Shallow salinity stratification and air-Sea interaction in the Bay of Bengal

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ICTP June 2016

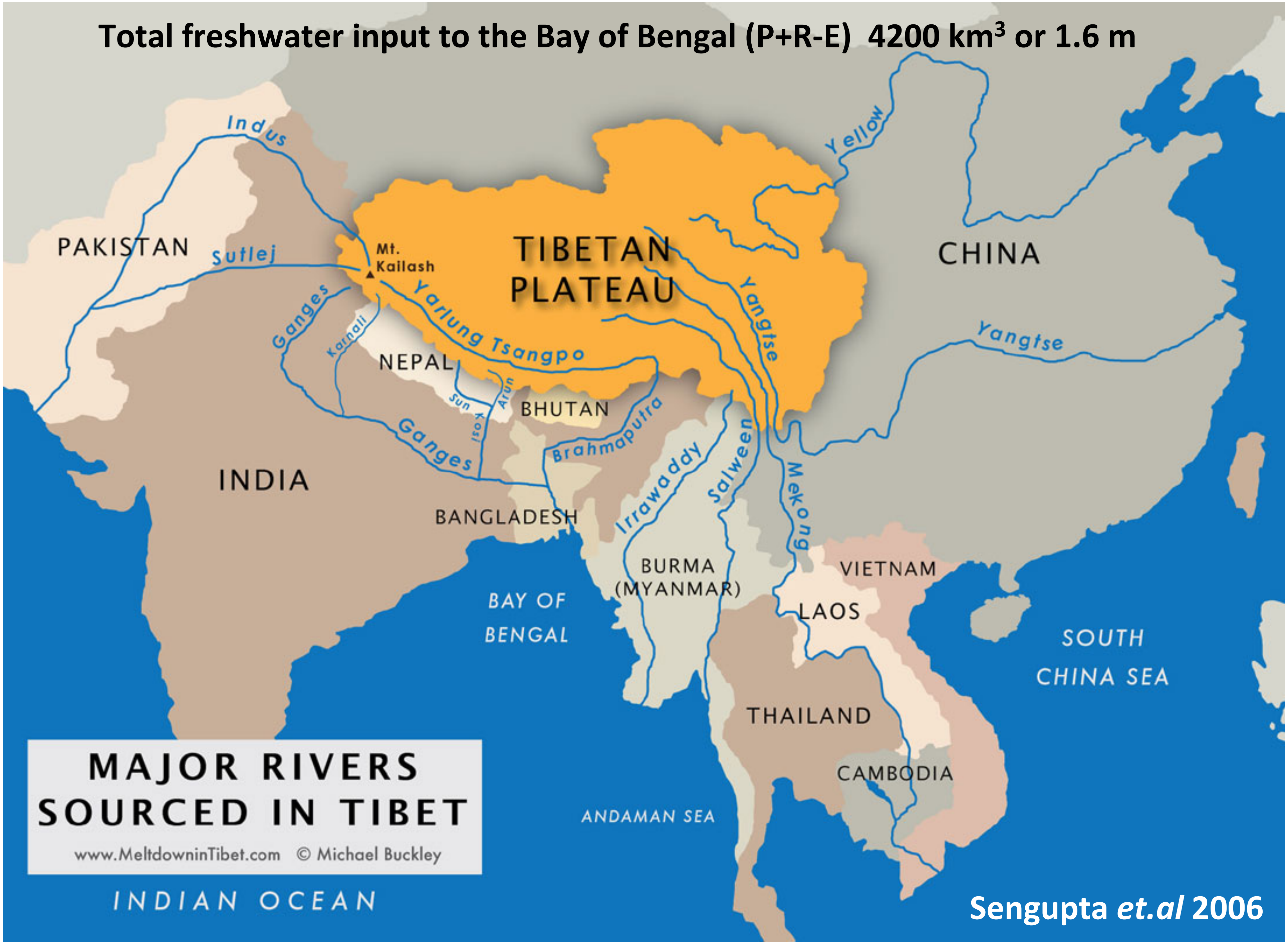
ASIRI

Dipanjan Chaudhuri Sree Lekha

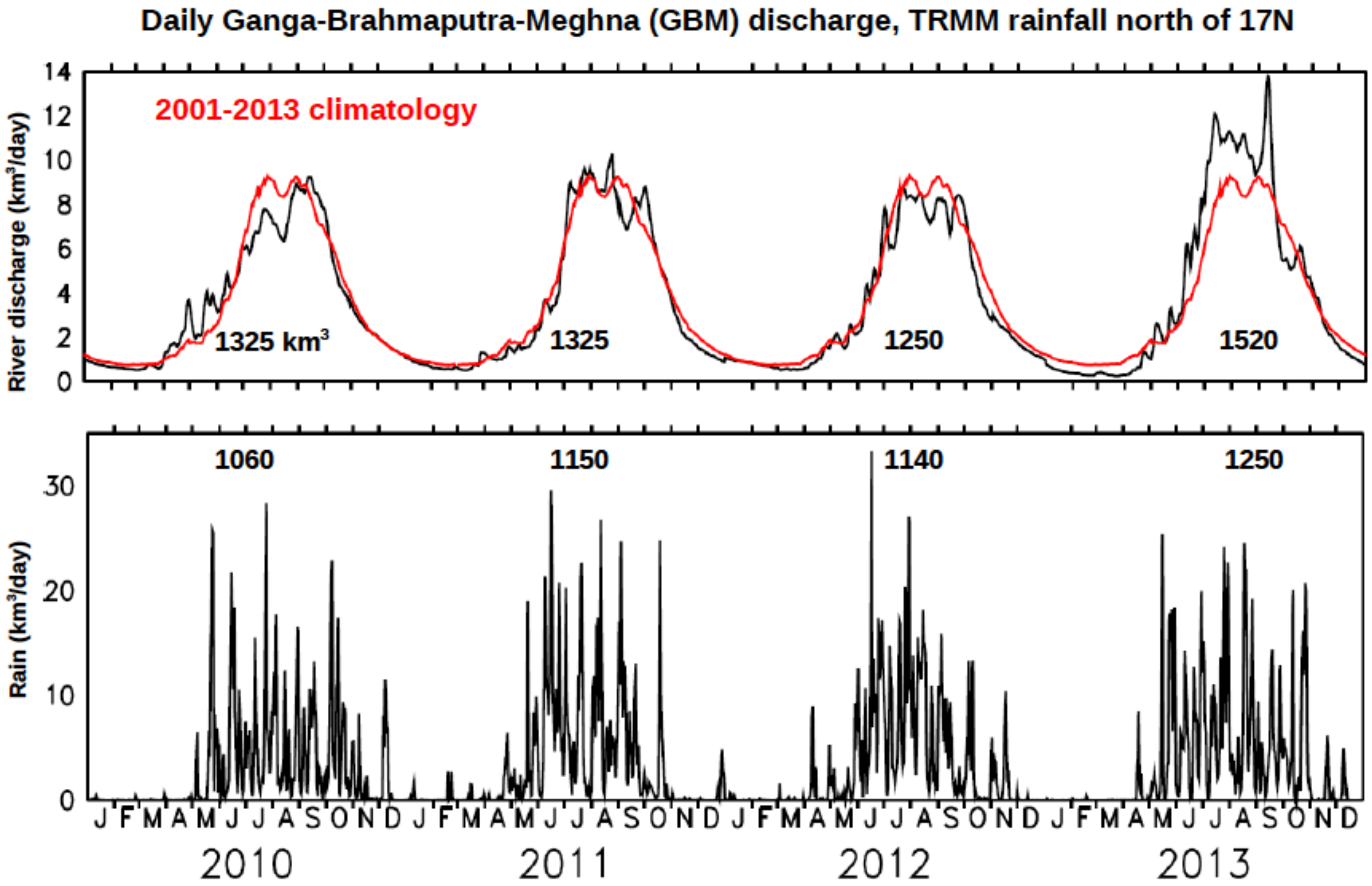
" …. truth flourishes where the student's light has shone,
And there alone."

W. B. Yeats

Total freshwater input to the Bay of Bengal (P+R-E) 4200 km^3 or 1.6 m



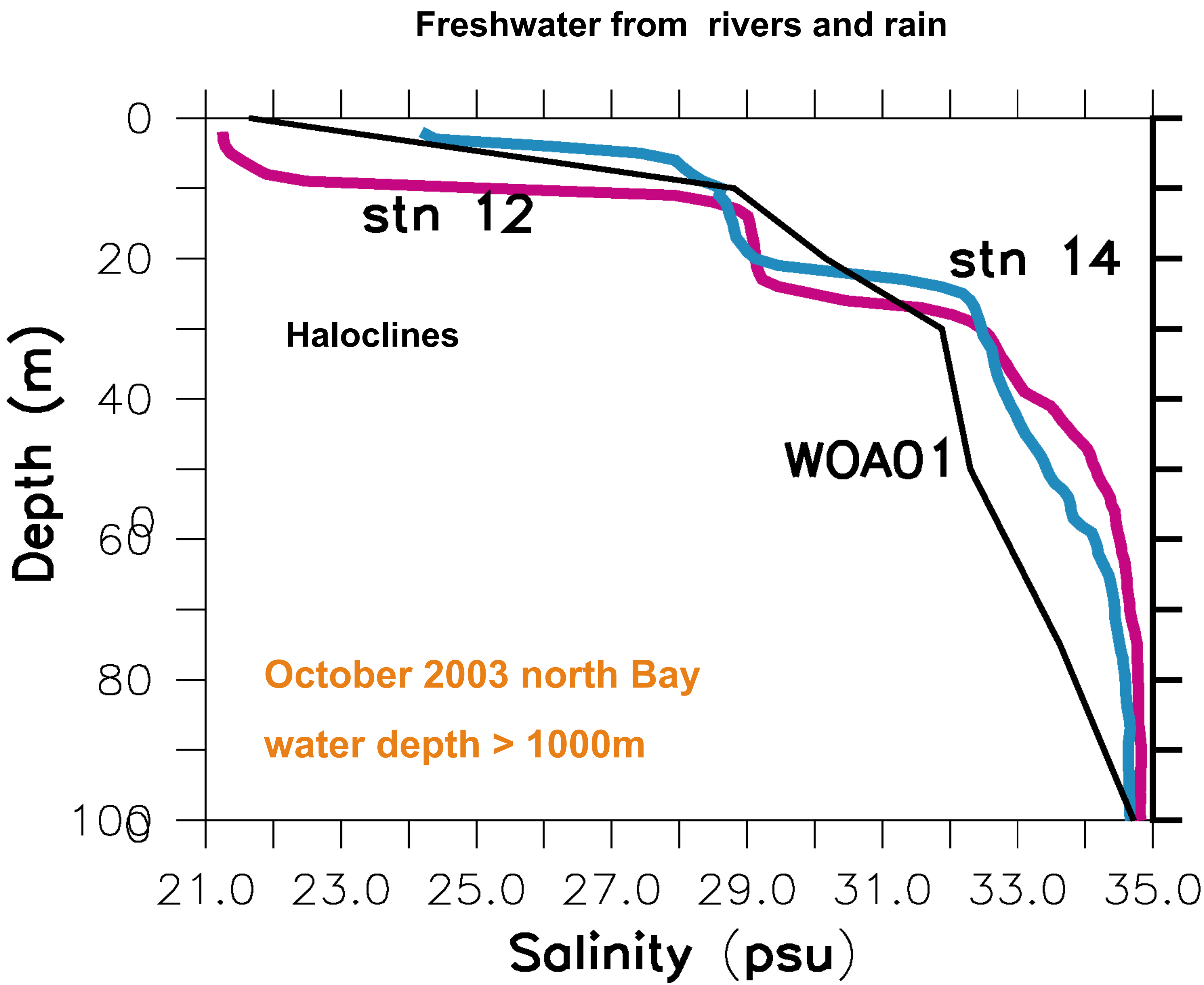
Sengupta *et.al* 2006



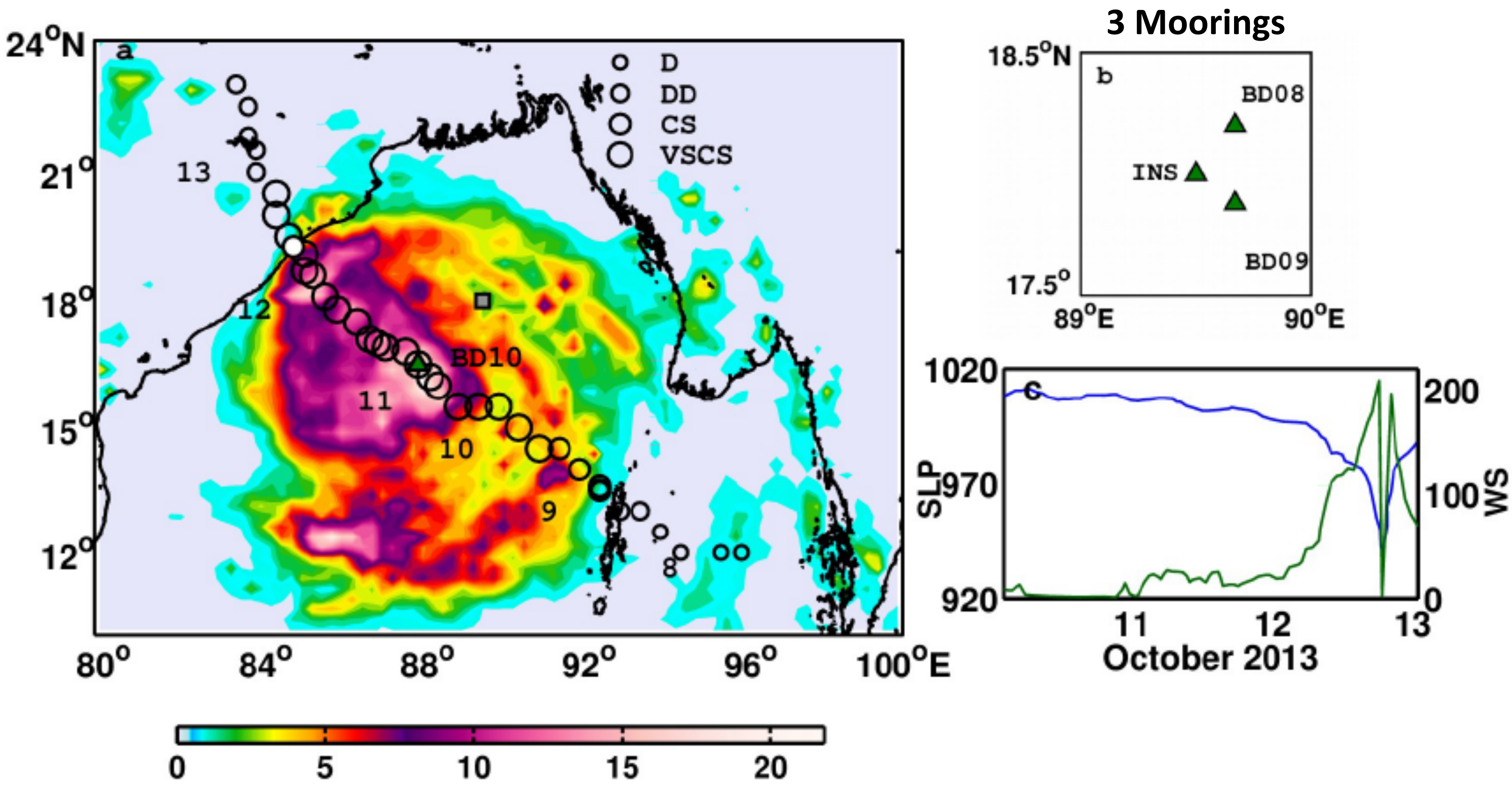
Discharge data courtesy: S. Bala, Fabrice Papa

Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka Papa 2012

Nearly 70 % of fresh water input in June-September

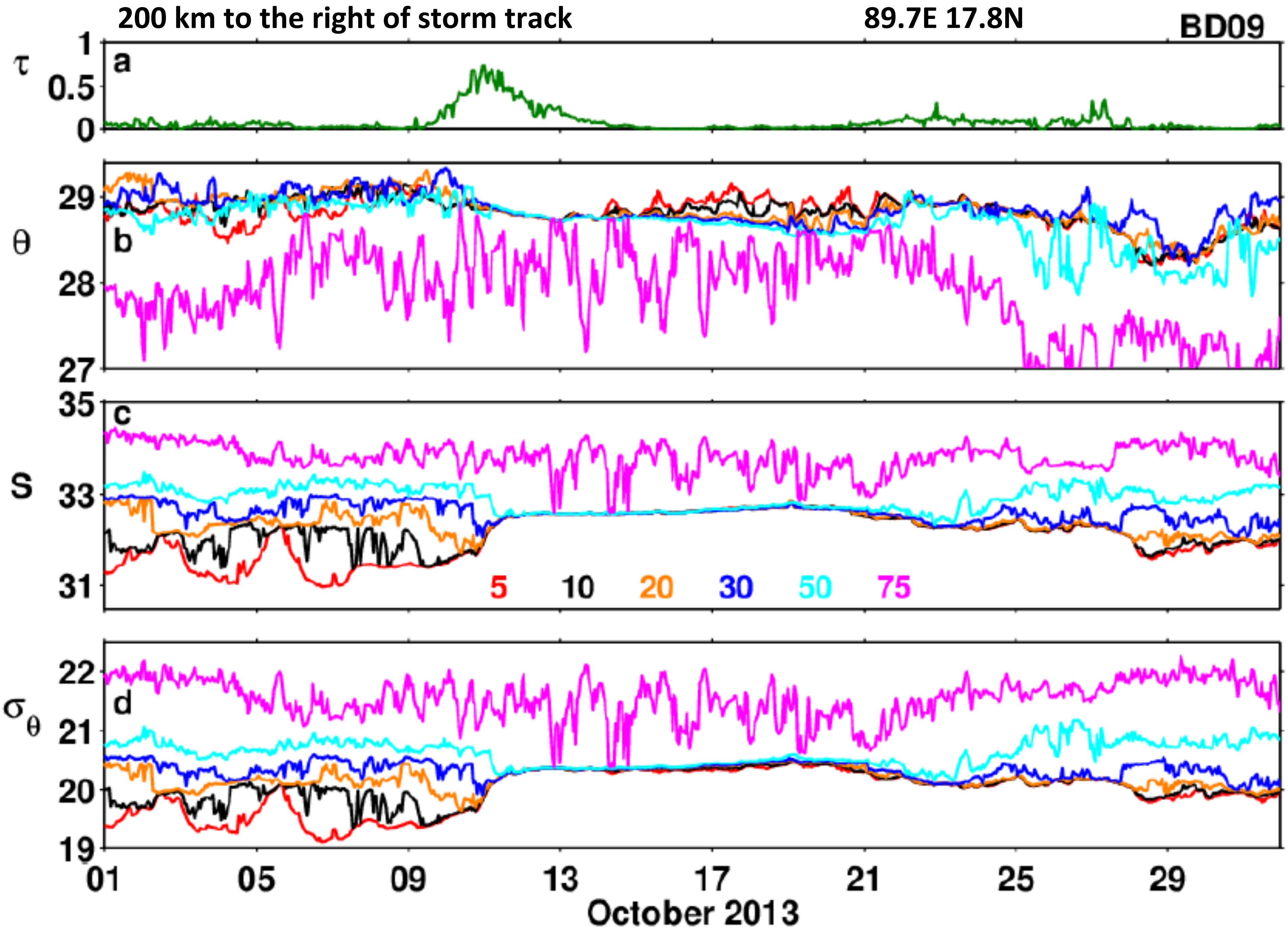

Freshwater from rivers and rain
stn 12
stn 14
Haloclines
WOA01
October 2003 north Bay
water depth > 1000m
0
20
40
60
80
100
21.0
23.0
25.0
27.0
29.0
31.0
33.0
35.0
Depth (m)
Salinity (psu)

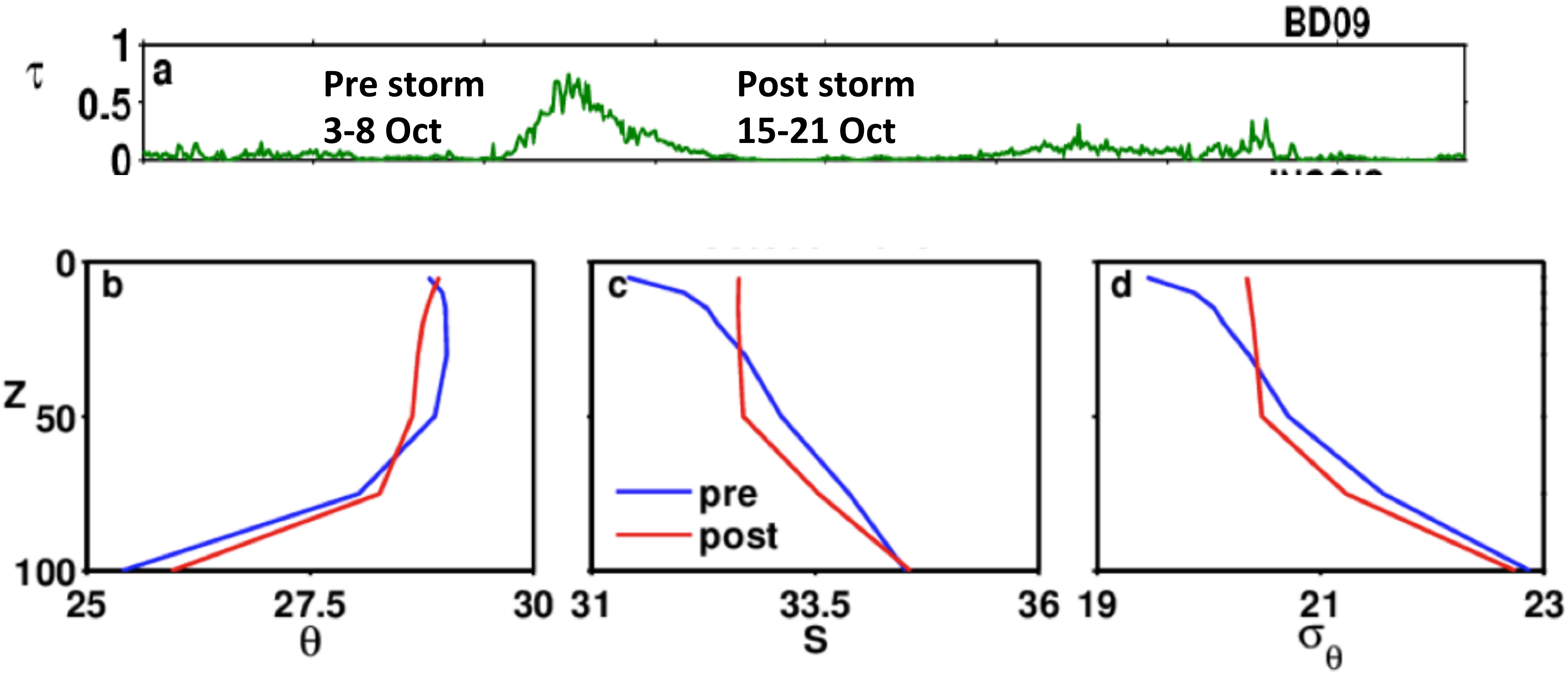
Tropical cyclone Phailin 8-13 October 2013



940 hPa, 215 km per hour sustained wind speed Gopalpur, Odisha

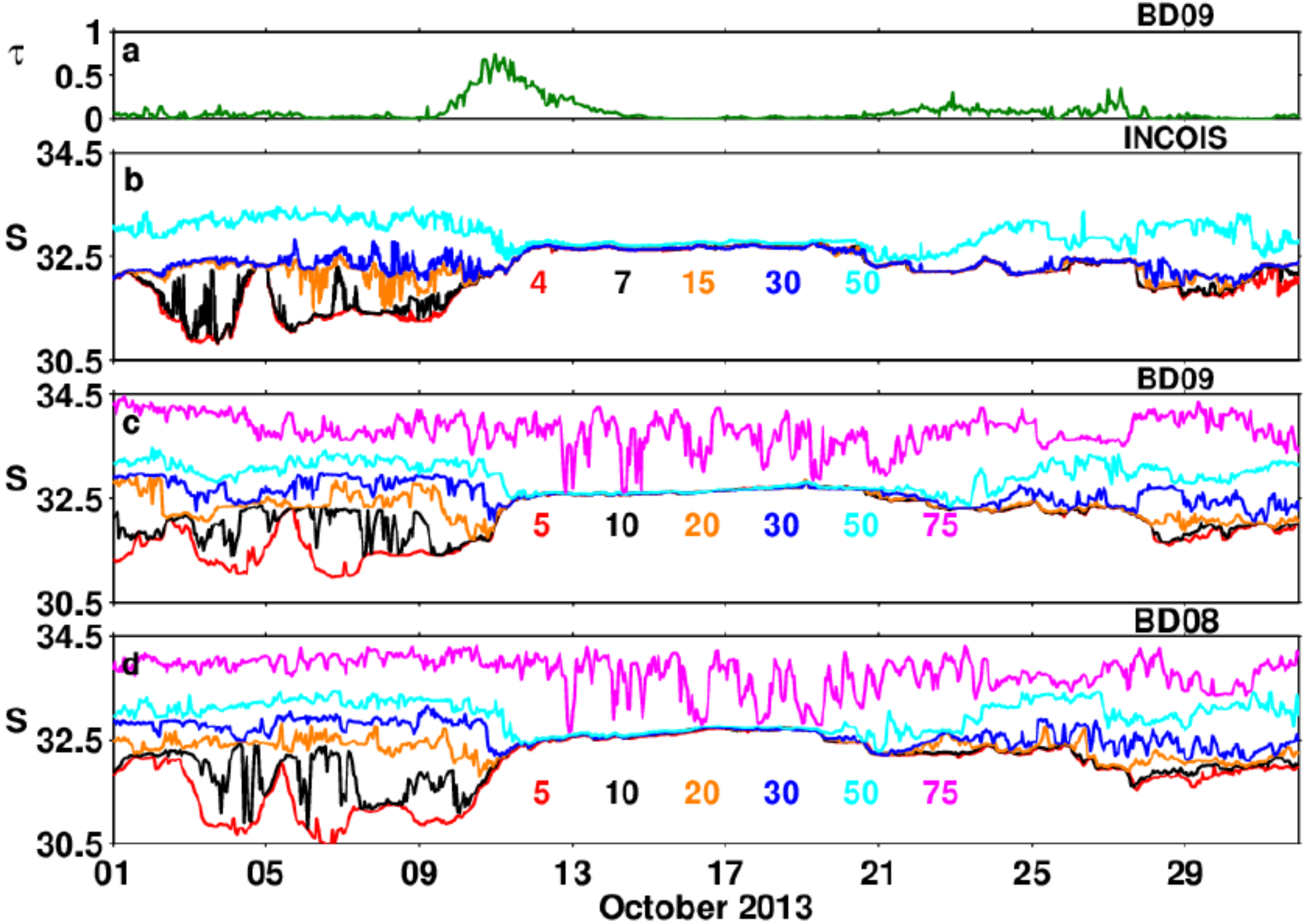
India Met Department Report 2013


200 km to the right of storm track
89.7E 17.8N
BD09
τ
a
1
0.5
0
θ
b
29
28
27
S
c
35
33
31
5
10
20
30
50
75
σθ
d
22
21
20
19
01
05
09
13
17
21
25
29
October 2013

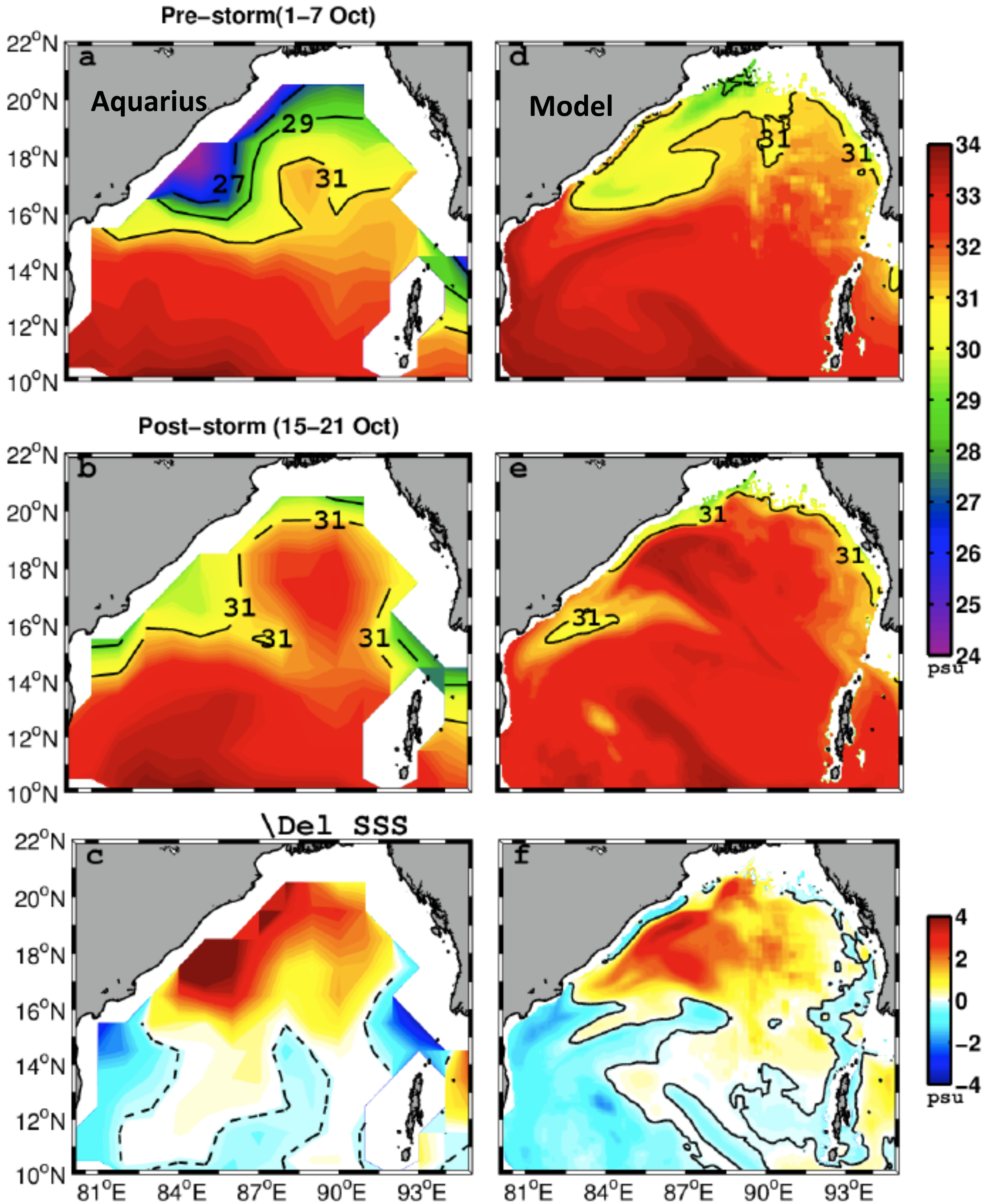


Thin, fresh surface layer above deep warm layer

Storm-induced vertical mixing: SST increases slightly SSS increases 1.6 psu

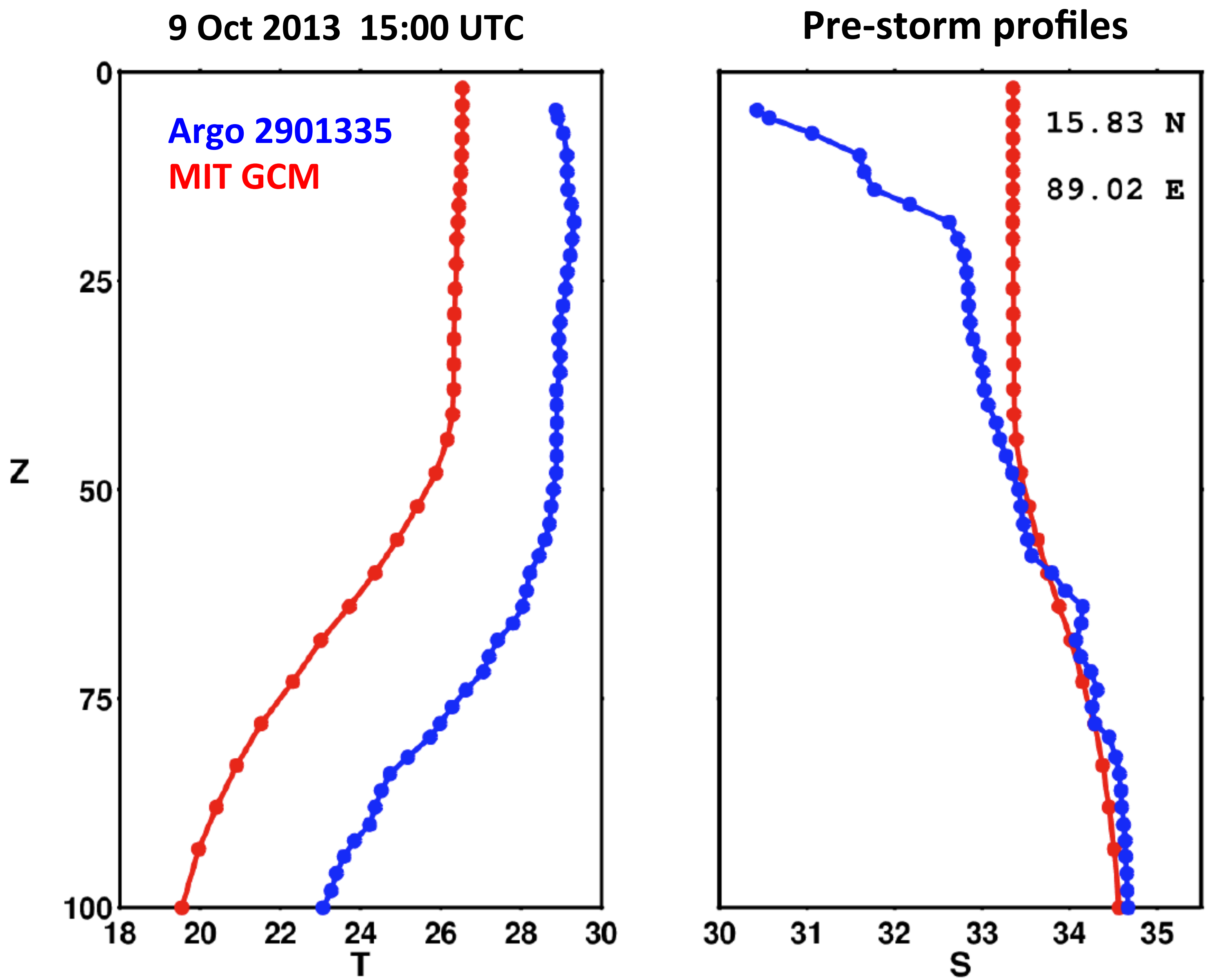


Sengupta 2008 *Singh 2012* *Balaguru 2012*



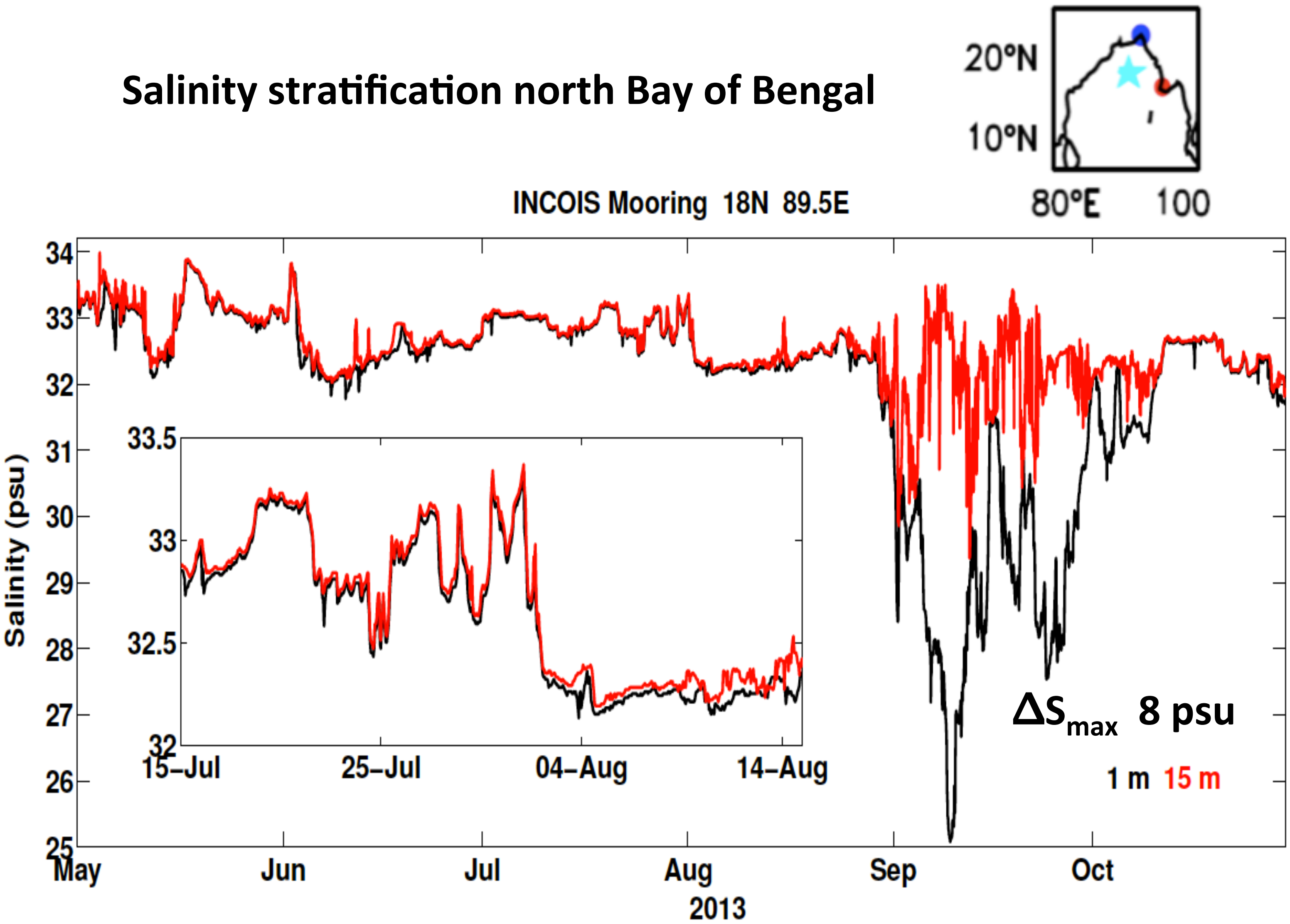
Aquarius satellite: SSS rises 1.6 psu at mooring location

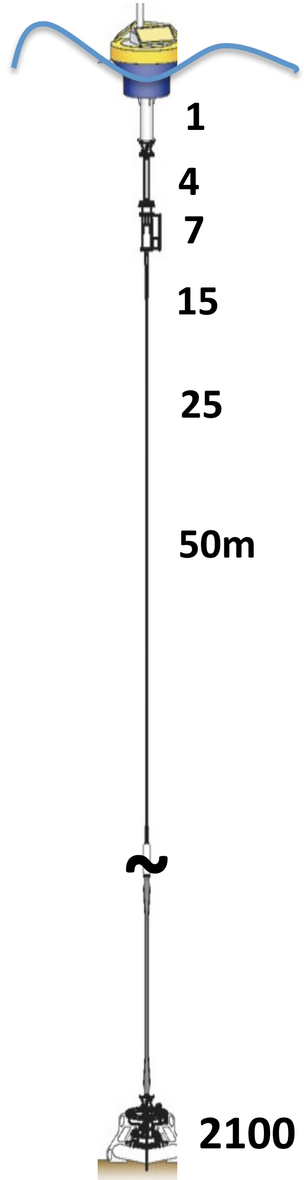
MIT GCM 5 km, 2 m res.
Courtesy: *Suneet Dwivedi*
U. Allahabad



Near-surface salinity stratification is too weak, and upper mixed layer is too deep in most ocean models

Salinity stratification north Bay of Bengal

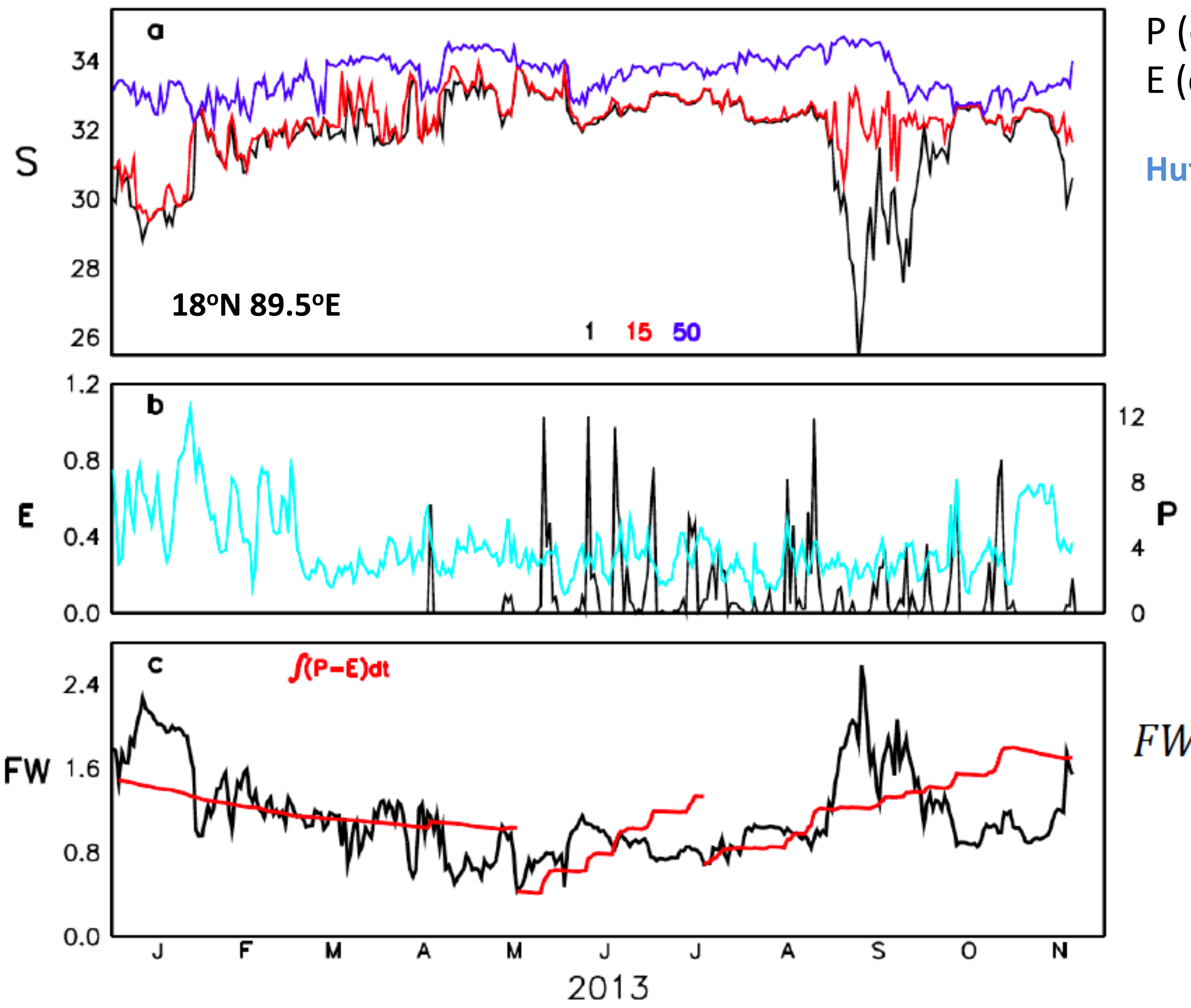




Hourly 1 m and 15 m salinity INCOIS Mooring north Bay of Bengal

What sustains shallow stratification in the face of mixing?

Fresh water balance in the upper 15 m from mooring



P (cm/day) TRMM
E (cm/day) TropFlux

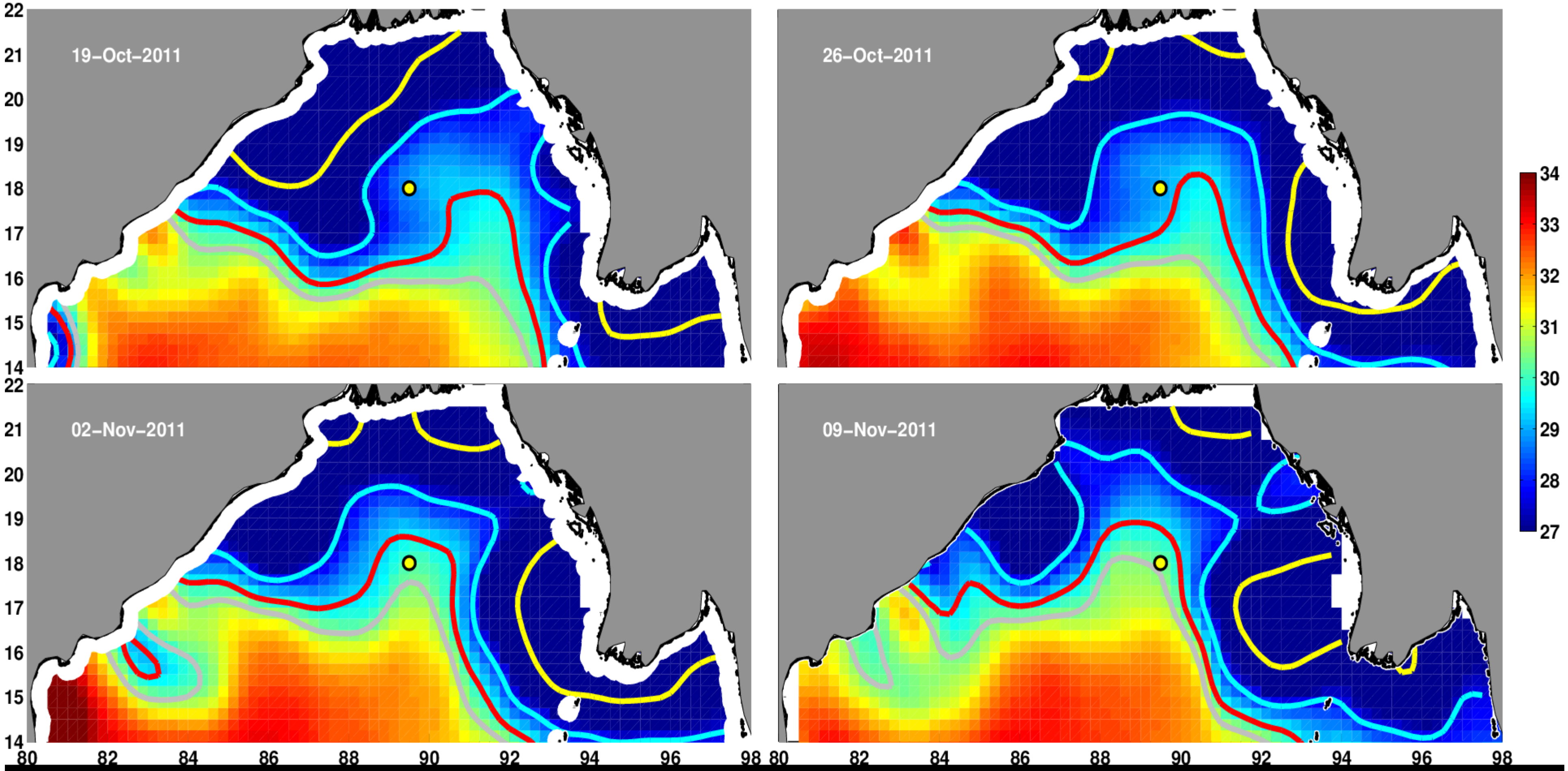
Huffman 2007 Kumar 2012

$$FW = \int_{-15}^{0} \left[1 - \frac{S(z)}{S_{ref}}\right] dz$$

Pulses of river water at the mooring in summer and winter
Persistence of river water for three seasons

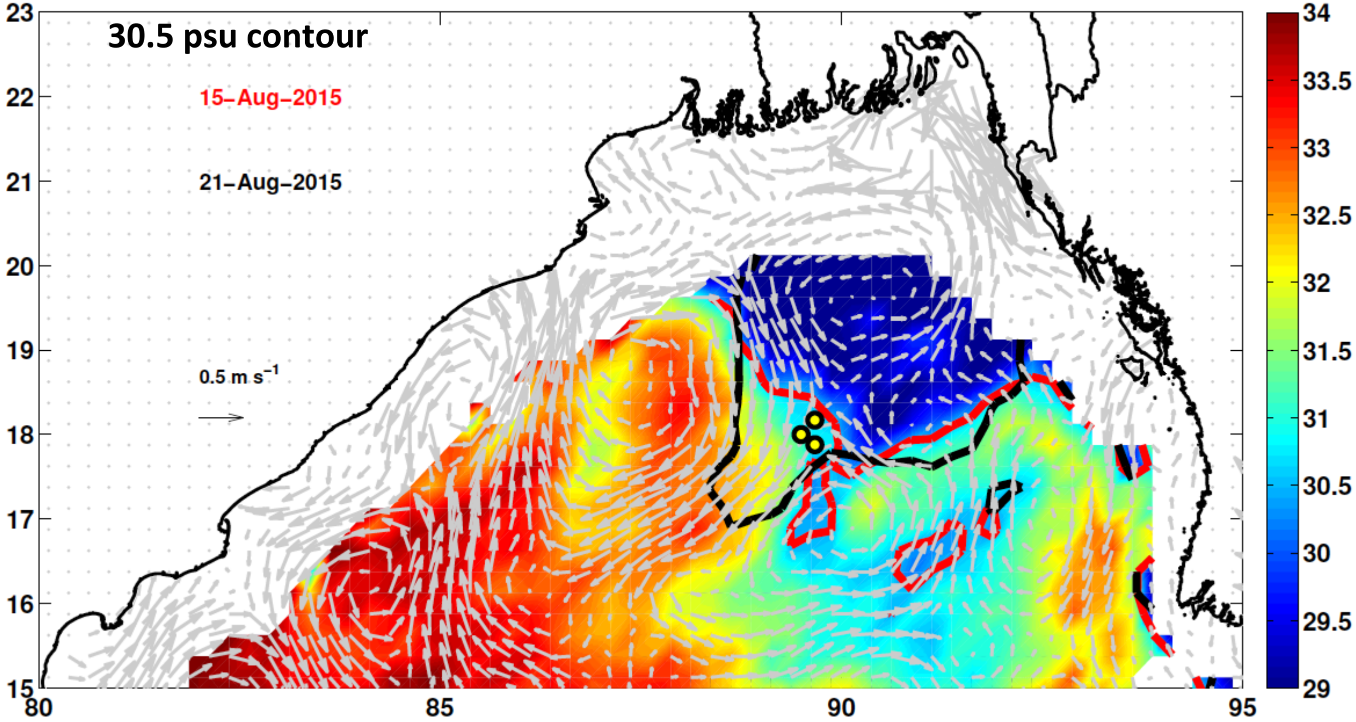
Sengupta et al., 2016

Aquarius sea surface salinity



30.3 29.3 27.5 24.5 psu contours

Irrawady water from previous year's (2010) summer monsoon discharge



300-400 km Eddies

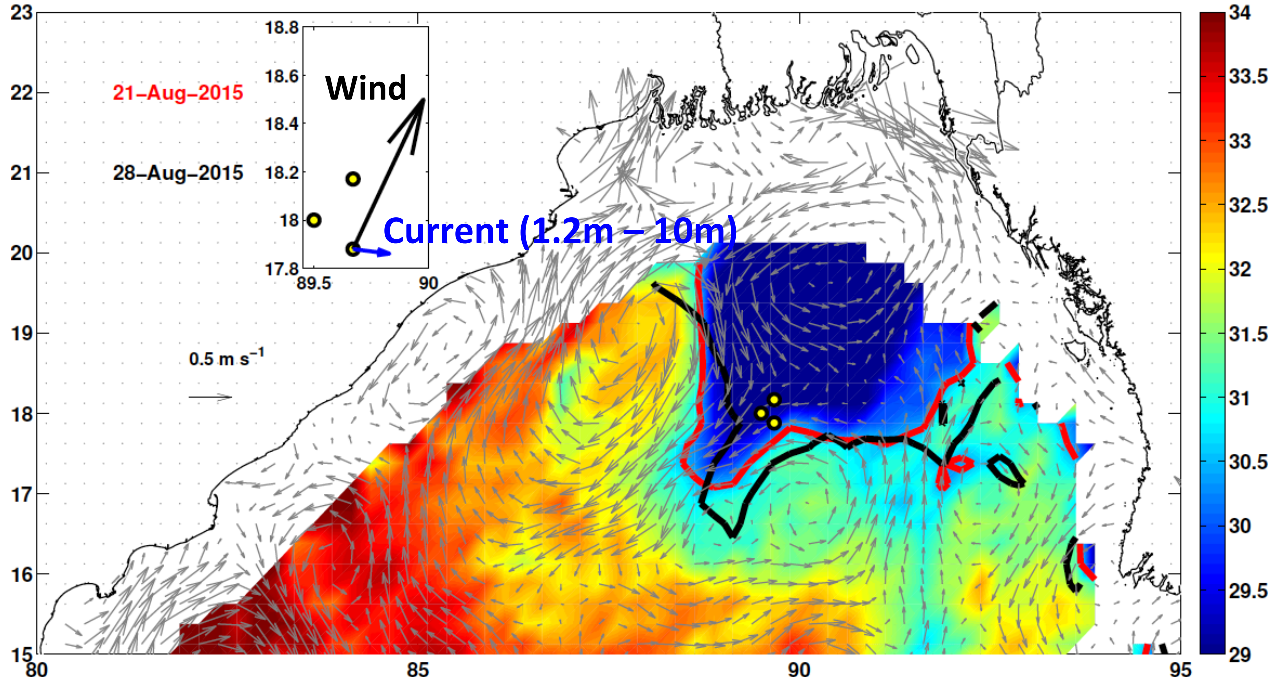
Wind stress 15 Aug 2015
0.07 N/m²

200 km/week due to anti-cyclonic eddy (0.35 m/s)

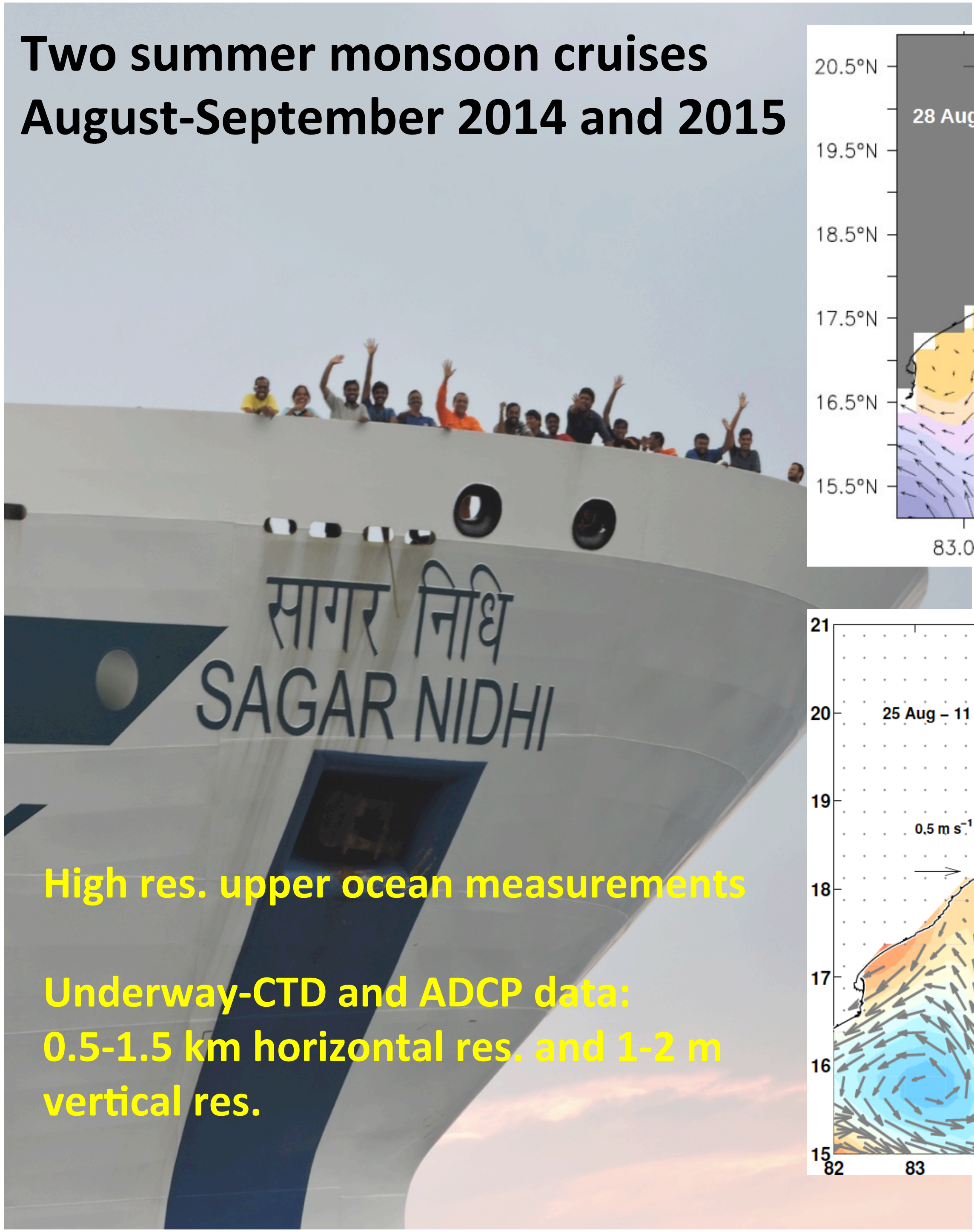
Wind stress 21 Aug 2015
0.14 N/m²

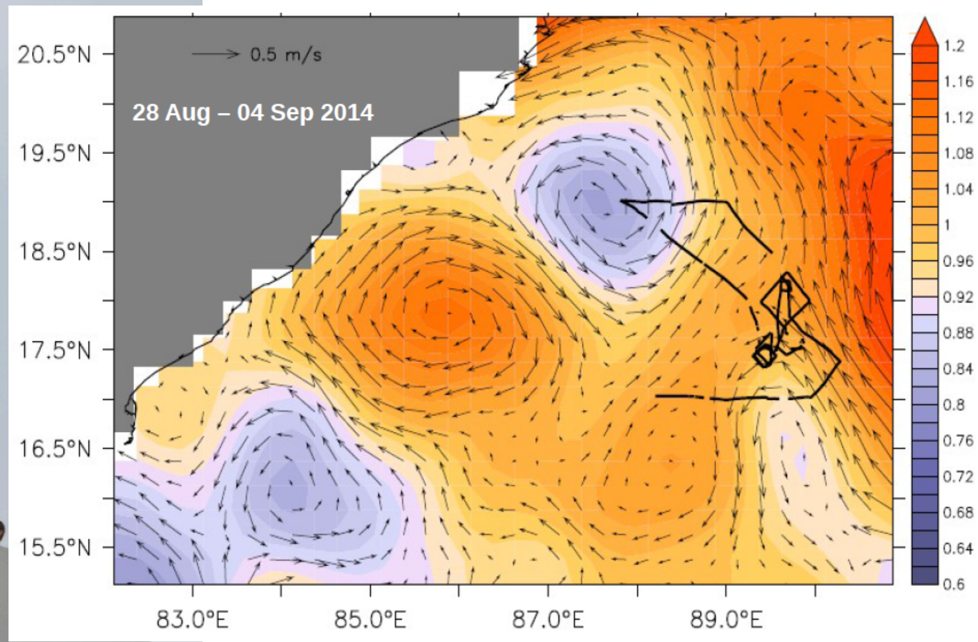
100 km/week shallow Ekman current (0.18 m/s)

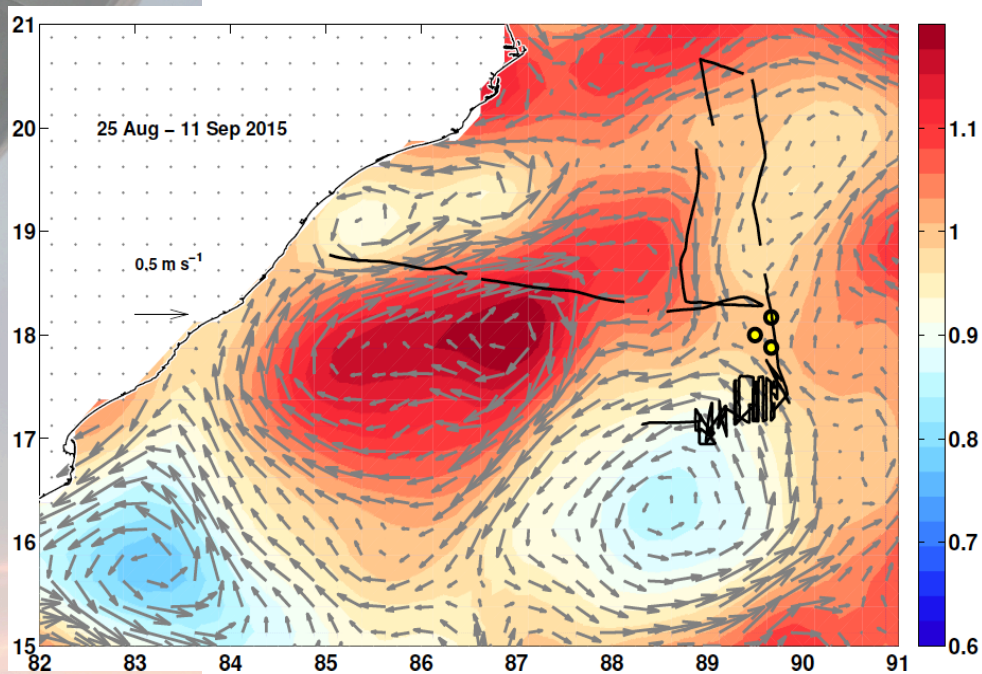
Shallow Ekman Flow



Two summer monsoon cruises August-September 2014 and 2015



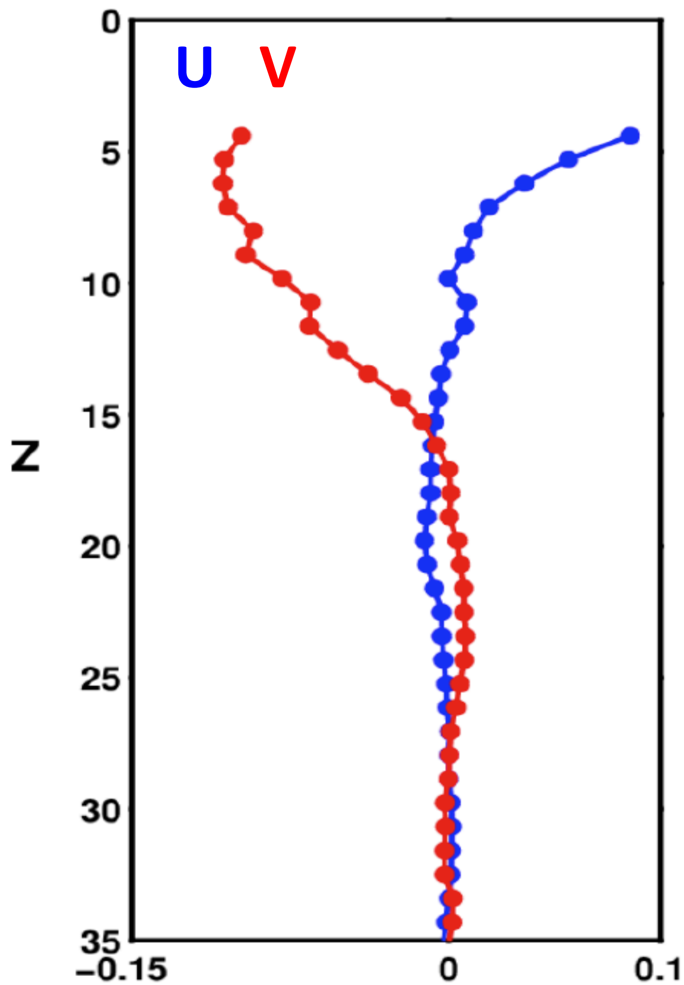




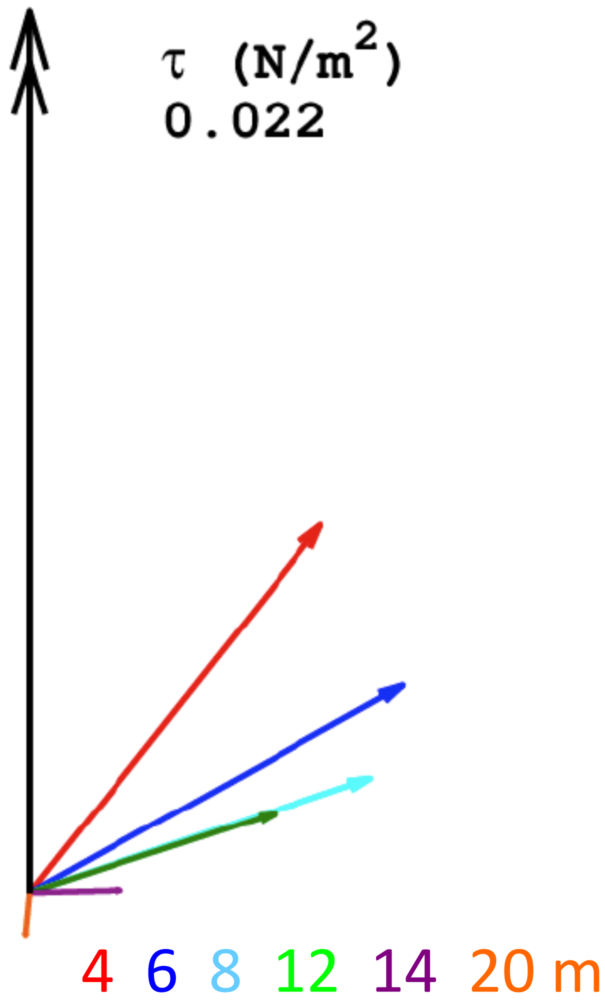
High res. upper ocean measurements

Underway-CTD and ADCP data: 0.5-1.5 km horizontal res. and 1-2 m vertical res.

Very shallow Ekman spiral

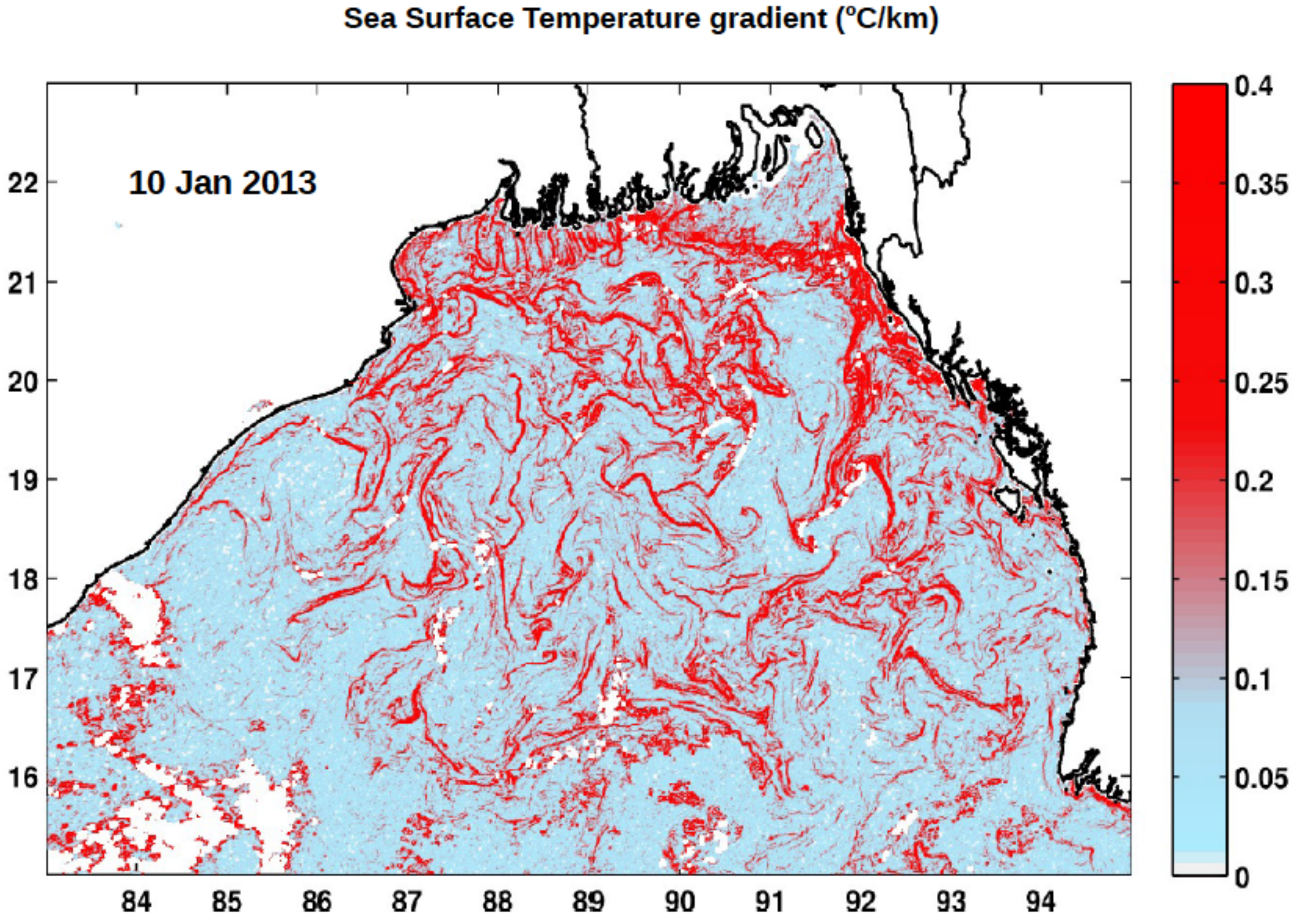


Mean U,V 500 kHz ADCP
Sagar Nidhi 3-11 Sep 2015



Ekman depth about 10m

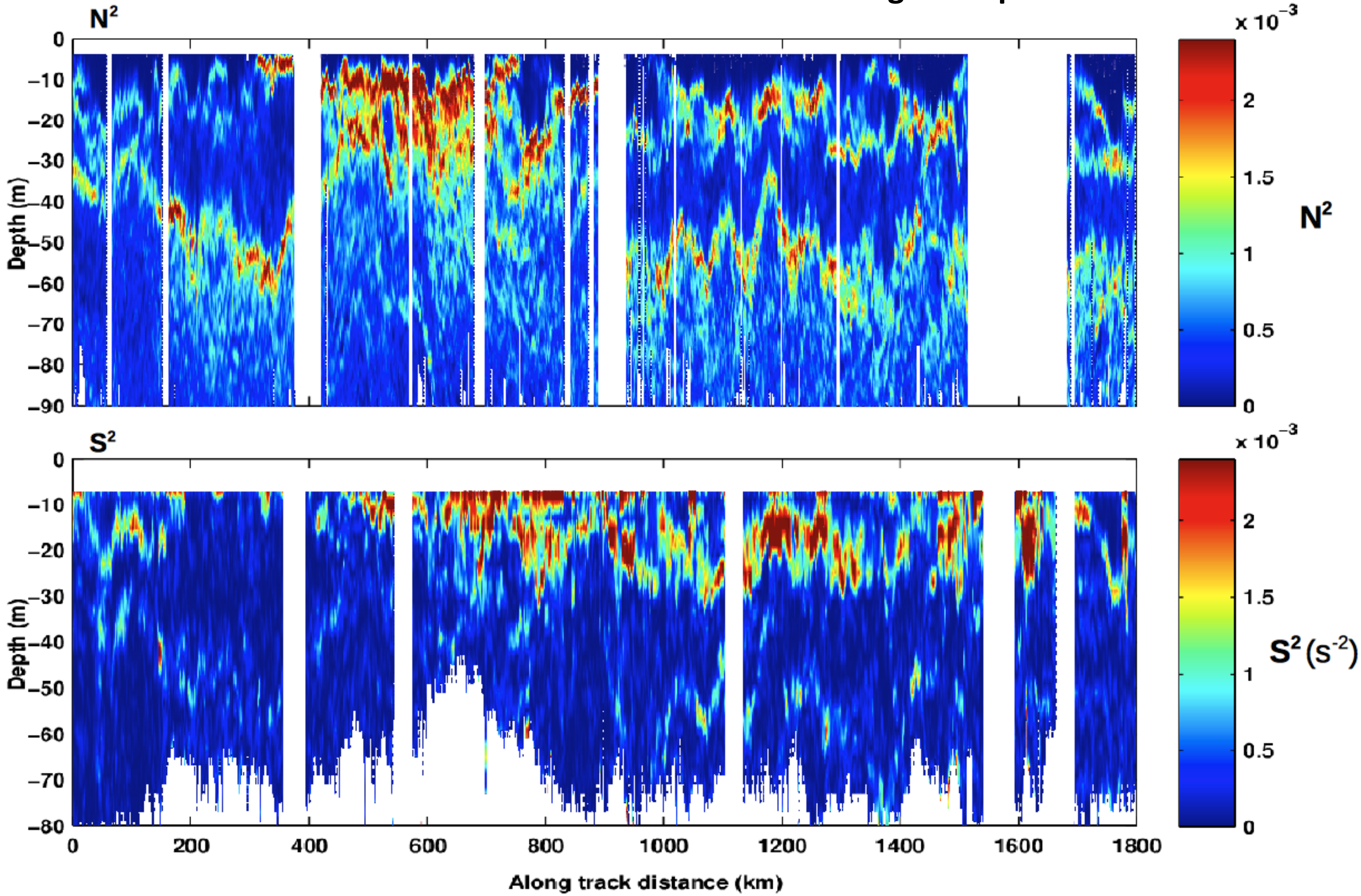
Many space scales



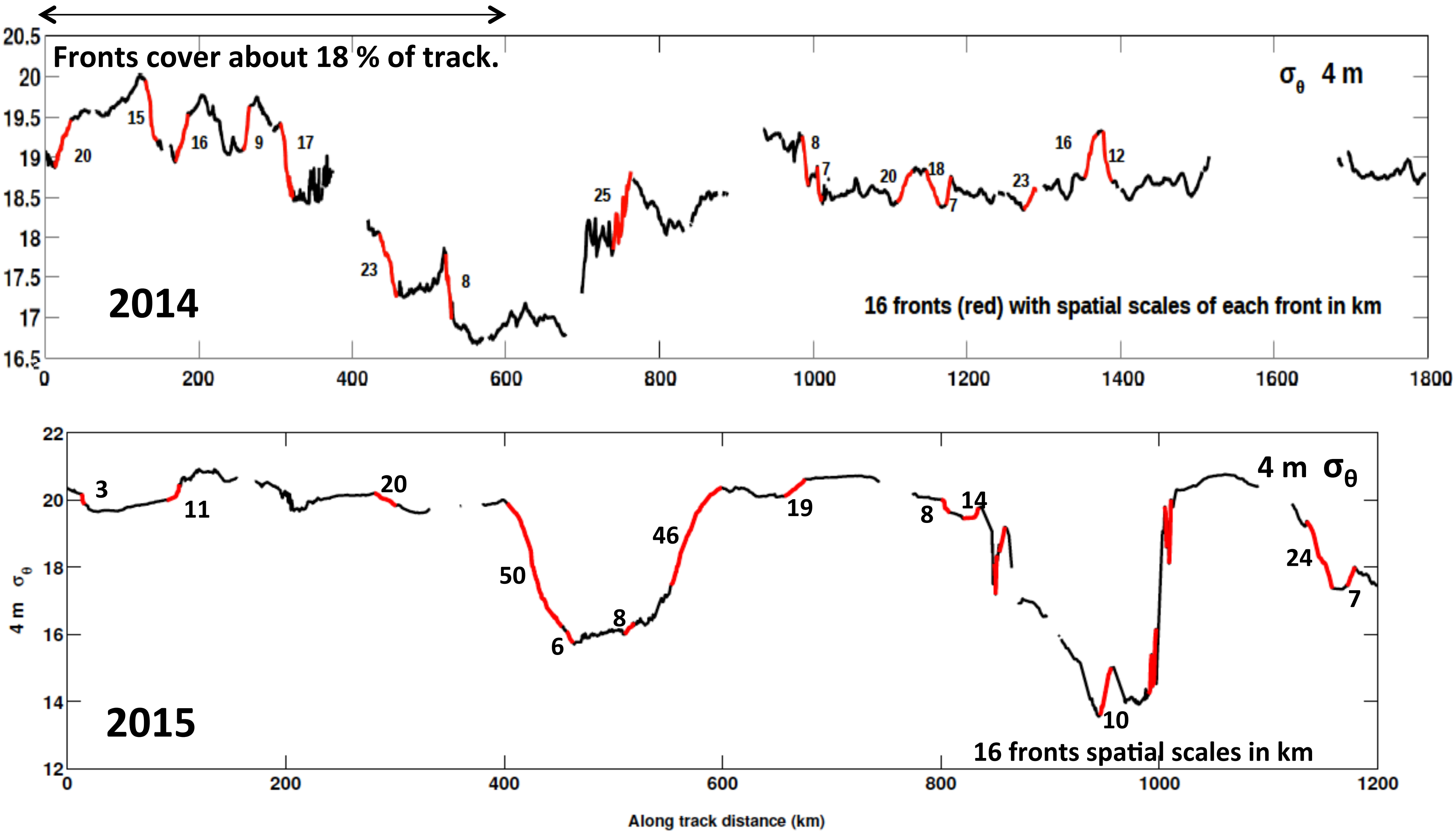
1.1 km resolution NOAA/AVHRR from INCOIS ground station

Courtesy: Venkat Seshu and Nimit

28 Aug – 4 Sep 2014

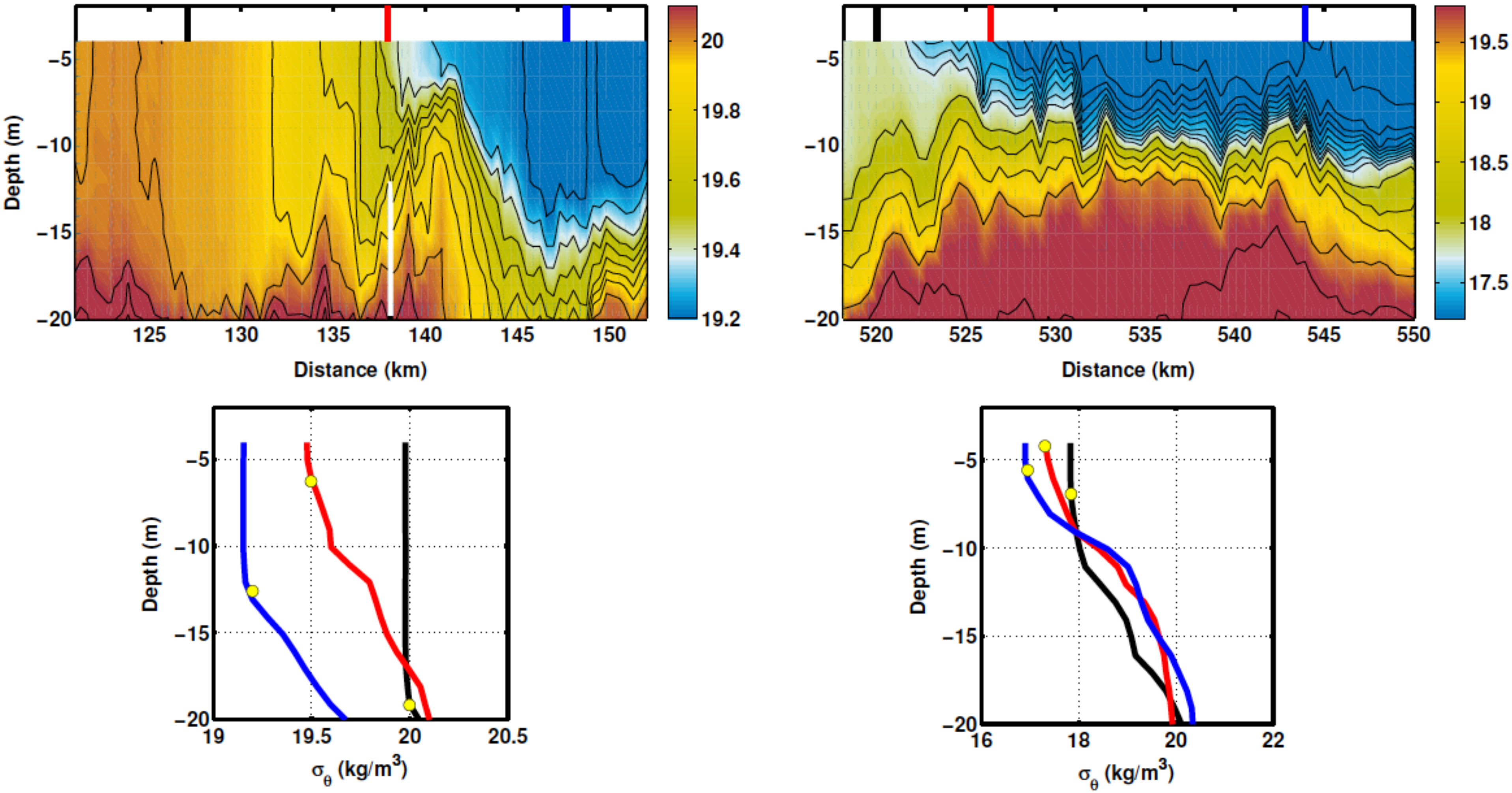


N^2 (top) and $S^2 = (du/dz)^2 + (dv/dz)^2$ from ADCP, with 6 m vertical smoothing and 1.4 km horizontal smoothing



More than 30 major fronts: Scales 3-50 km, sizes 0.3- 3 kg/m^3

> 10 km data gaps blank



Shallow mixed layers under sub-mesoscale fronts

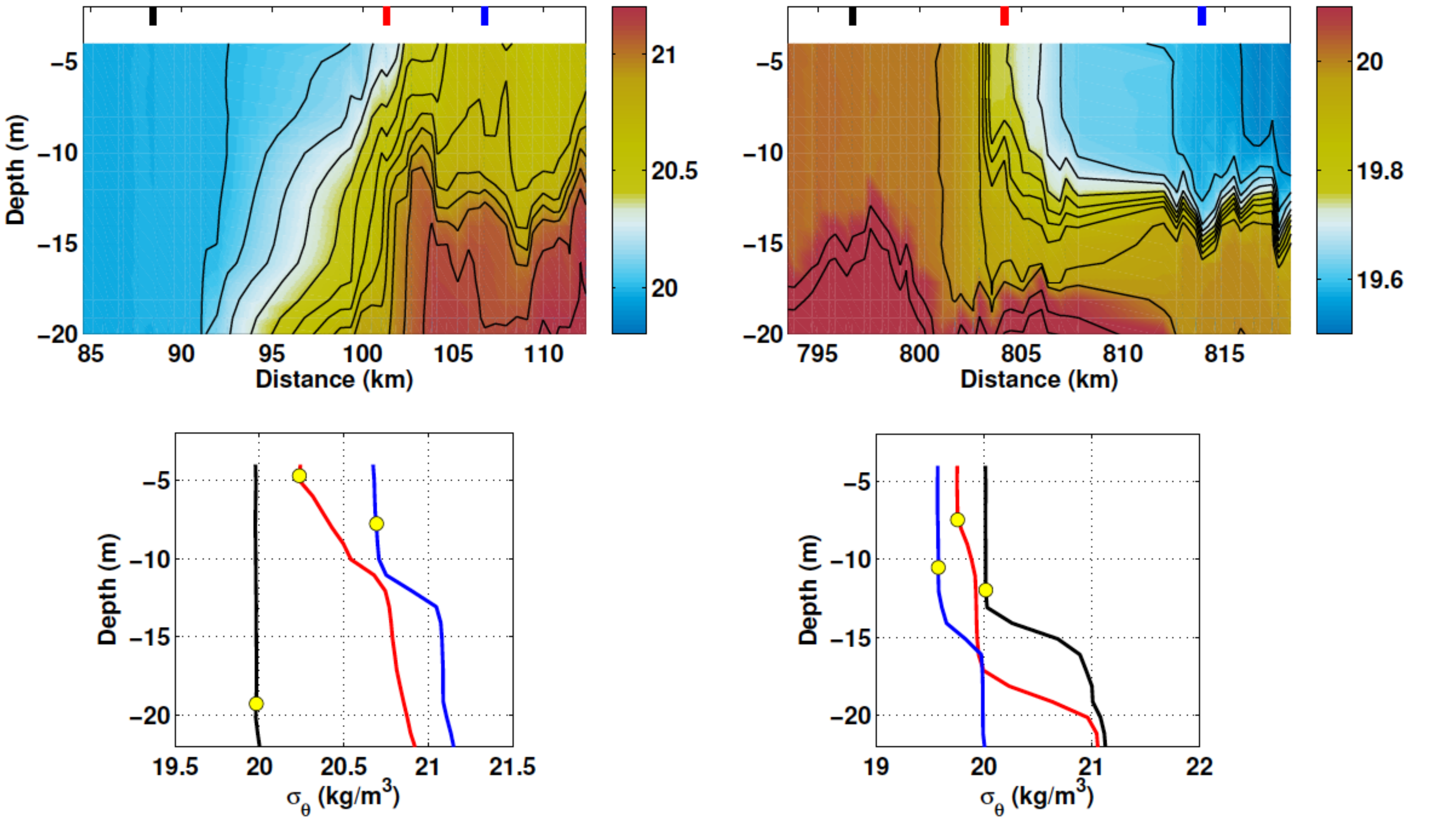
2014

Timmermans Winsor (2013) **120 m glider data Arctic**

Horizontal density gradient

0.46 kg/m³ in 11 km **0.38 kg/m³ in 7.5 km**

2015

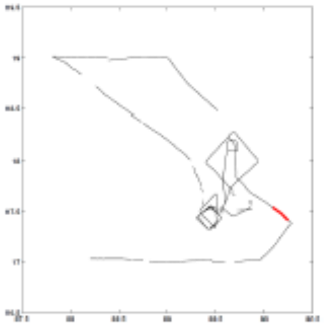


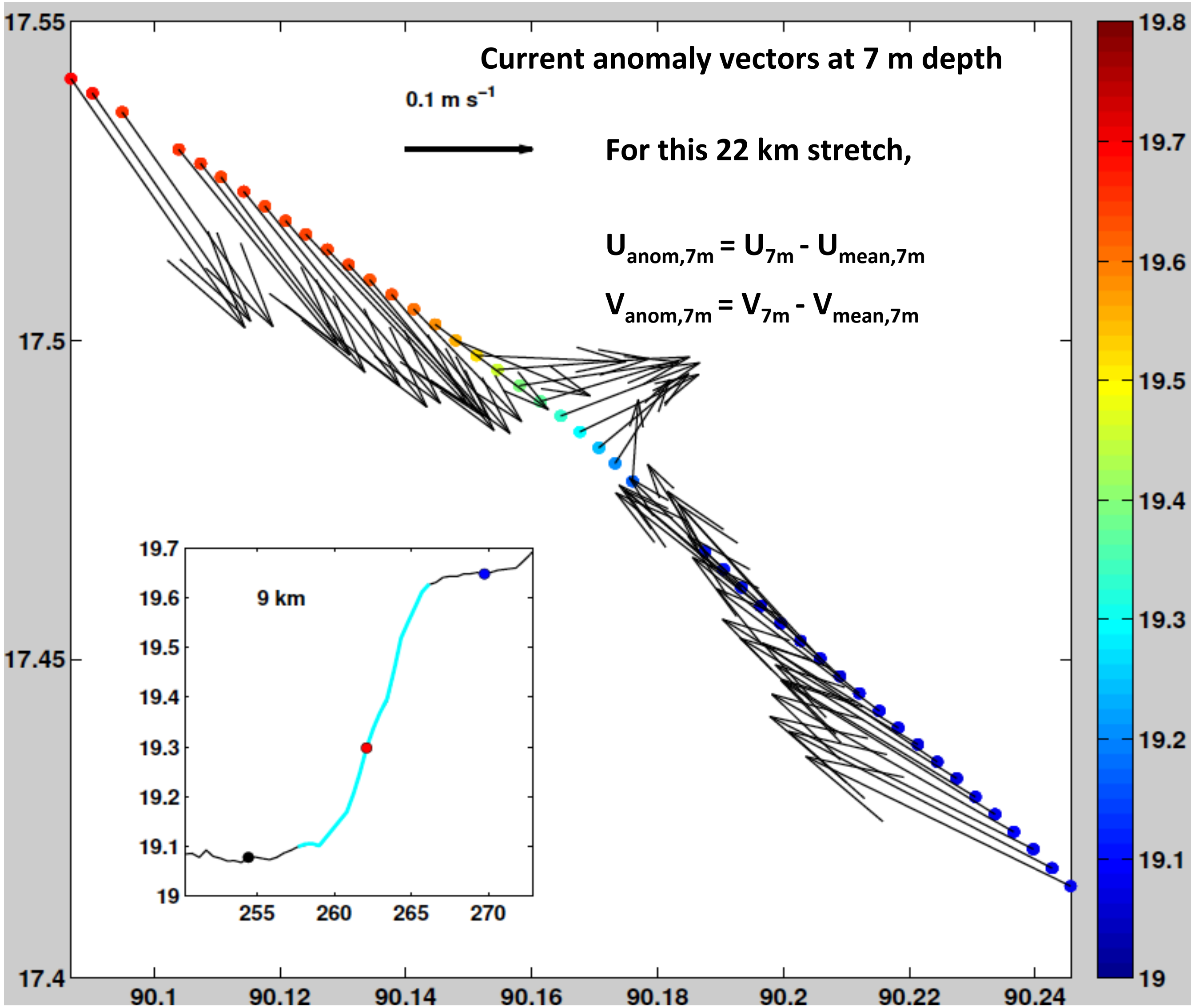
At 17 sub-mesoscale fronts: Shallow mixed layer under the front

Frontal Jet

$Ro = \zeta/f \sim 1.5$

Front marked on ship track



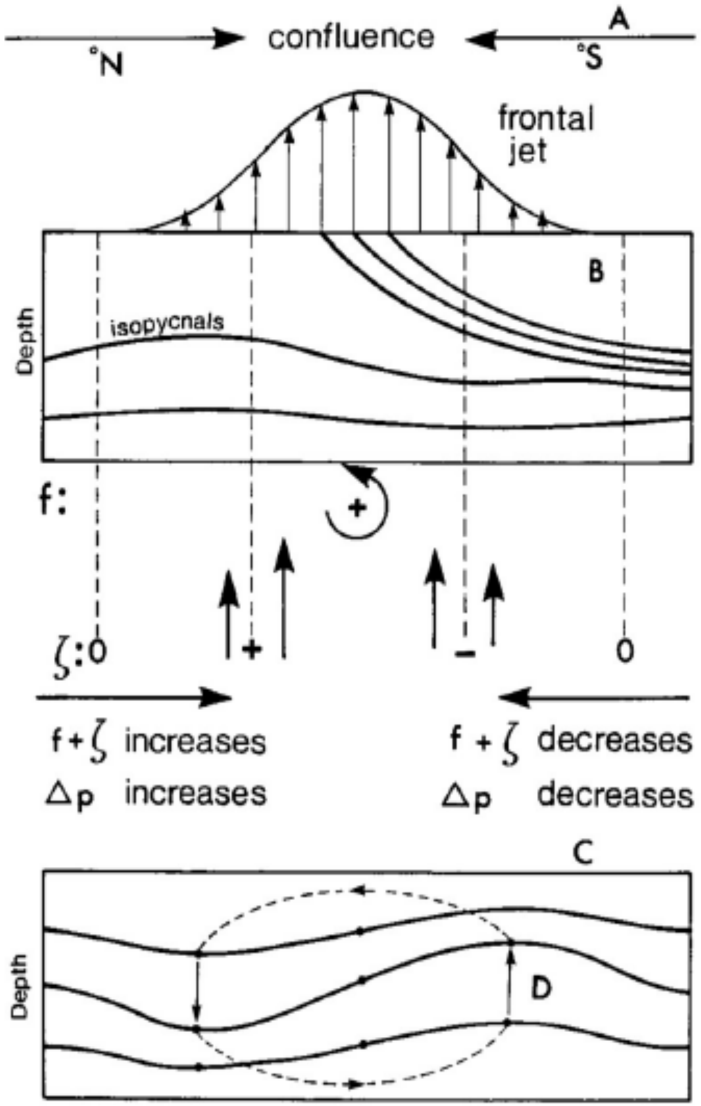


4 m σ_θ and 7 m velocity anomaly.

Size and lateral scale of front: 0.55 kg/m^3 and 9 km

Pollard Regier 1991

Slumping at sub-mesoscale fronts creates stratification



Pollard and Regier 1991

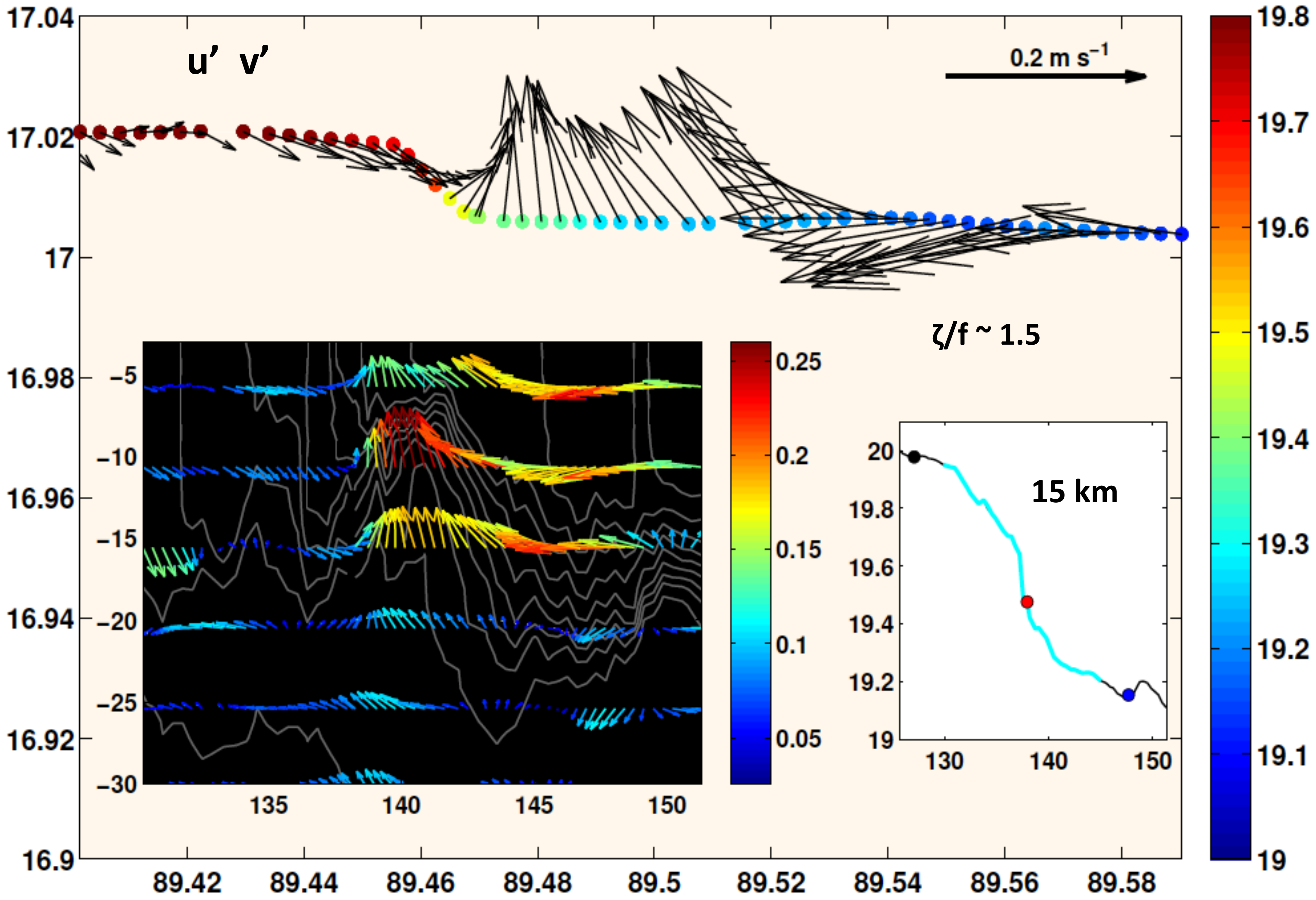
Potential vorticity is conserved

D(PV)/Dt = 0

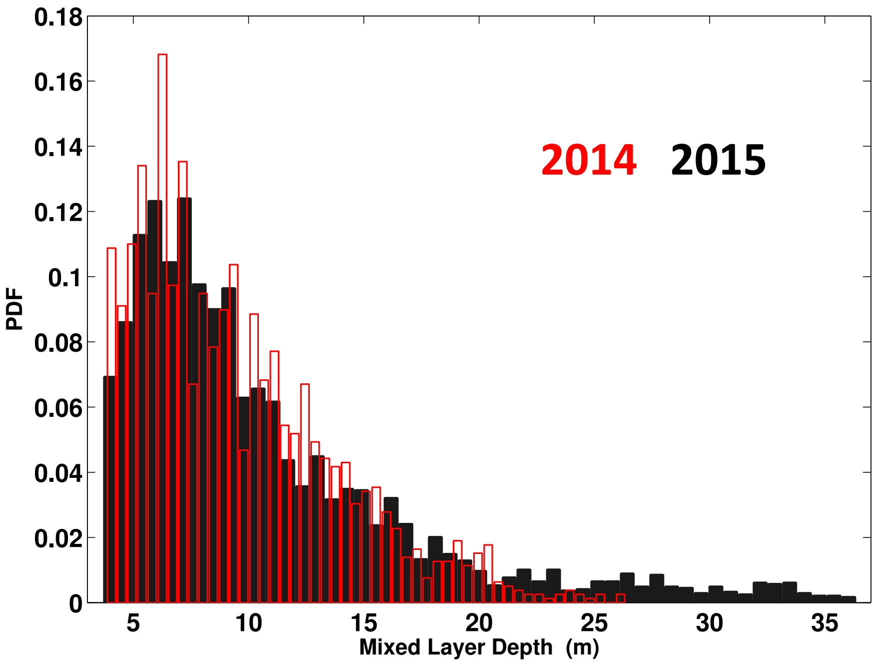
PV = (f + ς) . grad ρ

Downwelling on the dense side of the front and upwelling on the less dense side of the front

Tandon and Garrett 1995 Mahadevan and Tandon 2006 LN Thomas 2007

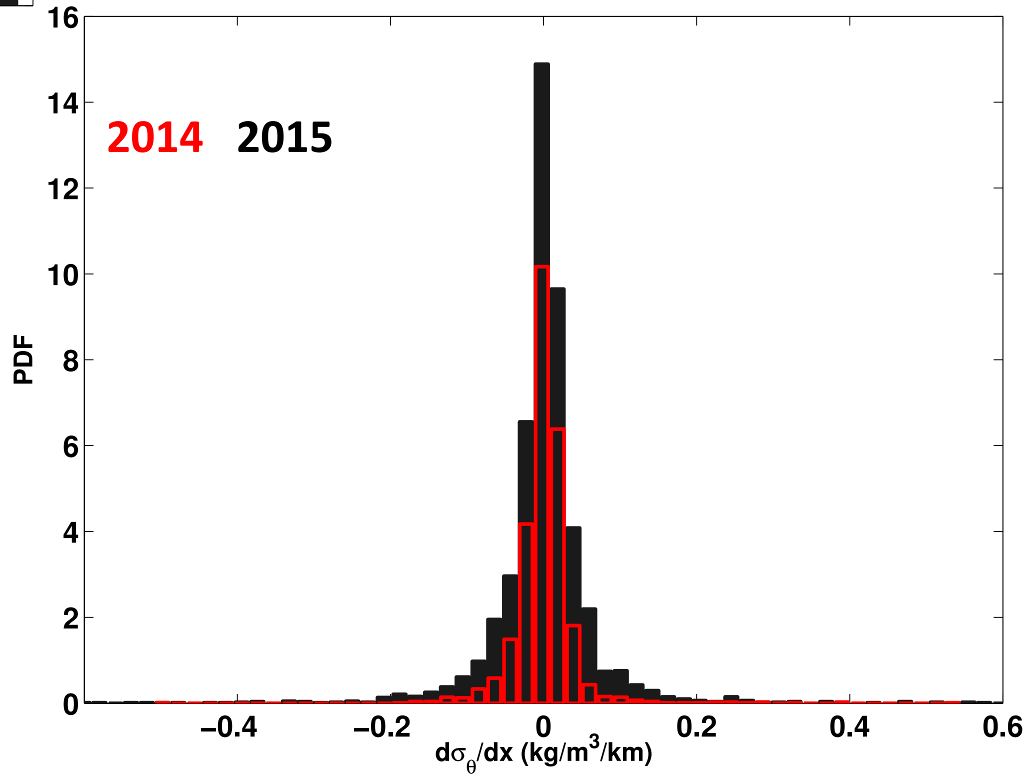


Frontal jet shallower than 20 m, lateral scale 5-10 km



Mixed Layer Depth

MLD < 10 m about 60 % of the time in both years



Lateral density gradient

$|d\sigma\theta/dx| > 0.05$ kg/m³/km ~ 10 % 22 %

Summary

Shallow, low-salinity surface layer and deep warm layer in the north Bay of Bengal is important for regional air-sea interaction. Most **models are inadequate at simulating this thermodynamic structure**.

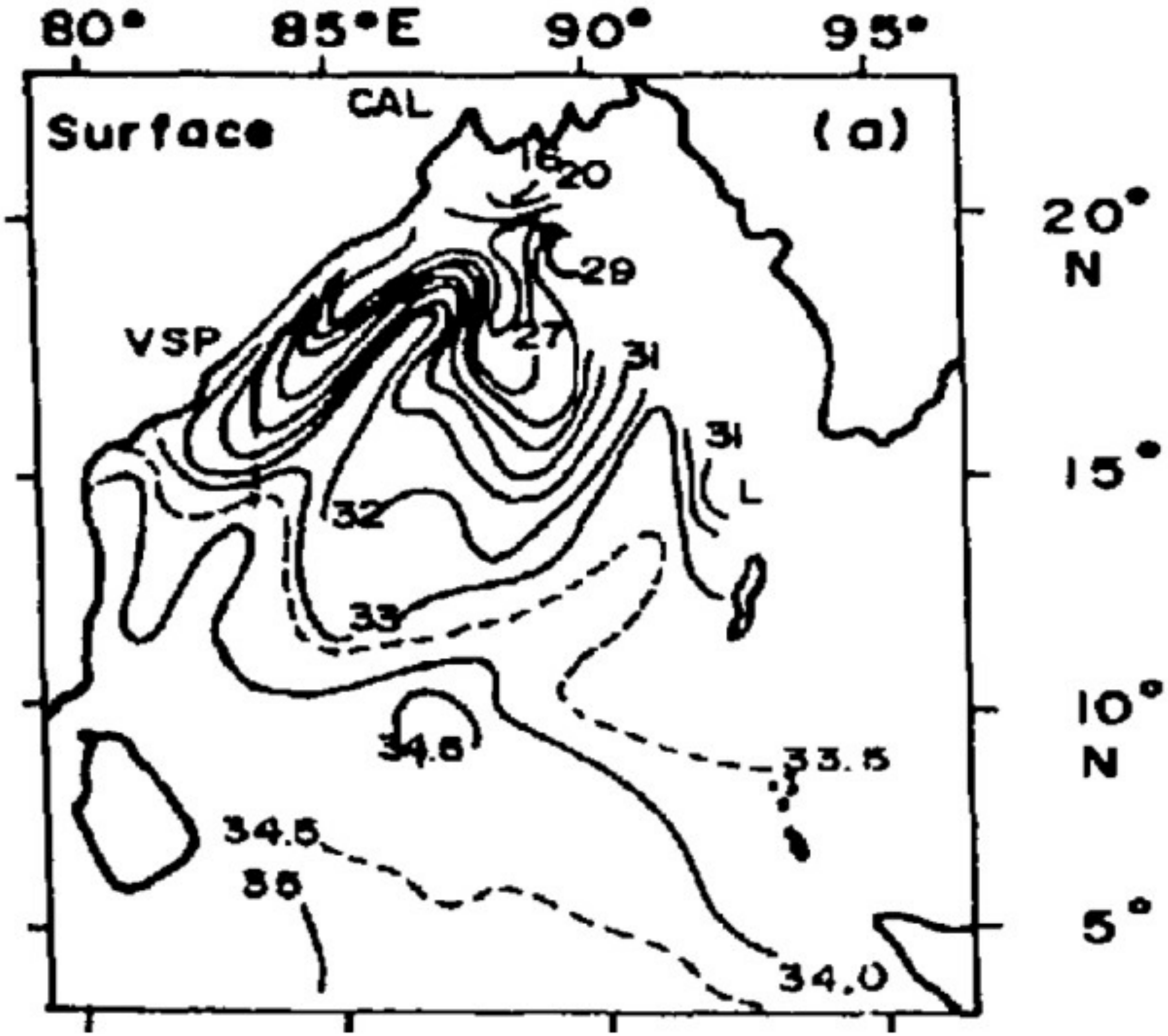
River water, dispersed by basin-scale circulation, O(100) km eddies and shallow Ekman flow, **persists for at least three seasons in the north Bay**.

First measurements with O(1 km) resolution in this basin show near-surface **salinity-dominated “sub-mesoscale” fronts with 1-10 km lateral scales**.

Mixed layer depth is often **shallower at the 1-10 km sub-mesoscale fronts**.

Slumping of sub-mesoscale fronts may sustain shallow stratification

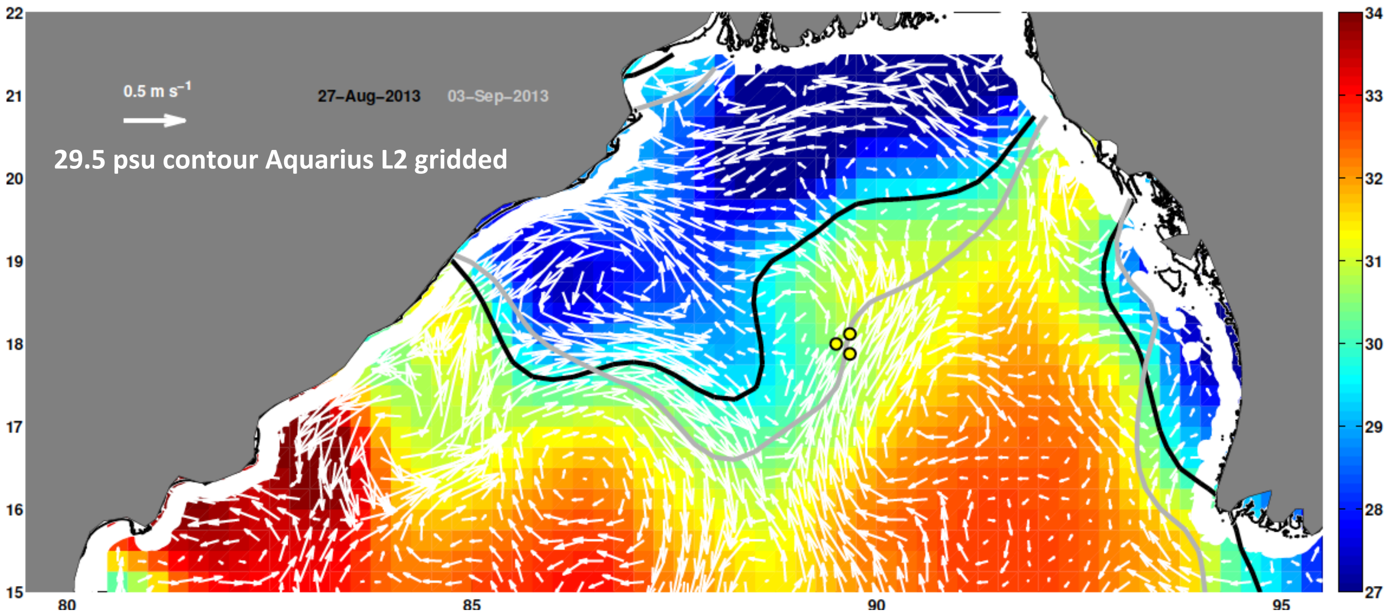
River plumes, July-September Sea Surface Salinty



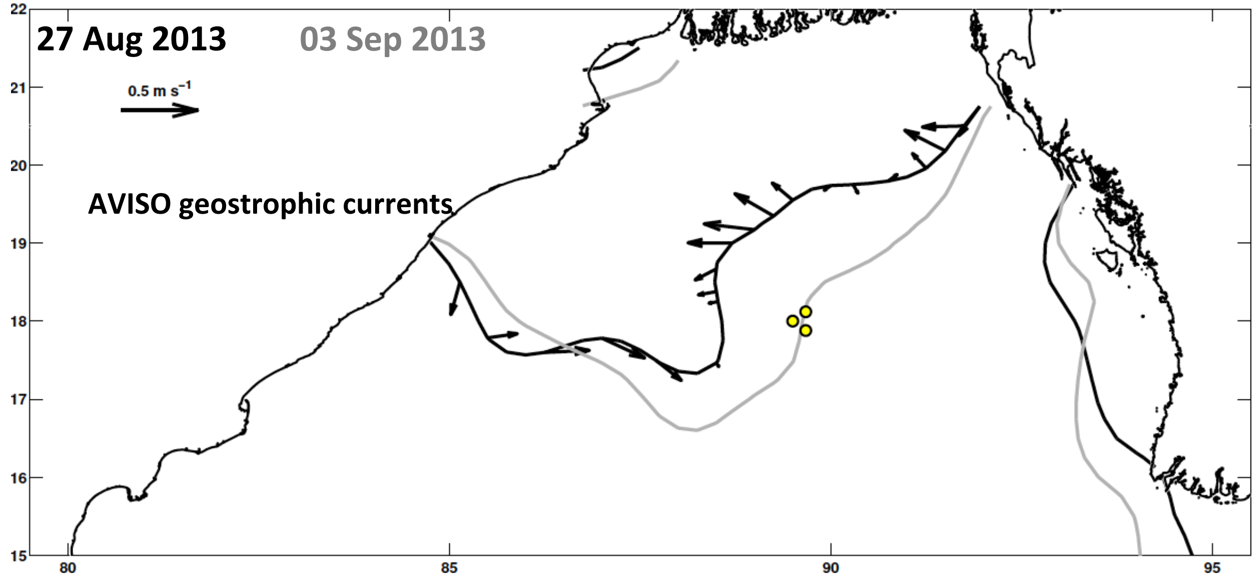
Sagar Kanya cruise 1984

Murty et al., 1992

Mechanisms of freshwater movement: Ekman transport



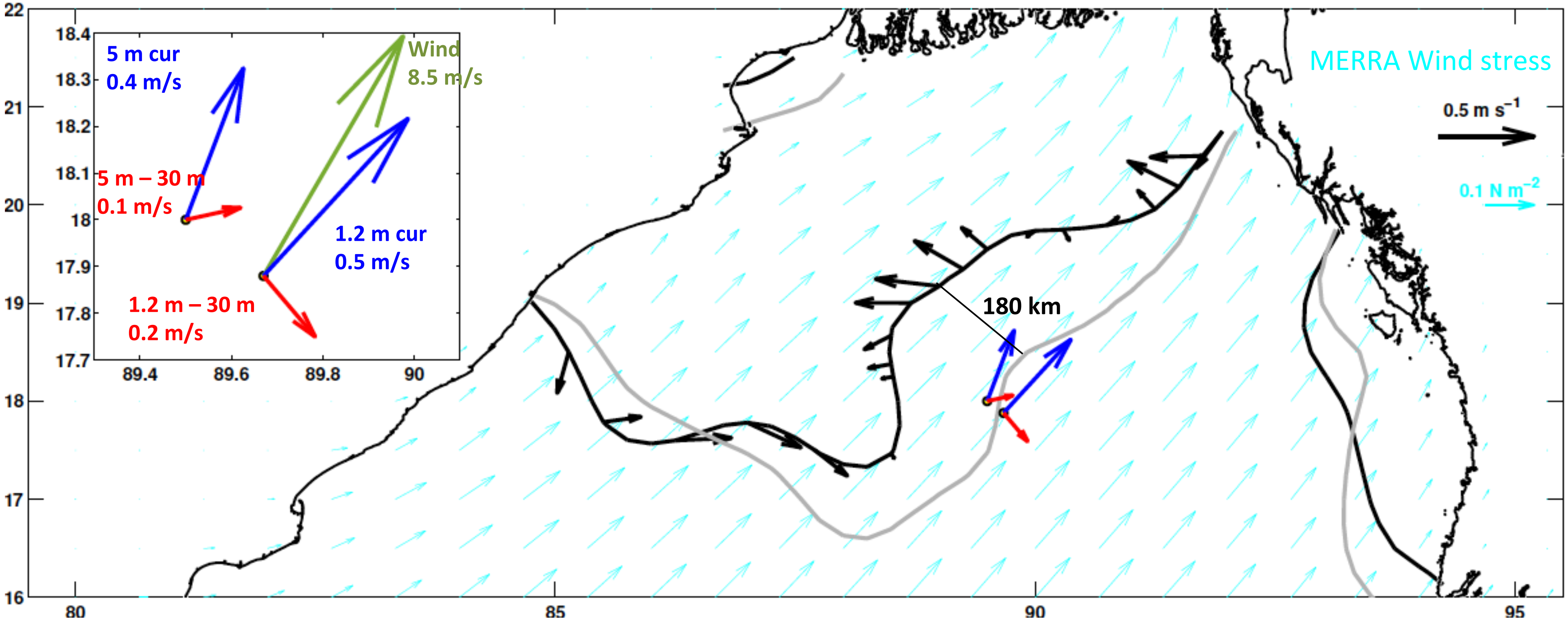
Freshening episode 2013



Why does the isohaline move to the south and east?

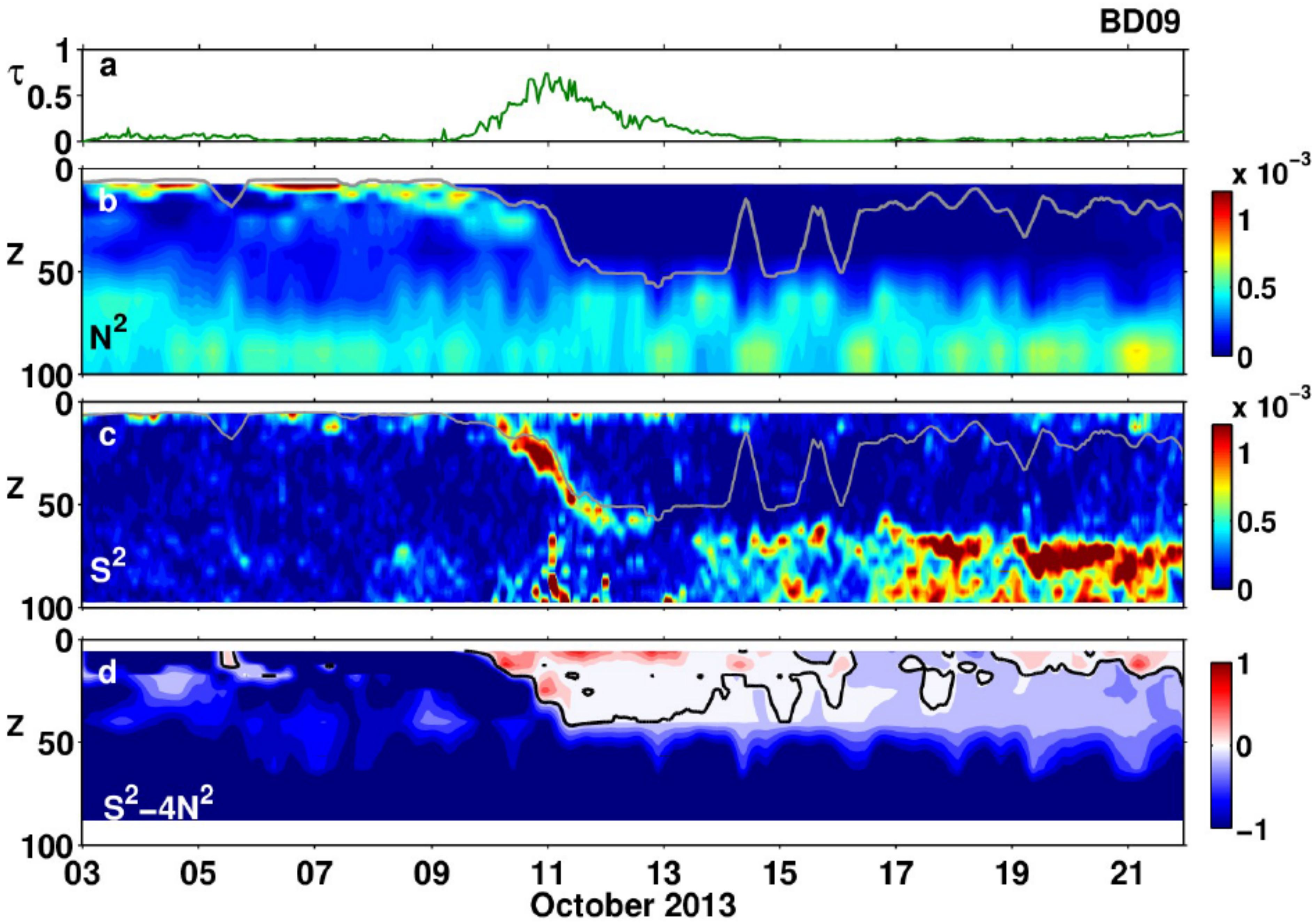
Contour displaced by velocity component normal to the isohaline.

Ekman velocity at 1.2 m depth is 0.2 m/s. Displacement in a week is 120 km

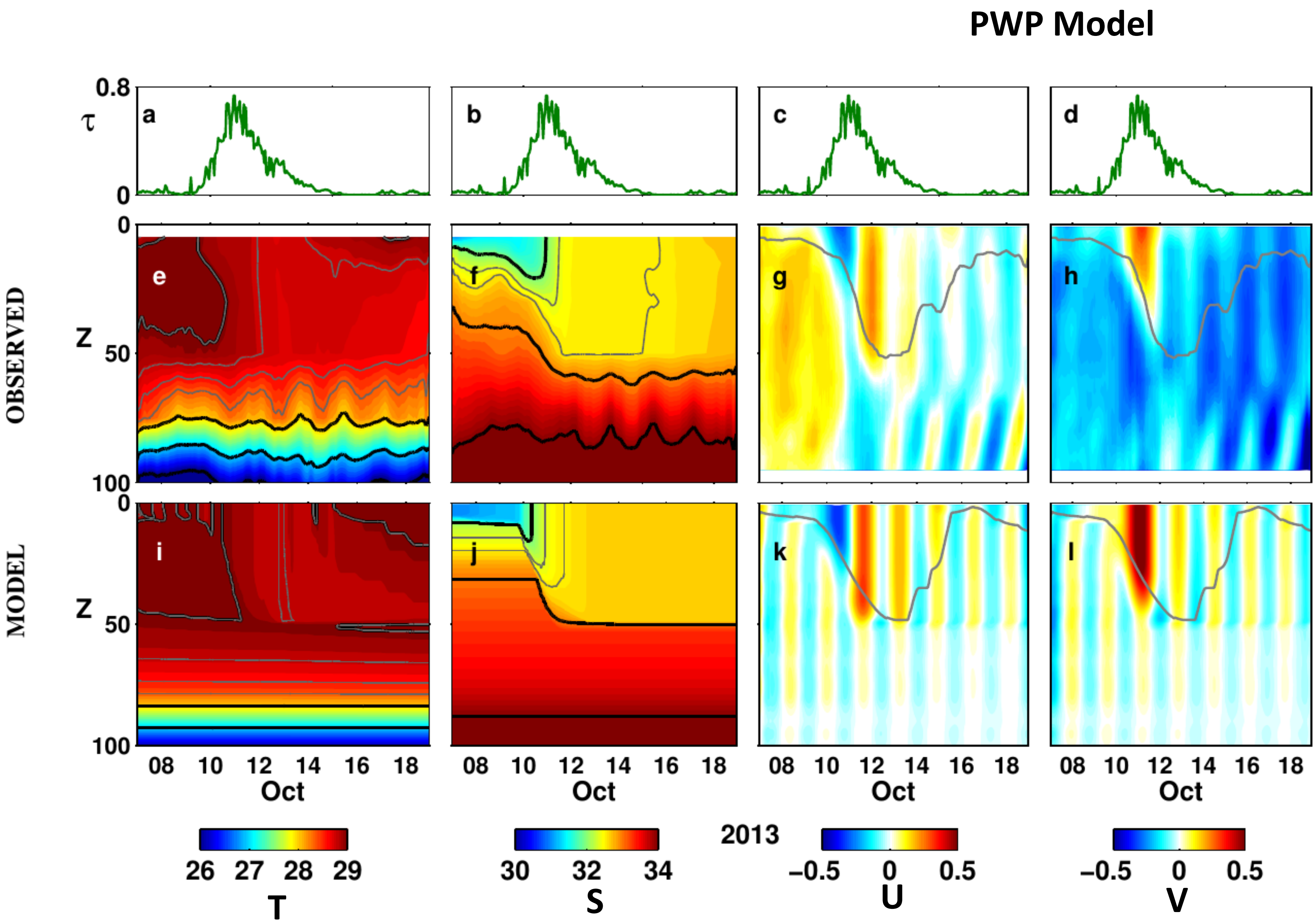


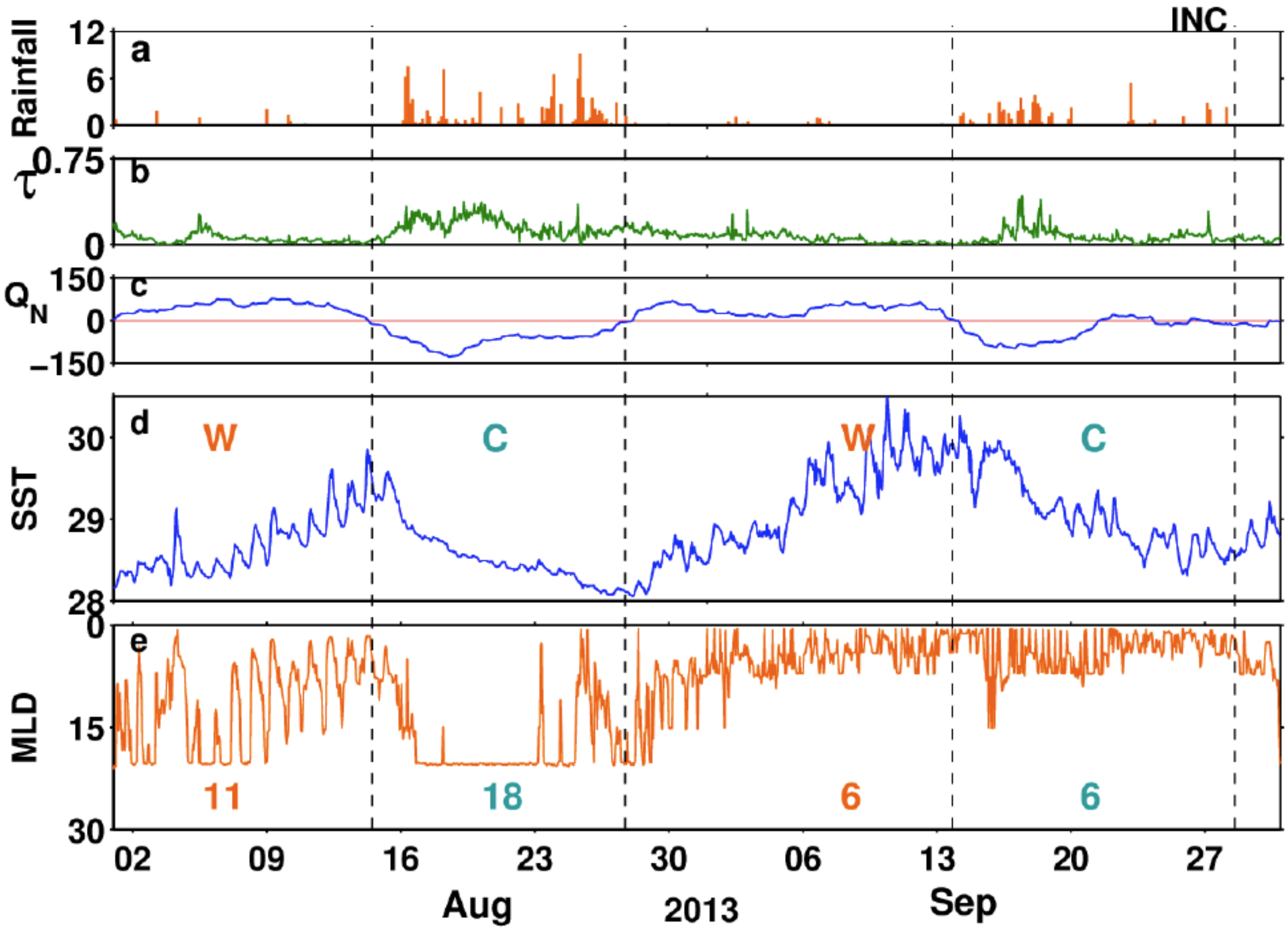
Ekman Transport = $\tau/\rho f = 2.2\ m^2/s$

Ekman depth = 2.2/0.19 = 11.5 m

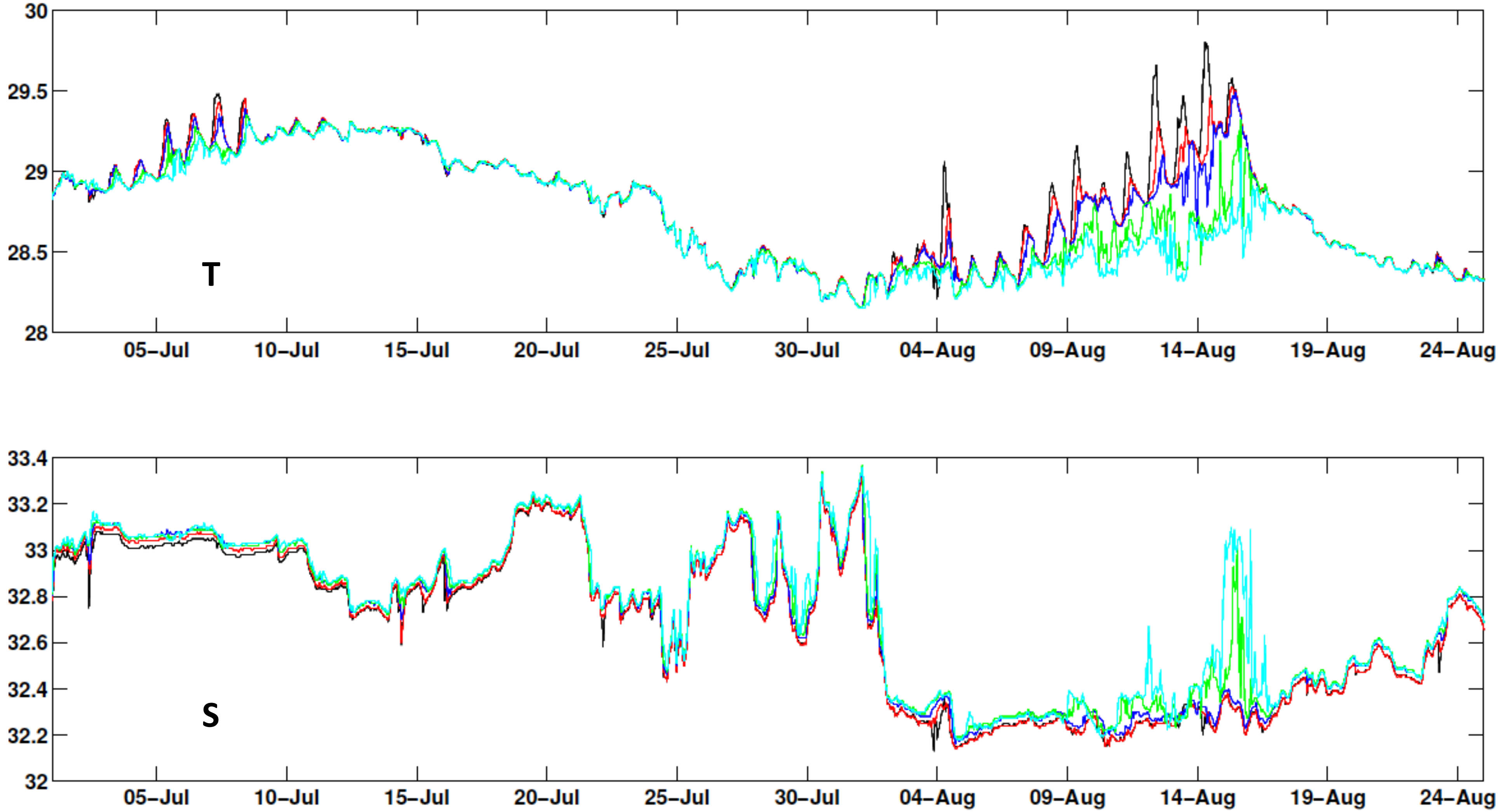


BD09
a
τ
1
0.5
0
b
Z
0
50
100
N^2
x 10^{-3}
1
0.5
0
c
S^2
d
S^2−4N^2
−1
03
05
07
09
11
13
15
17
19
21
October 2013

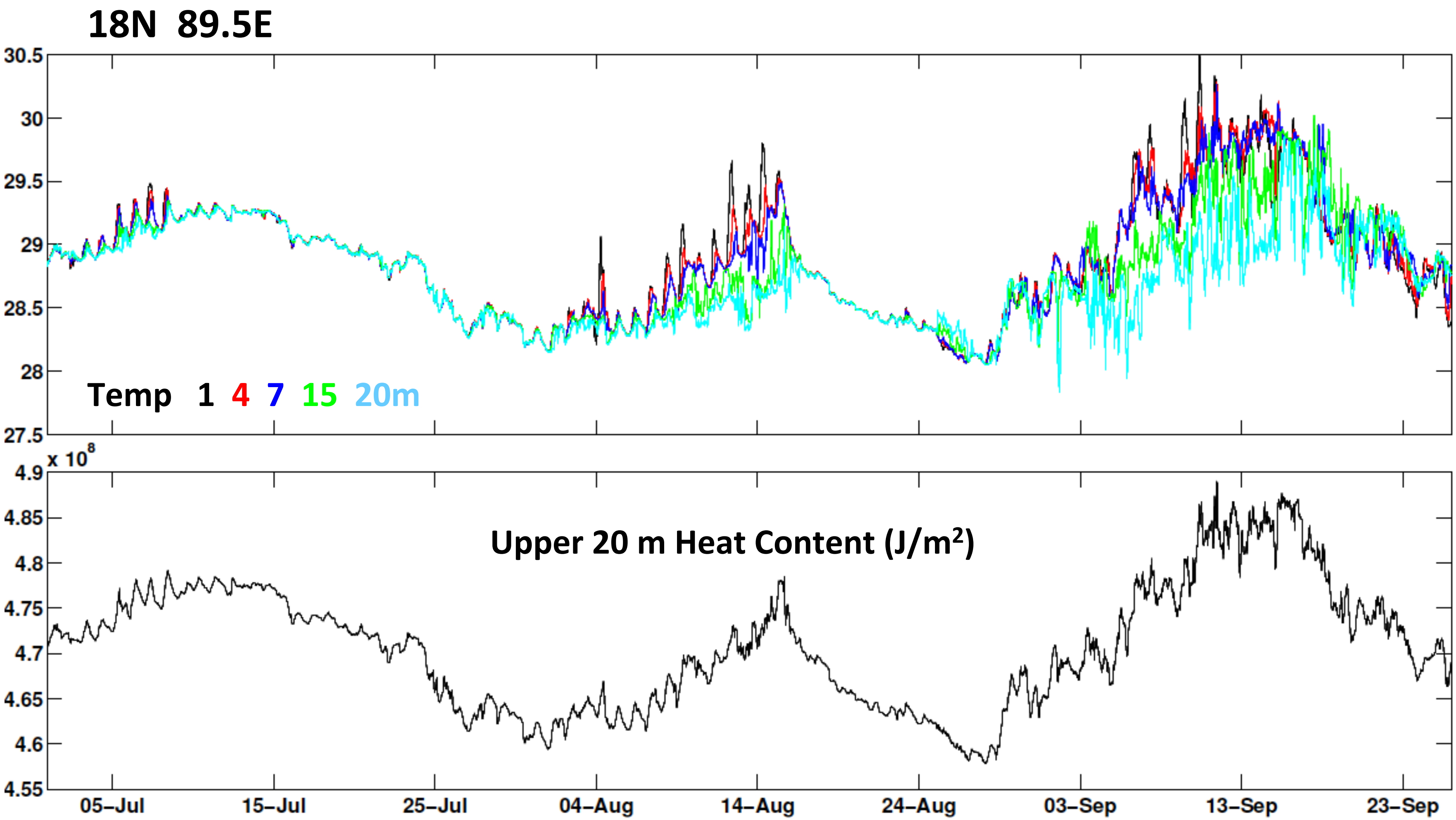

PWP Model
τ
0.8
0
a
b
c
d
0
Z
50
100
e
f
g
h
OBSERVED
0
Z
50
100
i
j
k
l
MODEL
08 10 12 14 16 18
Oct
2013
26 27 28 29
T
30 32 34
S
−0.5 0 0.5
U
−0.5 0 0.5
V



INC
Rainfall
12
6
0
a
τ
0.75
0
b
Q_N
150
0
−150
c
d
W
C
W
C
SST
30
29
28
e
MLD
0
15
30
11
18
6
6
02
09
16
23
30
06
13
20
27
Aug
2013
Sep

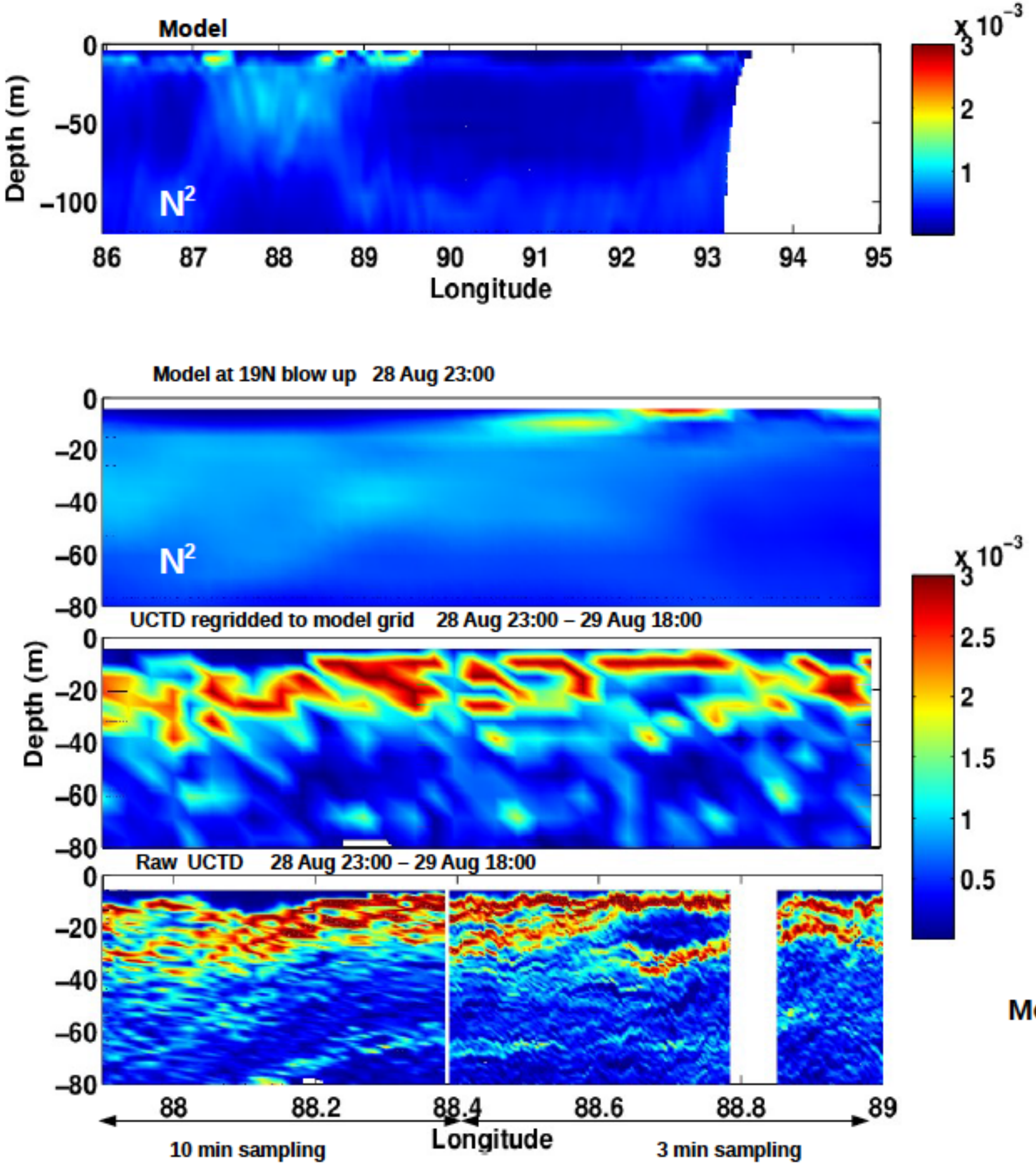


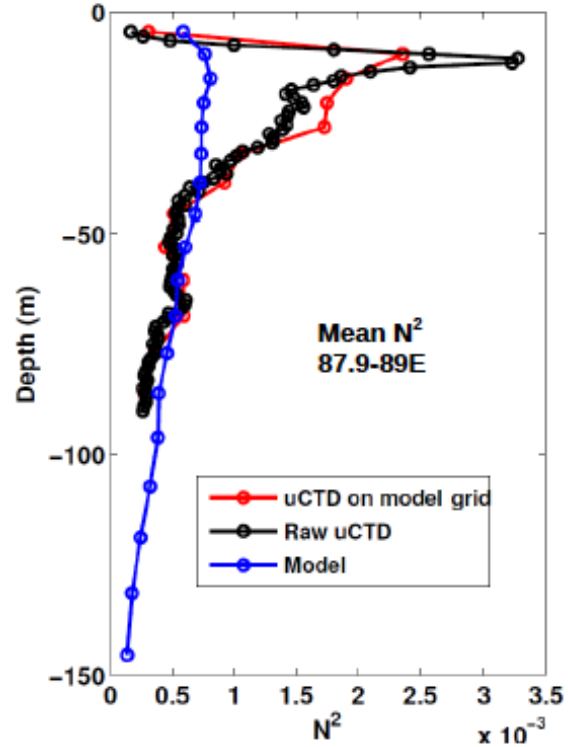
30
29.5
29
28.5
28
T
05-Jul
10-Jul
15-Jul
20-Jul
25-Jul
30-Jul
04-Aug
09-Aug
14-Aug
19-Aug
24-Aug
33.4
33.2
33
32.8
32.6
32.4
32.2
32
S
05-Jul
10-Jul
15-Jul
20-Jul
25-Jul
30-Jul
04-Aug
09-Aug
14-Aug
19-Aug
24-Aug


18N 89.5E
Temp 1 4 7 15 20m
Upper 20 m Heat Content (J/m²)
x 10⁸
30.5
30
29.5
29
28.5
28
27.5
4.9
4.85
4.8
4.75
4.7
4.65
4.6
4.55
05–Jul
15–Jul
25–Jul
04–Aug
14–Aug
24–Aug
03–Sep
13–Sep
23–Sep

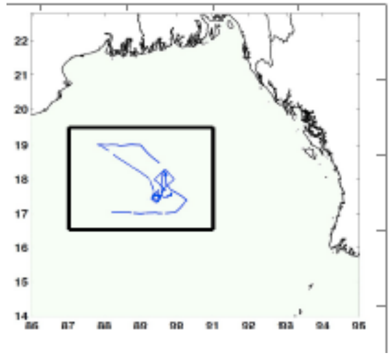
Model N^2 at 19N 28 Aug 23:00

uCTD N^2 at 19N
28 Aug 23:00 – 29 Aug 18:00



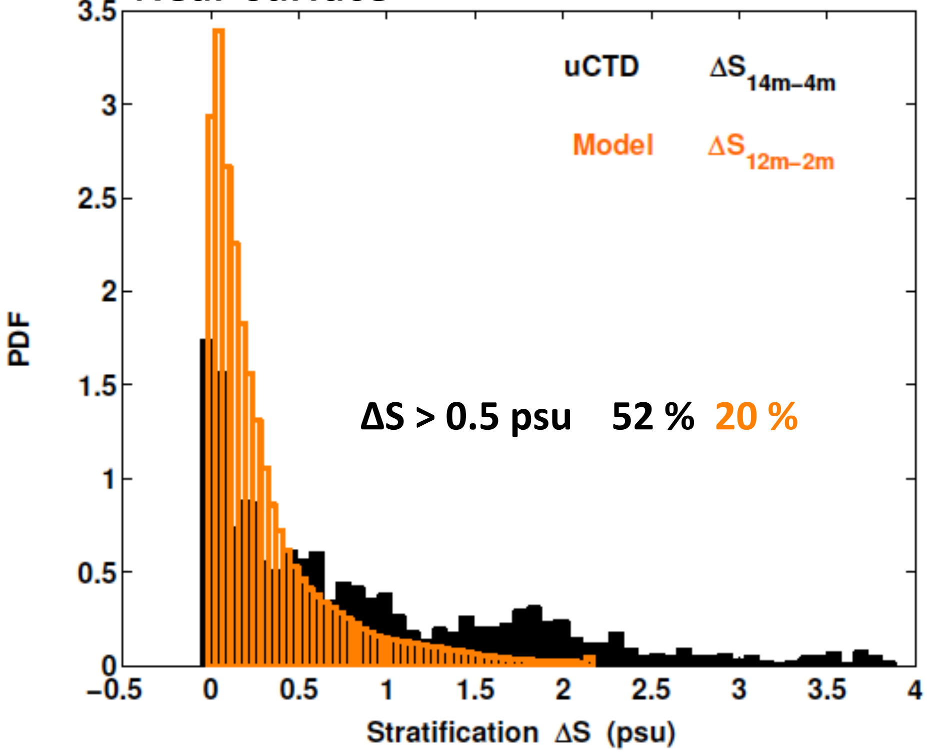


Model stratification is weak

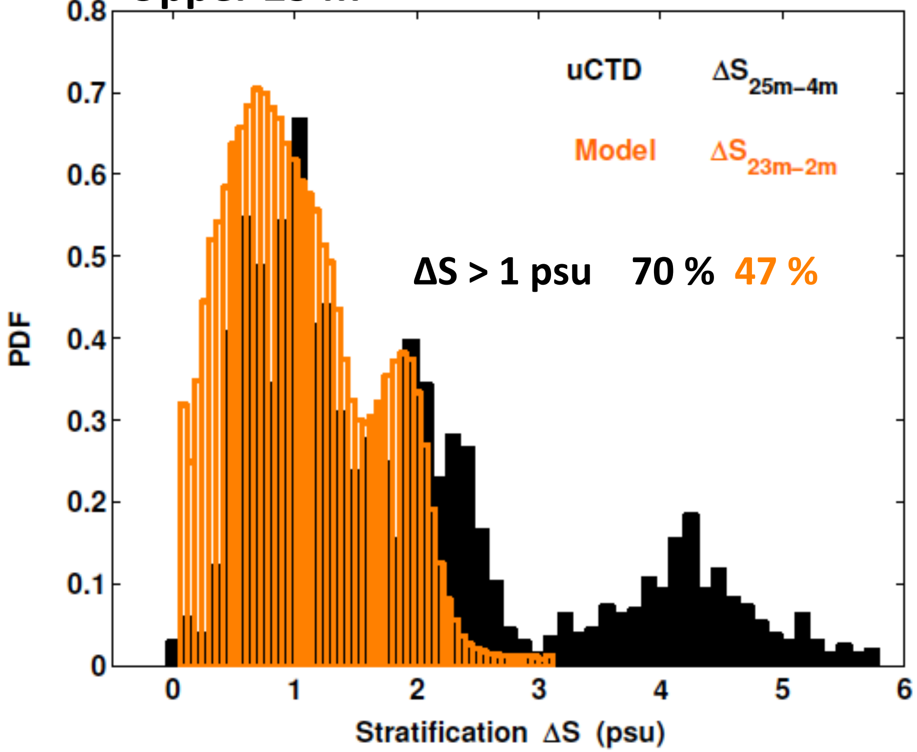


PDFs of observed and model vertical salinity gradients

Near-surface



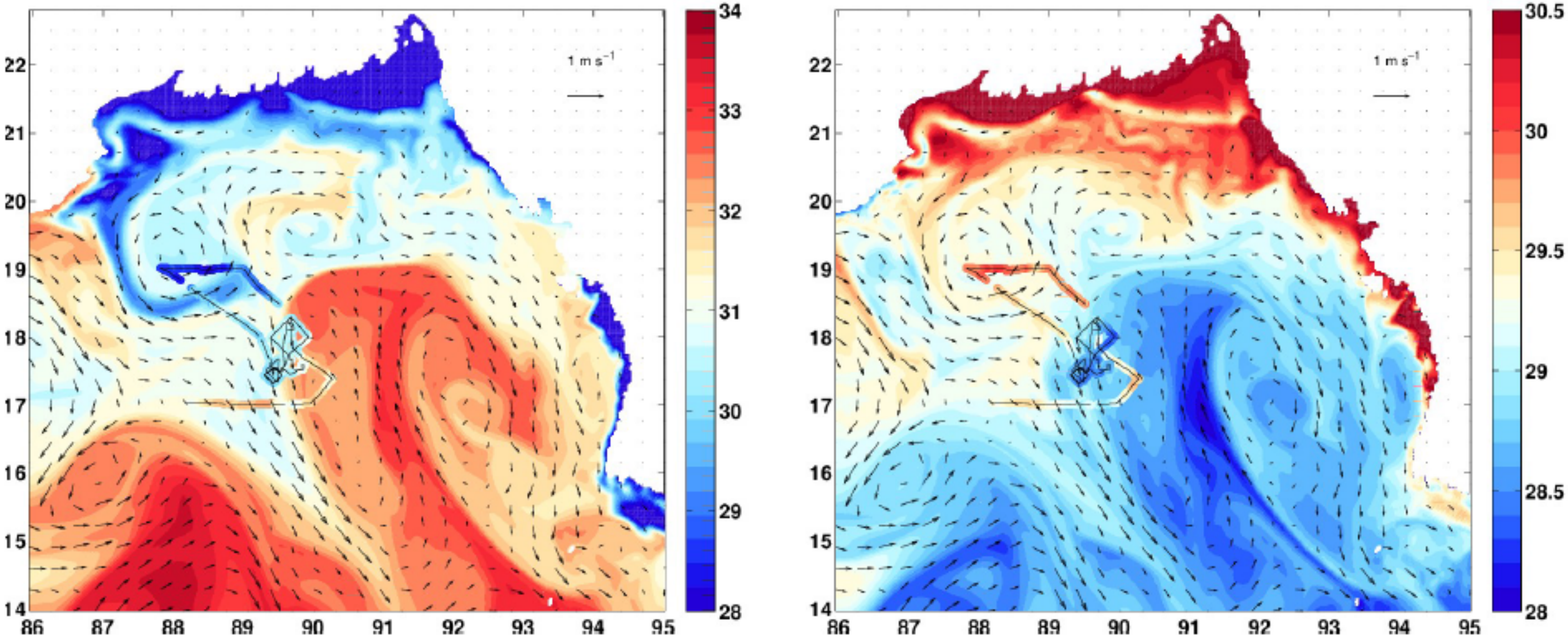
Upper 25 m



Model underestimates salinity stratification in fresh water

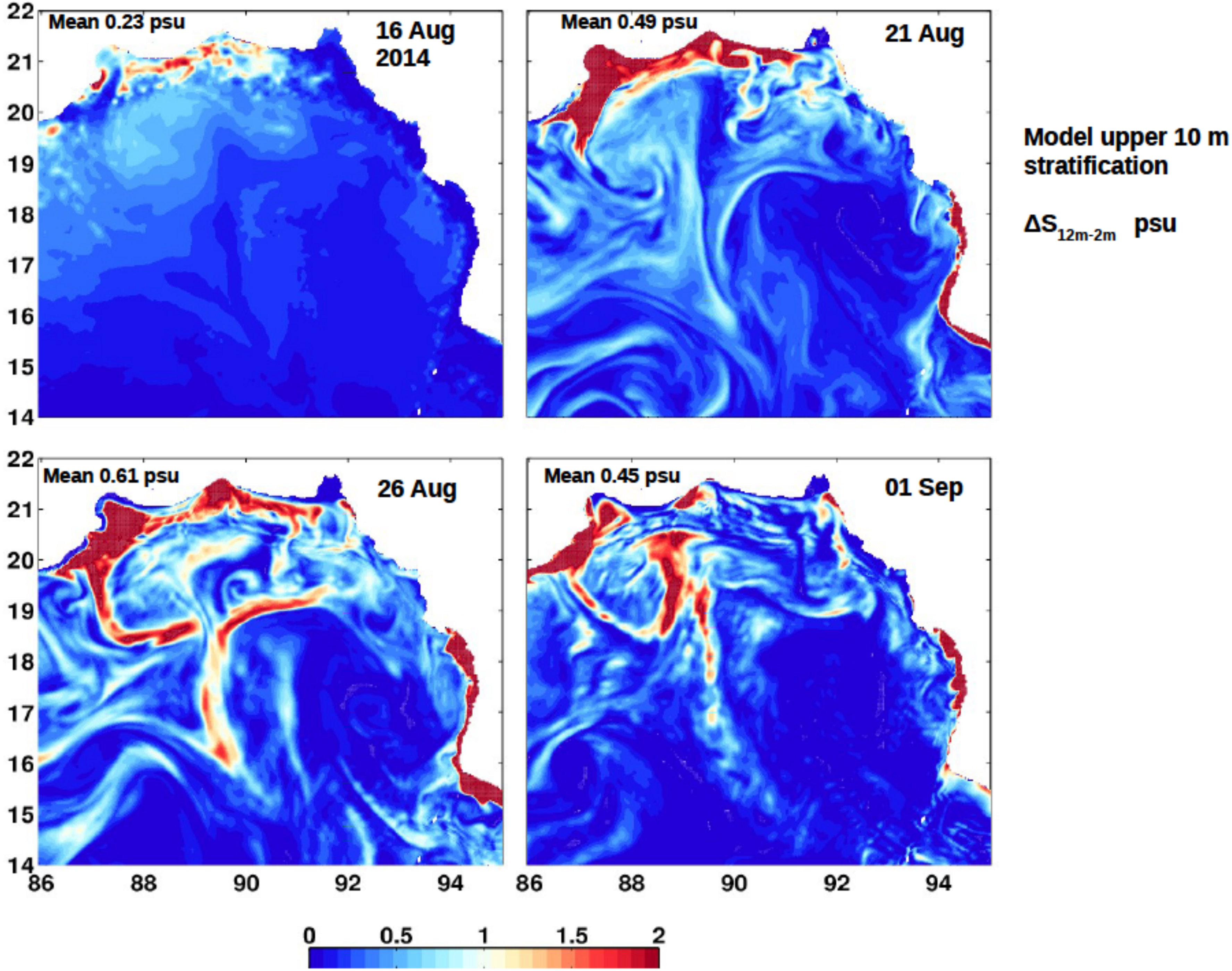
3 km ROMS 16 Aug-6 Sep 2014

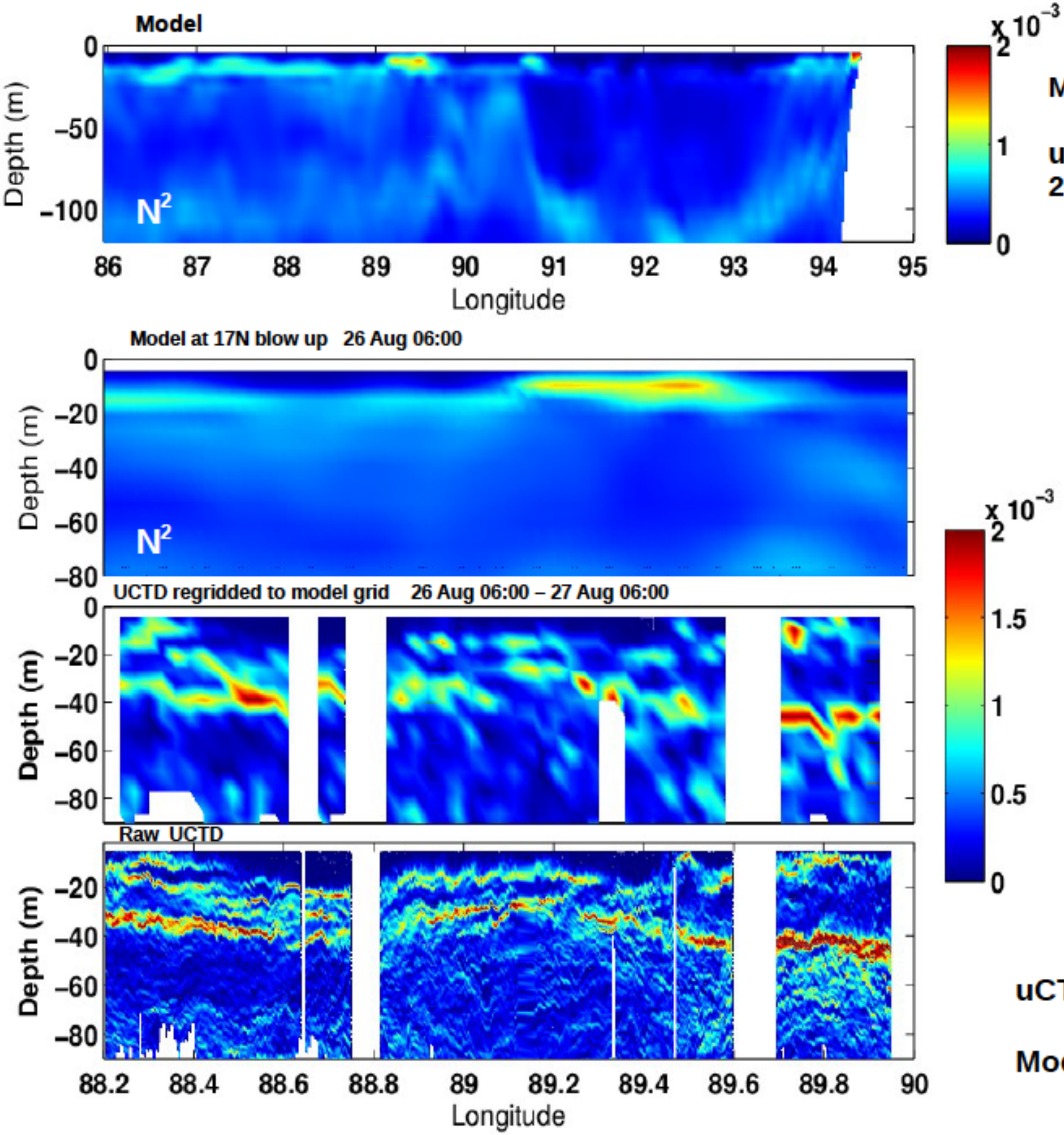
Model 2 m Salinity (left), Temperature (right) and currents   26 Aug 06:00 – 27 Aug 06:00



Bay of Bengal Regional Ocean Model

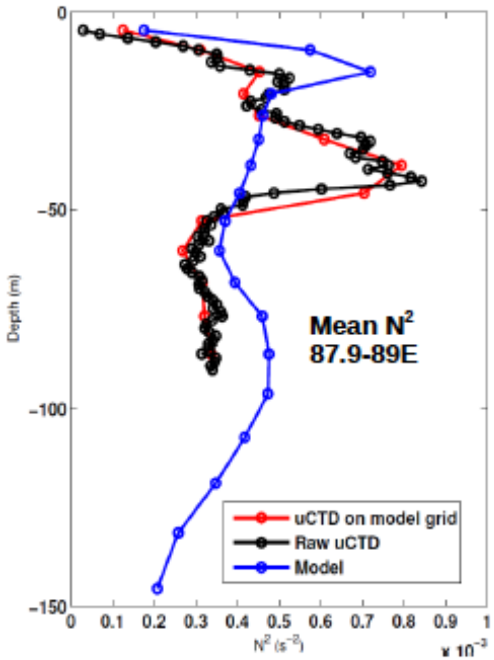
1/32^o 50 sigma levels Two-equation turbulence model
Initialised from data-assimilating HYCOM on 16 August 2014
Forced with 3-hourly MERRA surface fluxes, hourly model fields


Mean 0.23 psu
16 Aug
2014
Mean 0.49 psu
21 Aug
Mean 0.61 psu
26 Aug
Mean 0.45 psu
01 Sep
22
21
20
19
18
17
16
15
14
86
88
90
92
94
0
0.5
1
1.5
2
Model upper 10 m
stratification
ΔS12m-2m psu



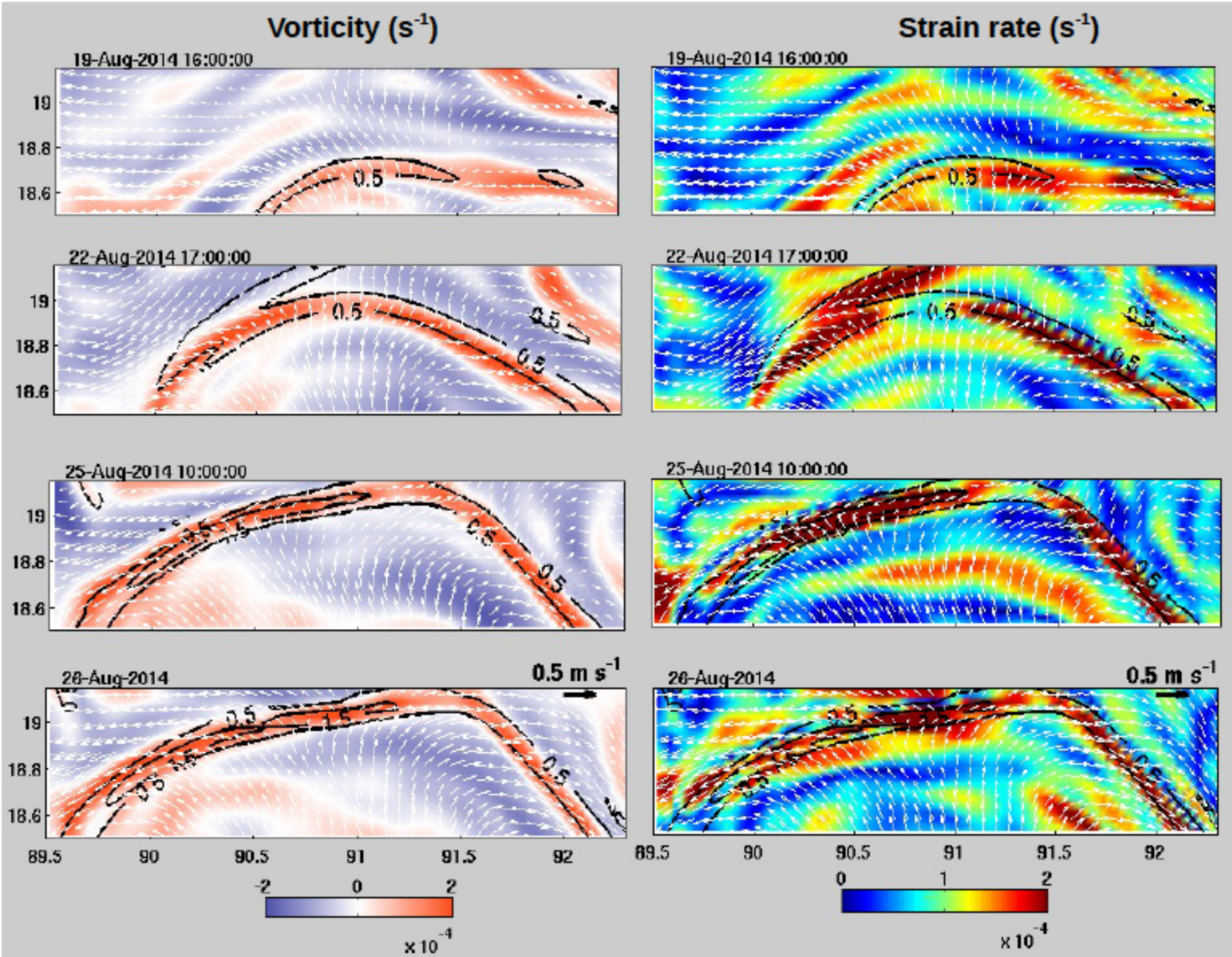
Model N^2 at 17N 26 Aug 06:00

uCTD N^2 at 17N
26 Aug 06:00 – 27 Aug 06:00



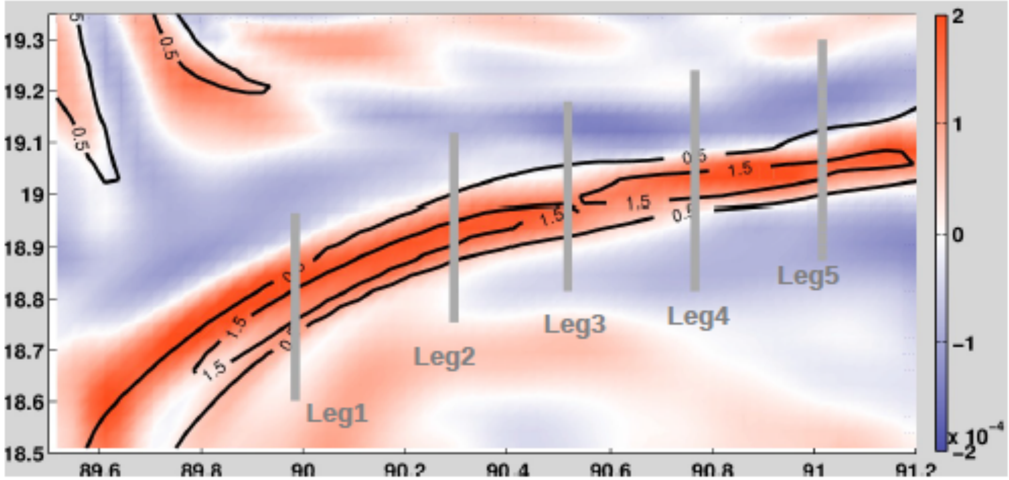
uCTD N^2 max at 30-50 m.

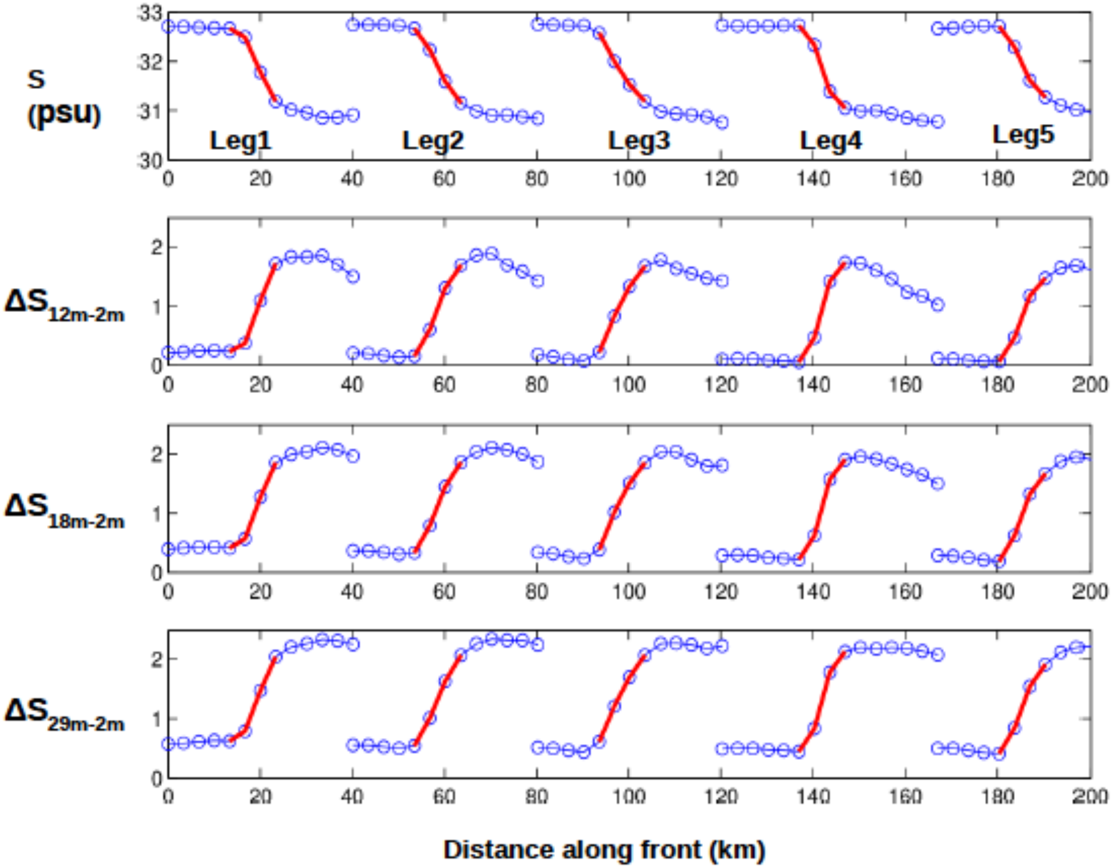
Model N^2 max at 5-20 m.



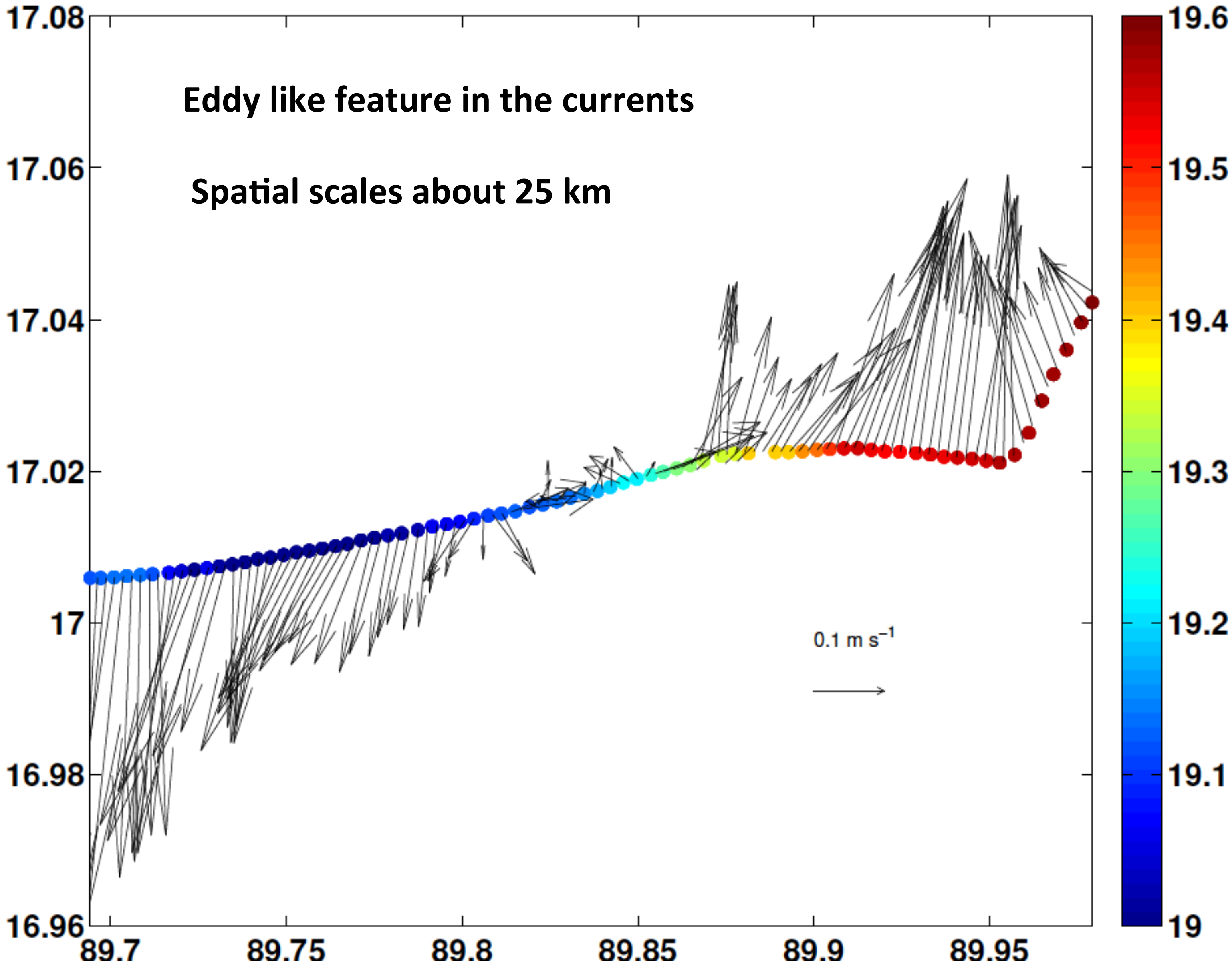
|grad$S_{x,y}$| (psu/km; black contour)

Vorticity and strain rates are high at the front





The near-surface salinity stratification is higher on the fresher side of the front rather than directly under the front

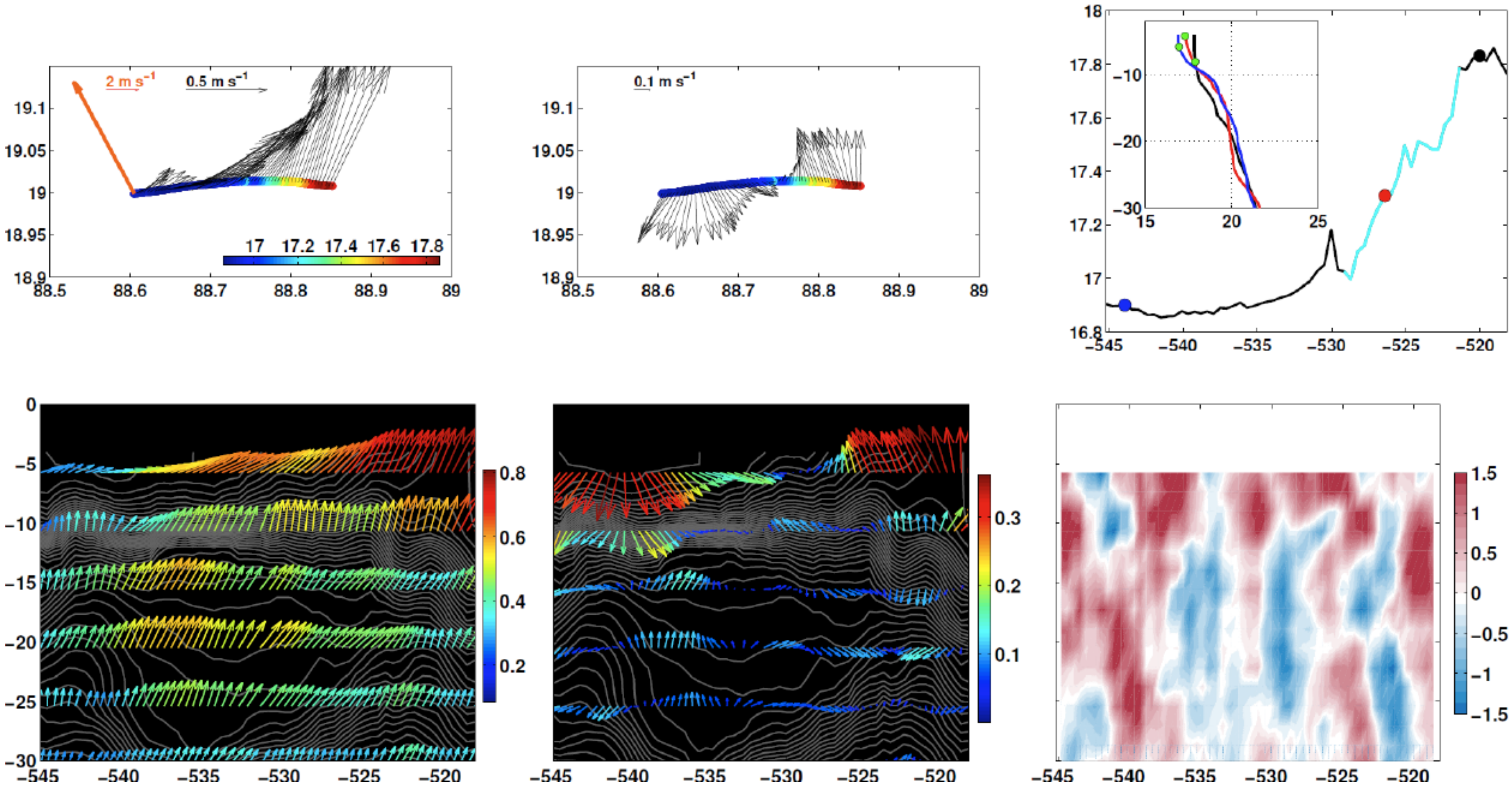


Eddy like feature in the currents
Spatial scales about 25 km
0.1 m s^{-1}
17.08
17.06
17.04
17.02
17
16.98
16.96
89.7
89.75
89.8
89.85
89.9
89.95
19.6
19.5
19.4
19.3
19.2
19.1
19

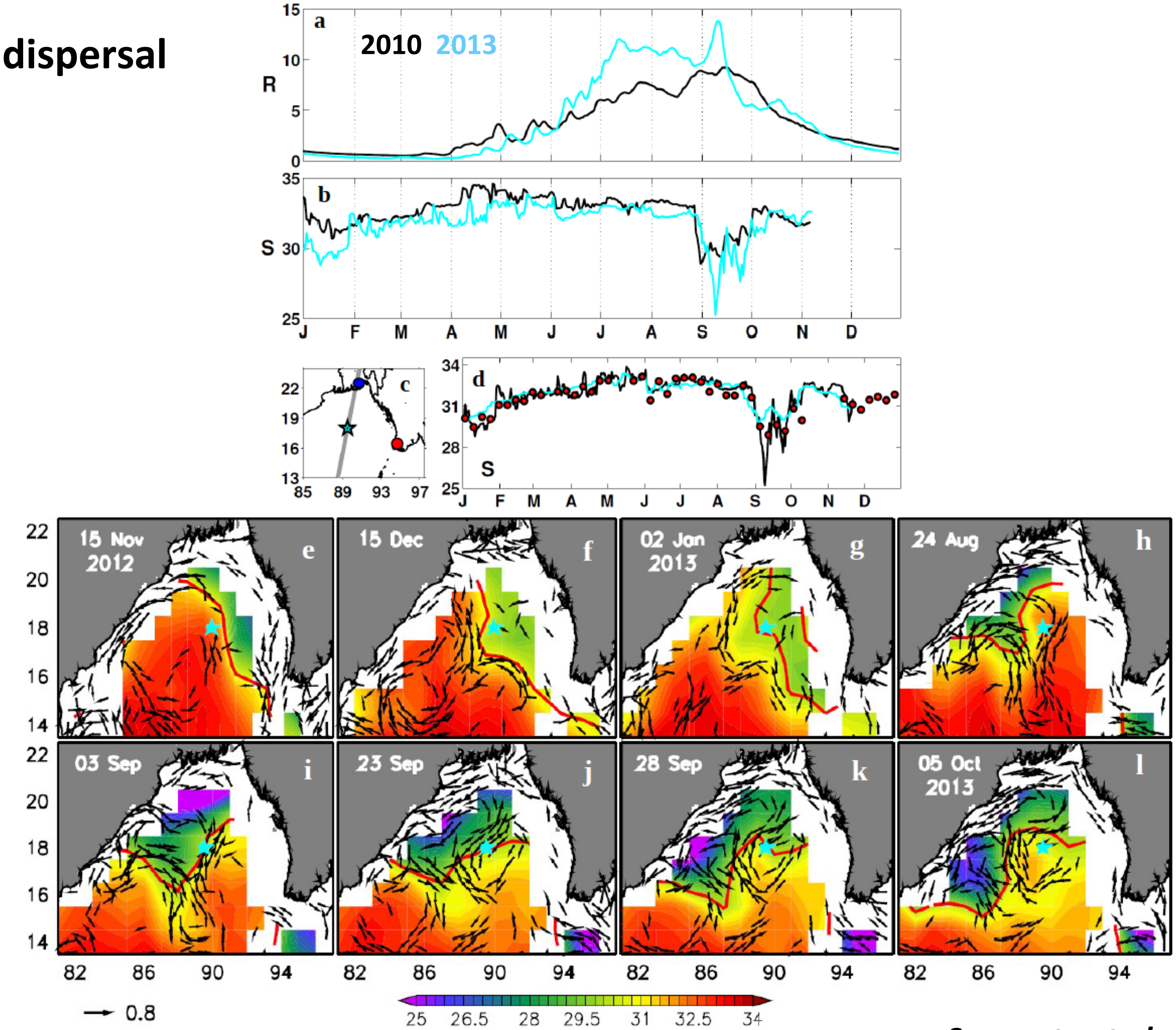
Rivers

D'Anville 1762

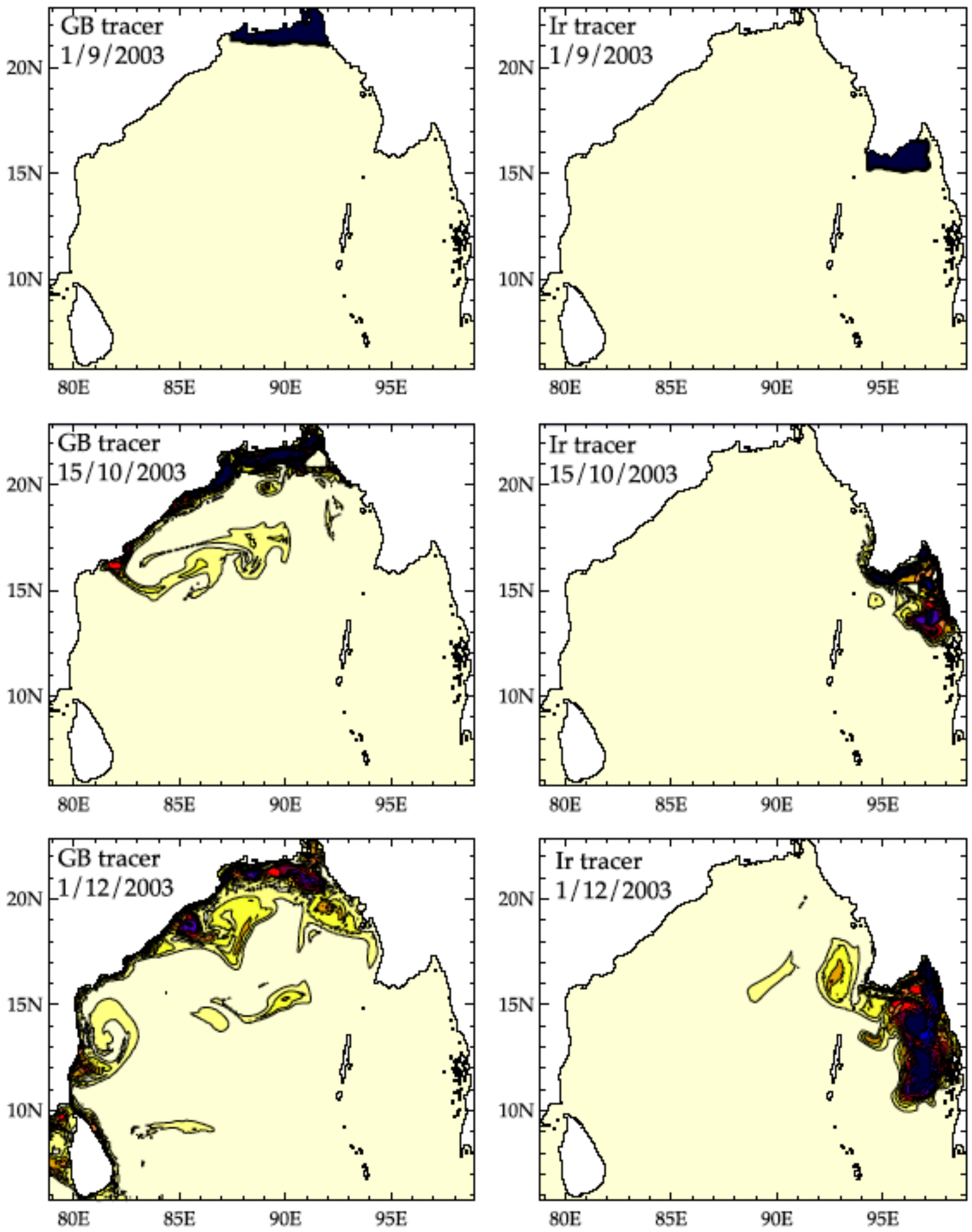
Submesoscale cyclonic eddy?



FW dispersal



Sengupta et al., 2016



NEMO 8 km 1 m res.

Benshila *et.al* 2014

Total freshwater input to the Bay of Bengal (P+R-E) is 4200 km^3 or 1.6 m

Several major monsoonal rivers flow into the north Bay of Bengal –

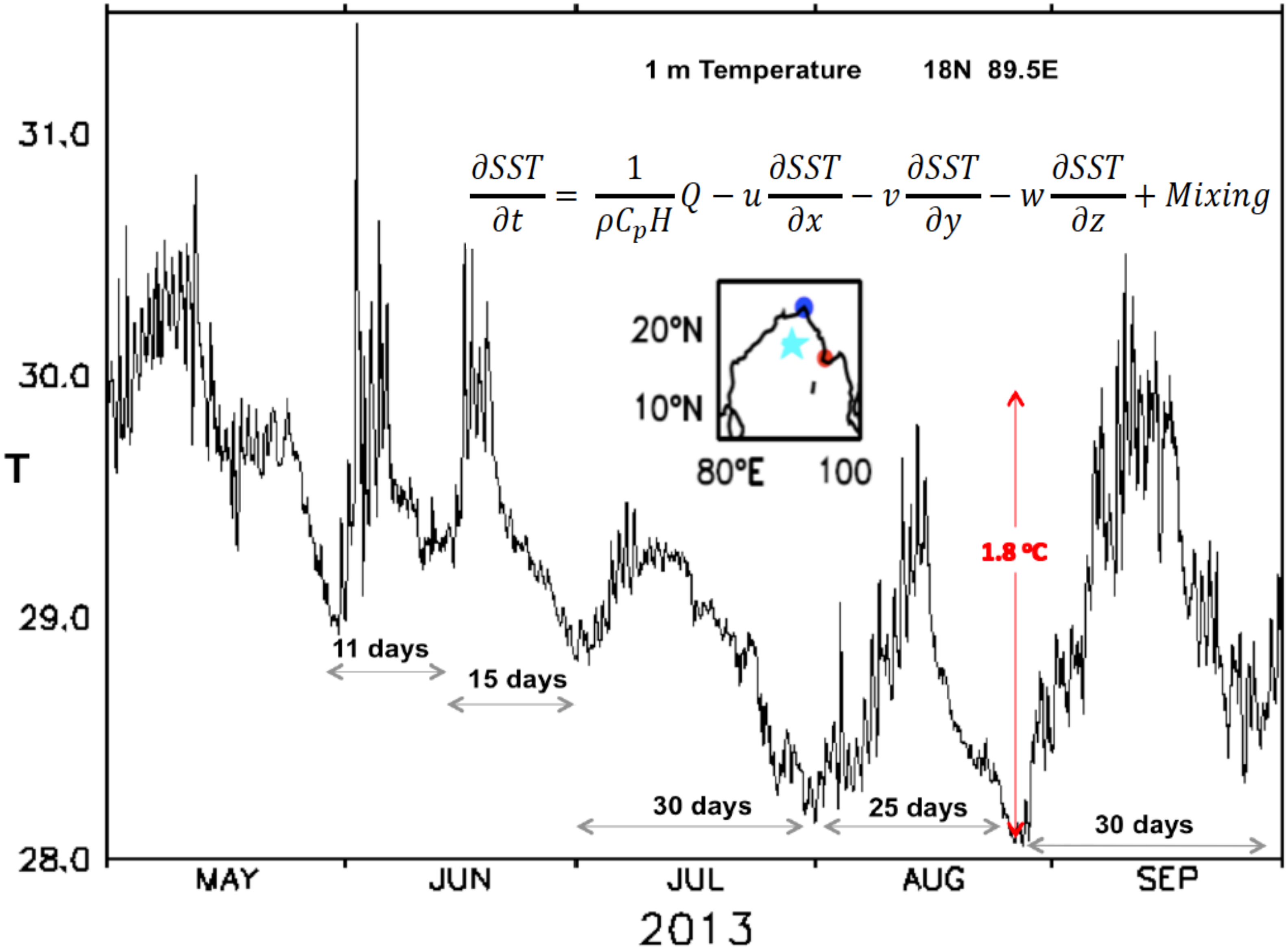
Ganga-Brahmaputra-Meghna, Irrawaddy, Salween, Godavari, Mahanadi, Krishna

Sengupta *et.al* 2006

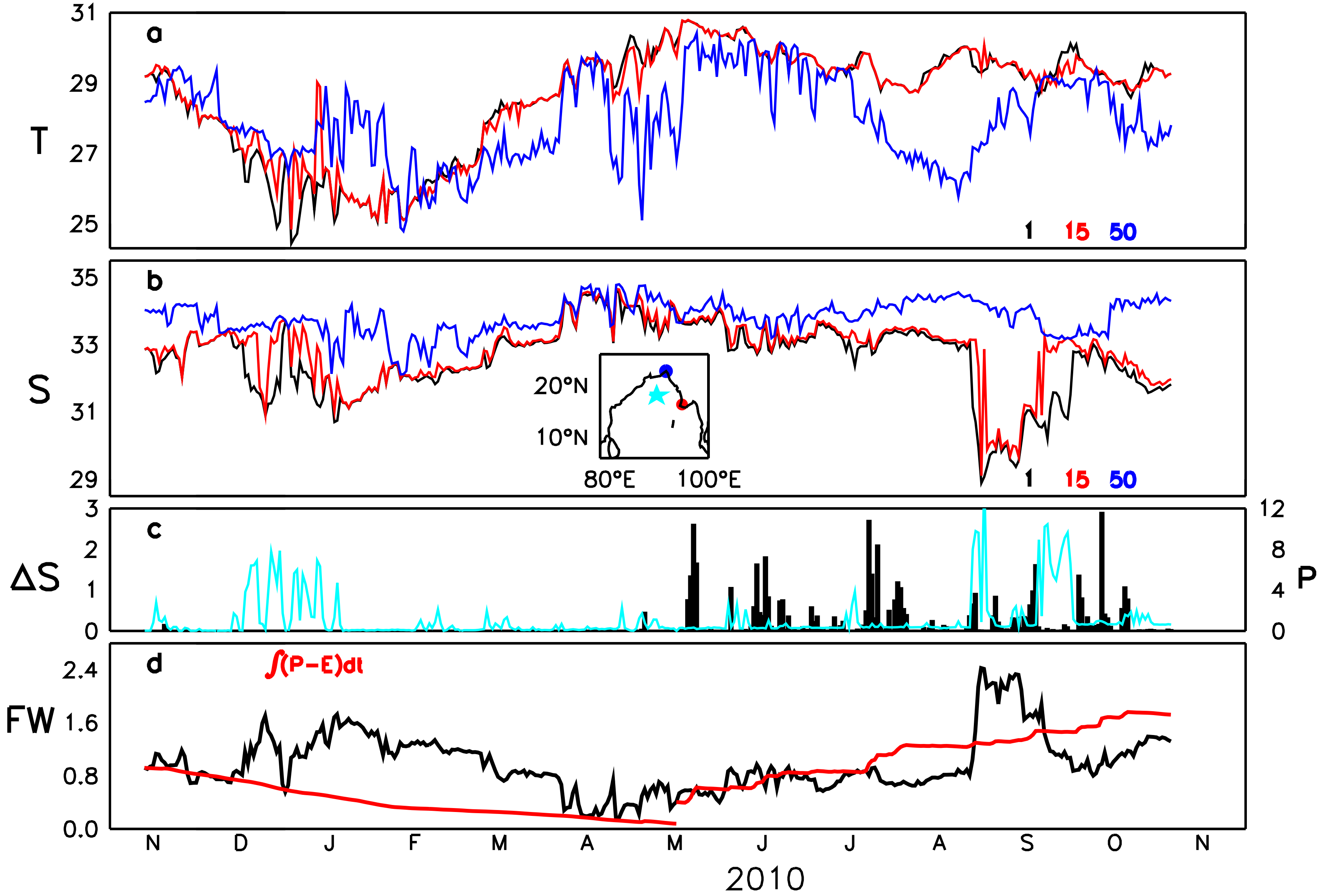
Ganga-Brahmaputra-Meghna river

NASA

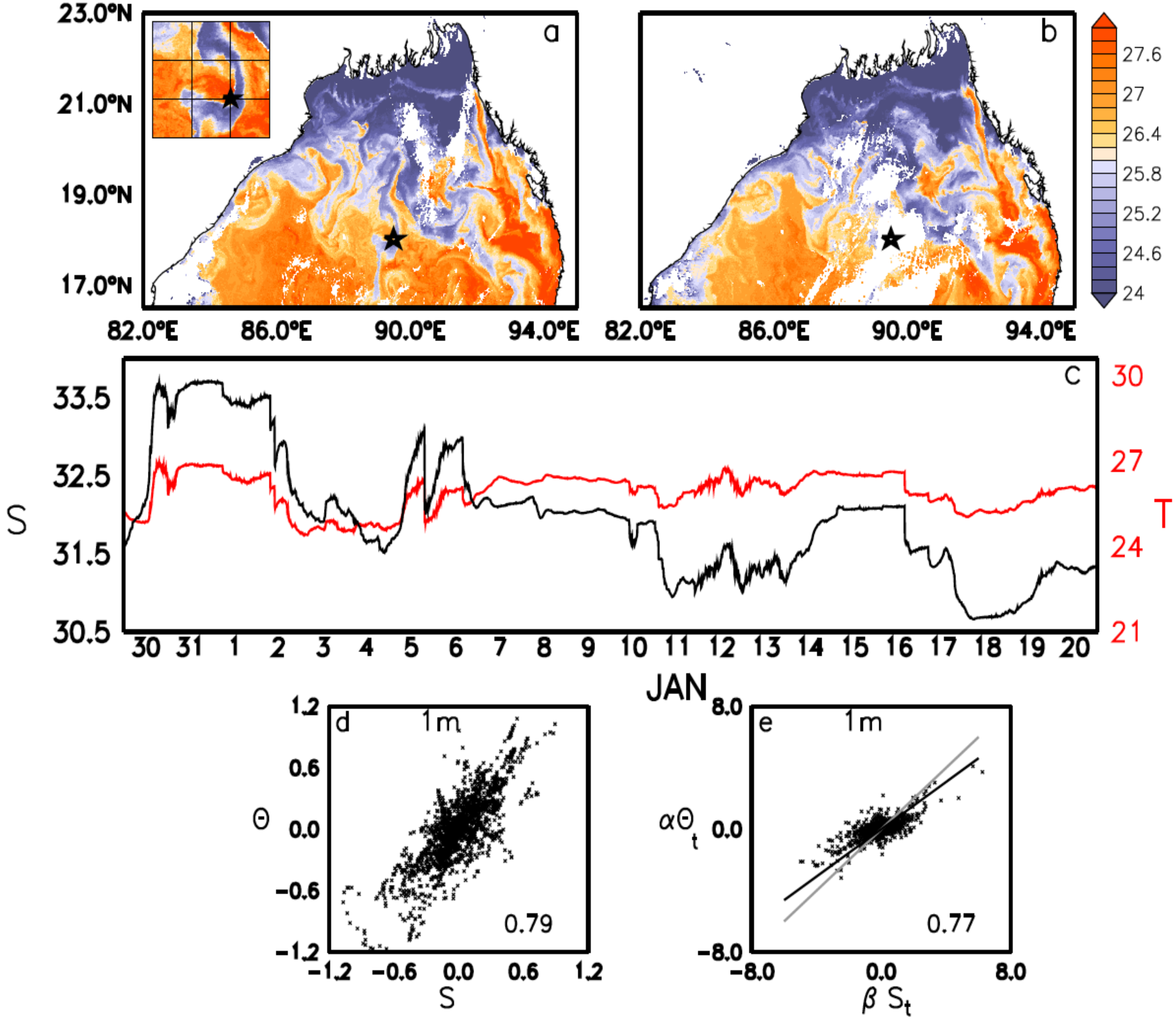
Heat balance



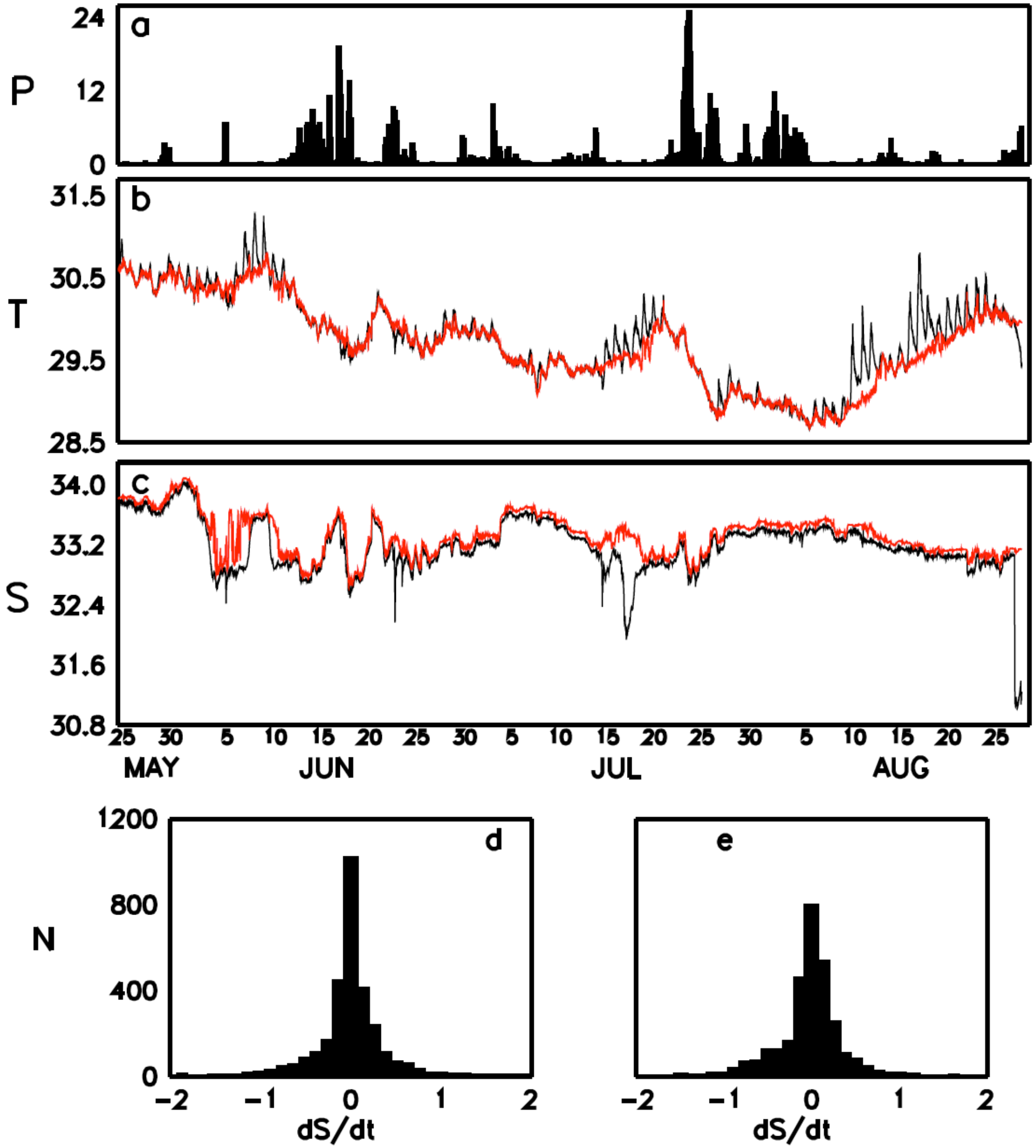
Very shallow mixed layer



a
T
31
29
27
25
1 15 50
b
S
35
33
31
29
20°N
10°N
80°E
100°E
1 15 50
c
ΔS
3
2
1
0
P
12
8
4
0
d
∫(P−E)dt
FW
2.4
1.6
0.8
0.0
N D J F M A M J J A S O N
2010



23.0°N
21.0°N
19.0°N
17.0°N
82.0°E
86.0°E
90.0°E
94.0°E
a
b
27.6
27
26.4
25.8
25.2
24.6
24
c
S
T
33.5
32.5
31.5
30.5
30
27
24
21
30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
JAN
d
1m
Θ
S
0.79
1.2
0.6
0.0
−0.6
−1.2
e
αΘt
β St
0.77
8.0
−8.0

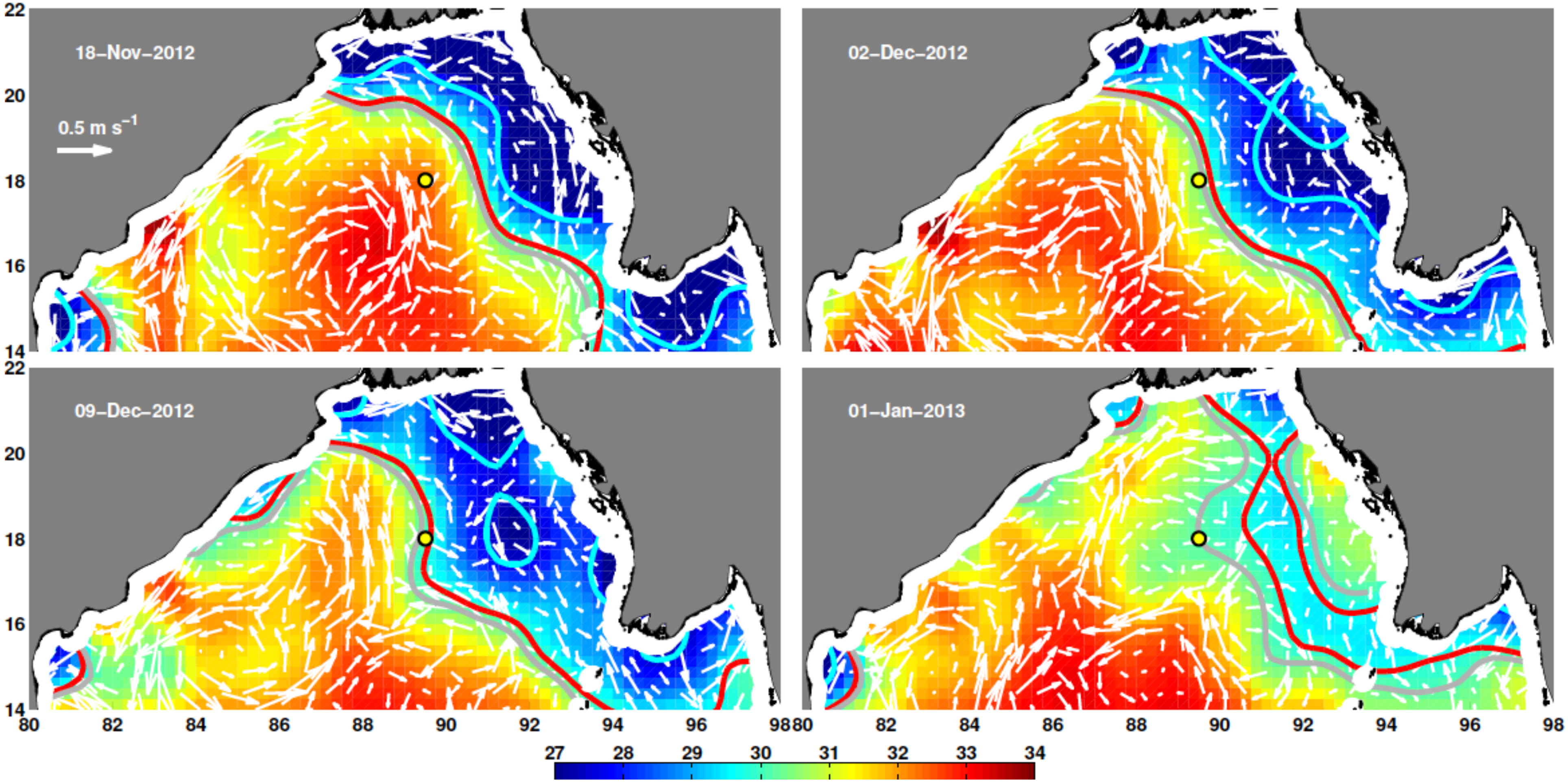


a
b
c
d
e
P
T
S
N
24
12
0
31.5
30.5
29.5
28.5
34.0
33.2
32.4
31.6
30.8
25 30 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25
MAY
JUN
JUL
AUG
1200
800
400
0
−2 −1 0 1 2
dS/dt

Pathway Nov-Dec 2012

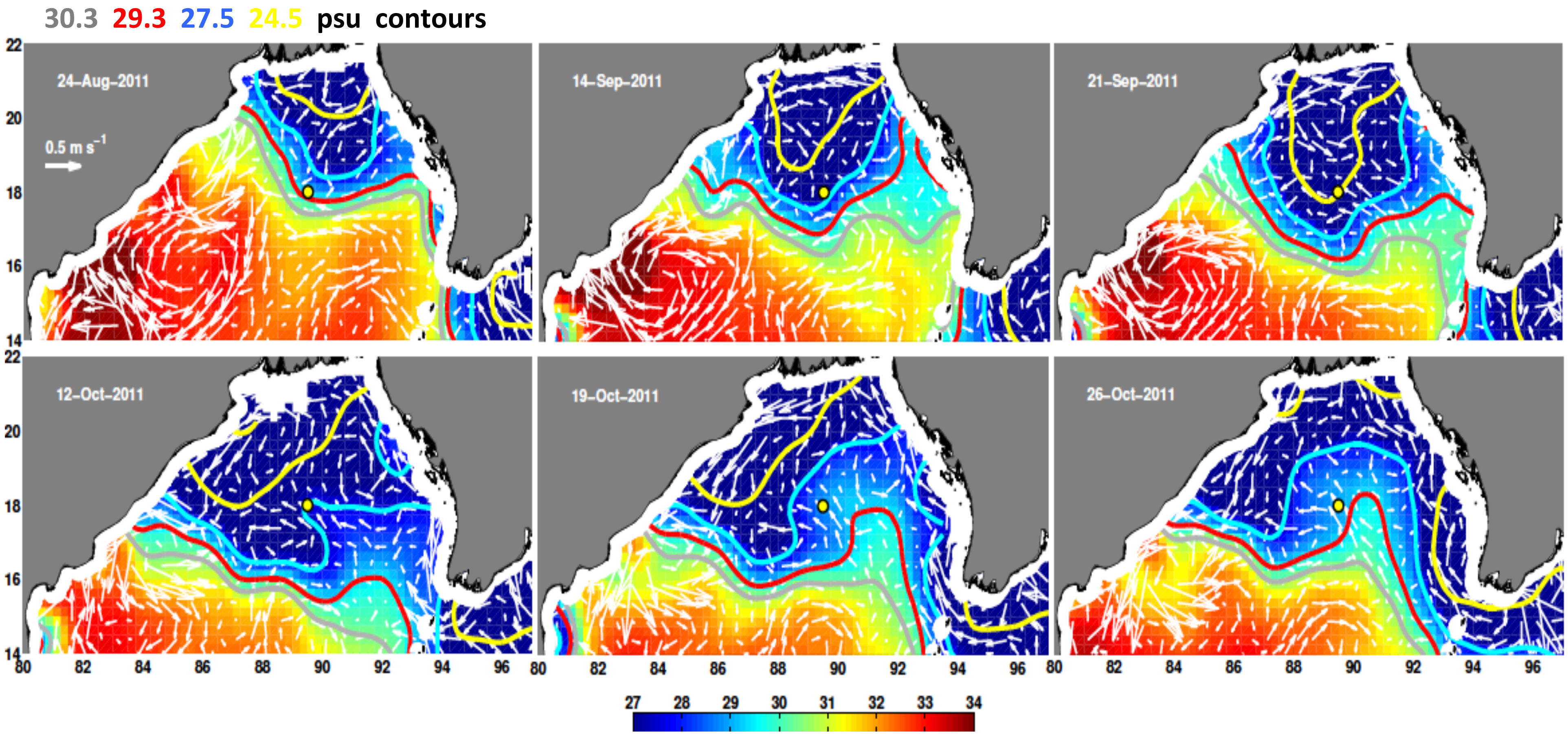
Aquarius sea surface salinity and AVISO geostrophic velocities

30.1 29.7 27.5 psu contours



Freshwater is advected by basin-scale flow and stirred by 200-400 km eddies.
Winter pulse from Andaman sea, Irrawady water.

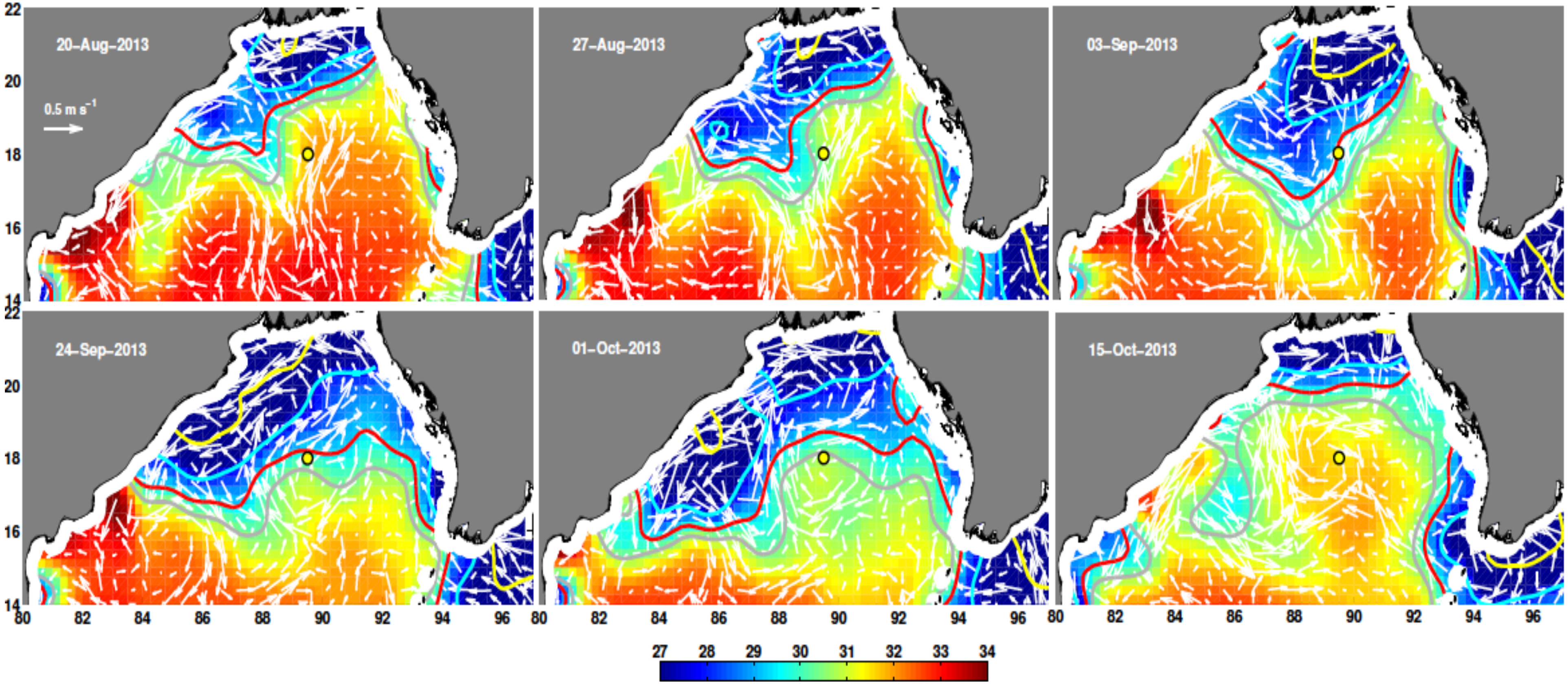
Pathway Aug-Sep 2011



Ganga-Brahmaputra-Meghna water flows down the center of the Bay.

Pathway Aug-Sep 2013

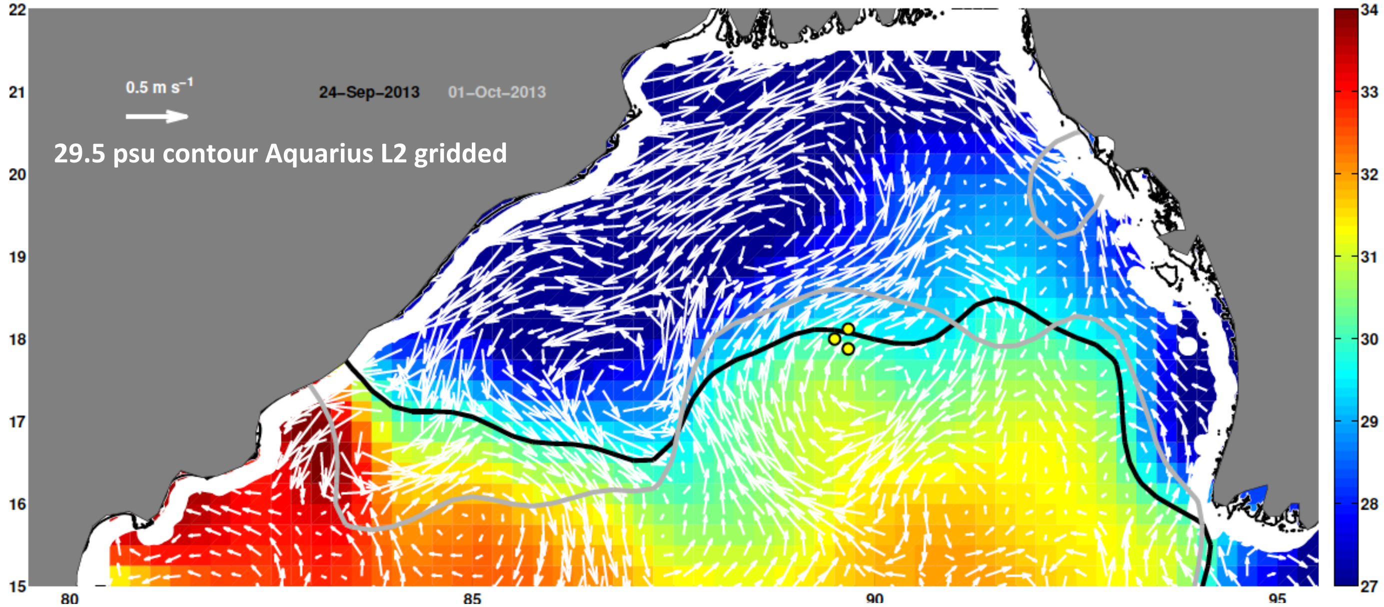
30.3 29.3 27.5 24.5 psu contours



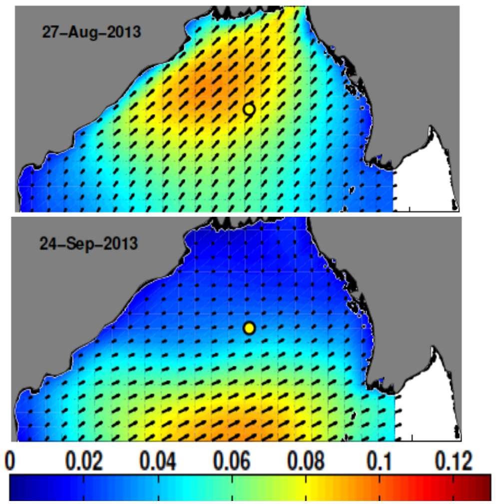
Ganga-Brahmaputra-Meghna water takes a longer path along the western boundary.

Murty et al., 1992 Gopalakrishna *et.al* 2001 Vinayachandran *et.al* 2002

Eddy Stirring: Salting episode 2013

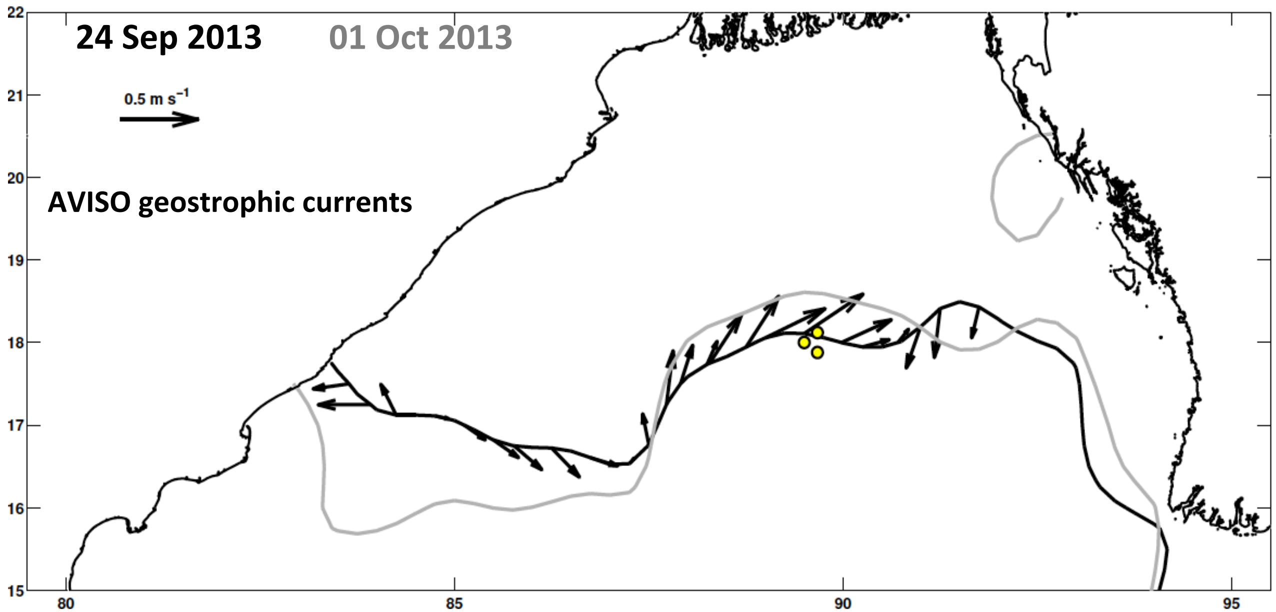


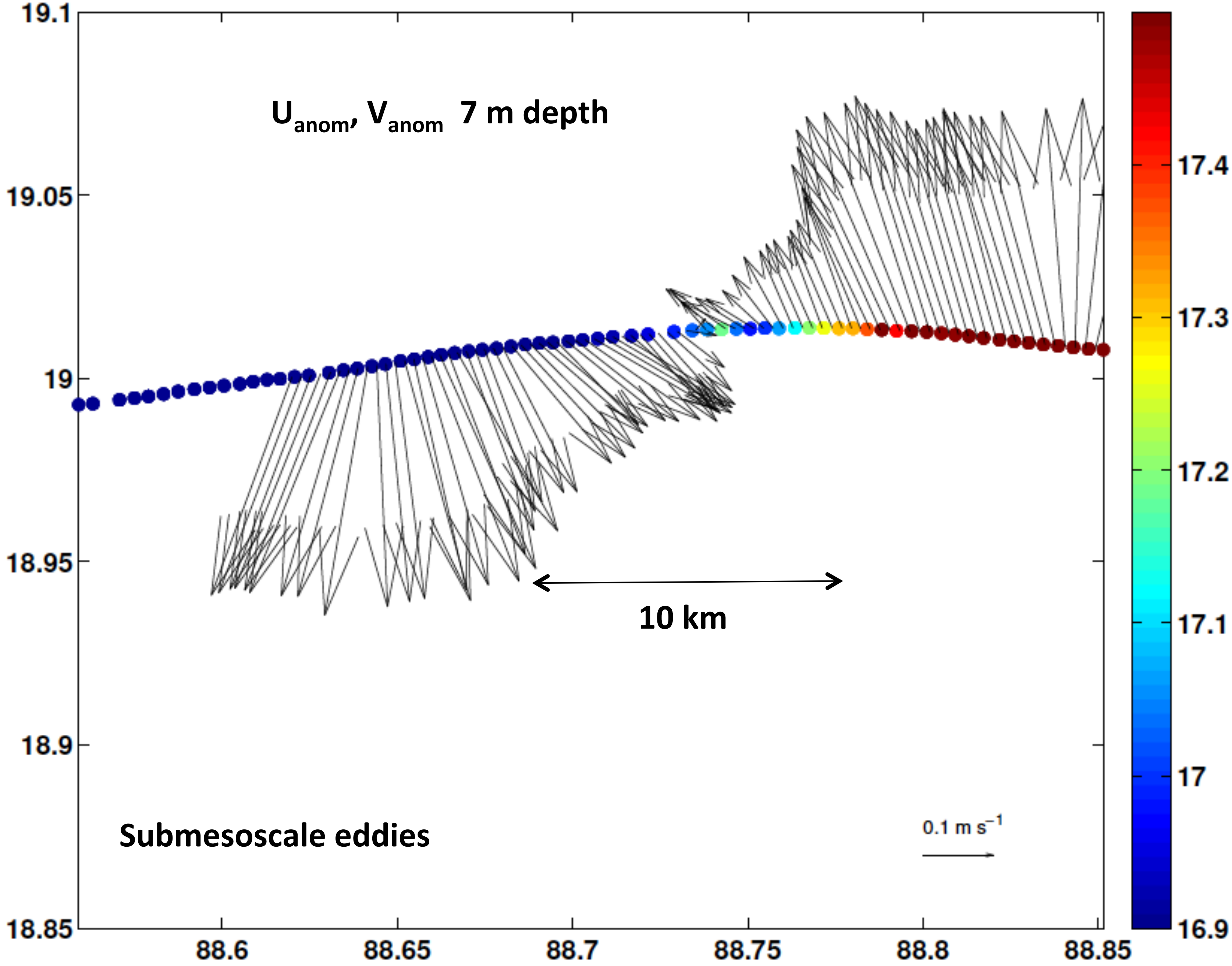
MERRA Wind stress (N/m²)



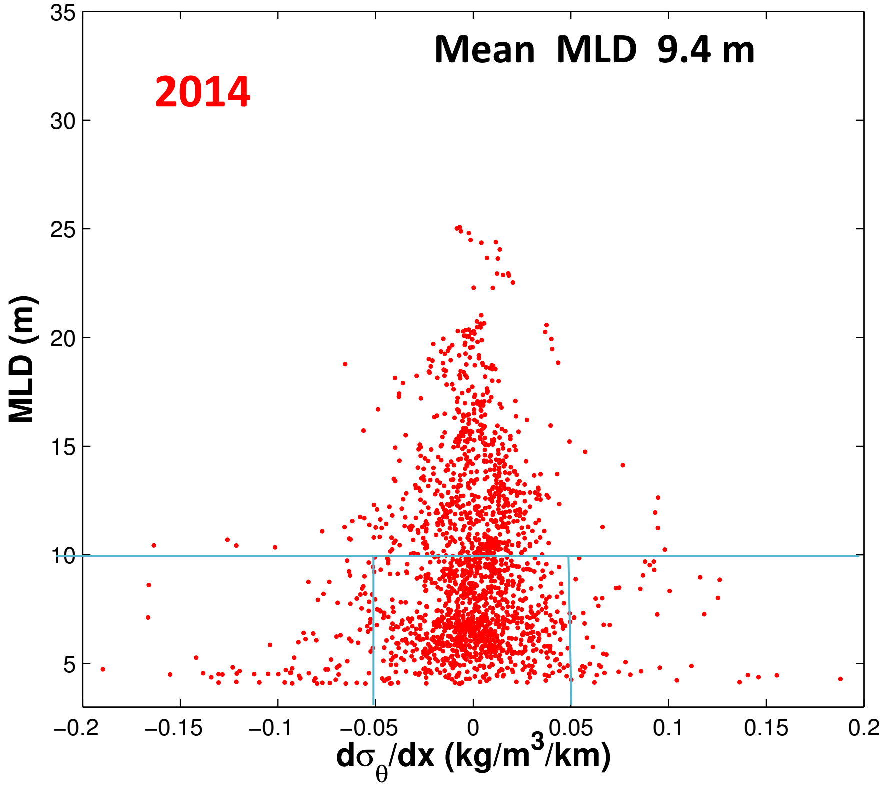
Weak winds 5.2 m/s

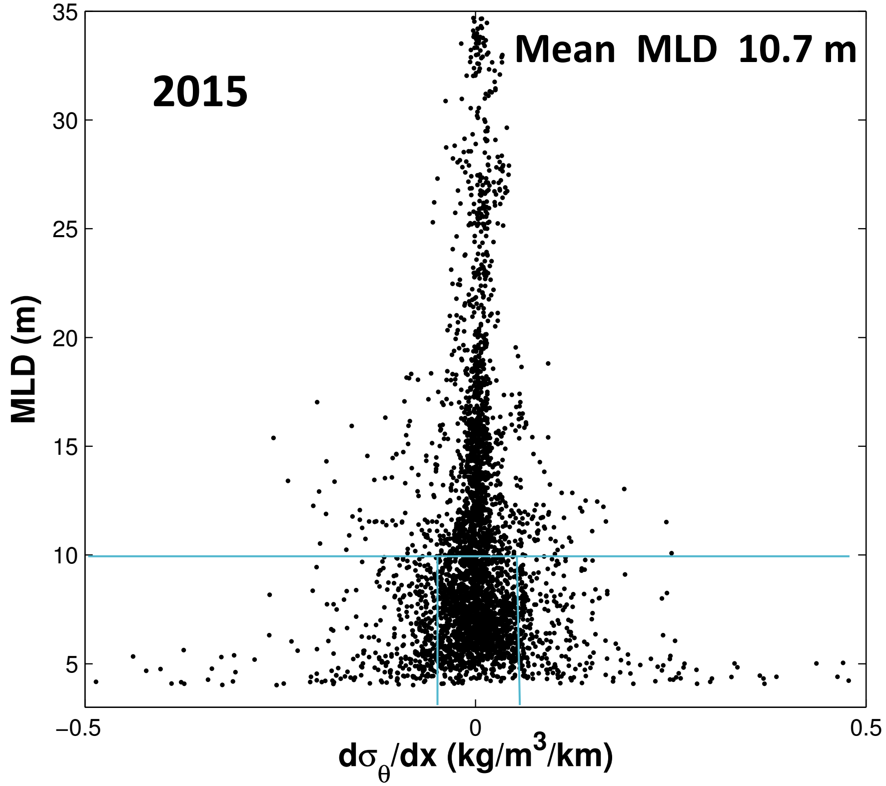
Advection by geostrophic currents





U_{anom}, V_{anom} 7 m depth
10 km
Submesoscale eddies
0.1 m s^{-1}
19.1
19.05
19
18.95
18.9
18.85
88.6
88.65
88.7
88.75
88.8
88.85
17.4
17.3
17.2
17.1
17
16.9

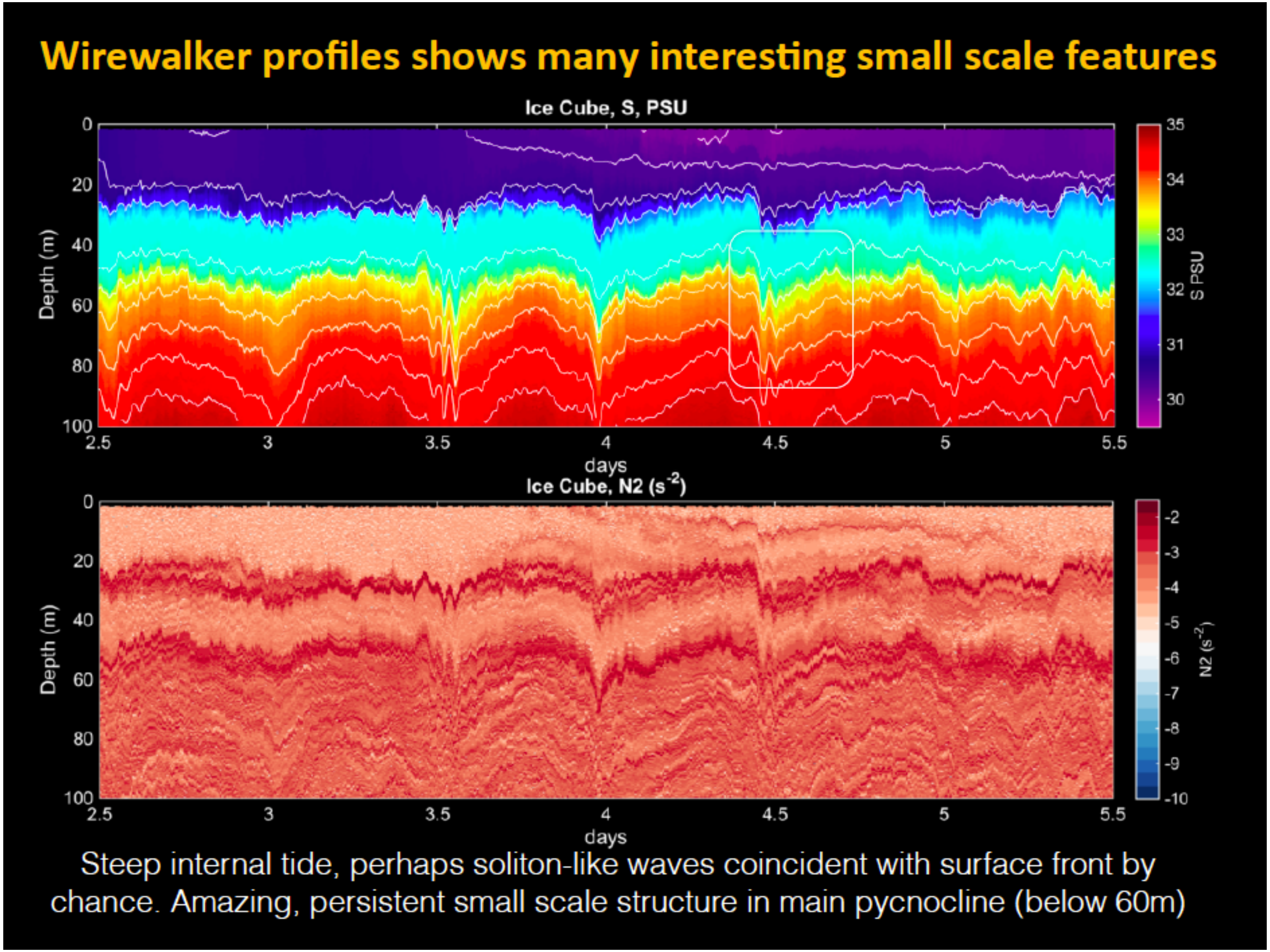




$\sigma_{mld} - \sigma_{4m} = 0.03$ kg/m^3

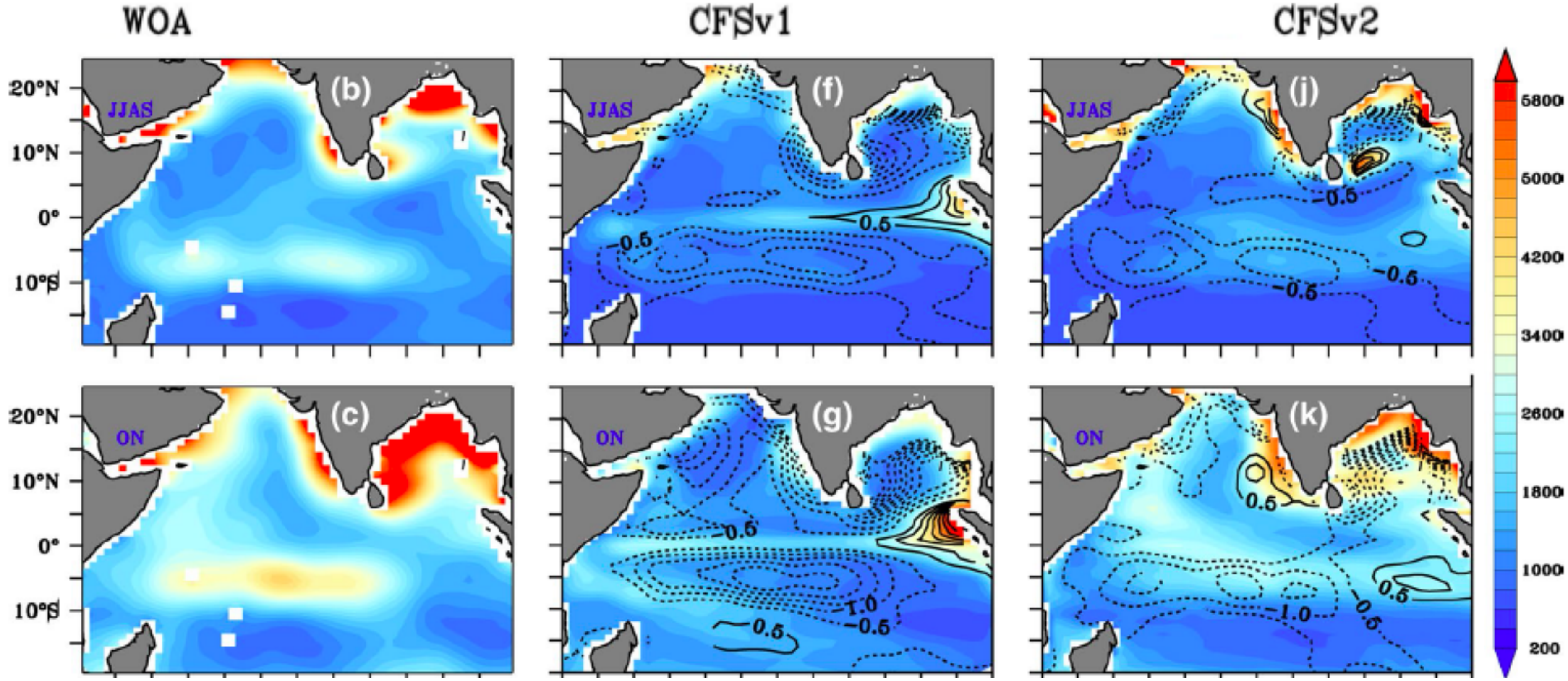
	$\lvert d\sigma_\theta/dx\rvert > 0.05$	$\lvert d\sigma_\theta/dx\rvert < 0.05$
MLD Mean	7 m 8 m	10 m 12 m
MLD Stdev	3 m 3 m	4 m 6 m

If $\lvert d\sigma_\theta/dx\rvert > 0.05$ kg/m^3 per km, mixed layer depth is less than 10 m 84 % of the time

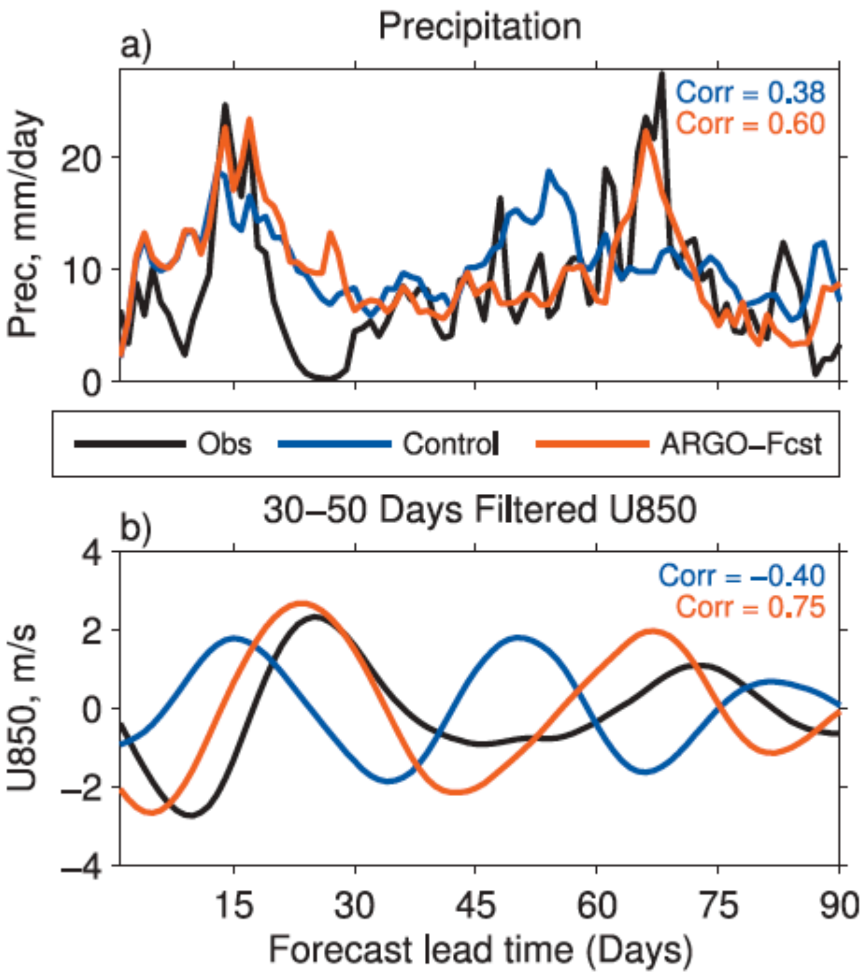


Courtesy: Drew Lucas

Energy required for mixing (ERM) J/m^2; model ERM bias in contours

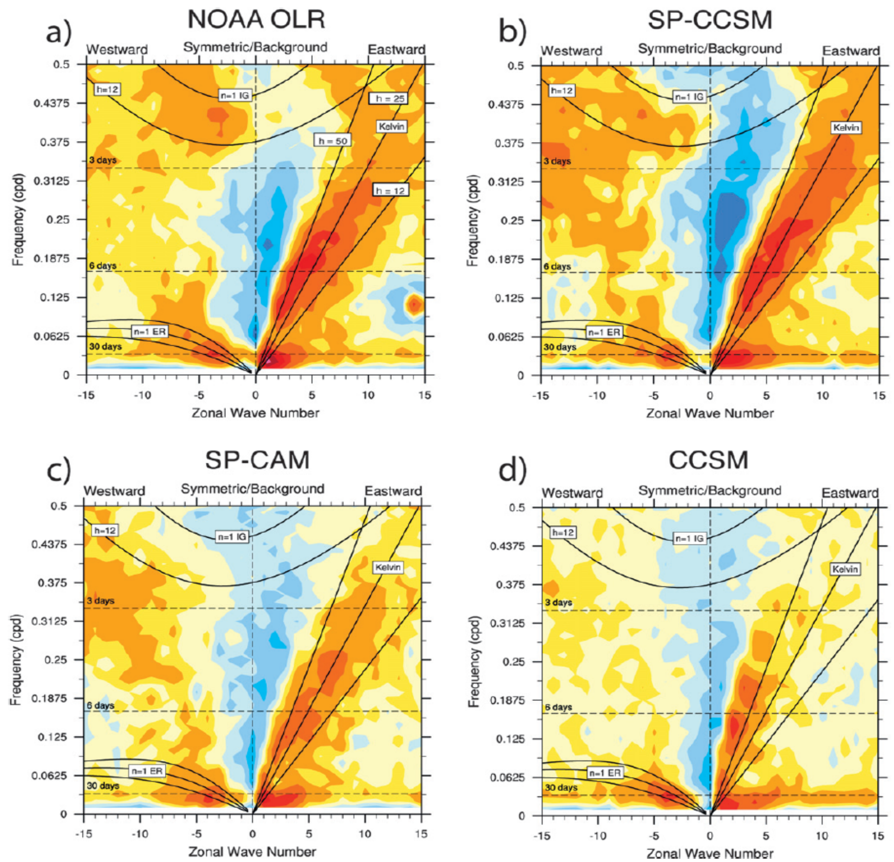


Parekh *et.al* 2015



P and U850 70-90E 15-25N

30 May – 27 Aug 2004



Assimilation of global ARGO subsurface obs to create ocean ICs improves forecast skill

Krishnamurti *et.al* 2007

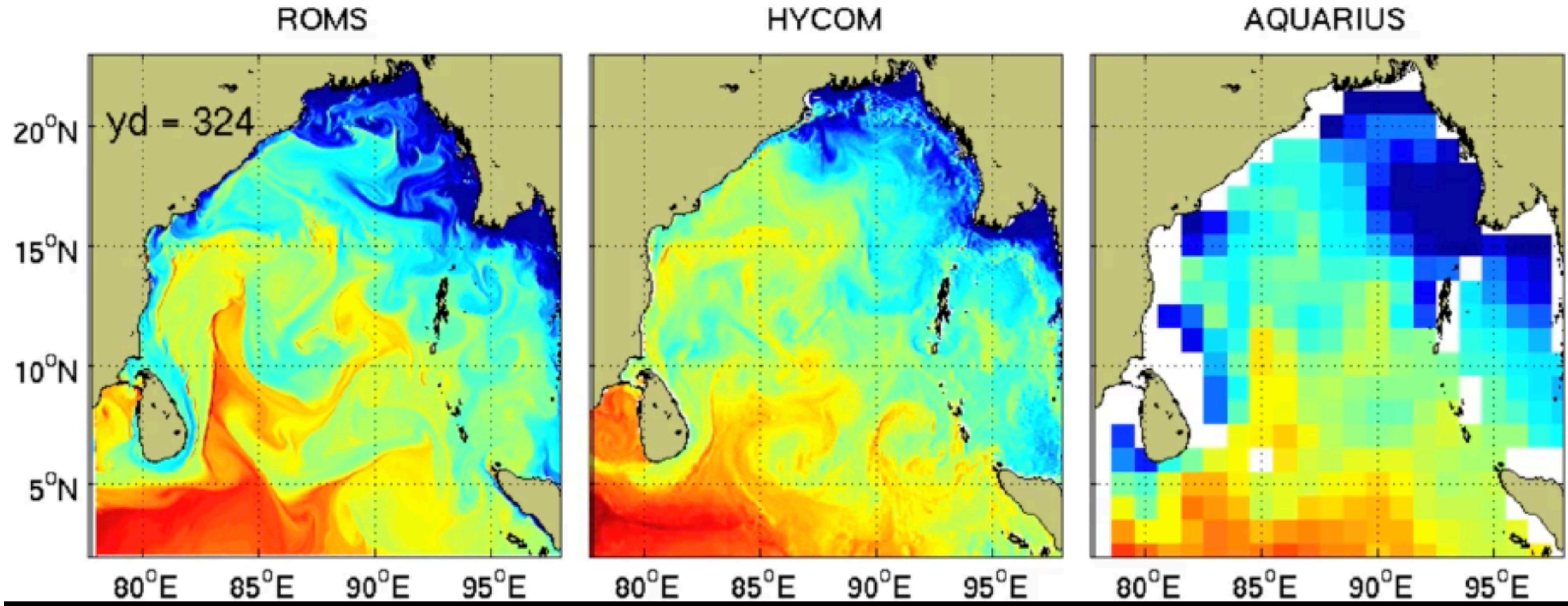
Coupling improves CCEW

DeMott *et. al* 2011

BoB variability at many scales is poorly known: Modeling

BoB Eddy rich at O(100km scales)

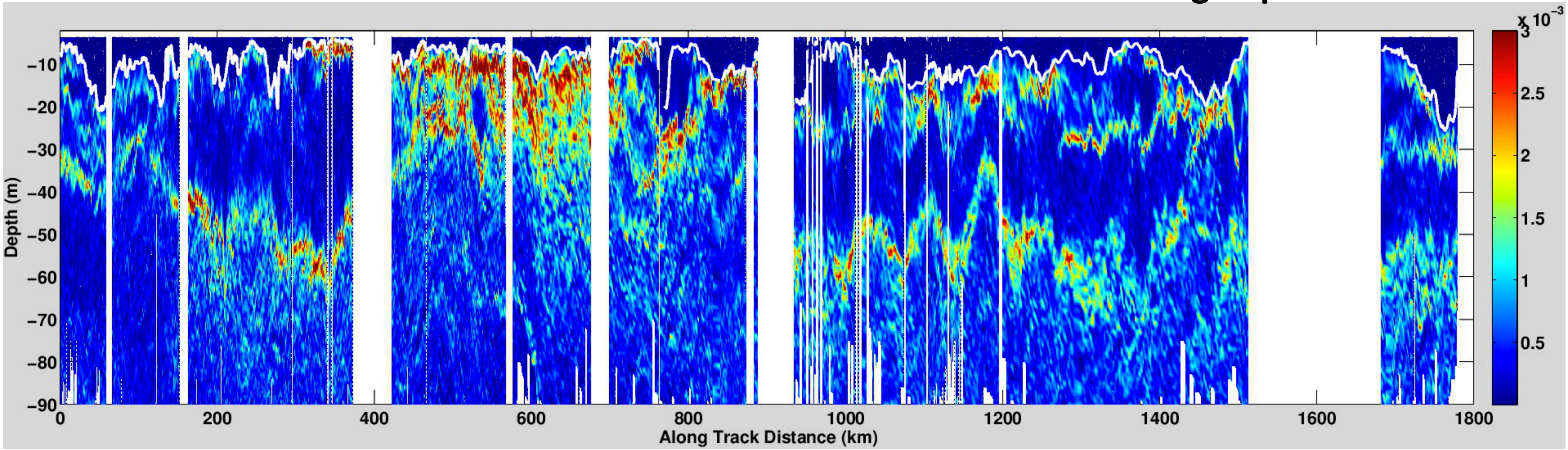
Hints of strong horizontal salinity and density gradients at O(1-10km) scales



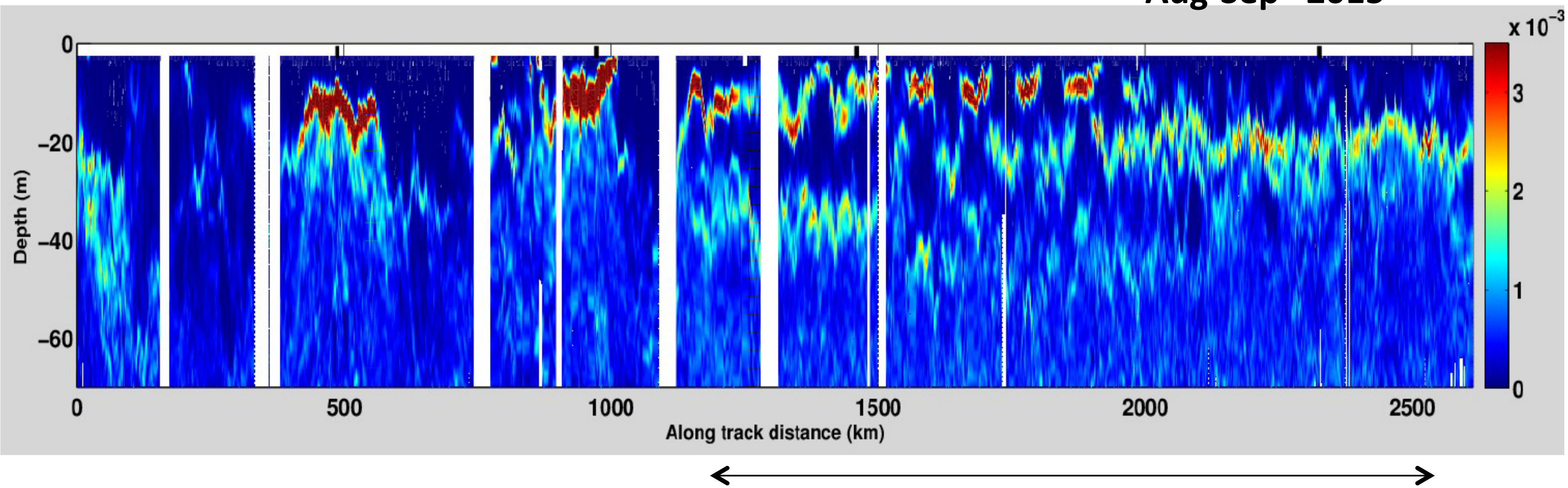
Models and remote imagery often miss stirring & mixing at smaller scales, which have a strong impact on stratification

Brunt Vaisala Frequency $N^2 = -g/\rho\ (d\rho/dz)$

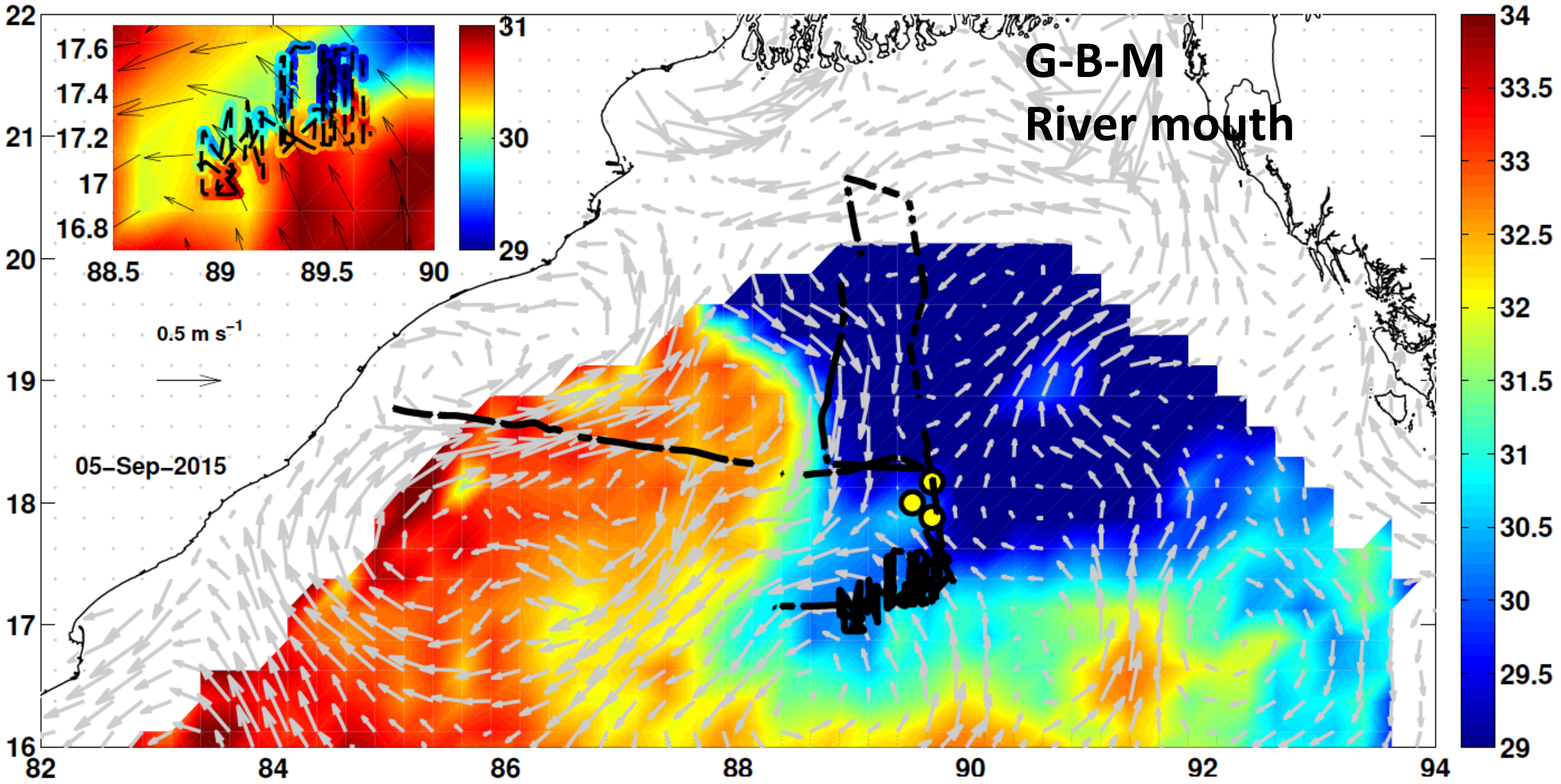
Aug-Sep 2014



Aug-Sep 2015



Two ship experiments

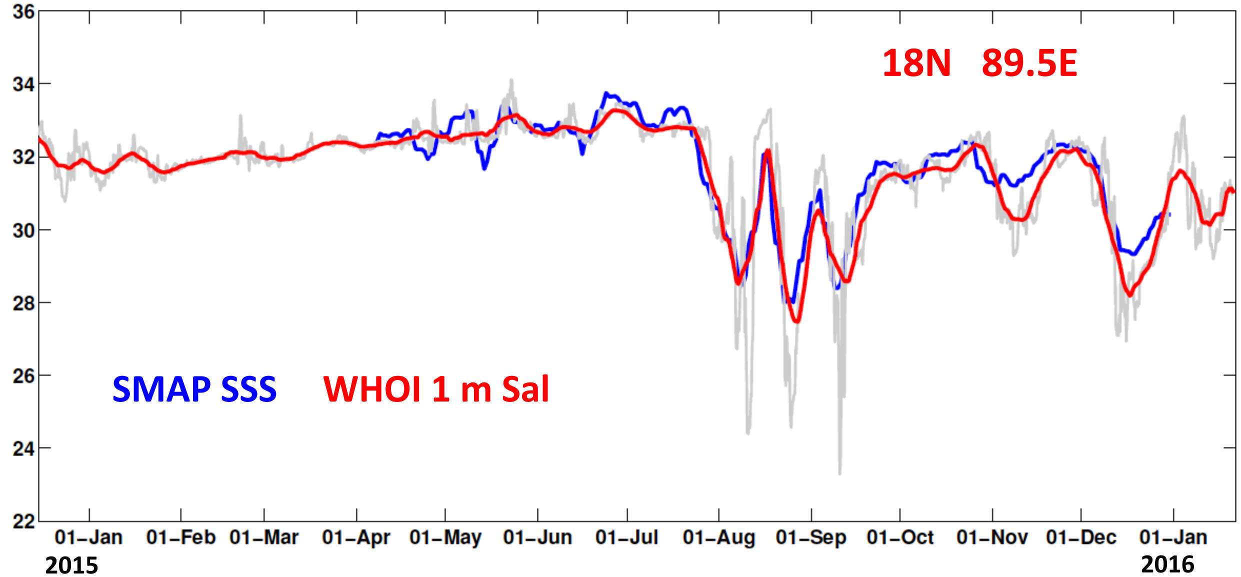


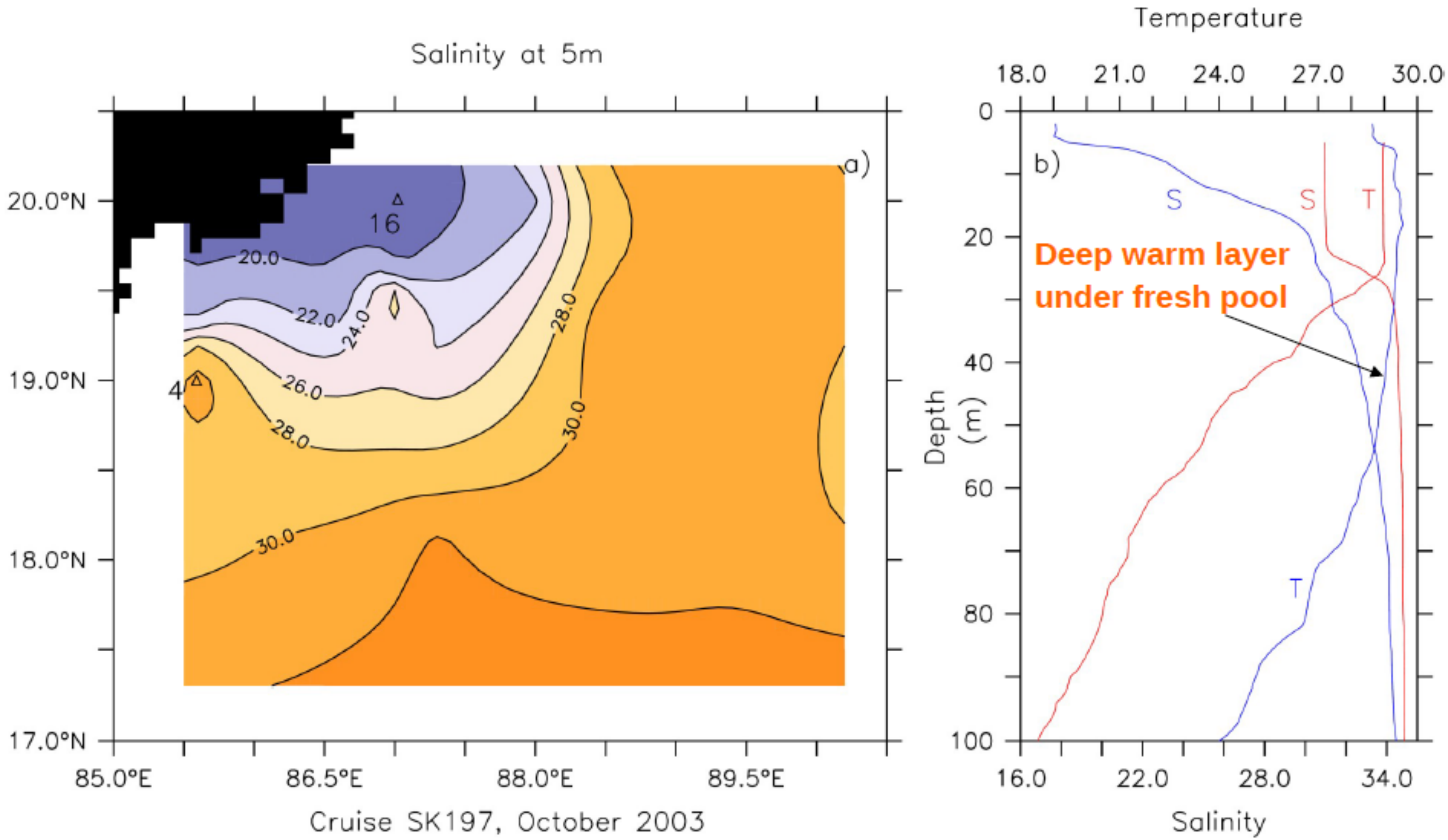
SMAP SSS

5 Sep 2015

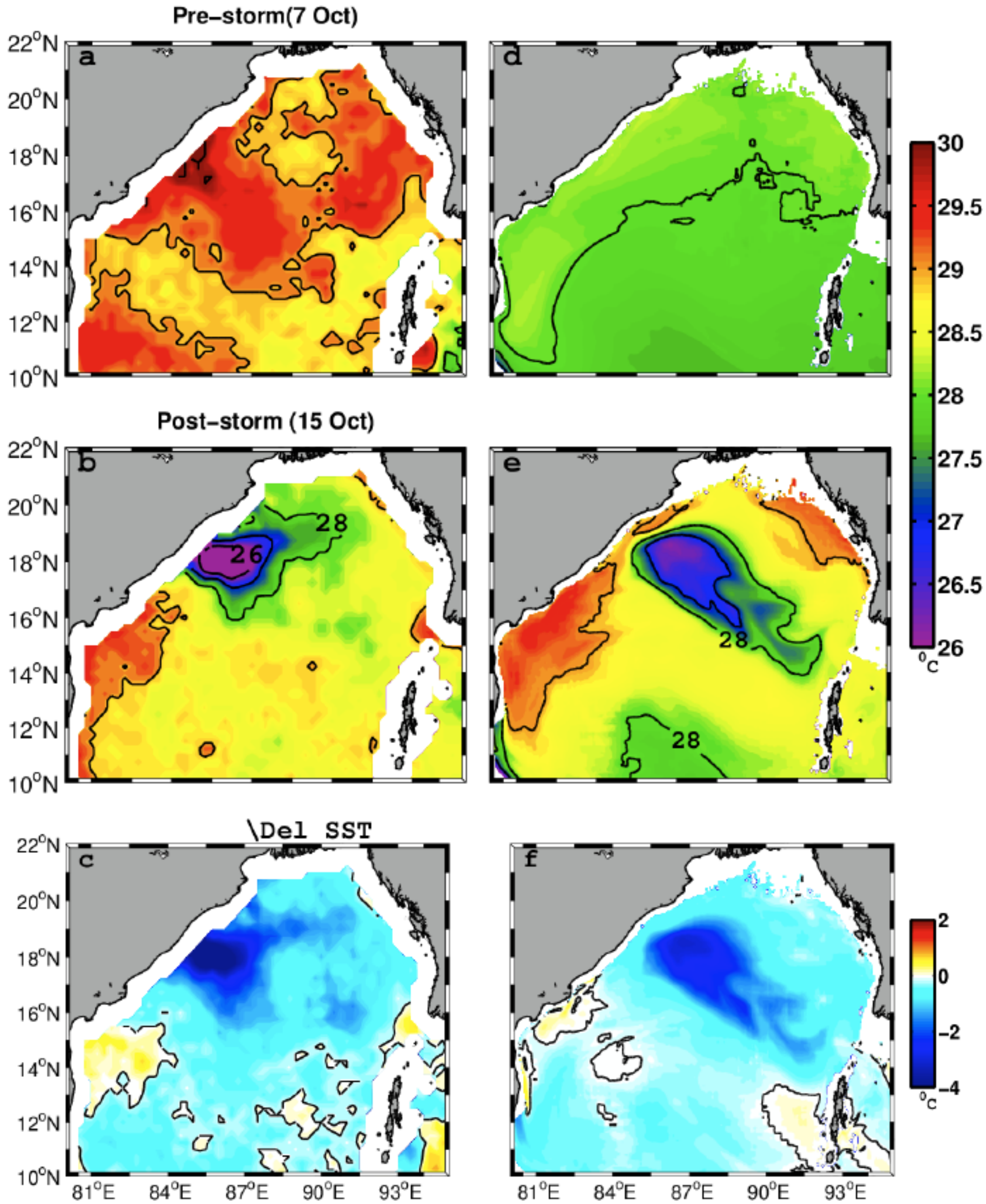
Soil Moisture Active Passive (SMAP) L3 data

0.25° x 0.25° resolution; 8 day running averages



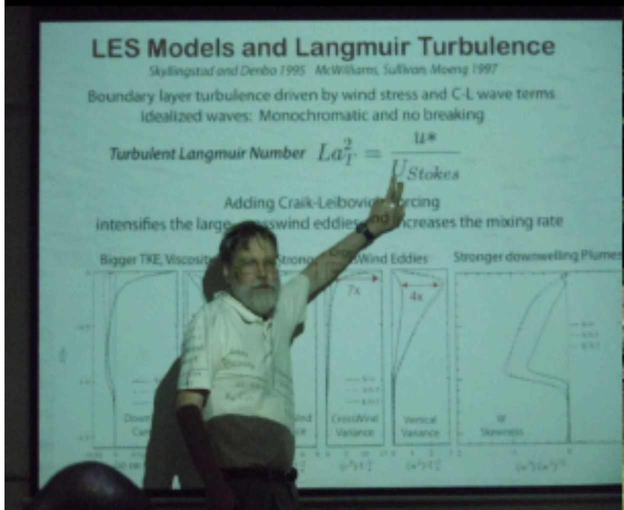


Deep warm layer under fresh pool due to penetrative sunlight and surface cooling



Pre-storm(7 Oct)
Post-storm (15 Oct)
\Del SST
a
b
c
d
e
f
28
26
22°N
20°N
18°N
16°N
14°N
12°N
10°N
81°E
84°E
87°E
90°E
93°E
30
29.5
29
28.5
28
27.5
27
26.5
26
°C
2
0
−2
−4

Shipboard training and research on joint cruises: Nov-Dec 2013, June 2014, August 2014, November 2014, August-September 2015



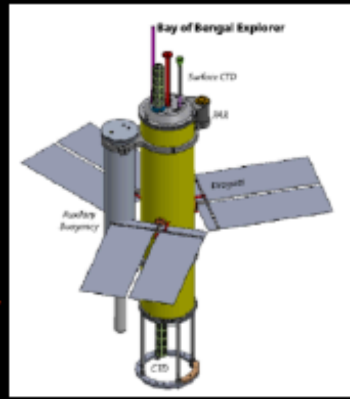
Bay of Bengal Upper Ocean Physics Workshop IISc Bengaluru July 9-21, 2014

Also, Marine Mammal Workshop NCBS India by ASIRI PIs

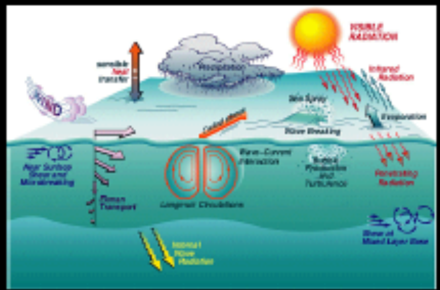
Observational Tools

Long term endurance gliders Spray (left) and Seaglider (right) measure subsurface temperature and salinity structure.

Lagrangian float follows density or pressure levels while taking measurements and is remotely programmable.



Lagrangian drifters measure near-surface ocean currents, atmospheric pressure, sea surface temperature and sea surface salinity

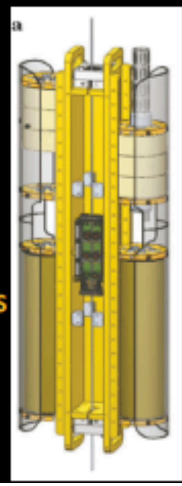


Air-sea flux mooring measures air-sea exchange of heat, momentum, and freshwater and temperature, salinity, and velocity in the ocean.

Turbulent motions are being measured from moorings, CTD rosettes, and autonomous profilers using chipods.

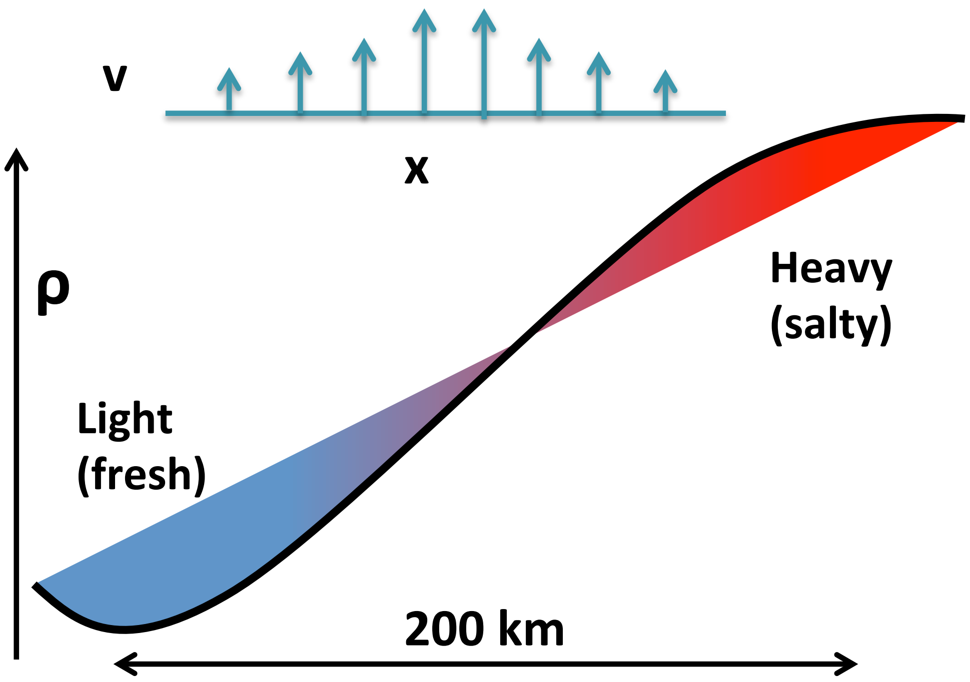
Slocum turbulence glider measures microstructure shear and mixing.

Surface wave-driven wirewalker measures temperature, salinity, currents and optical variables at cm scale resolution

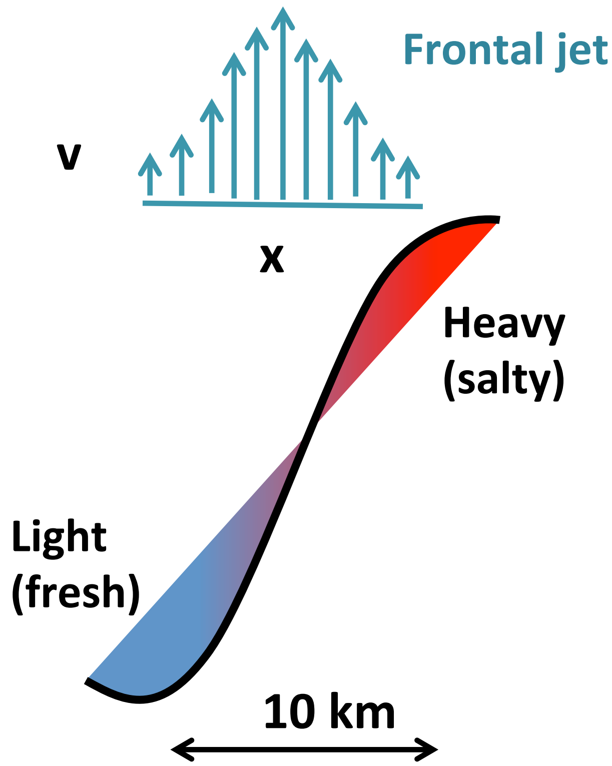


Lateral scales

Mesoscale Order 100 km
Ro << 1 weak lateral shear

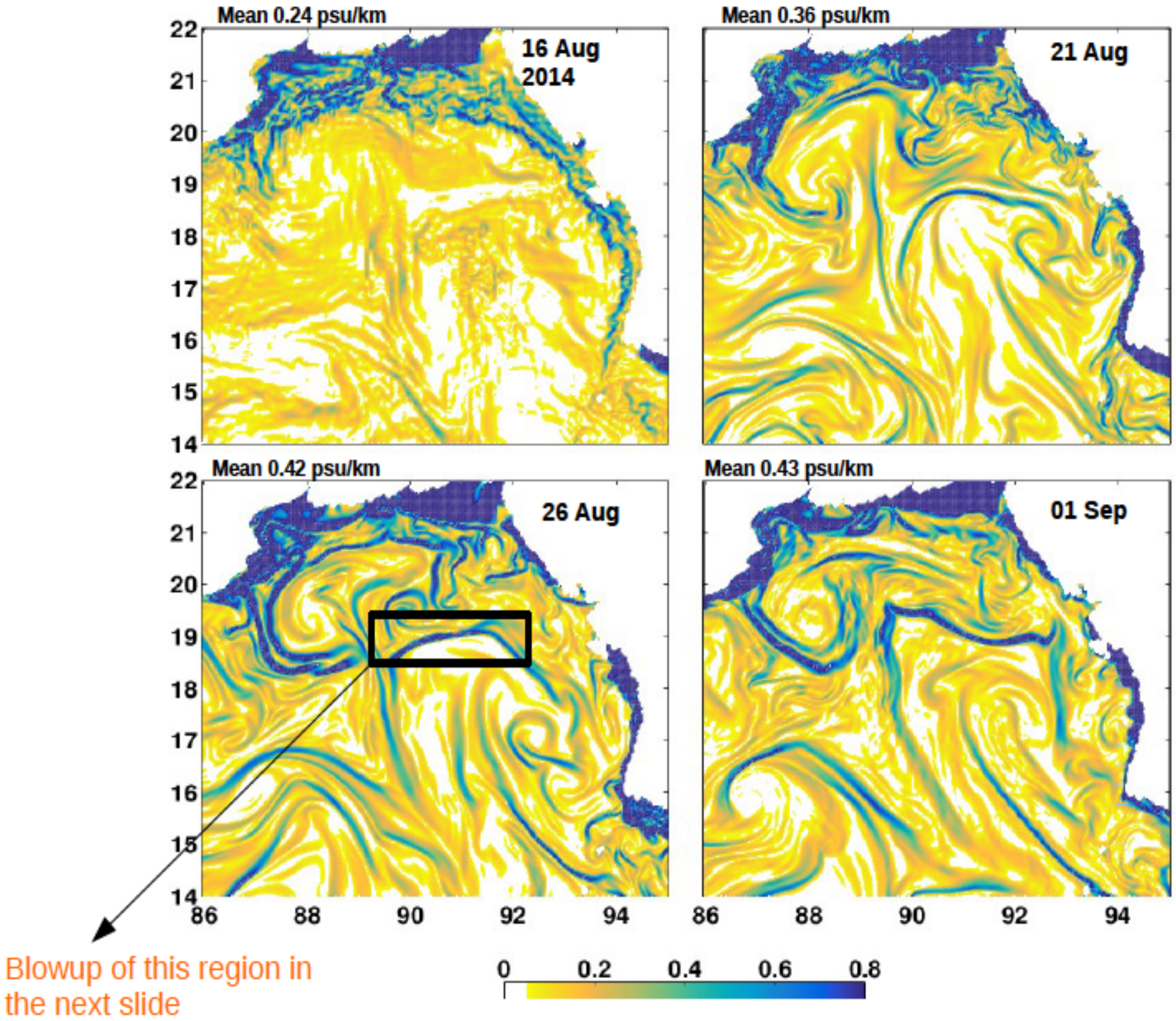


Sub-mesoscale Order 1-10 km
Ro O(1) strong lateral shear



Slumping of sub-mesoscale fronts creates shallow stratification, *T* O(1) day

Tandon Garrett 1995 Mahadevan Tandon 2006
Thomas 2007 D'Asaro 2013



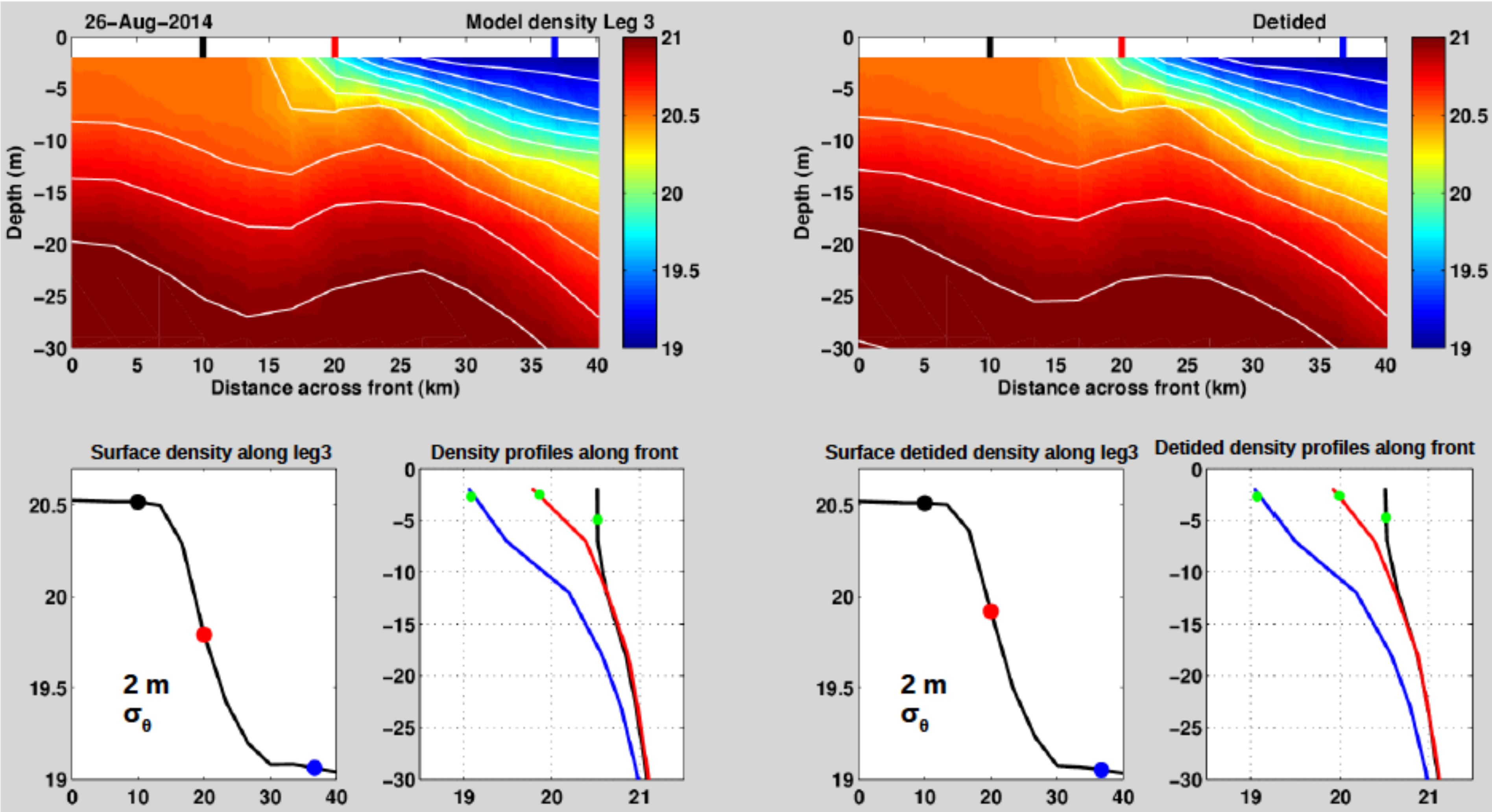
Model 2 m S

Magnitude of horizontal gradient

psu/km

Lateral salinity gradients sharpened by mesoscale flow (see slide 1)

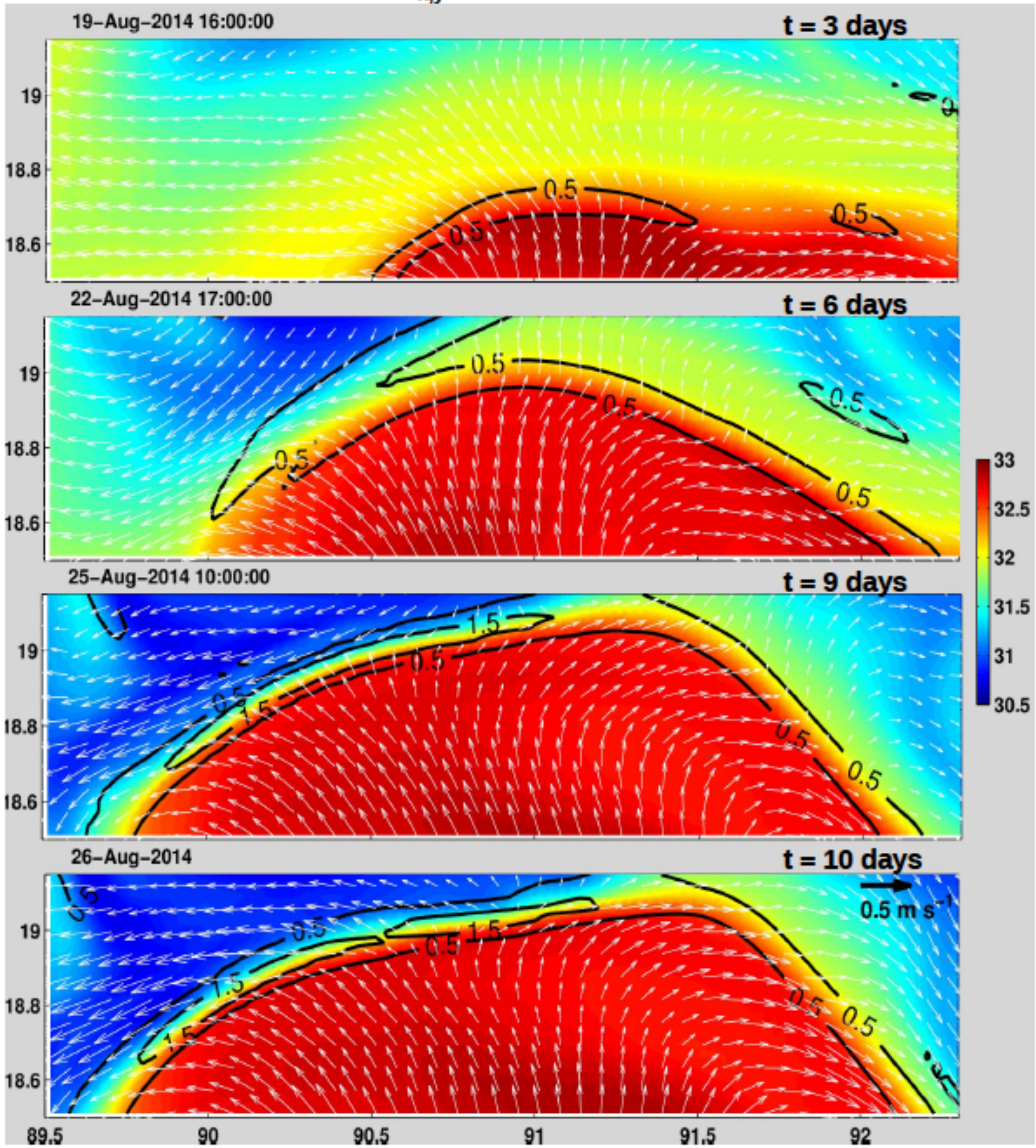
The domain average gradient magnitude increases 2 times from t=0 to t=15 days



The green dots on the density profiles indicate the mixed layer depth (m), calculated using the criteria σ_{mld}-$\sigma_{surface}$ = 0.3 kg/m^3

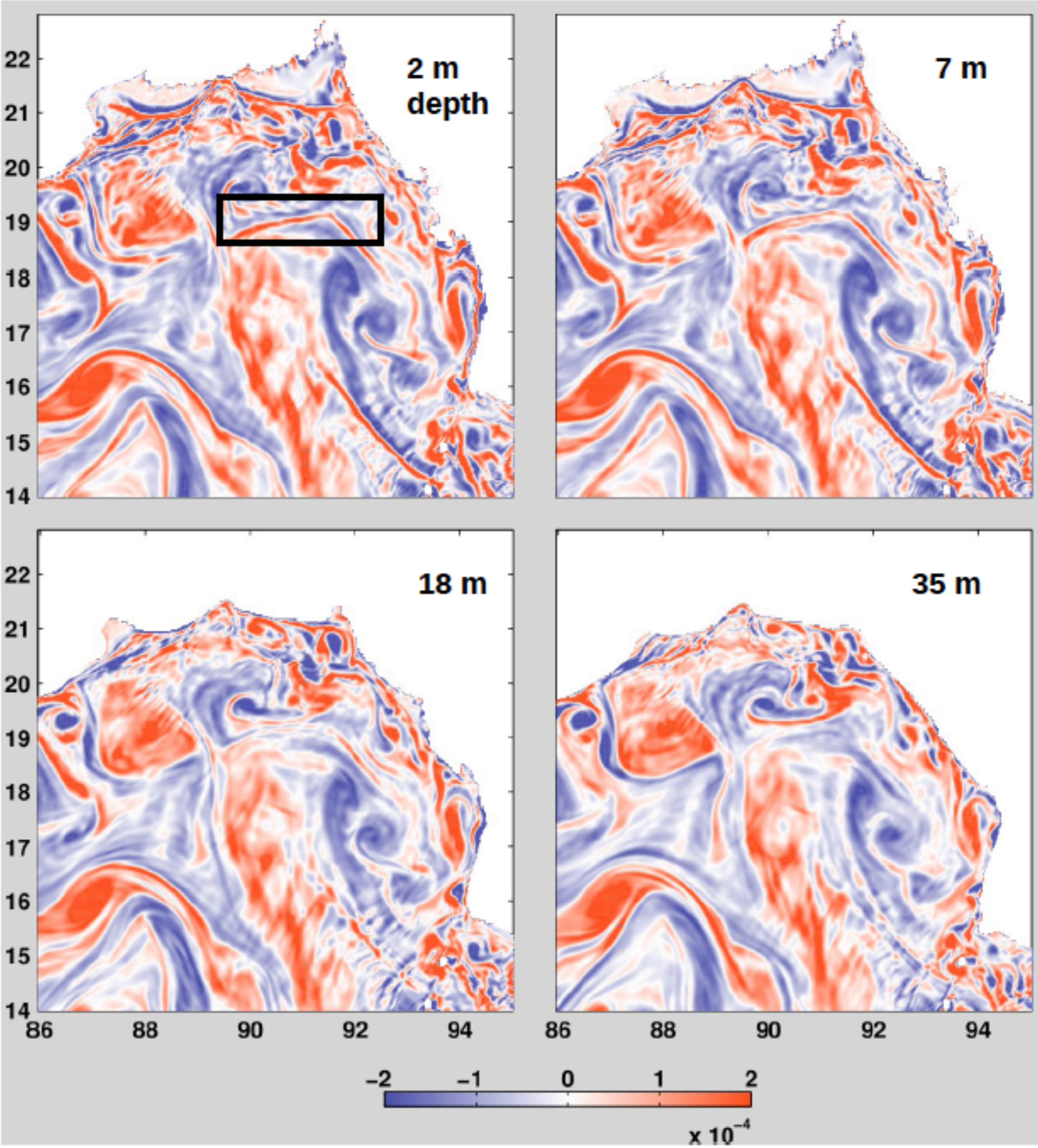
The mixed layer is shallow on the fresher side and under the front than on the saltier side.

2 m salinity (psu; color); $|gradS_{x,y}|$ (psu/km; black contour); current vectors (detided)



The front is formed due to confluence by mesoscale eddies.

By t=10 days, the magnitude of horizontal salinity gradient across the front strengthens (2 psu/km)



Vorticity
ζ (s^{-1})

t = 15 days

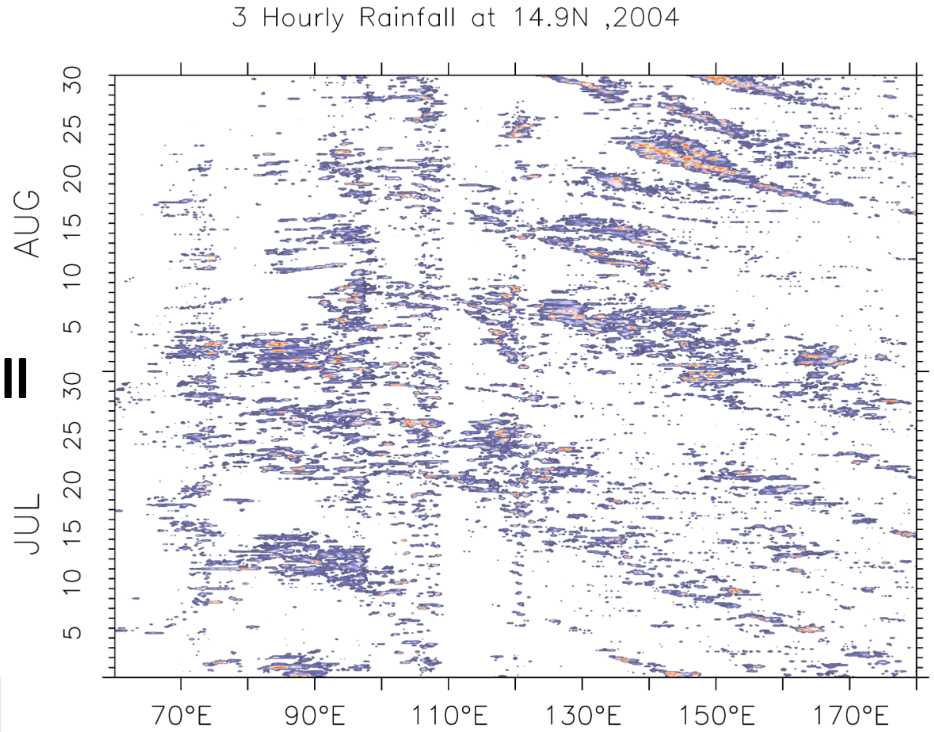
26 Aug 2014

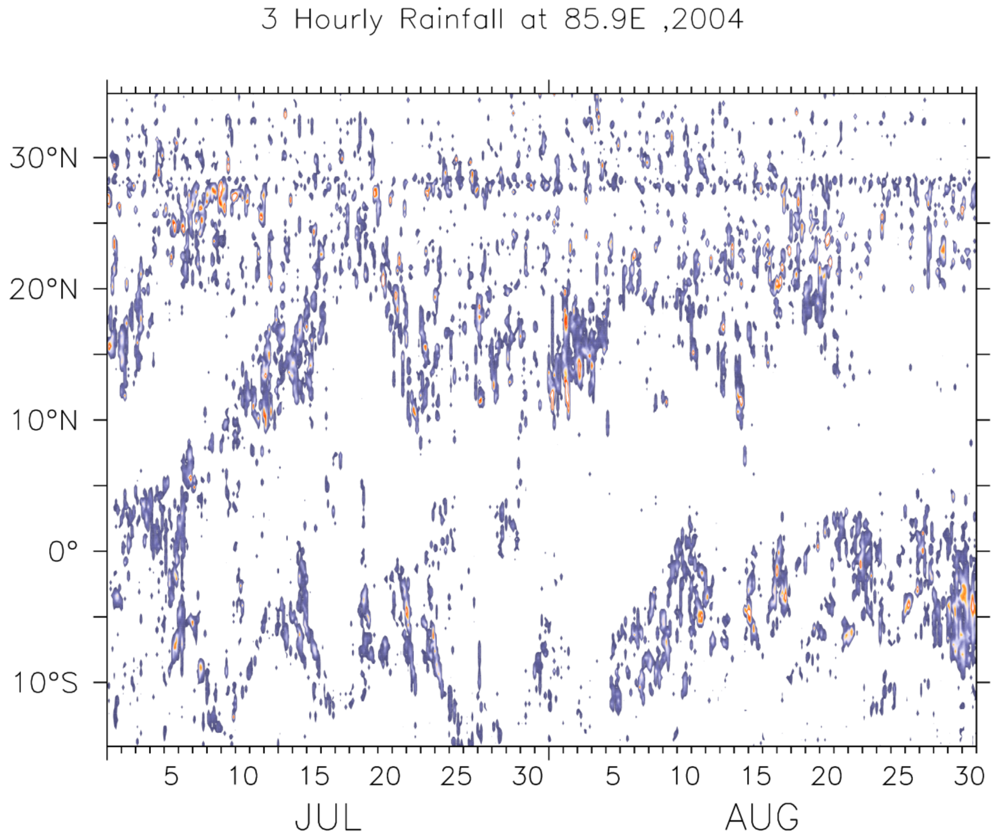
ζ/f ranges from -3 to 3

The vorticity at different depths suggest that the submesocale (order 10 km) frontal regions associated with high positive vorticity are confined to the upper 10 m.

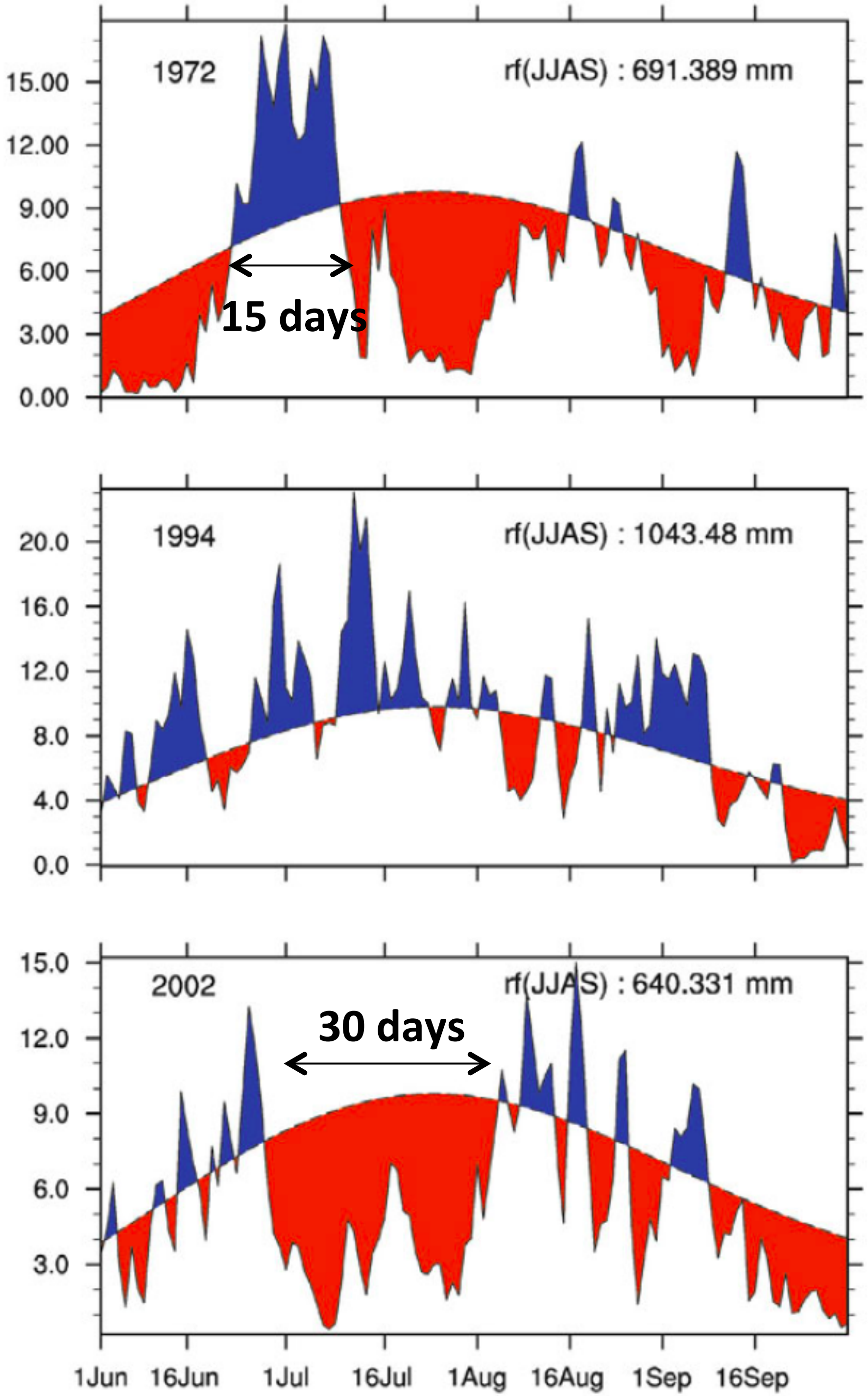
15 N

Jul-Aug 2004   TRMM 3-hourly rainfall





86 E

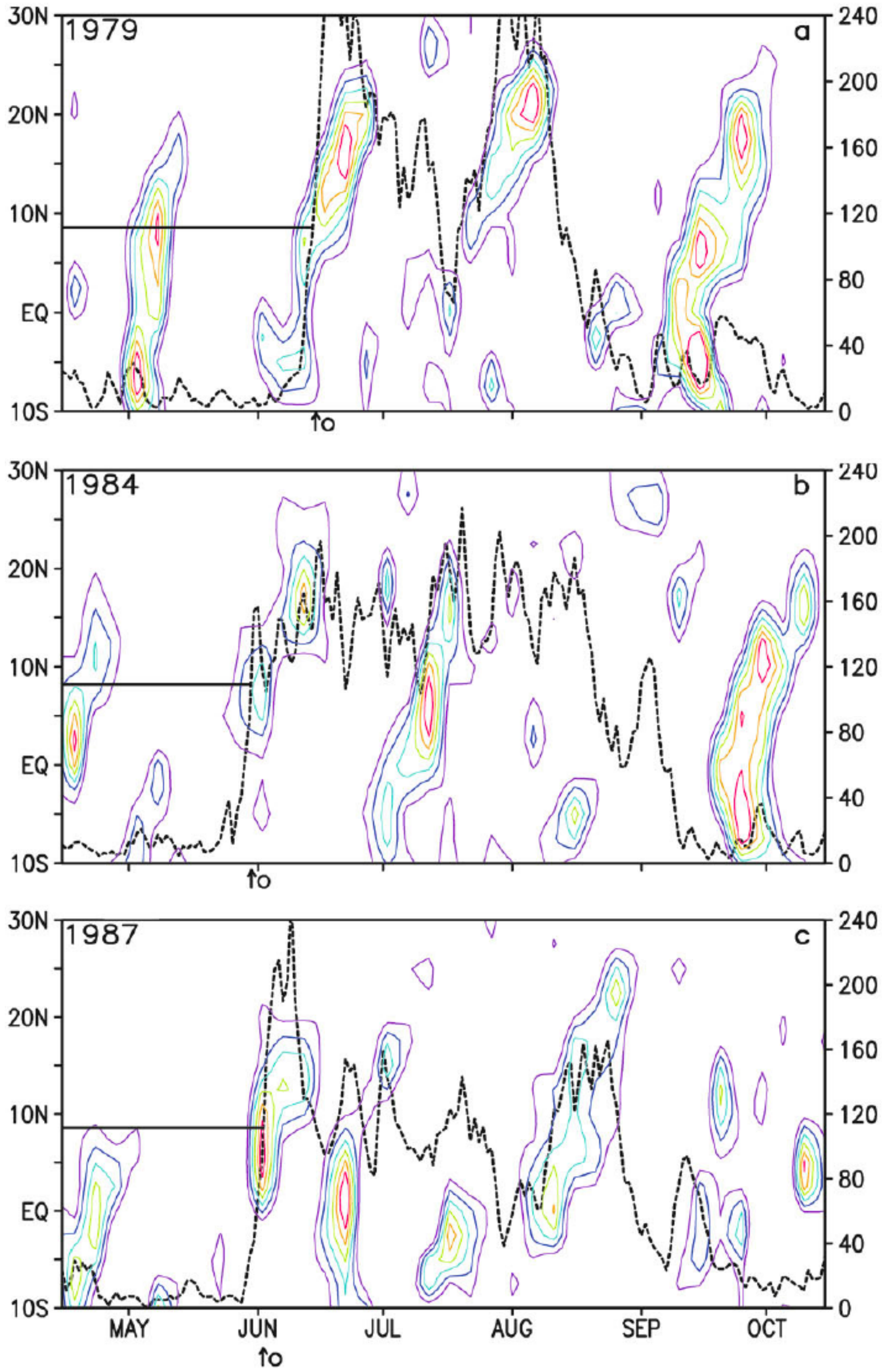


Daily gauge rainfall (mm/day) averaged over Central India

72.5E–85.5E 10.5N–25.5N

"Active-Break" cycle of monsoon

Goswami 2012

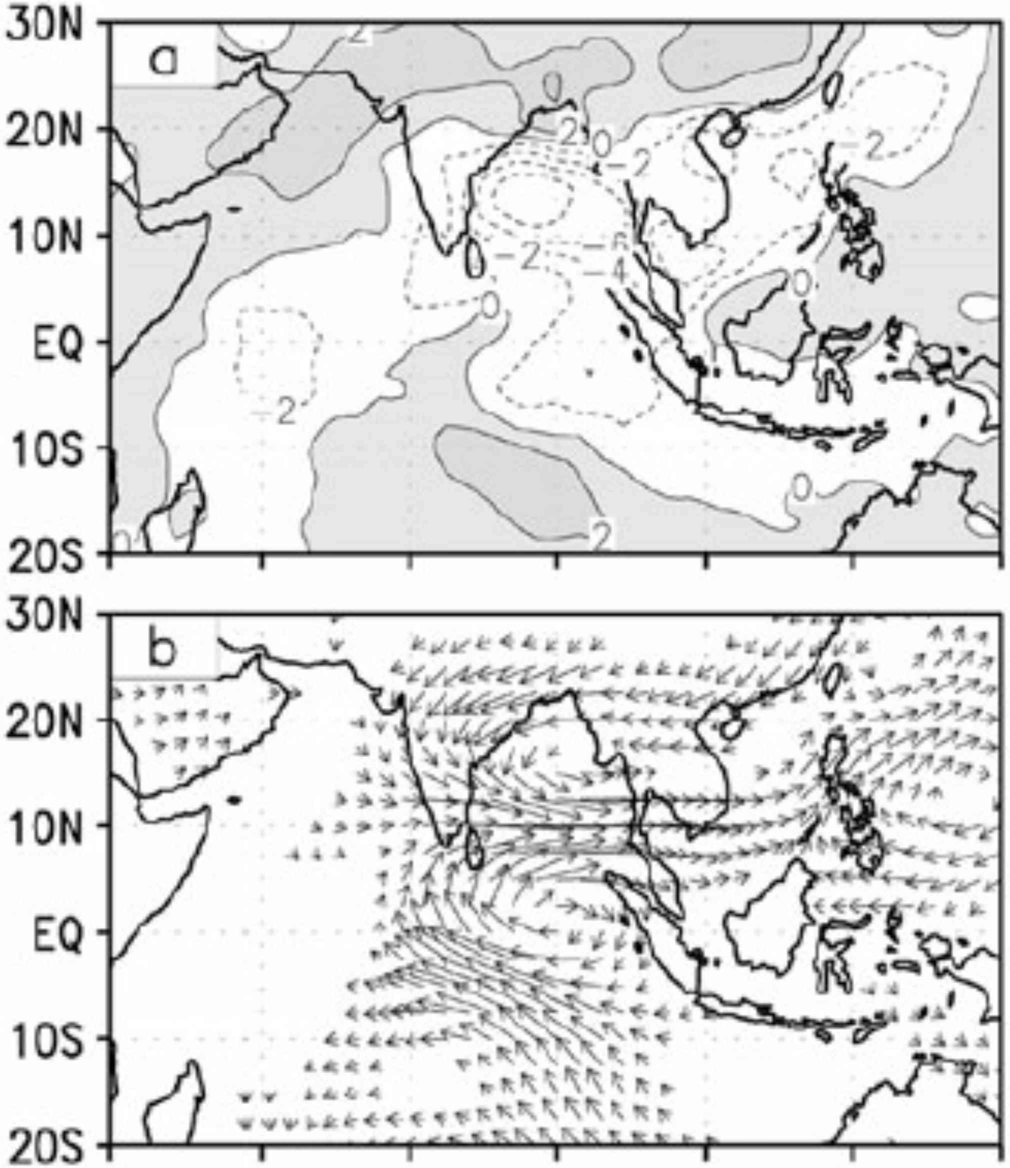


CMAP Rainfall 70E–90E

KE 850 hPa winds 55E–65E 5N–l5N

30-50 day mode

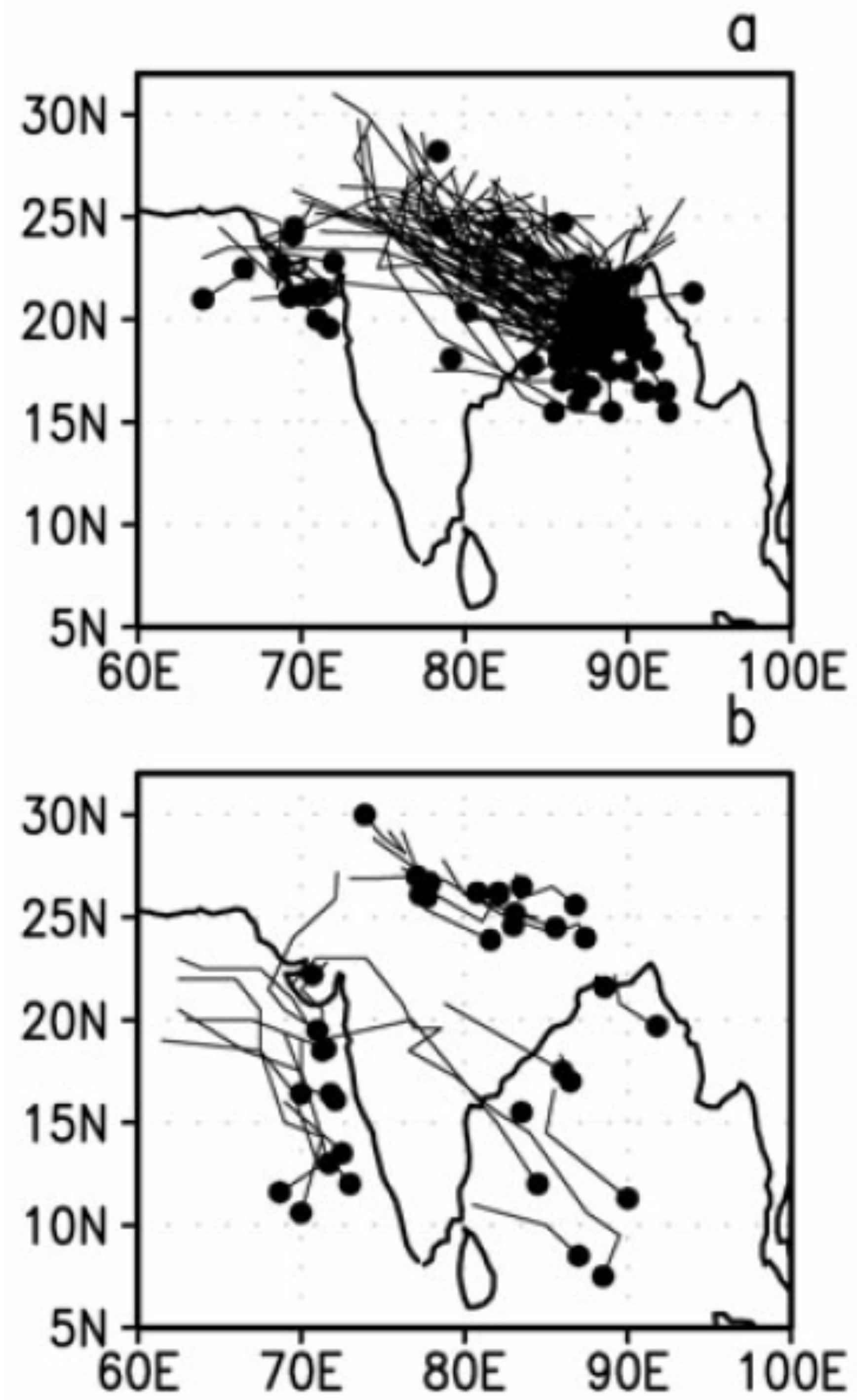
Goswami 2012



OLR 850 hPa winds

10-20 day mode

Goswami 2012



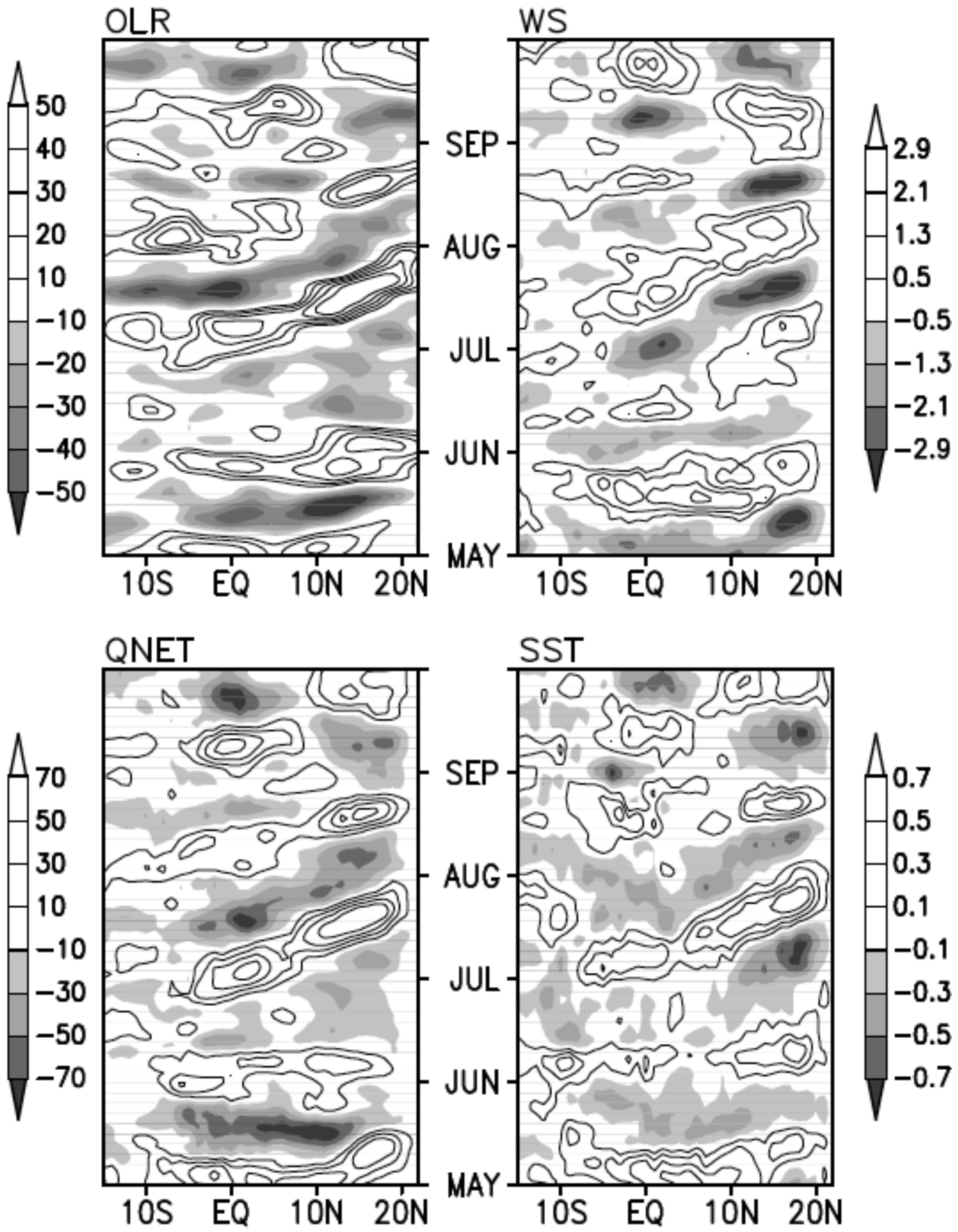
Tracks of Monsoon low-pressure systems/depressions 1954-1983

Active phase

Break phase

Goswami 2003

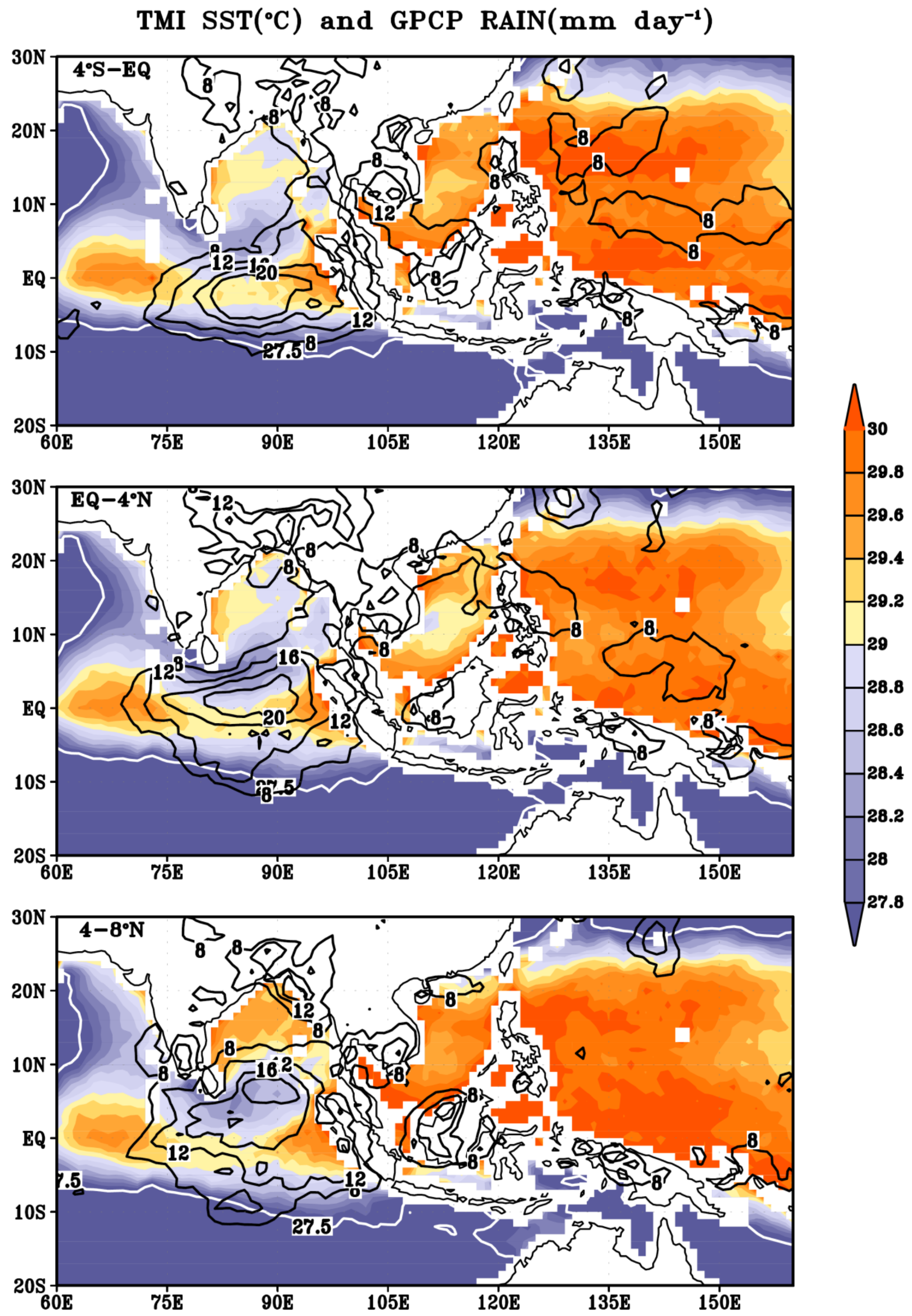
ISO



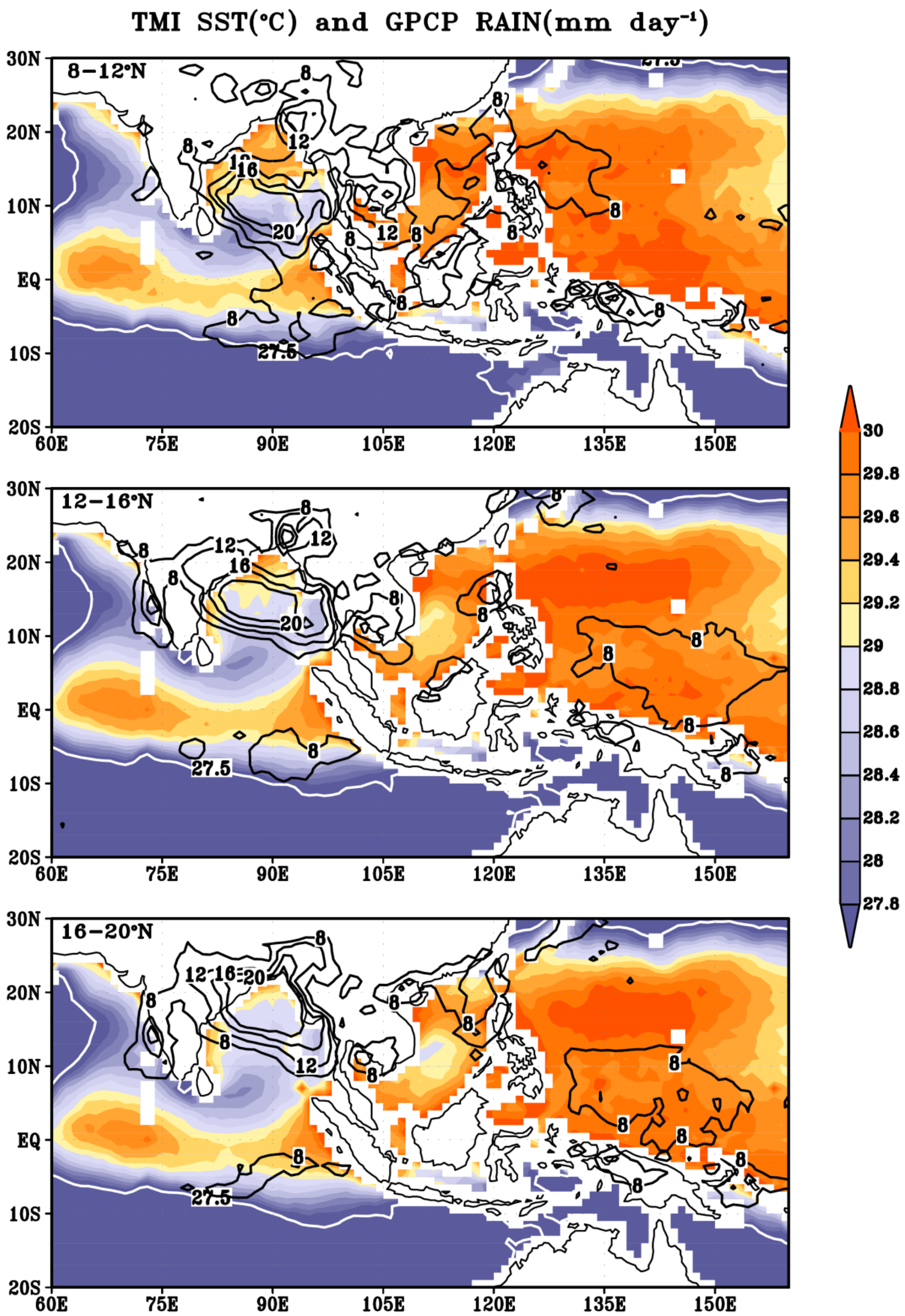
10-80 day
1998

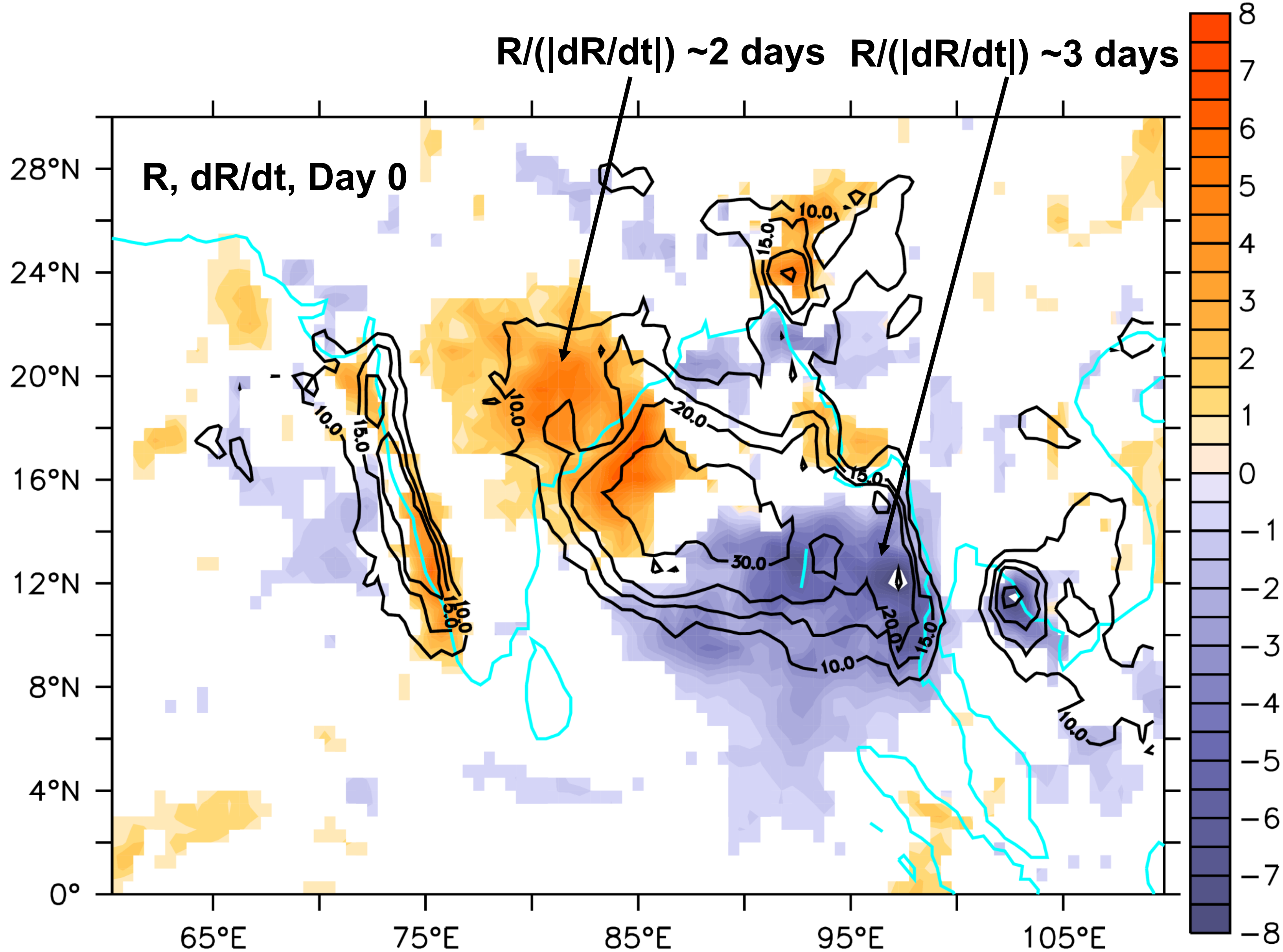
The summer monsoon has 2-3 “active” and “weak” spells each season

Monsoon rainband moves north from the equatorial Indian Ocean; repeat time ~30 days

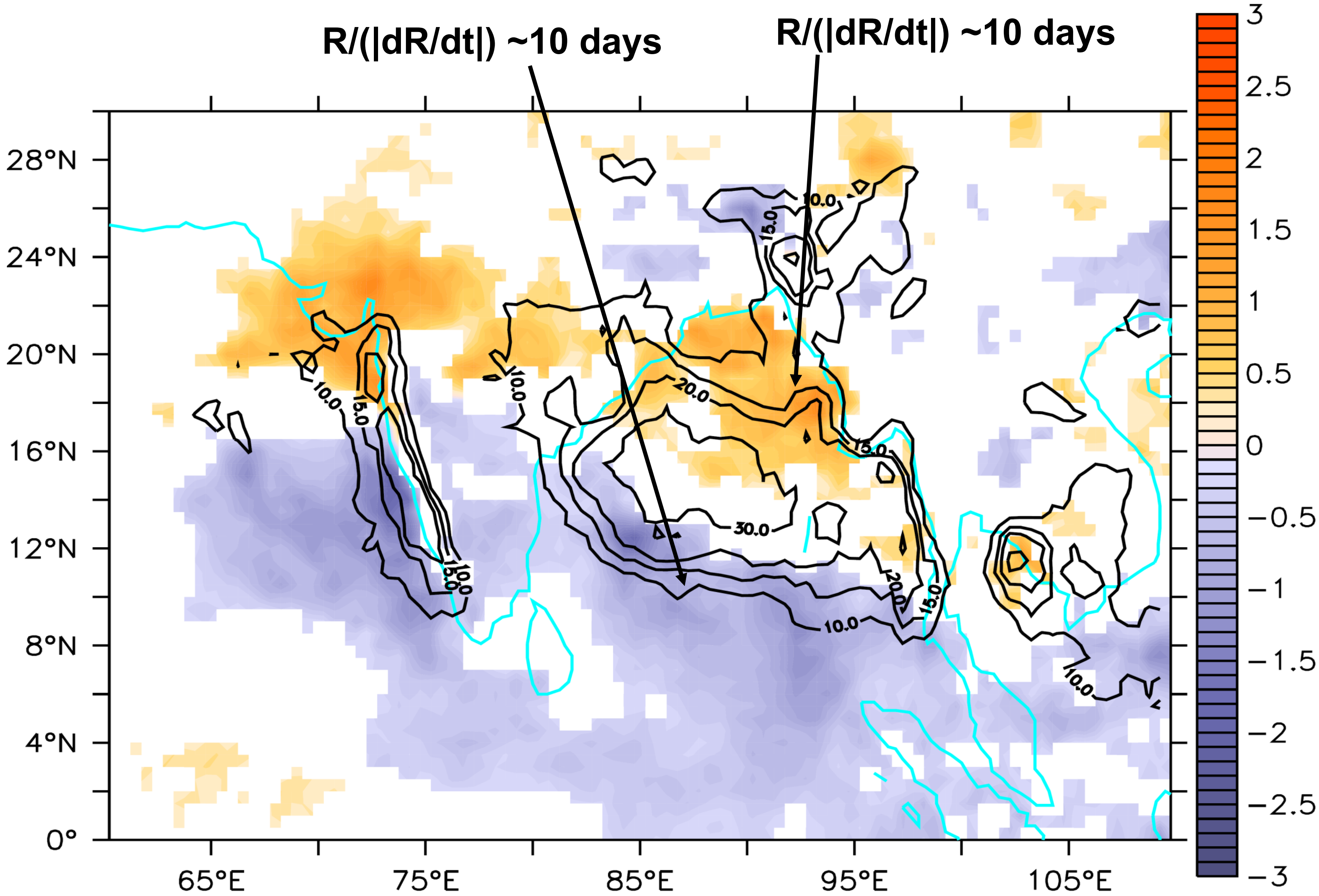


Warm SST to the north of the rainband





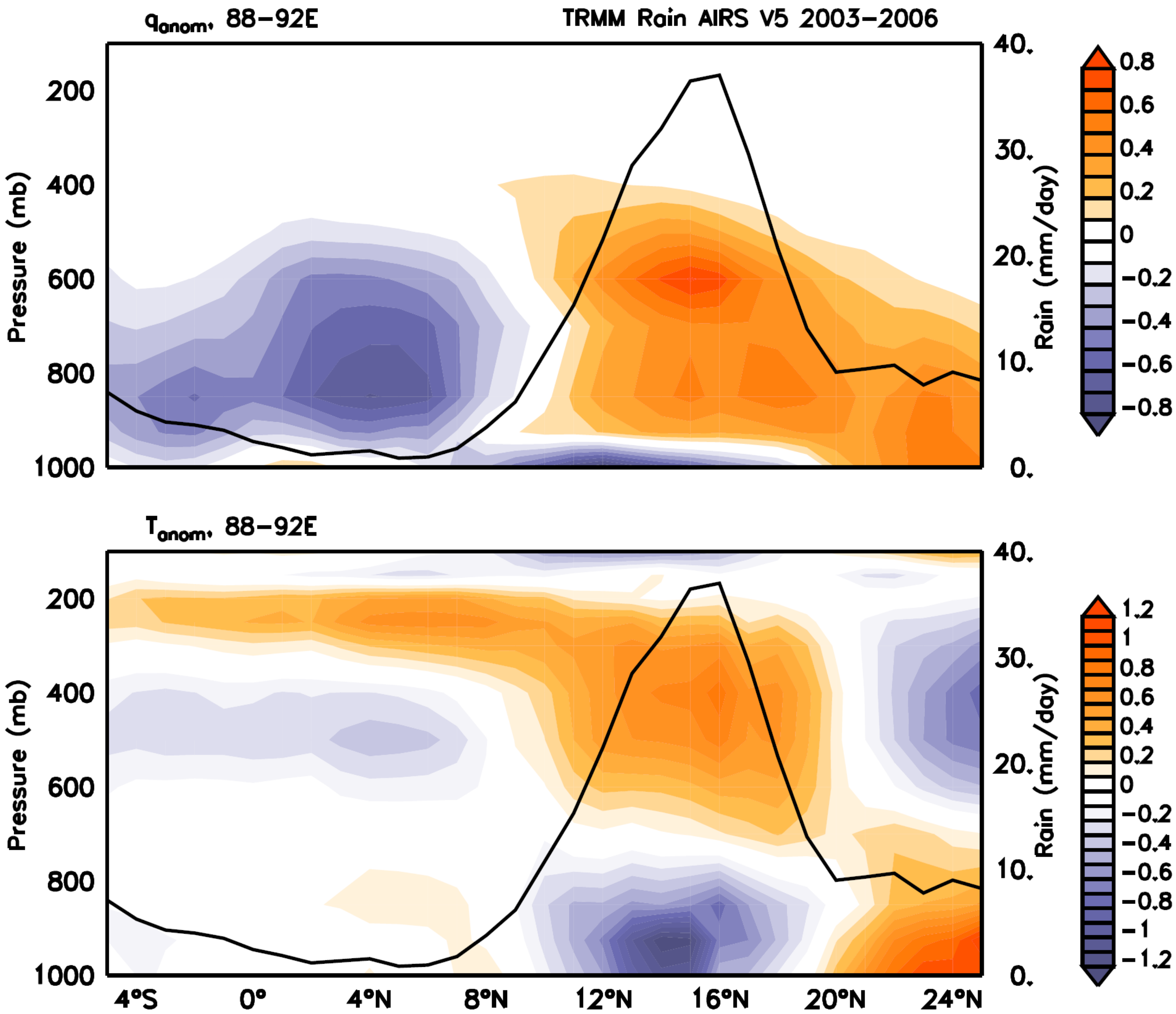
Rain grows in northwest and decays in southeast on fast timescale.

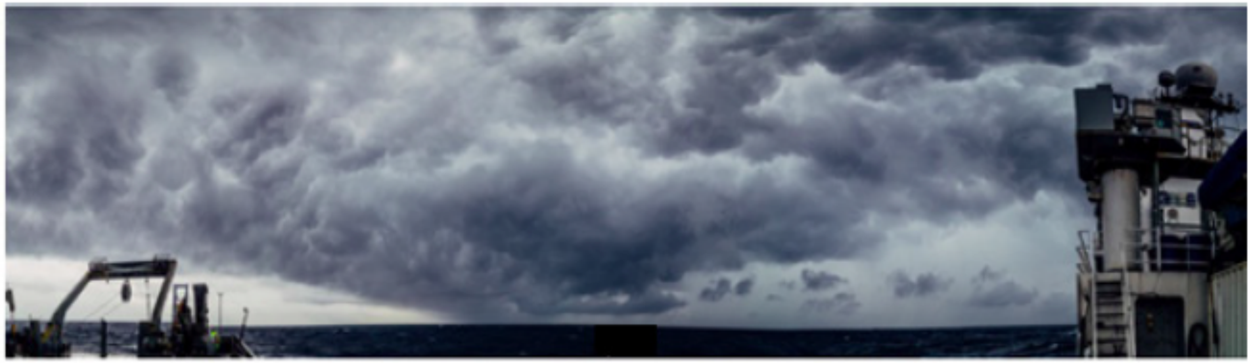


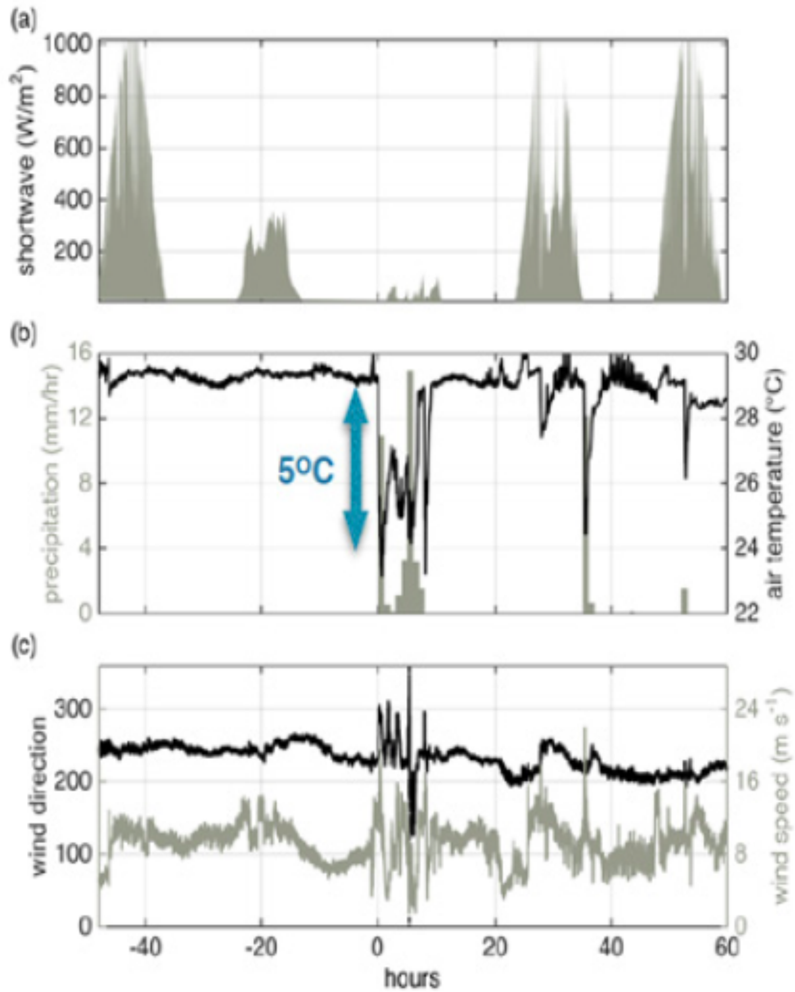
Movement of rainband parallel to itself on the slow timescale.

Monsoon rainfall has two time scales – synoptic and intraseasonal

ISO (2-90 day) q, Ta

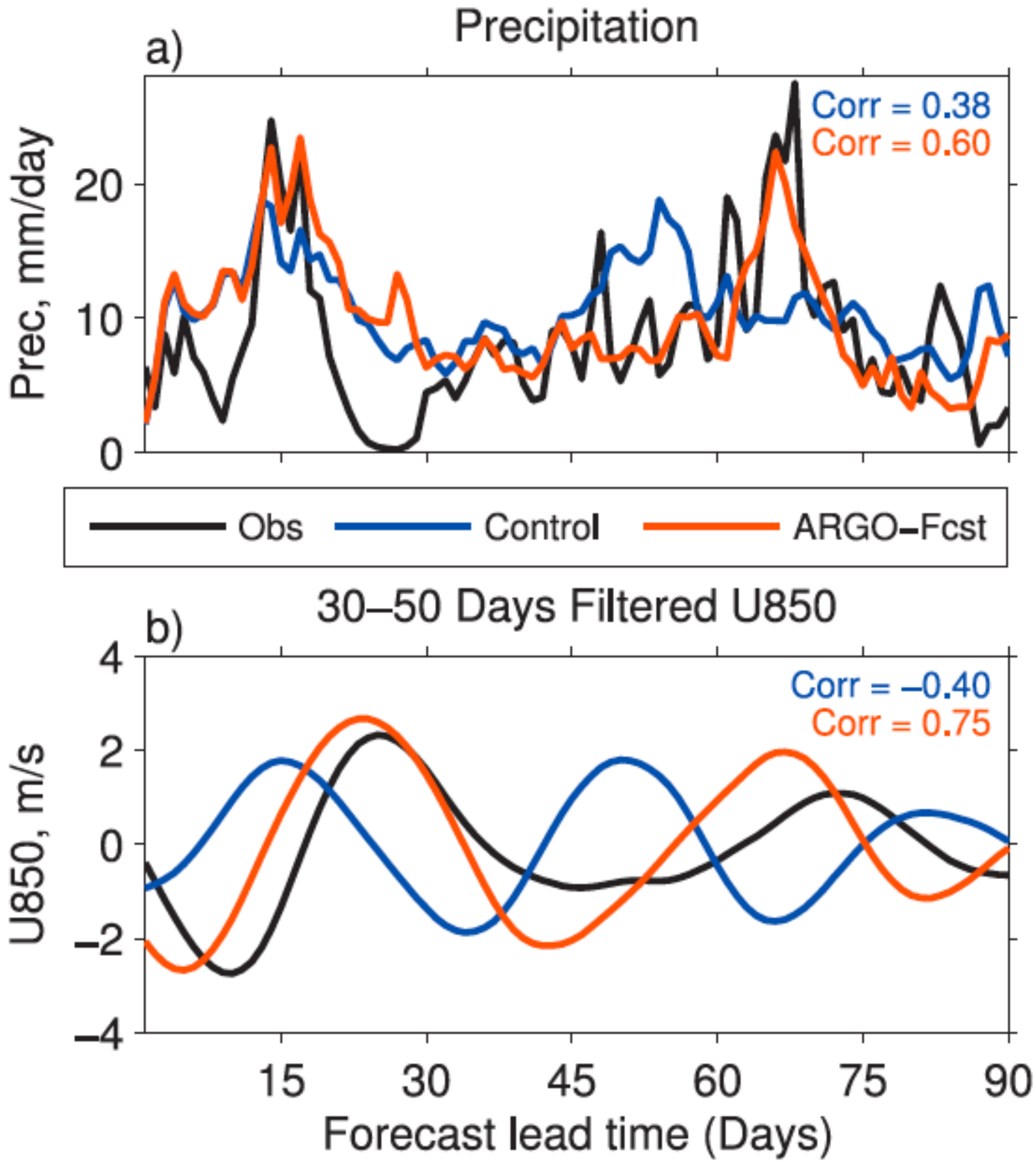




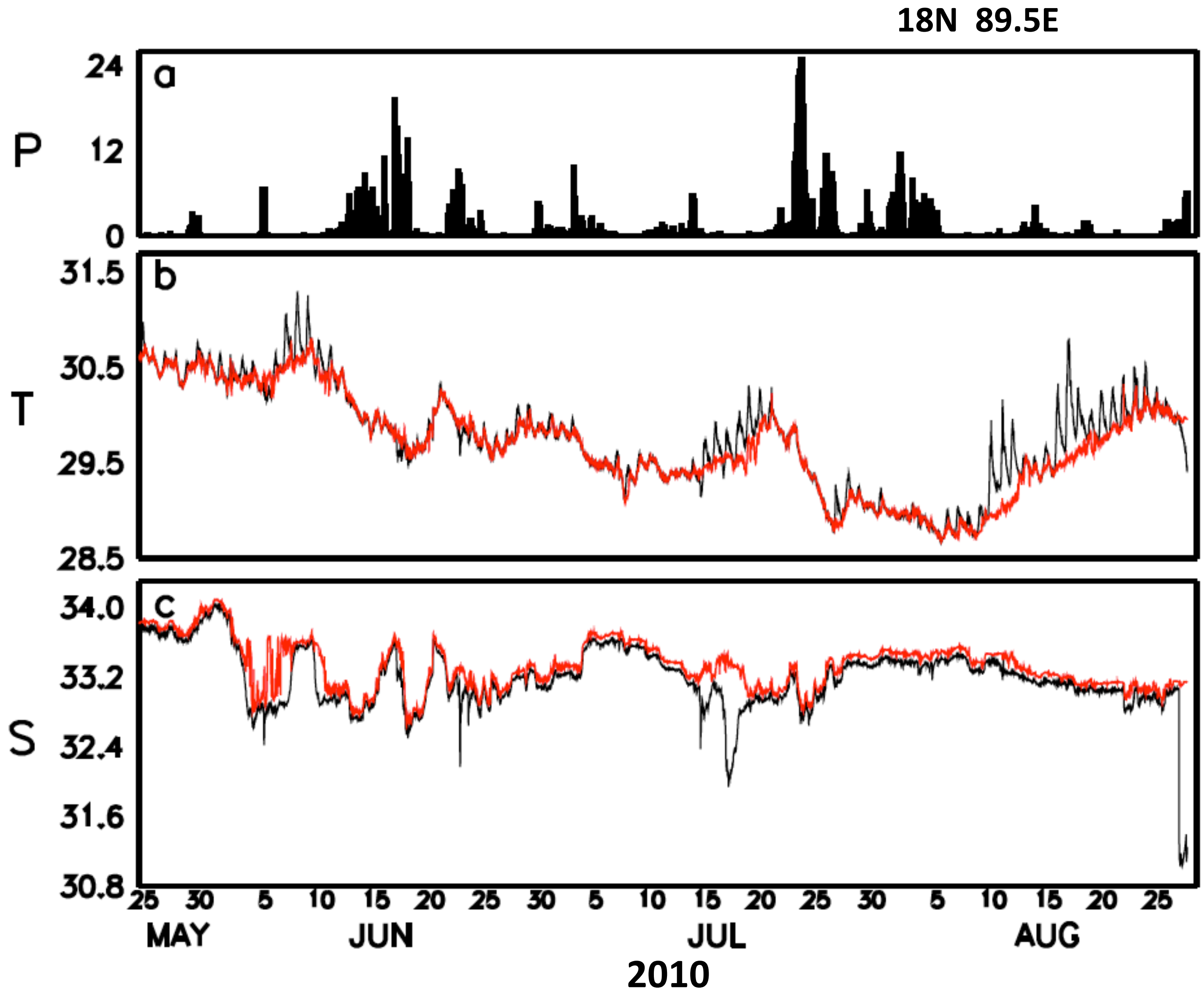


26 August 2015 ***Roger Revelle***

Courtesy: Emily and San

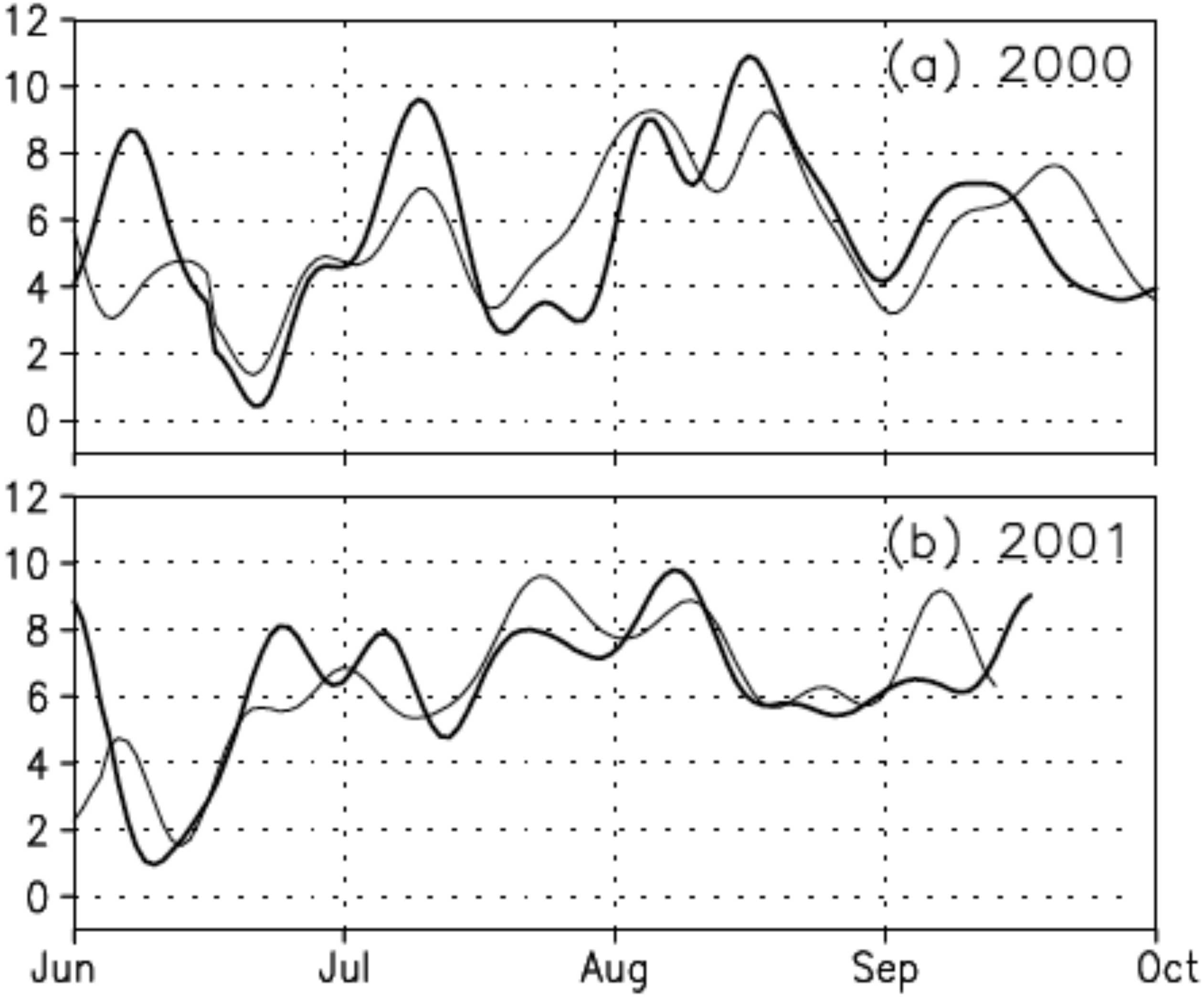


TN Krishnamurti 2007
DeMott 2011

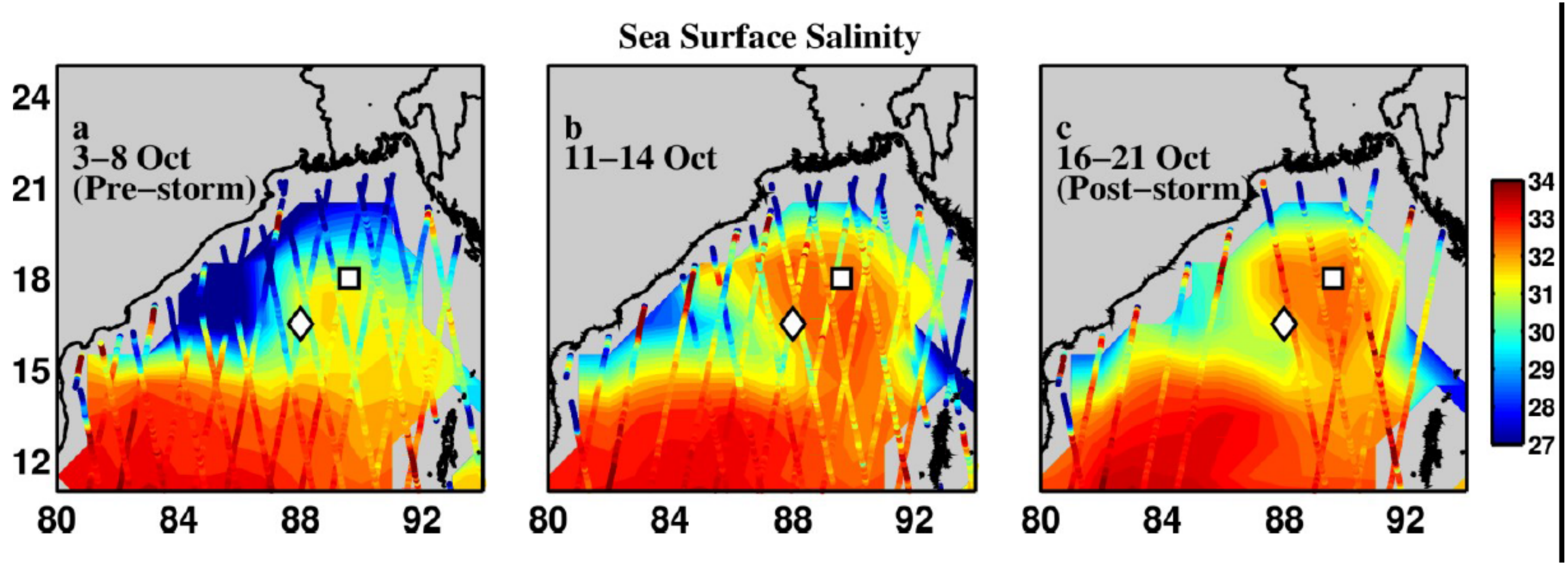


18N 89.5E
a
b
c
P
T
S
24
12
0
31.5
30.5
29.5
28.5
34.0
33.2
32.4
31.6
30.8
25 30 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25
MAY
JUN
JUL
AUG
2010

7th centuary cave temple Trichy



Goswami 2003


Sea Surface Salinity
a
3–8 Oct
(Pre–storm)
b
11–14 Oct
c
16–21 Oct
(Post–storm)
24
21
18
15
12
80
84
88
92
34
33
32
31
30
29
28
27

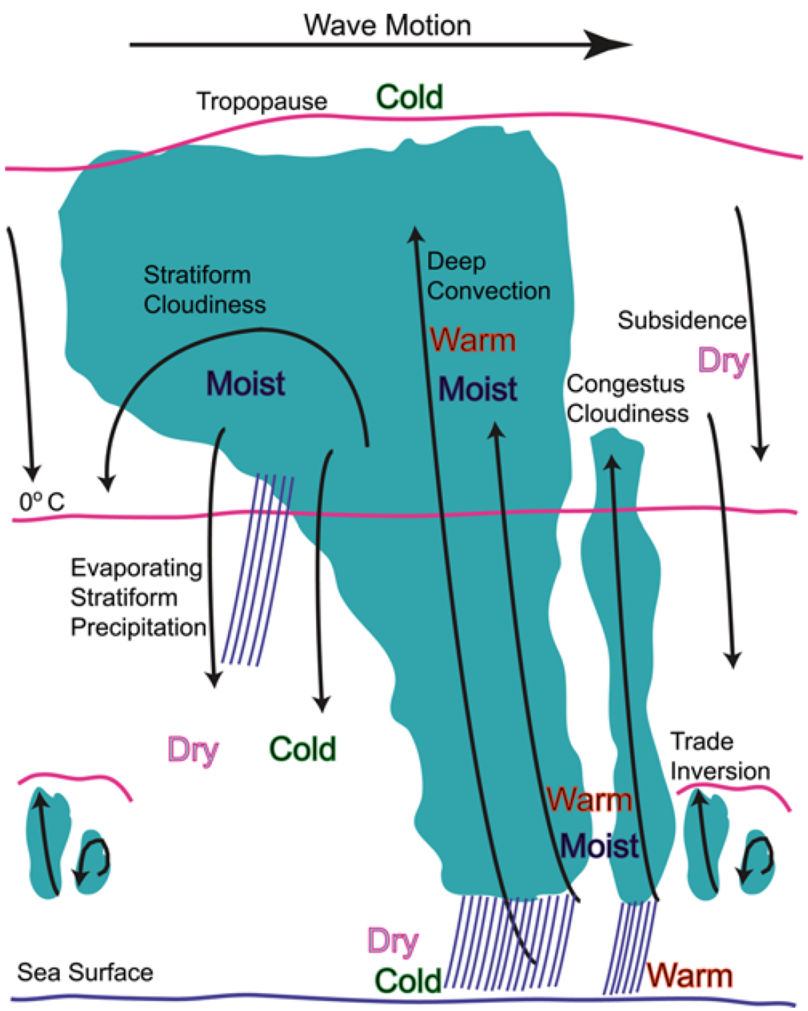
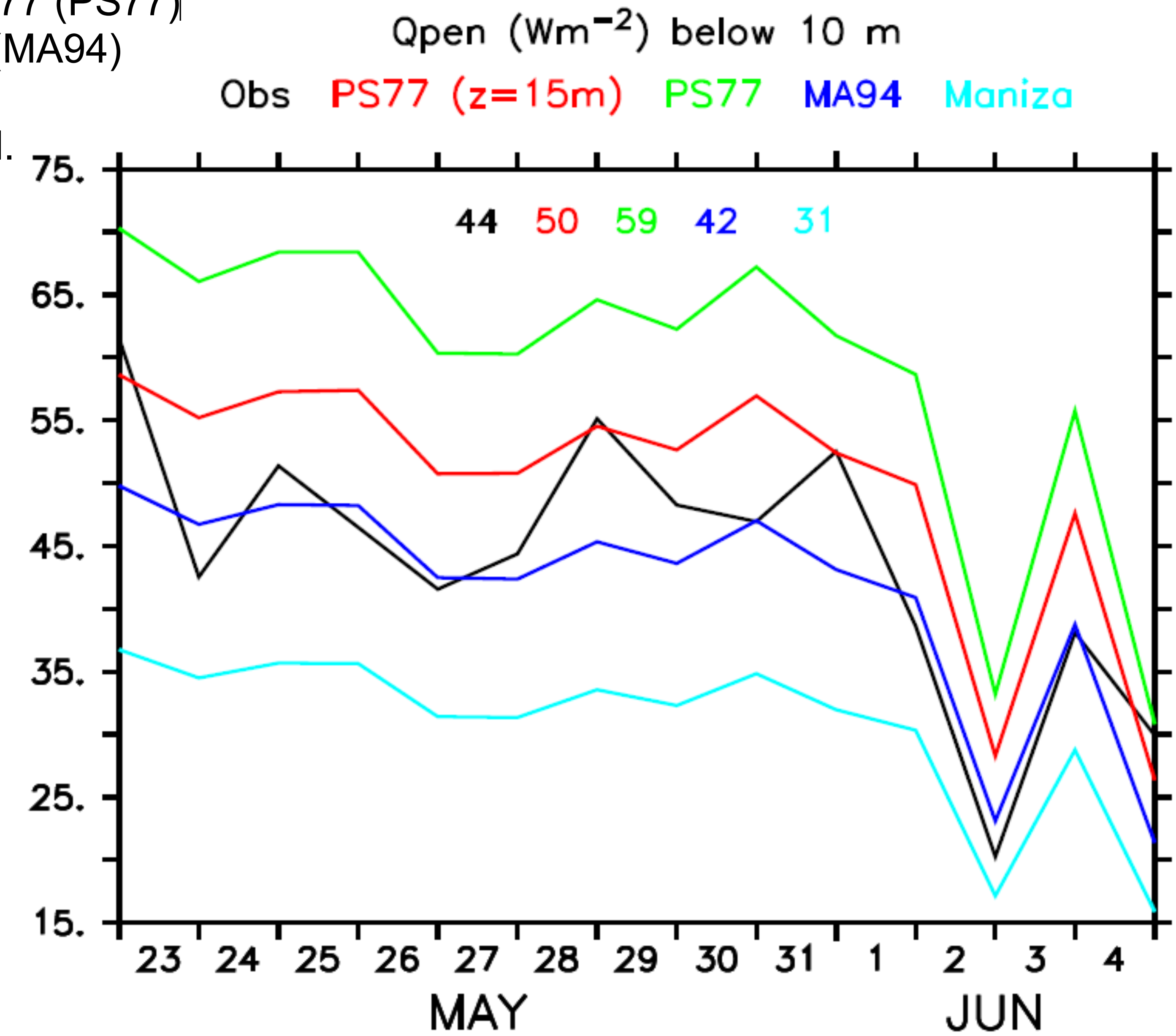


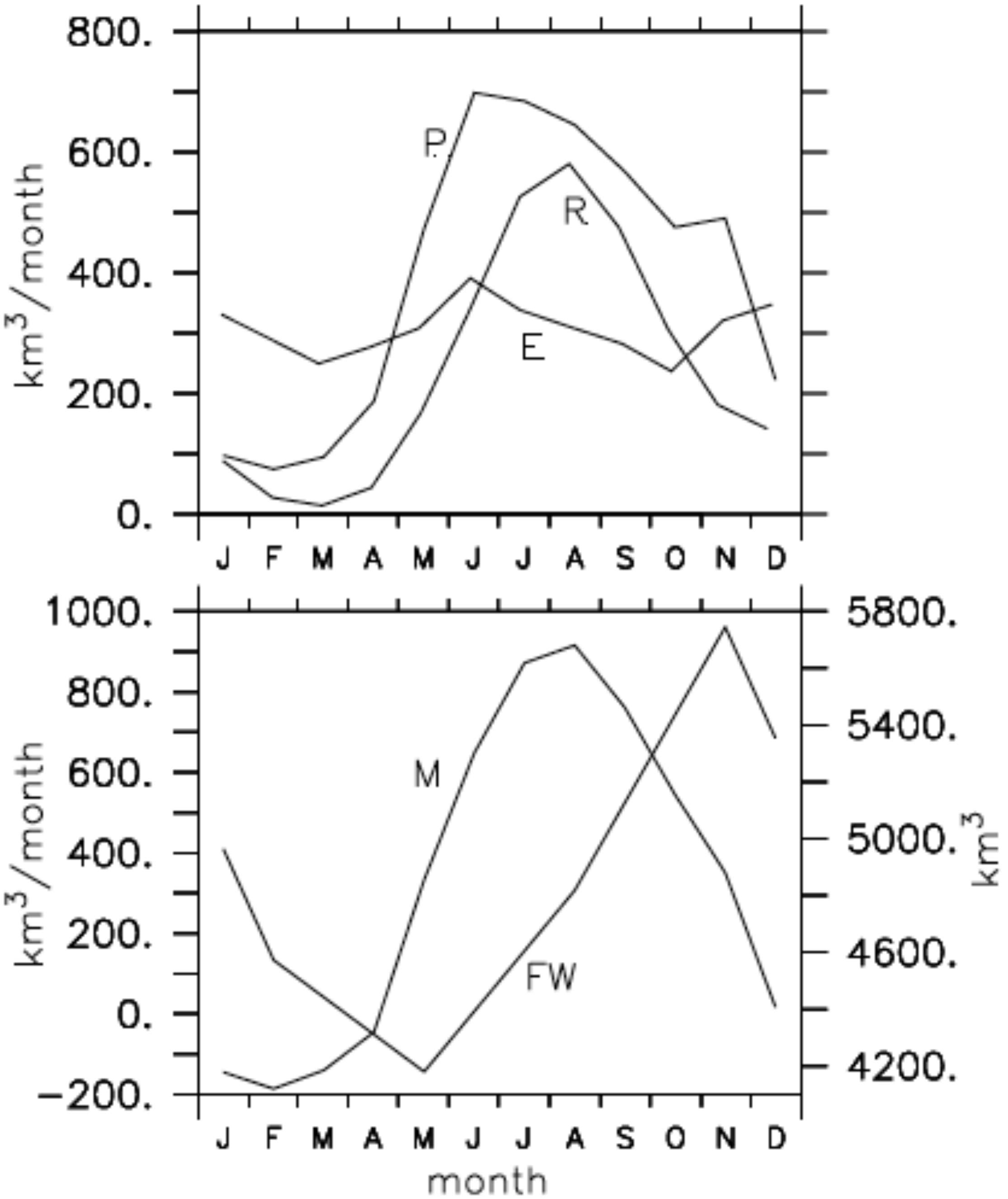
Figure 19. The hierarchy of cloudiness, temperature, and humidity within CCEWs, valid from MCS to MJO scales. Wave movement is from left to right (adapted from *Johnson et al.* [1999], *Straub and Kiladis* [2003c], and *Khouider and Majda* [2008]).

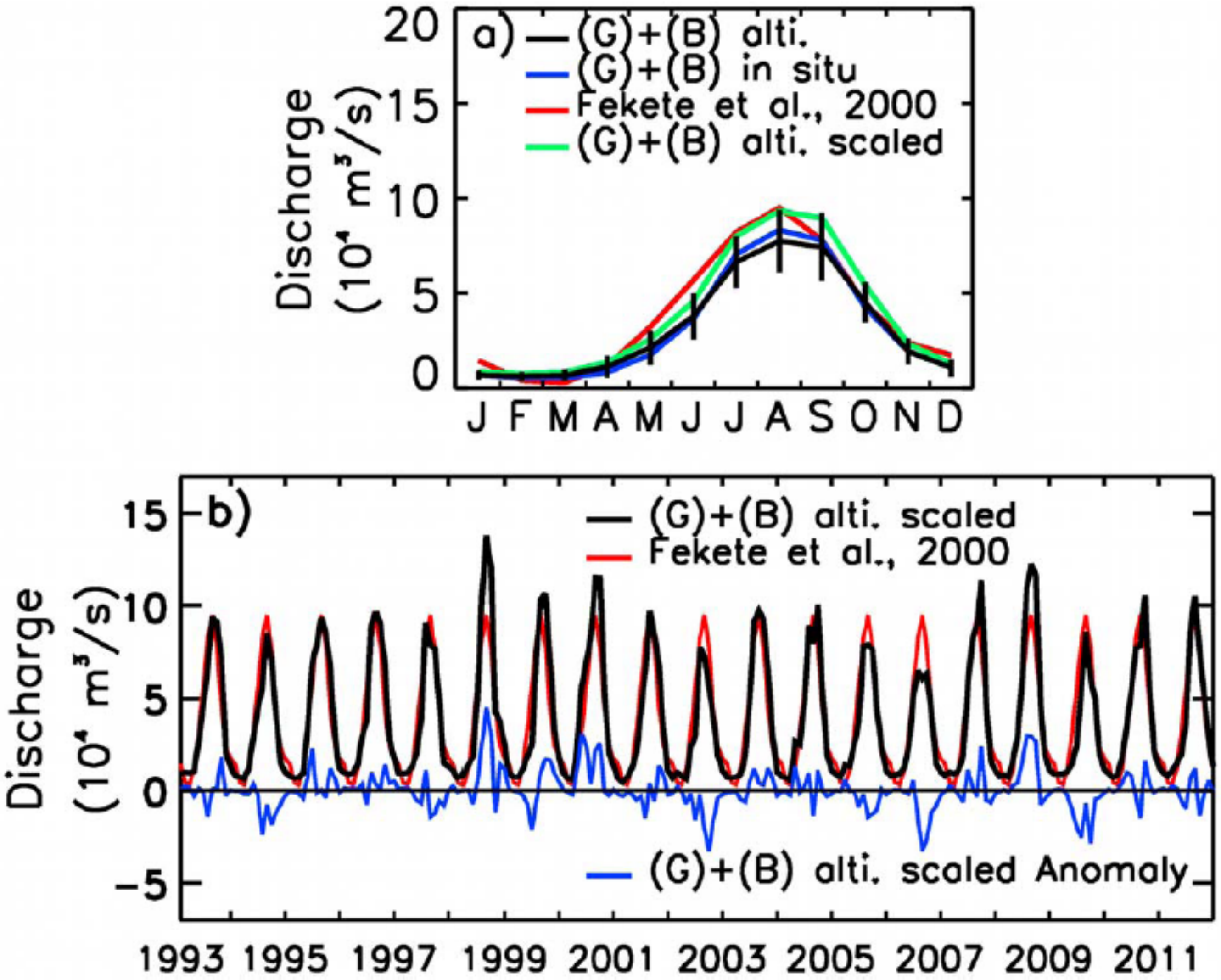
Kiladis et al. 2008,
Rev. Geophys.

Qpen

Paulson-Simpson 1977 (PS77)
Morel-Antoine 1994 (MA94)
Manizza et al., 2005
Weekly SeaWIFS chl.

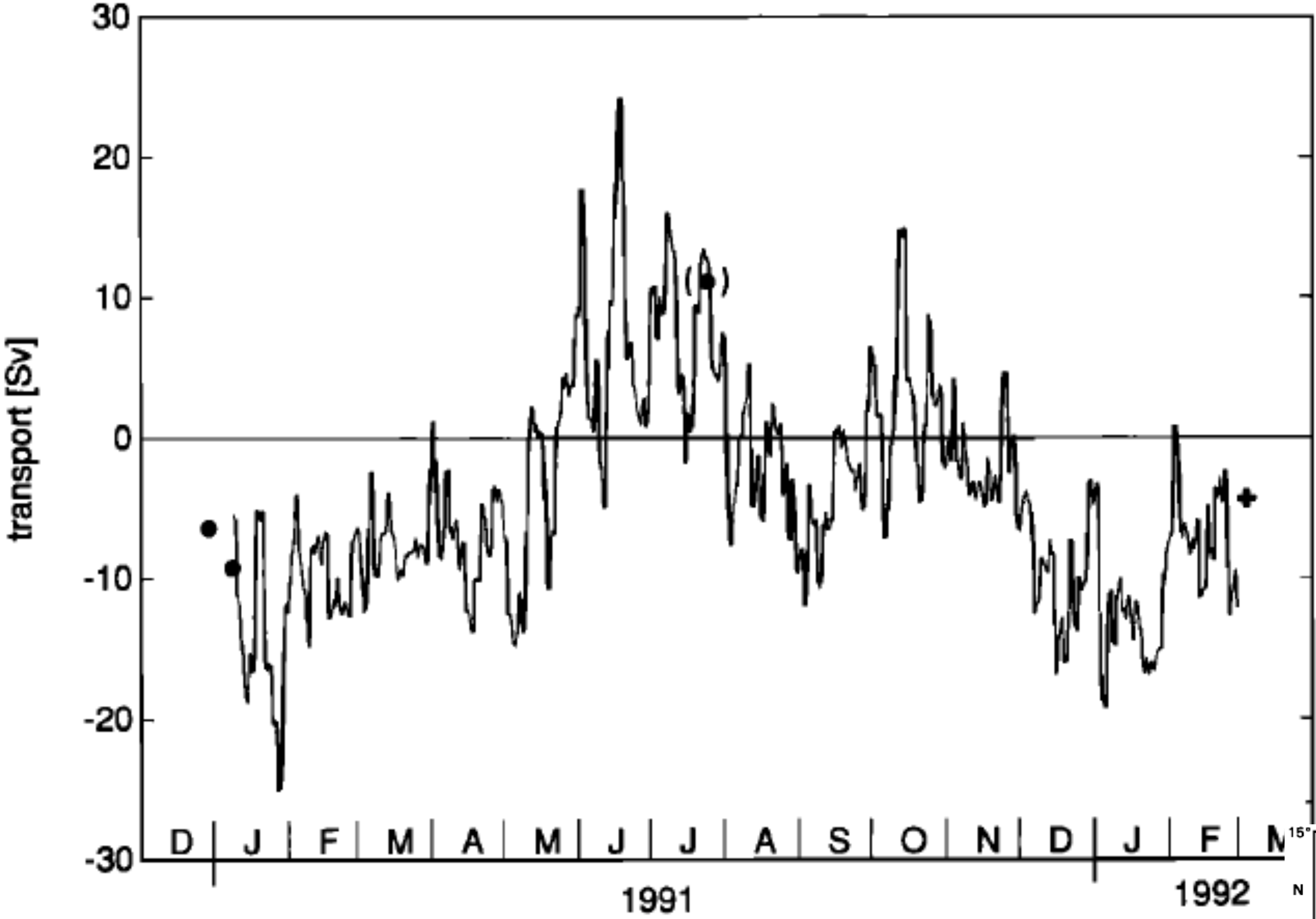


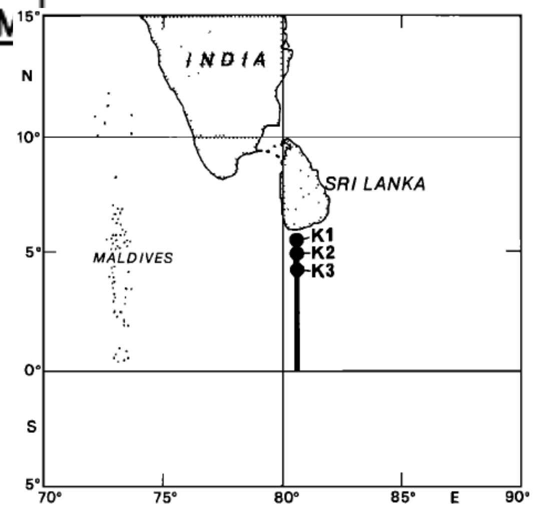

800.
600.
400.
200.
0.
km^3/month
P
R
E
J F M A M J J A S O N D
1000.
800.
600.
400.
200.
0.
−200.
km^3/month
5800.
5400.
5000.
4600.
4200.
km^3
M
FW
J F M A M J J A S O N D
month



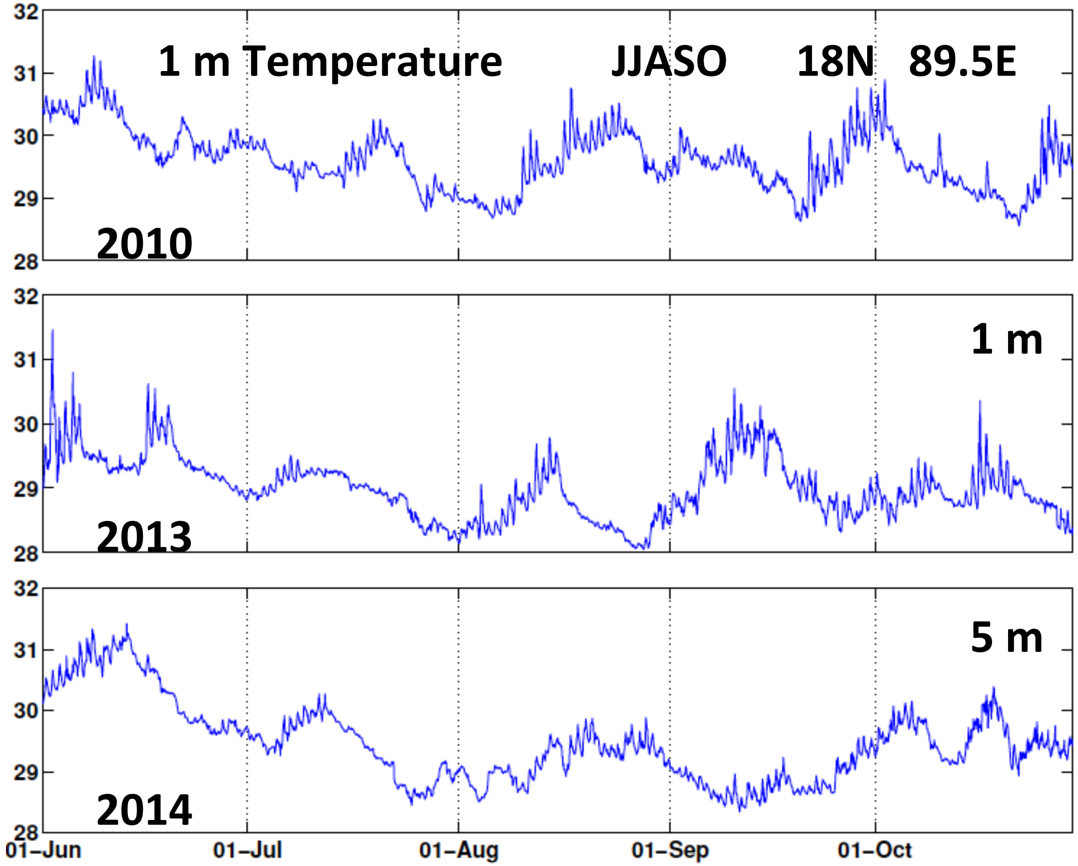
G-B-M discharge

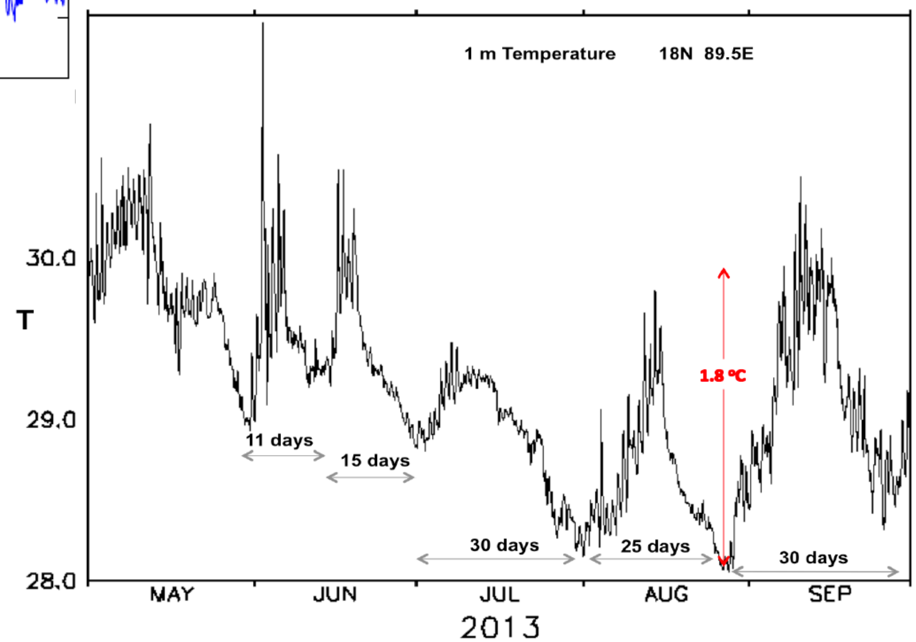
Papa JGR 2012



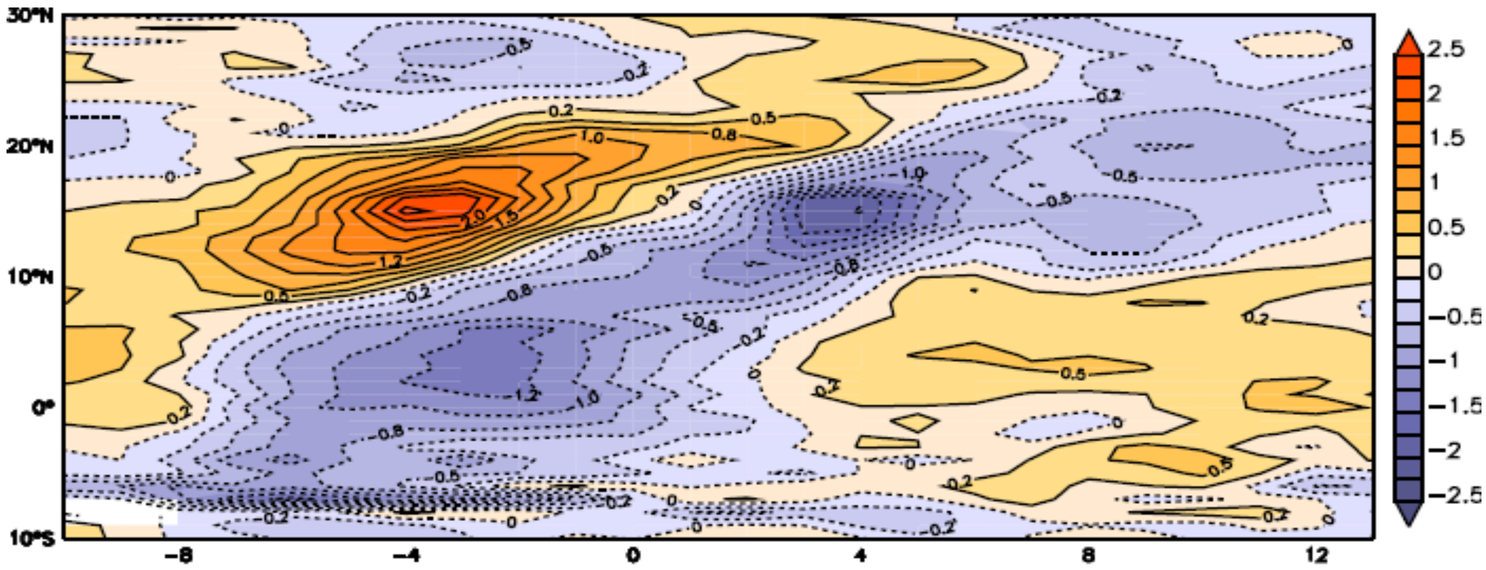


Schott *et.al* 1994


1 m Temperature
JJASO
18N 89.5E
2010
1 m
2013
5 m
2014
32
31
30
29
28
01–Jun
01–Jul
01–Aug
01–Sep
01–Oct

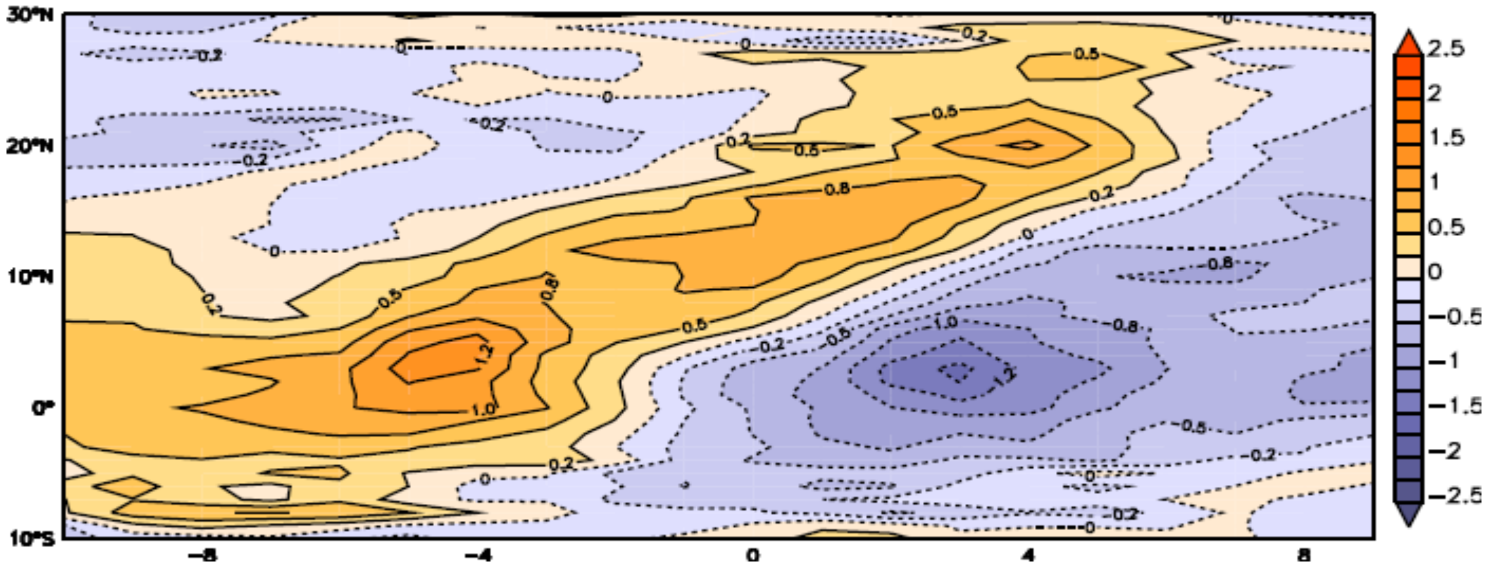

1 m Temperature
18N 89.5E
T
30.0
29.0
28.0
11 days
15 days
30 days
25 days
1.8 ºC
30 days
MAY
JUN
JUL
AUG
SEP
2013

7-day R, dR/dt CBay, EqWestPac

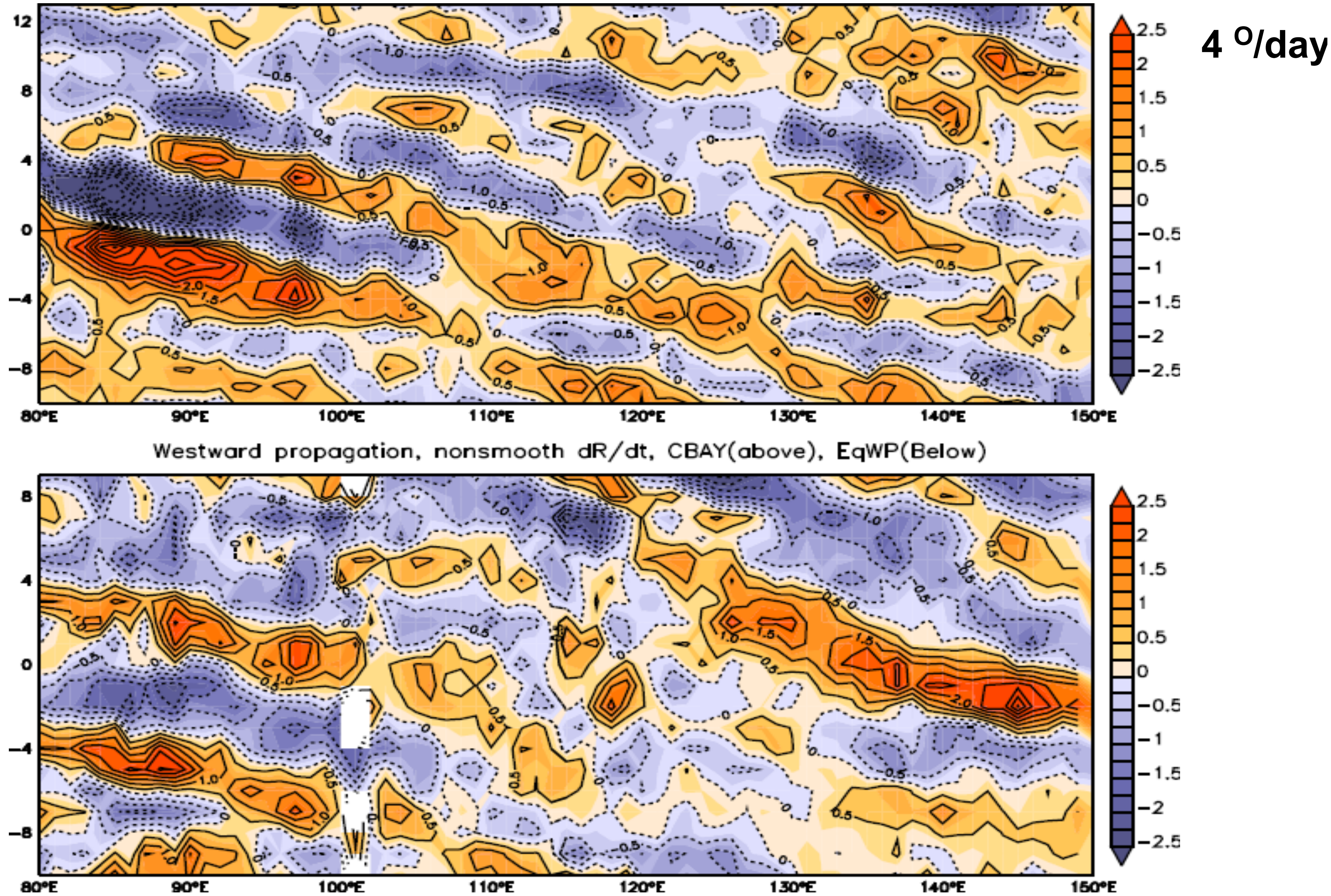


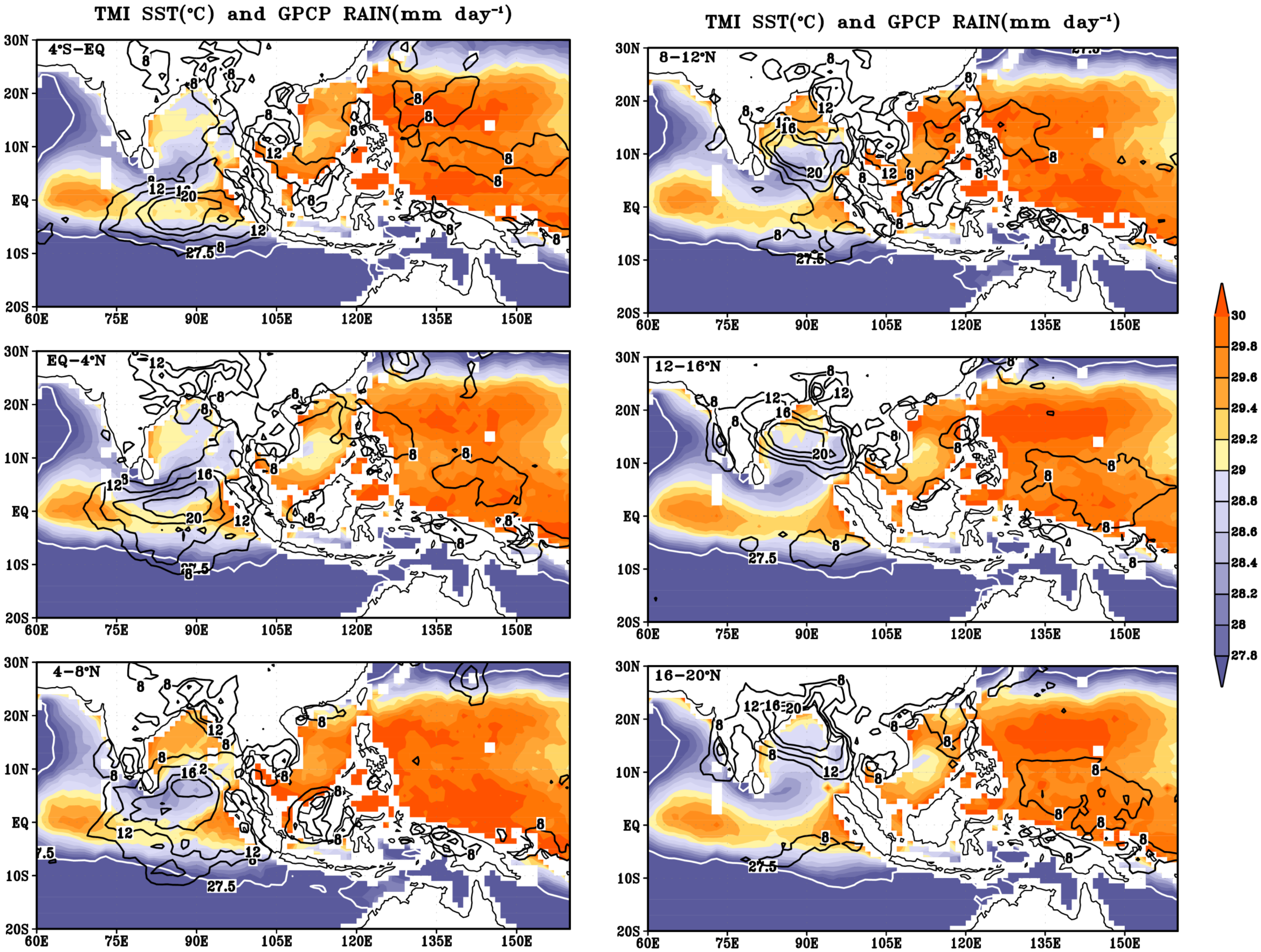
1.5^{O}/day

Northward propagation, smooth dR/dt, CBAY(above), EqWP(Below)

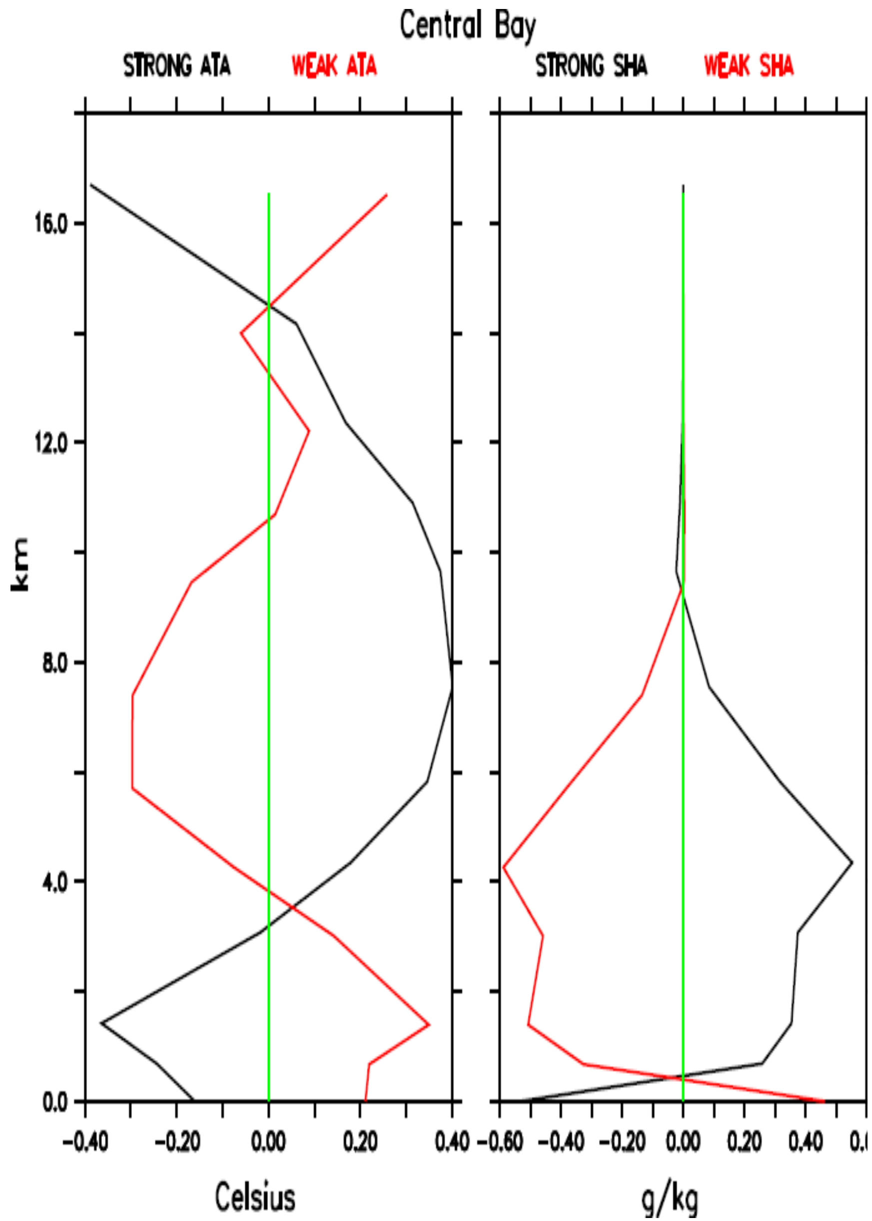


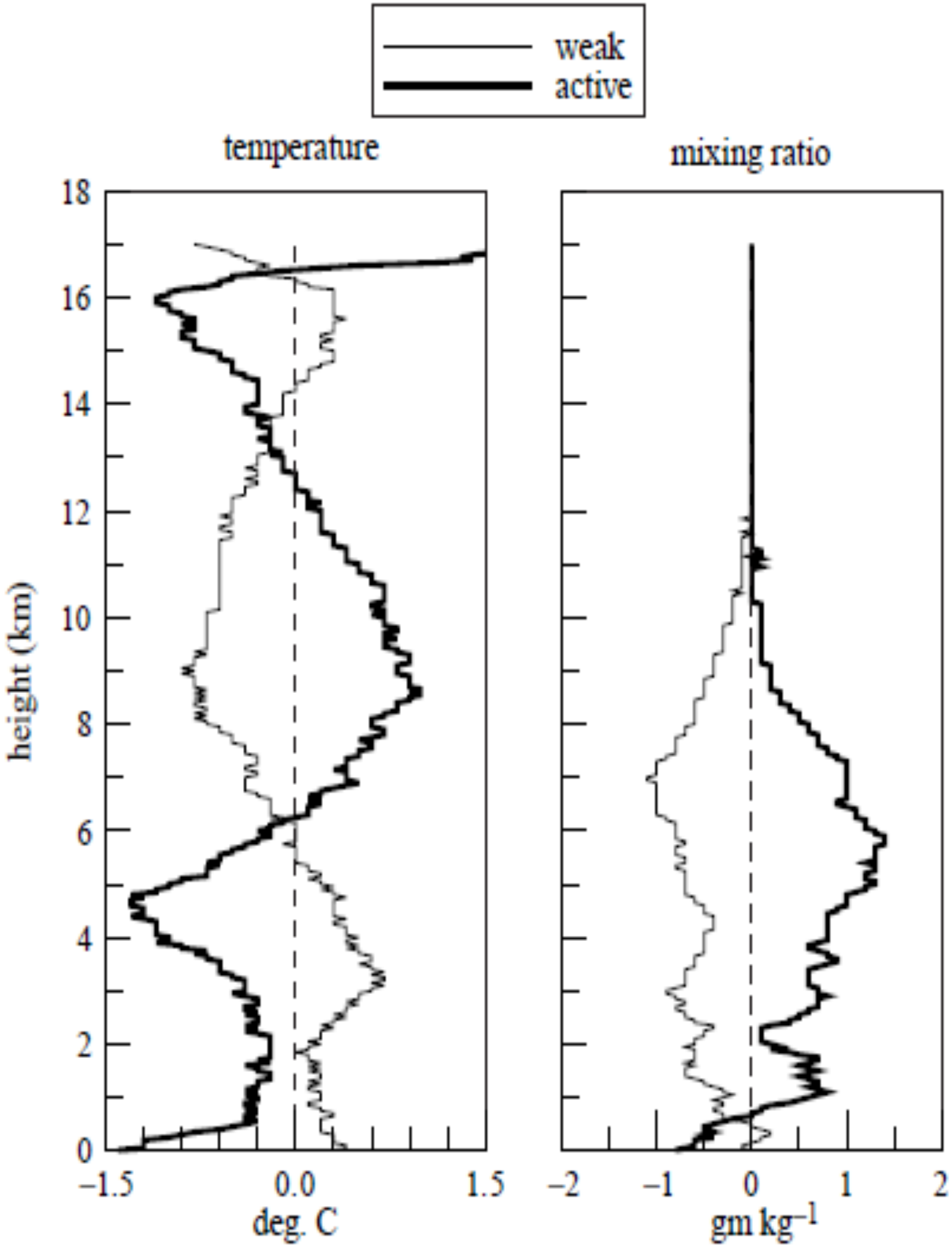
dR/dt Cbay, EqWestPac

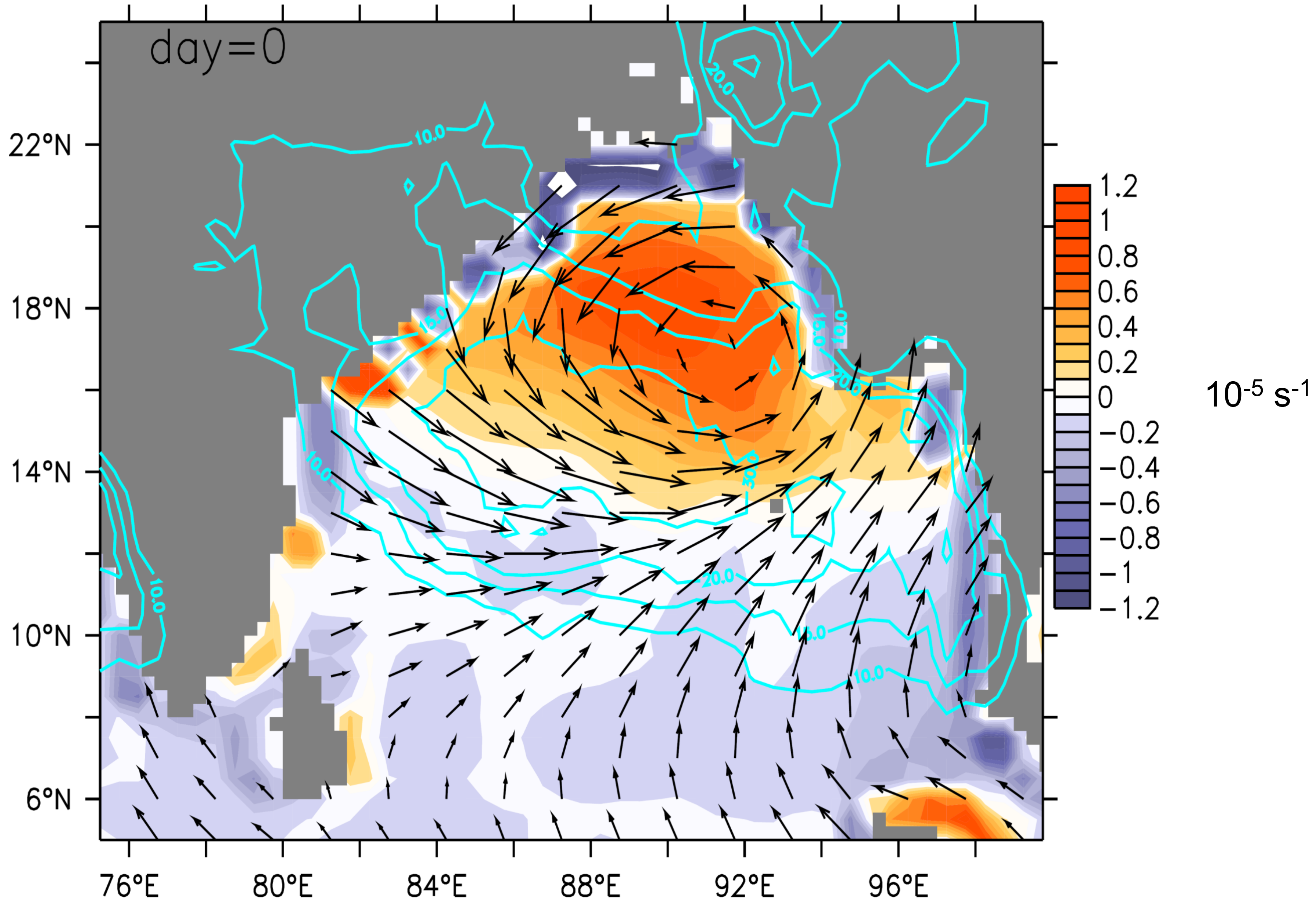



TMI SST(°C) and GPCP RAIN(mm day⁻¹)
TMI SST(°C) and GPCP RAIN(mm day⁻¹)
4°S–EQ
EQ–4°N
4–8°N
8–12°N
12–16°N
16–20°N
30N
20N
10N
EQ
10S
20S
60E
75E
90E
105E
120E
135E
150E
27.5
30
29.8
29.6
29.4
29.2
29
28.8
28.6
28.4
28.2
28
27.8

AIRS

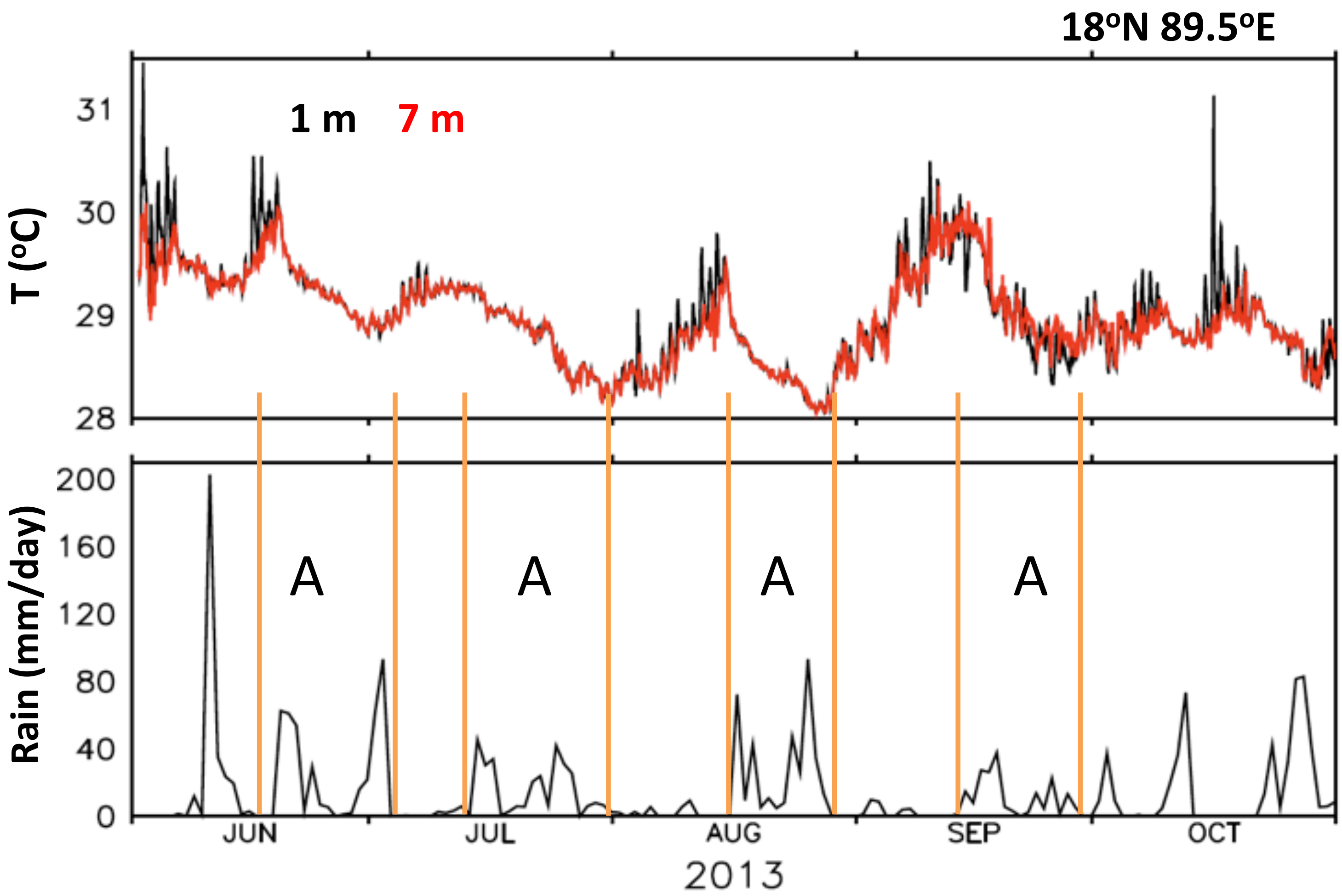

Central Bay
STRONG ATA
WEAK ATA
STRONG SHA
WEAK SHA
km
16.0
12.0
8.0
4.0
0.0
-0.40
-0.20
0.00
0.20
0.40
-0.60
-0.40
-0.20
0.00
0.20
0.40
Celsius
g/kg


weak
active
temperature
mixing ratio
height (km)
18
16
14
12
10
8
6
4
2
0
−1.5
0.0
1.5
deg. C
−2
−1
0
1
2
gm kg^{-1}



Maximum vorticity anomaly is 3-4 degrees north of the maximum rain

SST and monsoon rainfall



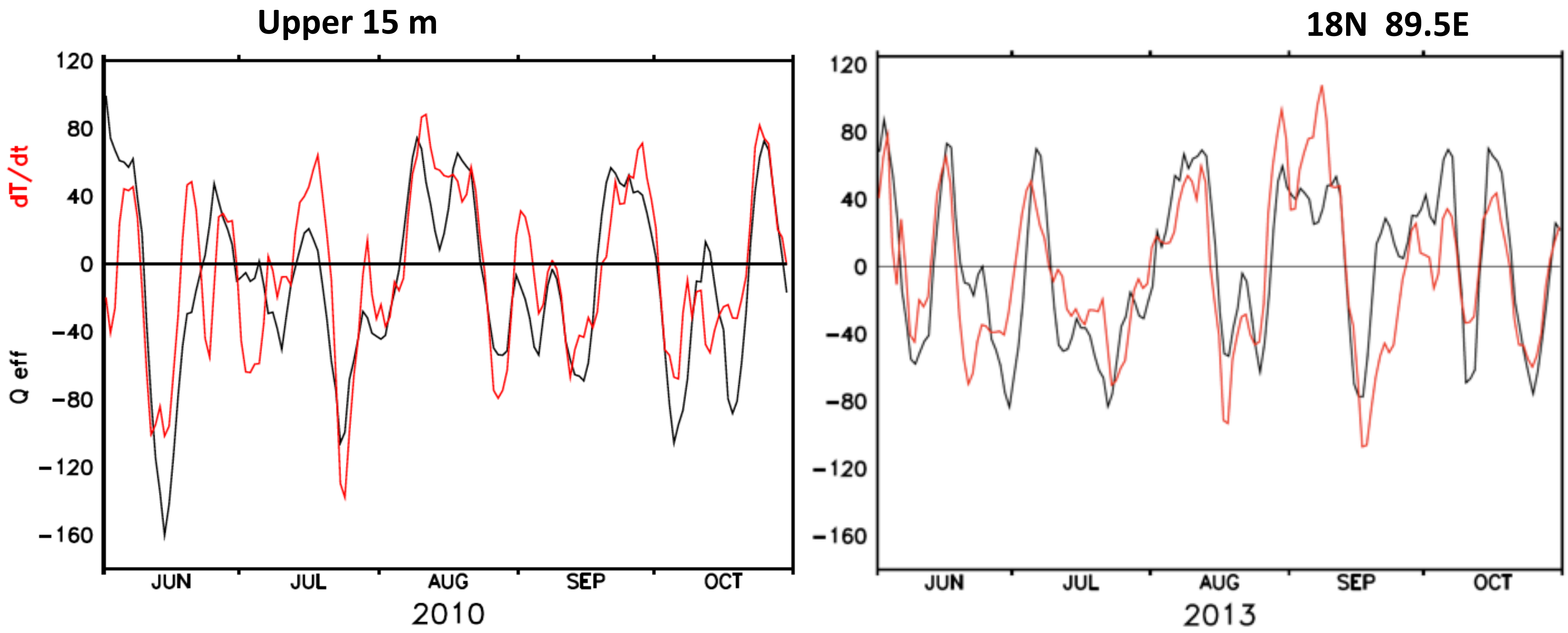
SST cools during active (cloudy, windy) spells

SST oscillations influence active-break spells of the summer monsoon

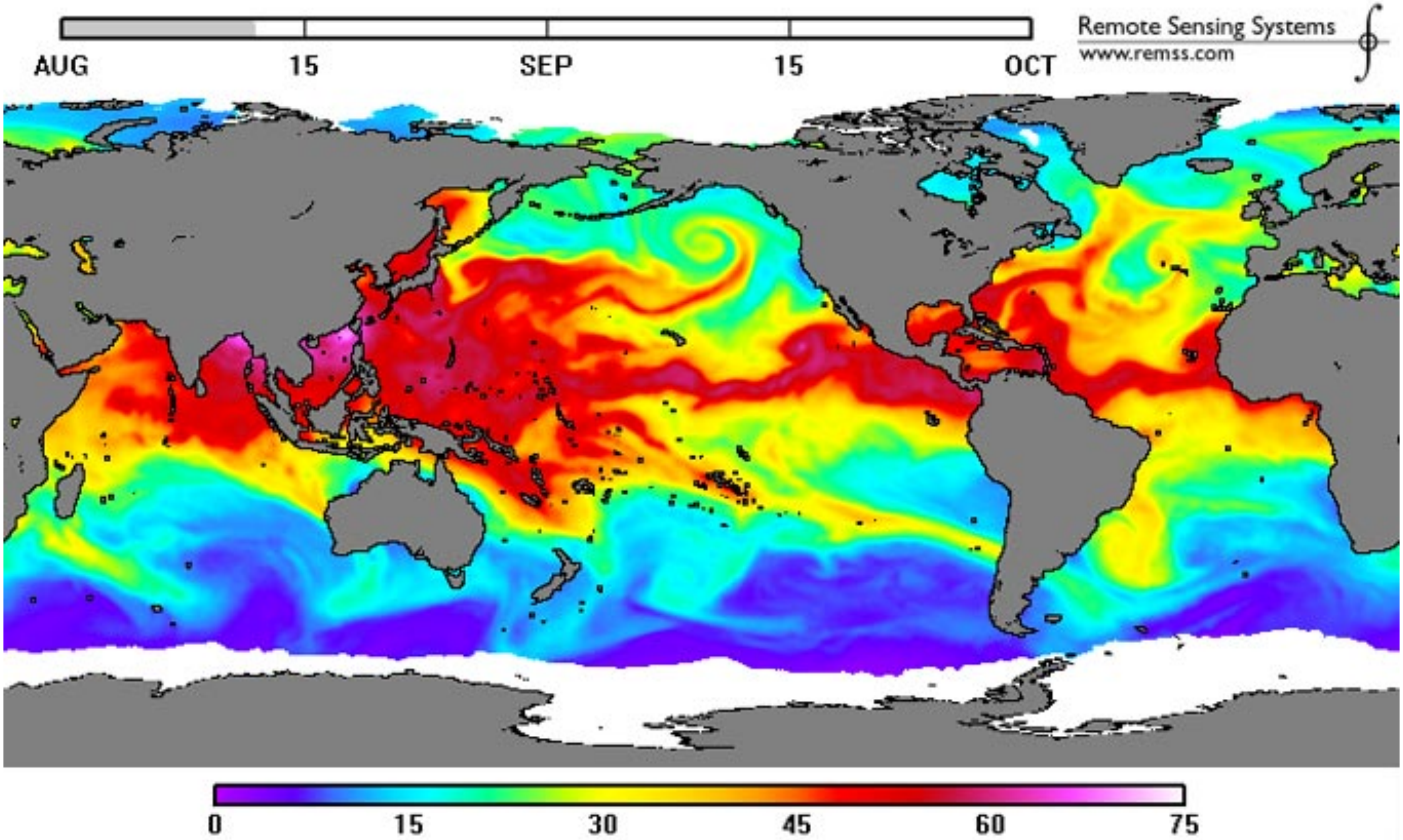
Sengupta Ravichandran 2001, Vecchi Harrison 2002, De Mott 2011

Heat balance equation

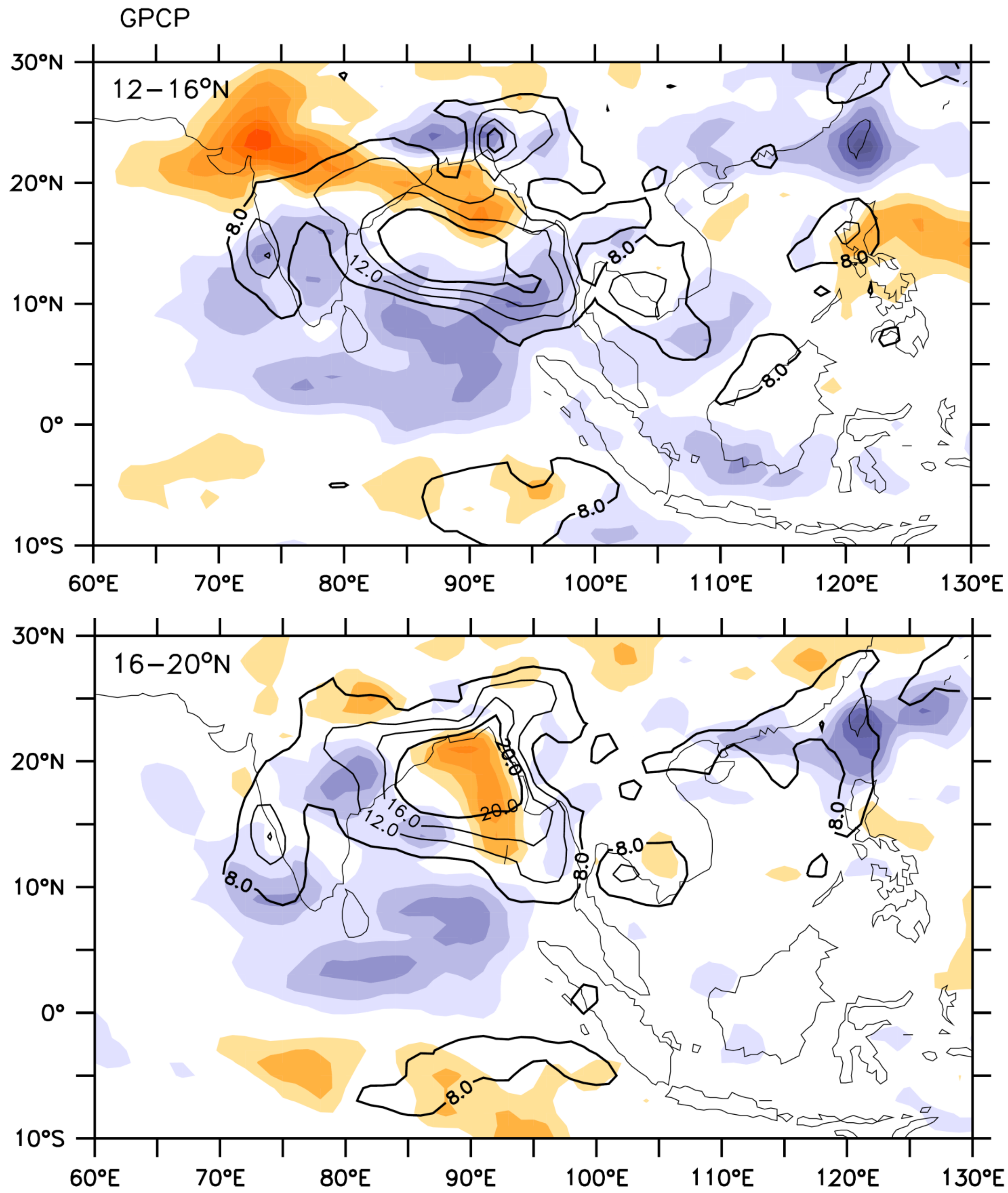
$$\frac{\partial SST}{\partial t} = \frac{1}{\rho C_p H} Q - u\frac{\partial SST}{\partial x} - v\frac{\partial SST}{\partial y} - w\frac{\partial SST}{\partial z} + Mixing$$

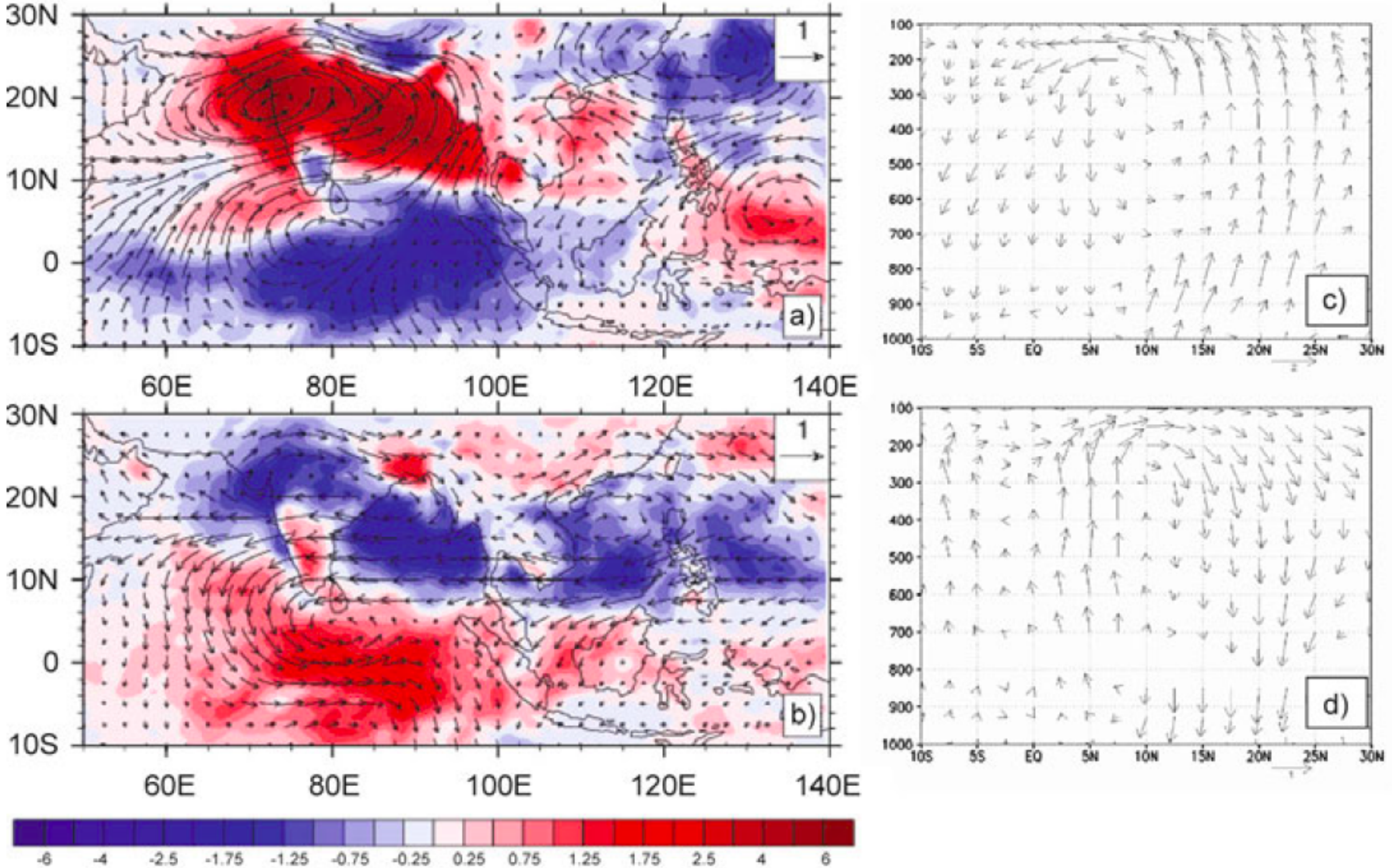


Column water vapour (mm) from SSM/I   12 August 2005

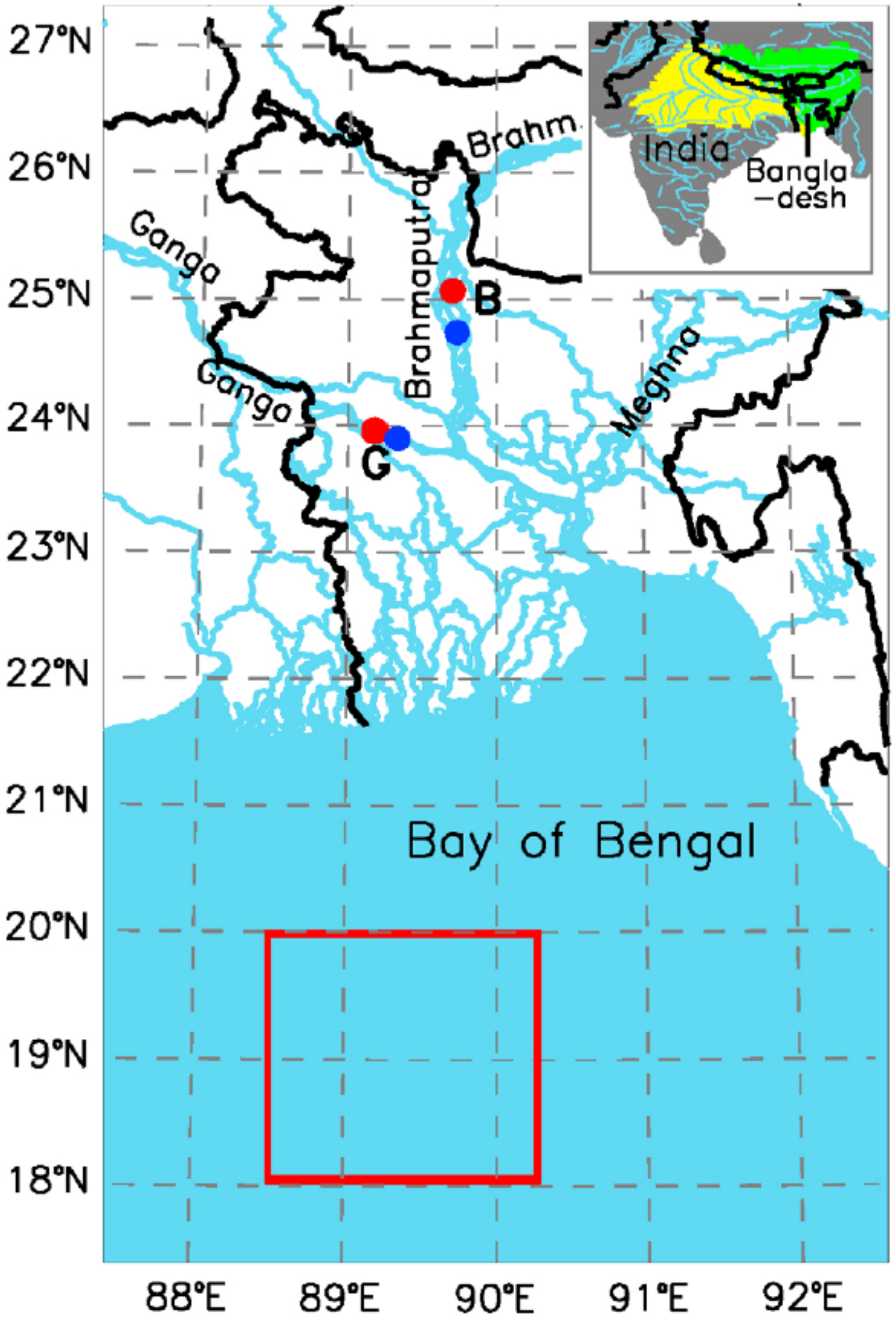


The rainband moves north parallel to itself





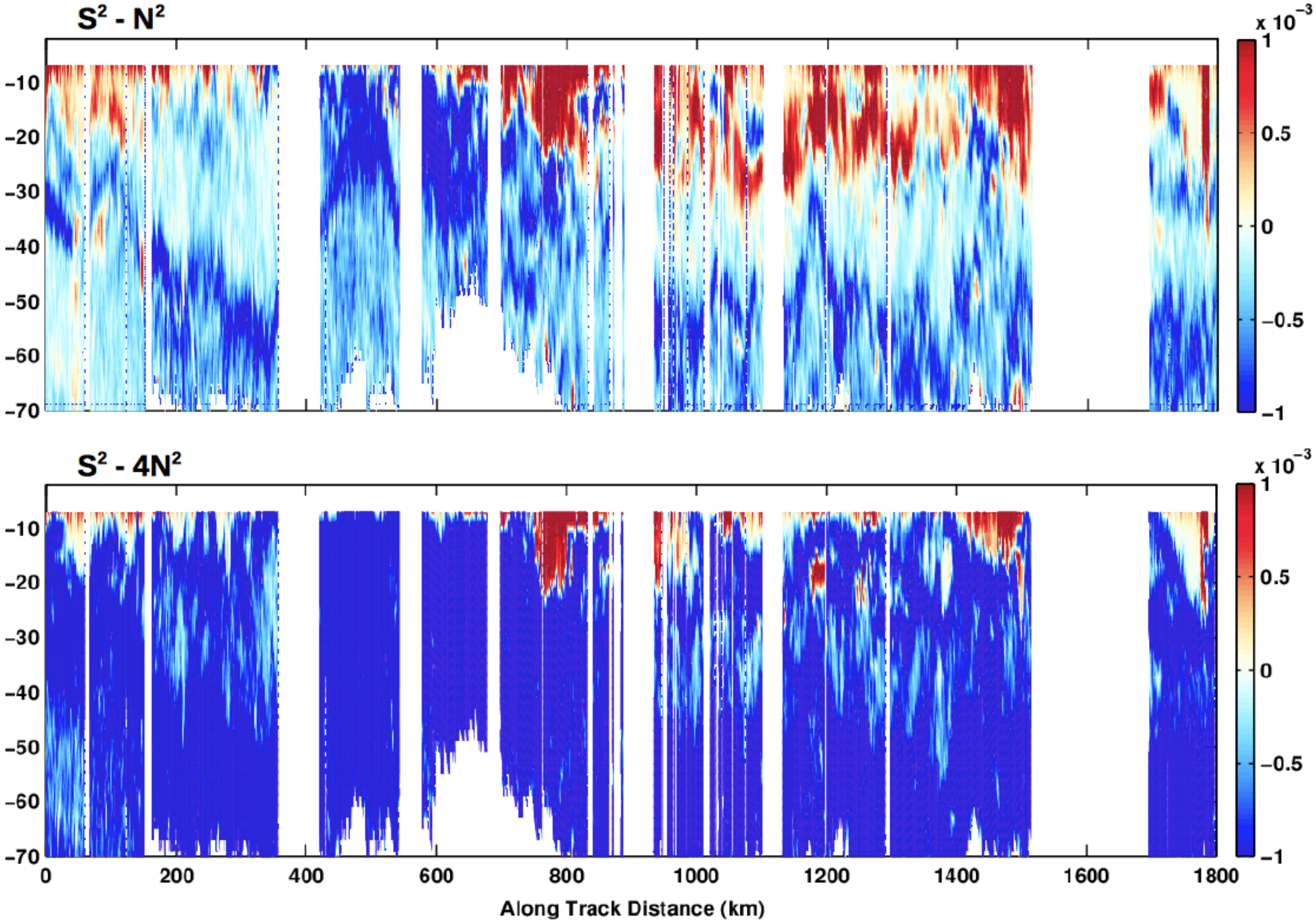
30N
20N
10N
0
10S
60E
80E
100E
120E
140E
1
a)
b)
100
200
300
400
500
600
700
800
900
1000
10S
5S
EQ
5N
10N
15N
20N
25N
30N
c)
d)
-6
-4
-2.5
-1.75
-1.25
-0.75
-0.25
0.25
0.75
1.25
1.75
2.5
4
6



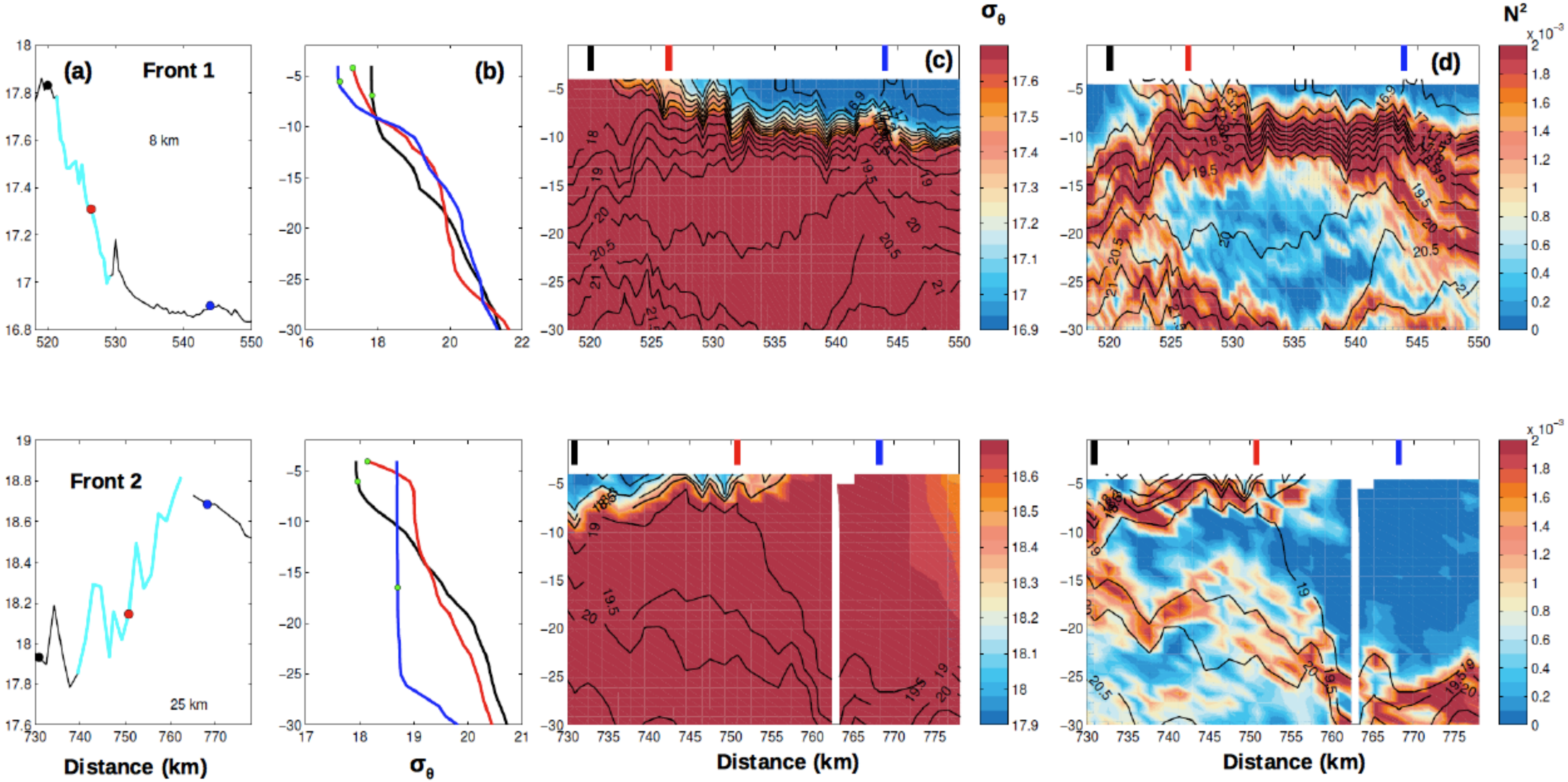
Rivers

Input of fresh water to the Bay of Bengal P-E+R ~ 4000 cubic km

Papa 2012
Sengupta 2006

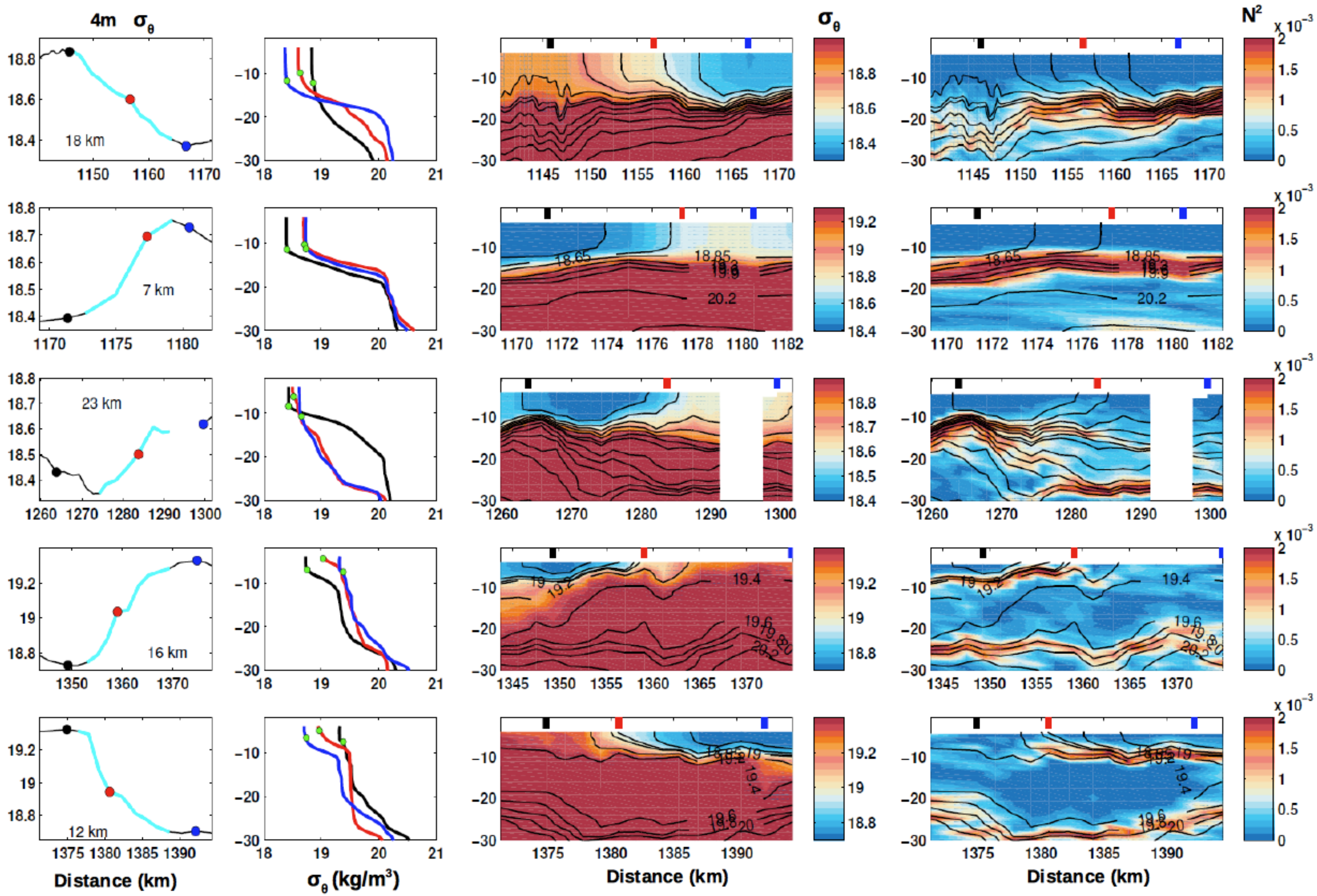


Reduced shear suggests mixing regions, mostly in the upper 30 m.



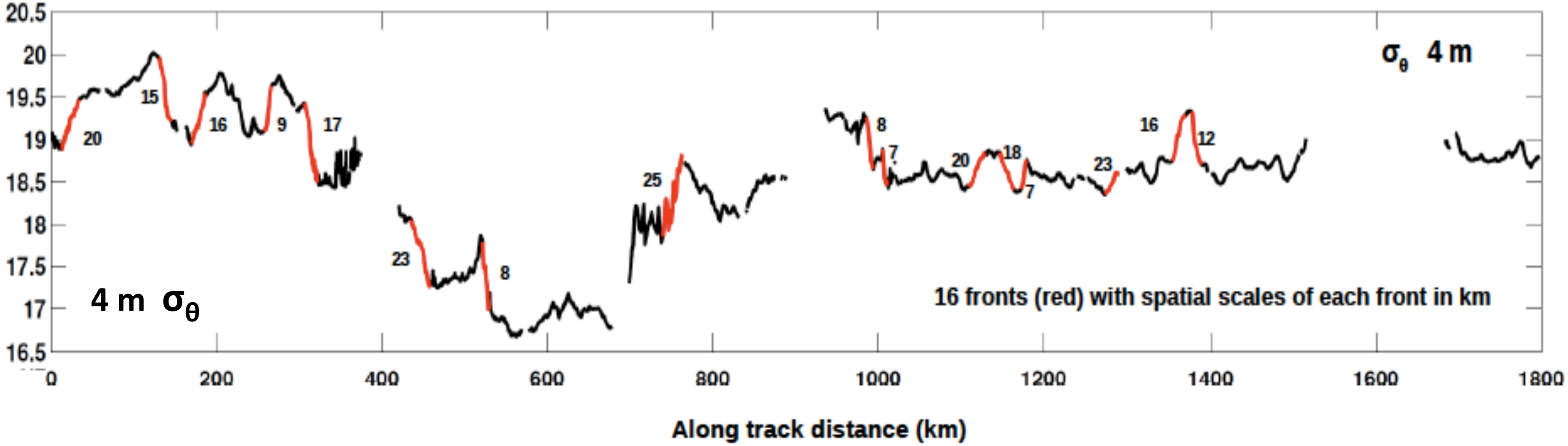
(a) Potential density along the ship track at 4m depth (b) σ_θ profiles under the front (red) and to the right (blue) and left (black) of the front. Mixed layer depth (MLD) marked by green dot. (c) Depth section of σ_θ along the ship track, with location of profiles marked on th top. The countours are isopycnals with interval of 0.5 kg/m³. (d) N^2 as function of distance and depth with σ_θ countours.

Shallow mixed layers under the fronts



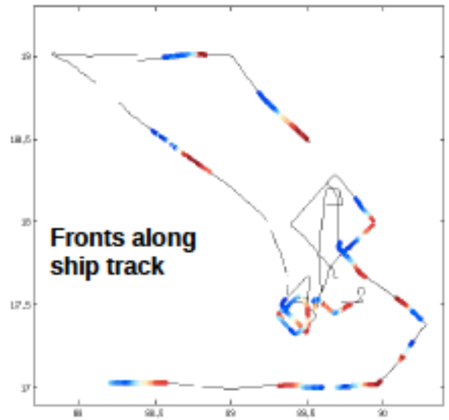
Shallow mixed layers under 13 out of 16 fronts

Salinity dominated density fronts *Sagar Nidhi* SN88



Size (kg/m^3)	No of fronts
0.3 < size < 0.5	5
size > 0.5	11

Scale (km)	No of fronts
7 – 20	11
20 - 25	5



Criteria: Total density change across the front ("size") > 0.3 kg/m^3, $|d\sigma_\theta/dx|$ > 1 std dev

16 major fronts, many smaller ones