UTILIZATION OF SATELLITE-DERIVED SALINITY AS A PREDICTOR FOR INDIAN MONSOON FORECASTING

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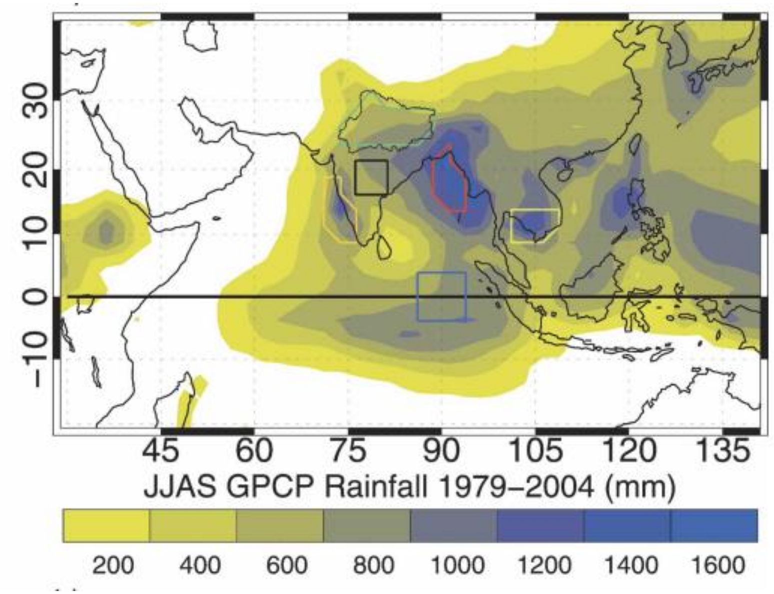
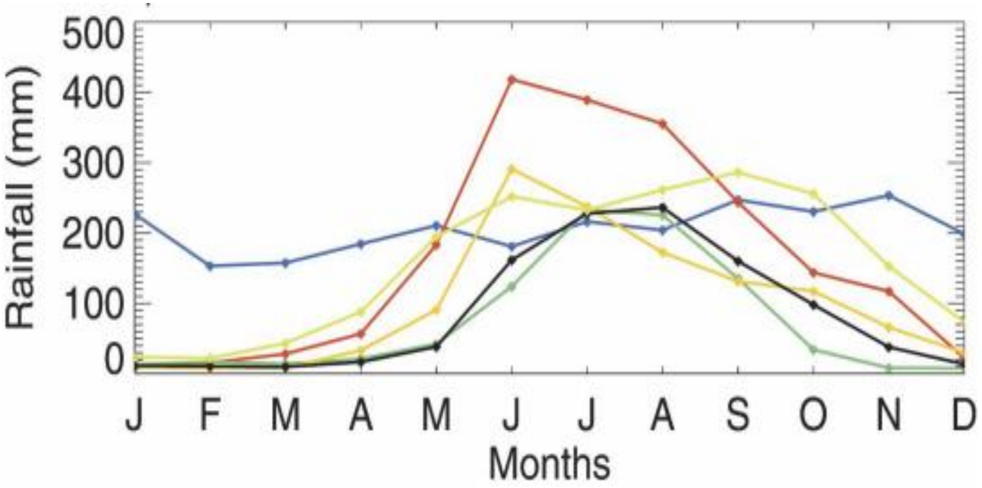
Oceanic Control of Monsoon Intraseasonal Oscillations in the Tropical Indian Ocean and Bay of Bengal (MISO-BOB)

BACKGROUND

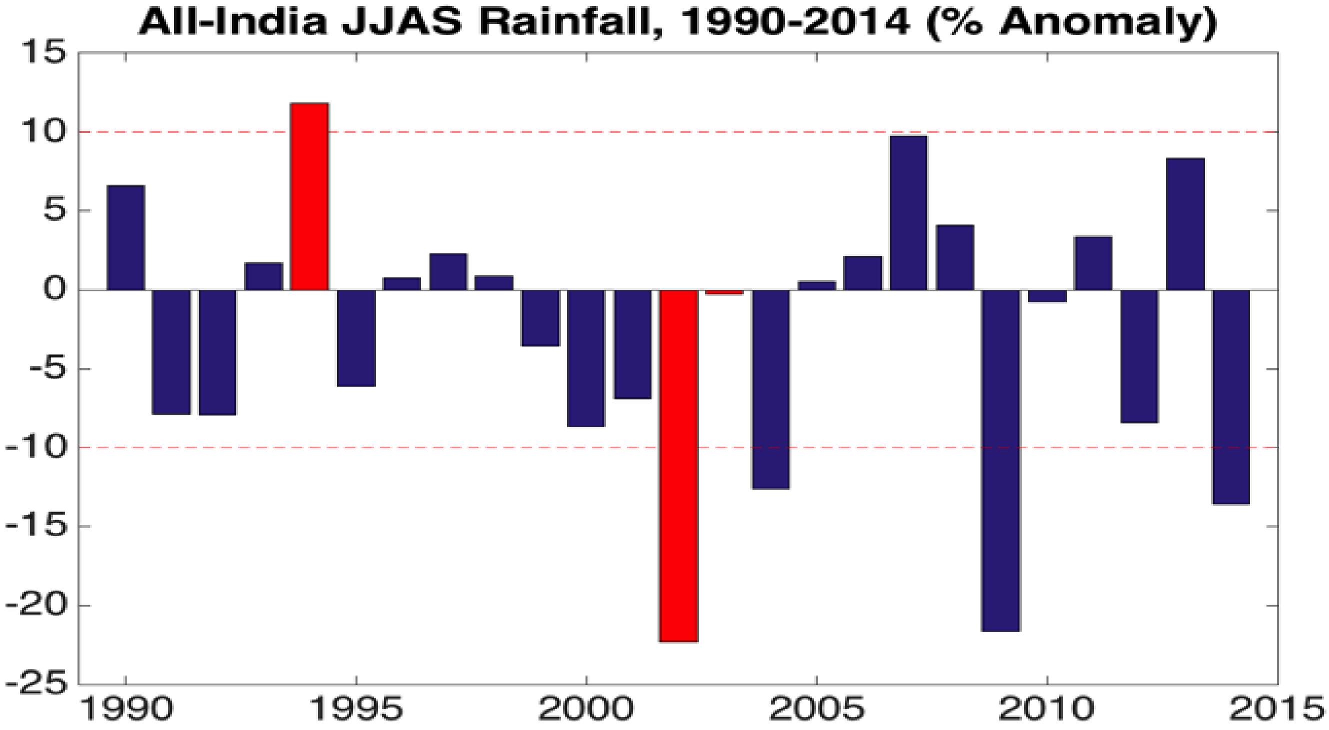
- India receives 78% of its annual rainfall June-September (>90% in some regions)
  - Population: ~1.3 billion people
  - Highly consequential and requires improved prediction





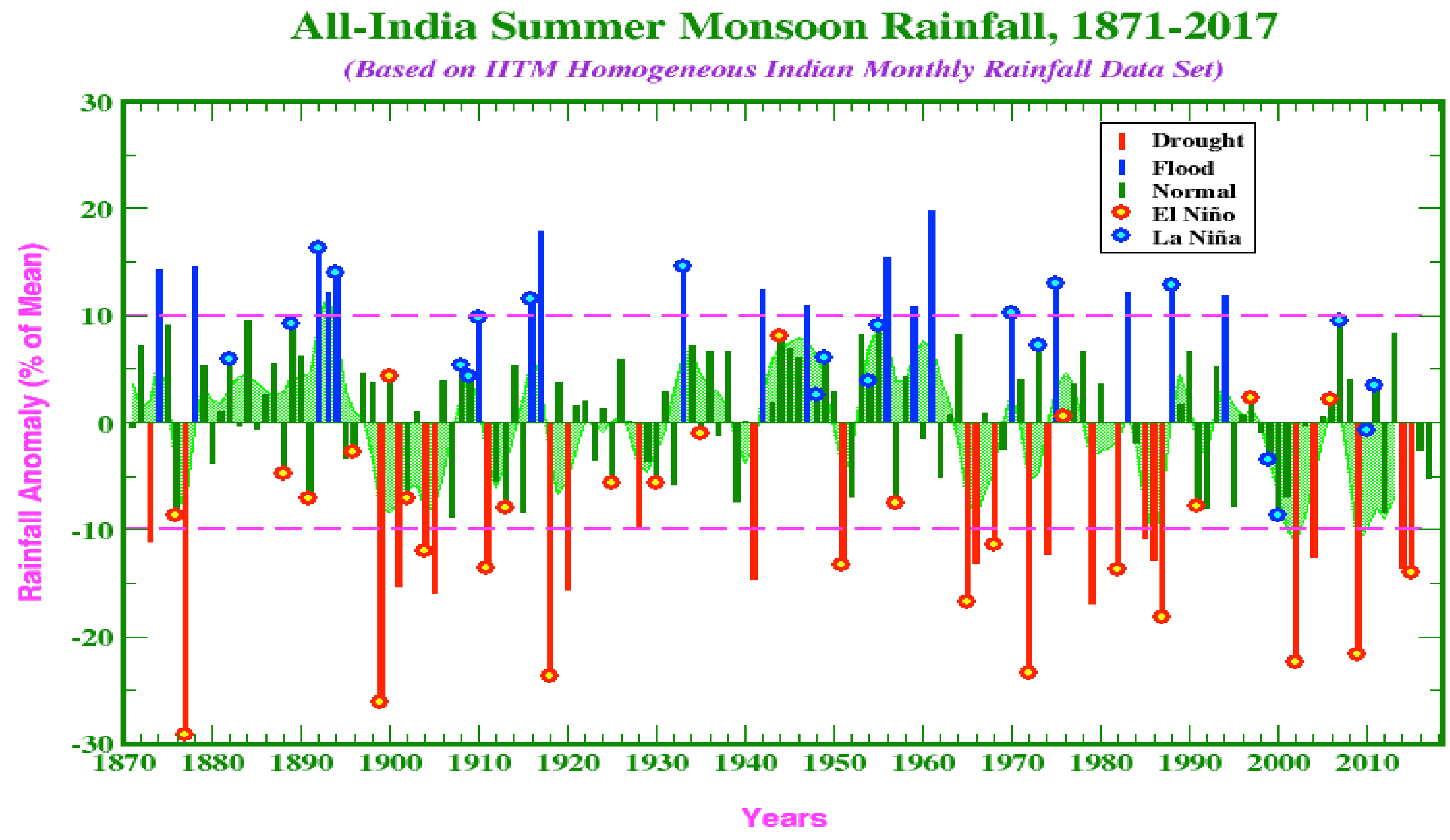
Top: Floods in Agartala, the capital of Tripura State in India (New York Times, August 2017)
Bottom Left: Hoyos and Webster, 2007

ACTIVE AND BREAK MONSOONS

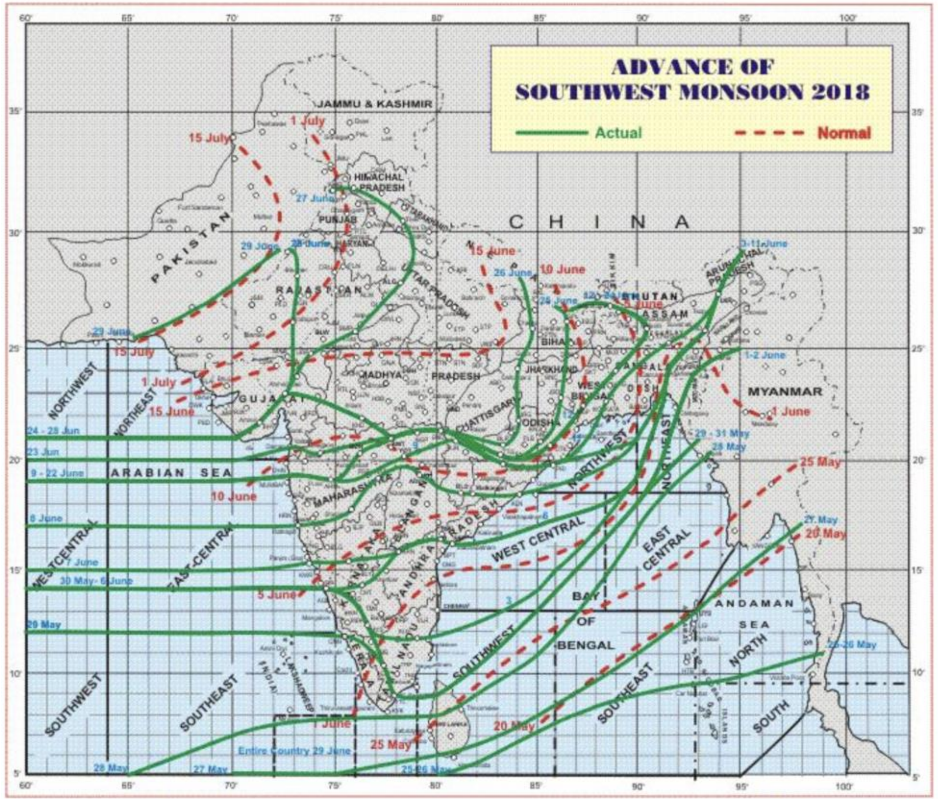


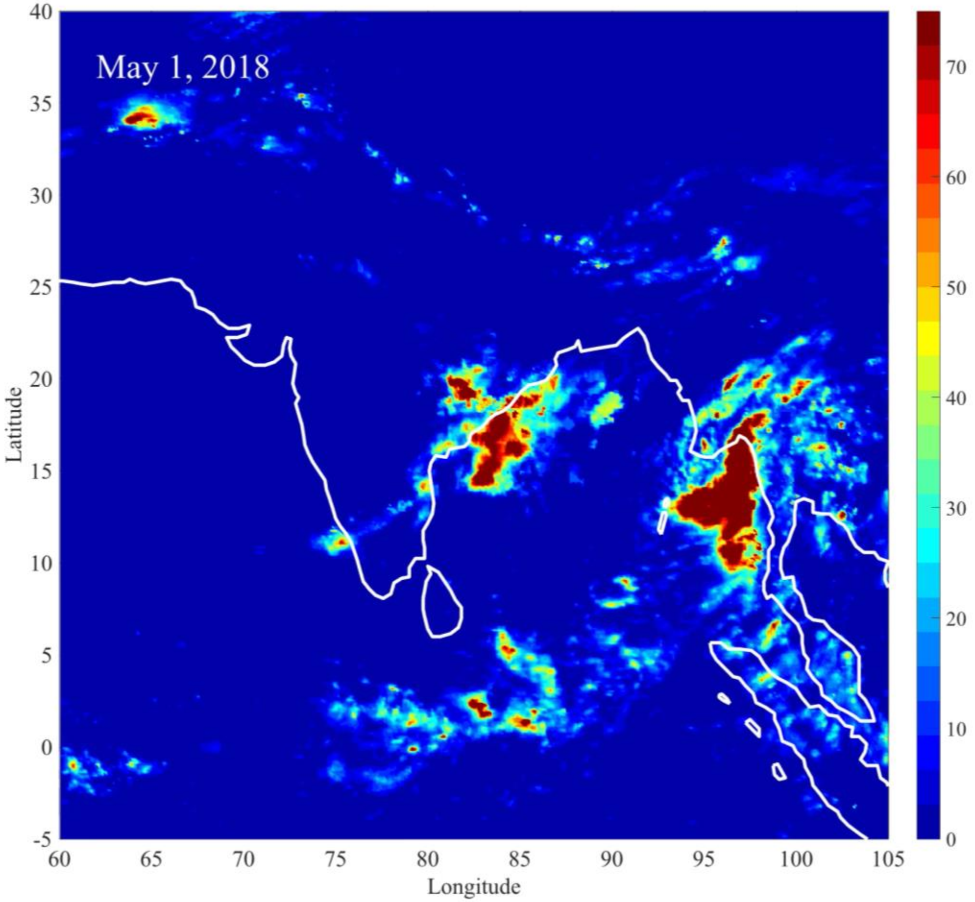
All-India Rainfall for the summer monsoon seasons (June through September) from 1990 to 2014. The percent anomalies are in reference to the mean JJAS rainfall from 1871 to 1990 (Source: Indian Institute of Tropical Meteorology, Pune, India). The mean JJAS rainfall is 852.1 mm. Red bars indicate the three chosen years with the highest (1994, +11.8%), lowest (2002, -22.3%), and smallest (2003, -0.3%) percent rainfall anomalies corresponding to the strong, weak and normal monsoon years respectively (Trott et al., 2017).

INDIAN SUMMER MONSOON RAINFALL



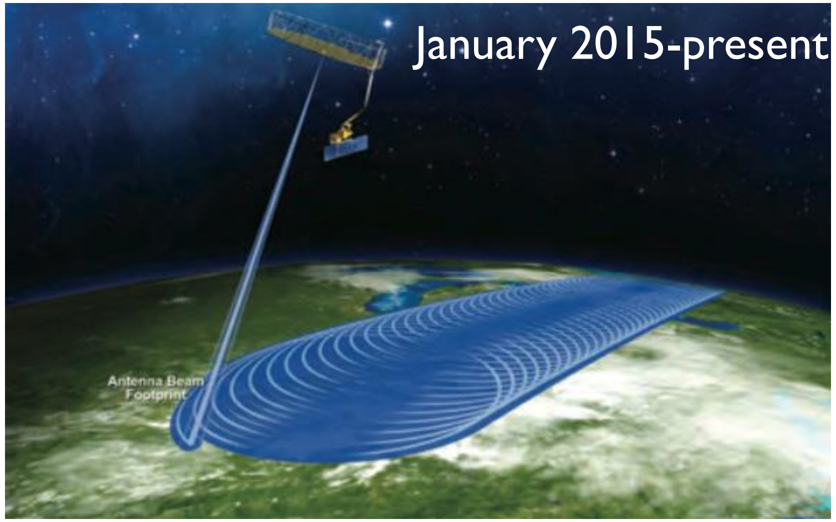
MONSOON ONSET





- Left: IMD southwest monsoon onset, 2018
- Right: Animation of daily GPM precipitation for May to October 2018 (mm/day)

SATELLITE DERIVED SALINITY



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

SATELLITE SANITY DATA

- **Aquarius/SAC-D SSS version 5.0**
  - Launched June 10, 2011, ended June 7, 2015
  - L-band radiometric frequencies (~1.4 GHz)
  - Active-Passive designs, with an active–band radar scatterometer
  - 100-150 km spatial resolution and 7–day exact repeat
  - 1.0° resolution with a global accuracy within 0.2 psu
  - Obtained from JPL/PO.DAAC

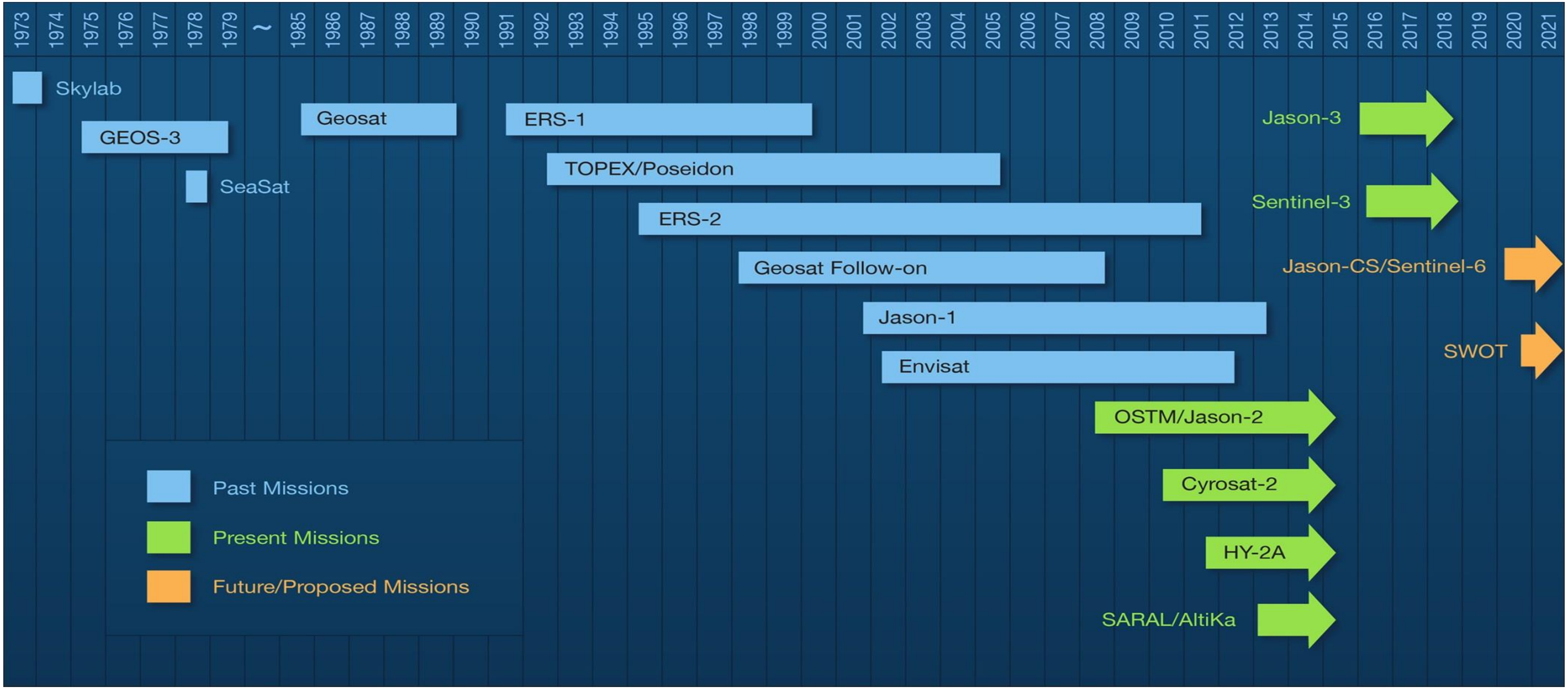
- **SMOS SSS version 3.0**
  - Launched November 2, 2009 (still active)
  - L-band radiometric frequencies (~1.4 GHz)
  - Passive L-band Interferometric radiometry design
  - 43-km spatial resolution with an 18-day near repeat cycle and 3-5 day revisit time
  - 0.25° resolution with a global accuracy within 0.2-0.3 psu (depends on coastal proximity)
  - Obtained from LOCEAN

- **SMAP SSS version 4.0**
  - Launched January 31, 2015 (still active)
  - L-band radiometric frequencies (~1.4 GHz)
  - Active-Passive designs, with an active–band radar scatterometer
  - 40 km spatial resolution and 8–day repeat with a 2-3 day revisit time
  - 0.25° horizontal resolution with a global accuracy within 0.2-0.25 psu
  - Obtained from JPL/PO.DAAC

SATELLITE DERIVED SALINITY

- Sea Surface salinity from space measurements from these missions are the only means to probe the very-near surface salinity (top cm).
- The capability of systematically sample 40-100 km scales every 4-days is unachievable by other salinity observing platforms, including the Argo program.
- Assimilation of satellite derived salinity (SSS) data helped to improve the accuracy of model salinity and Air-Sea Fluxes within the Estimating the Circulation and Climate of the Ocean (ECCO) solution (Kohl et al., 2014).
  - Unlike ocean/climate models, operational systems run close to real time, and thus input streams need to be robust and timely, as well as be of good quality with known accuracy.
  - The bias corrections of the satellite data relies on good quality *in situ* reference data, so improving the coverage of *in situ* data should be a priority, especially in marginal seas, coastal areas and high latitude oceans.
  - Satellite SSS retrievals represent the Gaussian-weighted average within the satellite foot print 40 km (150 km) for SMOS and SMAP (Aquarius). In contrast *in situ* measurements are pointwise observations.

SATELLITE ALTIMETRY DERIVED SEA SURFACE HEIGHT (SSH) DATA



COUPLED MODEL SIMULATIONS

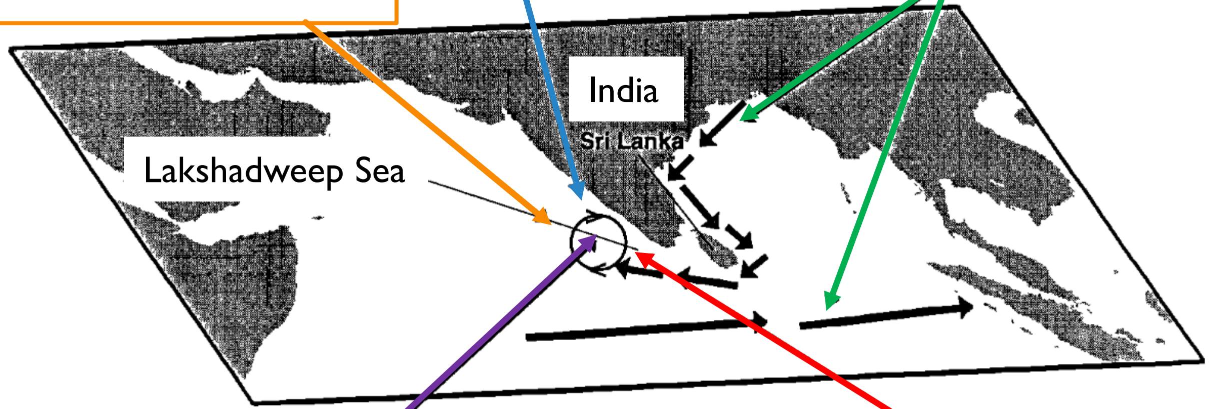
- **Climate Forecast System version 2.0 (CFSv2.0)**
  - NOAA/NCEP
  - Atmosphere-land-ocean-ice coupled model
  - Resolution of 0.25° at six-hourly intervals from 2011-present (CFS Reanalysis is from 1979-2011) with 40 vertical layers
    - Useful for upper- and lower-level processes
  - Simulates Indian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

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!

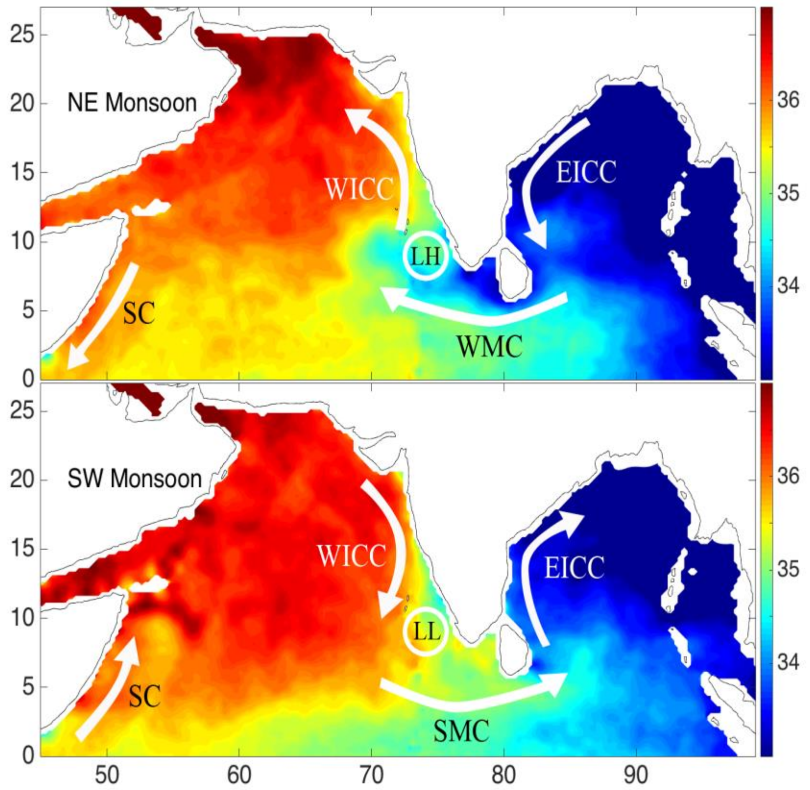
4. High April SSTs trigger pre-monsoon rainfall (not sufficient moisture for full onset)

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



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

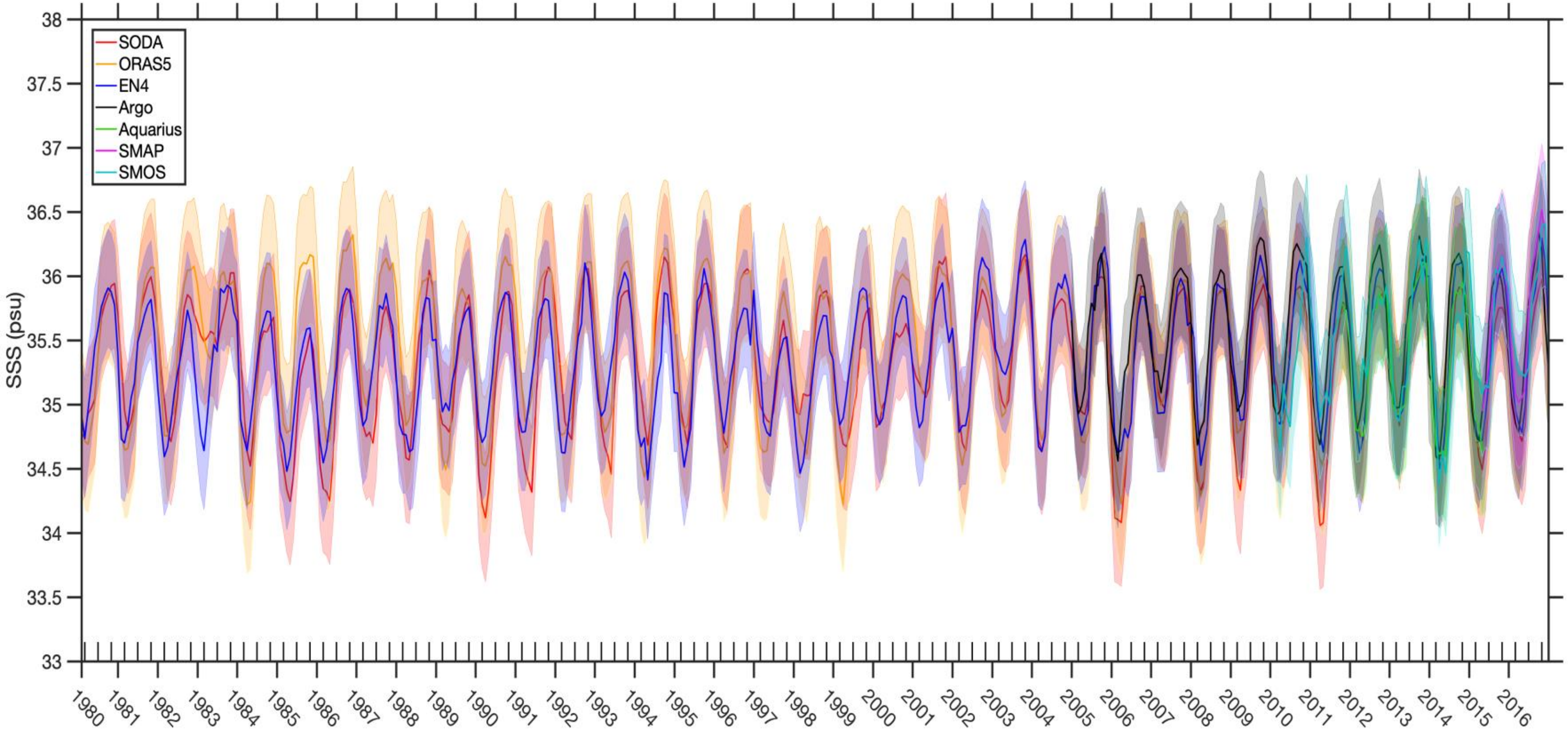
2. By January, a region of high sea level and low SSS forms in Lakshadweep Sea

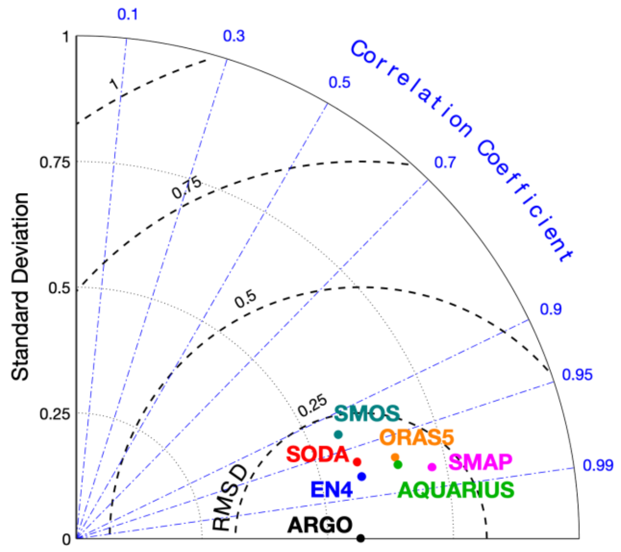


SMAP SSS during the NE and SW Monsoons of 2016

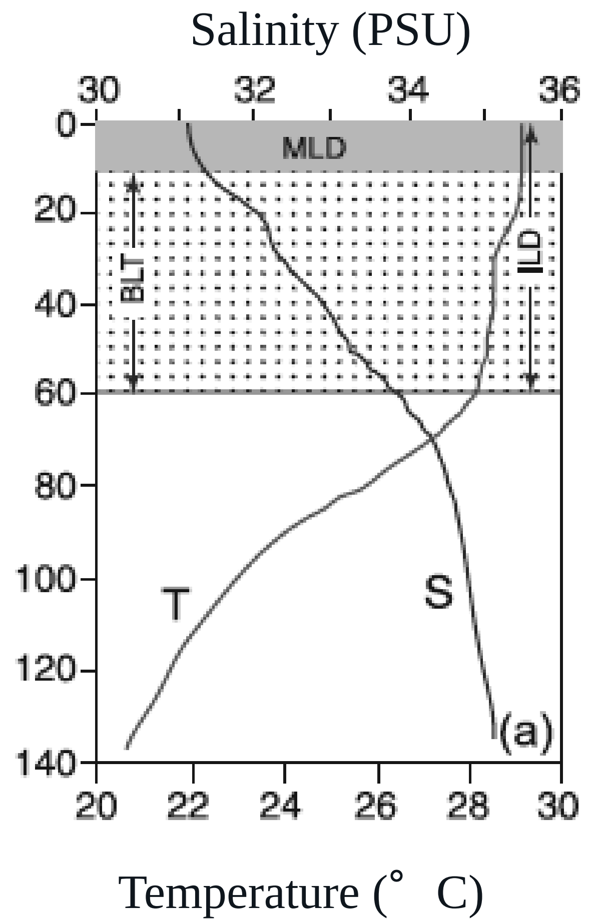
Left: adapted from Shenoi et al. (1999)

COMPARISON OF SATELLITE SALINITY PRODUCTS IN SOUTH EASTERN ARABIAN SEA (SEAS) REGION

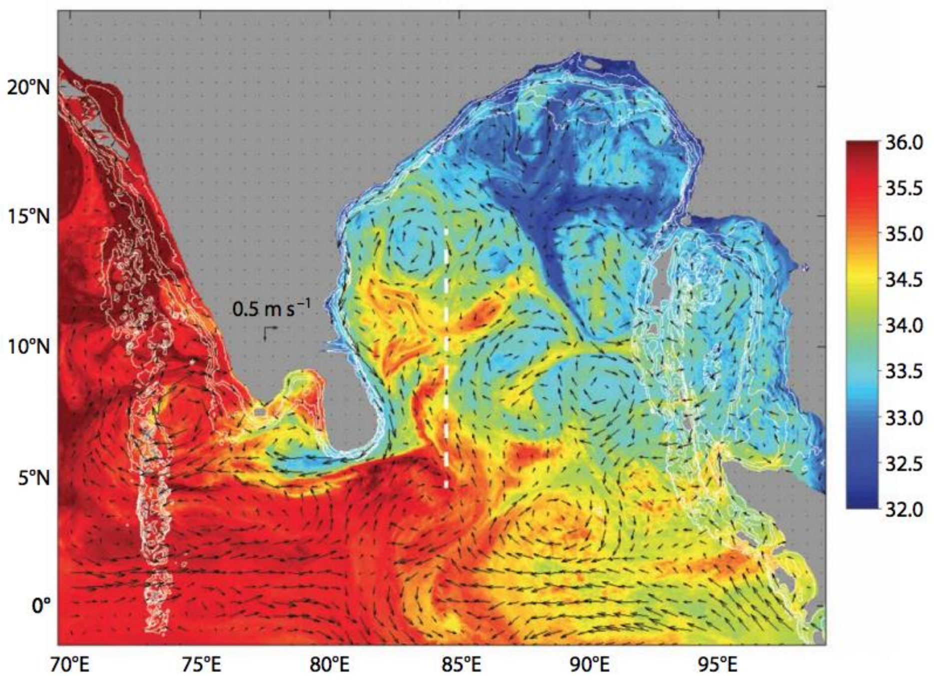




BARRIER LAYER



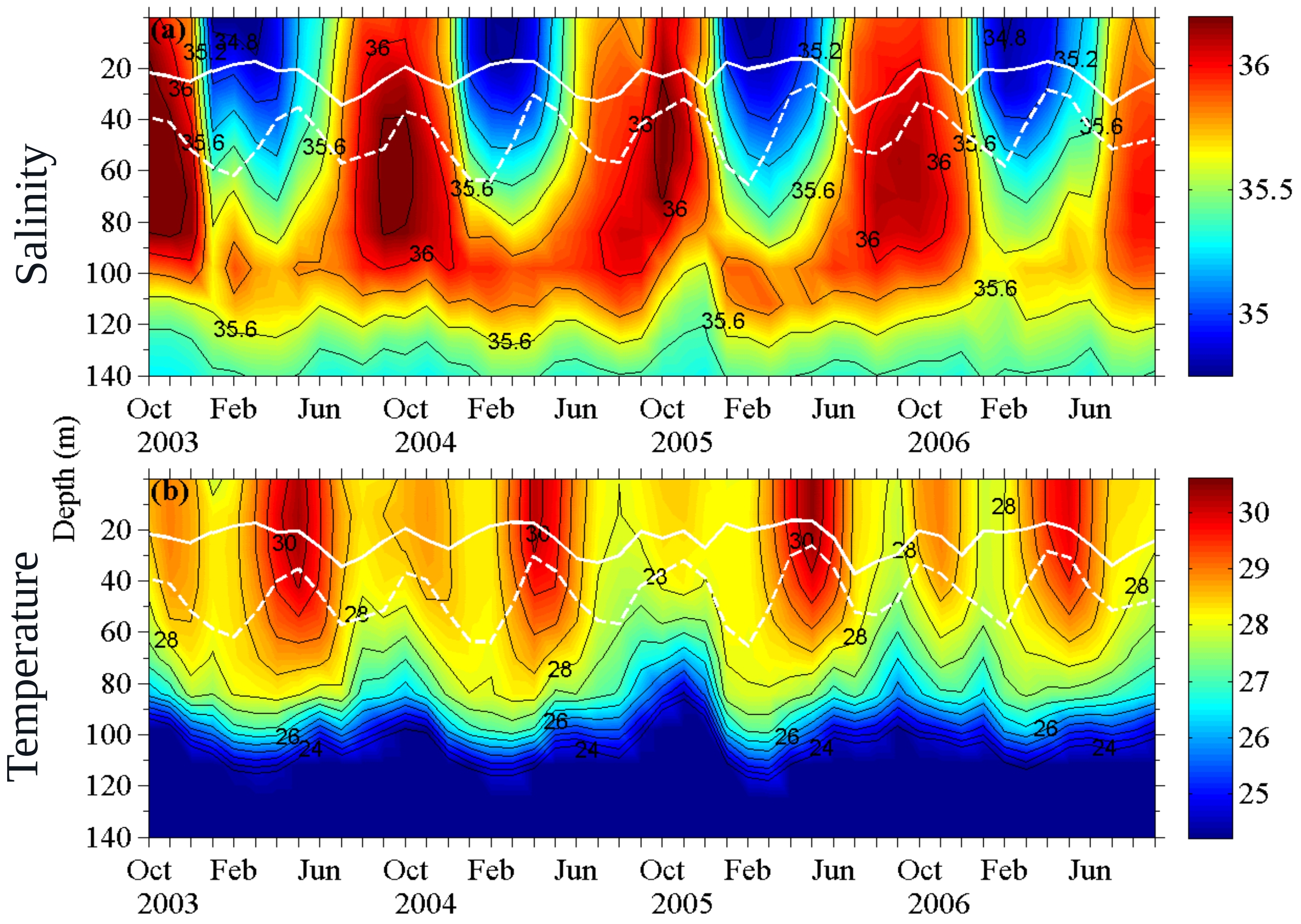
Thadathil et al. 2007



Daily averaged salinity and currents at 50 m depth on December 24, 2013 from the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS; Jensen et al., 2016)

- Barrier Layer results from surface salinity 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

SALINITY & TEMPERATURE IN THE ARABIAN SEA WARM POOL

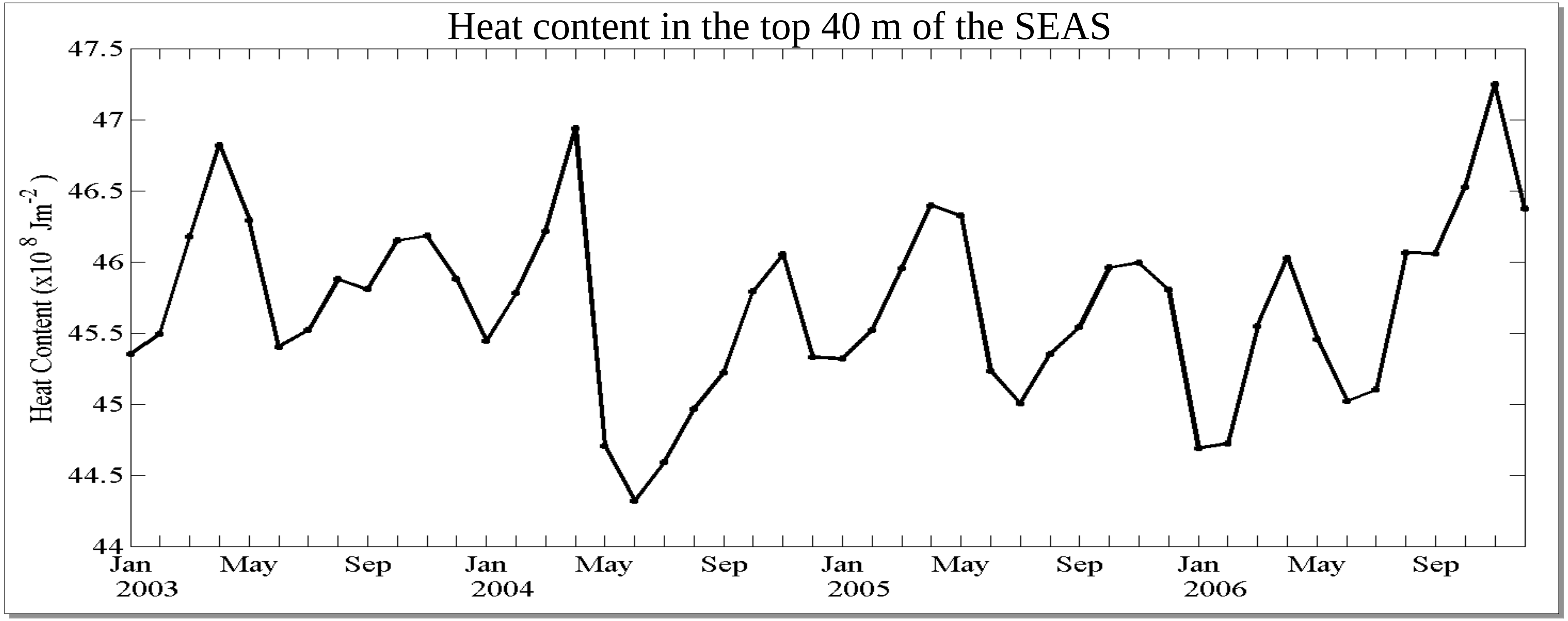


- Average depth of warm pool is 40 m.
- Two temperature warm cores; April-May, October-December
- Low saline (<34) water in top 60 m between December-June
- Higher salinity (~36) occur below 70 m between July-November.

Depth-time section of Argo (top) salinity and (bottom) temperature
MLD: solid white lines
Isothermal layer: dashed white line

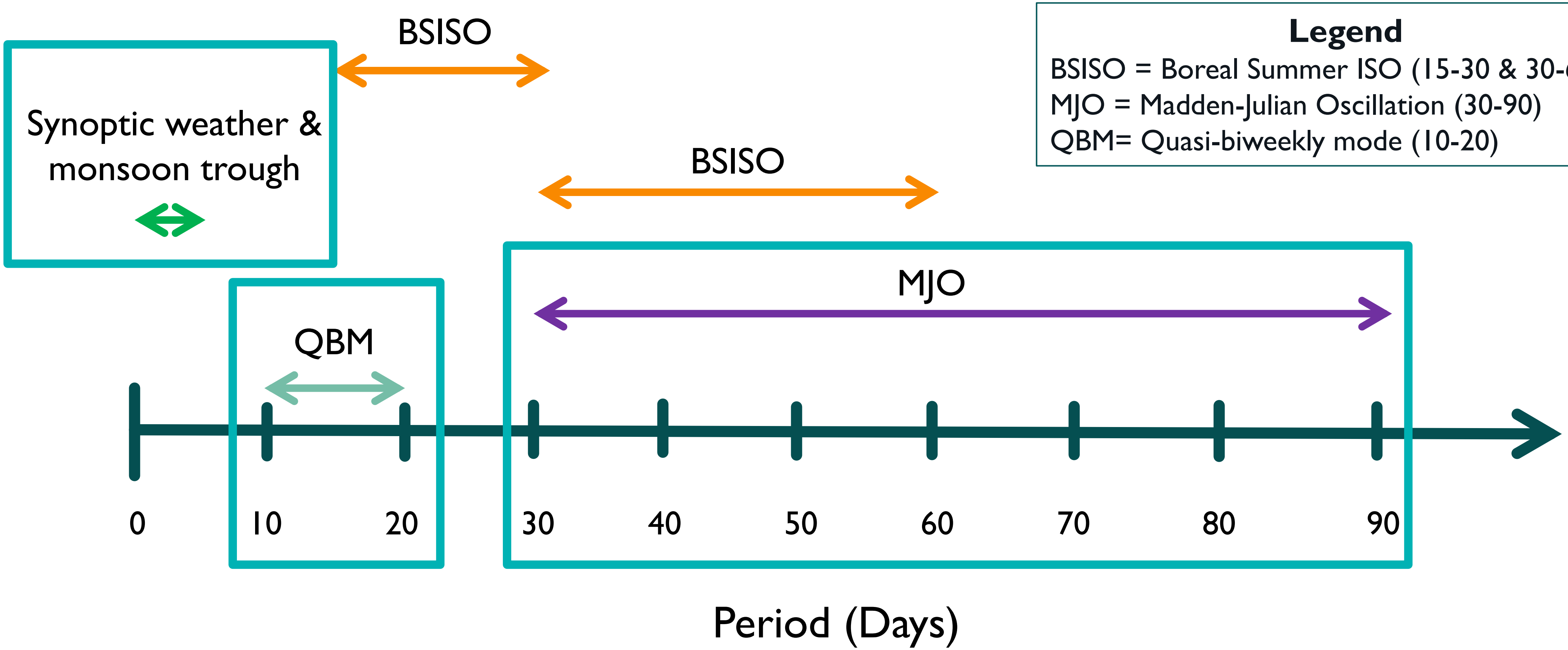
Nyadjro et al. (2012)

HEAT CONTENT AND MONSOON ONSET VORTEX



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

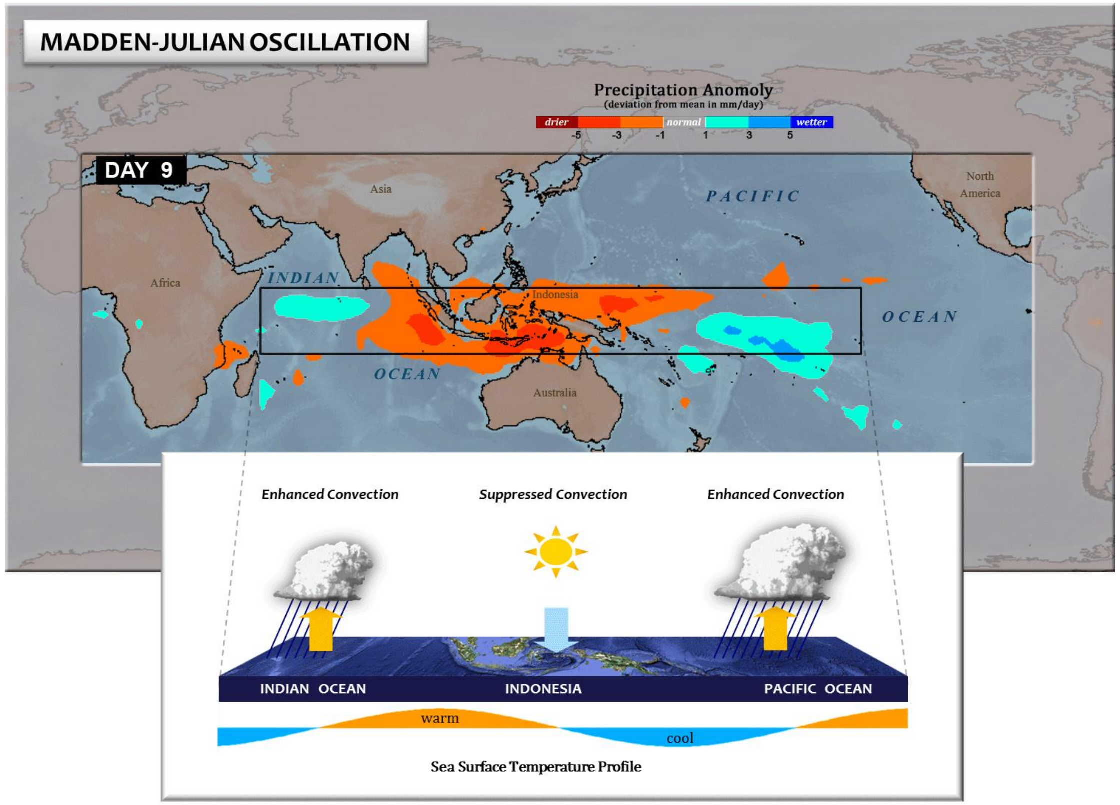
INTRASEASONAL OSCILLATIONS (ISOS)



Legend
BSISO = Boreal Summer ISO (15-30 & 30-60)
MJO = Madden-Julian Oscillation (30-90)
QBM= Quasi-biweekly mode (10-20)

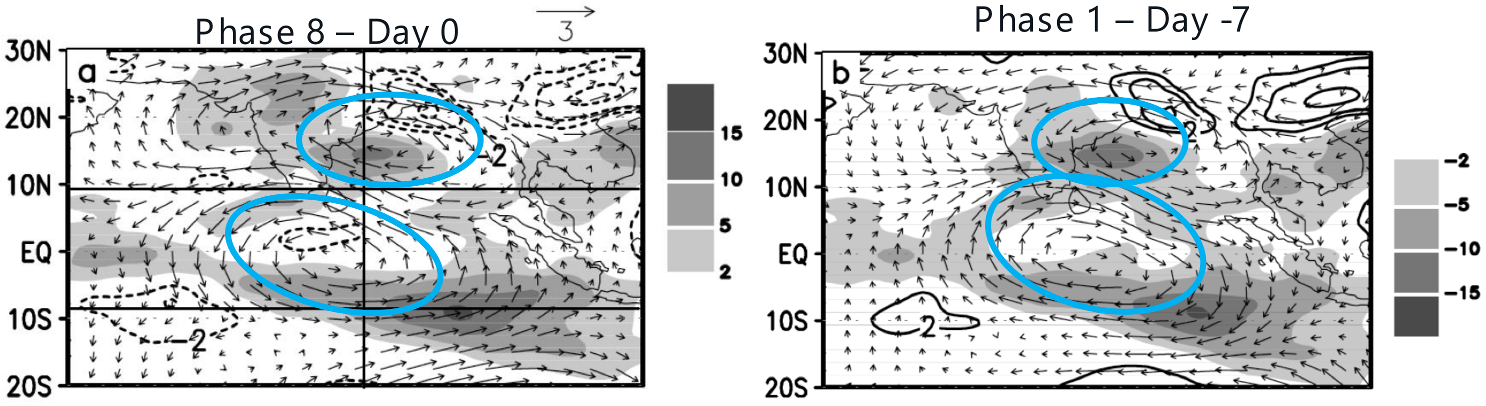
THE MADDEN-JULIAN OSCILLATION (30-90 DAY)

- Commonly defined as 30-90 days, consistent with spectral peaks in precipitation and low-level winds
- Wavelength of 10,000 km
- Reduced cloud-cover vs. enhanced convection.
- Equatorially trapped.
- Travels eastward. And towards north 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 (MJO), a complex process involving sea surface temperatures and their influence on atmospheric processes. (©UCAR. Illustration by Lex Ivey, based on data from Adrian Matthews.)

QUASI-BIWEEKLY OSCILLATIONS (10-20 DAY)



Double cell structure of the 10-20-day ISO during Phase 1 (Day -7) and Phase 8 (Day 0), where Day 0 is the day of maximum precipitation in the Bay of Bengal. Shading indicates TRMM precipitation, vectors are 850 mb winds, (Chatterjee and Goswami, (2004)

Overview:

- First characterized by Murakami (1976) as a mesocyclone over the Bay of Bengal
- One of the main controls on active/break cycles of monsoon rainfall
- Propagation speed: 4.5-6 ms^{-1} (NW or W)
- Dominant wavelength: 6,000 km

Structure and dynamics:

- **Double-cell structure** of either lows or highs around the equator and 15-20°N
- Structure propagates west, where the northernmost cell propagates along the monsoon trough → Mixed Rossby Gravity Waves translated north in the atmosphere
- Triggered by breaking Rossby Waves in upper atmosphere over Northern Pacific Ocean into the South China Sea/Western Pacific (Ortega et al., 2017)

SYNOPTIC SCALE (3-7 DAY)

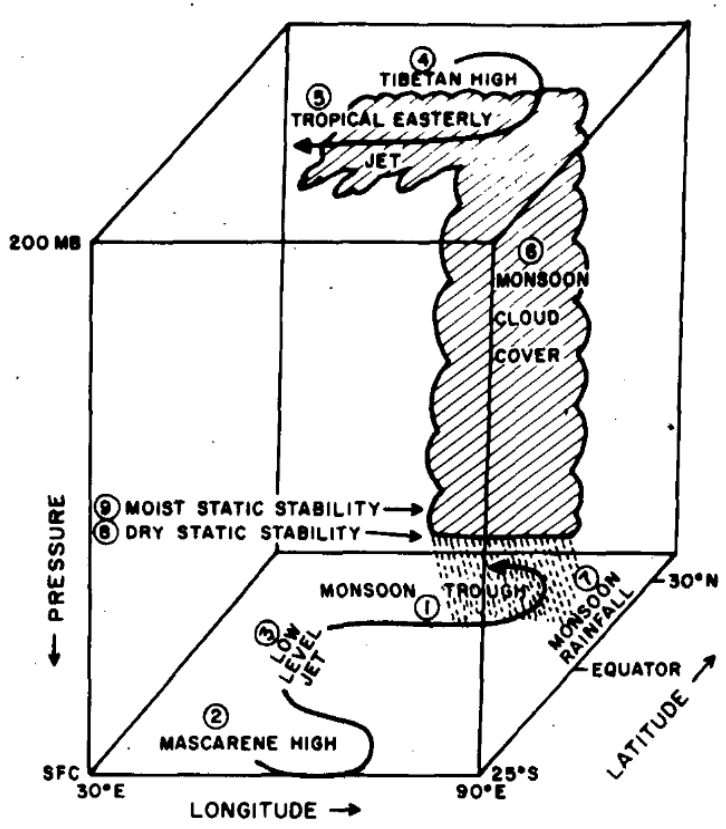


FIG. 1. Schematic diagram of the nine elements of the monsoon system considered in this study.

From Krishnamurti and Bhalme (1976)

- Associated with weather systems (lows and highs)
  - Tropical Convergence Zone (TCZ) over continent in active spells, over equatorial Indian Ocean in break spells
- Wavelength of 2,000 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 monsoon trough → variations in rainfall

USING SMAP SALINITY TO MONITOR ISOS IN THE BOB

- Stronger signal in lower frequency ISOs
- Higher frequency ISOs are within error of salinity product
- Can use changes in salinity to estimate freshwater fluxes, salt fluxes, and areas with upwelling
- Influences stratification and warm pool development

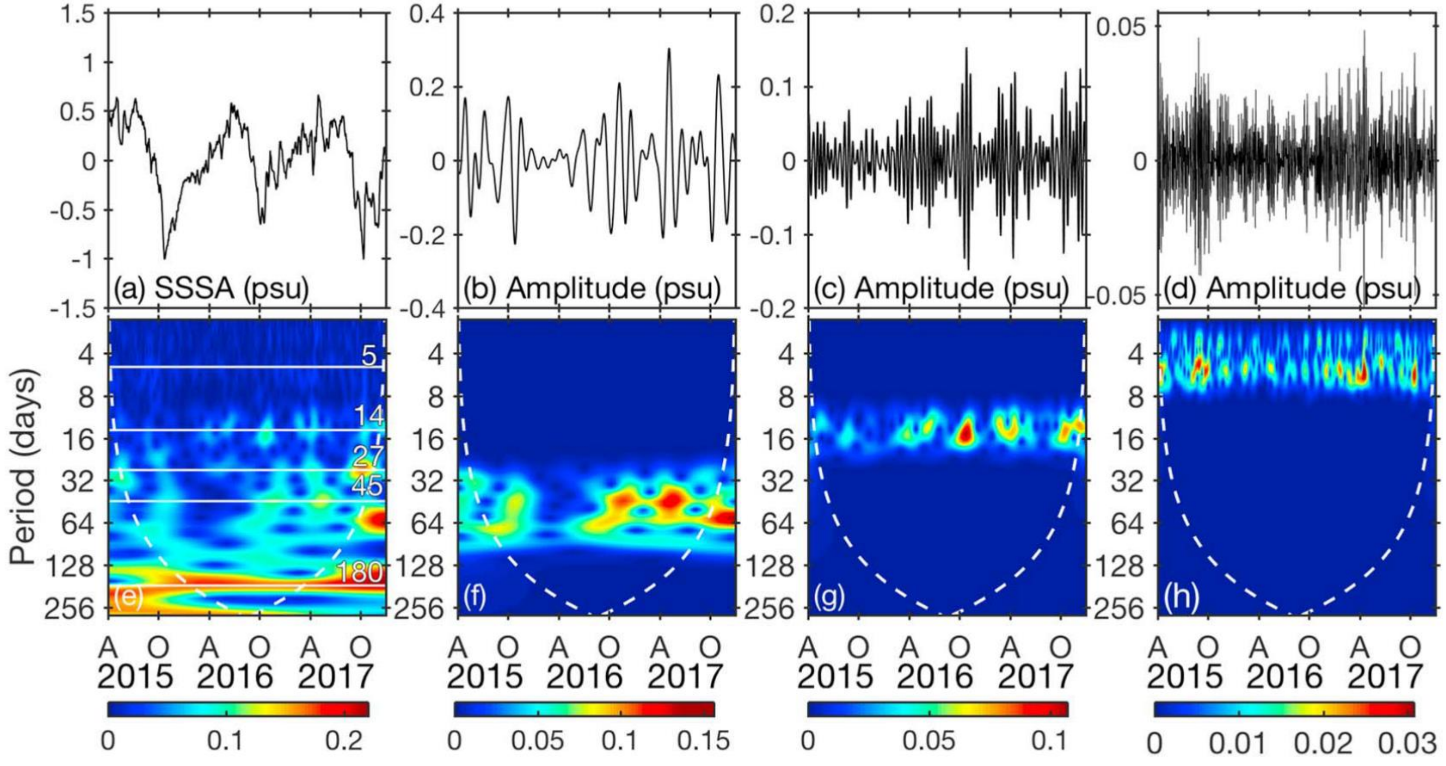
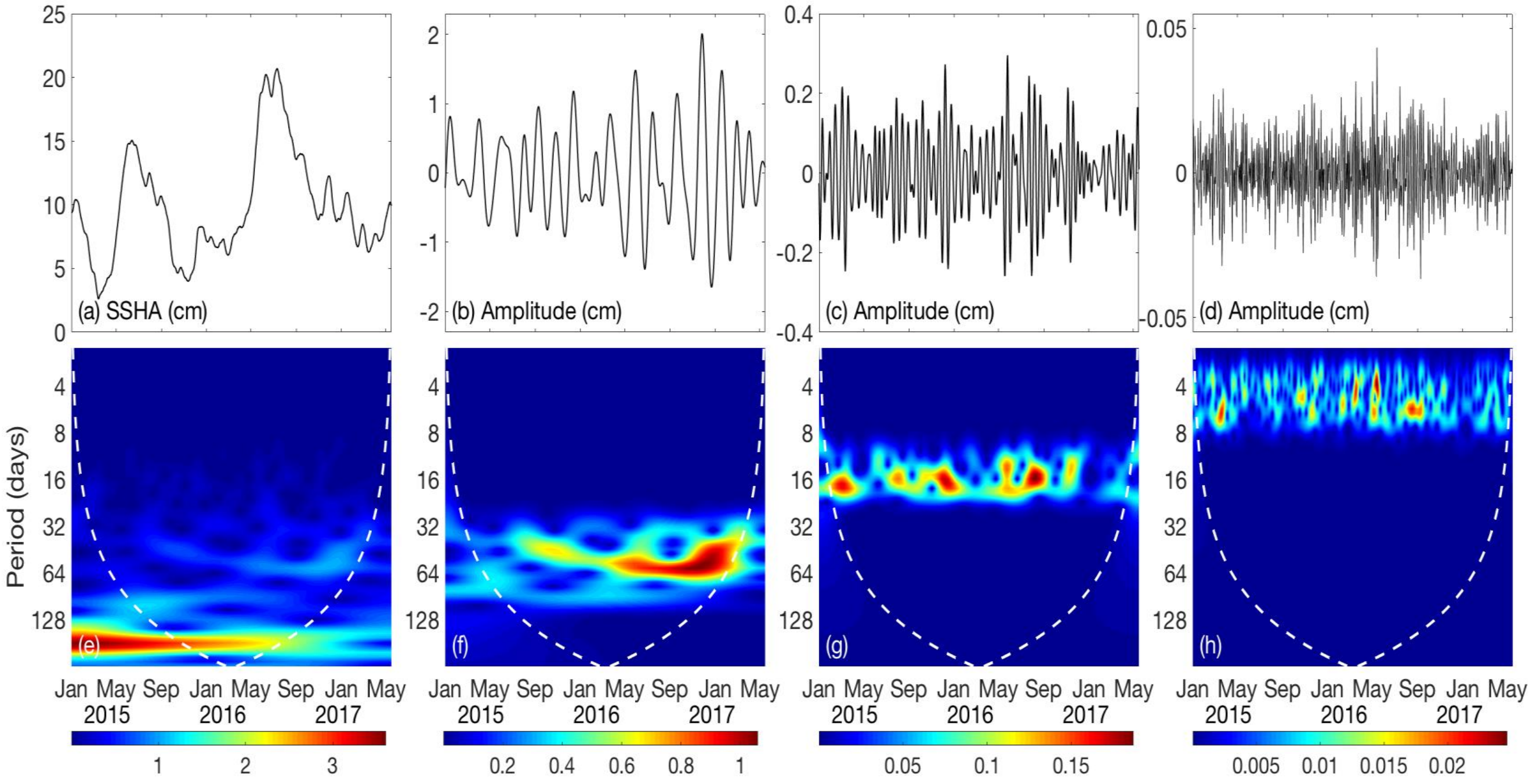


Figure 2. Top panel figures (a–d) represent the time series of the box averaged (85°E–95°E and 4°N–18°N) SMAP SSSA for (a) unfiltered SSSA and filtered SSSA for ISO periods of (b) 30–90 days and (c) 10–20 days and **(d)** synoptic oscillation of 3- to 7-day period, and the corresponding bottom panel figures (e–h) represent continuous wavelet power spectrum of the box-averaged time series in (a–d). The white horizontal lines in (e) denote the periods of peak wavelet power, and the white dotted line in each figure signifies the cone of influence (COI) where edge effects might distort the signal. Along the *x* axis, "A" represents April and "O" represents October.

Subrahmanyam et al. (2018)

USING ALTIMETRY SSH TO MONITOR ISOS IN THE BOB

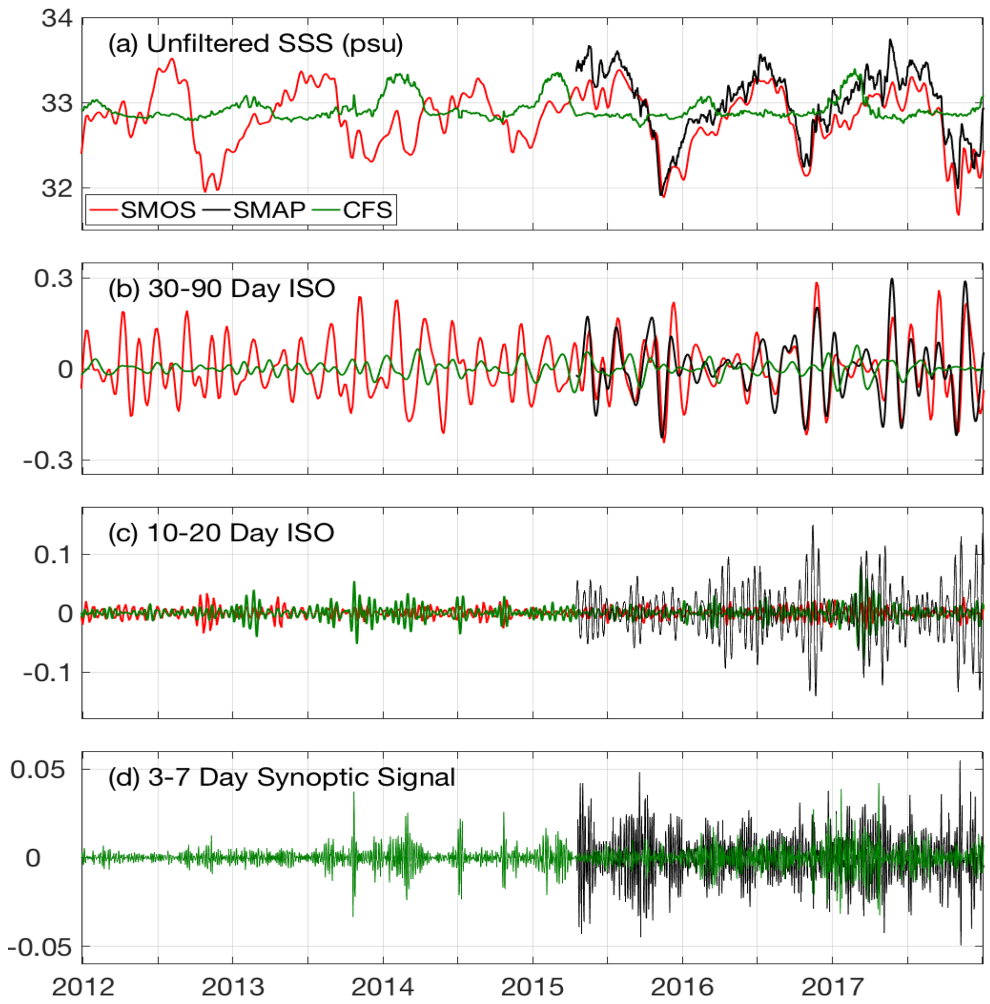
- Highest SSHA in SW monsoon, lowest in NE monsoon
  - Highest SSHA in unfiltered (a) and 30-90 day filtered (b) SSHA in 2016
- Strong 180-day period (e) due to semiannual Rossby waves
- Very small amplitudes in 10-20 day and 3-7 day signal
  - Especially 3-7 day signal, possibly indicating noisy response to ISOs



*Top panel figures **(a-d)** represent the time-series of the box averaged SSHA for the period 2015-17 for **(a)** unfiltered SSHA and filtered SSHA for ISO periods of **(b)** 30-90 day, **(c)** 10-20 day and **(d)** 3-7 day and bottom panel figures **(e to h)** represent the corresponding continuous wavelet power spectrum of the box-averaged [85°E-95°E and 4°N-18°N] SSHA (cm) for the time series in **(a-d)**. The white horizontal lines in **(a)** denote the periods of peak wavelet power, and the white dotted line in each figure **(e to h)** signifies the cone of influence (COI) where edge effects might distort the signal.*

ISO IN SALINITY

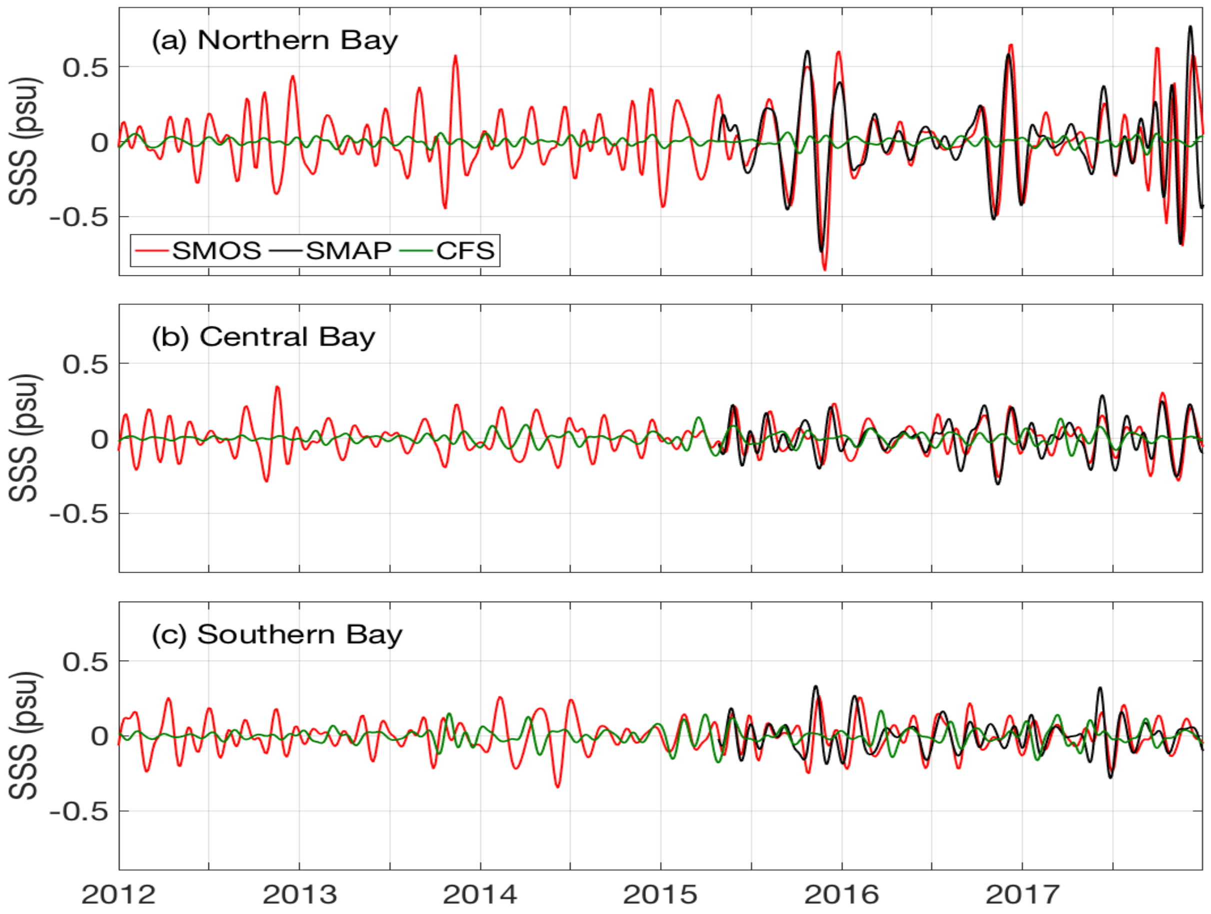
- CFS does well for detecting evaporative (saltier) fluctuations in the Bay of Bengal, but is not so good at tracking fresh events
- Leads to a lower amplitude of 30-90 day SSS
- Amplitude discrepancies in shorter periods are due to sampling rates



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.

30-90 OSCILLATIONS IN SALINITY

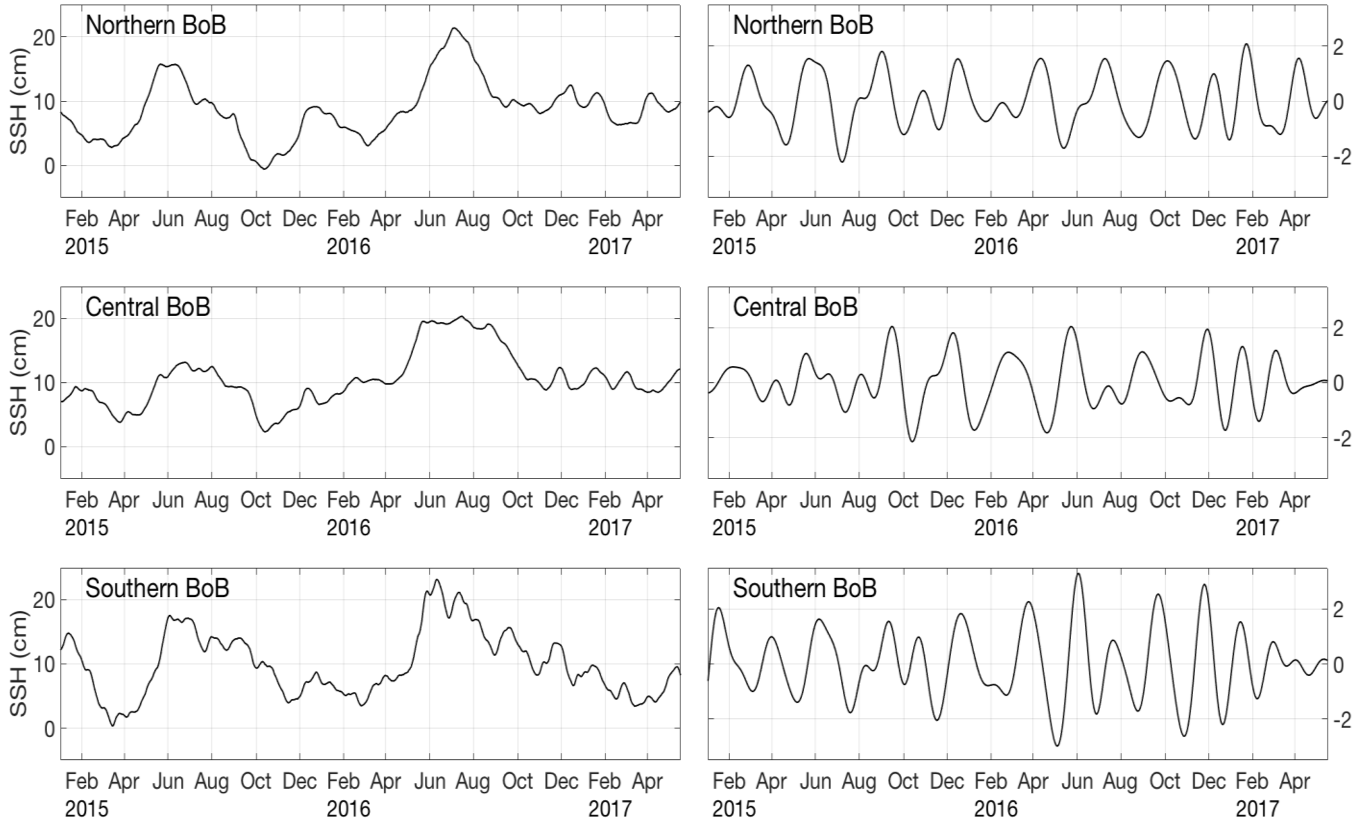
- Highest annual SSS variability is in the northern Bay due to the riverine freshwater flux inflow and high precipitation rates
  - Also reflected in the 30-90 day ISO
  - The aforementioned October-November 2015 MJO event is clearly seen in all regions of the Bay by all three products
- Highest-amplitude 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 OSCILLATIONS IN SSH

- Comparison of 30-90 day ISOs in the northern, southern, and central BoB
  - Unfiltered signal, 2016 SW Monsoon peak is a similar amplitude in entire basin, while in 2015, SSHA maxima is suppressed in the central basin
  - Strongest ISOs in southern BoB
    - Region of strongest Rossby waves
    - Northern and central BoB very similar



Unfiltered (left) and 30-90 day filtered (right) time series of SSHA (cm) for the northern (14-18 N, 85-95 E), central (10-14 N, 85-95 E), and southern Bay of Bengal (5-10 N, 85-95E).

SUMMARY

- Monsoonal rainfall intensity is directly tied to the strength and propagation of ISOs
- In the past, salinity has been neglected as it does not directly affect air-sea fluxes
  - However, it influences the development of the Arabian Sea Mini Warm Pool, which directly fuels the Monsoon Onset Vortex
- ISOs were clear in SMAP SSS, with the strongest oscillations for all periods in the northern BoB
  - CFS captures intraseasonal and smaller scale variability, however shows smaller amplitudes
- Satellite altimetry derived SLA is useful for monitoring ISOs
- These results will improve monsoon forecasting and understanding of how climate variability affects monsoons.
- Although presently no ocean forecasting systems assimilate satellite SSS data operationally, there have been a number of efforts to develop schemes to do so by investigating SSS data's impact on ocean analysis and forecasting.

QUESTIONS?

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