Role of coastal trapped waves of remote origin and local eddy-wind interaction in the formation of seasonal thermocline bulge in the Bay of Bengal

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Outline of the presentation

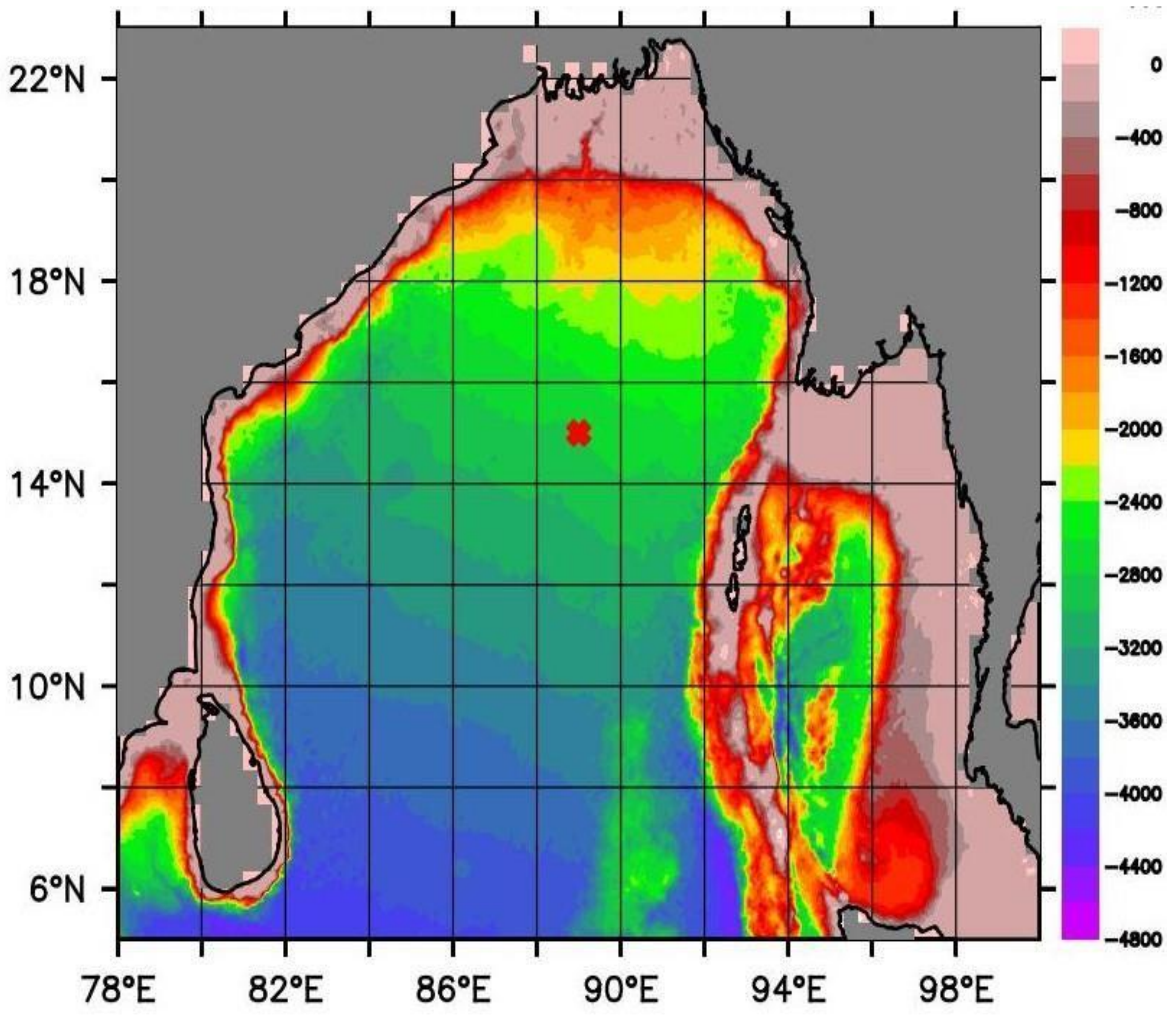
- Introduction: importance of the BOB
- Literature Survey
- Important unanswered questions
- Possible objectives of the thesis
- Work done so far: methods and results
- Conclusion
- Future Directions

Introduction

Bay of Bengal (BOB): unique Indian Ocean basin, compared many ocean basins as-

- Semi-enclosed (landlocked in 3 sides).
- Seasonally reversing monsoon wind forcing.
- Fertile ground for monsoon depressions [Gadgil 2000] and tropical cyclones (pre/post monsoon).
- Large amount of fresh-water discharge from continental river systems (e.g.- GB, Irrawaddy, GM etc.).
- Remote wind forcing from the equatorial Indian Ocean.
- Barrier layer formation in the northern bay during the summer monsoon.

Study Domain: Bay of Bengal
Background color = Topography (meters)



Literature Survey

BOB circulations

- Upper-ocean currents in the BOB are critical factors that determine its fresh-water/salt and heat transport.
- Western boundary current (EICC) is seasonally reversing. In summer, EICC splits into two parts, equatorward north part and poleward south part at 16˚N. In spring, EICC is poleward, and in fall, it is equatorward. (Shetye et al. 1991, 1993 and 1996; McCreary et al. 1996; Shankar et al. 1996).
- Summer Monsoon Current (SMC): instrumental for intrusion of high saline Arabian seawater into the bay during the ISM (Vinayachandran et al., 1999; Webber et al., 2018).
- Local and remote forcing on the bay circulations (Yu et al., 1991; McCreary et al., 1996; Shankar et al., 1996; Vinayachandran et al., 1996)

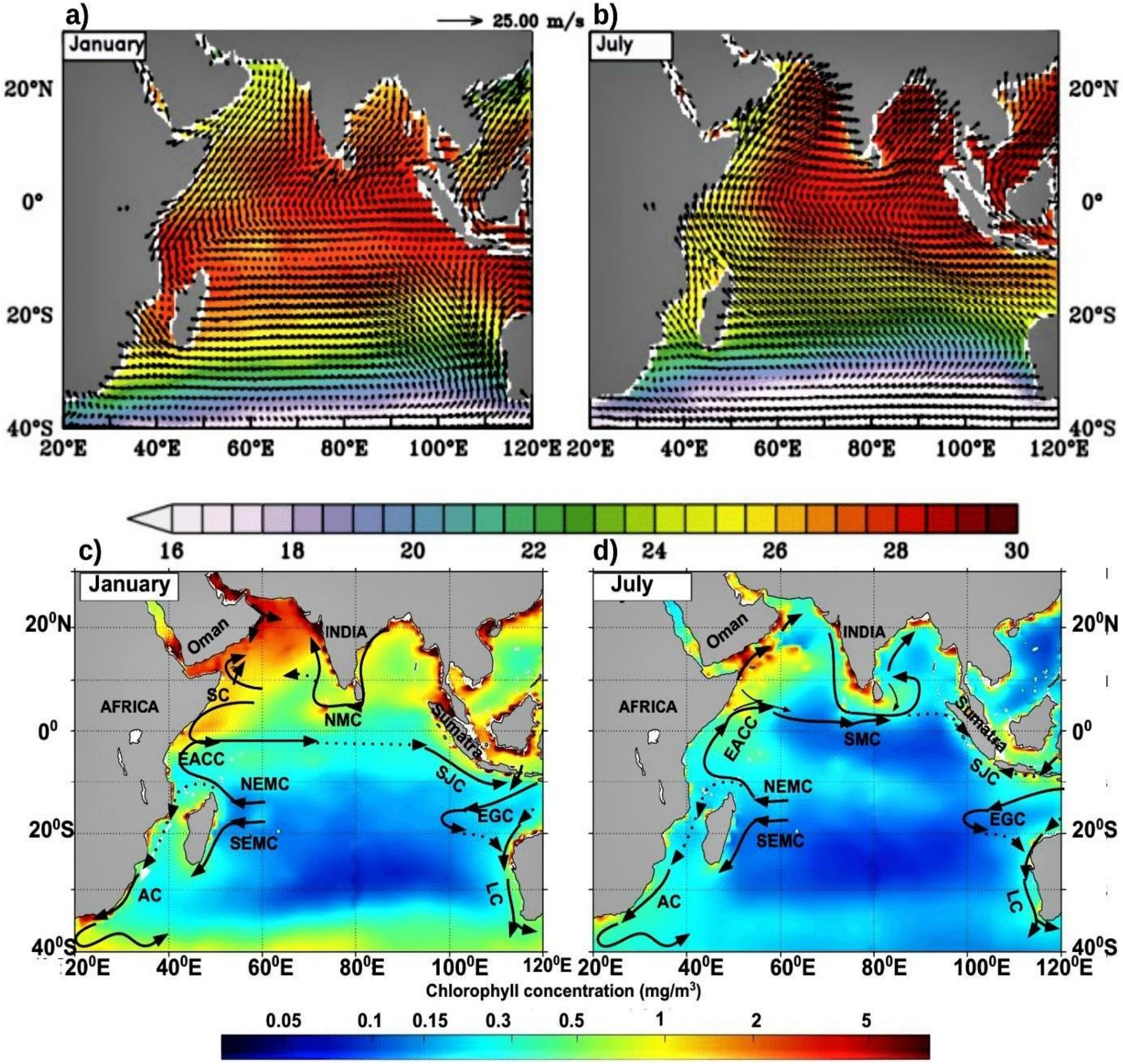


Figure Courtesy: Vinayachandran et al., 2021

Continue…

- BOB is subjected to monsoonal mixing by northward propagation of ISOs (Sengupta and Ravichandran 2001; Mahadevan et al 2016; Murthy et al, 1992).
- Spatial and temporal variability of upper ocean circulations in the BOB from sub-seasonal to seasonal to long timescale using observation/model and impact on biogeochemistry of the basin, were studied well. (Webber et al, 2018; Gopalakrishna et al, 2020; Babu 1990; Mukherjee et al, 2018; Phillips et al 2021; Somayajulu et al, 2003; Potemra et al, 1991; Eigenheer and Quadfasel, 2000; Shankar et al, 2002; Vinayachandran et al., 2005)

Bay circulations at higher resolutions

- Mesoscale circulations in the bay: Eddy dominated with typical radius of 100s km, life span of few weeks to months and amplitude +/- 10s cm (Gopalan et al., 2000; H. et al., 2019; He et al., 2020; Roman-Stork et al., 2019).
- Statistical analysis, vertical structure, dynamics, seasonal to annual variabilities of eddies are extensively studied in the previous researches (Chen et al., 2012; Dandapat and Chakraborty, 2016; Cui et al., 2016; Cheng et al., 2018; Gulakaram et al., 2020).
- Mesoscale eddies have a significant role in biological productivity in the bay through the upwelling of subsurface nutrient-rich water to the euphotic zone (Jyothibabu et al., 2014; Kumar et al., 2004; Jyotibabu et al, 2021)
- Dynamics of eddy generation in central BOB (Chen et al, 2018), role of Andaman-Nicobar island in generation of eddies in western BOB (Mukherjee et al, 2019)

Modified types of eddies

- There is two more modified type of eddies, called the mode-water anti-cyclonic (cyclonic thinny) eddies due to rising (deepening) of seasonal thermocline (McGillicuddy et al. 2007, 2015).
- Mode-water anti-cyclonic eddy has a similarity with Intra-thermocline eddies (ITE). ITEs are regular features in subtropical or subpolar waters (Barcel´o-Llull et al., 2017; Hormazzbal et al., 2013; Gordon et al., 2002; Nauw et al., 2006).
- Shi et al, 2018 studied a mode-water eddy in the Kuroshio extent in northern Pacific ocean. They also found that this type of eddies can transport more mass than usual cyclonic/anti-cyclonic eddies.
- In tropical basins like the BoB this kind of eddies are very rare.

We want to do study in this direction.

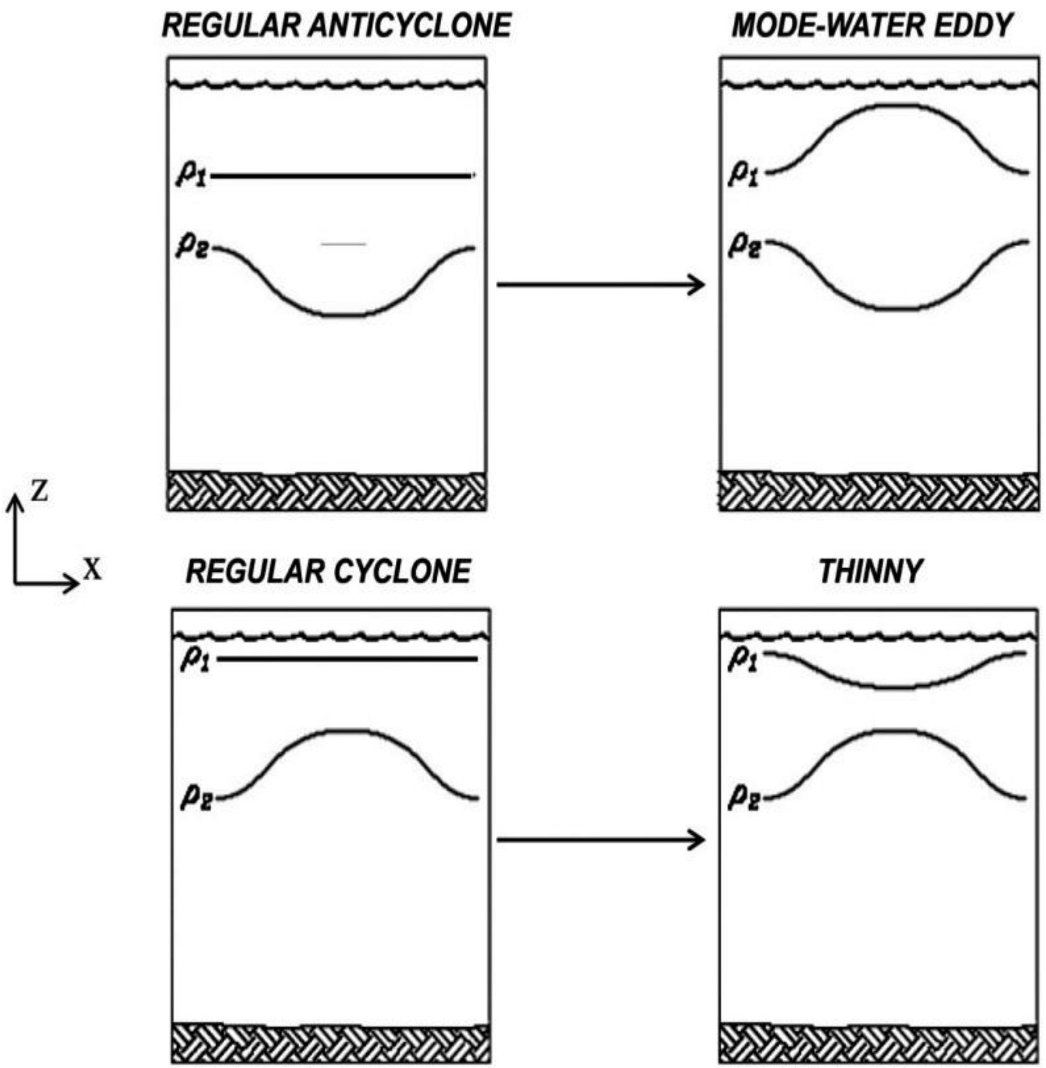


FIG. 1. Hypothesized transformations of a (top) regular anticyclone into a mode water eddy and (bottom) a regular cyclone into a cyclonic thinny. Each cross section depicts an isopycnal in the seasonal ρ_1 and main thermocline ρ_2.

Courtesy: McGillicuddy et al., 2015

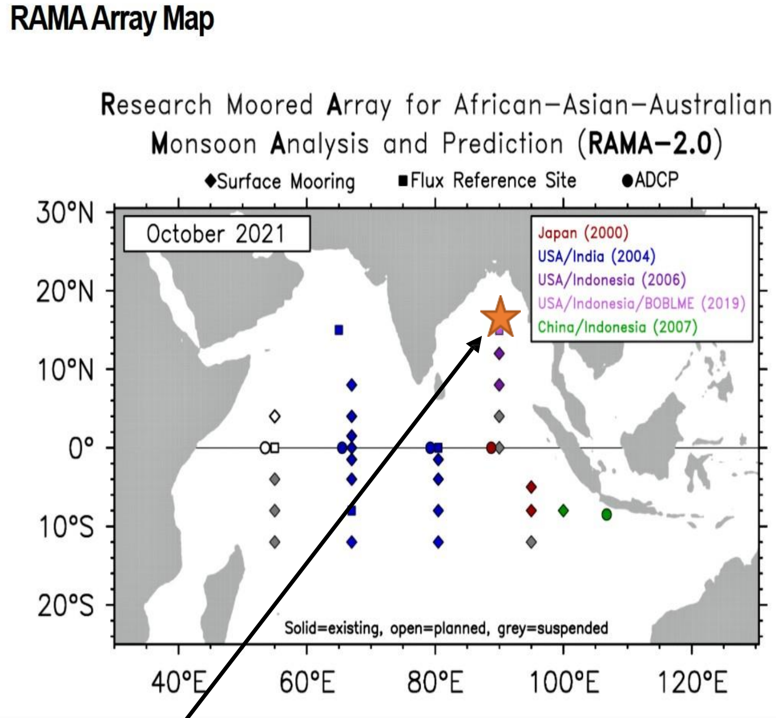
Subsurface eddy in the Bay of Bengal

- Very little is known about the subsurface circulation, and few available studies report active subsurface eddy fields.
- Madhusoodanan and James, 2003 analyzed the thermohaline features of the subsurface cyclonic eddy in the south-central bay during August 1999.
- Babu et al., 1991 showed a subsurface cold-core cyclonic eddy in July 1984 using CTD data centered at 17˚40‘N and 85˚19‘E.
- Gordon et al., 2017 has observed an ITE in the western BOB on 3 December 2013. They hypothesised that this ITE resulted from the interaction between a preceding Cyclone ”Nihar” and a westward-moving AC eddy (from the eastern BOB) on 27 November 2013.
- So far, it is unclear whether ITE in the bay is a seasonal or annual phenomenon or a rare exceptional event in response to external forcing for surface water subduction like tropical cyclones.
- <u>Importance:</u> Knowledge of the subsurface circulation is crucial to understand the salt and heat budget and the mechanisms that control the evolution of the warming and cooling cycle of the sea surface.

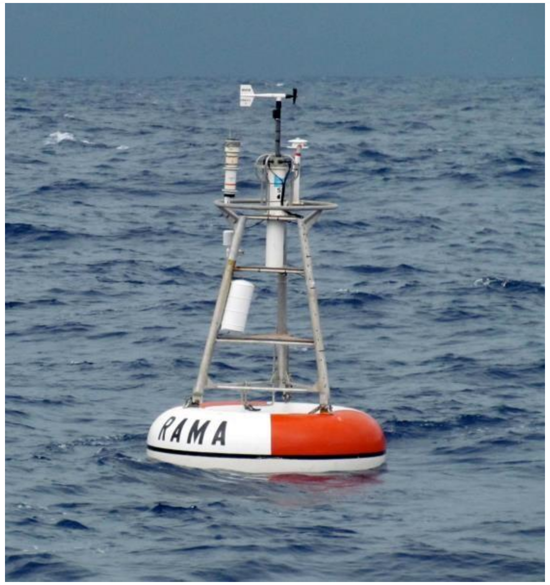
Seasonal thermocline bulge in the Bay of Bengal

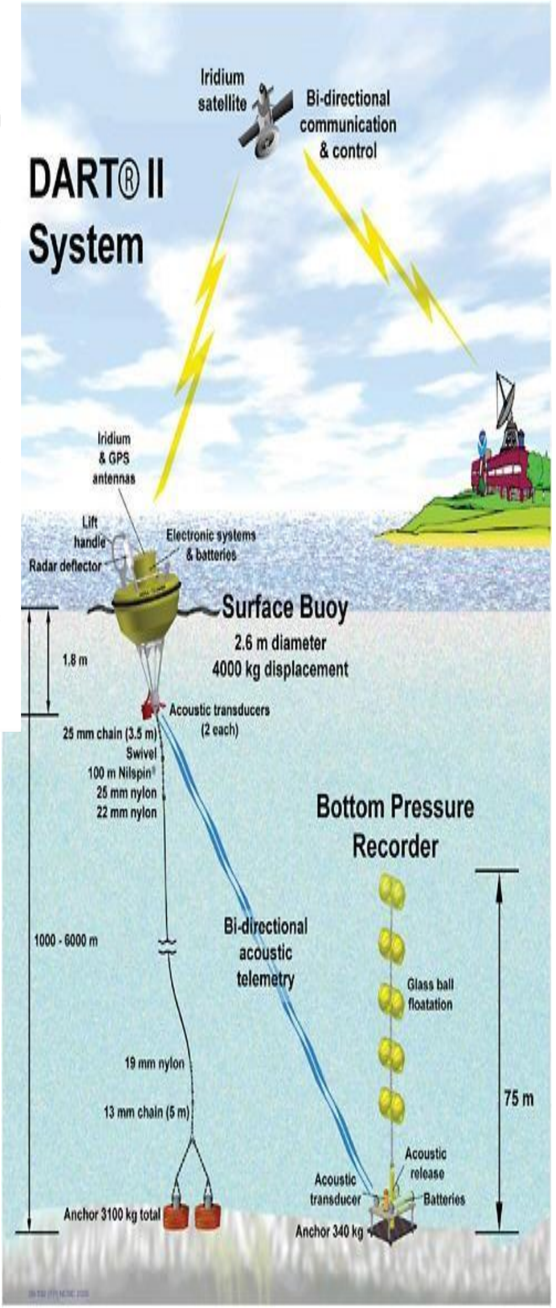
Data and methods

- We have used in-situ NOAA’s RAMA buoy (at 90˚E, 15˚N) surface to subsurface (T, S) data, satellite derived surface AVISO SLA and Ug data, surface OSCAR current data, near surface ASCAT atmospheric wind data.
- Daily data.
- Time period: Nov 2007 to Jan 2019.
- We also used HYCOM re-analysis model subsurface data to understand the possible dynamics.
- We have used PyFerret software tool in Linux environment to analysis and visualize the data products.



★ = 90˚E, 15˚N buoy





Acronym used

T = Temperature; S = Salinity; SLA = Sea Level Anomaly
Ug = (ug, vg) = Geostrophic ocean surface current
NOAA = National Ocean and Atmospheric Administration
AVISO = Achieving Validation and Interpretation of Satellite Oceanography
OSCAR = Ocean Surface Current Analysis Real-time
ASCAT = Advanced Scatterometer

HYCOM re-analysis data

- Source: APDRC data server.
- Resolution: 1/12˚x1/12˚ (horizontal); 41 vertical layer (with high resolution within the top 100 m) till 5000 m.
- Temporal range: Jan 1994 to Dec 2015; daily data.

Primary Results

Time-Depth sections of RAMA buoy subsurface temperature

Time-Depth section of RAMA subsurface temperature at 90E, 15N

TC bulging events are marked by cyan box from Nov 2007 to Oct 2019

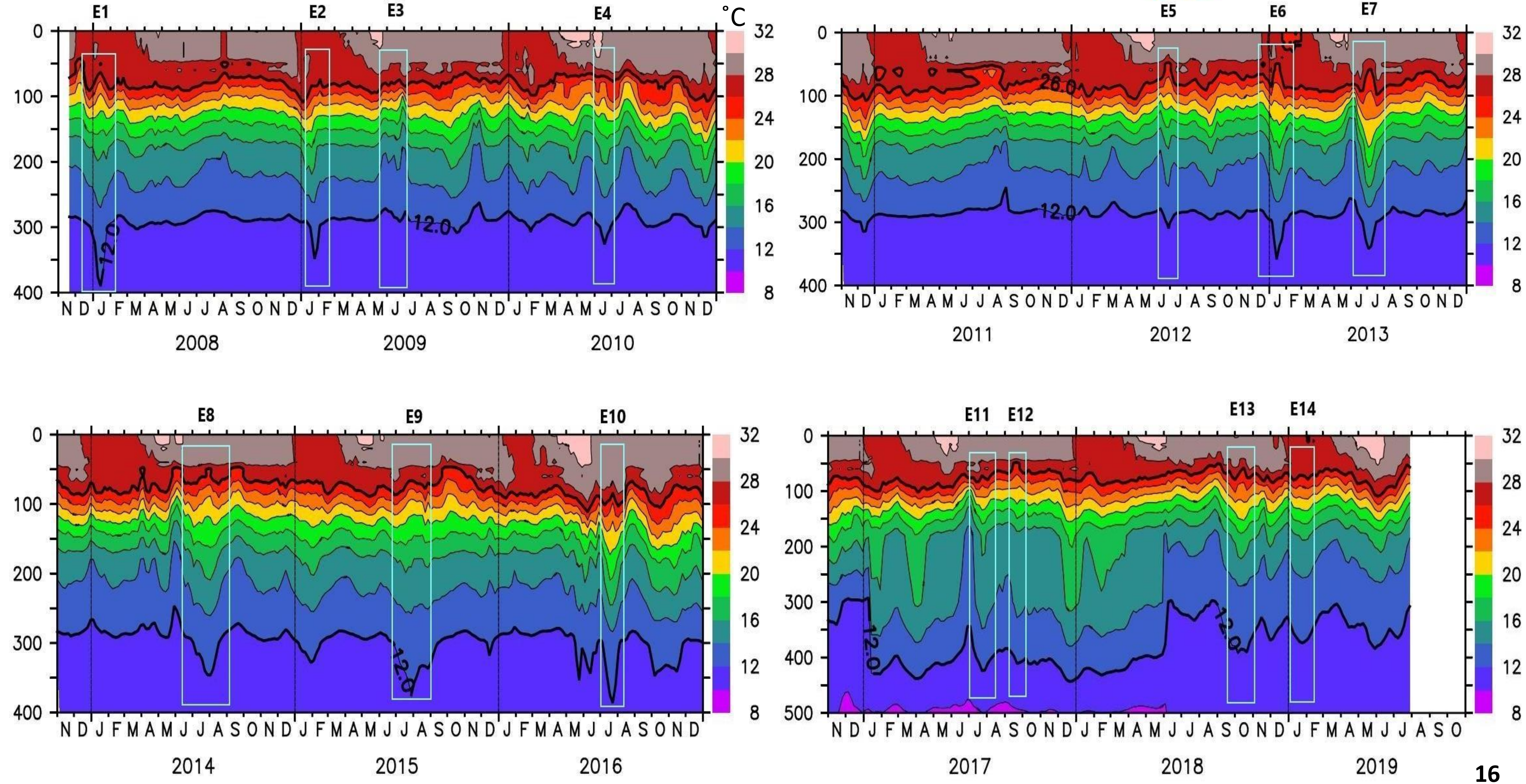
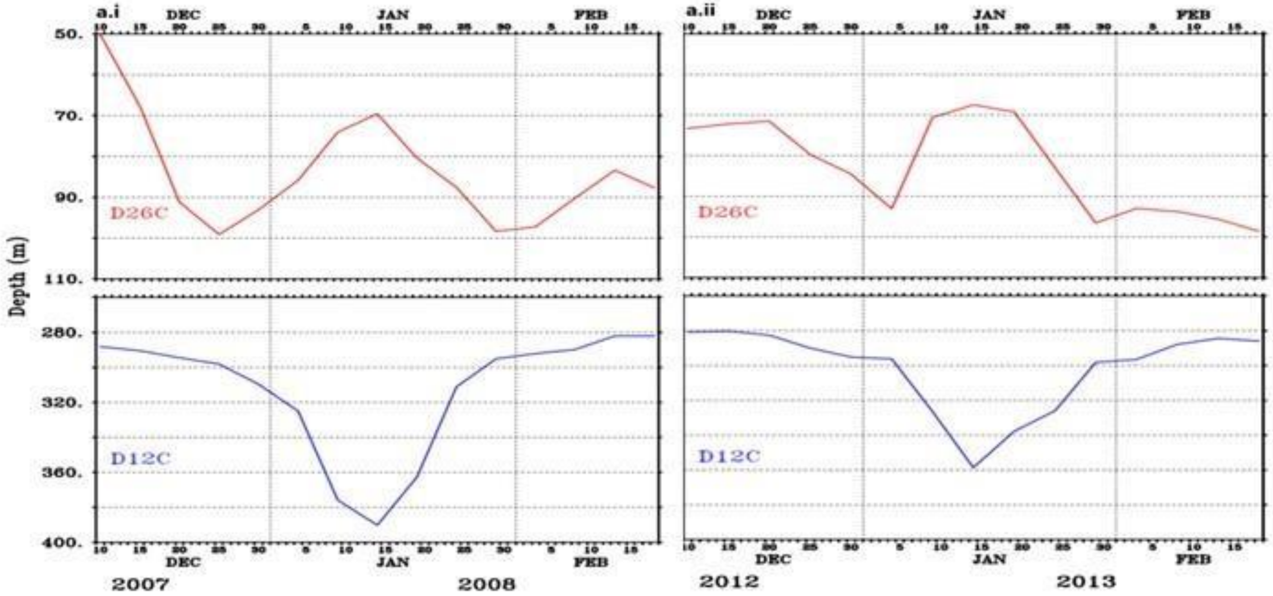


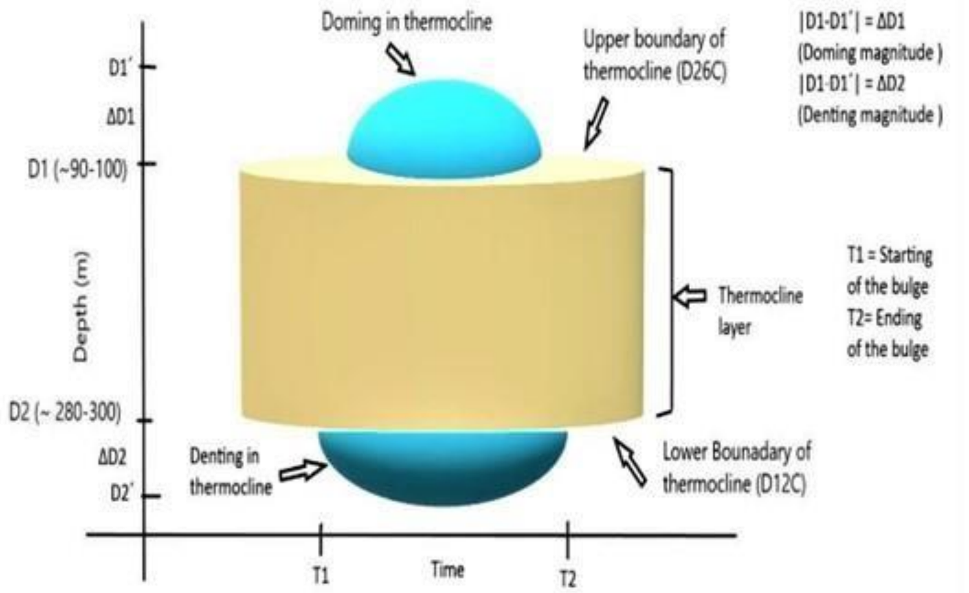
Table: Statistics of Thermocline Bulge events

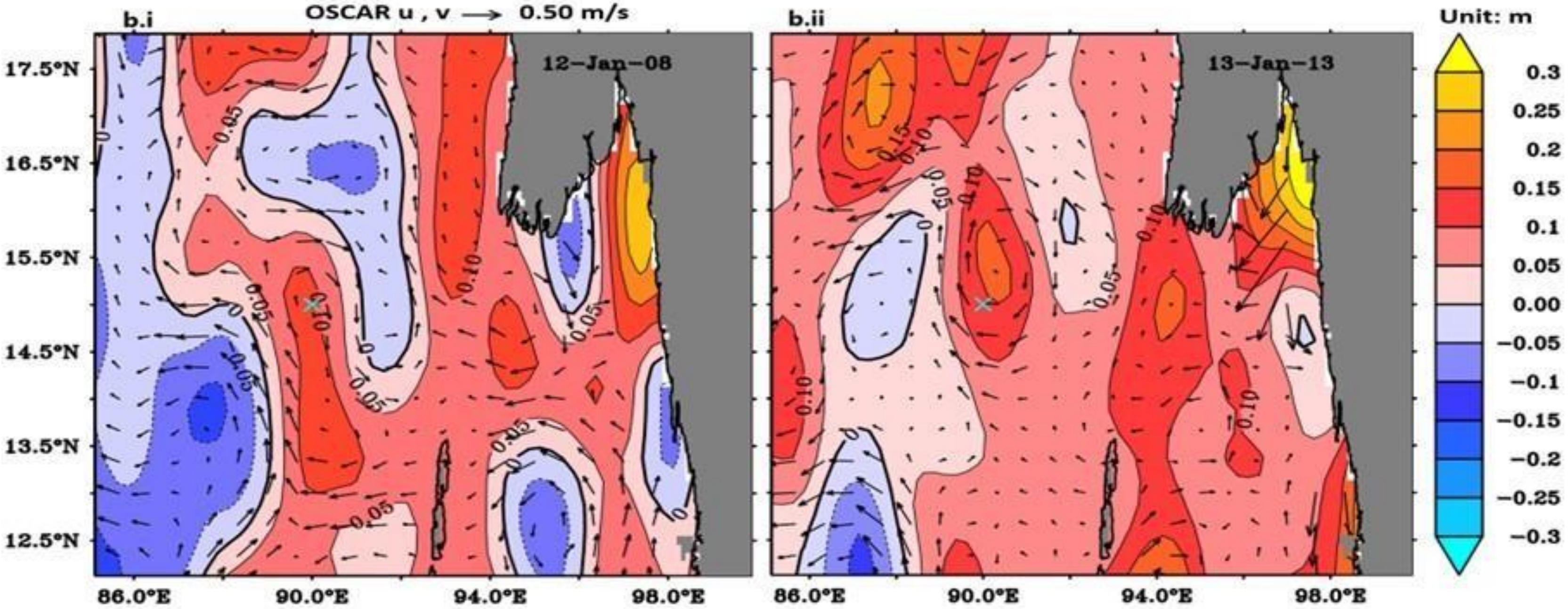
Year	Winter Months (DJF)	Summer Months (JJA)	Max. Magnitude in			Stretching Cycle of					
			D26C Doming ΔD1 (m)	D12C Denting ΔD2 (m)	TC-bulge ΔD (m)	D26C Doming			D12C Denting		
						Start Date	End Date	Duration (days)	Start Date	End Date	Duration (days)
2013	**Jan**		**26**	**78**	**104**	**03 Jan**	**27 Jan**	**24**	**15 Dec’12**	**13 Feb**	**58**
		Jul	**74**	**75**	**149**	**23 Jun**	**17 Jul**	**26**	**05 Jun**	**17 Aug**	**72**
2008	**Jan**		**28**	**105**	**133**	**24 Dec’12**	**27 Jan**	**35**	**24 Dec’12**	**11 Feb**	**50**
2009	**Jan-Feb**		**32**	**68**	**100**	**28 Jan**	**08 Feb**	**10**	**08 Jan**	**03 Feb**	**25**
2010		Jun	08	30	38	07 Jun	05 Jul	29	07 Jun	22 Jul	44
2012		Jun	28	33	61	07 Jun	13 Jul	35	13 Jun	14 Jul	32
2014		**Jun-Jul-Aug**	**13**	**90**	**103**	**07 Jul**	**16 Aug**	**40**	**13 Jun**	**16 Aug**	**64**
2015		**Jul-Aug**	**22**	**87**	**109**	**28 Jun**	**22 Aug**	**55**	**23 Jun**	**27 Aug**	**66**
2016		**Jul**	**19**	**90**	**109**	**07 Jul**	**02 Aug**	**27**	**03 Jul**	**07 Aug**	**36**
2017		Sept	16	36	52	05 Sept	05 Oct	30	01 Sept	05 Oct	34
2018	Dec’12-Jan’13		03	37	40	10 Dec	12 Jan	34	30 Dec	18 Jan	20
2019	Jan		06	47	53	29 Dec	2 Feb	36	29 Dec	23 Feb	57

Seasonal Thermocline Bulge

2007-2008 and 2012-2013 winter cases







3D Schematic of TC Bulge.

Upper part of the TC is doming up and lower part is denting down to form a bulge structure inside thermocline of a surface intensified Anti-cyclonic Eddy.

Fig 2: Thermocline Bulge formation in 2007-08 and 2012-13 winter and corresponding surface intensified ACE

Dynamics of the thermocline bulge at the buoy location

GENESIS AND PROPAGATION OF ACE

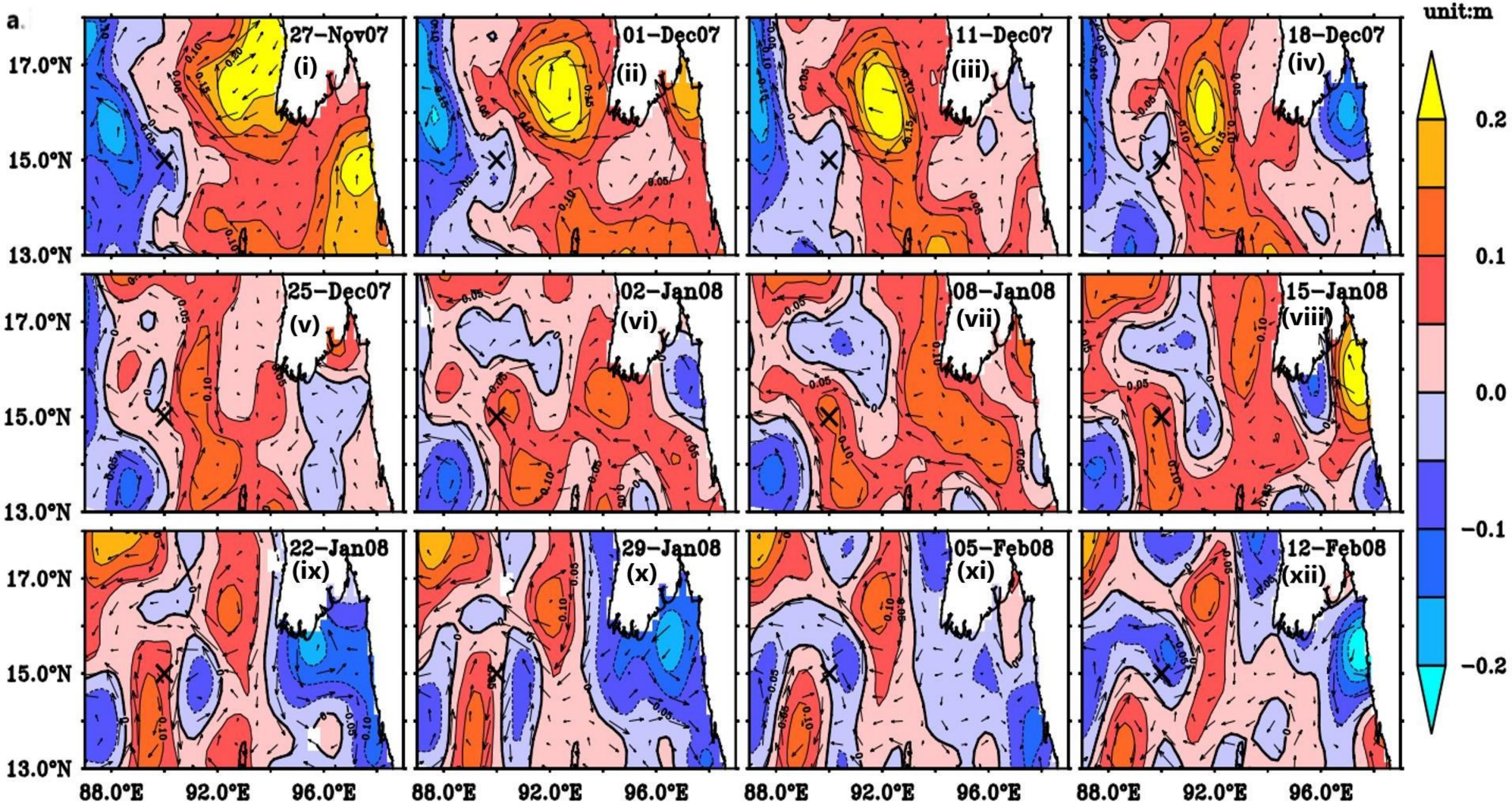


Fig 3: From surface current vector and SLA analysis, ACE is generated off-Myanmar and propagate south-west direction due to Rossby wave forcing and crosses the buoy location during Dec to next Jan.

HOW IS TC-BULGE RELATED TO ACE?

Answer:

“Eddy-wind” interaction (*Stern, 1987; Seo et al., 2019; Gaube et al, 2014; McGillicudy et al., 2014, 2015*):

1. Eddy current effect on local relative wind-stress (linear)
2. Eddy current vorticity gradient effect on local wind-stress (non-linear)
3. Eddy-induced SST gradient effect on local wind-stress (less contribution in most of the basins like Bay of Bengal (Seo et al., 2019))

$$|\vec{\omega}_{tot}| = \frac{|\vec{\nabla}\times\vec{\tau}_{rel}|}{\rho_o(f+\zeta)} + \frac{1}{\rho_o(f+\zeta)^2}\left(\tau^x_{rel}\frac{\partial\zeta}{\partial y} - \tau^y_{rel}\frac{\partial\zeta}{\partial x}\right) + \frac{\beta\tau^x_{rel}}{f^2\rho_o} \qquad (1)$$

$$f = f_o + \beta\Delta y \qquad (2)$$

$$\tilde{\boldsymbol{\tau}} = \rho_a C_D(\mathbf{u}_{\mathrm{bg}} - \mathbf{u}_o)|\mathbf{u}_{\mathrm{bg}} - \mathbf{u}_o|,$$

$$\tilde{W}_{\mathrm{tot}} = W_c + W_\zeta + W_{\mathrm{SST}},$$

$$W_c = \frac{\nabla\times\tilde{\boldsymbol{\tau}}}{\rho_o(f+\zeta)},$$

$$W_\zeta = \frac{1}{\rho_o(f+\zeta)^2}\left(\tilde{\tau}^x\frac{\partial\zeta}{\partial y} - \tilde{\tau}^y\frac{\partial\zeta}{\partial x}\right),$$

$$W_{\mathrm{SST}} = \frac{\nabla\times\boldsymbol{\tau}'_{\mathrm{SST}}}{\rho_o(f+\zeta)}.$$

Eddy-wind interaction along the off-Myanmar coast

- Positive value of Ekman Pumping velocity means: Upwelling.
- Till Mid May: upwelling in-between 92˚-94˚E .
- Along 92˚-94˚E and 14˚-17˚N, Anti-cyclonic eddy (ACE) formed during late May to early June 2013.
- Hence, upwelled thermocline got trapped by the ACE in the same space and time and further formed the bulge structure in its west-southward journey.
- West-southward movement of the system was enforced by the Rossby wave radiated from the coastal Kelvin waves along 14˚-16˚N.

McGillicuddy et al., 2015 studies the "eddy-wind" interaction to form lens like mode-water eddy (of biconvex lens shape) from regular ACE in Sargasso Sea, Atlantic Ocean.

WIND FIELD OFF-MYANMAR IN WINTER

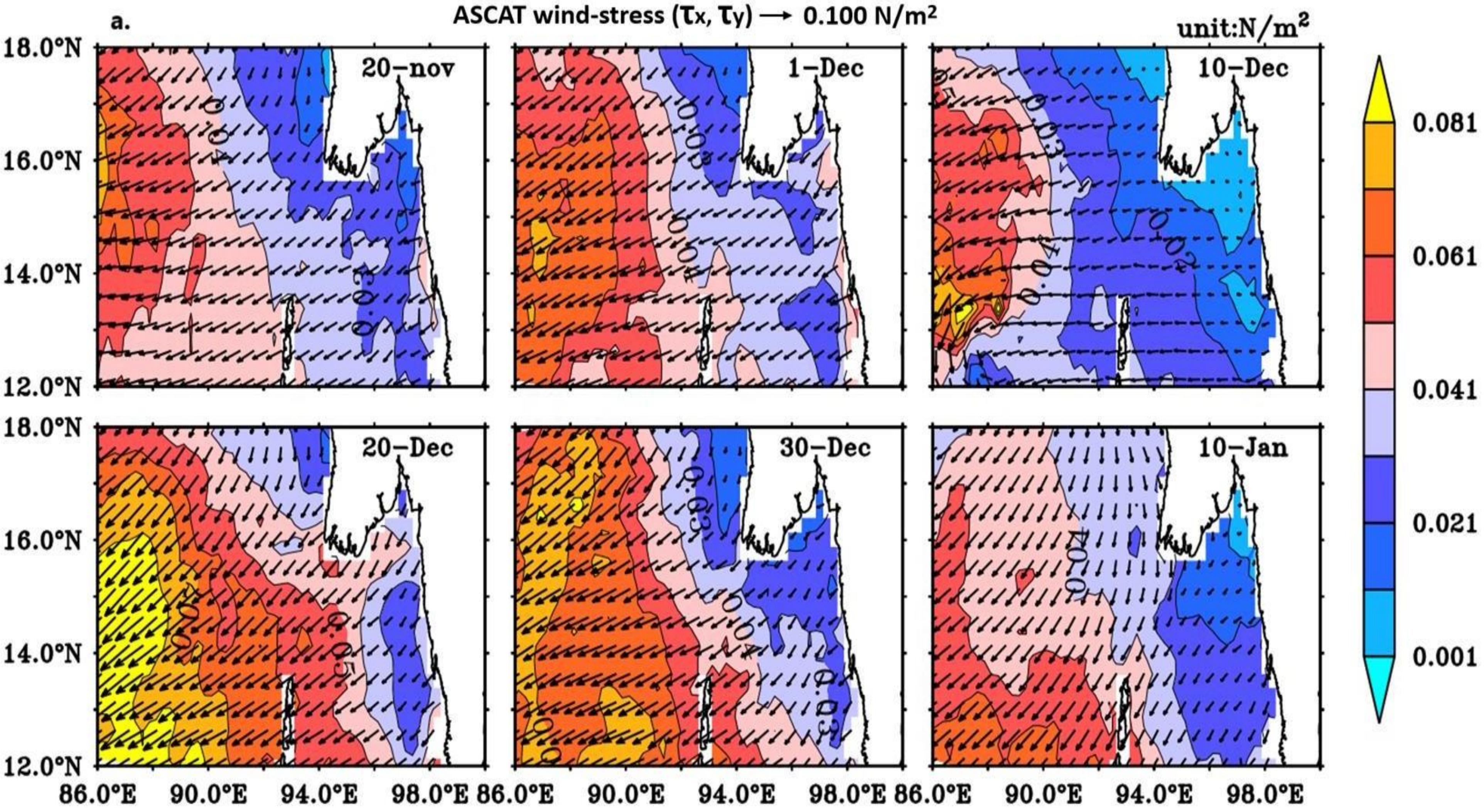
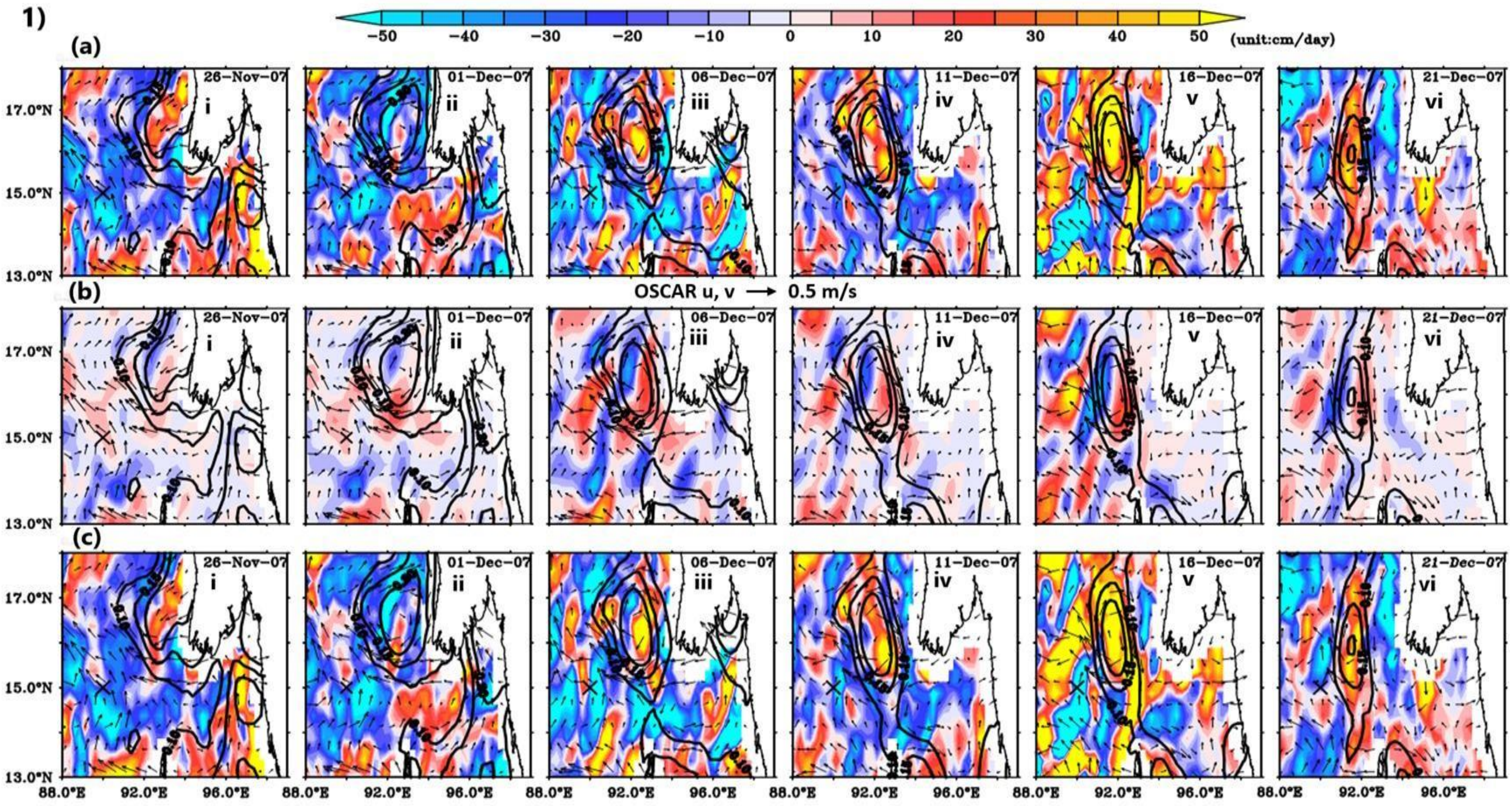


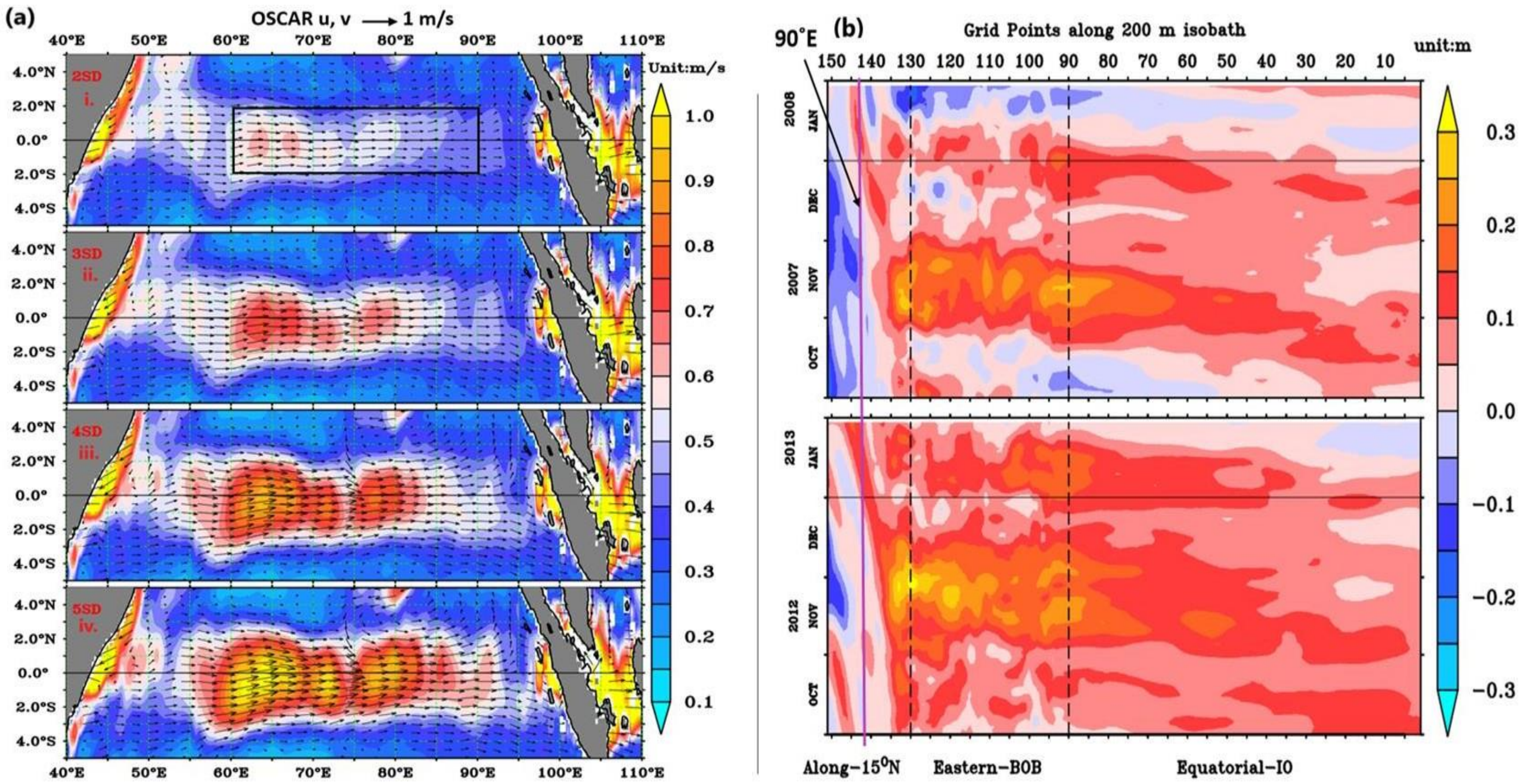
Fig 5: Upwelling favorable winter monsoon wind-stress field (climatology) off-Myanmar.

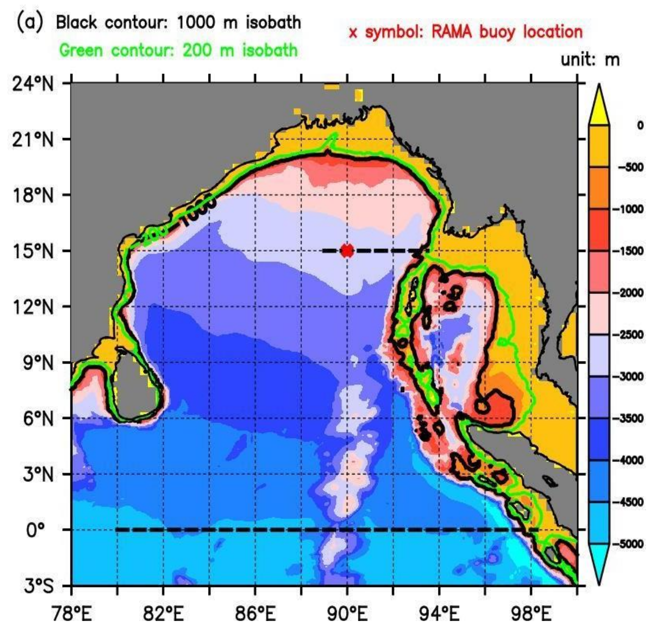
EDDY-WIND INTERACTION IN WINTER



Eddy-Wind interaction leads to upwelling (or shoaling in seasonal TC) at the center of ACE and propagates south-west direction. Background Color: Ekman Pumping velocity (cm/day)

CONNECTION TO EQUATORIAL DYNAMICS

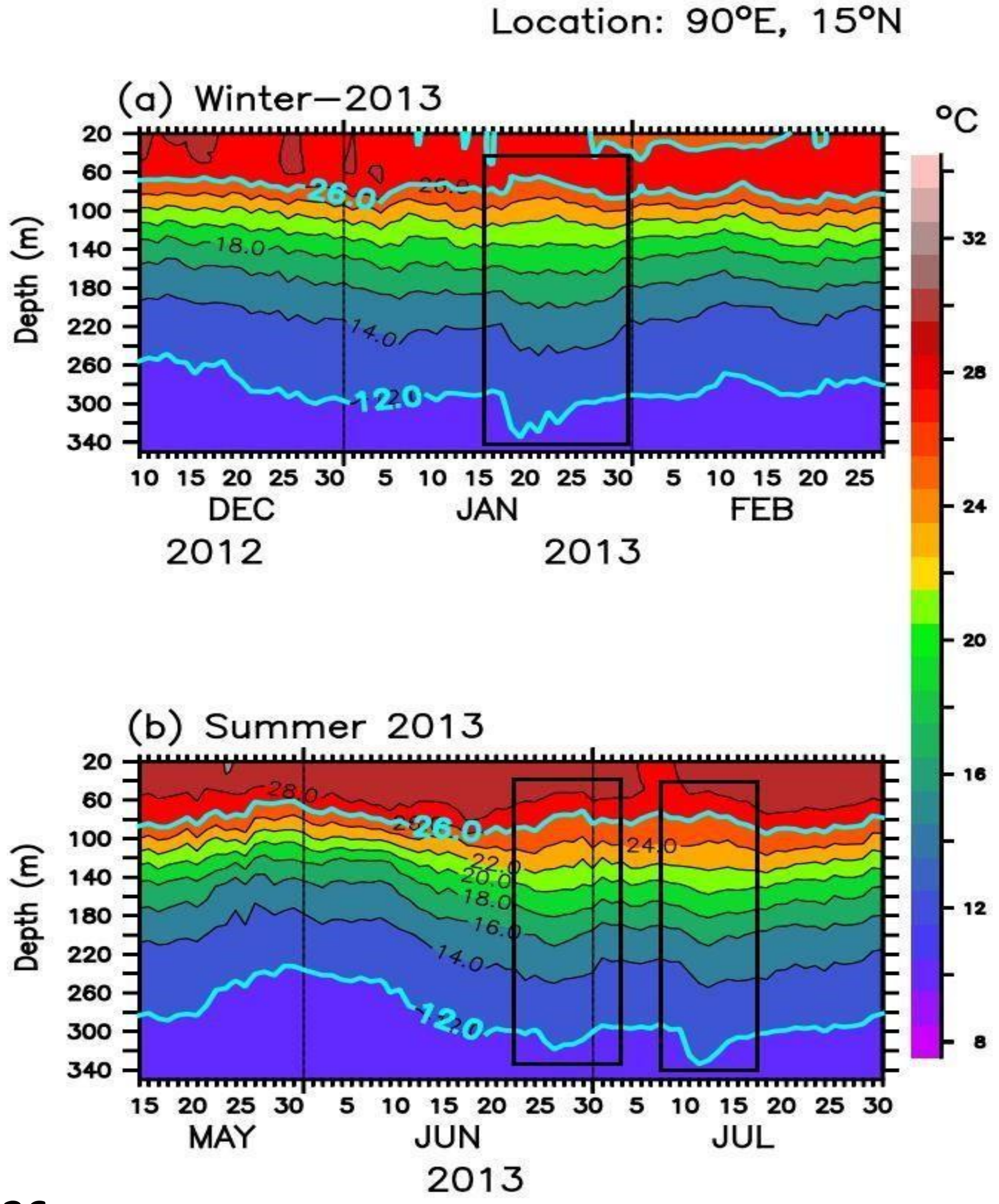


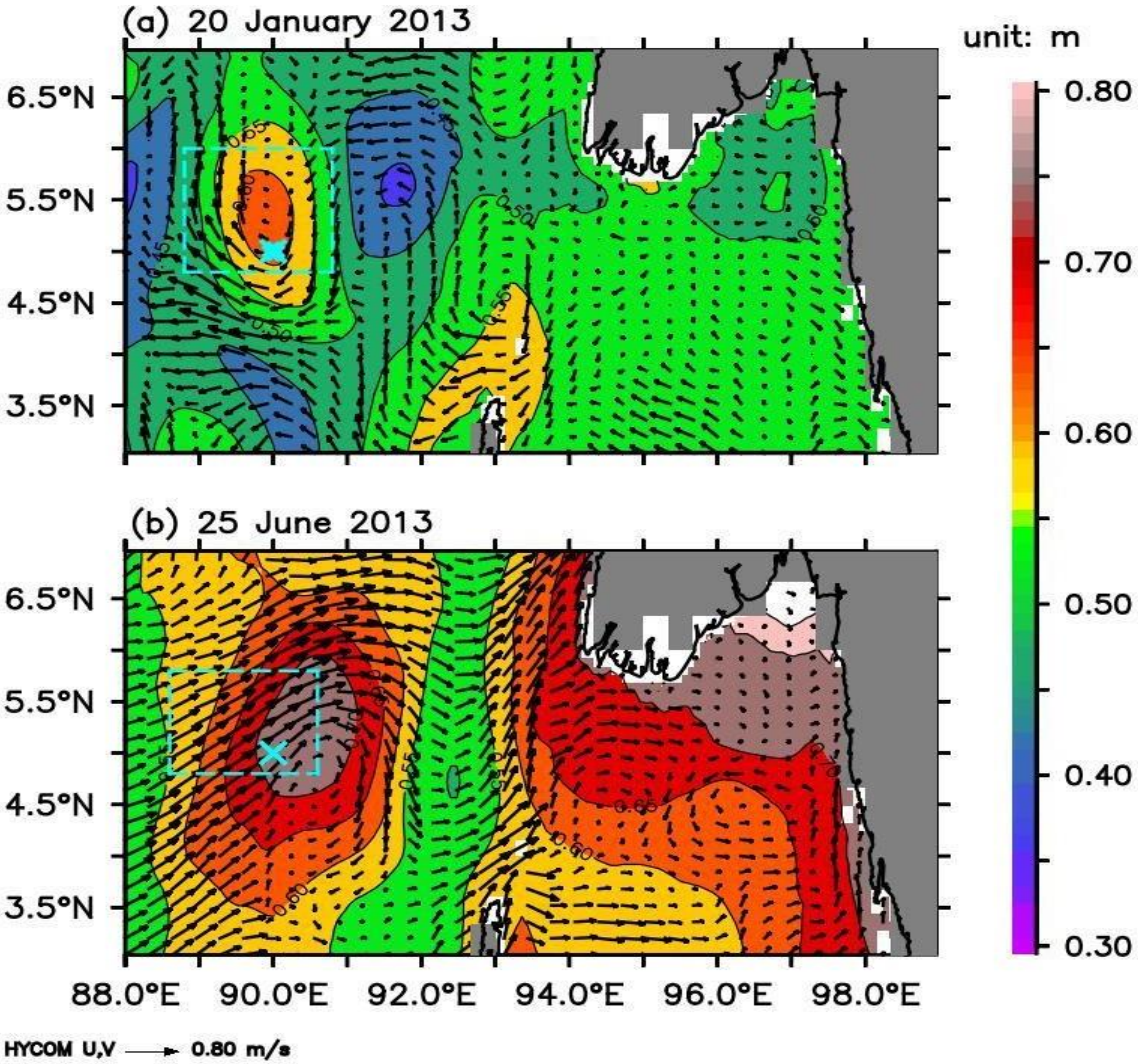


Coastally trapped downwelling Kelvin waves due to equatorial Wrytki jet helps in genesis of ACE off-Myanmar. Then local upwelling favorable winds act of ACE. Thus, TC-bulge forms by “Eddy-Wind” interactions and propagates with ACE to RAMA location.

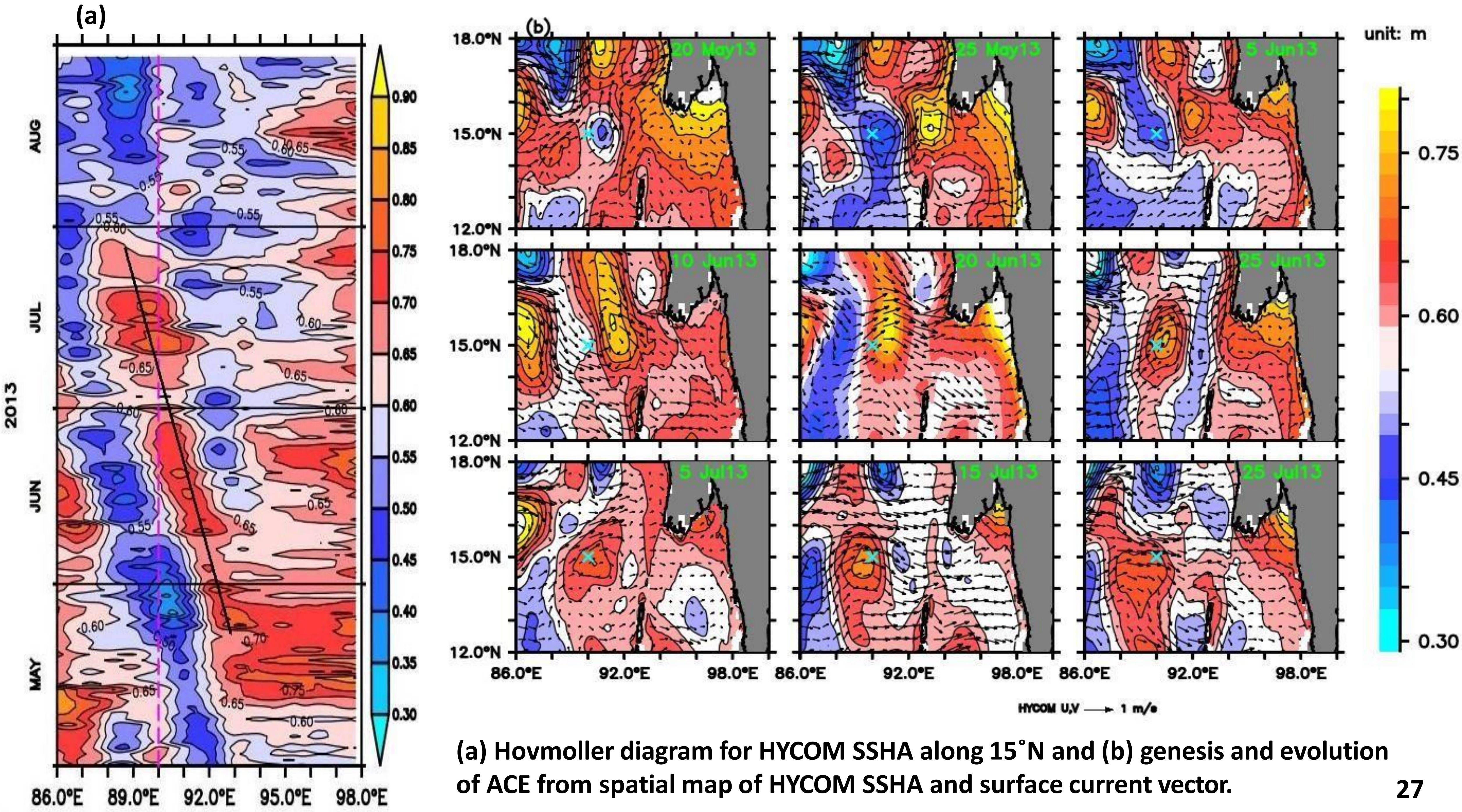
Results from HYCOM re-analysis data

HYCOM re-analysis model data





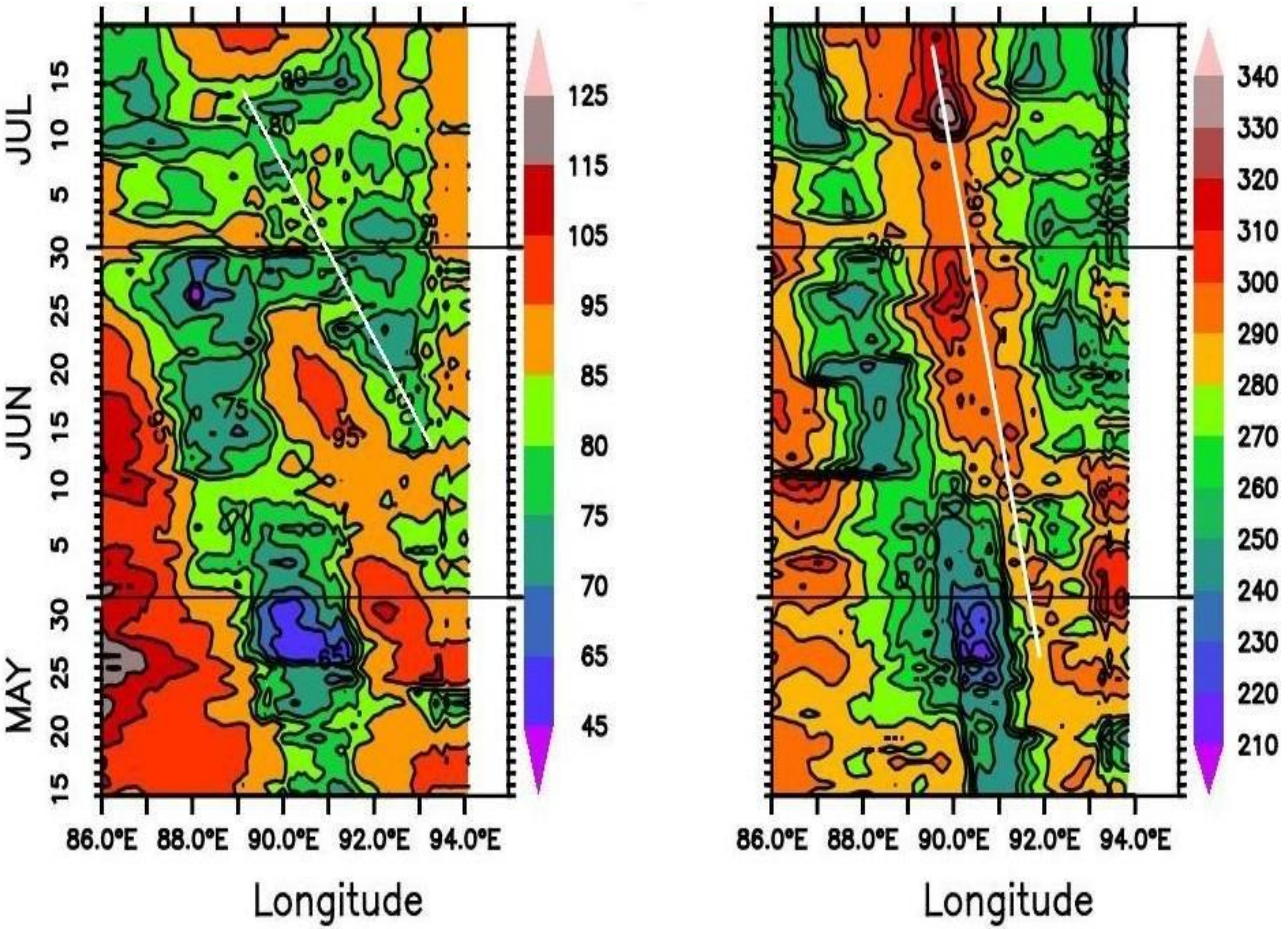
A week difference in peak simulated TC bulge events than observed



(a) Hovmoller diagram for HYCOM SSHA along 15˚N and (b) genesis and evolution of ACE from spatial map of HYCOM SSHA and surface current vector.

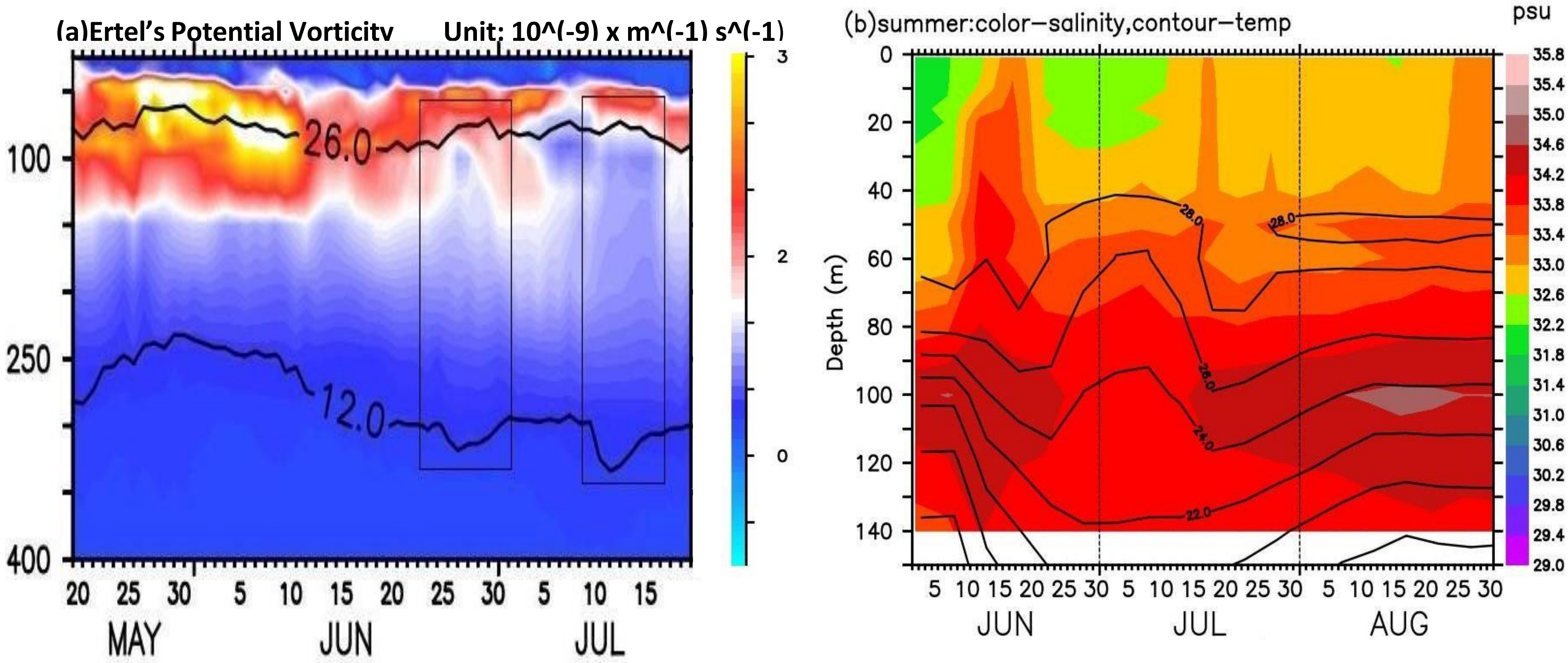
Propagation of D26C and D12C from East to west

D26C **Unit: m** **D12C**



Hovmoller diagram of HYCOM D26C (depth of 26˚C isotherm) and D12C (depth of 12˚C isotherm) along 15˚-16˚N during the summer (from May to July13) in the bay which show westward propagation of D26C and D12C along 15˚-16˚N from Irrawaddy Coast and close association of SSHA. Also, D26C and D12C provide the location of genesis/termination of the seasonal bulging events.

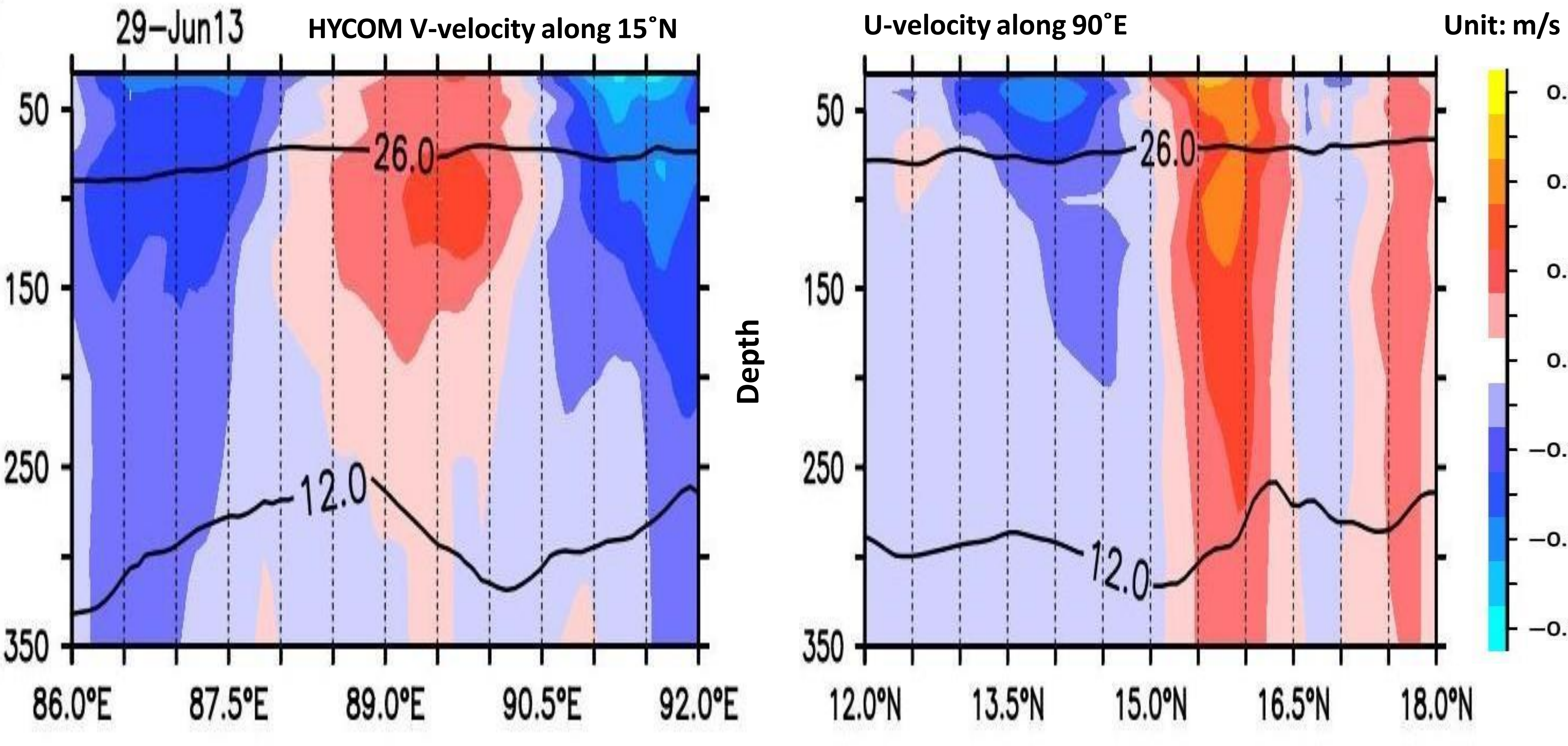
How is it link to subsurface type ACE ?



(a)Ertel’s Potential Vorticity Unit: 10^(-9) x m^(-1) s^(-1)

(b)summer:color–salinity,contour–temp

Left: Low PV core (HYCOM simulation) and Right: Low salinity core (RAMA data), in the upper part of the bulged TC.



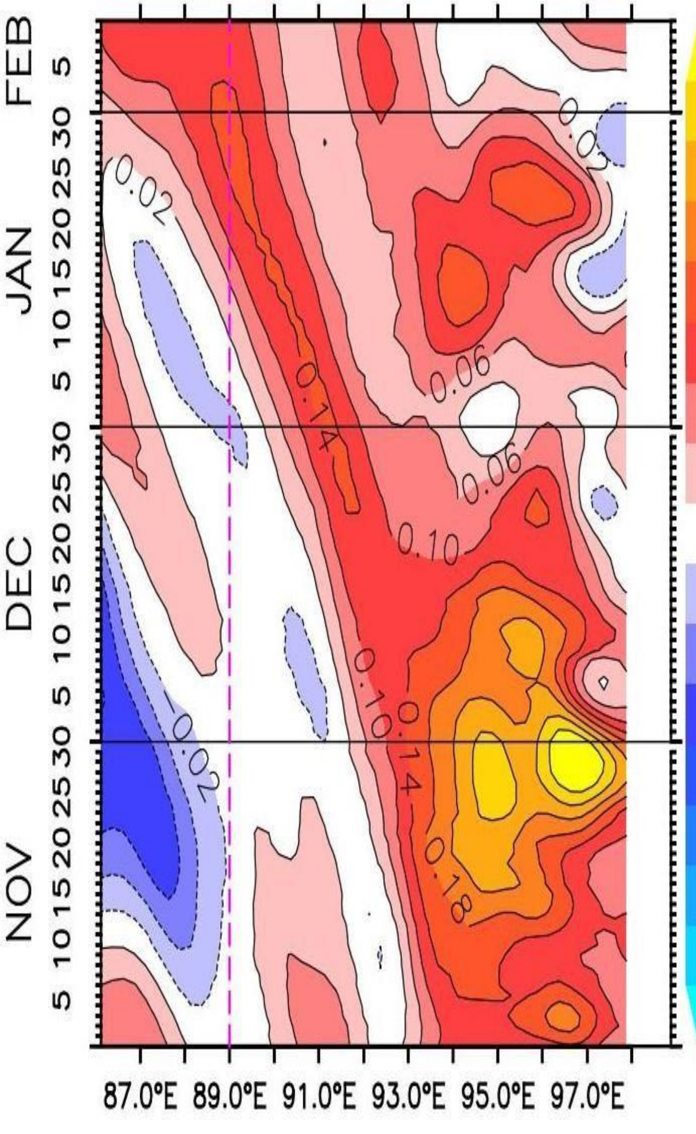
HYCOM V-velocity along 15˚N

U-velocity along 90˚E

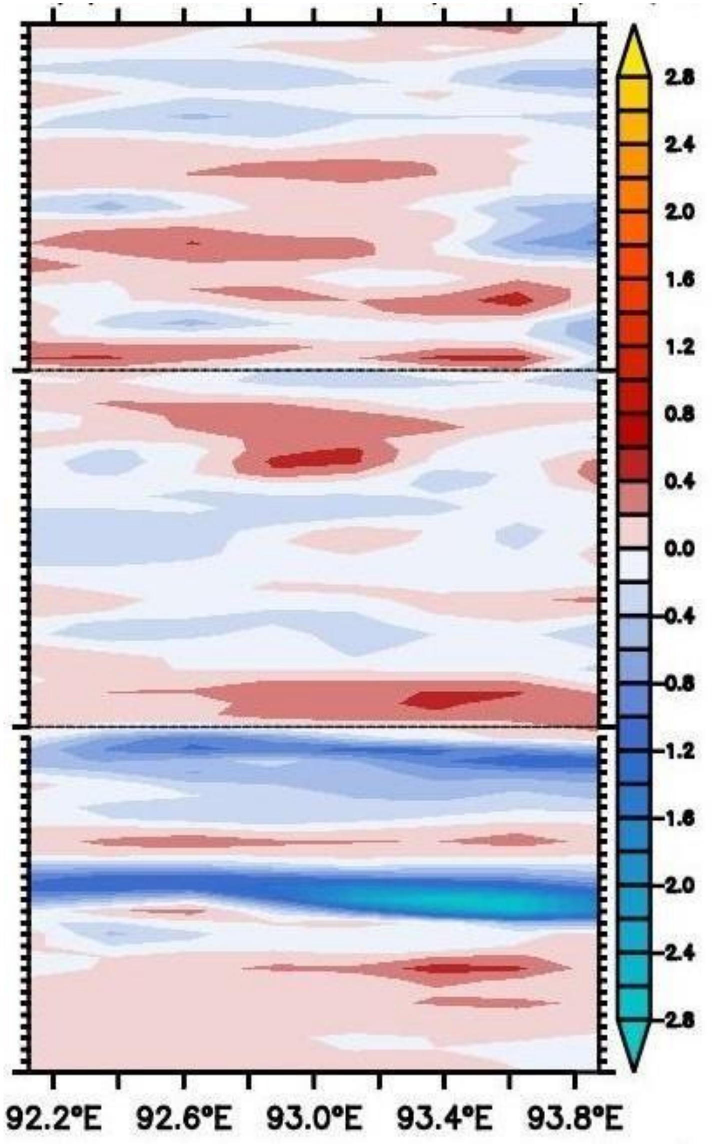
Unit: m/s

Subsurface velocity structure (Longitude-depth section in the right and Latitude-depth section in the left) in the peak summer TC bugle from HYCOM simulation. It shows similarity with a subsurface type ITE (Shi et al., 2018)

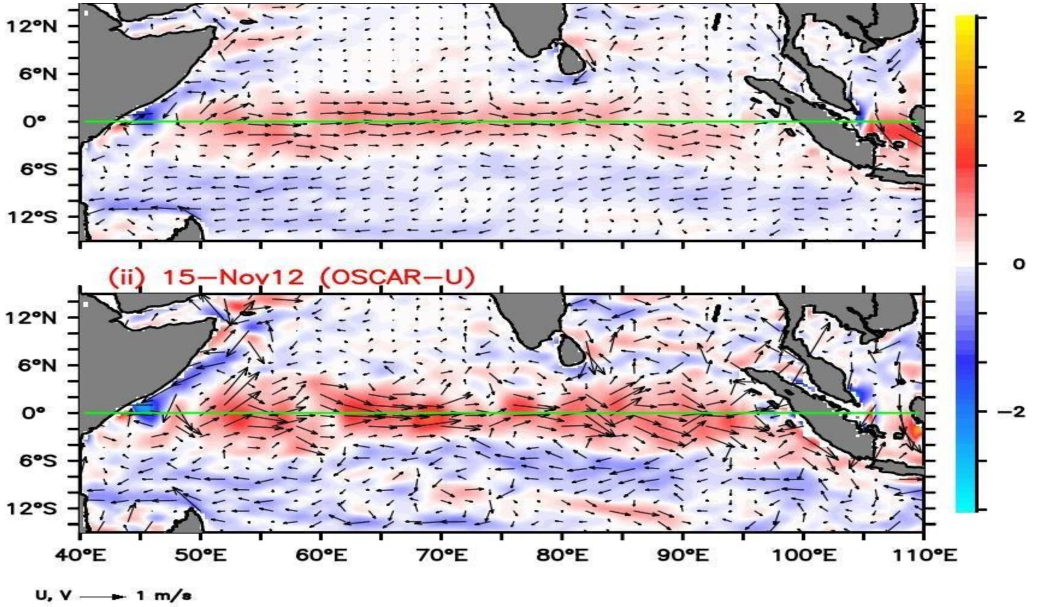
TC bulge event in winter (Nov12 to Feb13) has the similar mechanism



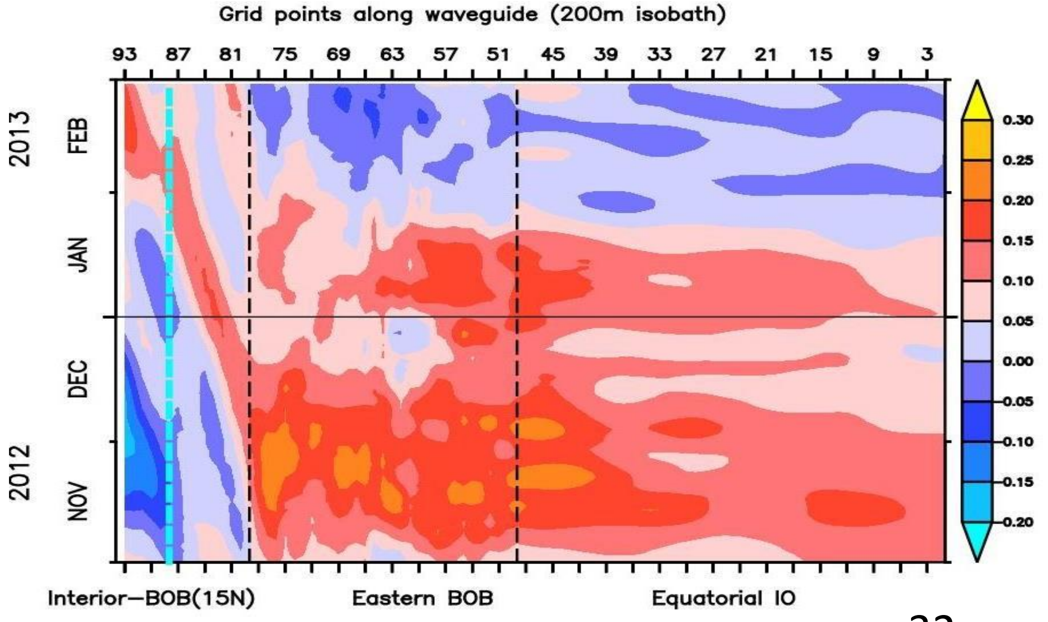
(a) SLA (Unit: m) along 15˚N



(b) Ekman Pumping velocity [10^(-5)x m/s]

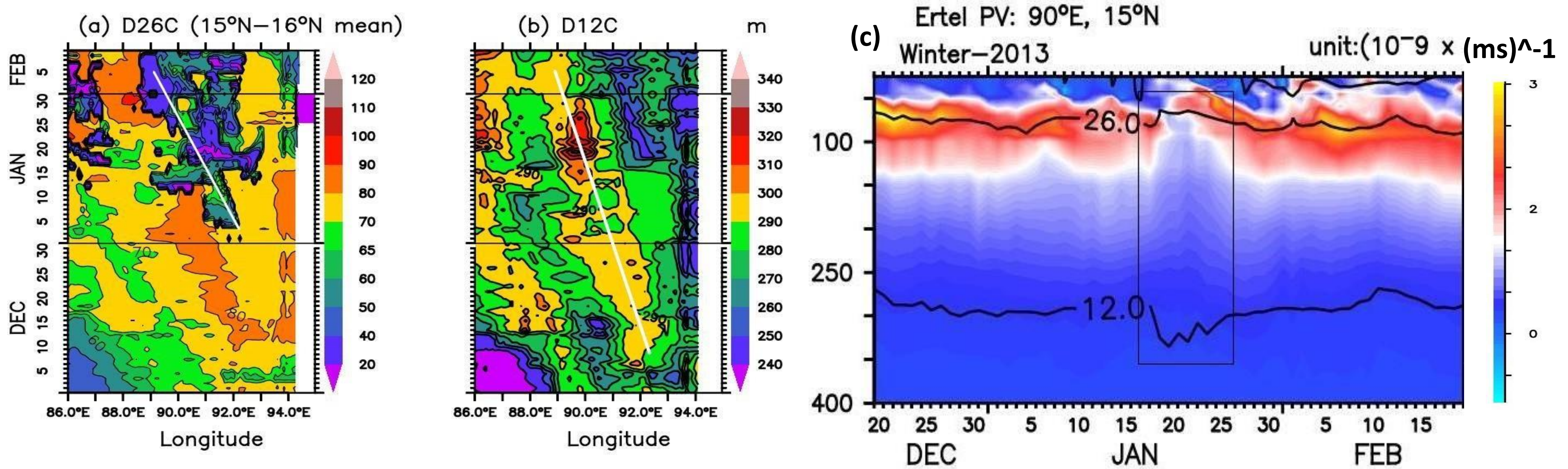


(c).i Wrytki jet Nov climatology (m/s)

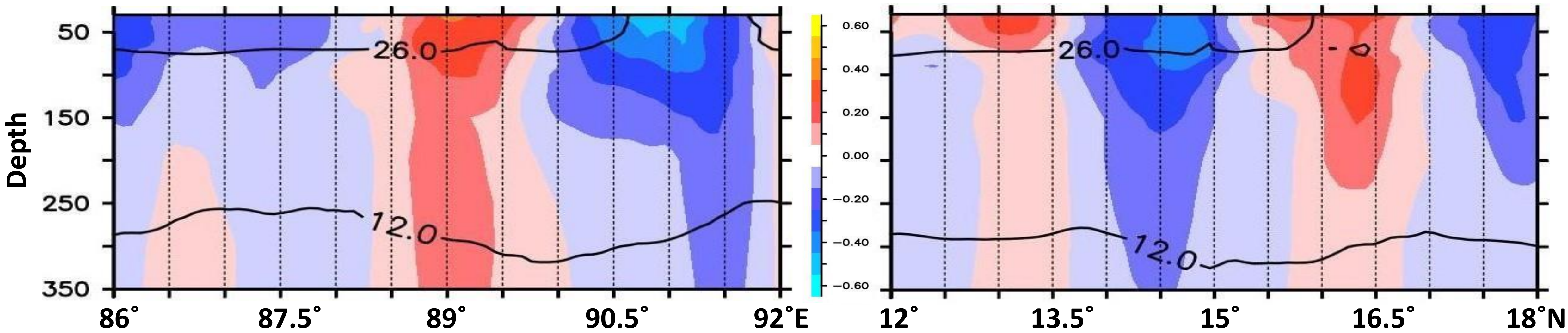


(d) Kelvin wave propagation from +ve SLA (m)

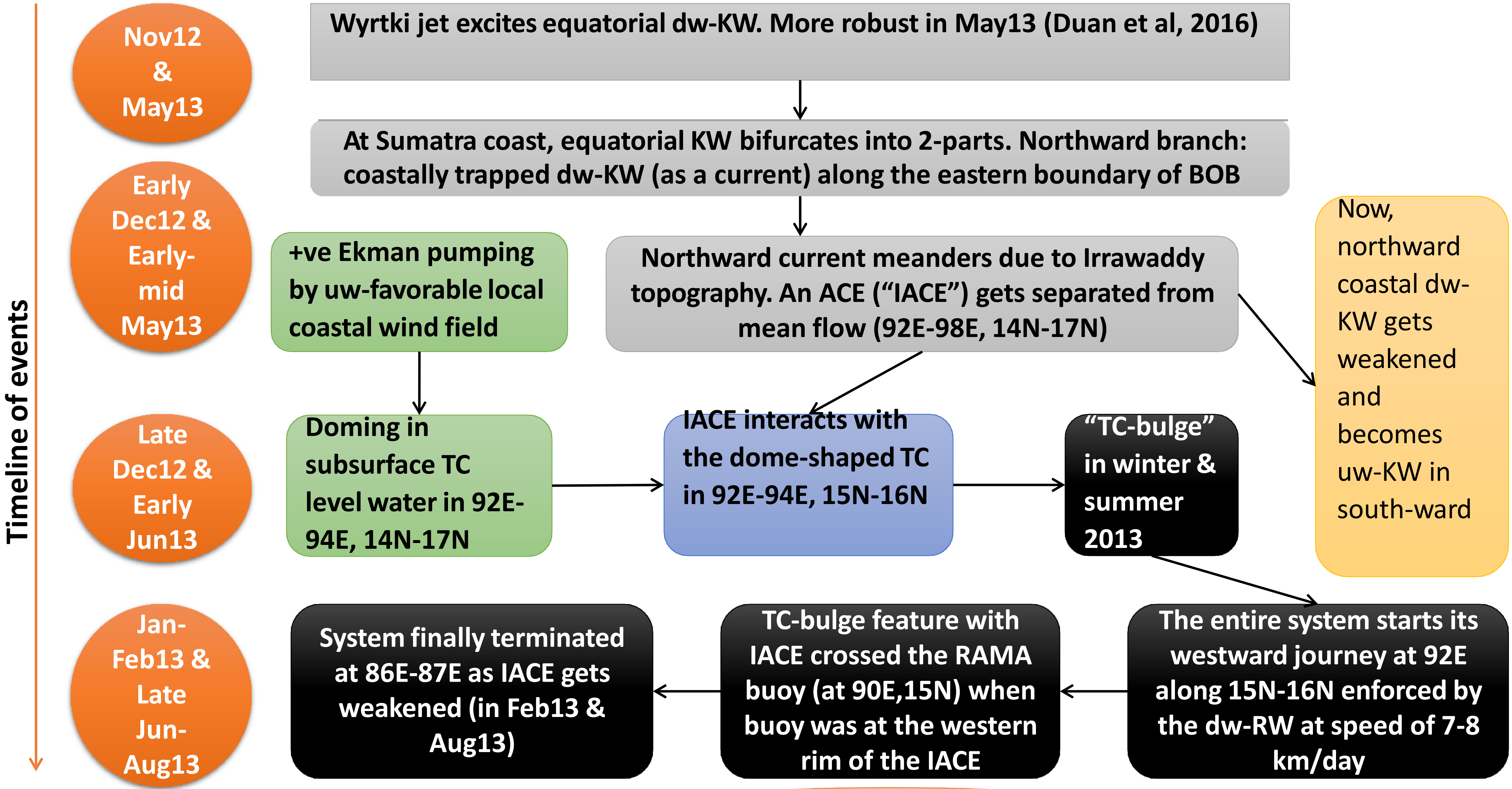
In the winter (Nov12 to Feb13), TC bulge is related to same genesis and propagation mechanism as in the summer 2013



(d) HYCOM V-velocity along 15˚N **unit: m/s** **(d) U-velocity along 90˚E on 19-Jan 2013**



In the winter also TC bulge embedded inside an ACE is related to the mode-water formation alike the summer case



Timeline of events

Nov12 & May13

Wyrtki jet excites equatorial dw-KW. More robust in May13 (Duan et al, 2016)

At Sumatra coast, equatorial KW bifurcates into 2-parts. Northward branch: coastally trapped dw-KW (as a current) along the eastern boundary of BOB

Early Dec12 & Early-mid May13

+ve Ekman pumping by uw-favorable local coastal wind field

Northward current meanders due to Irrawaddy topography. An ACE ("IACE") gets separated from mean flow (92E-98E, 14N-17N)

Now, northward coastal dw-KW gets weakened and becomes uw-KW in south-ward

Late Dec12 & Early Jun13

Doming in subsurface TC level water in 92E-94E, 14N-17N

IACE interacts with the dome-shaped TC in 92E-94E, 15N-16N

"TC-bulge" in winter & summer 2013

Jan-Feb13 & Late Jun-Aug13

The entire system starts its westward journey at 92E along 15N-16N enforced by the dw-RW at speed of 7-8 km/day

TC-bulge feature with IACE crossed the RAMA buoy (at 90E,15N) when buoy was at the western rim of the IACE

System finally terminated at 86E-87E as IACE gets weakened (in Feb13 & Aug13)

Flowchart of events that leads to TC bulge

Peak Bulge: 13 Jan & 2/7 Jul13