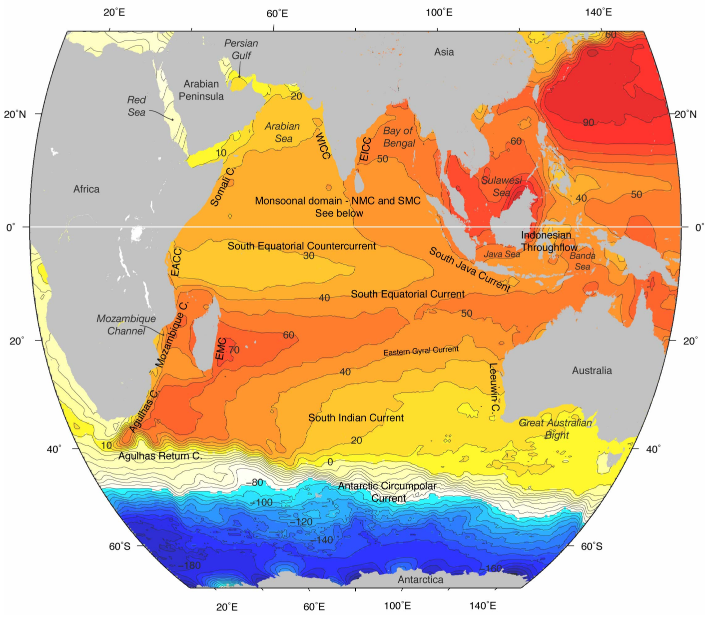
MESOSCALE EDDY VARIABILITY AND ITS LINKAGE TO DEEP CONVECTION OVER THE BAY OF BENGAL

HEATHER L. ROMAN-STORK, SUBRAHMANYAM BULUSU, CORINNE B. TROTT

BACKGROUND

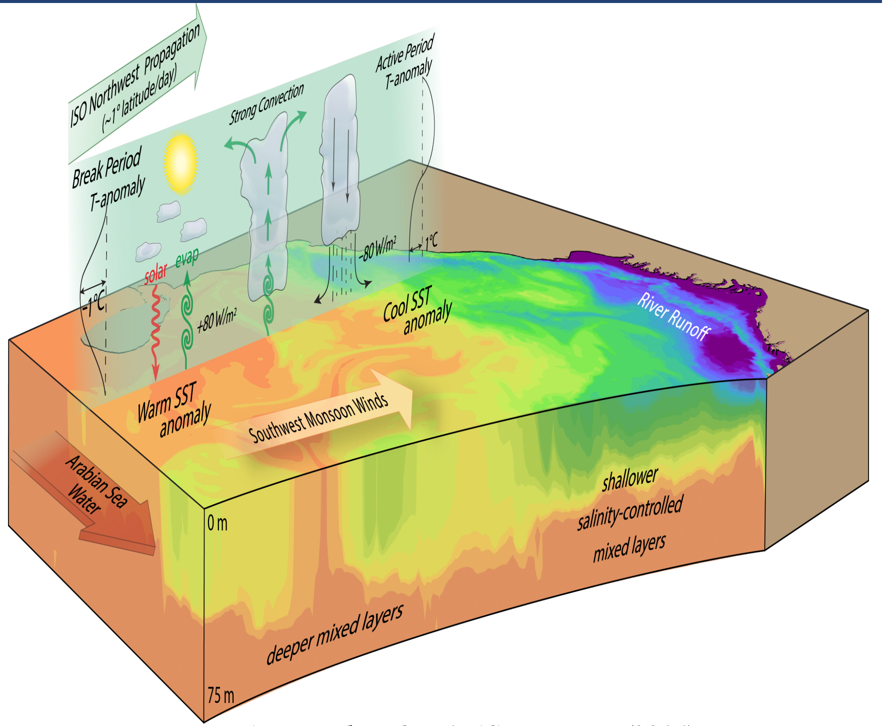
- The Bay of Bengal (BoB) surface circulation is strongly influenced by eddies and the East India Coastal Current (EICC), the western boundary current.
- EICC starts at 10°N as part of the subtropical gyre which forms in January (and develops during Feb-Apr) and transports saline waters from the AS into the BoB.
- The equatorward flowing EICC during Oct-Dec brings fresher waters from the head of the BoB during the NE monsoon.
- The EICC geostrophic current anomalies are ~20-30 cm/s.
- Upwelling Kelvin waves reach the EICC region during Mar-April and play a role for the well-defined EICC.



Surface circulations and dynamic ocean topography (cm) in the Indian Ocean, (Talley, 2011)

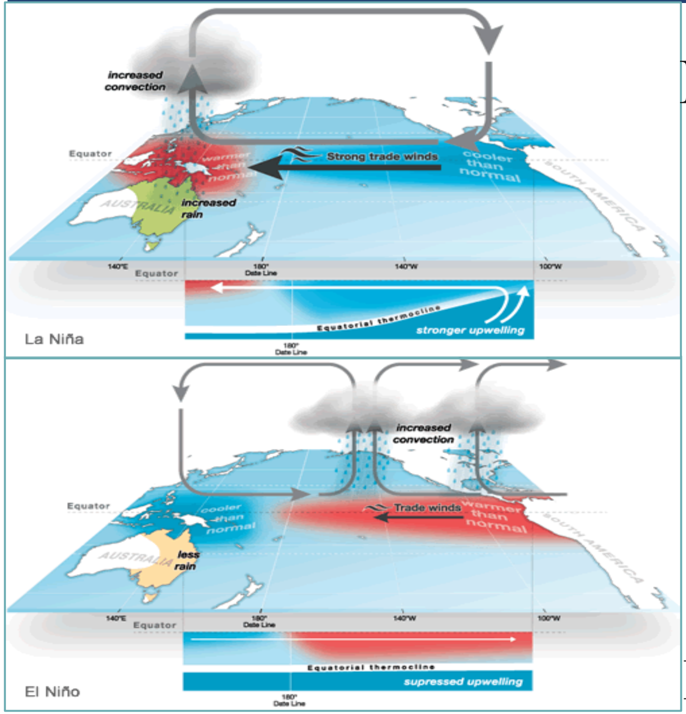
OBJECTIVES OF THIS STUDY

- We have applied an eddy tracking algorithm to 25 years (1993-2018) of satellite altimetric observations to identify, analyze, and track mesoscale eddies in the BoB from their generation to dissipation.
- Investigate the role of planetary waves and interannual variability on mesoscale eddies and convection in the BoB.
- Look at the warm-core eddies in the BoB, how they play a critical role in the strength and intensification of convective disturbances and storms in the region.



Amit Tandon, ONR's ASIRI project (2016)

EL NIÑO-SOUTHERN OSCILLATION (ENSO)



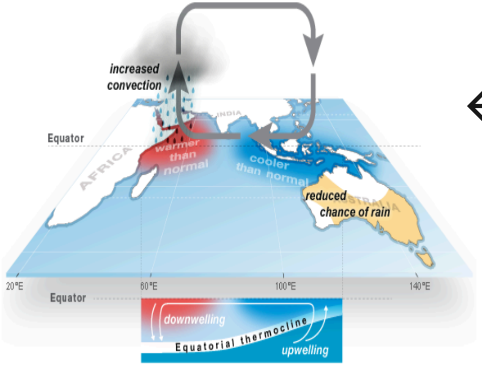
Australian Bureau of Meteorology, 2017

La Niña

El Niño

- Timing of arrival of the CKW to EICC region were strongly related to the phase of the ENSO and Indian Ocean Dipole (IOD), which in turn influenced sea level anomalies (SLA) in the BoB.
- Phase of the ENSO also play a role in eddy variability and may also contribute to eddy-associated convection in the BoB.
- ENSO has a strong influence on OHC values in the region, but not on the relative abundance of warm-core eddies in the BoB.

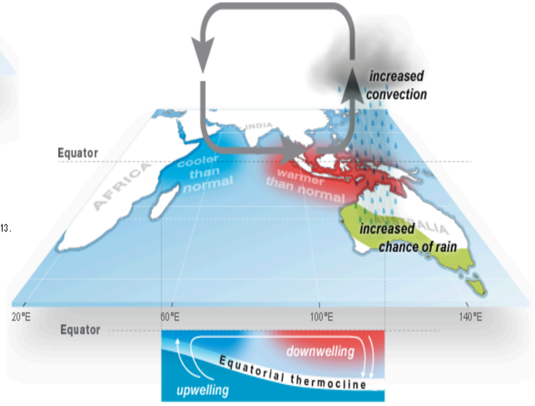
INDIAN OCEAN DIPOLE (IOD)



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

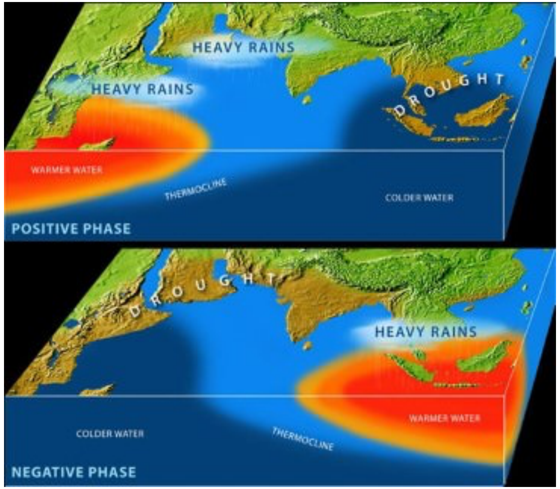
← Positive Phase

Negative Phase →



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

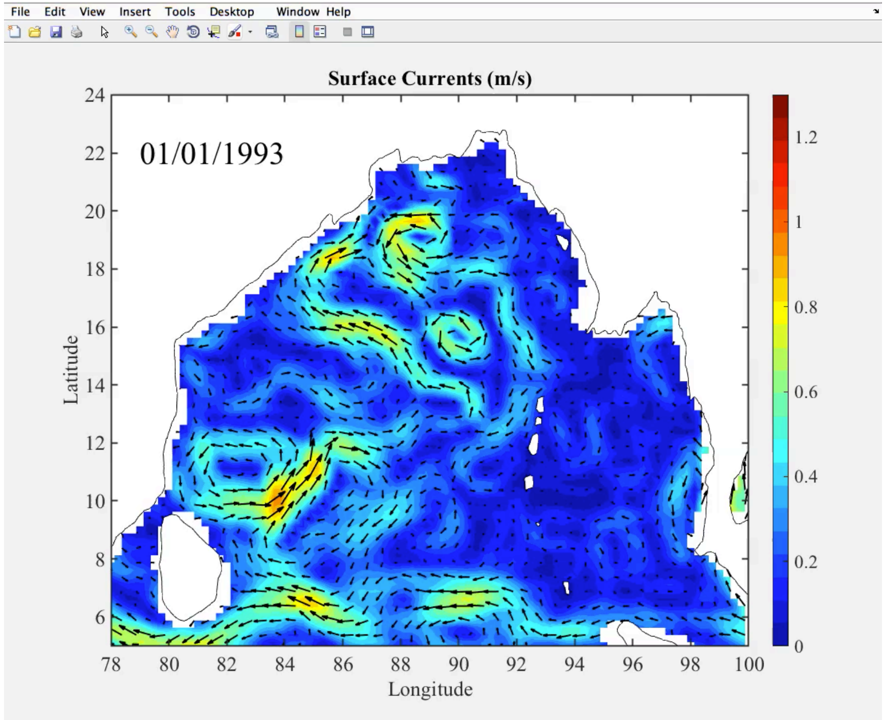
- Defined by a temperature differential between the eastern and western Indian Ocean
- Alters circulation and regions of convection



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

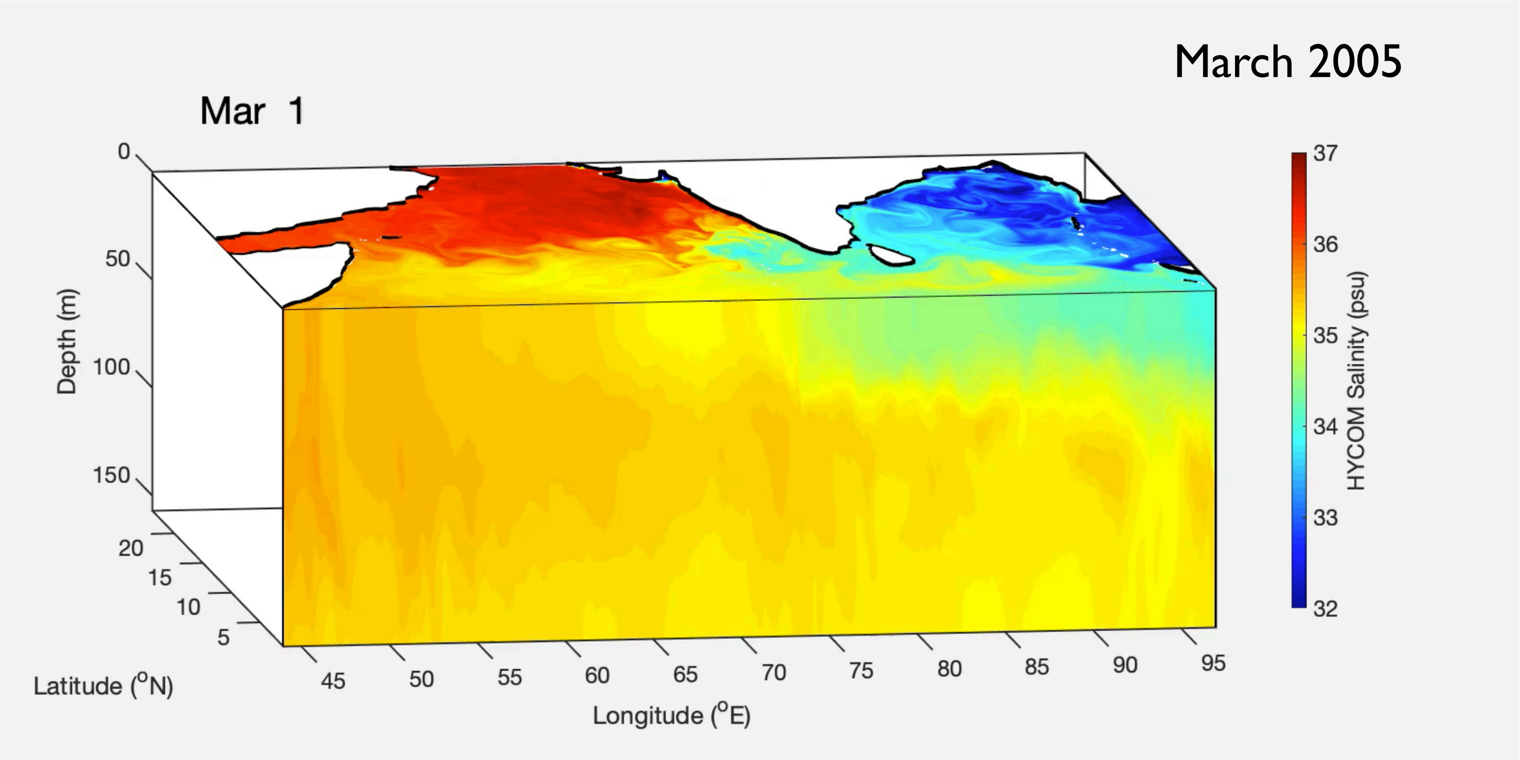
SURFACE CIRCULATION

- The EICC experiences seasonal intensification as a response to both remote and local forcings.
- There are four sources of current and eddy generation in this region:
  - Along-shore winds
  - Ekman pumping in the central BoB
  - Forcing from the eastern and northern BoB (typically attributed to coastal Kelvin waves)
  - Remote forcing from the equatorial Indian Ocean

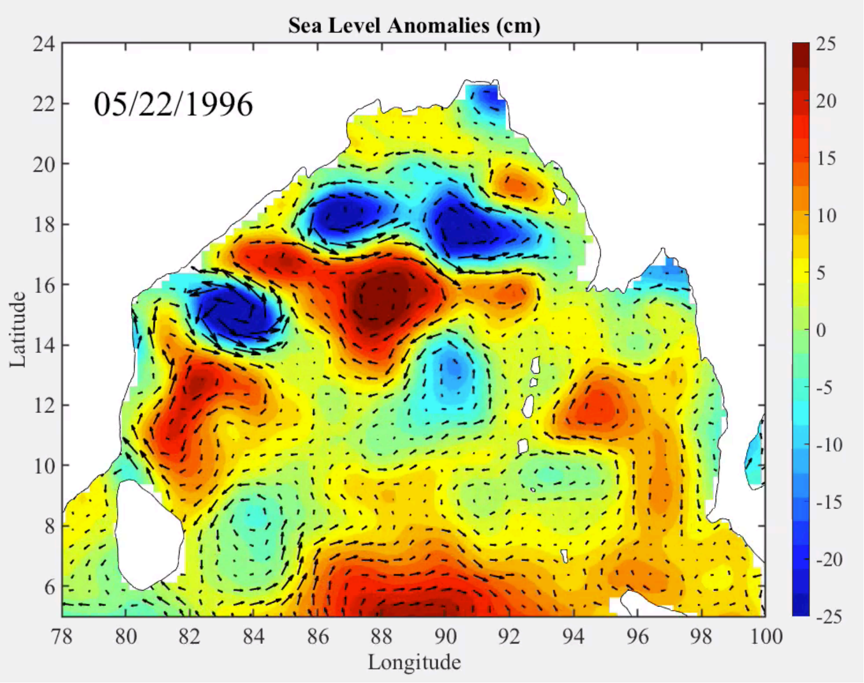


AVISO surface currents and magnitude, 2017

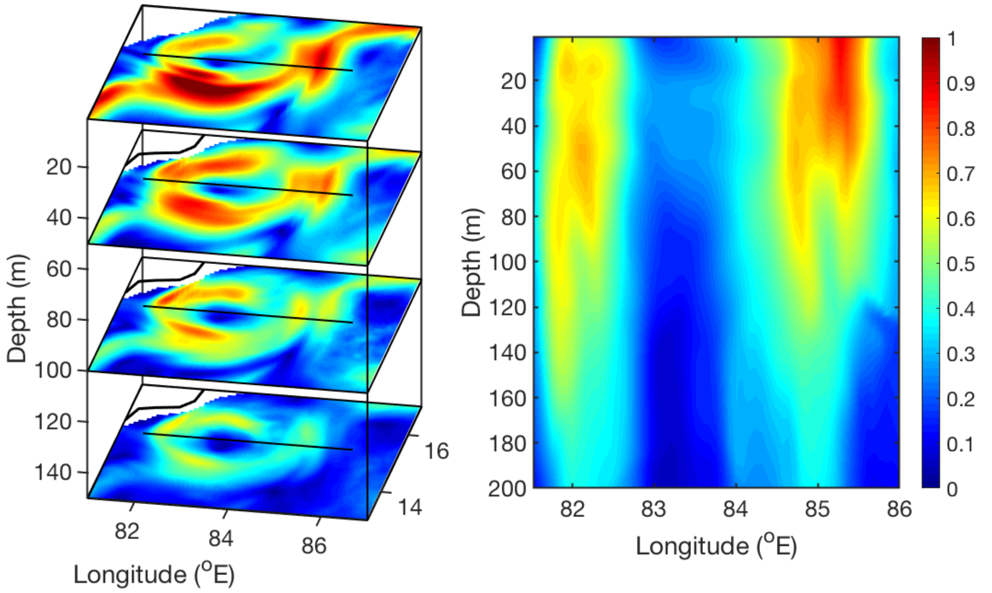
NORTHWARD PROPAGATION OF EICC – HYCOM SALINITY



SUBSURFACE SIGNATURE OF THESE EDDIES

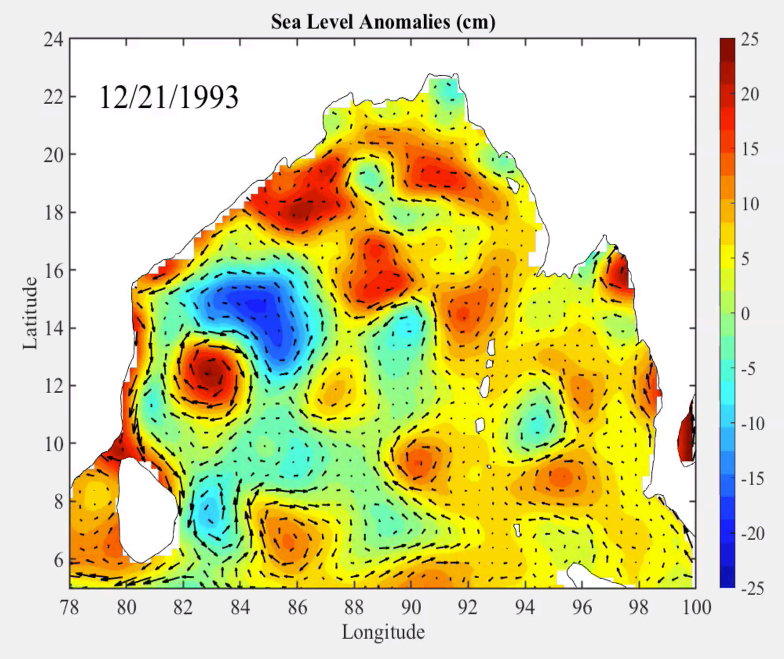


AVISO SLA and surface currents May 22, 1996

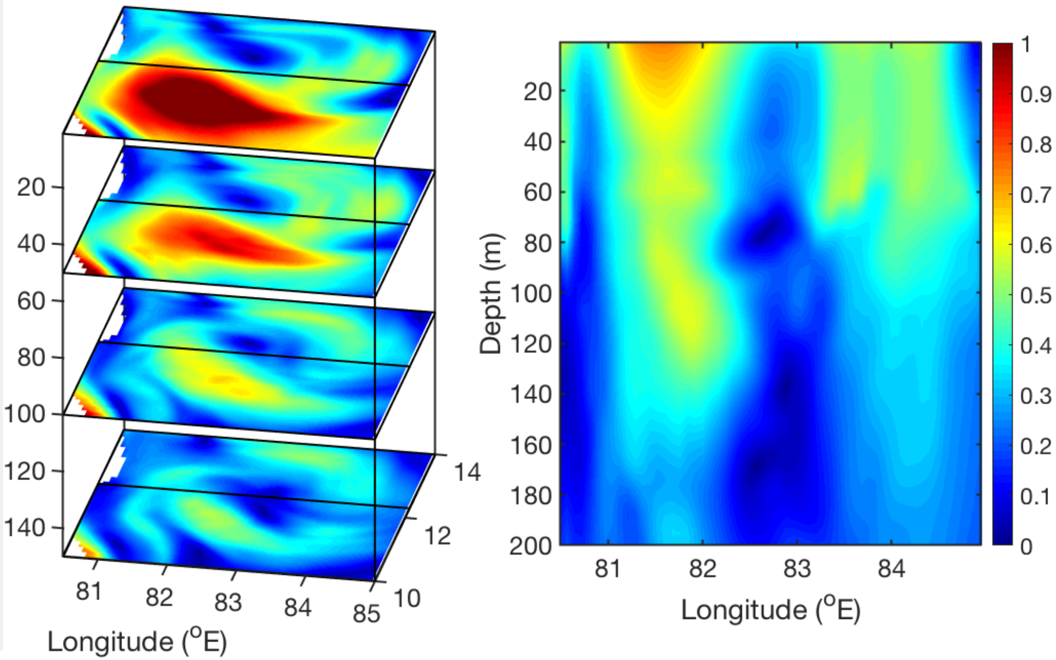


HYCOM eddy (cyclonic) velocity at 15°N during May 22, 1996

SUBSURFACE SIGNATURE OF THESE EDDIES



AVISO SLA and surface currents December 21, 1993



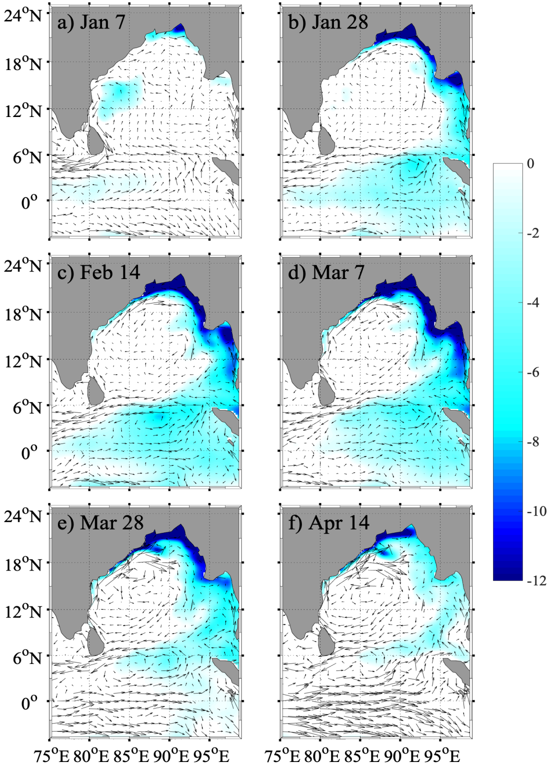
HYCOM anticyclonic eddy velocity at 12°N during December 21, 1993

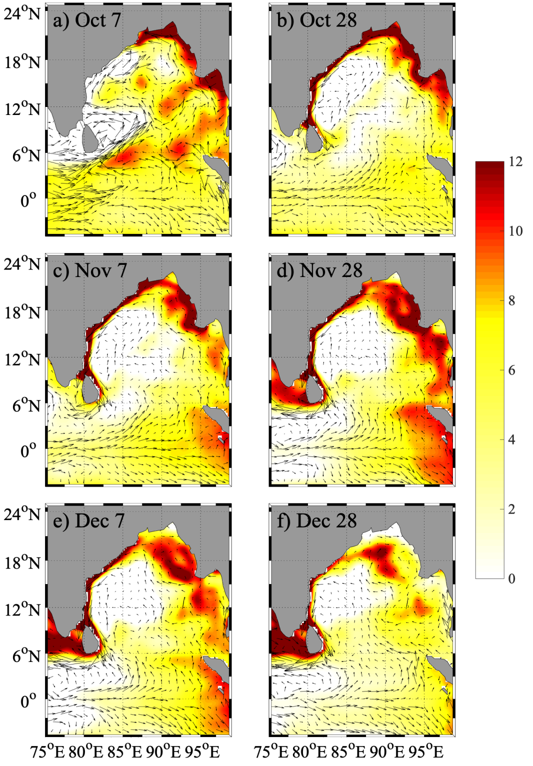
COASTAL KELVIN WAVES

- Four CKW per year- Two upwelling (Jan-Mar, July-Sep) Two downwelling (Apr-June, Oct-Dec).

Left: A 25-year average of the first upwelling coastal kelvin wave propagation in the Bay of Bengal roughly every three weeks from (a) Jan 7 to (f) April 14, from 1993 to 2018. in AVISO SLA (cm; shaded). Only negative values are shown to isolate the upwelling signature.

Right: A 25-year average of the second downwelling coastal kelvin wave propagation in the Bay of Bengal roughly every three weeks from (a) Oct 7 to (f) Dec 28, from 1993 to 2018. in AVISO SLA (cm; shaded). Only positive values are shown to isolate the downwelling signature.



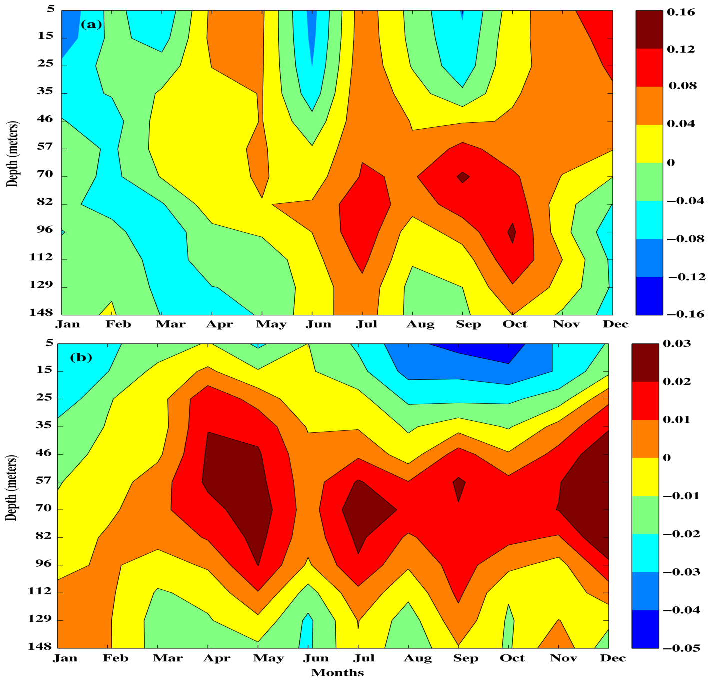


COASTAL KELVIN WAVES

- Current magnitude along coastal Kelvin waves (CKWs) is strongest at about 95 m depth
- Zonal current velocity anomalies Seasonal peaks are in July, September, and October
- Meridional current velocity anomalies peaks are in April, May, September, and December
- Signal extends to nearly 150 m depth
- Horizontal Speed of 2.5 m/s and vertical speed of 1.2 m/day

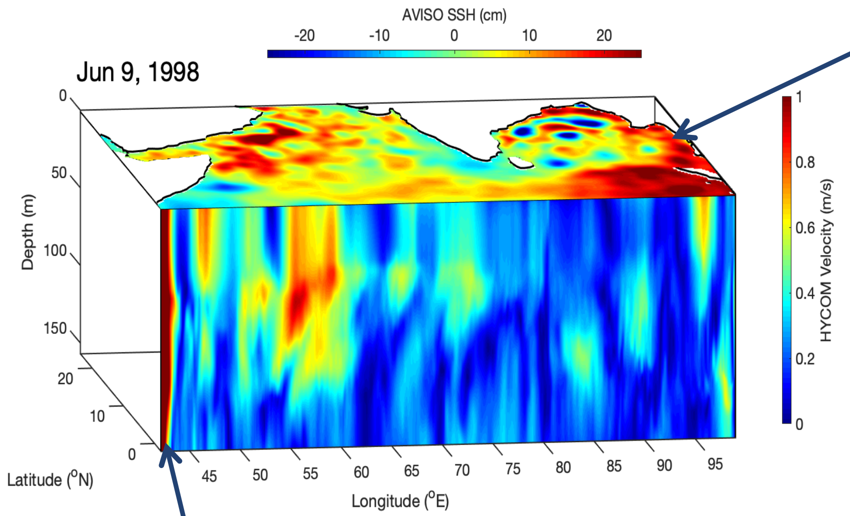
Right: Time series of (a) zonal (U) current velocity anomalies (m/s) averaged from SODA reanalysis at 0N, 77E (south of India on equator) and (b) alongshore current velocity (V) anomalies (m/s) averaged from SODA reanalysis at 2N, 94E (near Sumatra coast) over the period from 1993-2006.

Zonal Current Velocity anomalies (m/s) 0°N, 77°E



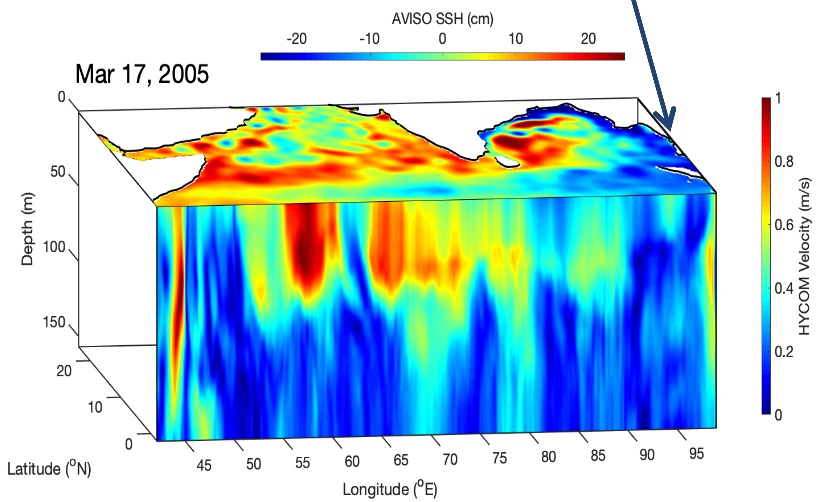
Alongshore Current Velocity anomalies (m/s) 2°N, 94°E

COASTAL KELVIN WAVES



Downwelling CKW

Upwelling CKW

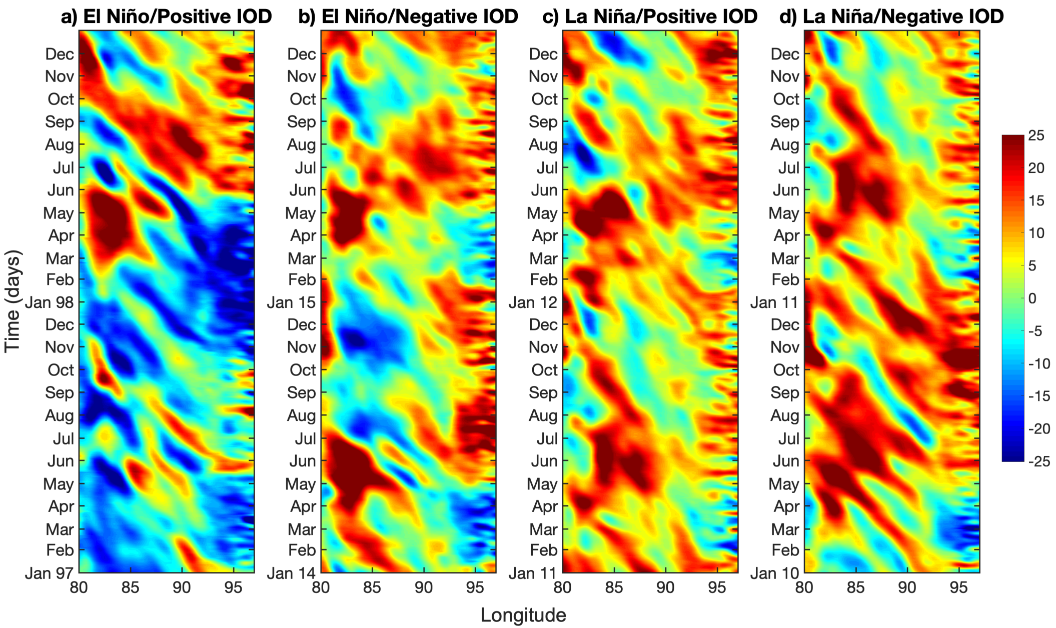


Somali Current

Surface: AVISO SSH (cm) anomalies
Depth: HYCOM current speed (m/s) at 2°S

ROSSBY WAVES

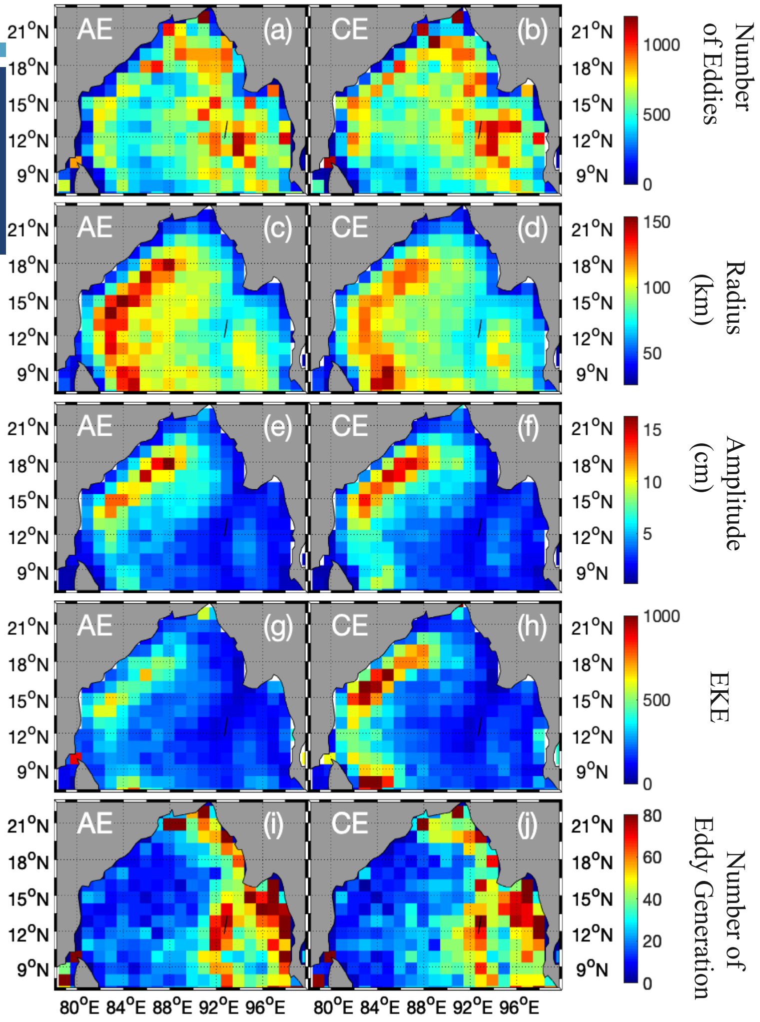
- Consistently propagate westward across the BoB
- Comparison of Rossby wave strength between different ENSO/IOD conditions reveals anomalously weak downwelling Rossby waves during El Niño/IOD+ conditions
  - Due to anomalously eastward equatorial wind stress
  - Weakens the downwelling CKWs and strengthens the upwelling CKWs
- Strong signal during La Niña/IOD- conditions



Time-longitude plots at 15°N of Rossby waves in SLA (cm) in the BoB during a) an El Niño and positive IOD year (1997-1998), b) an El Niño and negative IOD year (2014-2015), c) a La Niña and positive IOD year (2011-2012), and d) a La Niña and negative IOD year.

EDDY CHARACTERISTICS

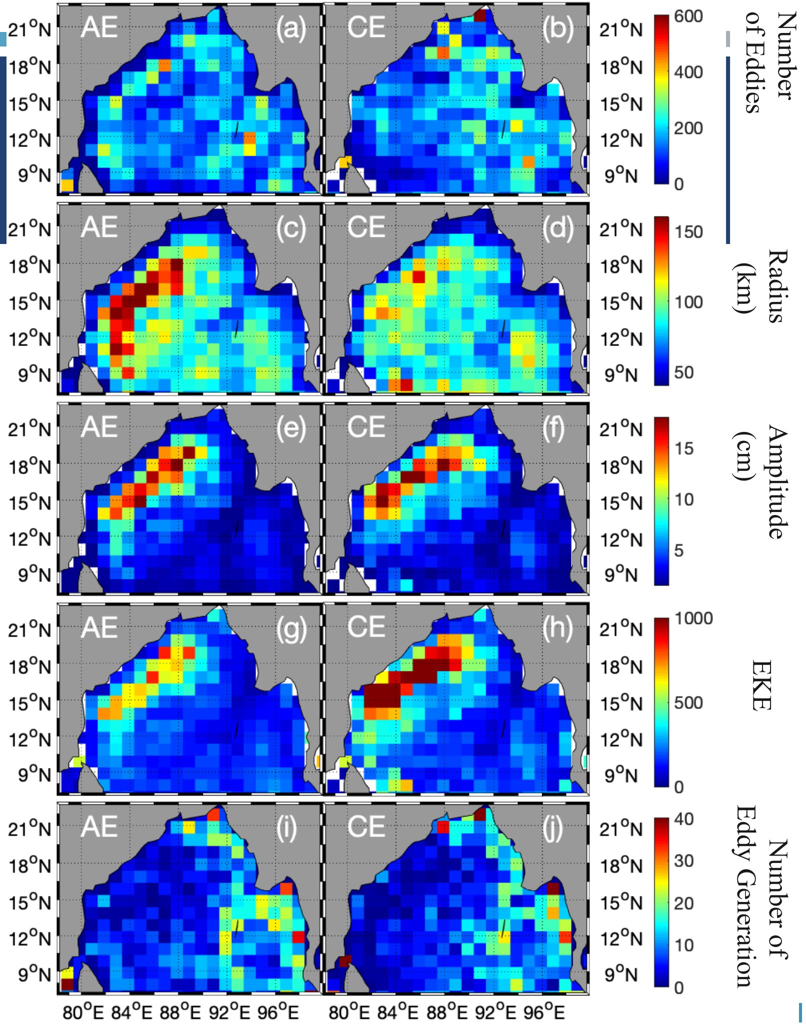
- Eddy tracking (Trott et al., 2018) allowed for extraction and quantification of eddy characteristics
- Highest number of eddies was found in the eastern Bay along EICC
  - Also the location of highest eddy generation
  - Due to the influence of CKWs
- Most robust eddies were found in the western Bay
  - Directly impact the path of the EICC
    - Important for water mass exchange between the BoB and Arabian Sea



Mean spatial distribution of eddy characteristics from 1993-2018 for AEs (left panel) and CEs (right panel). (a-b) Number of eddies; (c-d) radius (in km); (e-f) amplitude (in cm); (g-h) EKE (in $cm^2 s^{-2}$); (i-j) Number of eddy generation.

INTERMONSOON (MAR-MAY)

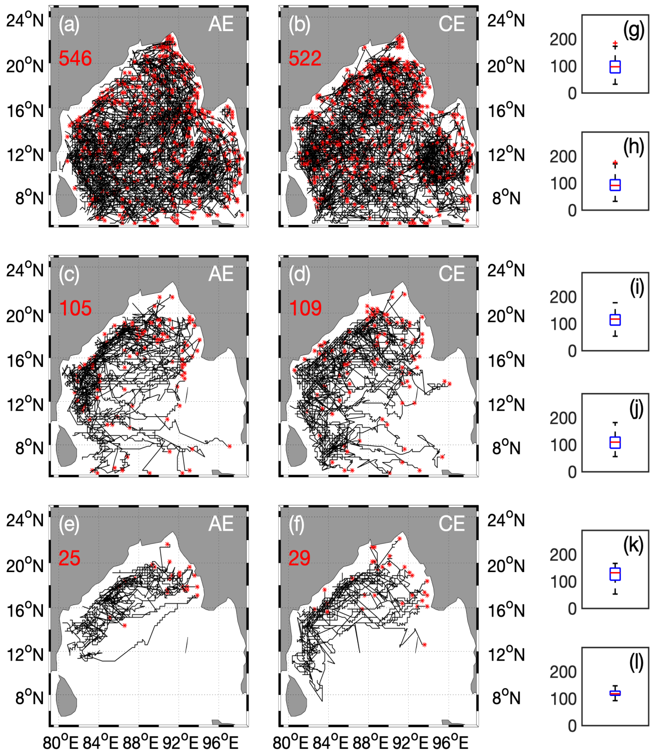
- EICC is very strong during this time
- Strong eddy field in the western BoB
  - CEs have low radii, but high EKEs
    - Due to a combination of arrival of first upwelling CKW and strong EICC
    - Also high energy induced by positive wind stress
  - AEs very large radii and amplitudes



Mean spatial distribution of eddy characteristics for the intermonsoon season (Mar-May) from 1993-2018 for AEs (left panel) and CEs (right panel). (a-b) Number of eddies; (c-d) radius (in km); (e-f) amplitude (in cm); (g-h) EKE (in $cm^2 s^{-2}$); (i-j) Number of eddy generation.

TOTAL ANNUAL EDDY TRAJECTORIES

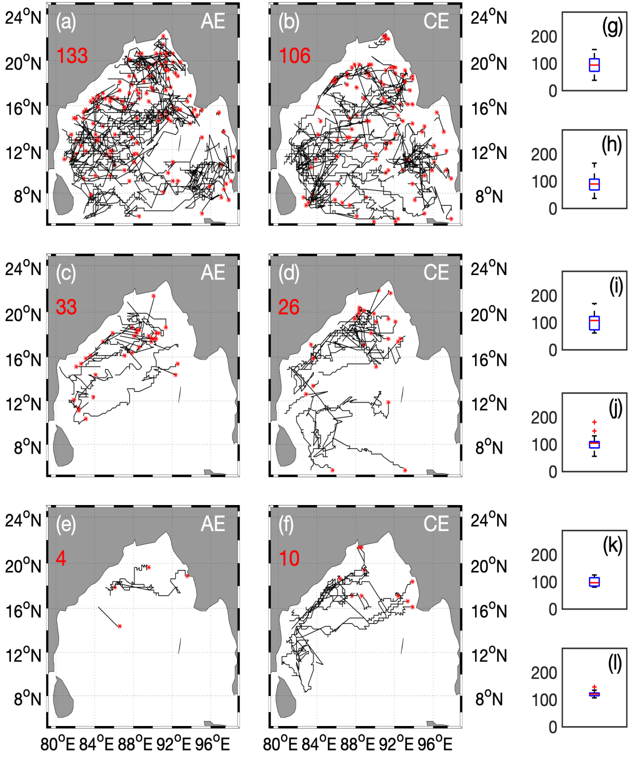
- Trajectories of eddies with maximum amplitudes of 10-20 cm were abundant throughout the BoB
- Medium and large amplitude eddies (20-30 and 30-40 cm, respectively) showed strong westward propagation
  - Due to:
    - Advection
    - Topography
    - Beta Effect



Total annual eddy trajectories from 1993-2018 for AEs (left) and CEs (middle) for 10-20 cm (a-b), 20-30 (c-d), 30-40 (e-f), and box plots of radius (km; right), with (g) corresponding to (a), (h) to (b), and so on. Red stars indicate genesis location and black lines to indicate eddy trajectories. Red numbers are the number of eddies shown.

INTERMONSOON (MAR-MAY) EDDY TRAJECTORIES

- Trajectories of MAM eddies from 1993 to 2018
- Most larger eddies occur in the EICC region and northern BoB
- Most eddies propagate westward if generated in the east (e-f)
- Large CEs than AEs due to wind/current forcing
- More AEs than CEs, but CEs last longer

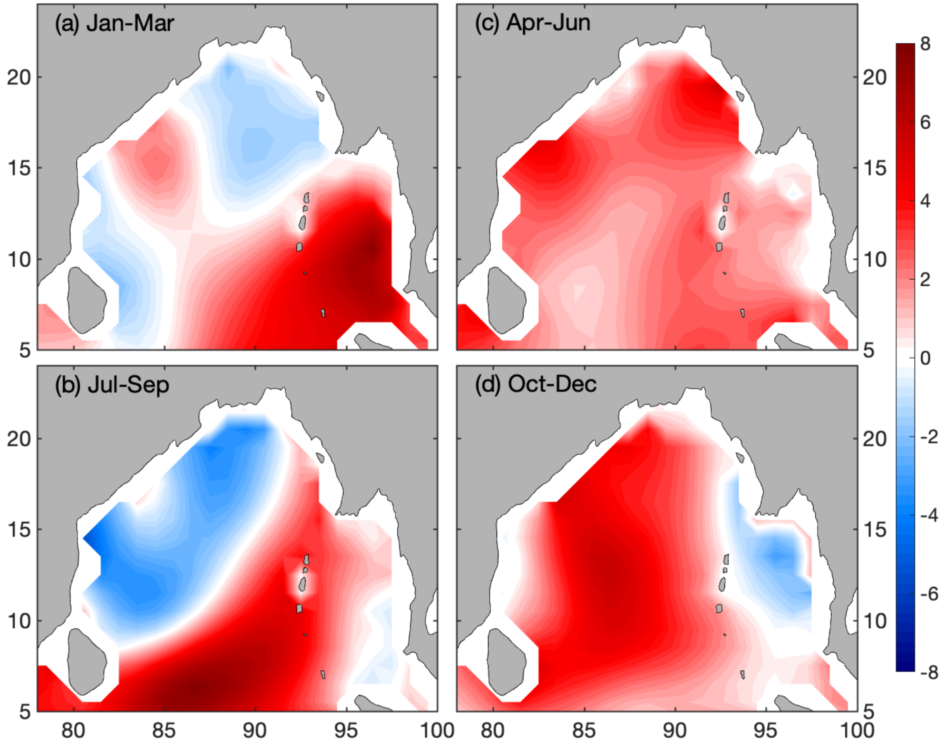


Total MAM monsoon eddy trajectories from 1993 to 2018 for AEs (left) and CEs (middle) for 10-20 cm (a-b), 20-30 (c-d), 30-40 (e-f), and box plots of radius (km; right), with (g) corresponding to (a), (h) to (b), and so on. Red stars indicate genesis location and black lines to indicate eddy trajectories. Red numbers are the number of eddies shown.

OCEAN HEAT CONTENT (OHC)

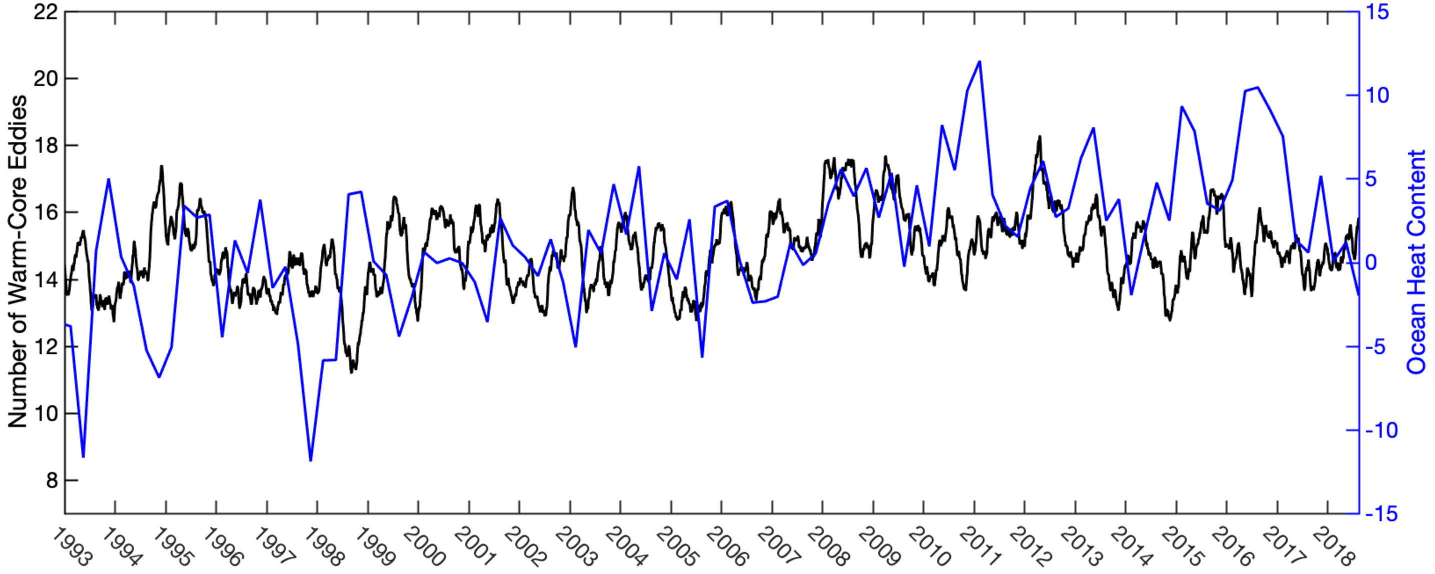
- OHC strongly contributes to SST variability and eddy core temperatures
- Western BoB has high OHC during spring and low OHC during winter
  - Region of highest eddy amplitudes and radii and greatest seasonal changes in OHC
- Warm-core eddies generating convection works to transfer heat from ocean to atmosphere

NOAA Climatological depth-integrated (700m) ocean heat content averaged over 1993-2018 seasonally using Argo Temperature measurements. Units for ocean heat content are in x10[19] J.



OCEAN EDDIES & HEAT CONTENT

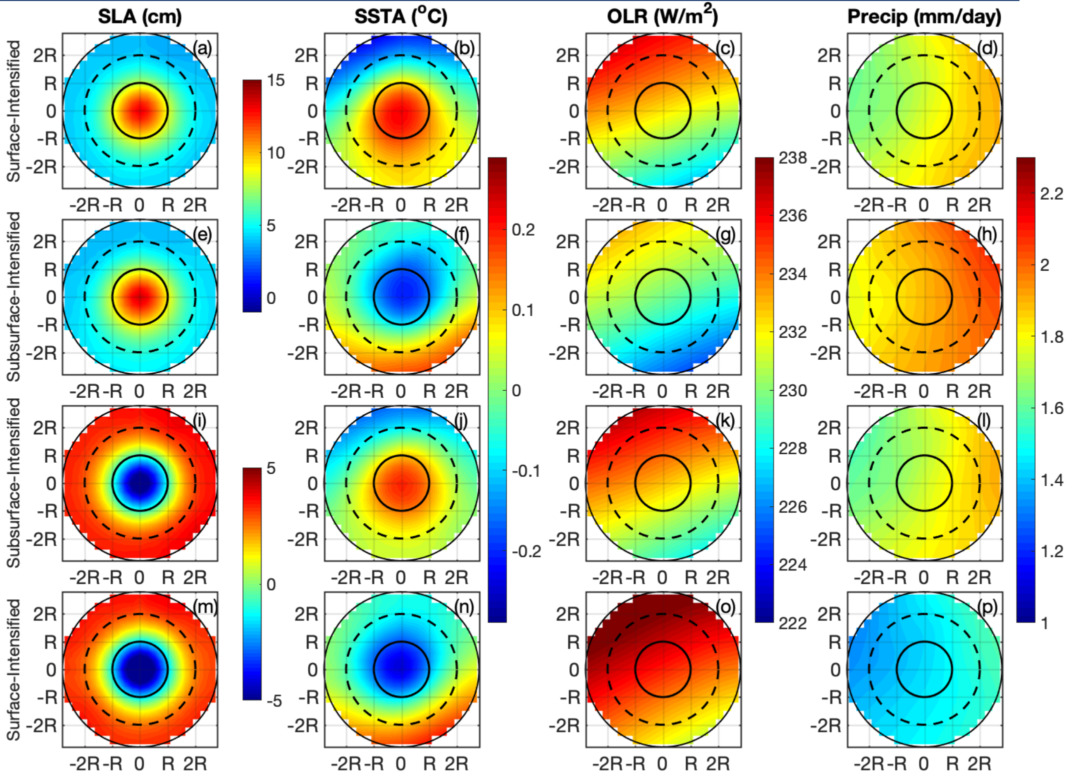
IOD & ENSO events cause large changes in OHC, otherwise OHC follows number of warm core eddies



Number of warm-core eddies in the BoB (blue) and basin-wide ocean heat content (black) from 1993-2018. Units for ocean heat content are in x10^{19} J.

OCEAN EDDIES & CONVECTION

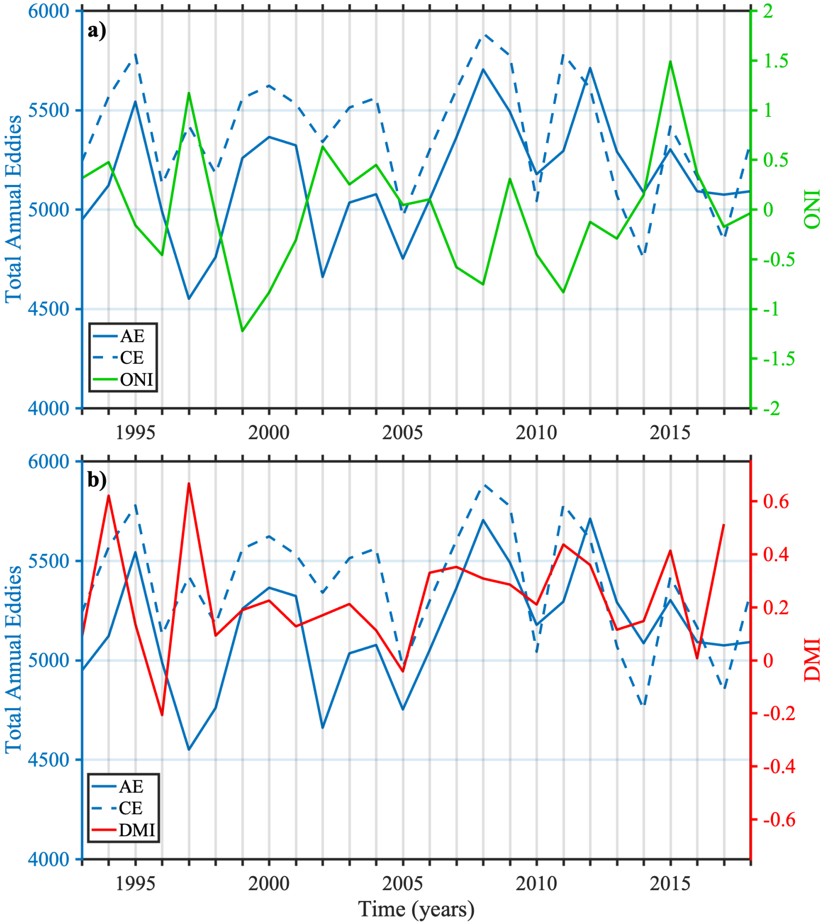
- Composites of SLA, SSTA, OLR, and Precipitation shows a close relationship between eddy temperatures and local convection
- 4-day lag in Precipitation wrt OLR



Eddy composites with normalized radius from 1993 to 2018 in the Bay of Bengal in SLA (left; cm), SSTA (left middle; ℃), OLR (right middle; W/m²), and precipitation (right; mm/day) for (a-d) surface intensified, warm core AEs, (e-h) subsurface-intensified, cold core AEs, (i-l) subsurface intensified, warm core CEs, and (m-p) surface intensified, cold core CEs.

EDDIES – IOD & ENSO

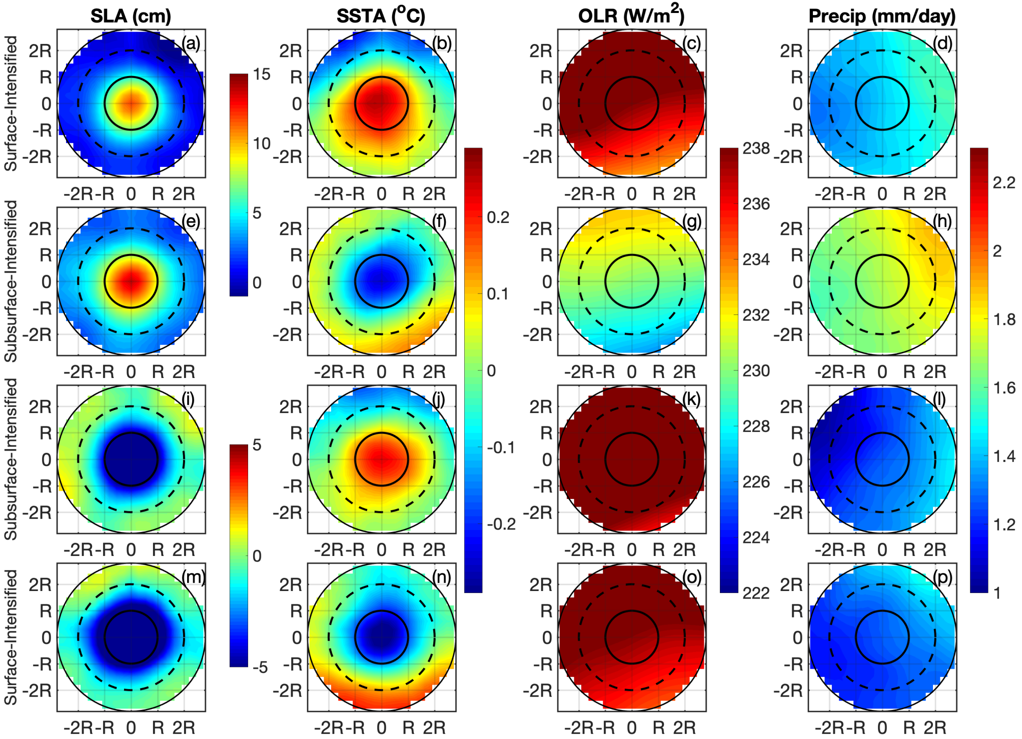
- Total AEs and CEs in each year (total = sum of eddies present on each day over each year) from 1993 to 2018
- Compared with ONI ENSO Index (green; top figure)
- Compared with DMI IOD Index (red; bottom figure)
- CEs show stronger relationship to ENSO and IOD
- Fewer AEs during El Niño years (ex: 1997, 2002)
- Influenced by CKW propagation



Total annual AEs (solid blue) and CEs (dashed blue) in the Bay of Bengal compared to the annual mean (a) the ONI ENSO index (℃; solid green) and (b) DMI IOD index (℃; solid red) from 1993 to 2018, where the total number of eddies is taken to be the accumulated number of eddies present on each day over a year.

AFTER EL NIÑO AND POSITIVE IOD YEAR - 1998

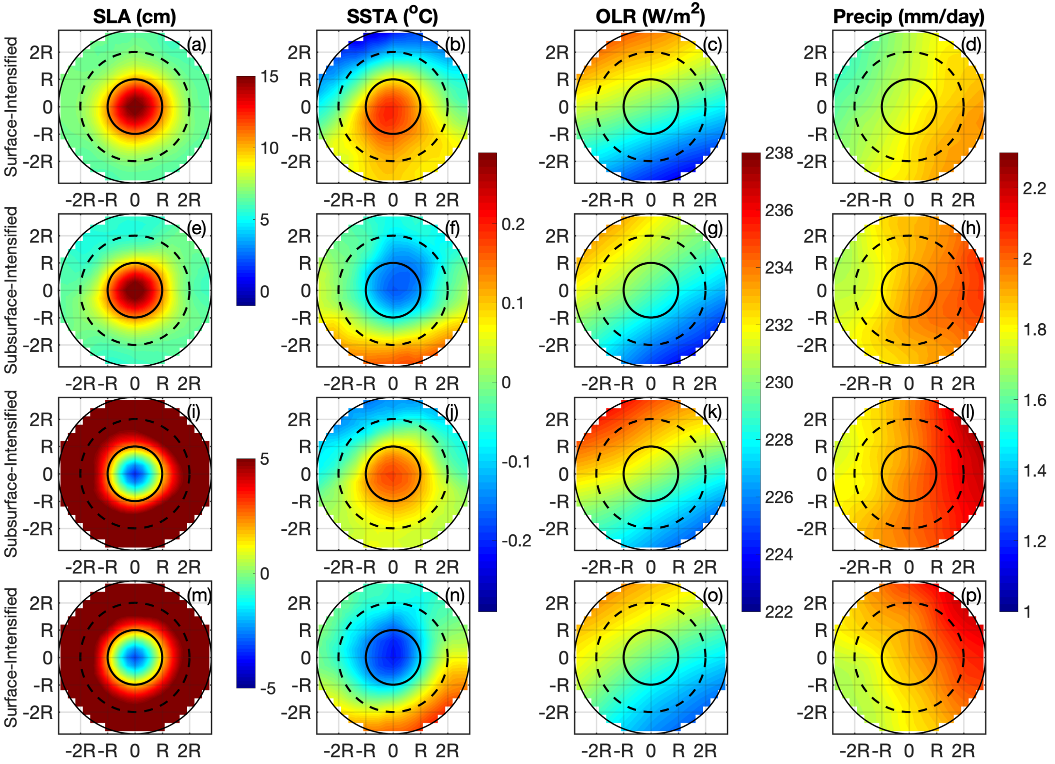
- SST anomalies in center of eddy are higher magnitude than long-term composite.
- Large OLR values and low precipitation indicate clear skies



Eddy composites with normalized radius for 1998 in the Bay of Bengal in SLA (left; cm), SSTA (left middle; °C), OLR (right middle; W/m²), and precipitation (right; mm/day) for (a-d) surface intensified, warm core AEs, (e-h) subsurface-intensified, cold core AEs, (i-l) subsurface intensified, warm core CEs, and (m-p) surface intensified, cold core CEs.

AFTER LA NIÑA AND NEGATIVE IOD YEAR - 2011

- Higher amplitude eddies with a more moderate SSTs
- OLR response more similar to climatological values
- More deep convection



Eddy composites with normalized radius for 2011 in the Bay of Bengal in SLA (left; cm), SSTA (left middle; °C), OLR (right middle; W/m²), and precipitation (right; mm/day) for (a-d) surface intensified, warm core AEs, (e-h) subsurface-intensified, cold core AEs, (i-l) subsurface intensified, warm core CEs, and (m-p) surface intensified, cold core CEs.

SUMMARY

- We found high eddy generation in the eastern BoB associated with instability induced by CKW and the westward propagating Rossby waves, but the most robust eddies (with large radii, amplitudes, and eddy kinetic energies) in the western BoB around the EICC.
- OHC in the BoB was compared with warm-core eddies and we find that warm-core eddies drive changes in OHC.
- We also compared the eddy field during strong and weak SW monsoon forcing and with varying IOD and ENSO conditions.
  - Timing of Kelvin waves were strongly related to the phase of ENSO & IOD, and also contribute to eddy associated convection in the BoB.
- We found the composite surface structure of AEs and CEs with warm-core and cold-core structures, having a close relationship between the eddy-composite SSTs and composites of OLR.
  - AEs in the BoB were strongly influenced by the strength of the downwelling Kelvin waves that propagate (along the coast) in the BoB, with stronger Kelvin waves producing stronger eddies