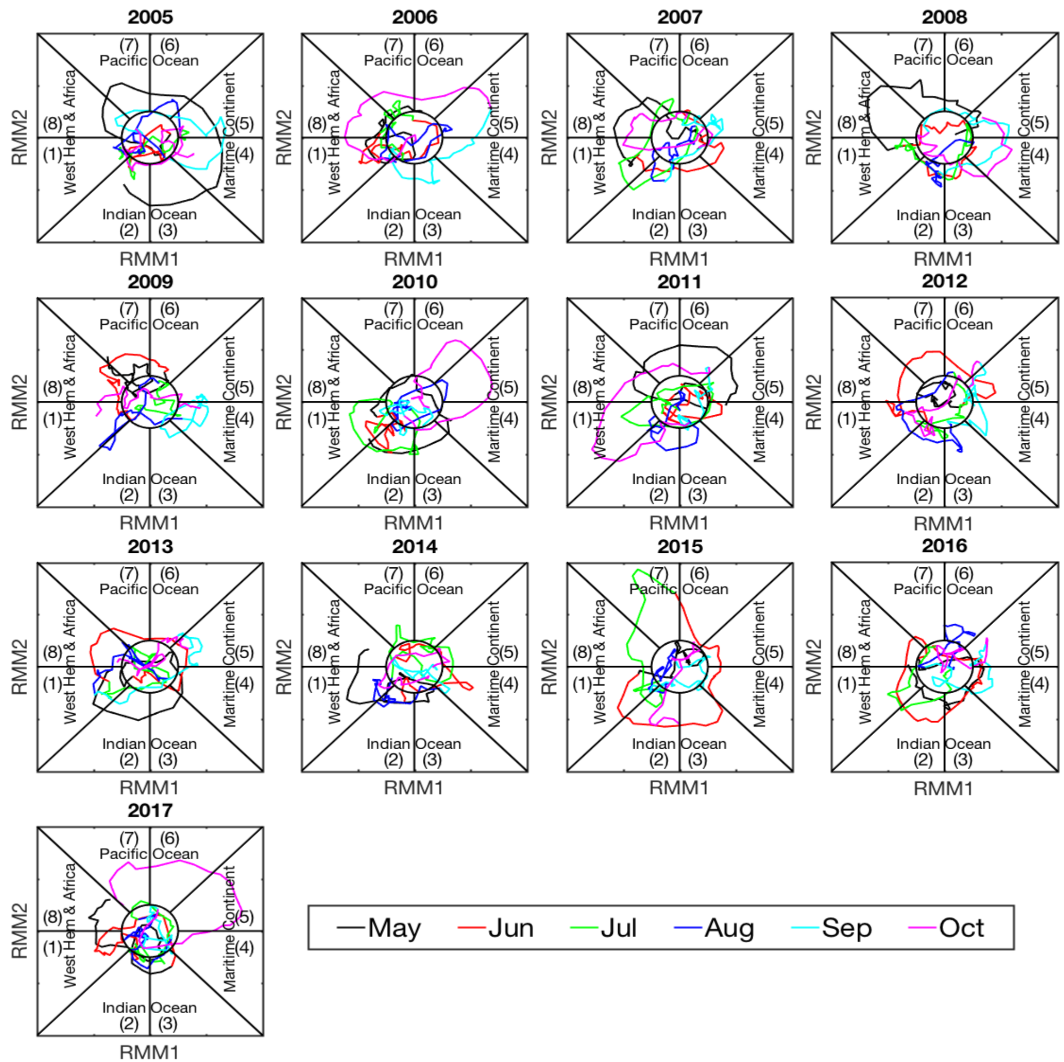
Product Comparison



Taylor diagrams comparing CFS 5 m salinity and SMOS SSS with SMAP SSS during 2016-2017 in the (a) larger Bay of Bengal box (5-18°N, 85-95°E) as shown in (b) and in the boxes of (c) northern Bay (5-10°N, 85-95°E), (d) central Bay (10-14°N, 85-95°E), and (e) southern Bay (14-18°N, 85-95°E) as shown in (b). The color shading in (b) represents the average SMAP SSS (psu) during 2016-2017.

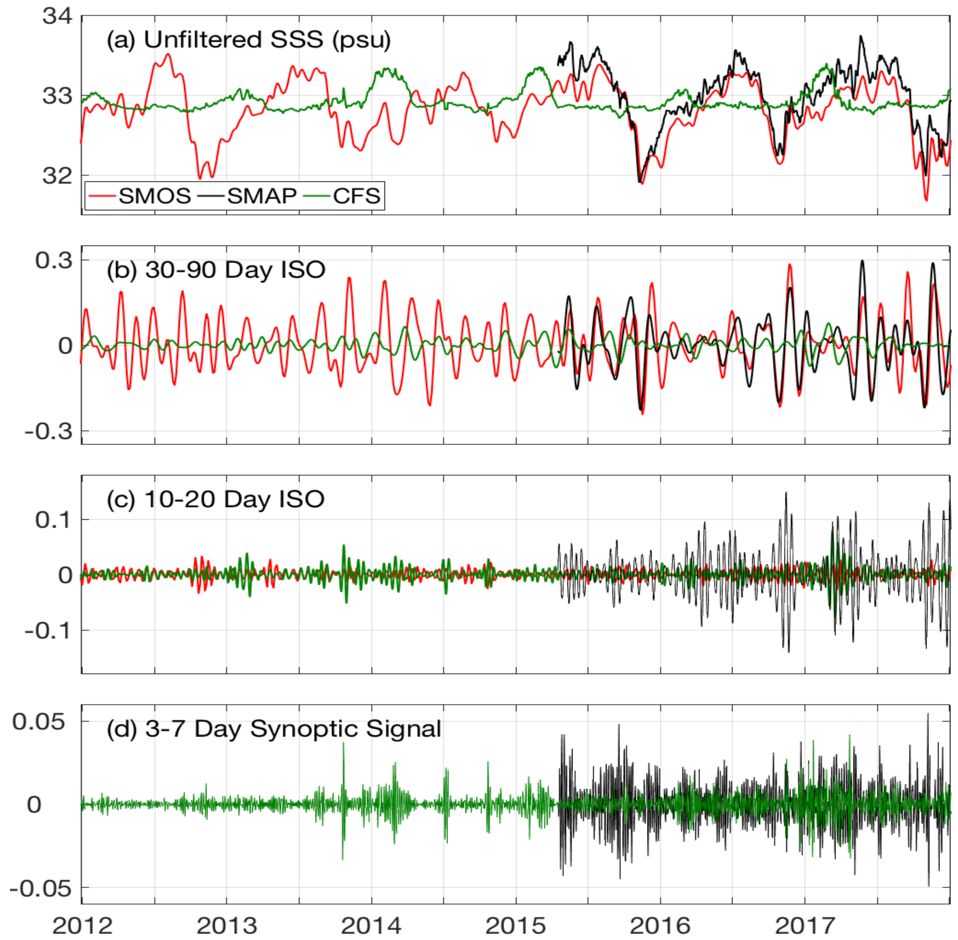
Intraseasonal Oscillations

- RMM phase space plots detect the strength and location of MJO events
- Phase-space plots of Real-time Multivariate MJO Series 1 (RMM1) and Series 2 (RMM2) for May through October in the years 2005 through 2017
- Points within the middle circle (RMM<1) signify weak MJO while the eight quadrants represent the approximate spatial location of the MJO signal.



Intraseasonal Oscillations

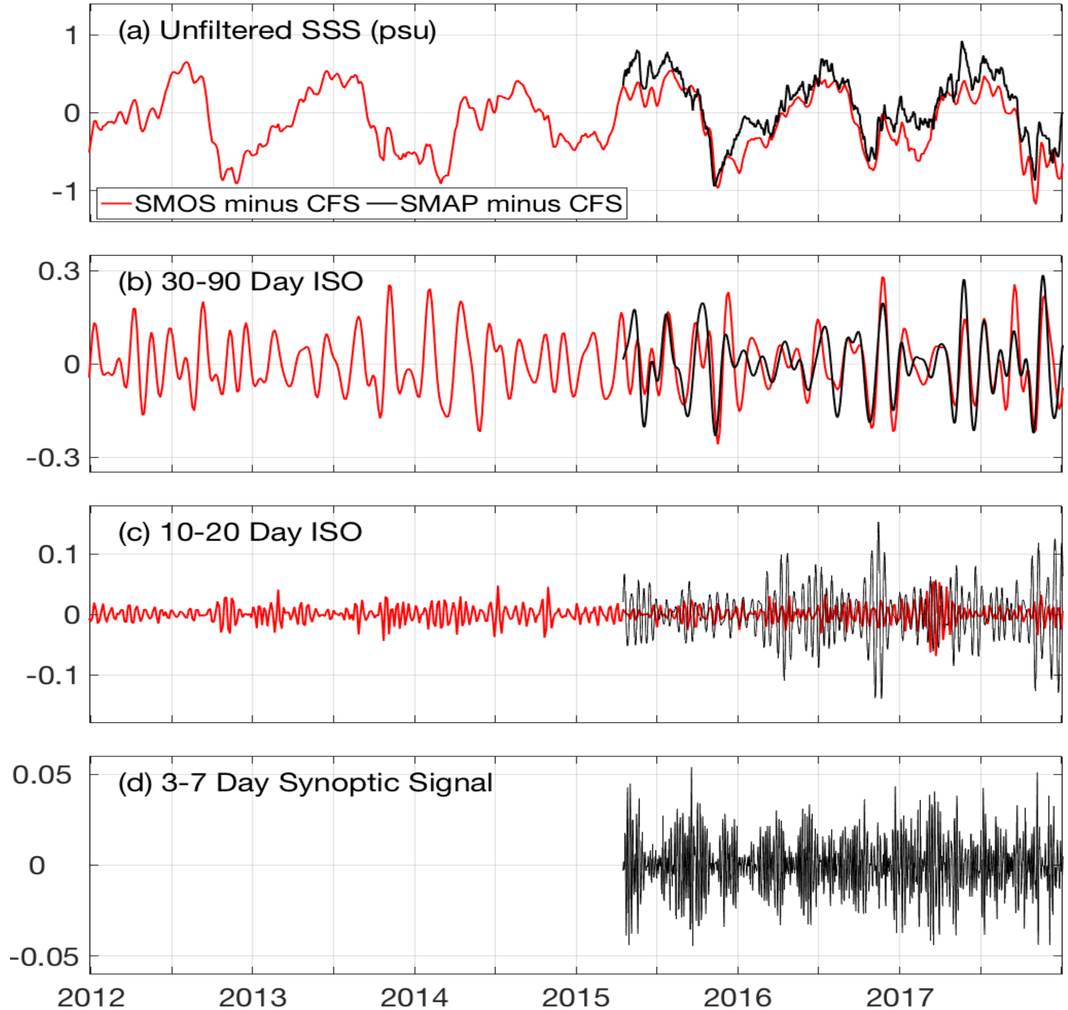
- CFS does well for detecting evaporative (saltier) fluctuations in the Bay of Bengal, but is not so good at tracking fresh events
- Leads to a lower amplitude of 30-90 day SSS
- Amplitude discrepancies in shorter periods are due to sampling rates



Time-series of box averaged (5-18°N, 85-95°E) SMOS SSS (red; psu), SMAP SSS (black; psu), CFS 5 m depth salinity (green, psu) in the Bay of Bengal from 2012 through 2017 for (a) original unfiltered data, and filtered data with (b) 30-90 day period ISO, (c) 10-20 day period ISO, and (d) 3-7 day period synoptic signal.

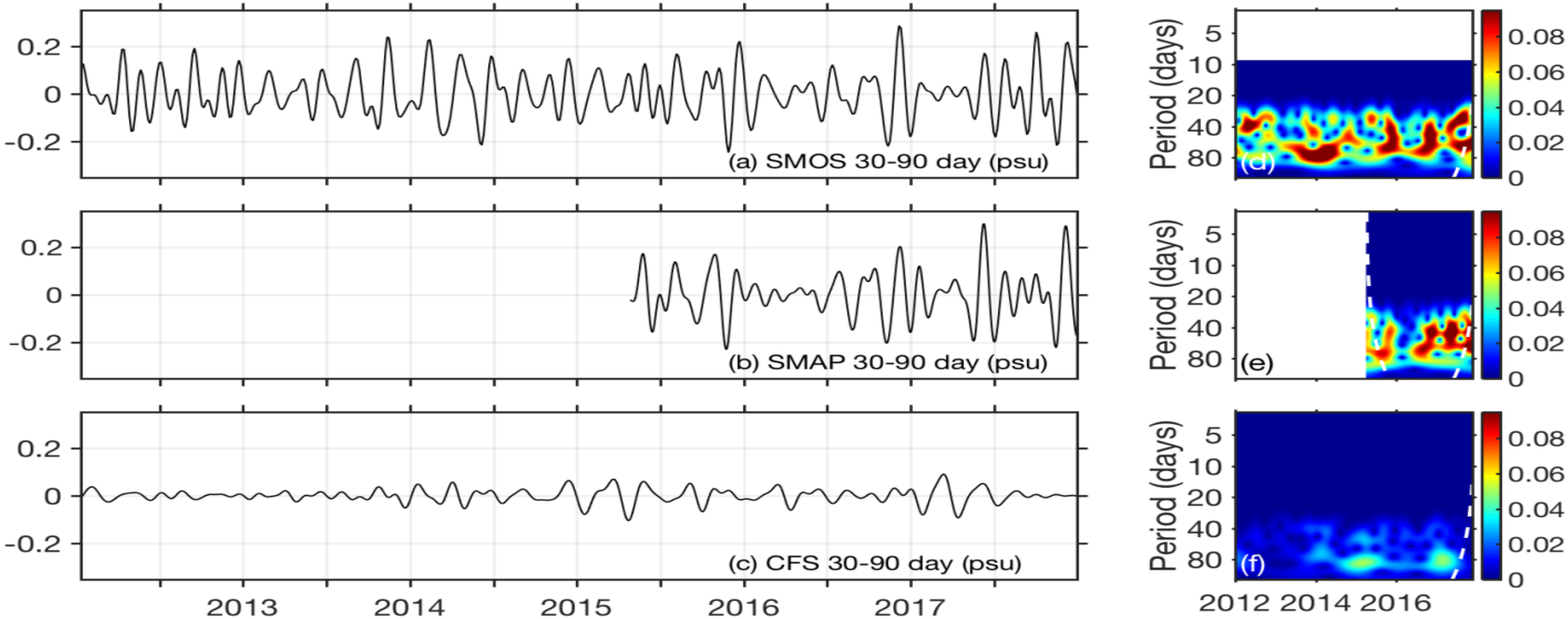
Intraseasonal Oscillations

- Difference between CFS and satellite-derived salinity is temporally consistent
  - Seasonally varies from -1 to +1 psu
- Difference in 30-90 day ISO is also in phase
- Coupled model-simulated SSS would benefit from integration of satellite-derived SSS



Time-series of the differences between SMOS SSS and CFS 5m SSS (red curve) and between SMAP SSS and CFS 5 m SSS (black curve) over a box (5-18°N, 85-95°E) in the Bay of Bengal from 2012 through 2017 for (a) unfiltered original time-series, and filtered time-series with (b) 30-90 day ISO, (c) 10-20 day ISO, and (d) 3-7 day synoptic signal.

30-90 Day ISO

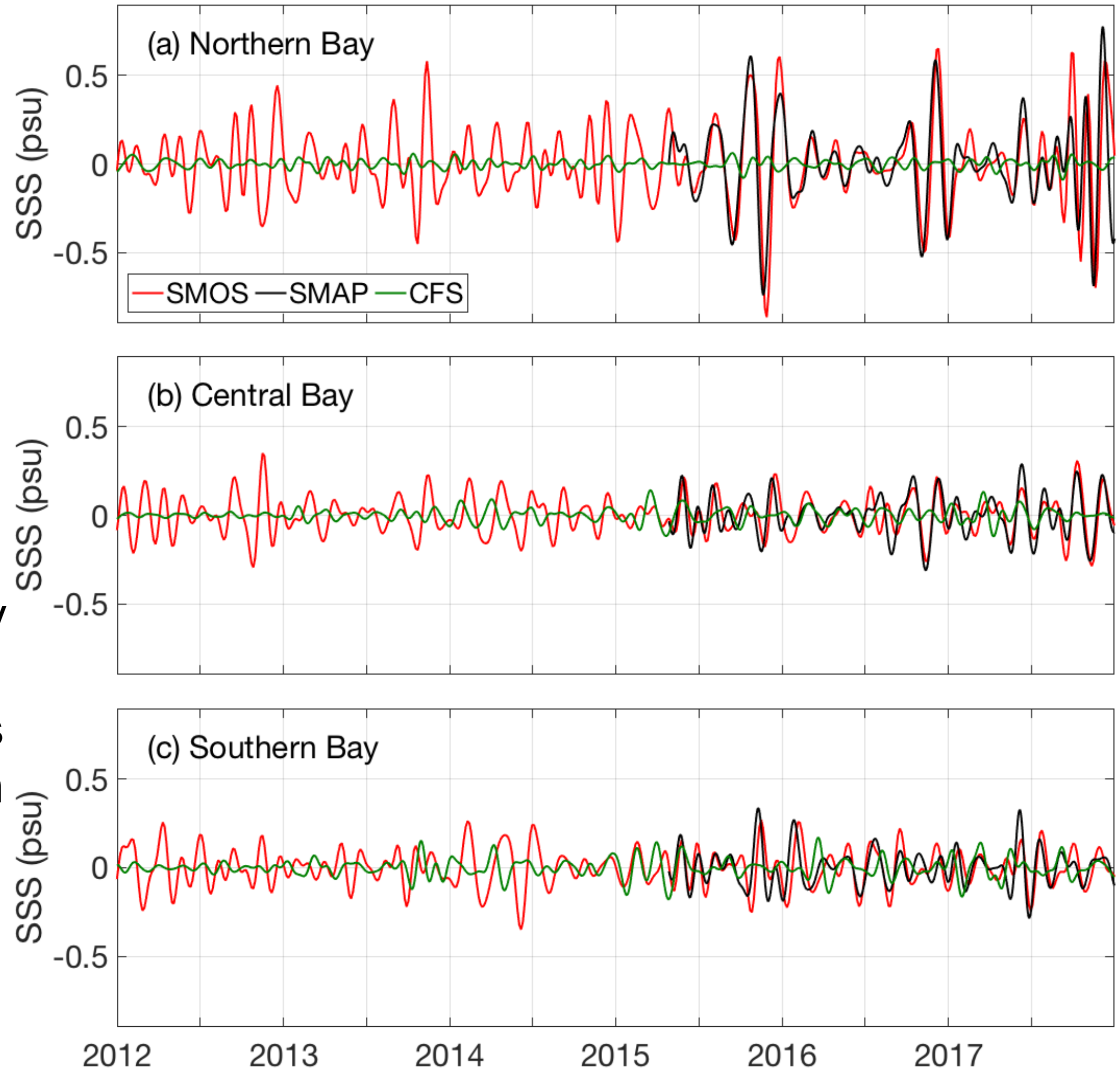


- CFS amplitude is consistently lower
  - May be attributed to skin vs bulk salinity
  - Some variation in the top 10 m of the ocean, but does not capture the complete signal

Time-series of 30-90 day filtered (a) SMOS salinity (psu), (b) SMAP SSS (psu), and (c) CFS 5 m SSS (psu) amplitudes averaged over the box [85°E-95°E and 4°N-18°N] for the period of 2005-2015, and (d to f) represent the corresponding wavelet power spectrum of the time-series in (a to c). The white dotted line in each figure (d to f) signifies the part of the cone of influence (COI) where edge effects might distort the signal.

30-90 Day ISO

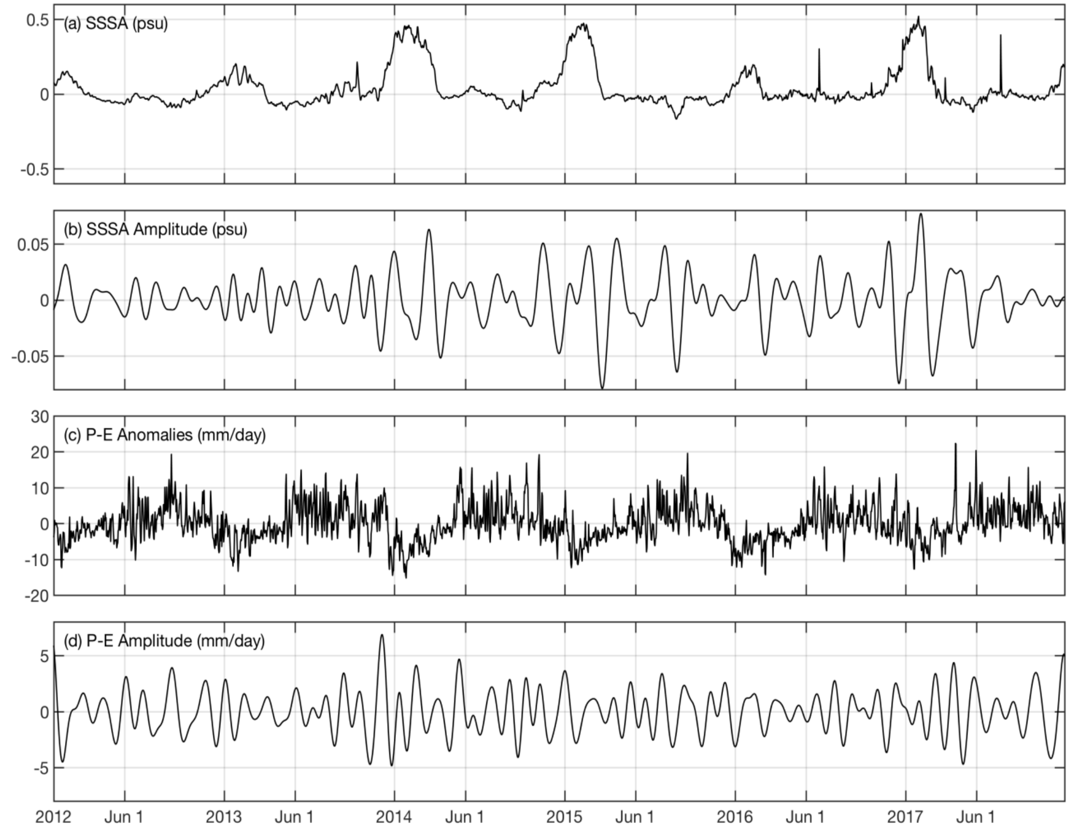
- Highest annual SSS variability is in the northern Bay due to the riverine freshwater flux inflow and high precipitation rates
    - Also reflected in the 30-90 day ISO
    - The aforementioned October-November 2015 MJO event is clearly seen in all regions of the Bay by all three products
- Highest-amplitude MJO events during the period 2012 through 2017 typically peak in either October or November and appear suppressed in the monsoon season



Time-series of 30-90 day filtered SMOS SSS (red; psu), SMAP SSS (black; psu), and CFS 5 m depth salinity (green, psu) for (a) northern Bay (14-18°N, 85-95°E), (b) central Bay (10-14°N, 85-95°E), and (c) southern Bay (5-10°N, 85-95°E) regions from 2012 to 2017.

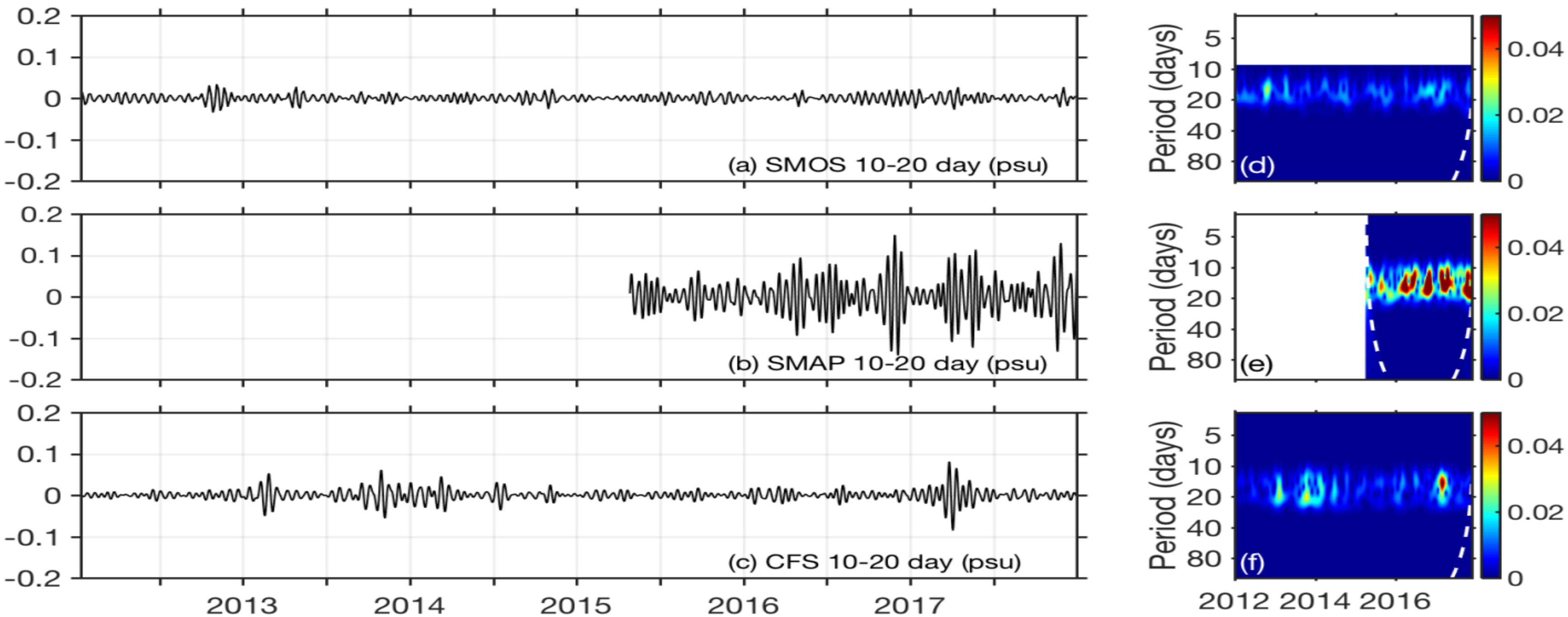
30-90 Day ISO

- Basin-wide distribution of 30-90 day P-E ISOs reveals an interesting relationship
  - The 30-90 day CFS SSS anomalies and the 30-90 day P-E (as well as the two unfiltered time series in the BoB) shows alignment between the dips in P-E (evaporation-dominated conditions) and MJO events
  - Means CFS does well in “dry” MJO phases



Box-averaged (5-19°N, 84-95°E) CFS 5m salinity anomalies (psu) (a) unfiltered and (b) 30-90 day filtered time-series, and GPCP precipitation minus ECMWF evaporation (P-E) (c) unfiltered and (d) 30-90 day filtered time-series during 2012-2017.

10-20 Day ISO

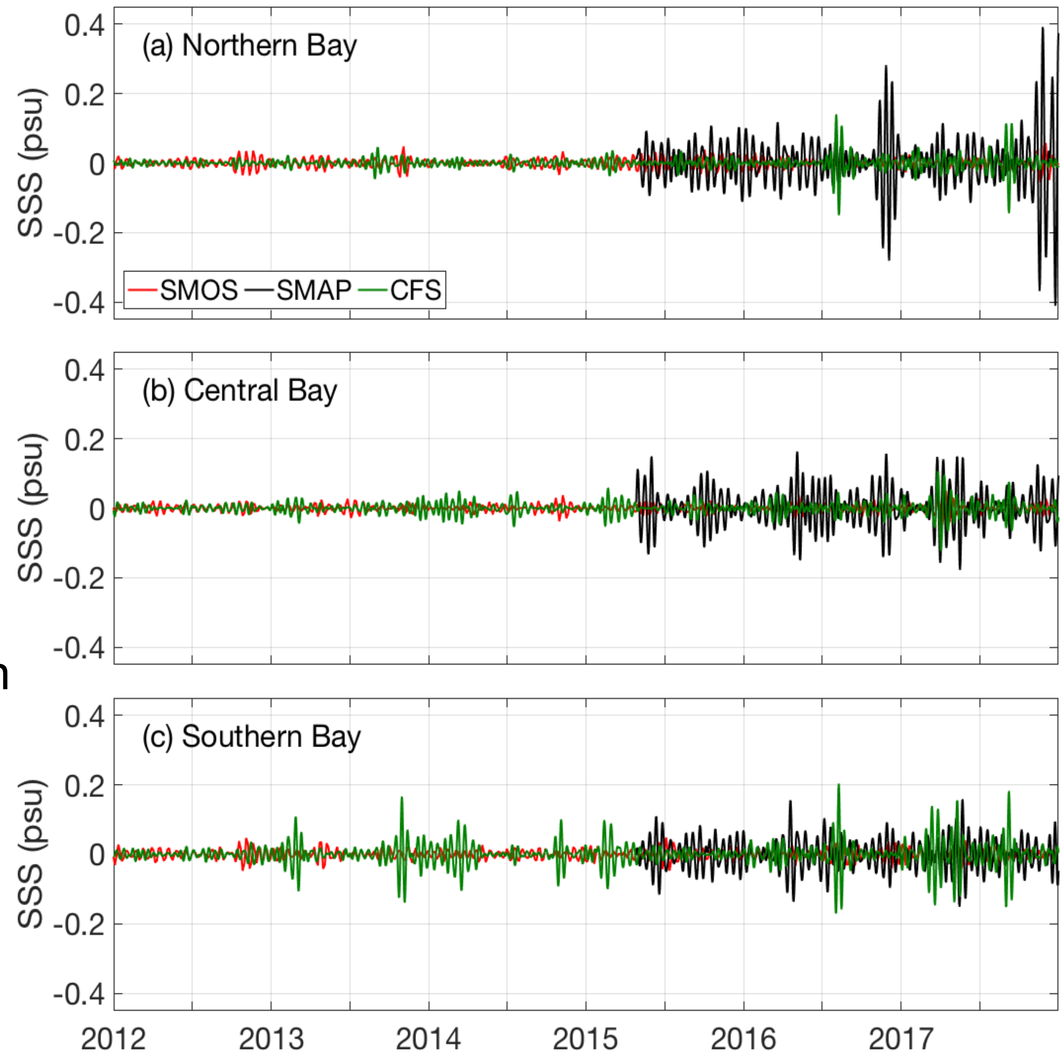


- At smaller-period ISOs, sampling is key
  - Results in a strong difference between SMAP and SMOS
  - CFS should do just as well (as it has 6-hourly data), but only detects some events

Time-series of 10-20 day filtered (a) SMOS salinity (psu), (b) SMAP SSS (psu), and (c) CFS 5 m SSS (psu) amplitudes averaged over the box [85°E-95°E and 4°N-18°N] for the period of 2005-2015, and (d to f) represent the corresponding wavelet power spectrum of the time-series in (a to c). The white dotted line in each figure (d to f) signifies the part of the cone of influence (COI) where edge effects might distort the signal.

10-20 Day ISO

- The disparity between CFS and SMAP can be attributed to the inclusion of freshwater fluxes. SMAP (or SMOS or Aquarius) measures salinity but includes freshwater fluxes
- CFS lacks the variability in freshwater flux off the mainland that observations are able to capture.
- Instead, changes in CFS salinity are largely controlled by changes in the monsoon current pulling higher salinity waters out of the Arabian Sea, causing a pulse in the southern Bay of Bengal instead of the northern Bay of Bengal.



Time-series of 10-20 day filtered SMOS SSS (red; psu), SMAP SSS (black; psu), and CFS 5 m salinity (green, psu) for (a) northern Bay (14-18°N, 85-95°E), (b) central Bay (10-14°N, 85-95°E), and (c) southern Bay (5-10°N, 85-95°E) boxes from 2012 to 2017.

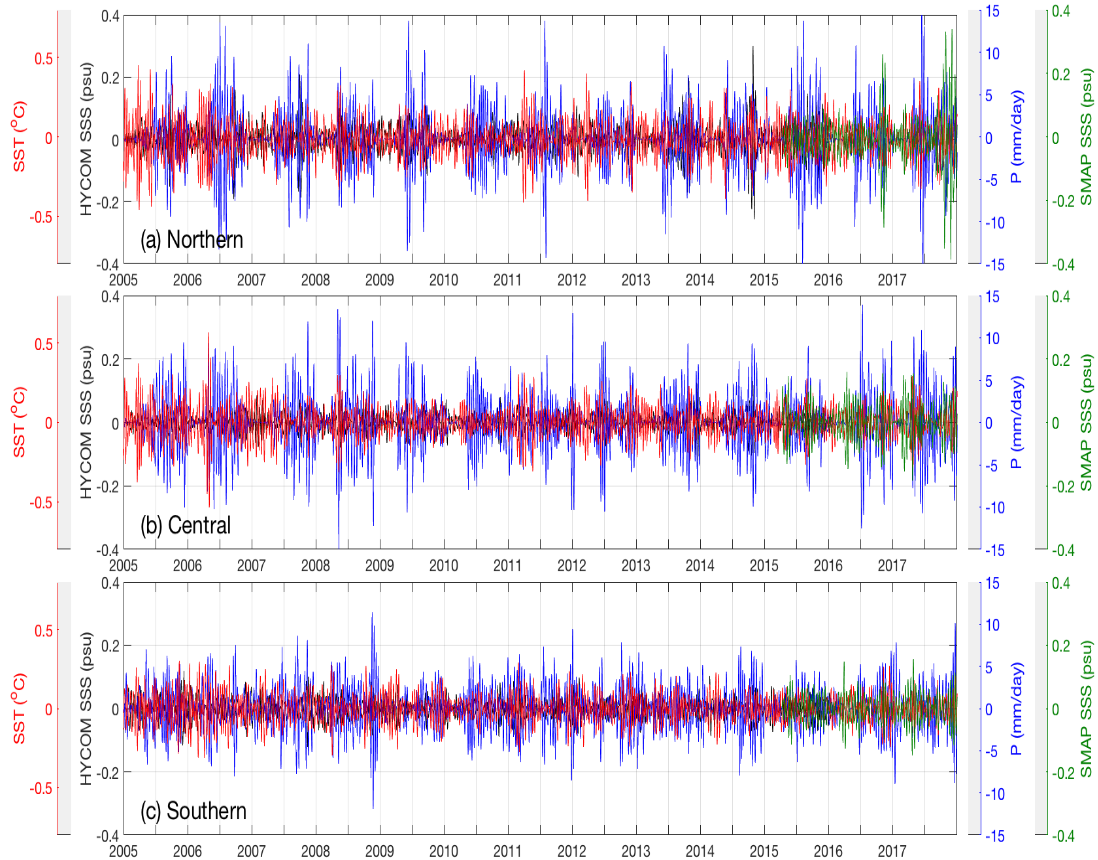
10-20 Day ISO

- The SST anomalies lead the precipitation anomalies by an average of 7 days in the northern BoB, 7 days in the central BoB and 8 days in the southern BoB

- Though high SSTs are not the only condition necessary for precipitation, anomalous SSTs create conditions favorable for convection.

- Increased precipitation then drives SSS anomalies

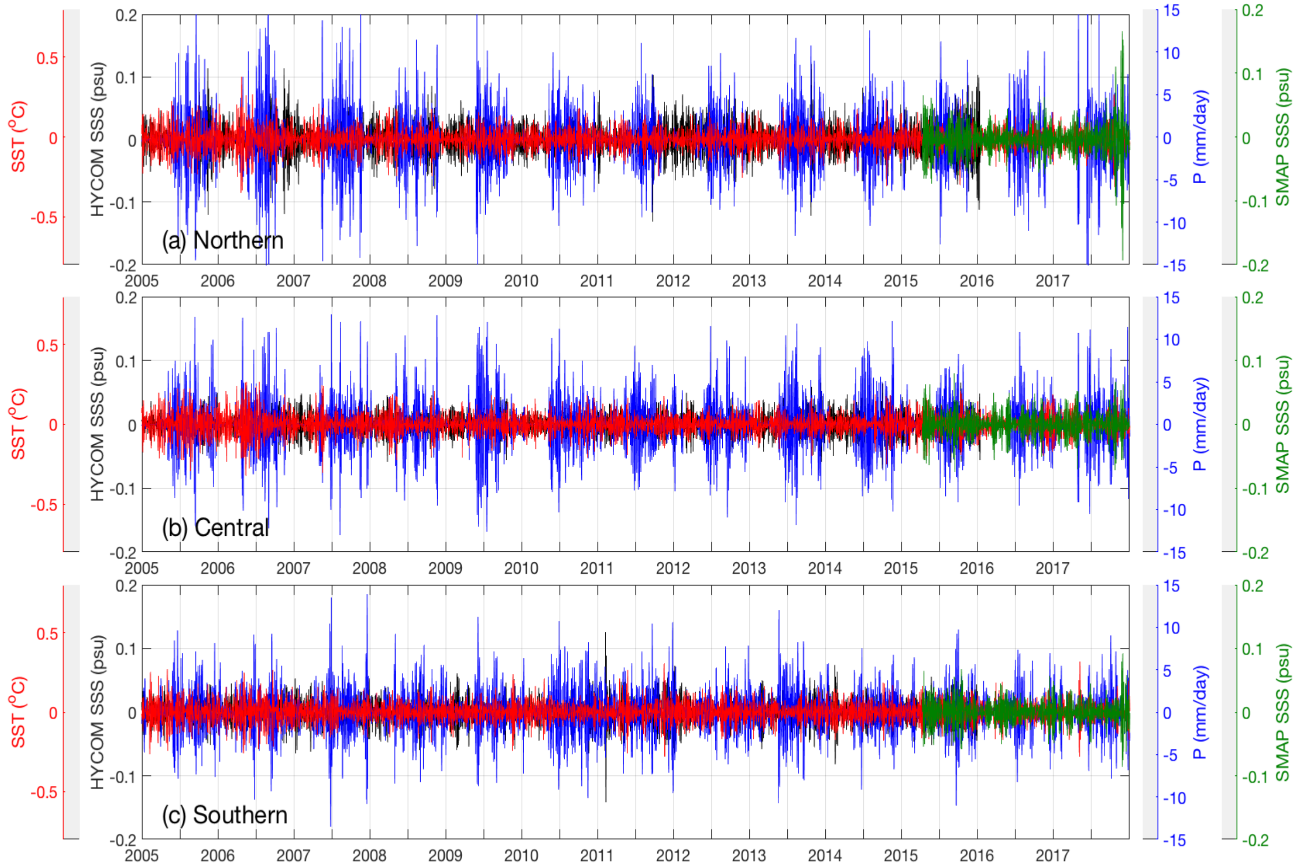
- The largest discrepancy between 10-20 day SSS and precipitation ISOs is in the northern Bay, reinforcing the impact of relatively fresh river outflow.



Time-series of 10-20 day filtered HYCOM SSS anomalies (black, psu), OISST anomalies (red, °C), GPCP precipitation anomalies (blue, mm/day) and SMAP SSS anomalies (green; psu) for the (a) northern Bay (14-18°N, 85-95°E), (b) central Bay (10-14°N, 85-95°E), and (c) southern Bay (5-10°N, 85-95°E) boxes from 2005 to 2017.

3-7 Day ISO

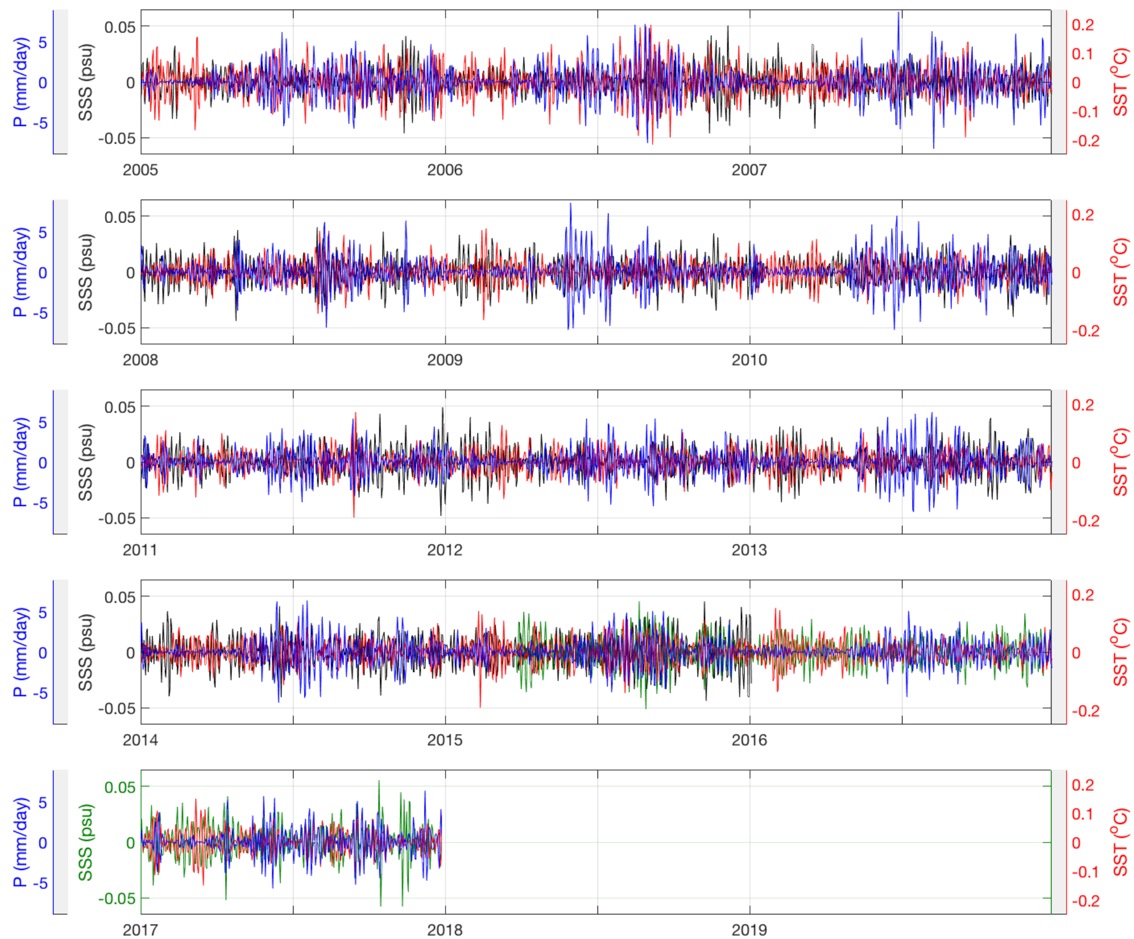
- Much of the SST 3-7 day events occur before and after the summer monsoon season
- 3-7 day precipitation anomalies peak during the summer monsoon season and during major tropical storms
- 3-7 day SSS events respond to synoptic and seasonal forcings



Time-series of 3-7 day filtered daily OISST (red, °C), HYCOM SSS (black, psu), GPCP precipitation (blue, mm/day) and SMAP SSS (green, psu) for the (a) northern Bay (14-18°N, 85-95°E), (b) central Bay (10-14°N, 85-95°E), and (c) southern Bay (5-10°N, 85-95°E) boxes.

3-7 Day ISO

- IOD events can either intensify or weaken the impact of ENSO events on the Indian monsoon rainfall
- The 2006 cyclone season in the BoB had the highest number of storms during July through September coincident with the peaking positive IOD phase
- The year 2009 was primarily dominated by strong El Niño conditions and experienced only two depressions, two cyclonic storms, and one severe cyclonic storm



Time-series of 3-7 day filtered daily HYCOM SSS (blue, psu), GPCP precipitation (black, mm/day), OISST (red, °C), and SMAP SSS (green, psu) in the Bay of Bengal (averaged over 4-18°N, 85-95°E) from 2005 through 2017.

Conclusions

- The Indian monsoon is a complex, nonlinear phenomenon involving atmospheric, oceanic, and land-based interactions.
- Because it does not directly affect air-sea fluxes, salinity is often neglected in climate-related studies, though recent works have shown that regional salinity can play an integral role in ocean-atmosphere interactions in the South Eastern Arabian Sea (SEAS) region.
- Monsoonal rainfall intensity is directly tied to the strength and northward propagation of intraseasonal oscillations (ISOs) with periodicities of 30-90 days (MJO events), 10-20 days (quasi-biweekly oscillation) and 3-7 days (synoptic events).
- Evaluation of coupled models such as the Climate Forecast System (CFS) version 2.0 reveals insufficient detection of ISOs when compared with those detected by satellite-derived salinity from Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP).
- The usage of satellite-derived salinity in coupled atmospheric-ocean models will improve model simulations with respect to the influence of salinity on monsoonal processes.

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