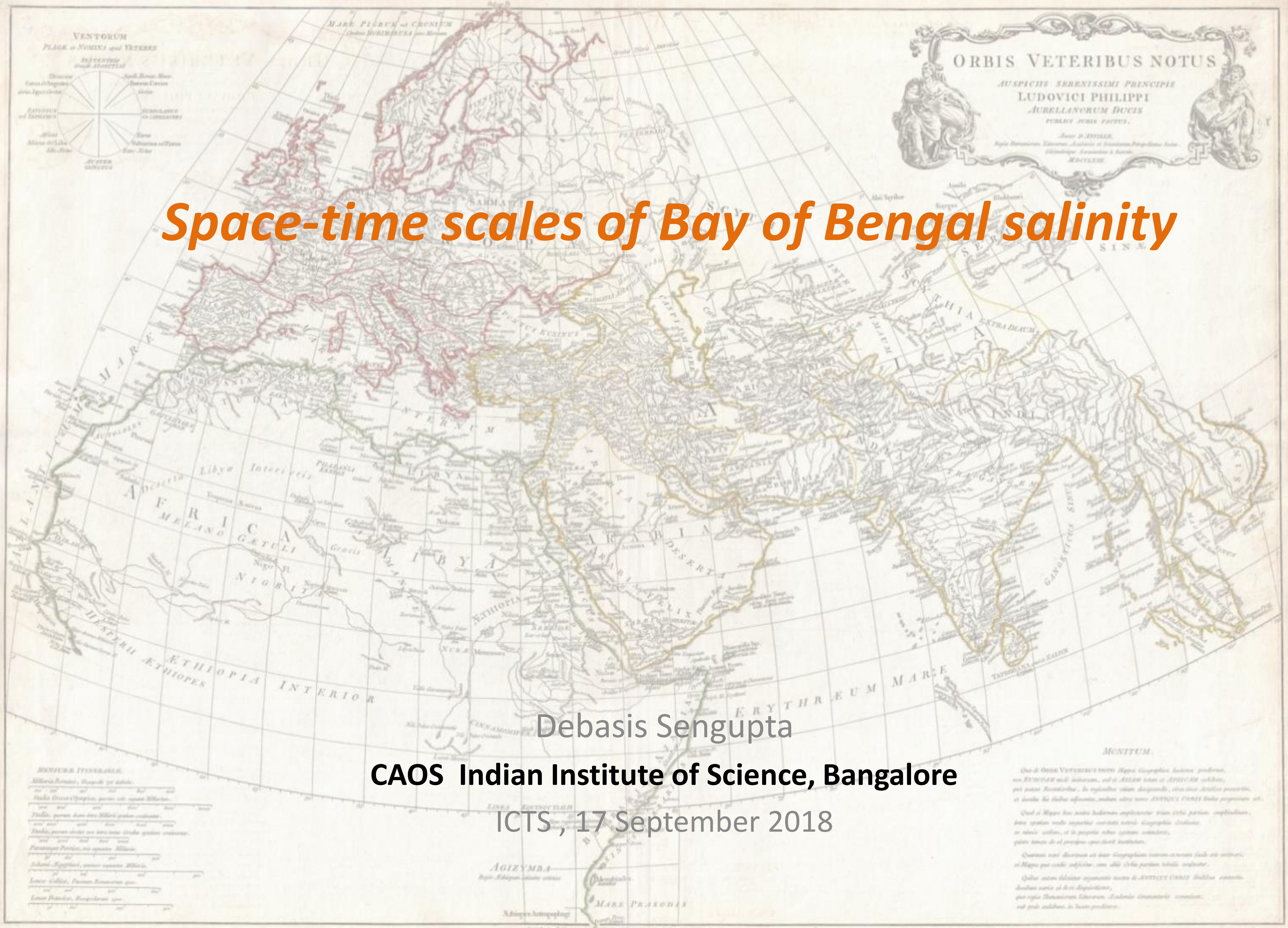


Space-time scales of Bay of Bengal salinity

Debasis Sengupta

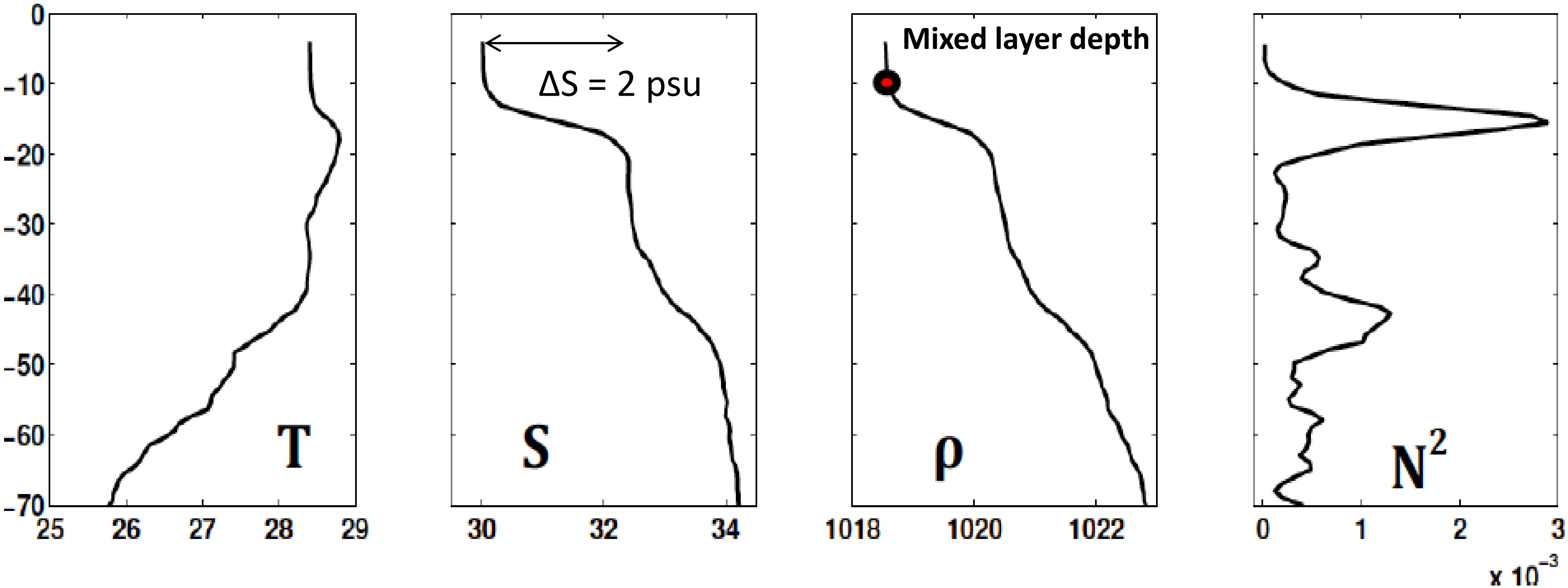
CAOS Indian Institute of Science, Bangalore

ICTS , 17 September 2018

Rivers

Map: Michael Buckley

Vertical profiles at 17.5N 89.5E from ORV *Sagar Nidhi*, 1 Sep 2014



Salinity = Total dissolved salts (grams) in 1 kg of seawater

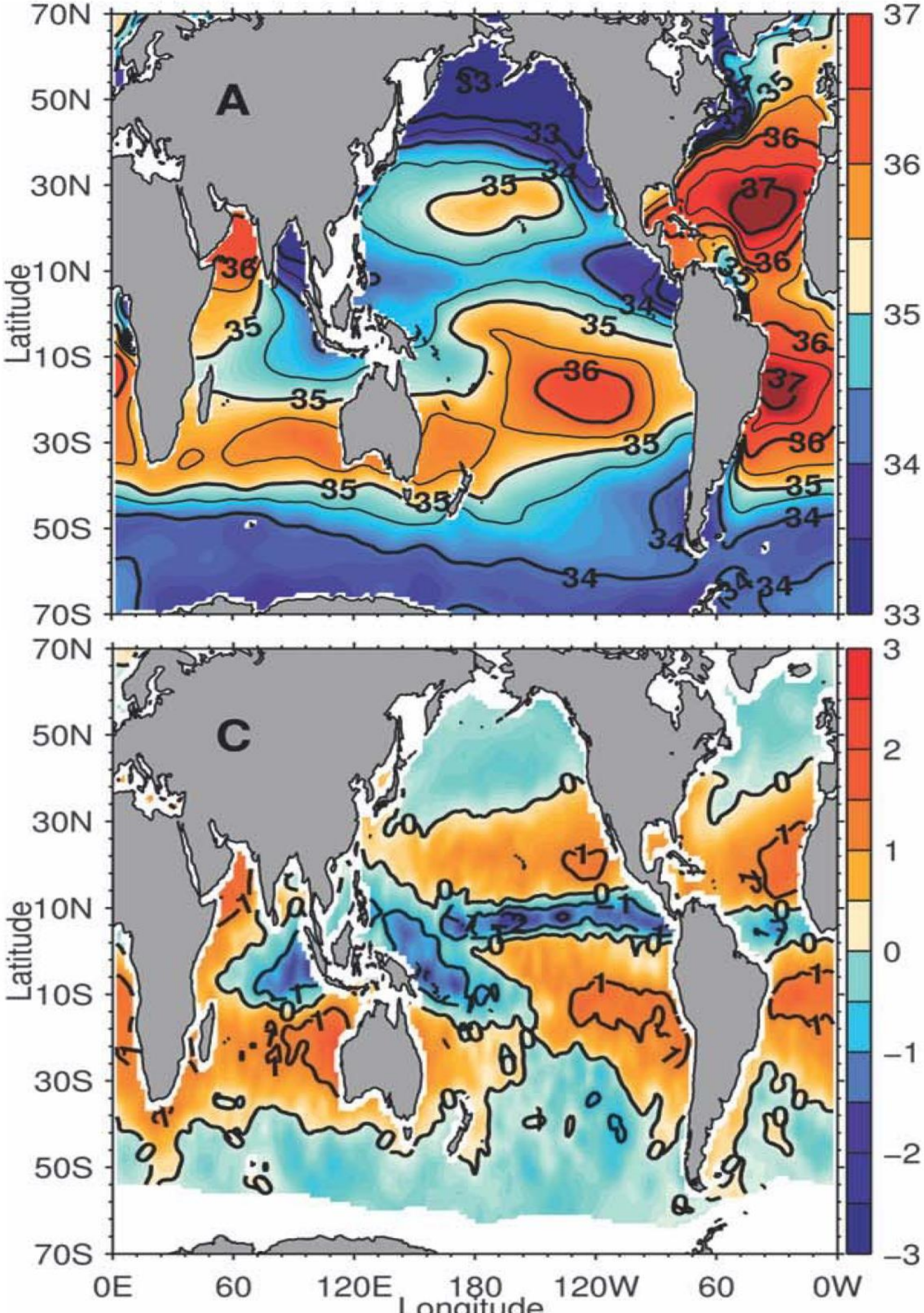
Global ocean mean salinity 34.7 psu (practical salinity units)

$$N^2 = \frac{-g}{\rho_o}\frac{d\rho}{dz}$$

Density of sea water ρ (T,S,P)

Linearised equation of state $\rho = \rho_o - \alpha (T-T_o) + \beta (S-S_o)$

At 31 psu and 29°C, $S-S_o$ = 1 psu or $T-T_o$ = 2.4°C gives $\rho-\rho_o$ = 0.75 kg/m^3



Sea Surface Salinity

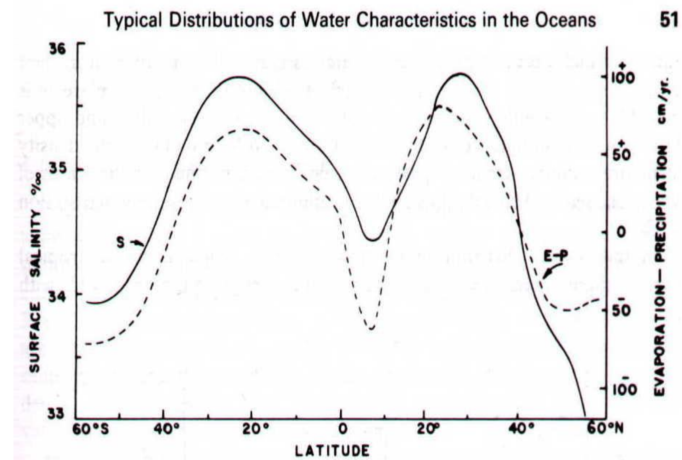
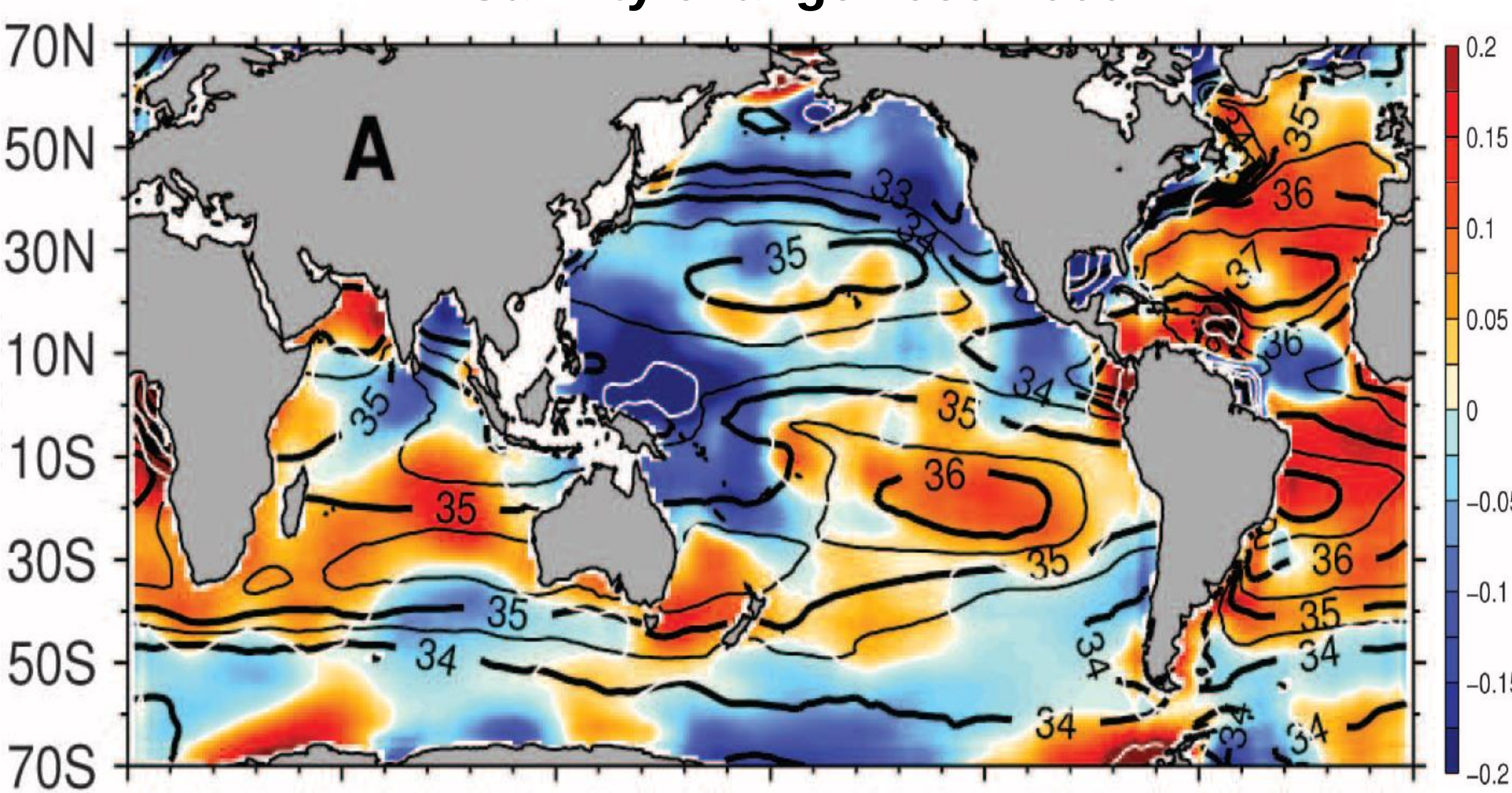


FIG. 4.10. Surface salinity (S, average for all oceans) and difference between evaporation and precipitation (E−P) versus latitude.

Evap-Precip (metre)

Durack *2010; Pond 1983*

Salinity change 1950-2000

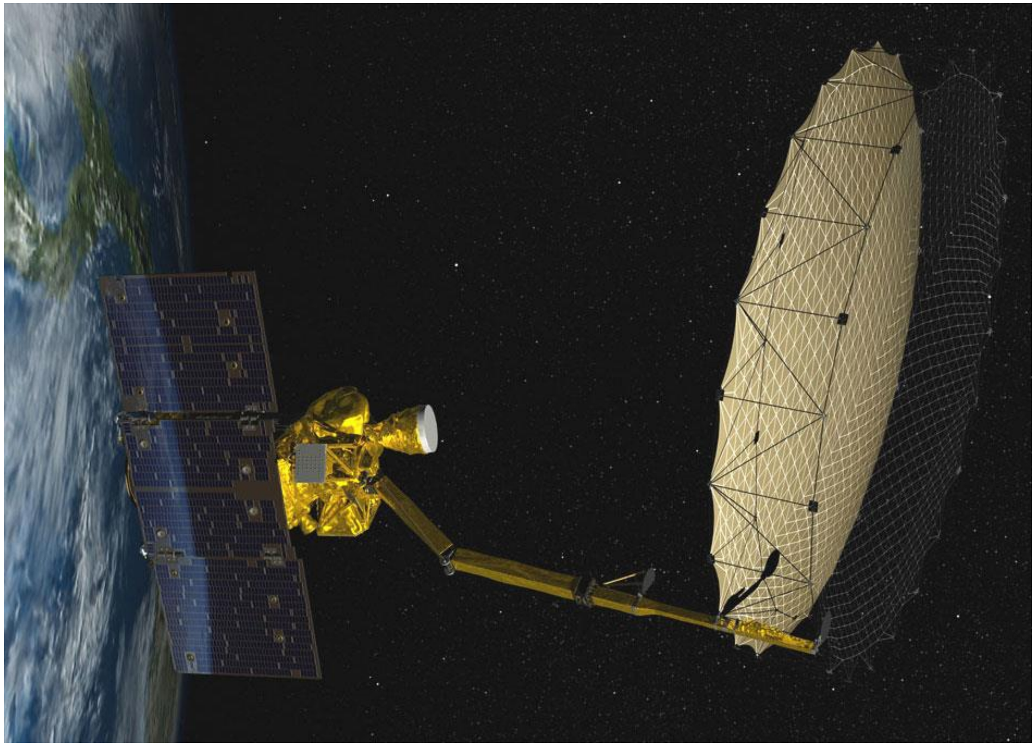


The ocean as rain gauge

Durack *2012*

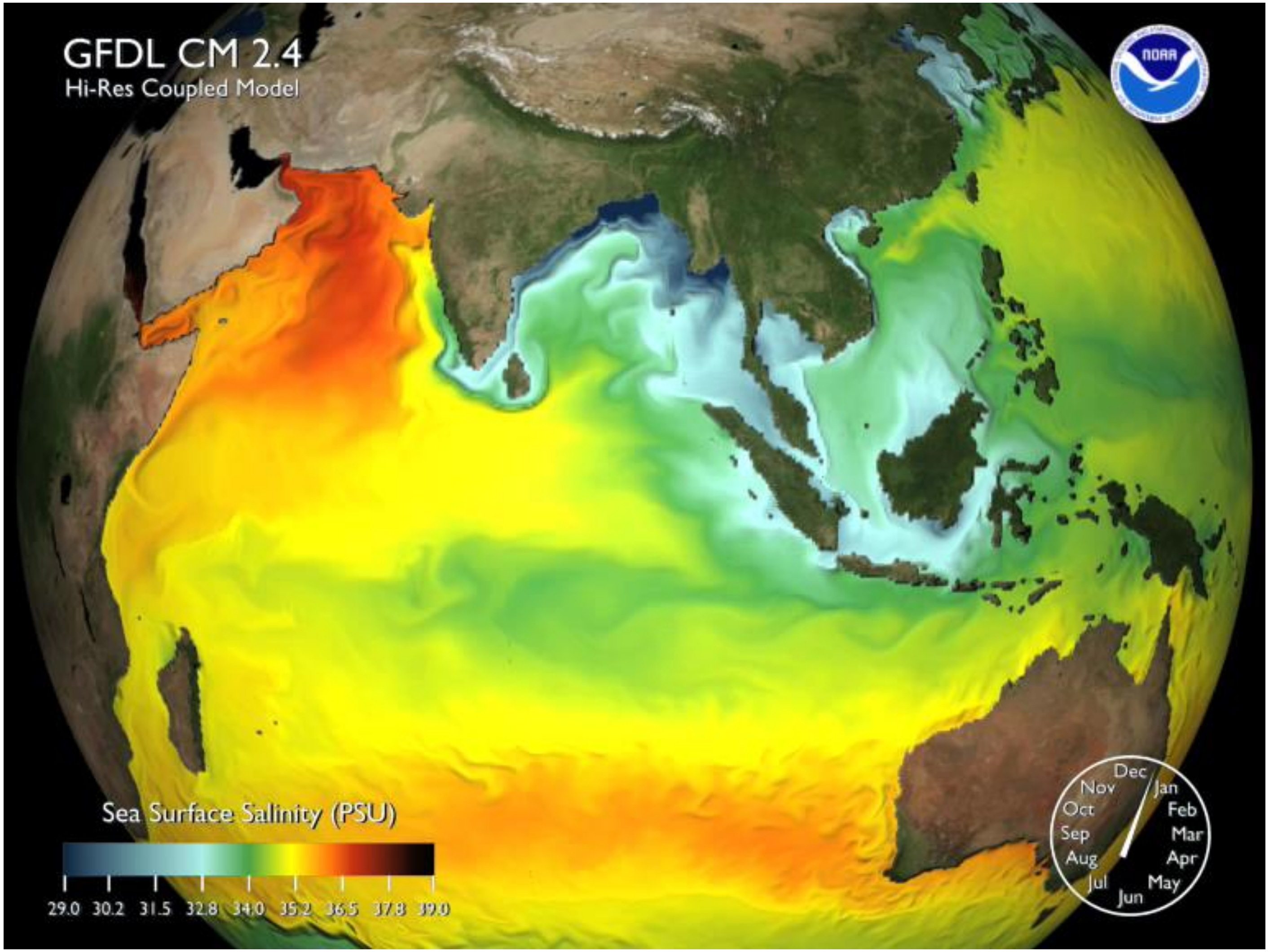
Sea surface salinity (SSS) based on brightness temperature of ocean (T_b) at 1.20-1.41 GHz. $T_b = \varepsilon T$, emissivity ε decreases as conductivity and SSS increase.

SMAP satellite - Altitude 685 km. Repeat time 8 days. Global coverage of SSS at 0.25^o resolution.



The satellite carries a radiometer and a synthetic aperture radar.

Sea Surface Salinity (SSS) **GFDL Climate model 2.4**

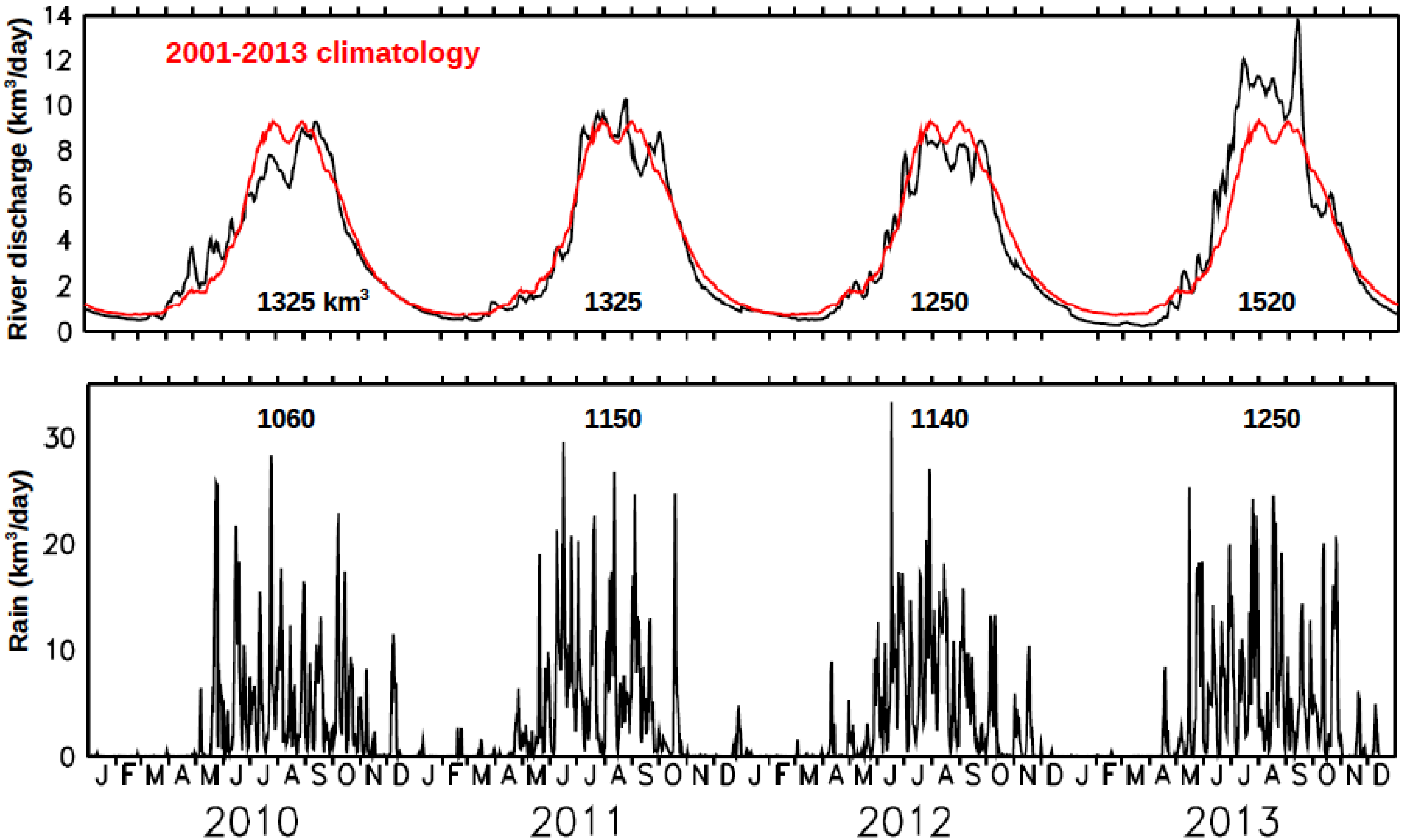


Bay of Bengal river water reaches the east coast of Africa in one year

Sengupta et al. 2006

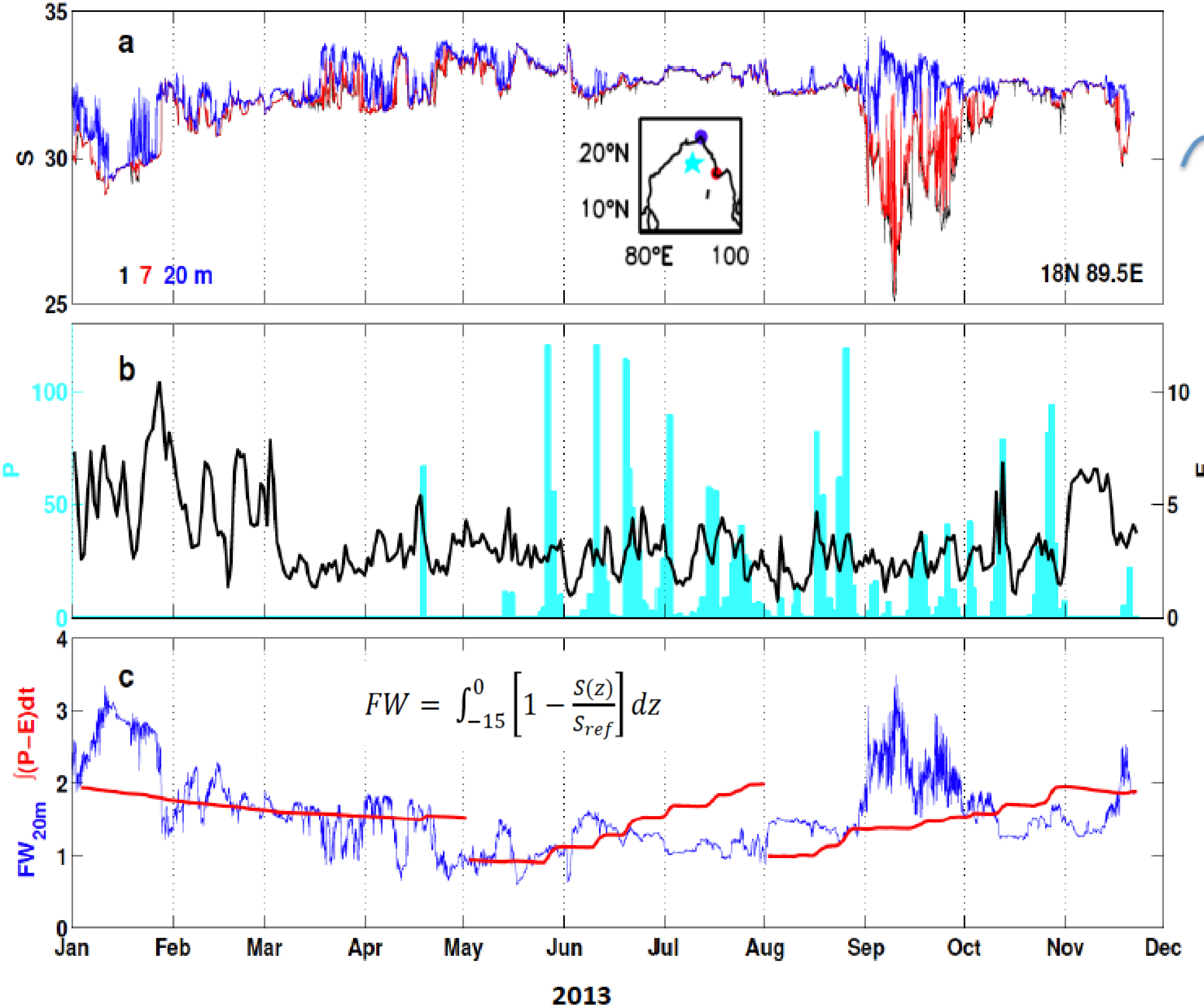
Bay of Bengal annual freshwater input P+R-E ~ 4000 km^3 1.6 m 0.13 Sv

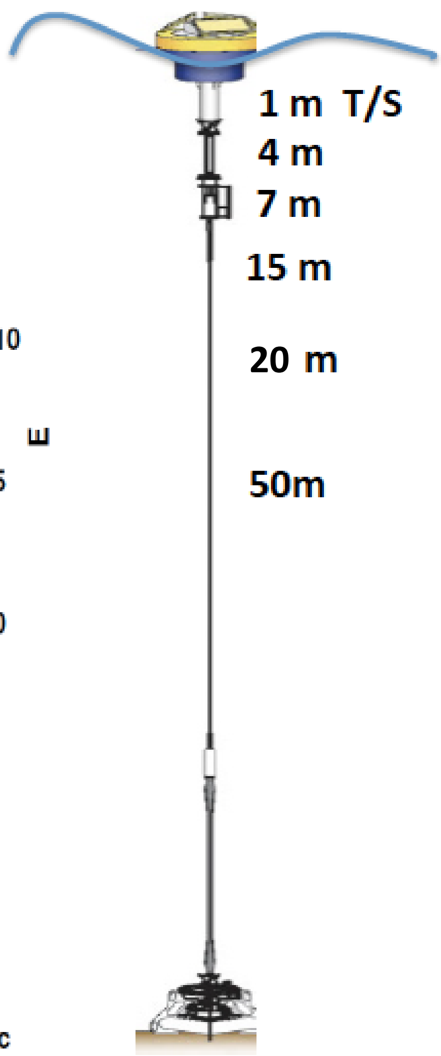
Ganga-Brahmaputra-Meghna daily river discharge and TRMM daily rainfall north of 17N



Discharge data courtesy: Bangladesh River Service, Fabrice Papa

Sengupta et al. 2006, 2016

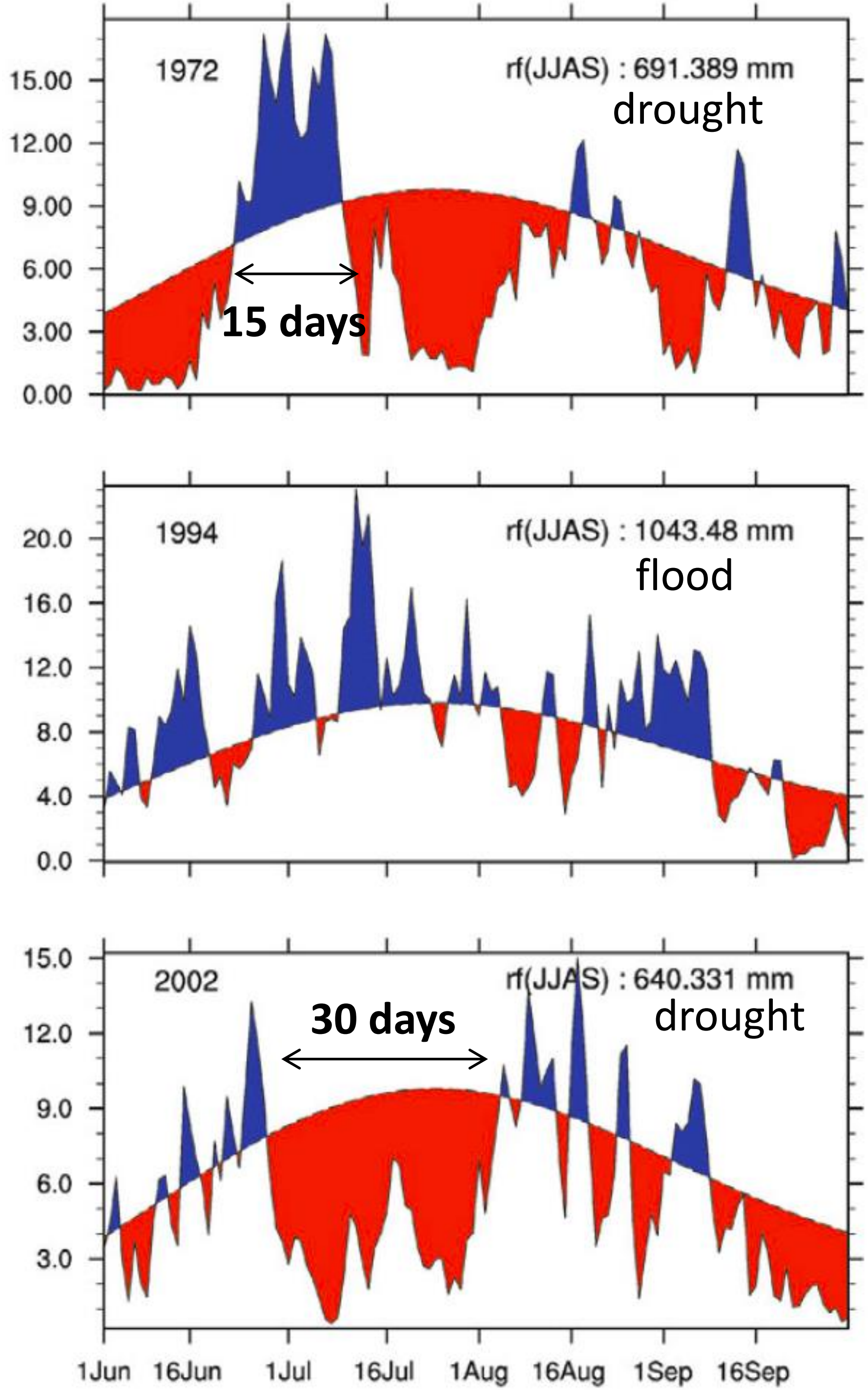




Pulses of river water at the mooring in summer and winter
Aug-Sep river water from Ganga-Brahmaputra; Jan from 2012 Irrawady discharge

Sengupta *et al.* 2016

River water movie



Daily rainfall in central India (mm/day; 73–86E, 11–26N)

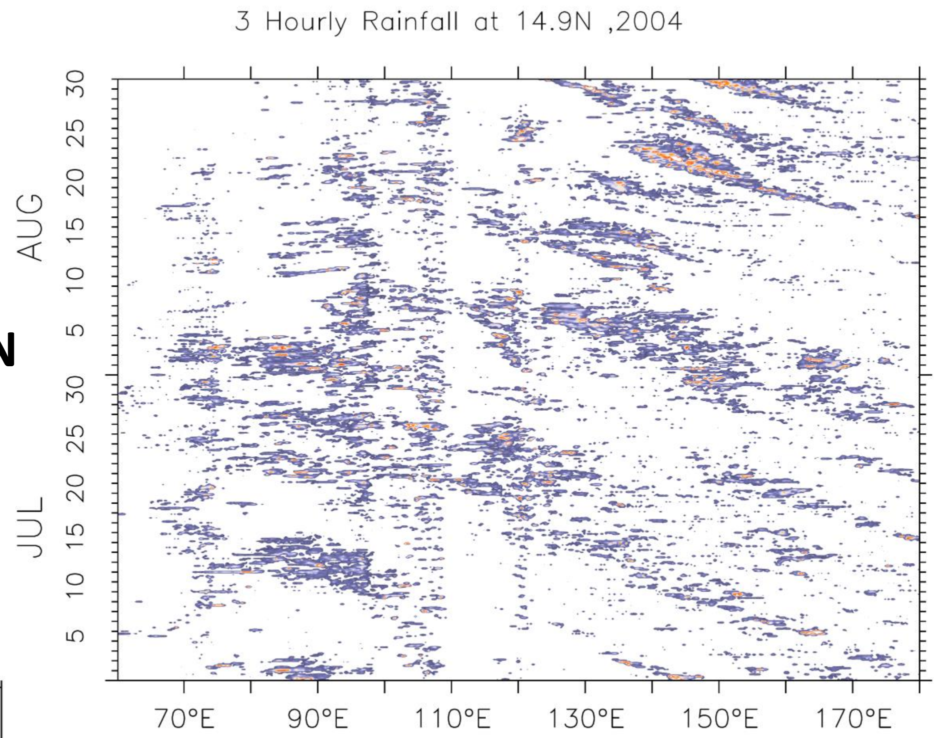
“Active-Break” cycle

Keshavamurthy 1973 Goswami 2012

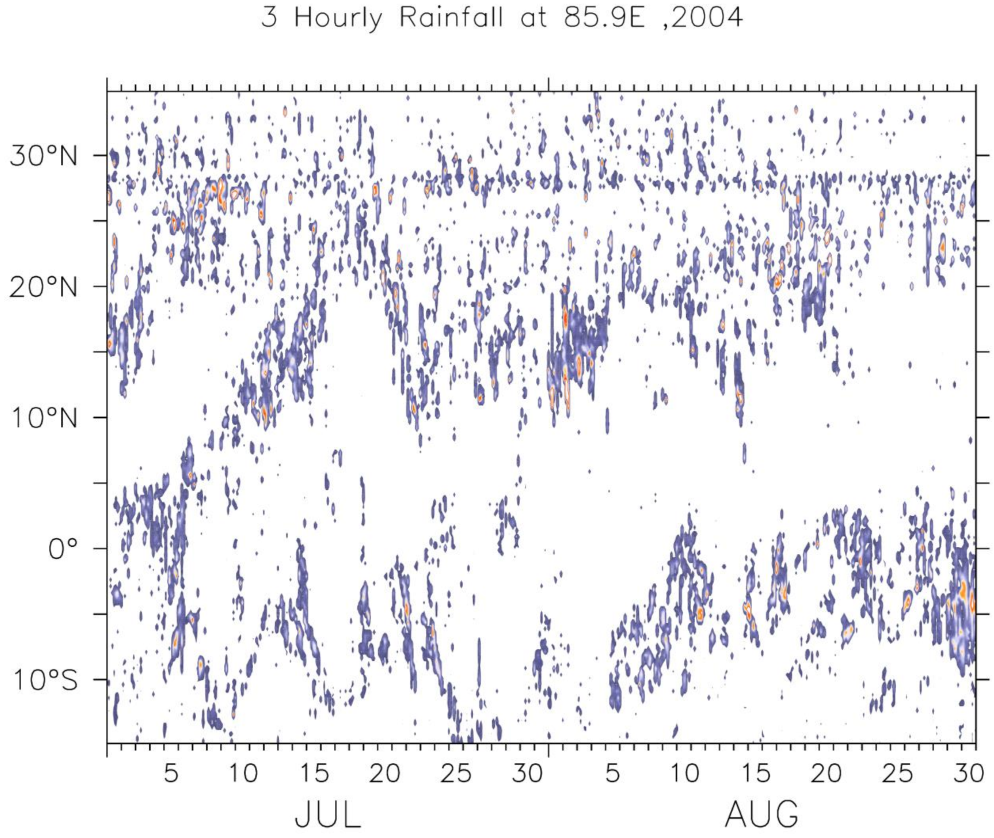
Summer monsoon variability

TRMM ¼ deg 3 hrly rainfall
July-August 2004

15N



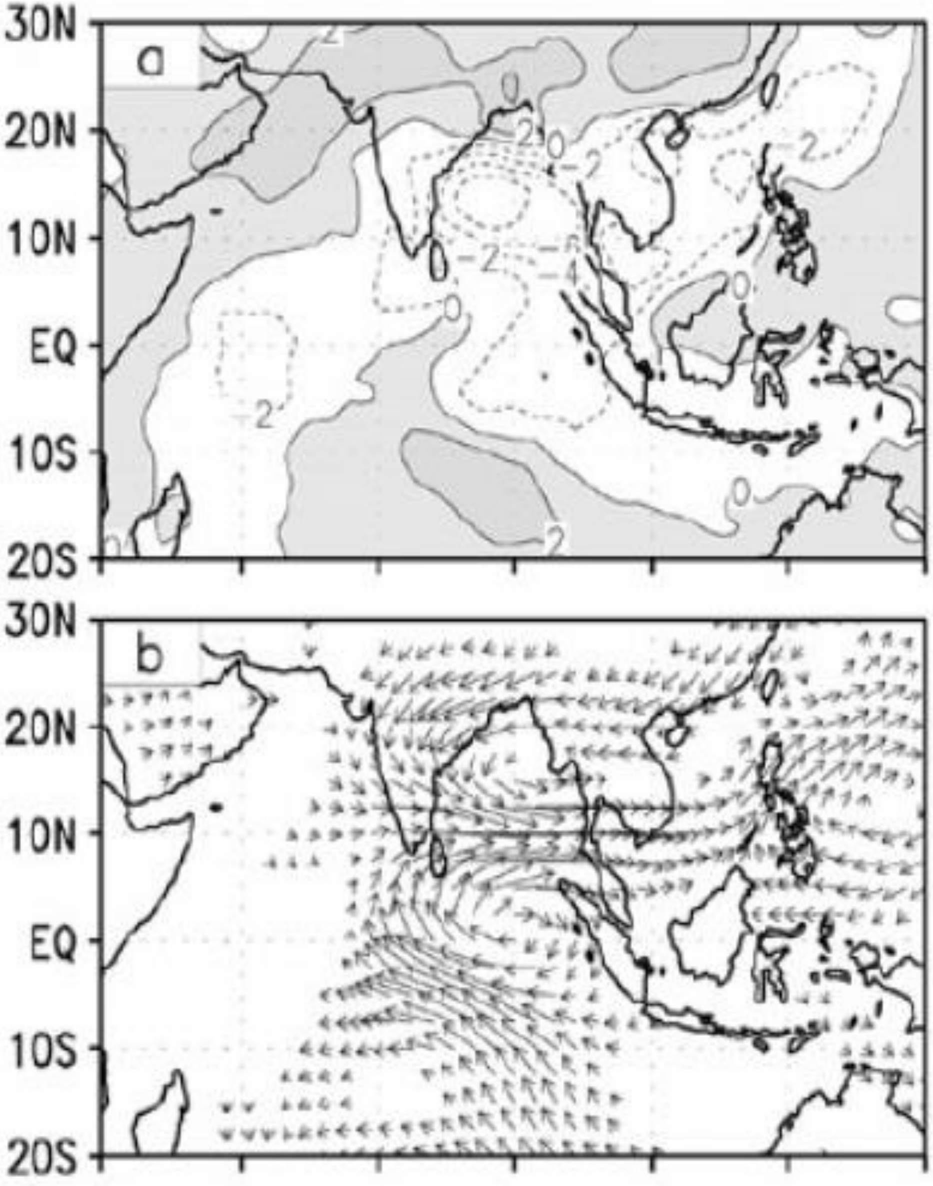
30-60 day : 1 m/s northward



10-20 day: 5 m/s westward

86E

Murakami, Yasunari, Krishnamurti
Sikka & Gadgil, Chen & Chen, Goswami ……



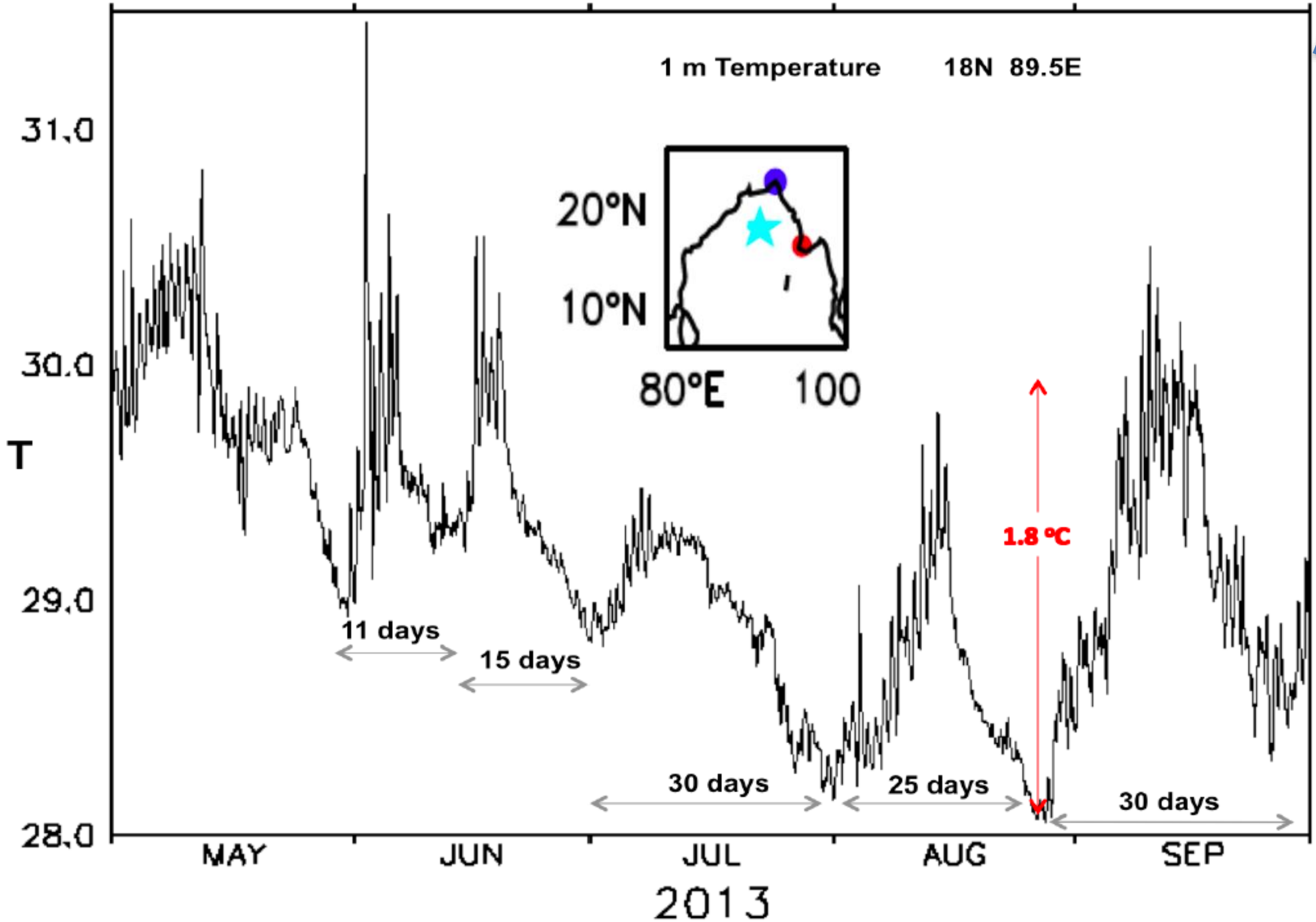
The “quasi-biweekly” mode

Composites of 10-20 day filtered OLR and 850 hPa winds during the summer monsoon season (JJAS)

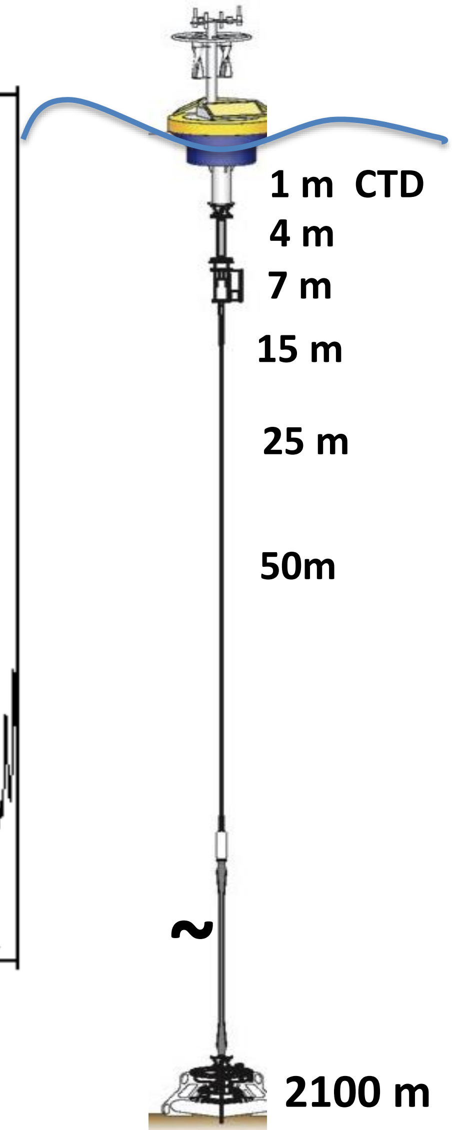
10-20 day “quasi-biweekly” mode

Chatterji and Goswami 2004

INCOIS Mooring 18°N 89.5°E



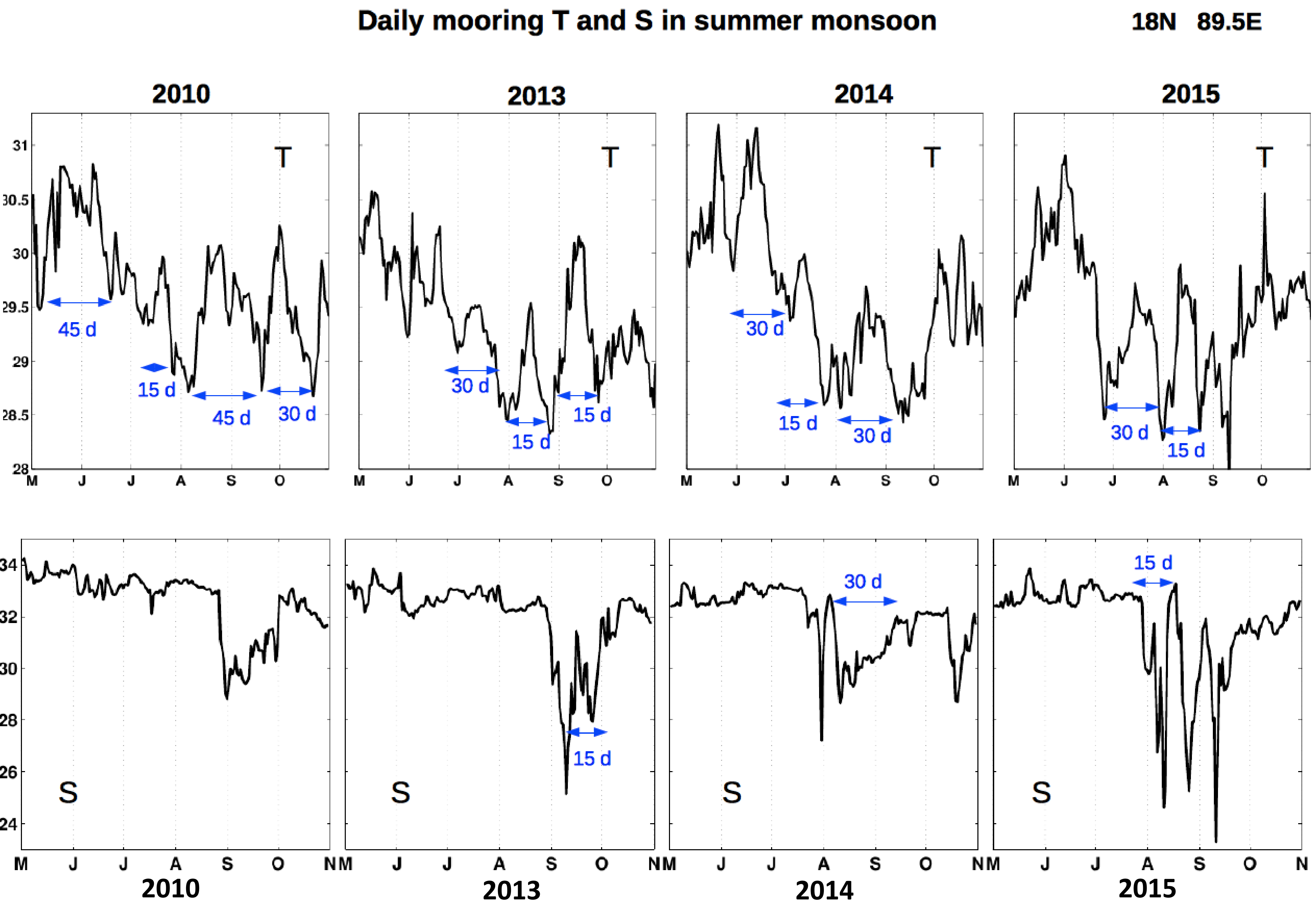
Sea Surface Temperature (SST)



$$\frac{\partial SST}{\partial t} = \frac{1}{\rho C_p H} Q$$

Why is the surface mixed layer shallow ?

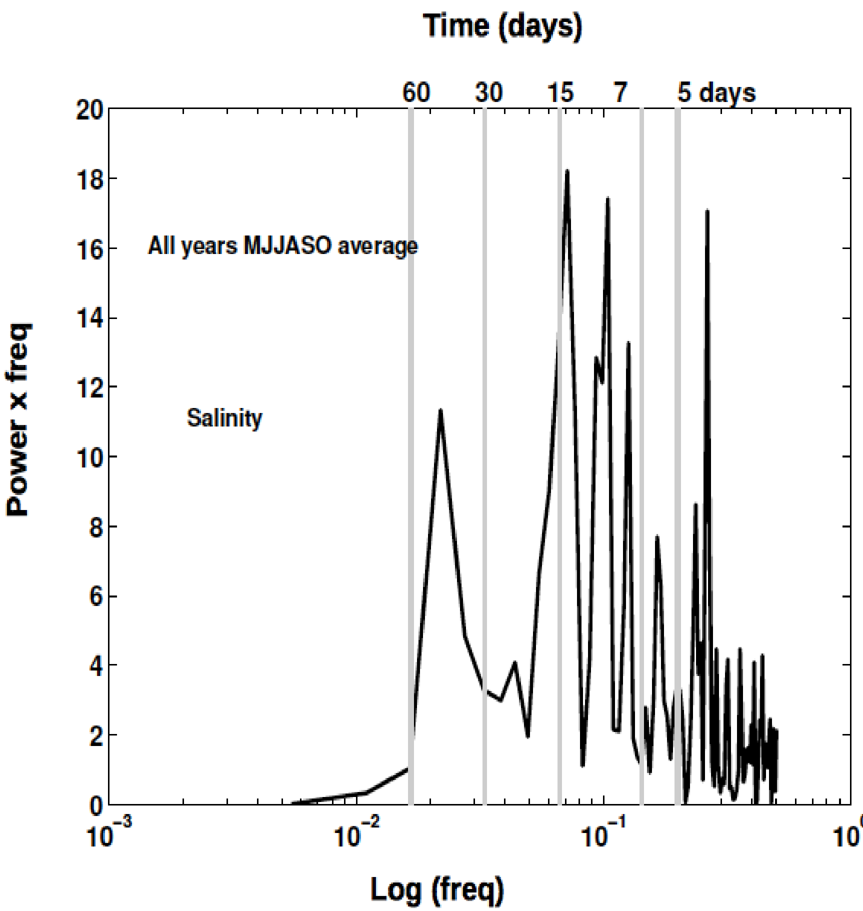
Sengupta Ravichandran 2001, Vecchi Harrison 2002, De Mott 2011

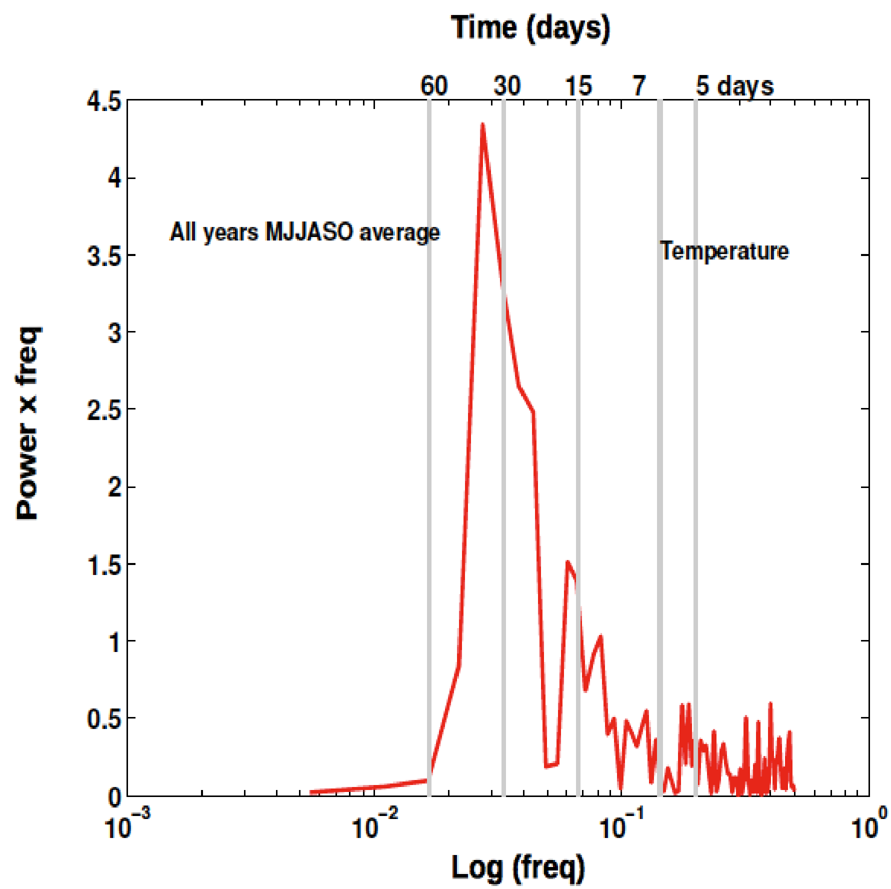


Daily mooring T and S in summer monsoon
18N 89.5E
2010
2013
2014
2015
T
S
45 d
15 d
30 d
M J J A S O N

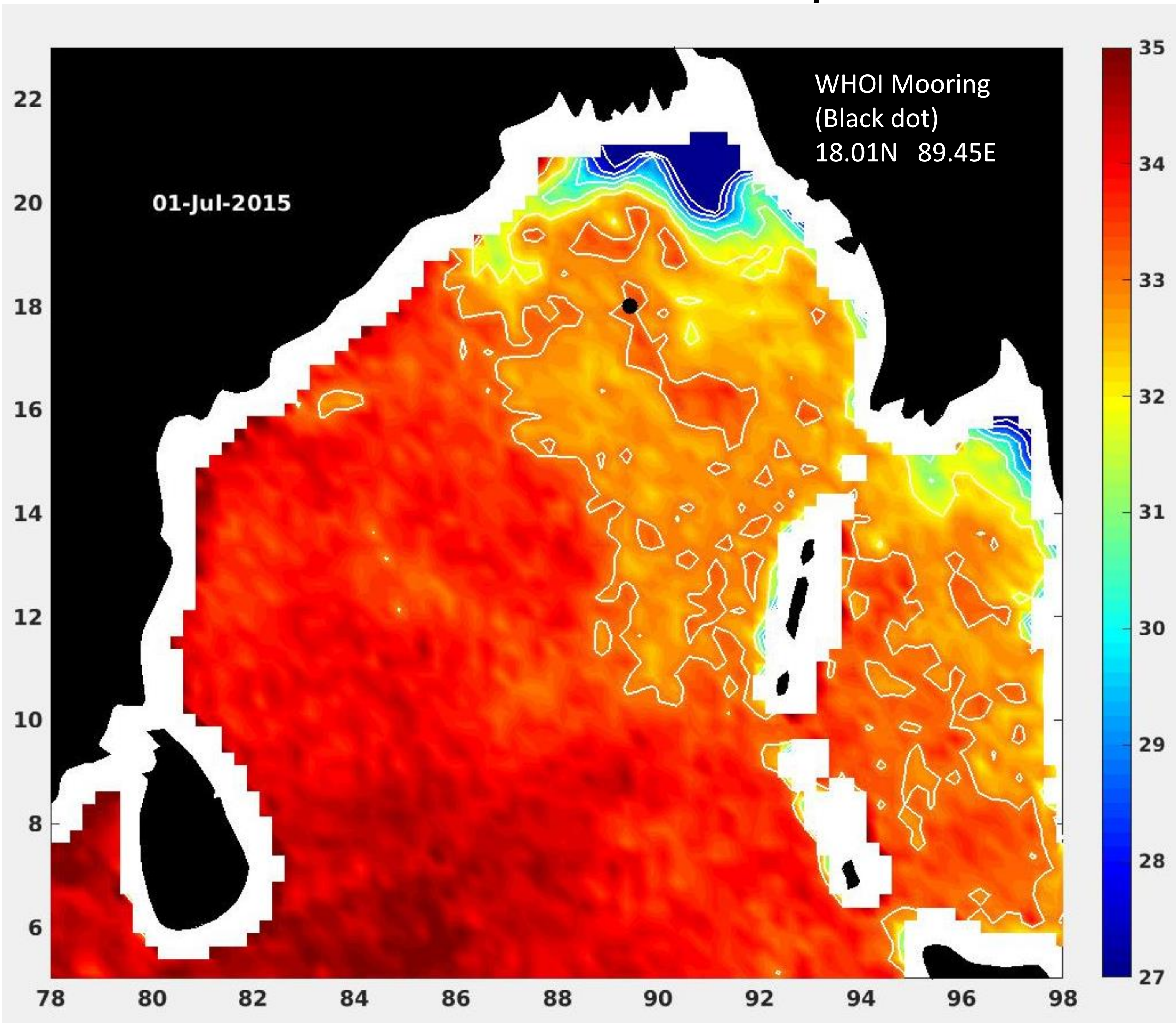
Variance-preserving spectra of sub-60 day mooring S (left) and T (right)

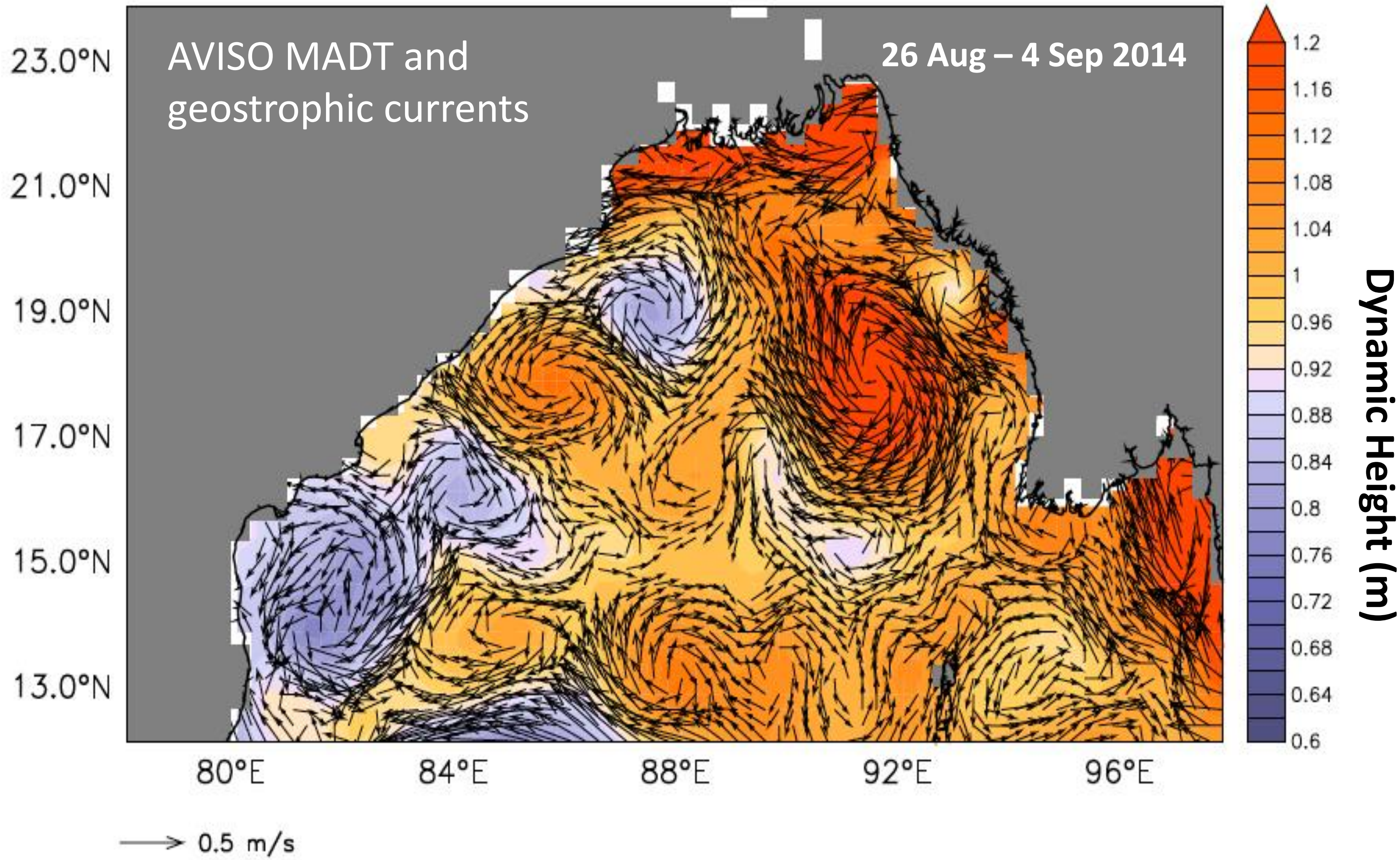
MJJASO average for 2010, 2013, 2014 and 2015





SMAP Sea Surface Salinity

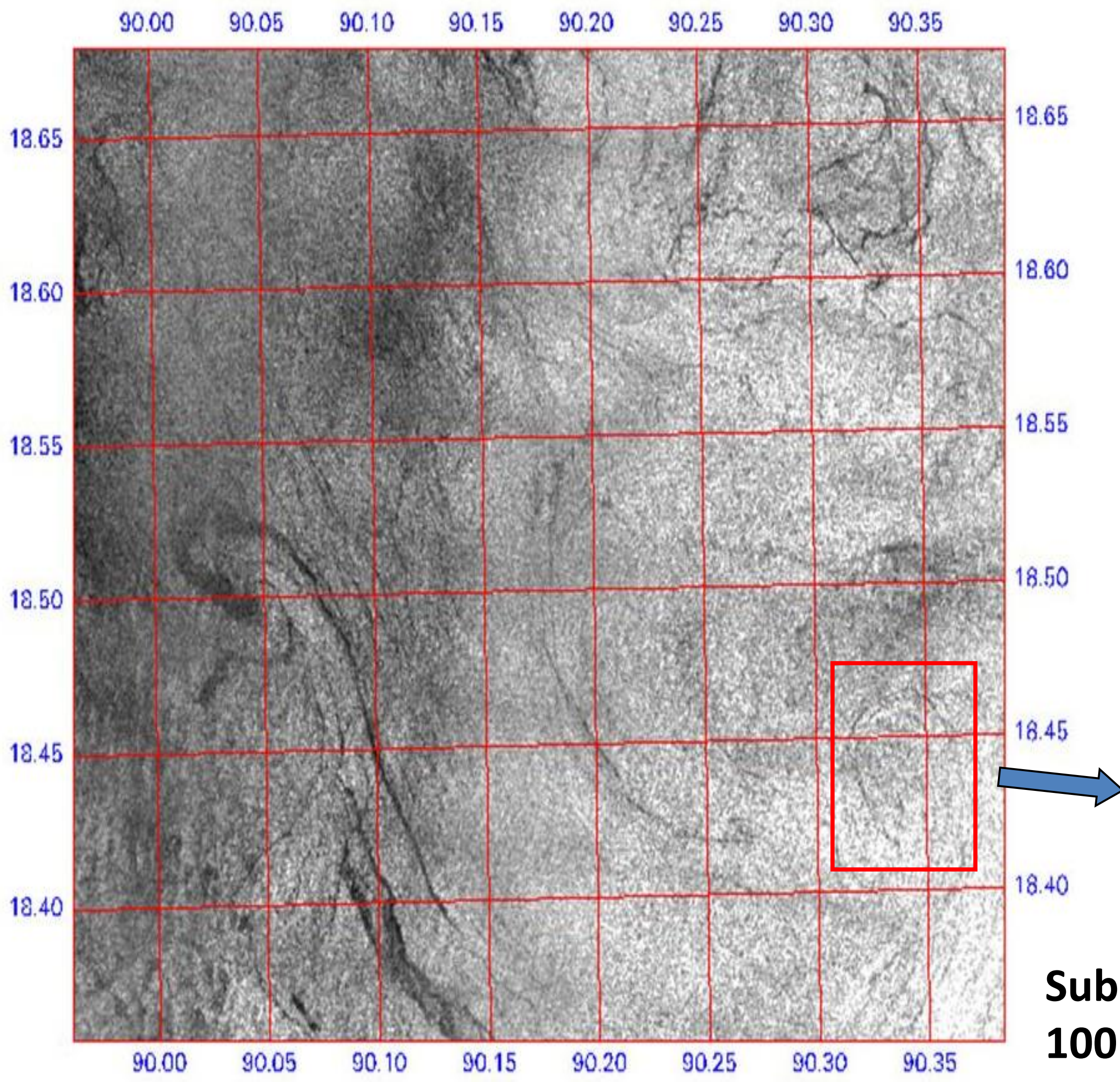




“Mesoscale” 200-400 km eddies are everywhere in the Bay of Bengal

RISAT-1 SAR ocean surface signature 25 m spatial resolution

Central Bay of Bengal



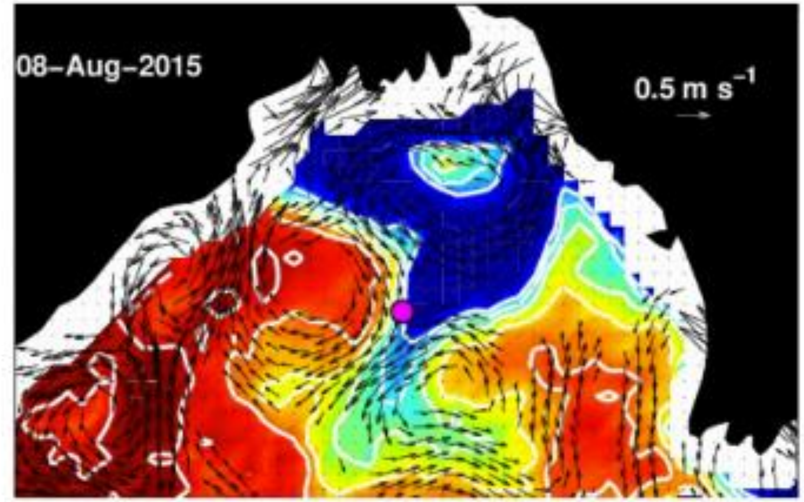
NH/f ~ 5 km

Submesoscales:
100m – 1 km filaments, 6.5 km eddy

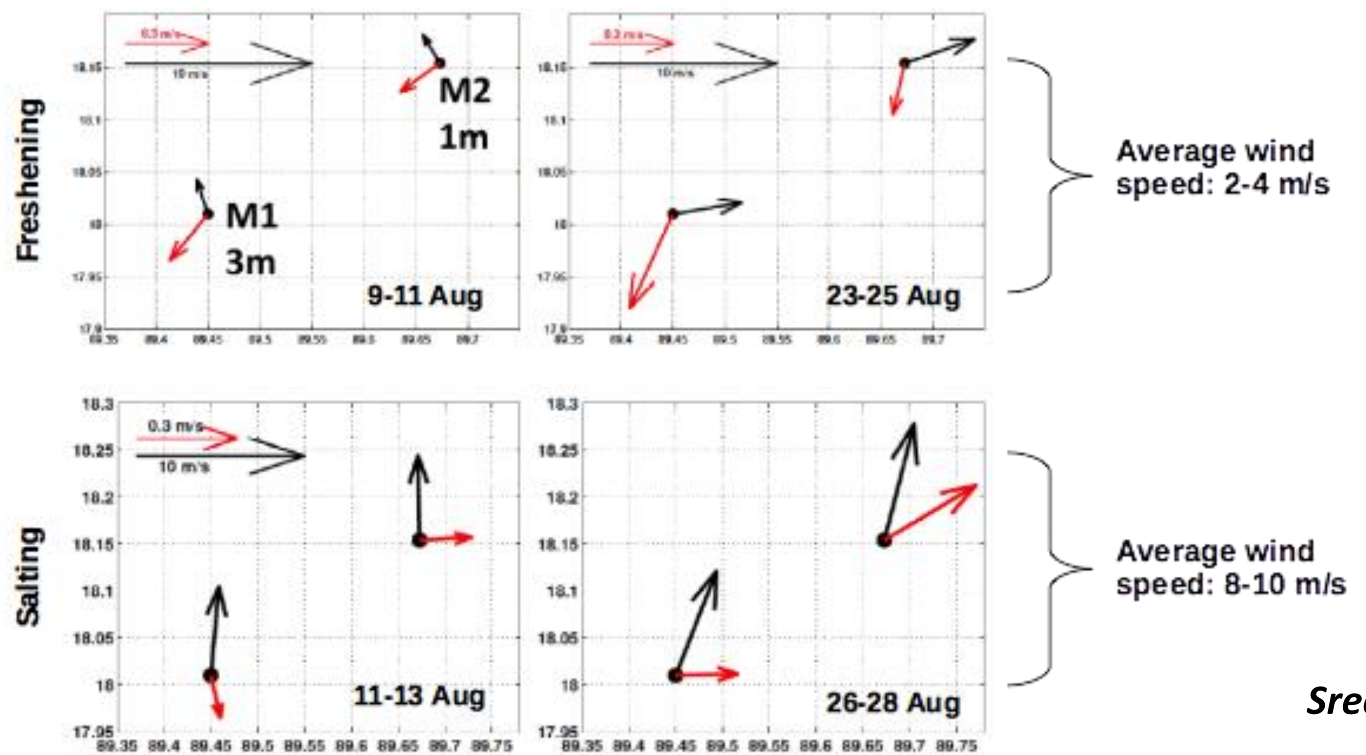
Courtesy: Rashmi Sharma, Abhisek Chakraborty, SAC

Low winds: The geostrophic flow between two counter-rotating mesoscale eddies draws river water to the mooring.

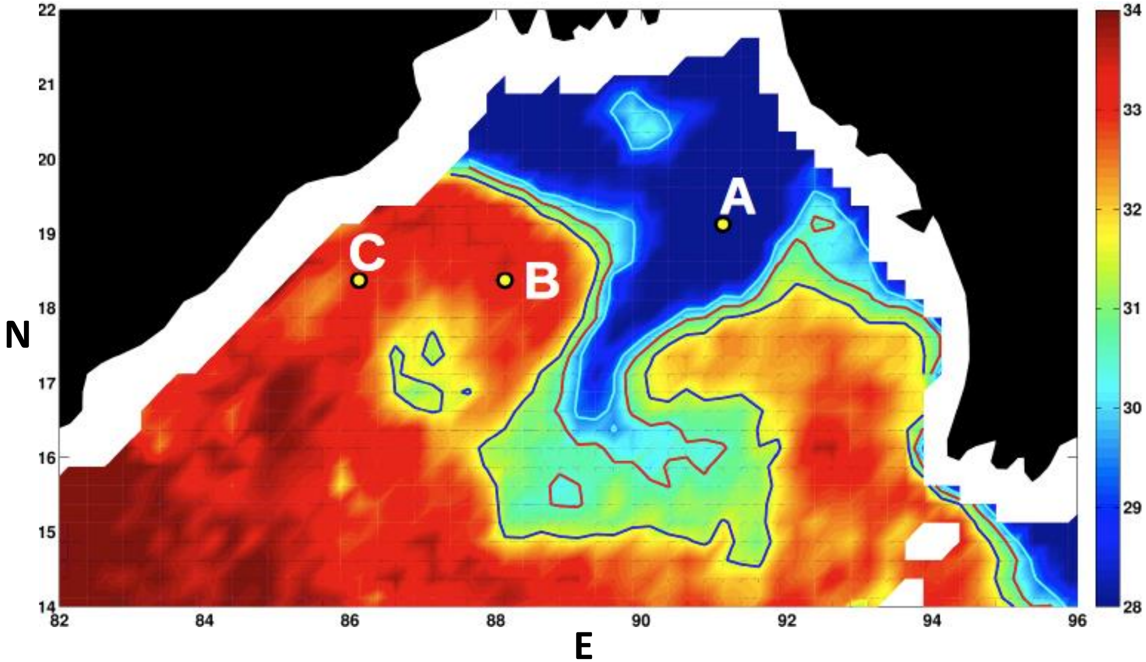
High winds: The shallow wind driven "Ekman" flow pushes river water away from the mooring



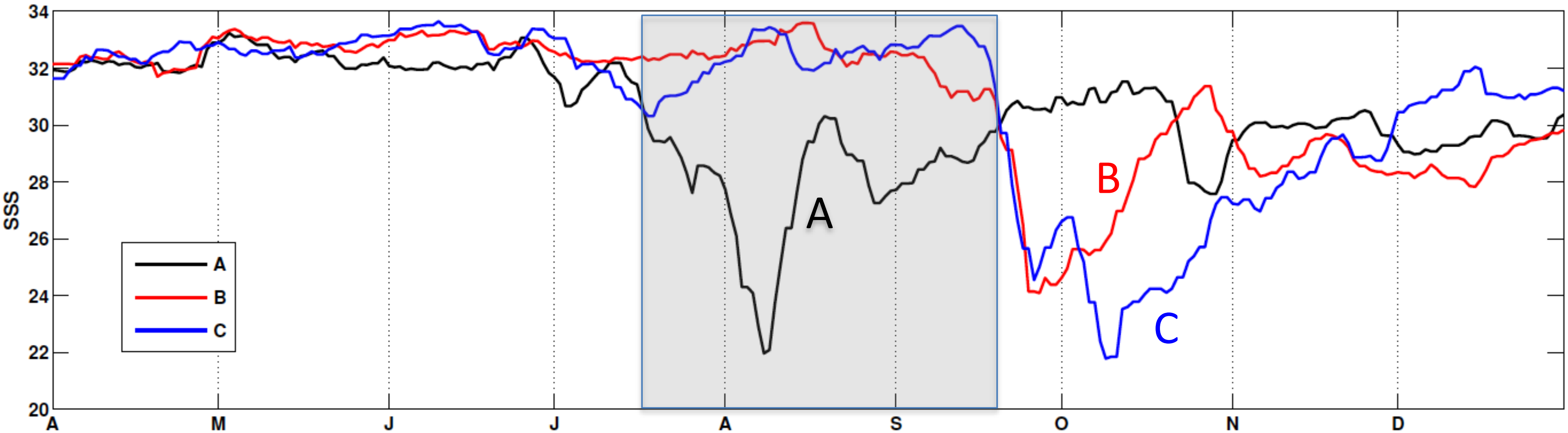
Wind (black) and ocean currents (red) at moorings M1 (WHOI) and M2 (NIOT) averaged across 2 inertial periods



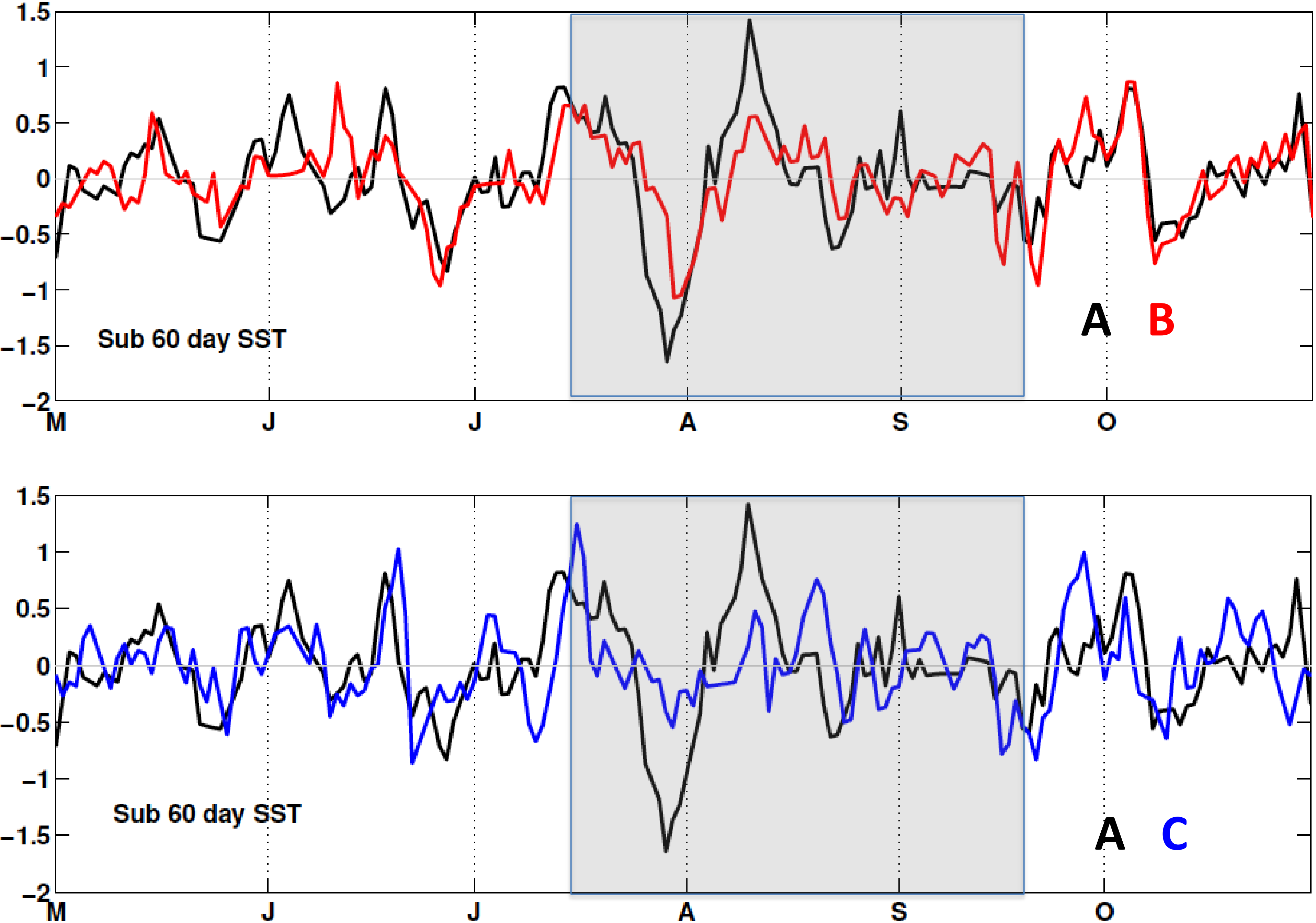
Sree Lekha et al. 2018



SMAP SSS 11 August 2015



SMAP SSS April-December 2015



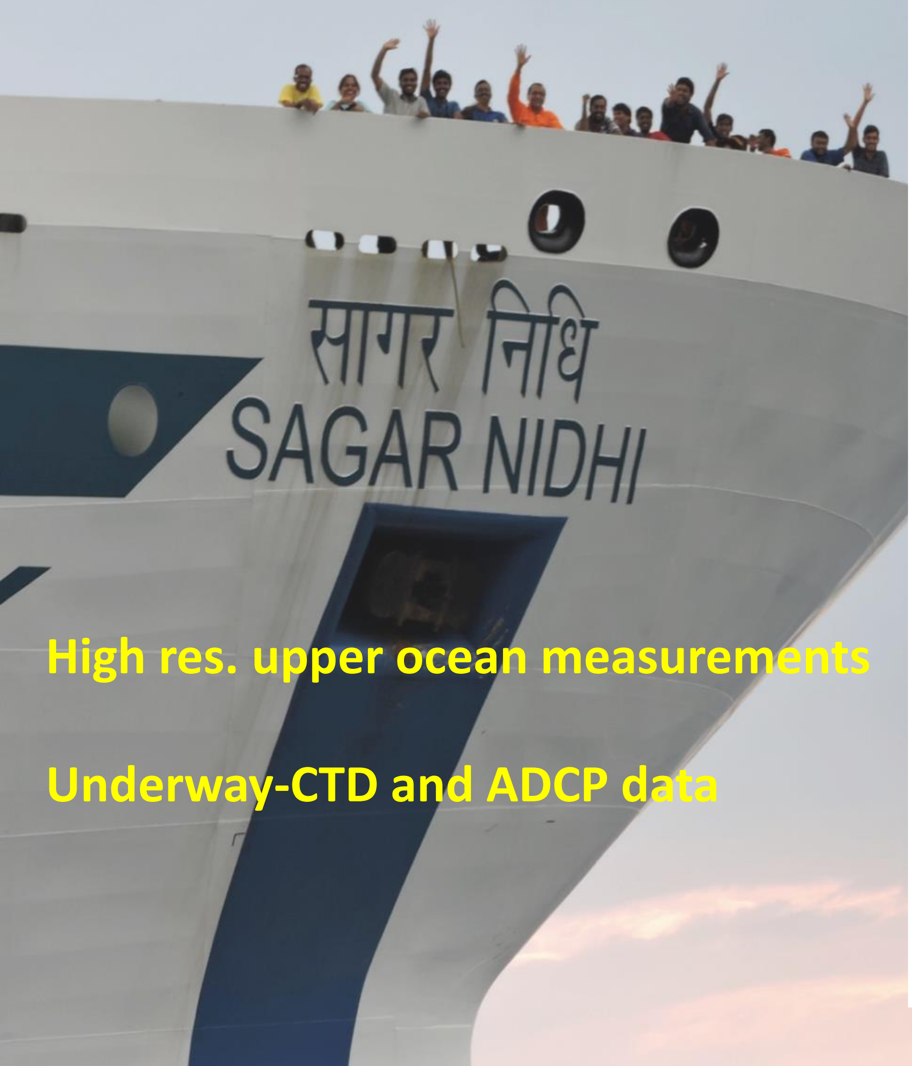
1.5
1
0.5
0
−0.5
−1
−1.5
−2
Sub 60 day SST
A
B
M
J
J
A
S
O
1.5
1
0.5
0
−0.5
−1
−1.5
−2
Sub 60 day SST
A
C
M
J
J
A
S
O

Going to sea…

The Bay of Bengal story…

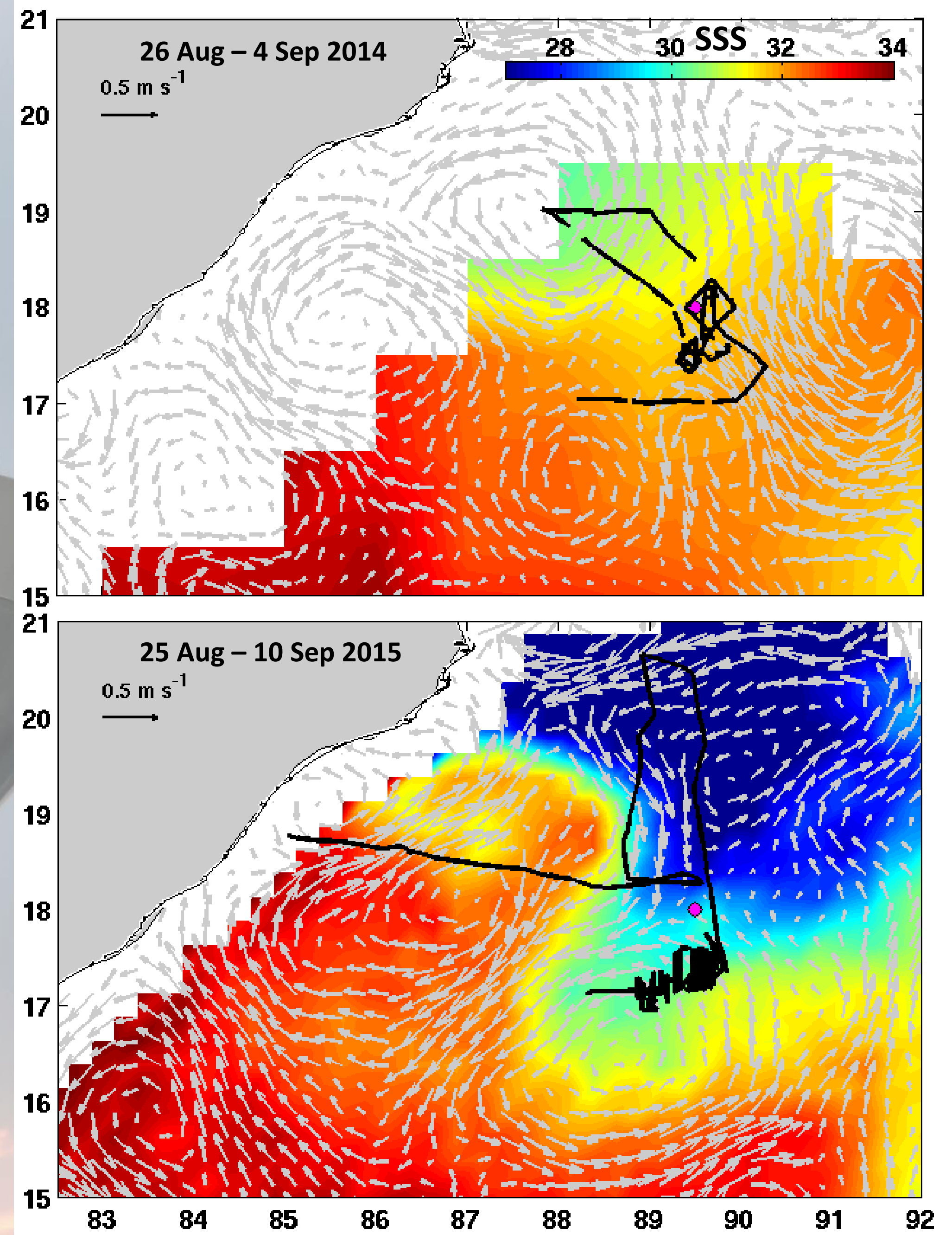
Dipanjan Chaudhuri J. Sree Lekha

Summer monsoon cruises
Aug-Sep 2014 and 2015

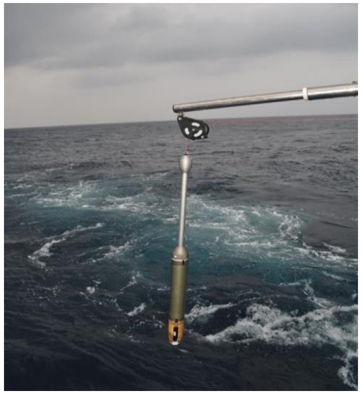


High res. upper ocean measurements

Underway-CTD and ADCP data



Underway CTD



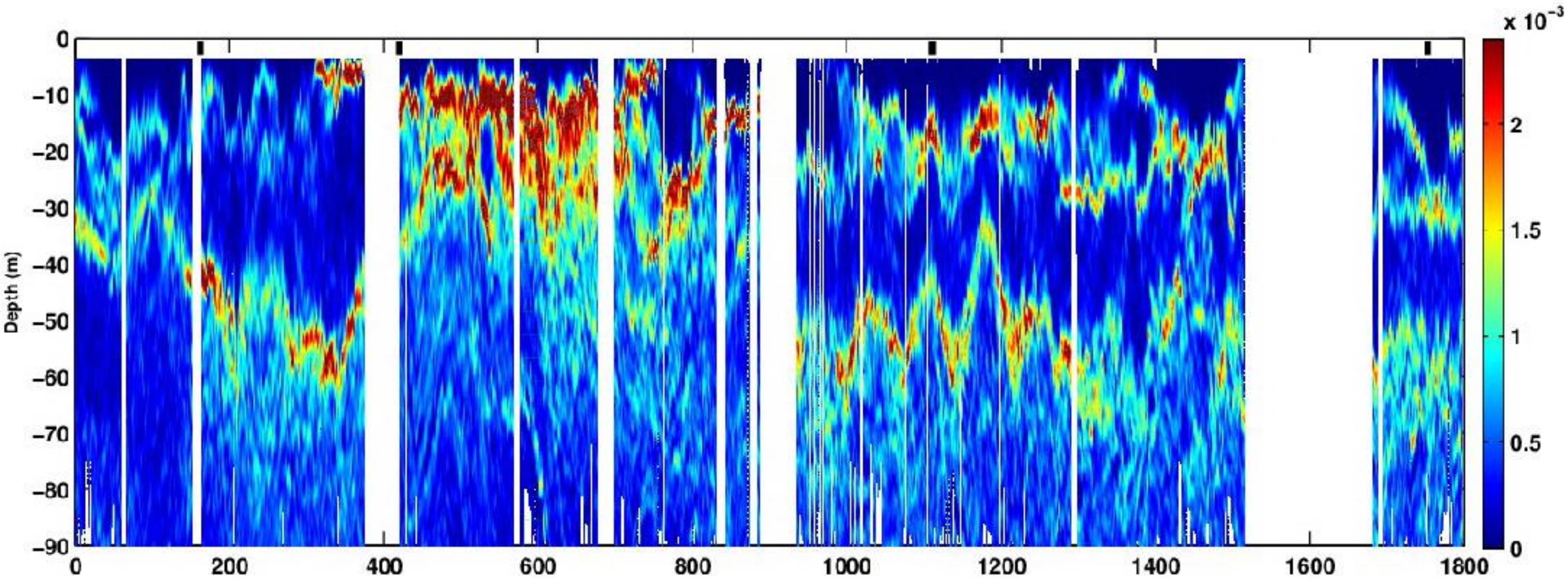
Along-track T, S profiles at ship speed 4 knots (7 kmph); depth 4-100 m. Accuracy 0.05 psu.

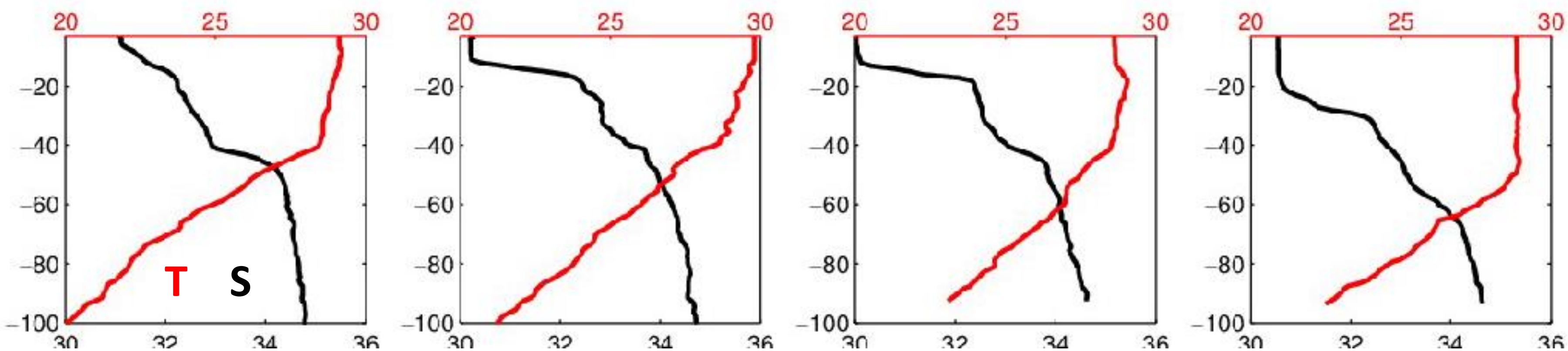
Horizontal res 0.5-1.5 km
Vertical resolution 1 m

300 & 500 kHz ADCP

Doppler velocity profiles; depth from 5-80 m

Horizontal res. 270 m
Vertical res. 2 m

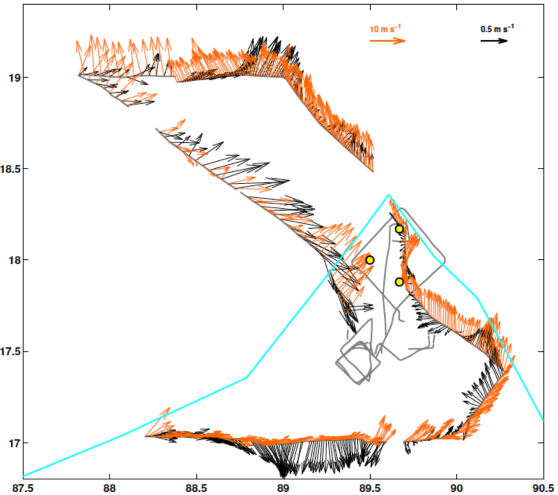


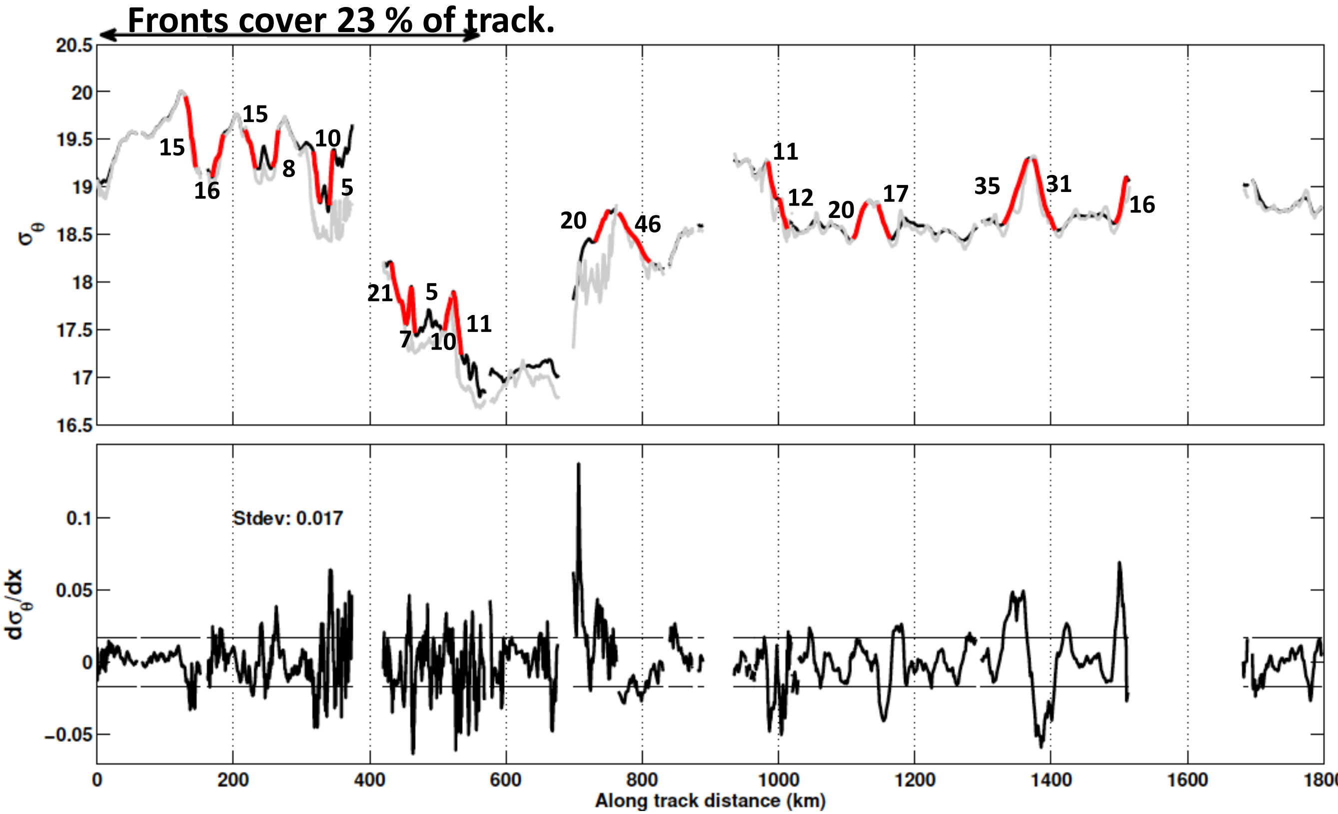


Two haloclines and two stratification maxima

$$N^2 = \frac{-g}{\rho_o}\frac{d\rho}{dz} \quad (s^{-2})$$

Direct observations of submesoscale fronts





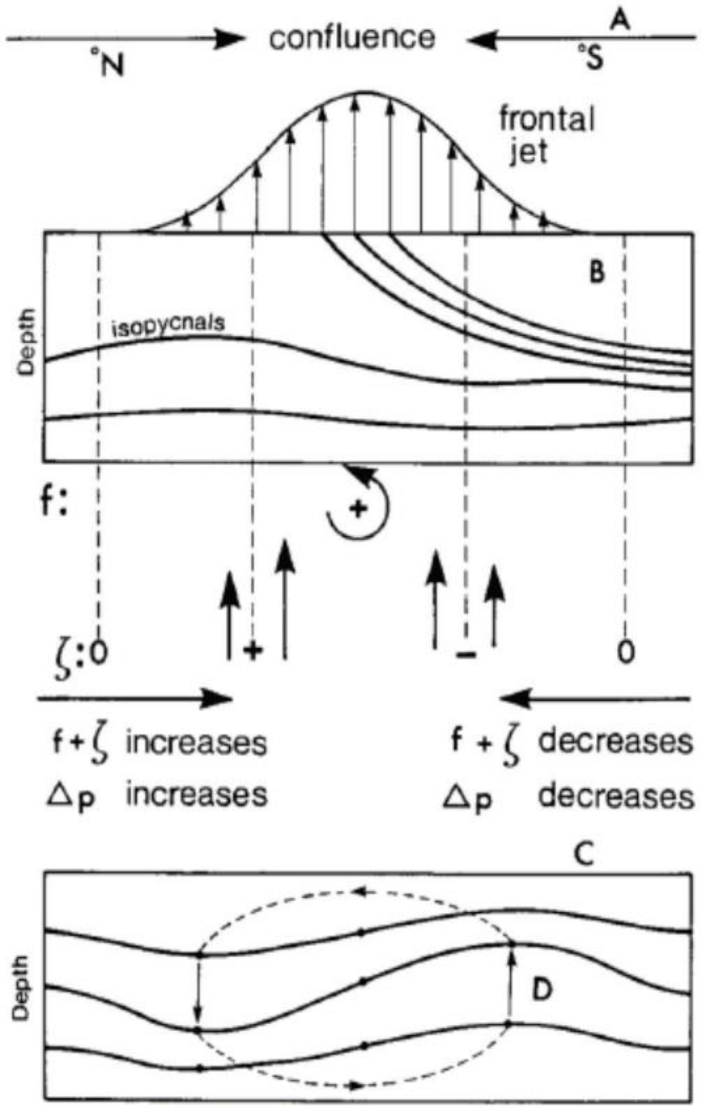
Fronts: $d\sigma_{\Theta}/dx$ > 1 SD. Total density change across front, i.e., "Strength" > 0.3 kg/m^3

20 major fronts: Scales 5-50 km, Strengths 0.3-0.8 kg/m^3

Lateral density gradients in BoB are about 10 times larger than those measured in North Atlantic

Thompson et al. 2016

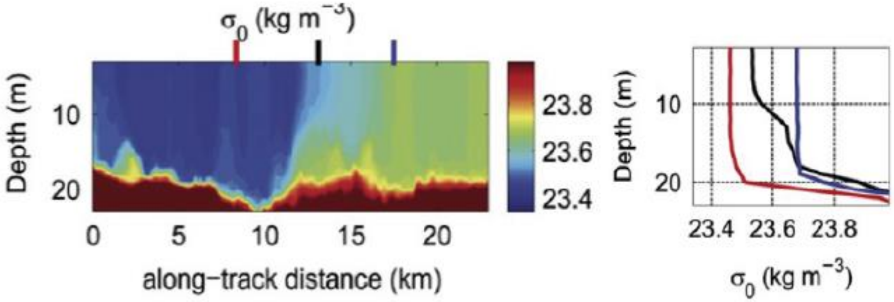
Slumping at sub-mesoscale fronts creates stratification



Pollard and Regier 1991

Potential vorticity

$PV = (f + \zeta).\nabla \rho$



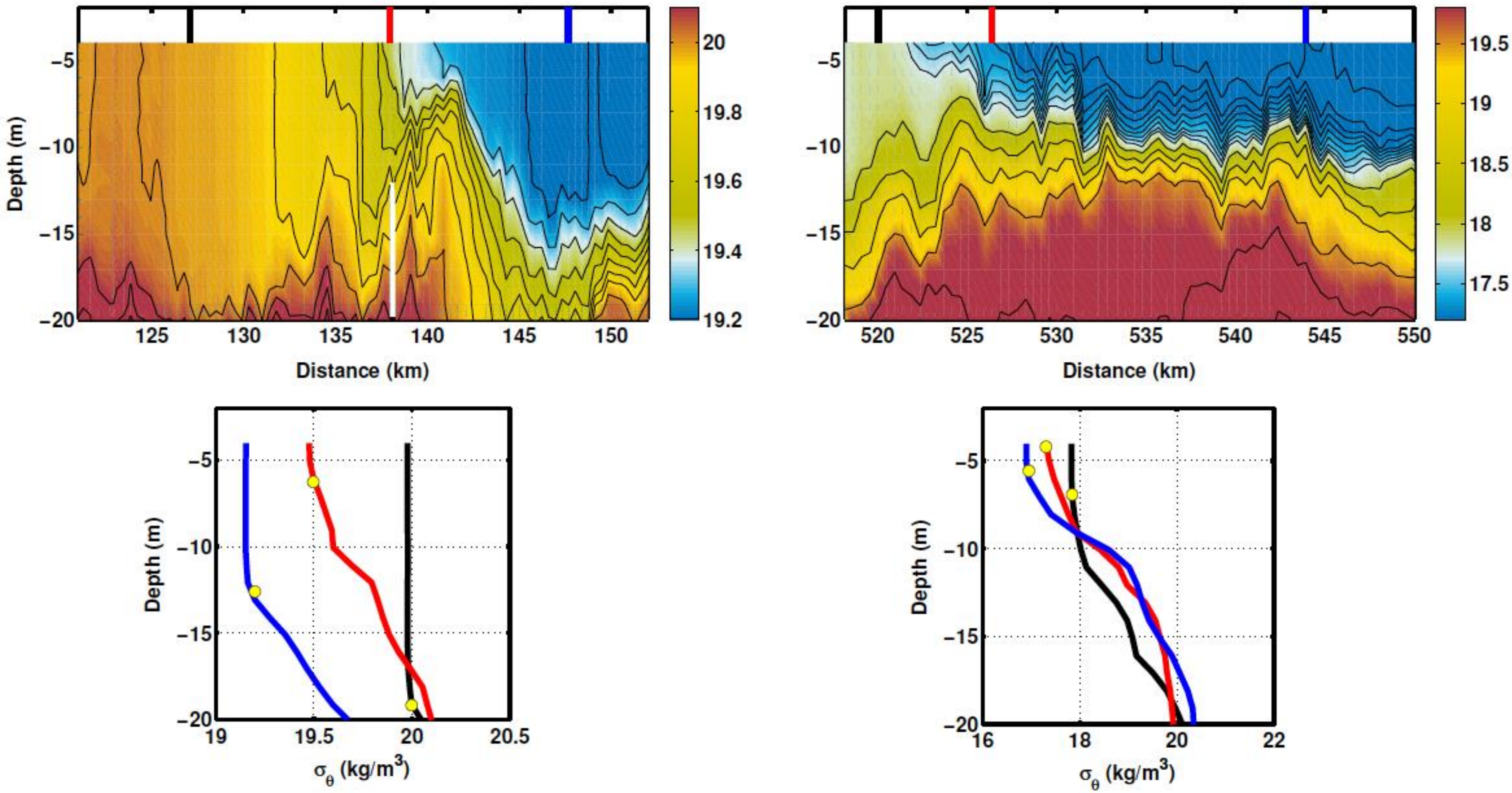
Chukchi sea, Arctic ocean

Timmermans 2013

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

Mc Williams 2016

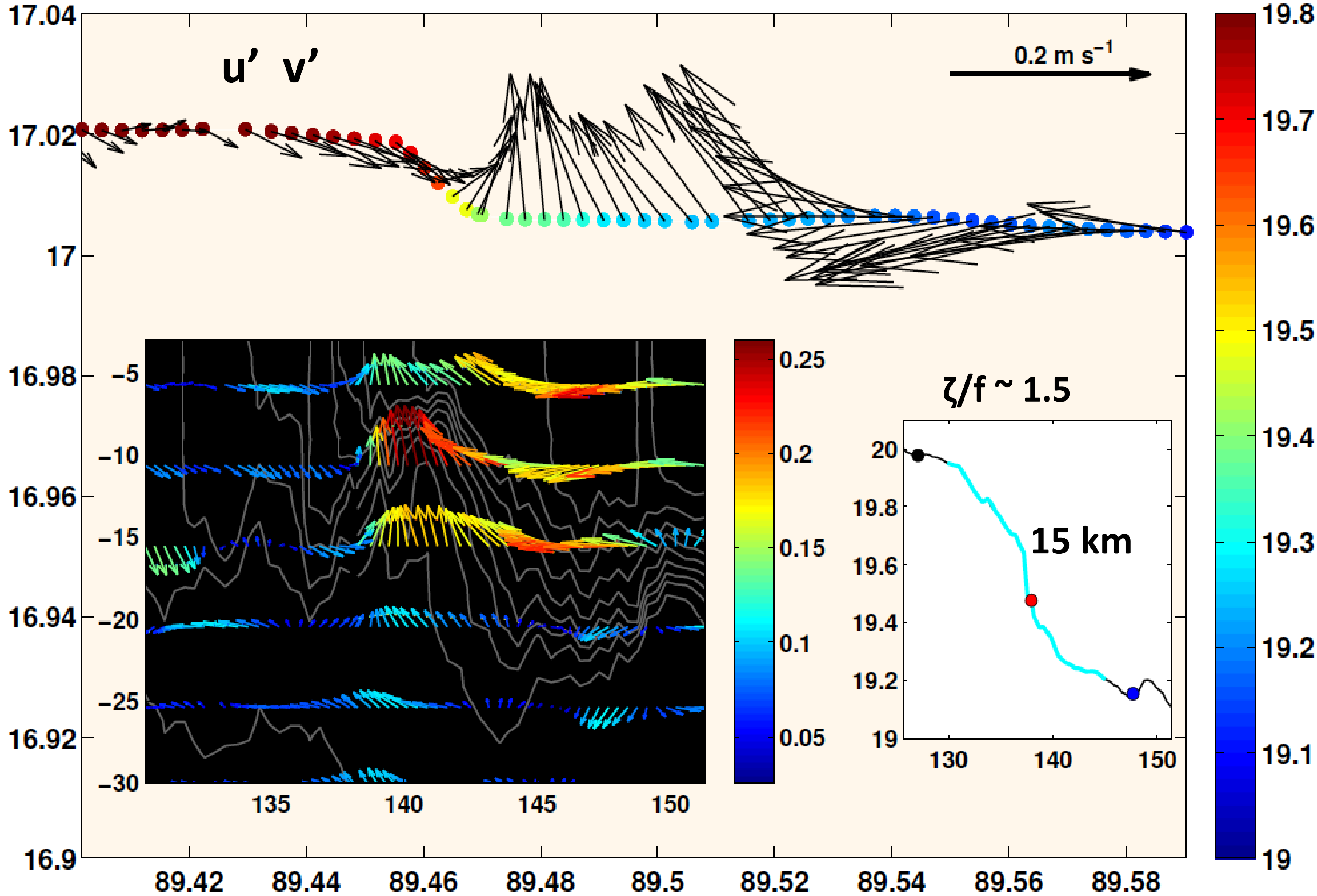
2014



At majority of sub-mesoscale fronts: Shallow mixed layer under the front suggesting restratification due to frontal slumping

Similar strong salinity fronts and haloclines in the Arctic

Timmermans Winsor (2013) Mackinnon et al (2016)

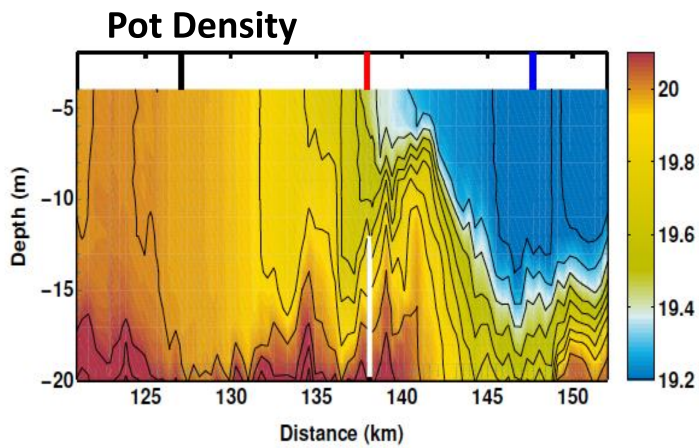


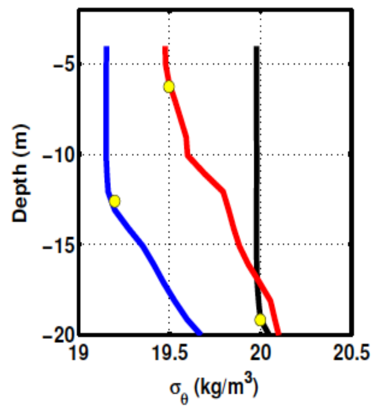
Shallow frontal jet, lateral scale 5-10 km Ro > 1

Vorticity dynamics at confluence and frontal jet stratifies the upper ocean

Pollard & Regier 1991 Tandon & Garrett 1995 Mahadevan & Tandon 2006 Thomas 2007

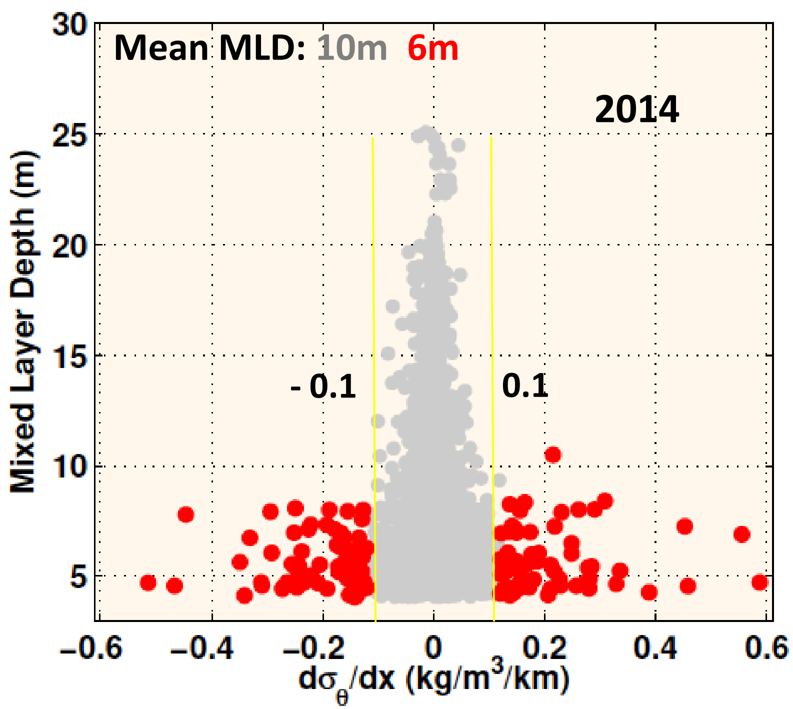
Evidence of frontal slumping

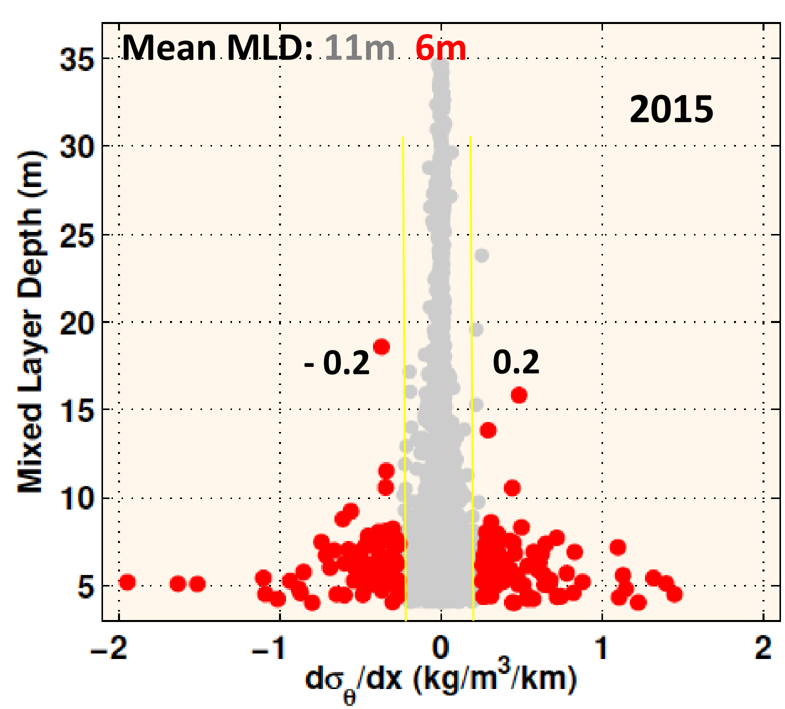




Restratification due to frontal slumping

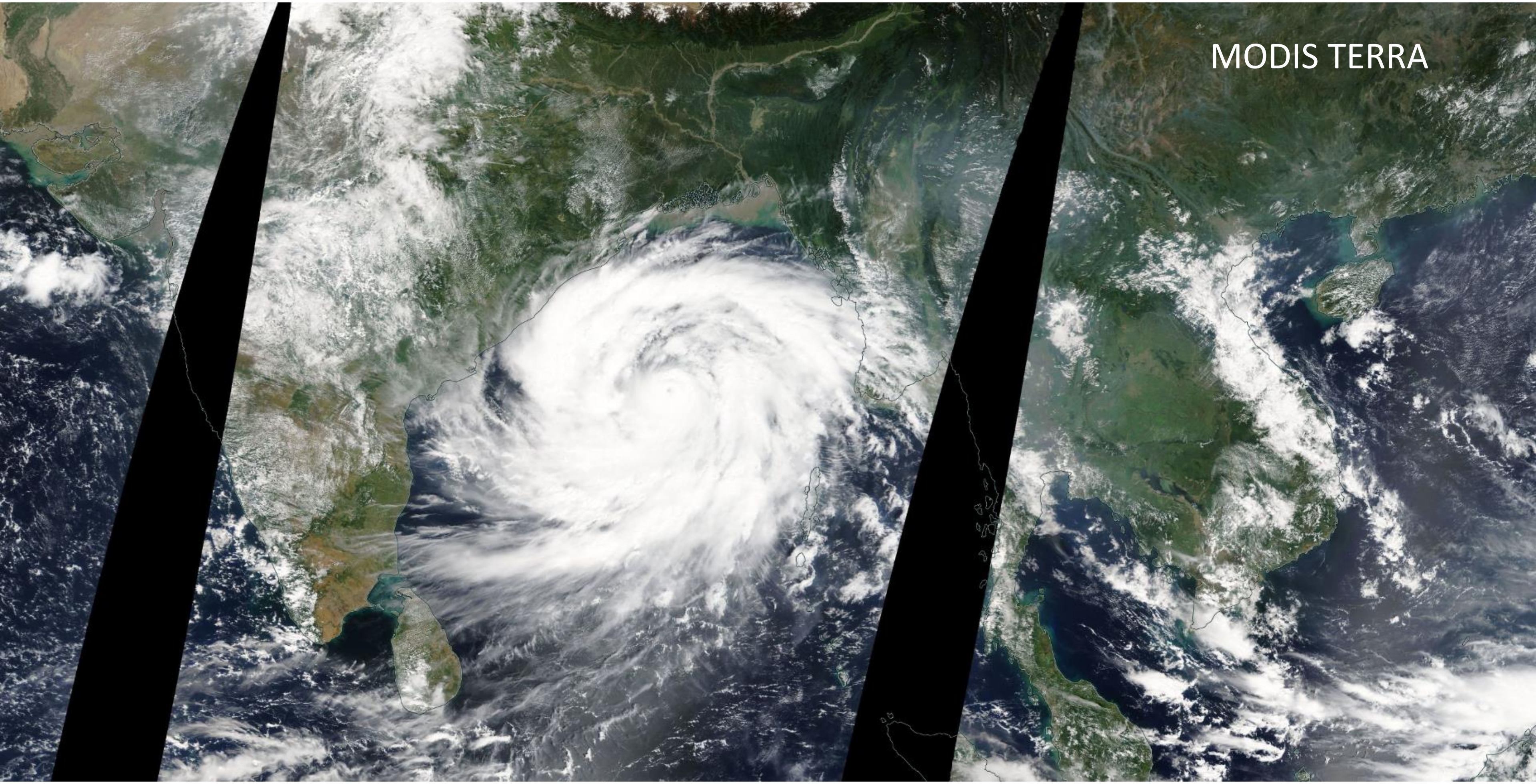
$\sigma_{MLD} - \sigma_{4m} = 0.03\ kg/m^3$





If the lateral density gradient exceeds 2 Stdev, MLD < 10m 95% of the time

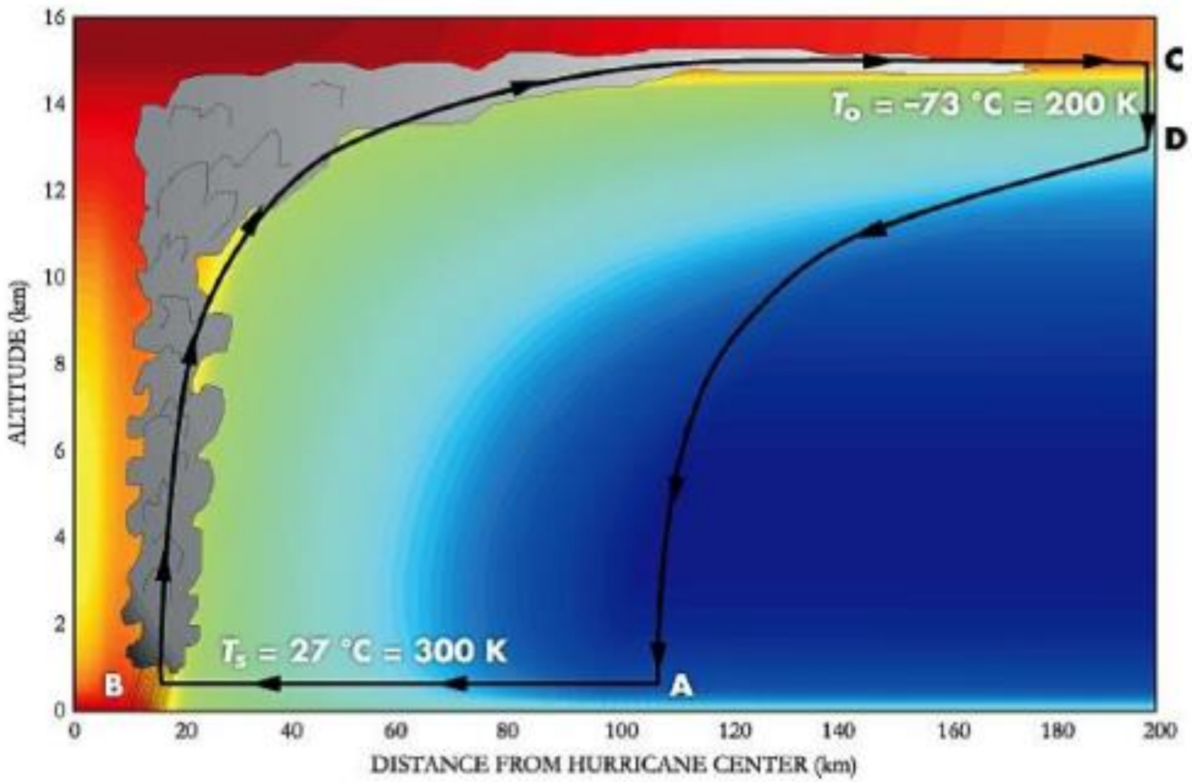
Tropical Cyclone Phailin 11 October 2013



Courtesy: NASA Worldview

Estimated maximum 1-minute sustained wind speed 250 km/hr.
Phailin intensified by 15 m/s on 10 October 2013.

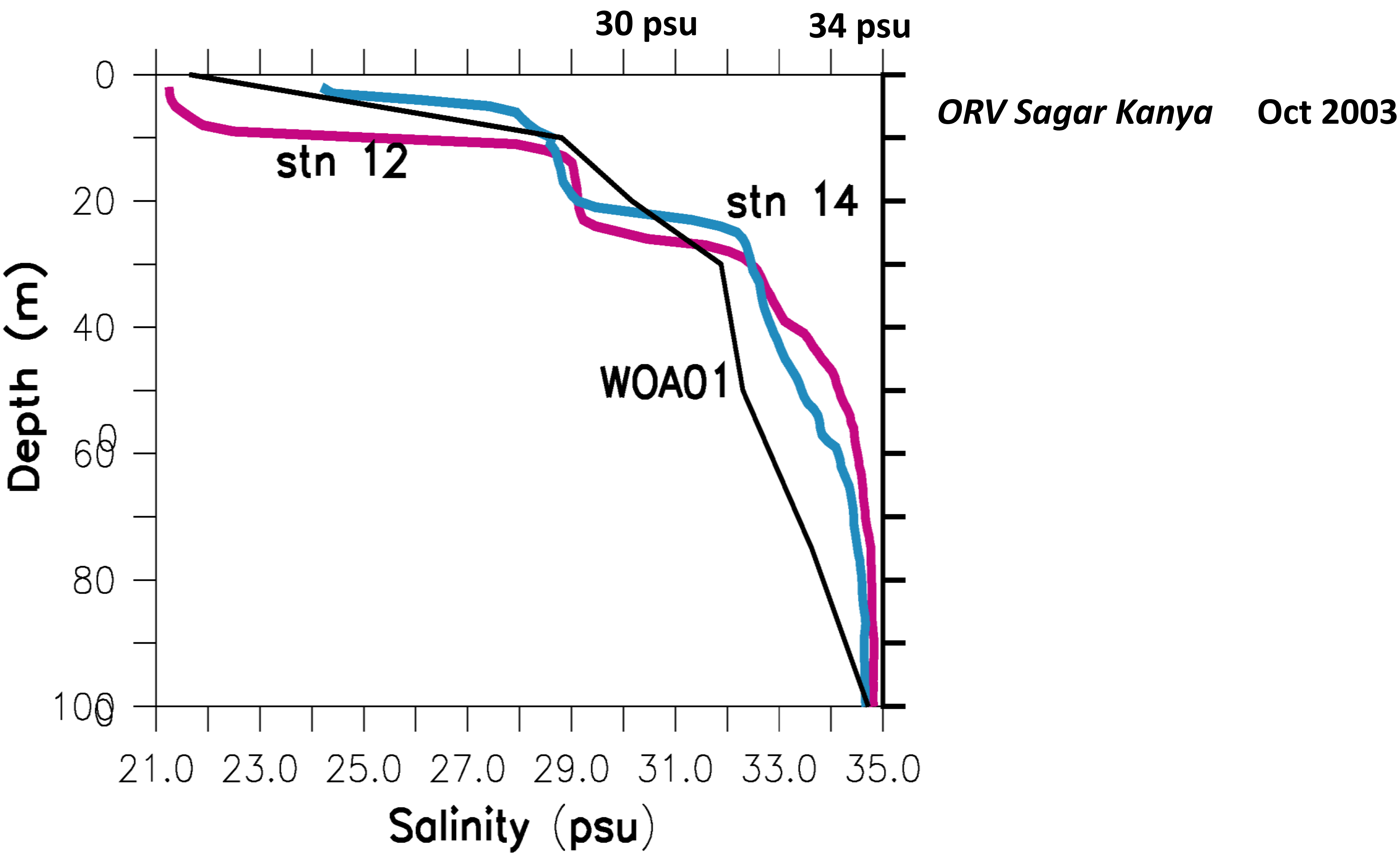
Tropical Cyclone as Heat Engine



Energy balance: *Evaporation : U Δq   Dissipation: U^3*

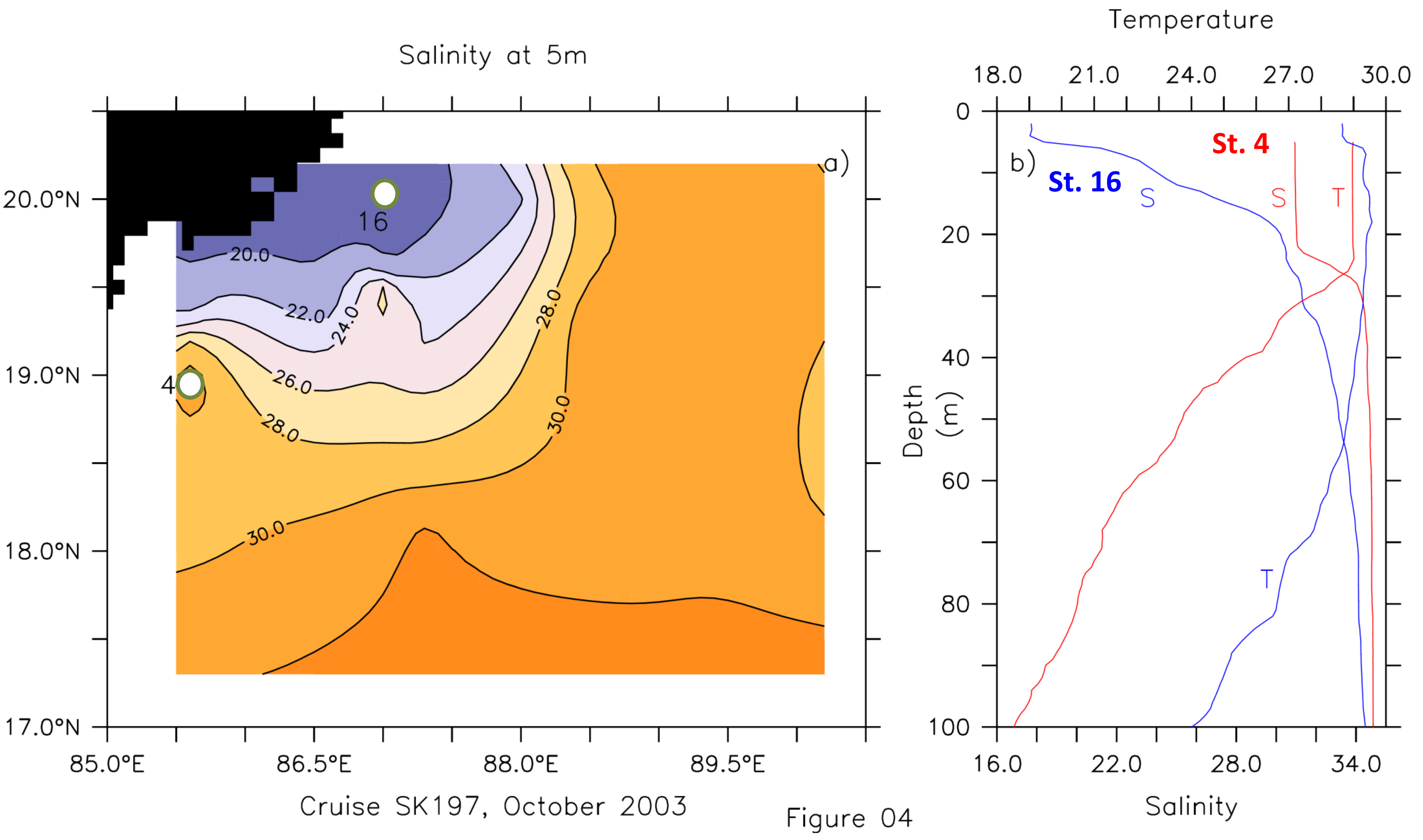
U^2 goes as [(Ts-To)/Ts] Δq

Emanuel *2005*

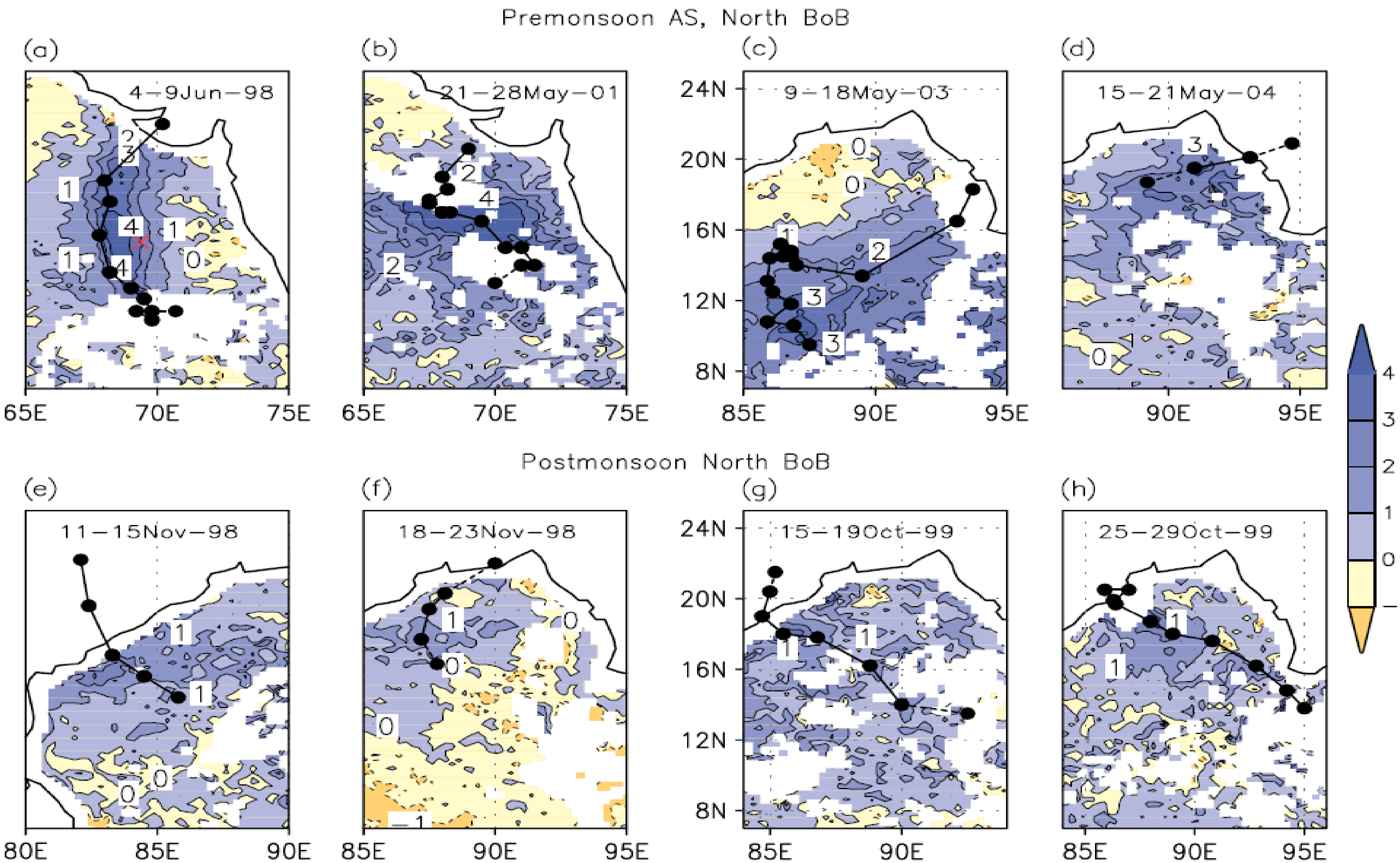


Shallow fresh layers, two haloclines, Oct 2003 northwest Bay of Bengal

Gravitationally stable stratification: **Resists vertical mixing of upper ocean, Penetrative solar radiation to 80m helps create deep subsurface warm layer**



Deep warm layer under fresh pool (barrier layer) due to upper ocean subsidence, penetrative sunlight …

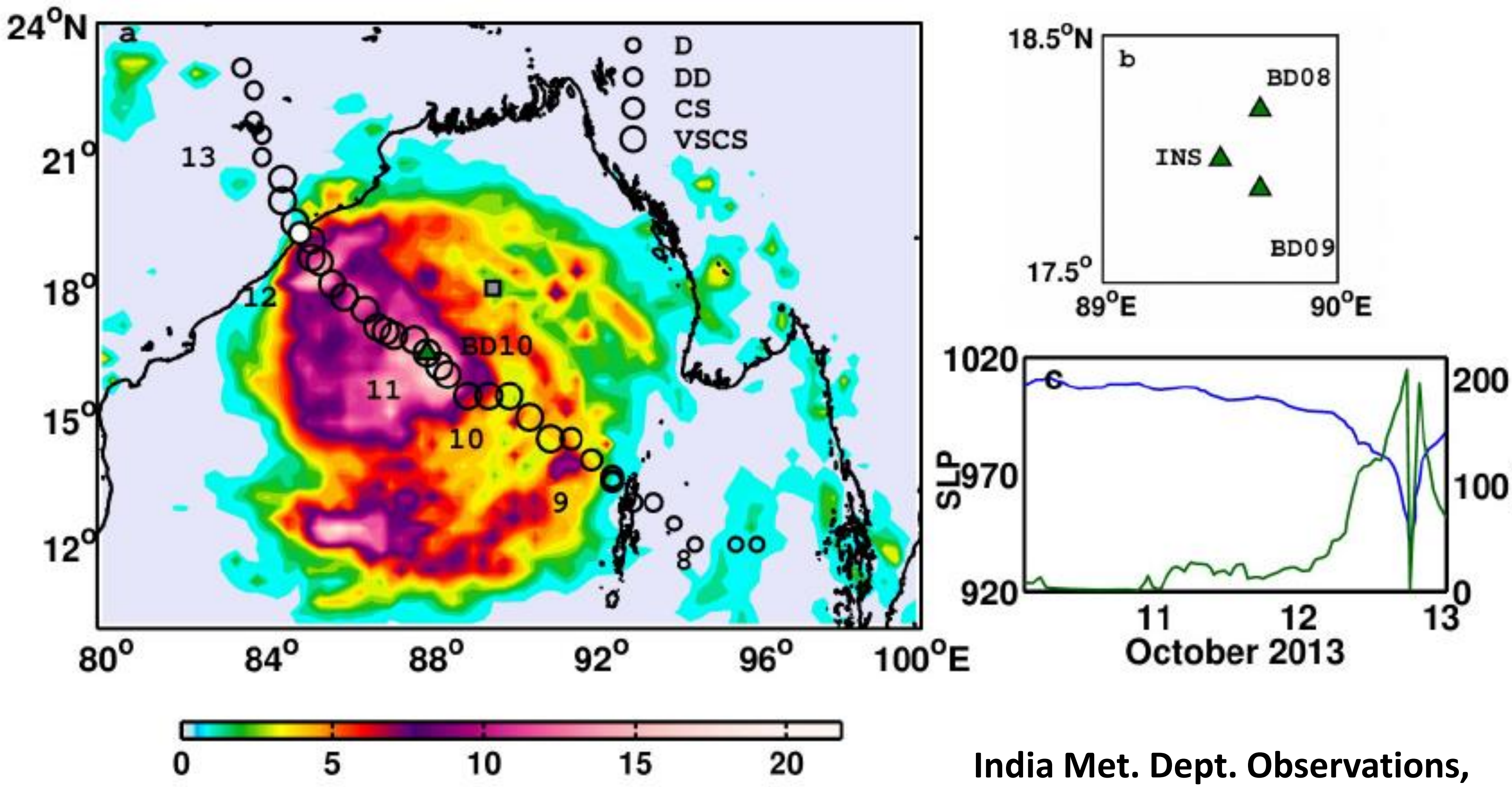


North Bay of Bengal SST cools very little under post monsoon tropical cyclones

Dots: 12 hourly storm location India Met. Dept.

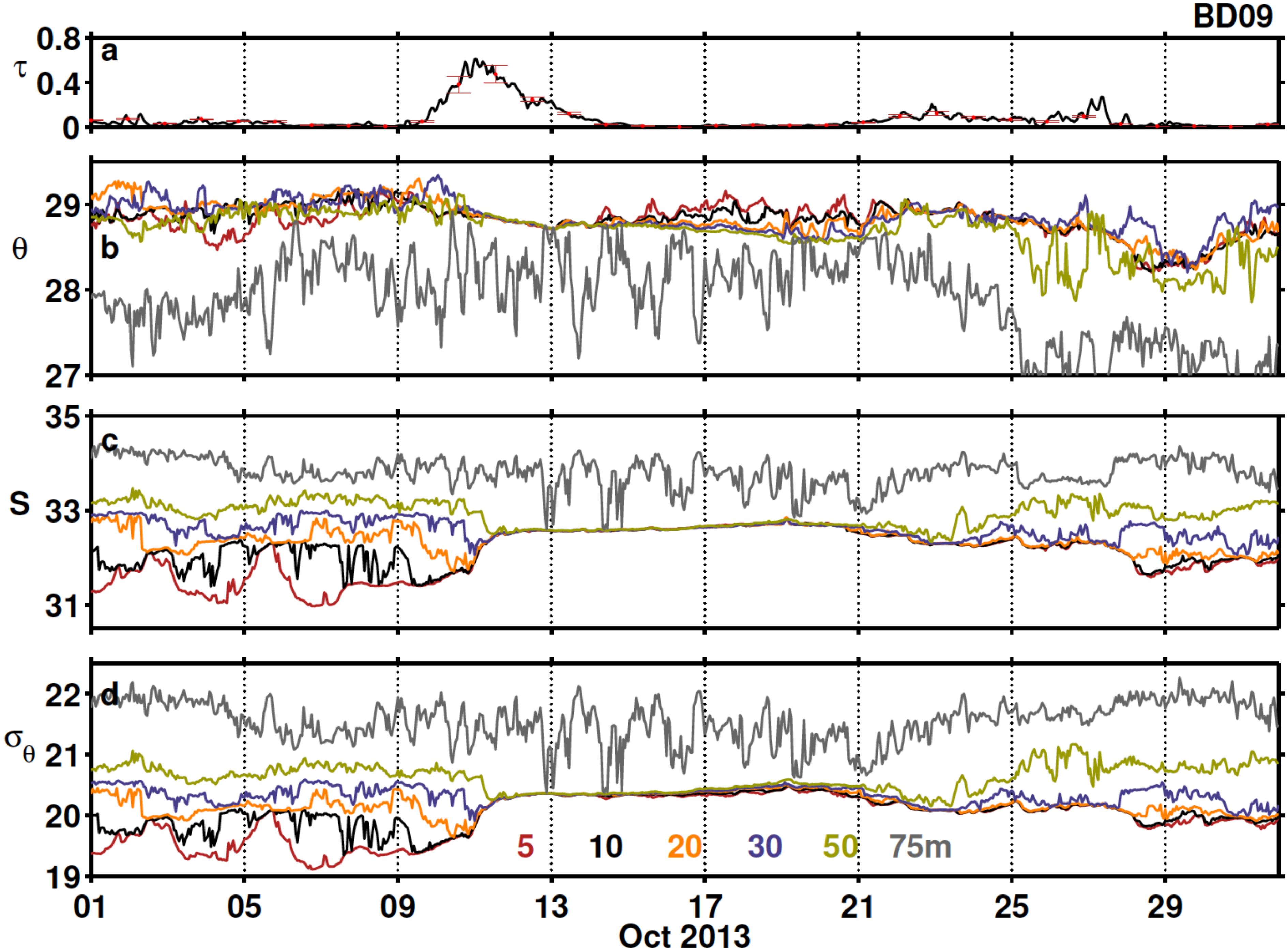
Sengupta et al. 2008 Singh et al. 2012 Balaguru et al. 2012 Yan et al. 2017

Cyclone Phailin

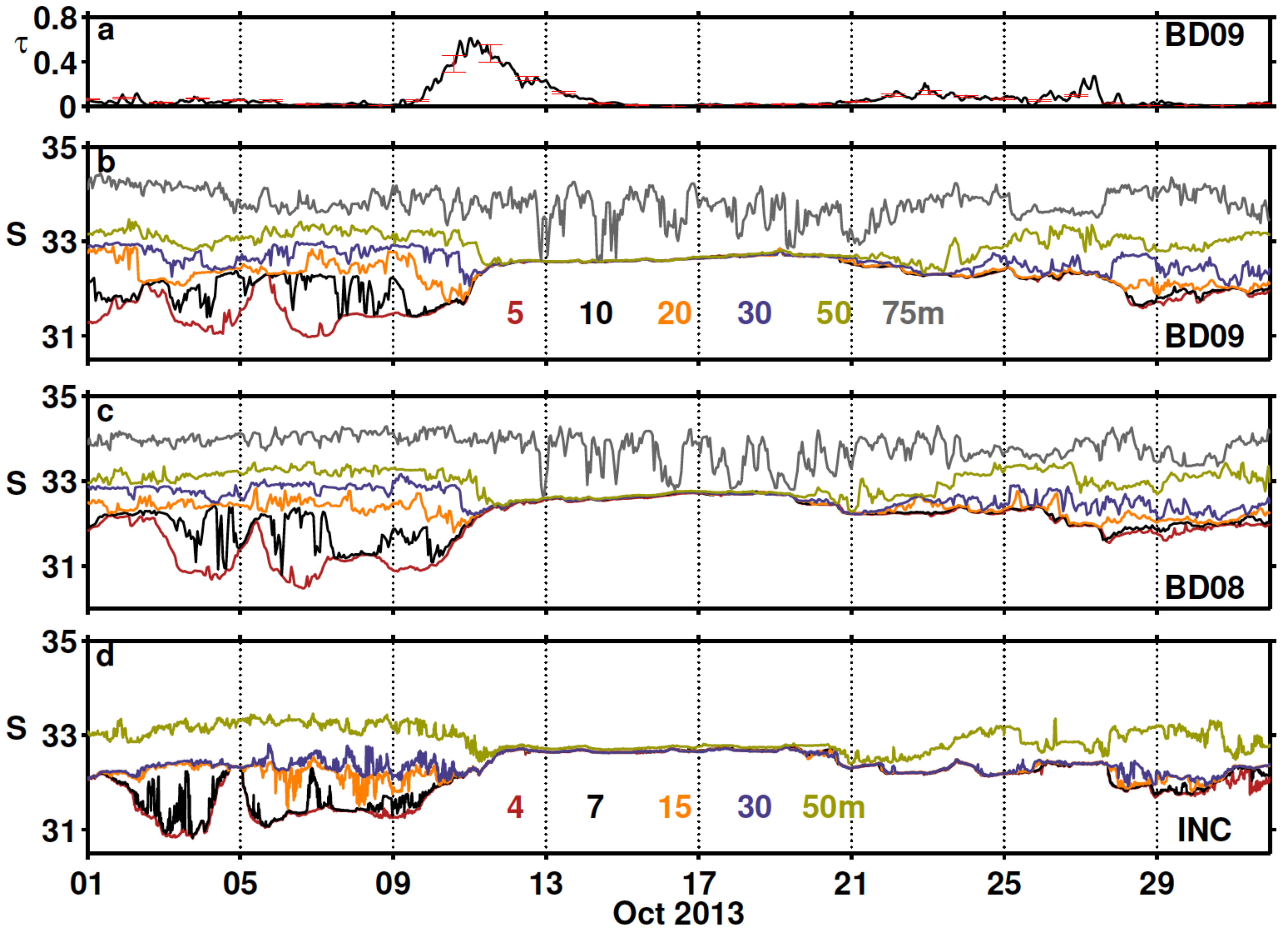


India Met. Dept. Observations, Gopalpur, Orissa

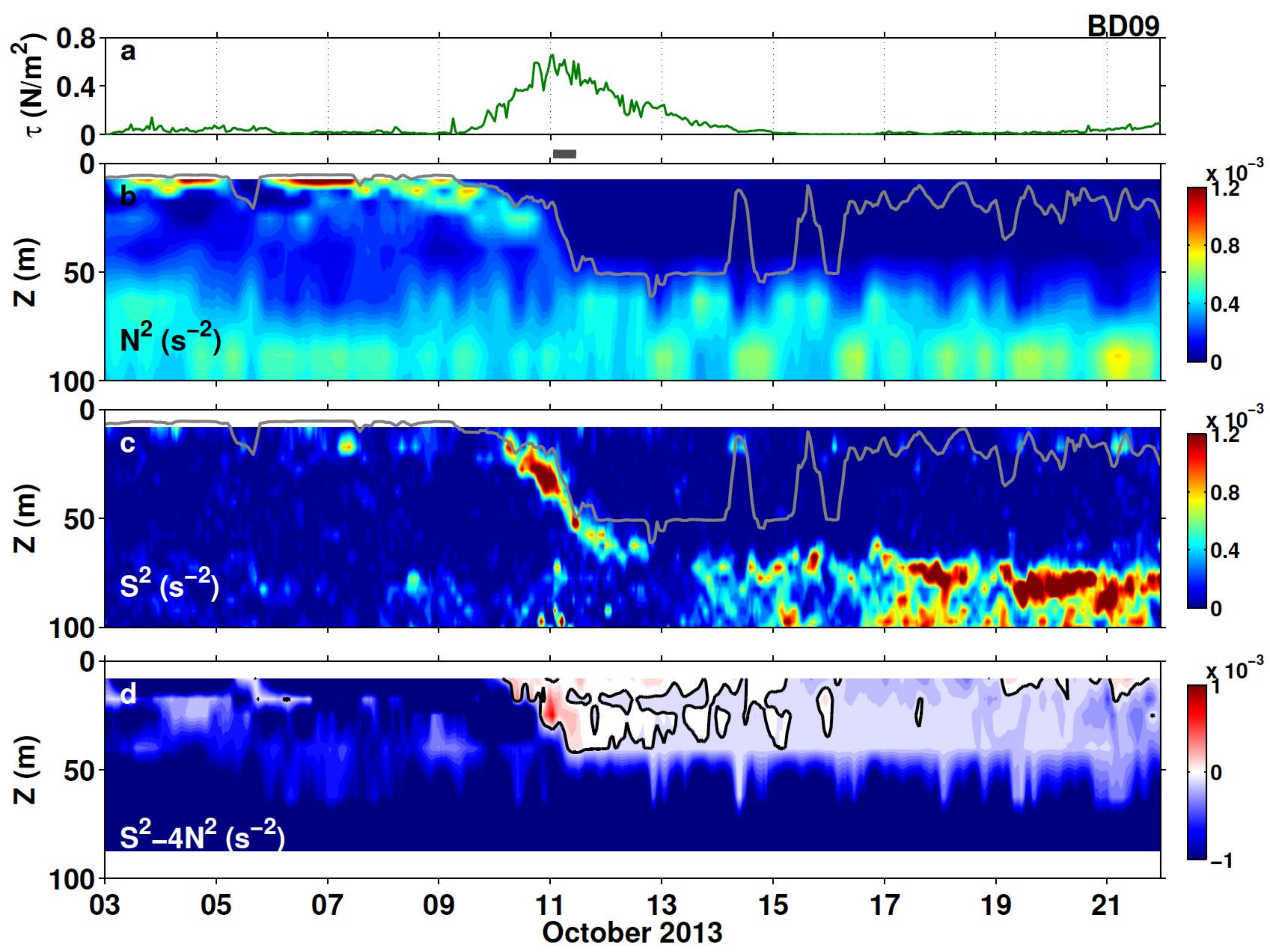
Ocean response to cyclone Phailin,
Chaudhuri et al. 2018 (JPO, in review)



BD09
τ
a
0.8
0.4
0
θ
b
29
28
27
S
c
35
33
31
σθ
d
22
21
20
19
5
10
20
30
50
75m
01
05
09
13
17
21
25
29
Oct 2013

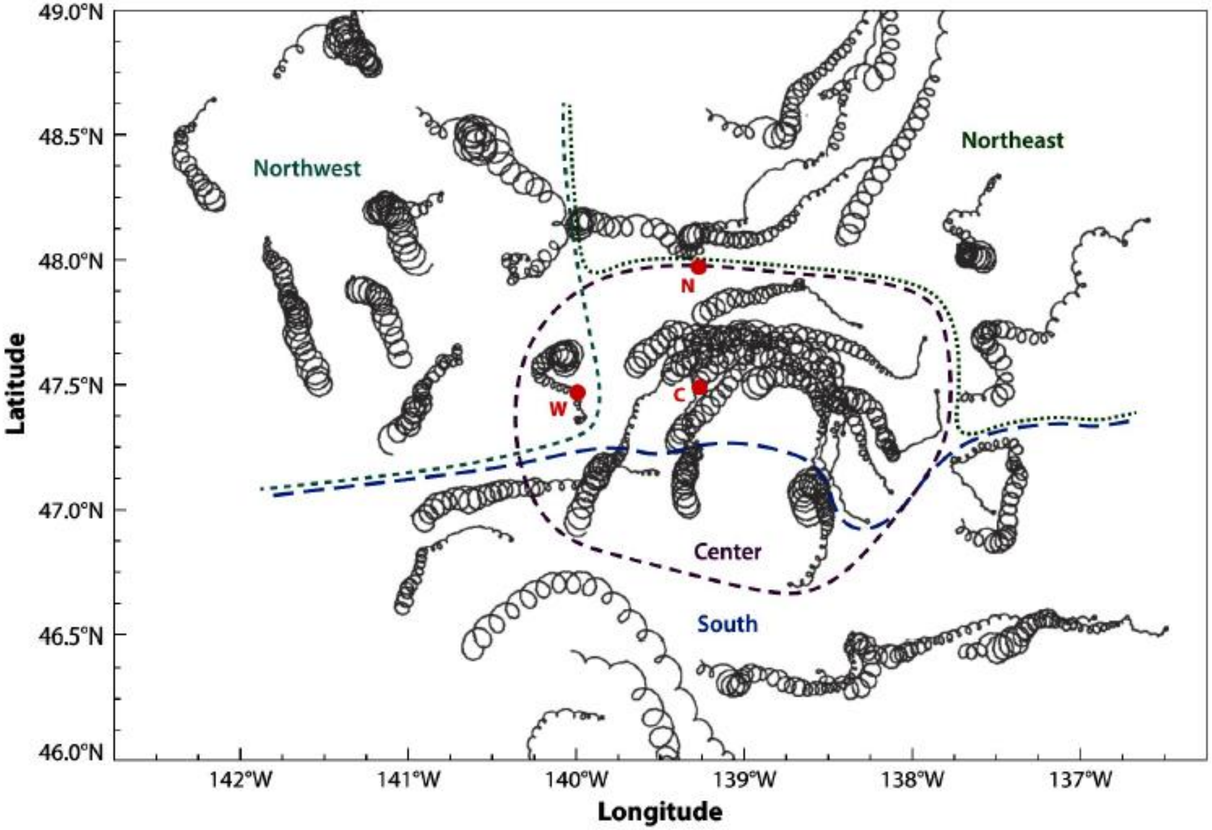


τ
0.8
0.4
0
a
BD09
35
33
31
S
b
5
10
20
30
50
75m
BD09
c
BD08
d
4
7
15
30
50m
INC
01
05
09
13
17
21
25
29
Oct 2013

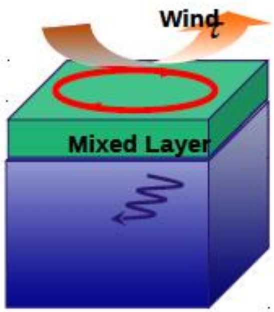


BD09
a
τ (N/m2)
0.8
0.4
0
b
Z (m)
N2 (s−2)
x 10−3
1.2
0.8
0.4
0
c
S2 (s−2)
d
S2−4N2 (s−2)
1
−1
50
100
03
05
07
09
11
13
15
17
19
21
October 2013

Inertial currents

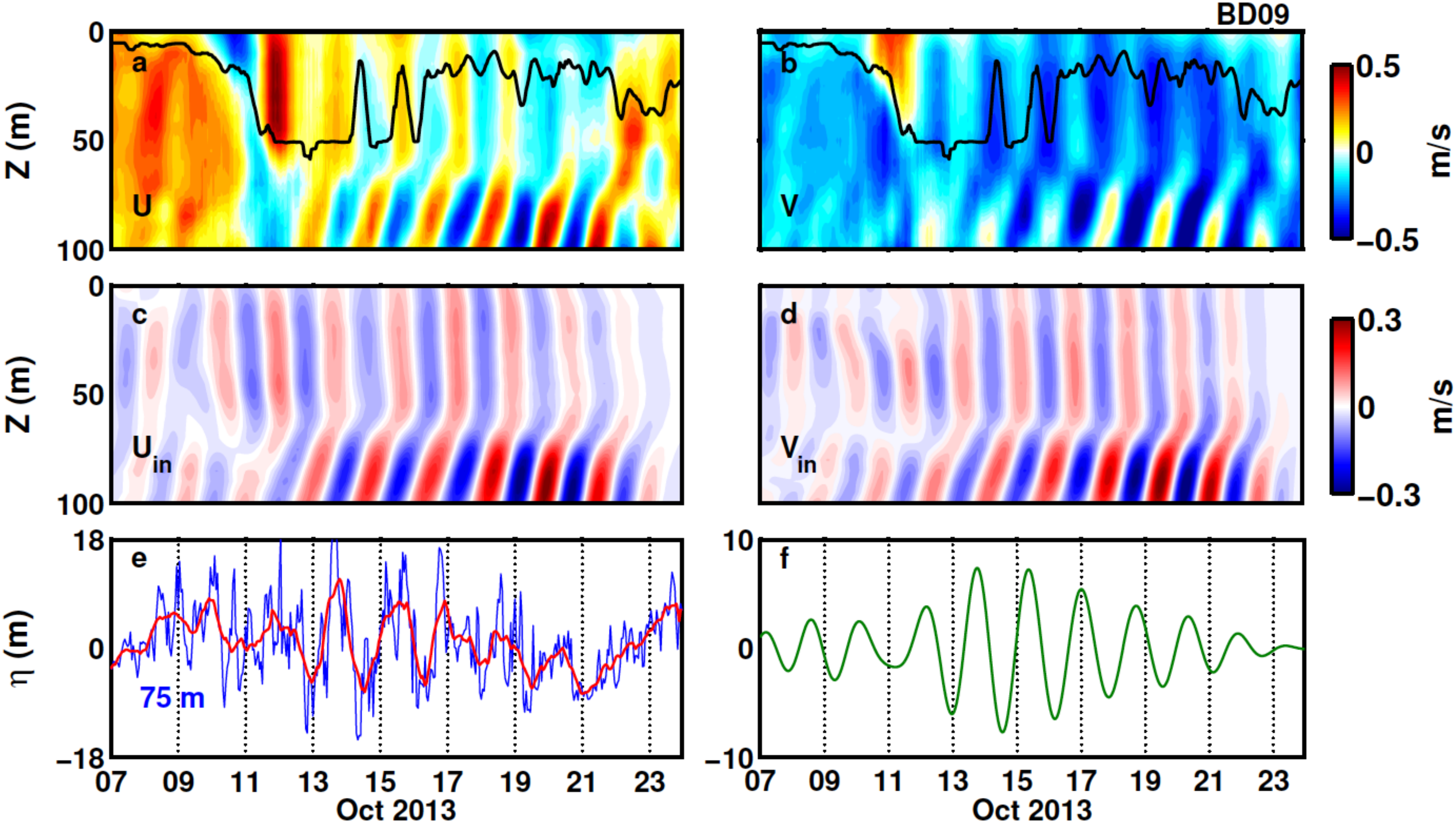


Drifter tracks in the Ocean Storms Experiment

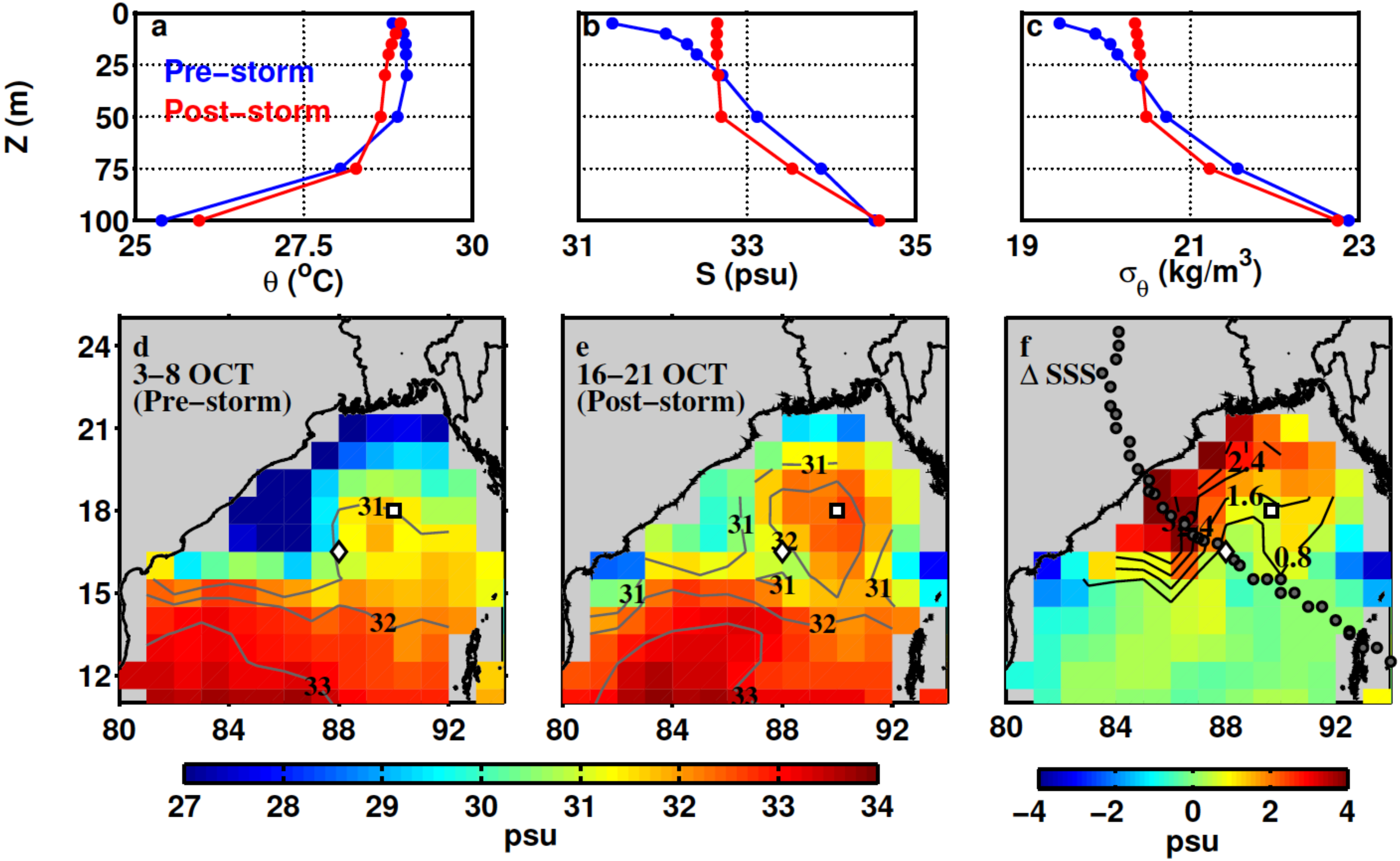


$$\frac{\partial u}{\partial t} - fv = \frac{\tau_x}{\rho H}$$

$$\frac{\partial v}{\partial t} + fu = \frac{\tau_y}{\rho H}$$

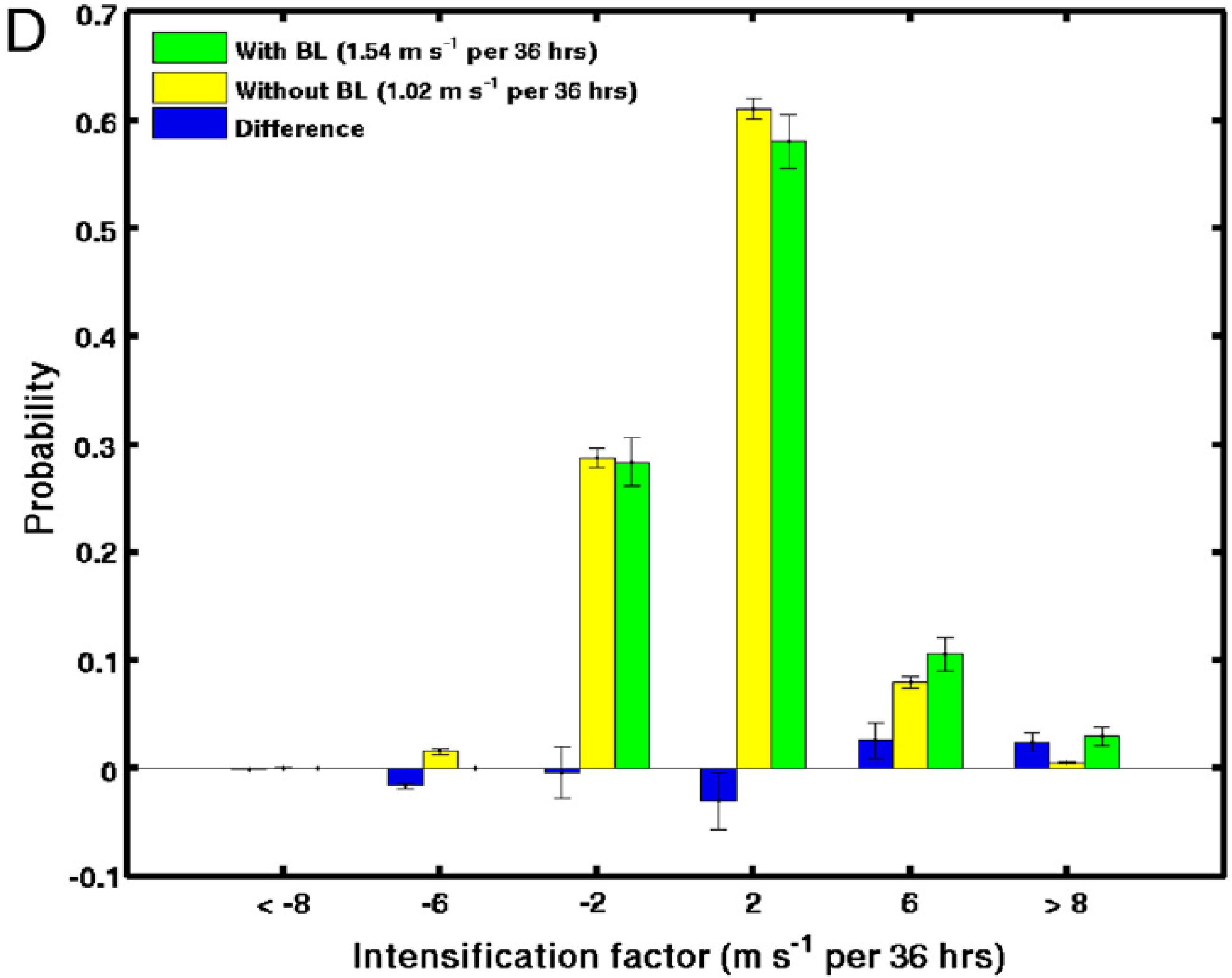


BD09
a
U
b
V
c
U_in
d
V_in
e
75 m
f
Z (m)
η (m)
m/s
0.5
0
−0.5
0.3
0
−0.3
0
50
100
18
0
−18
10
0
−10
07
09
11
13
15
17
19
21
23
Oct 2013



a
b
c
Pre–storm
Post–storm
Z (m)
0
25
50
75
100
25
27.5
30
θ (°C)
31
33
35
S (psu)
19
21
23
σθ (kg/m3)
d
3–8 OCT
(Pre–storm)
e
16–21 OCT
(Post–storm)
f
Δ SSS
31
32
33
2.4
1.6
0.8
24
21
18
15
12
80
84
88
92
27
28
29
30
31
32
33
34
psu
−4
−2
0
2
4
psu

Total Tropical cyclone tracks 1998-2007 : 587



Tropical cyclones intensify rapidly over a barrier layer

Cyclone Phailin intensified by 15 m/s on 10 October 2013

Balaguru et al. 2012

Conclusions

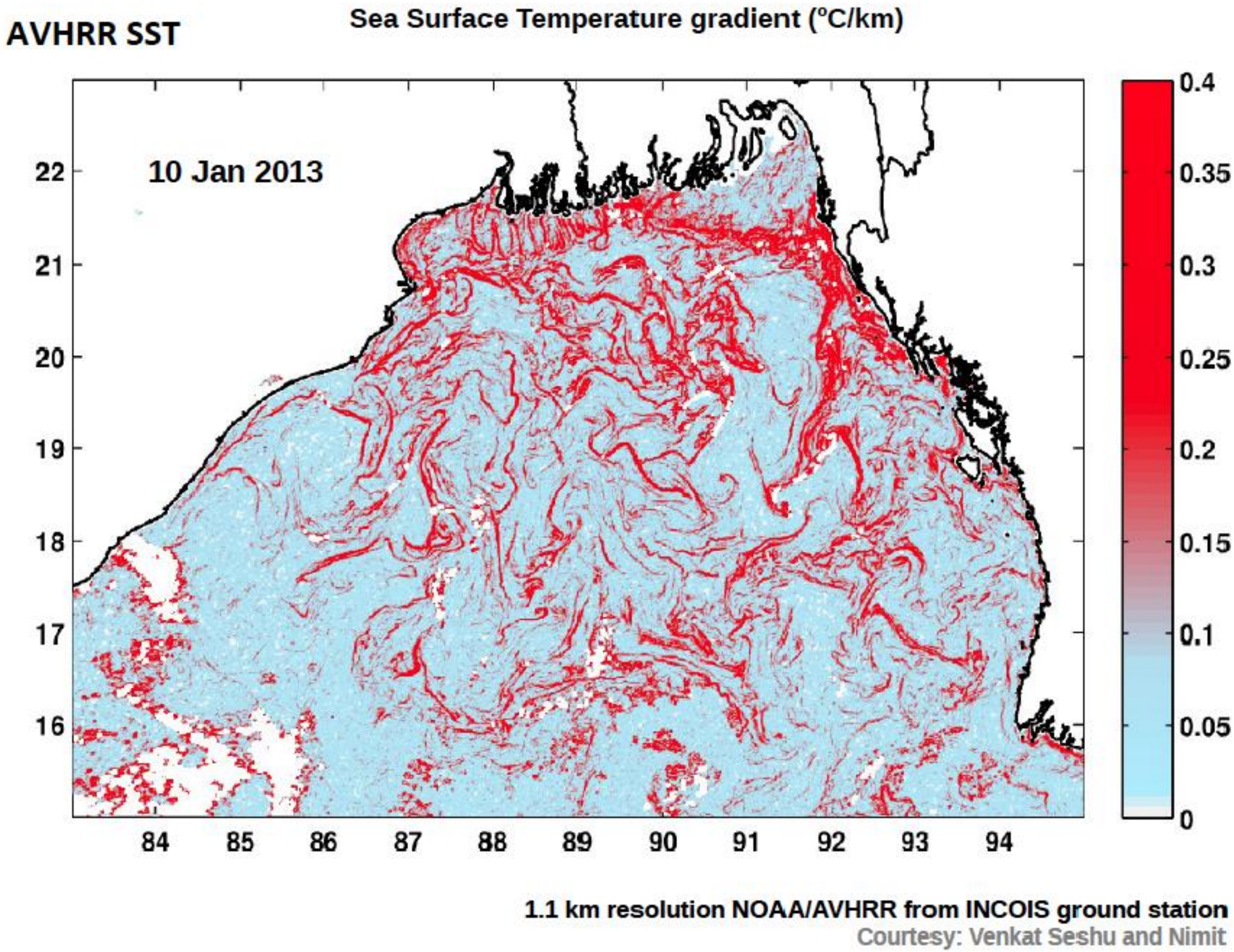
Order 100 km-scale ocean eddies, and a shallow wind-forced (Ekman) current determine dispersal of river water in the north Bay of Bengal

River and rain water create a shallow, stable layer, promoting subsurface warming, and reducing SST cooling under tropical cyclones.

River and rain water impacts air-sea coupling on weather scales to sub-seasonal scales.

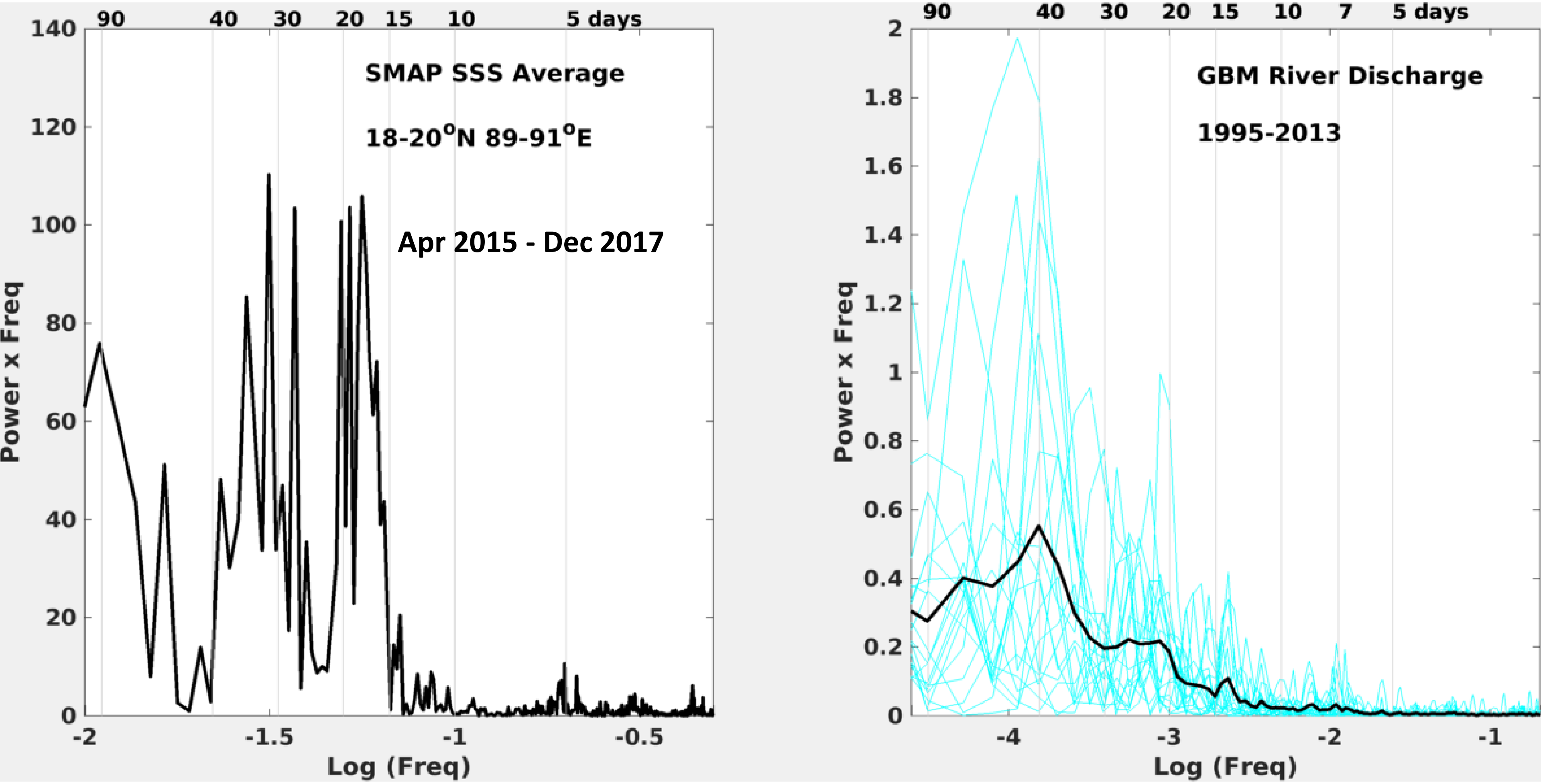
Slumping of sub-mesoscale (order 1-10 km) salinity-dominated fronts enhances shallow stratification.

Way forward: Realistic representation of upper ocean physics on 1-10 km lateral scales, 0.1-10 m vertical scales in weather & monsoon prediction models

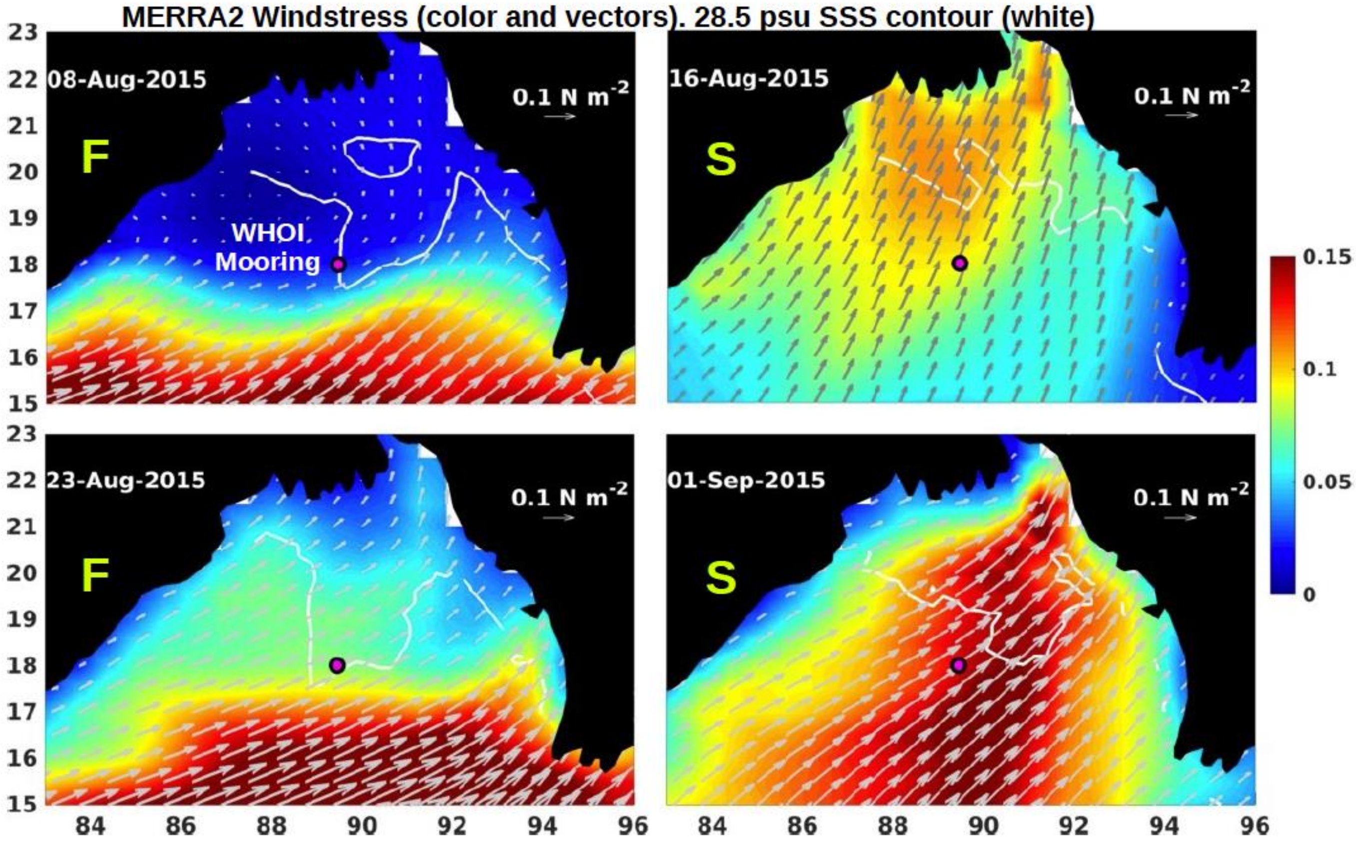


Thin fresh layers cool rapidly in winter

Sub-seasonal scales in sea surface salinity

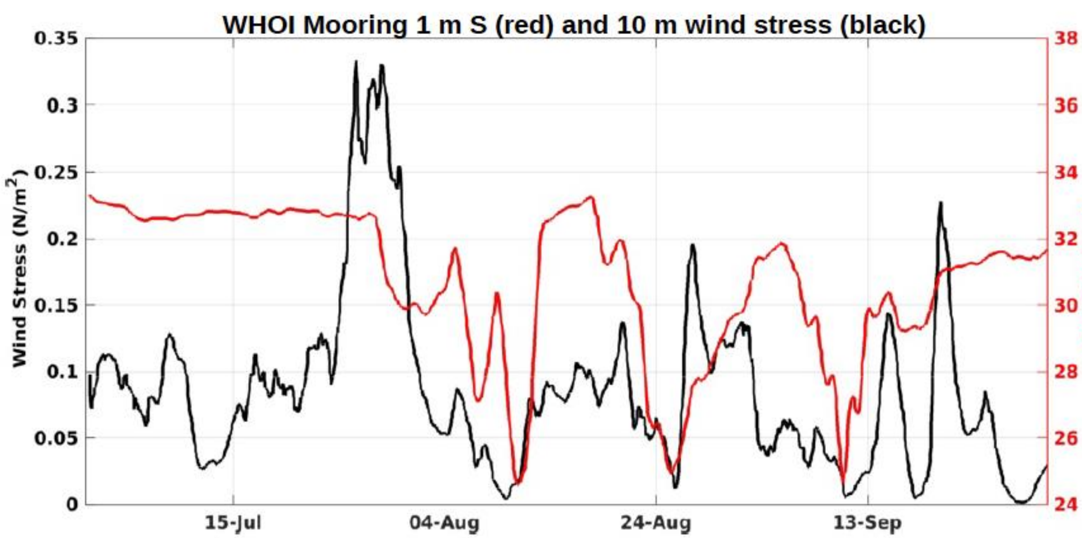


River Discharge data courtesy: Bangladesh Univ. Engg. Tech. and Fabrice Papa



Surface winds strengthen and weaken on quasi-biweekly scale.

Surface wind stress (black), 1m salinity (red) WHOI Mooring, July-September 2015

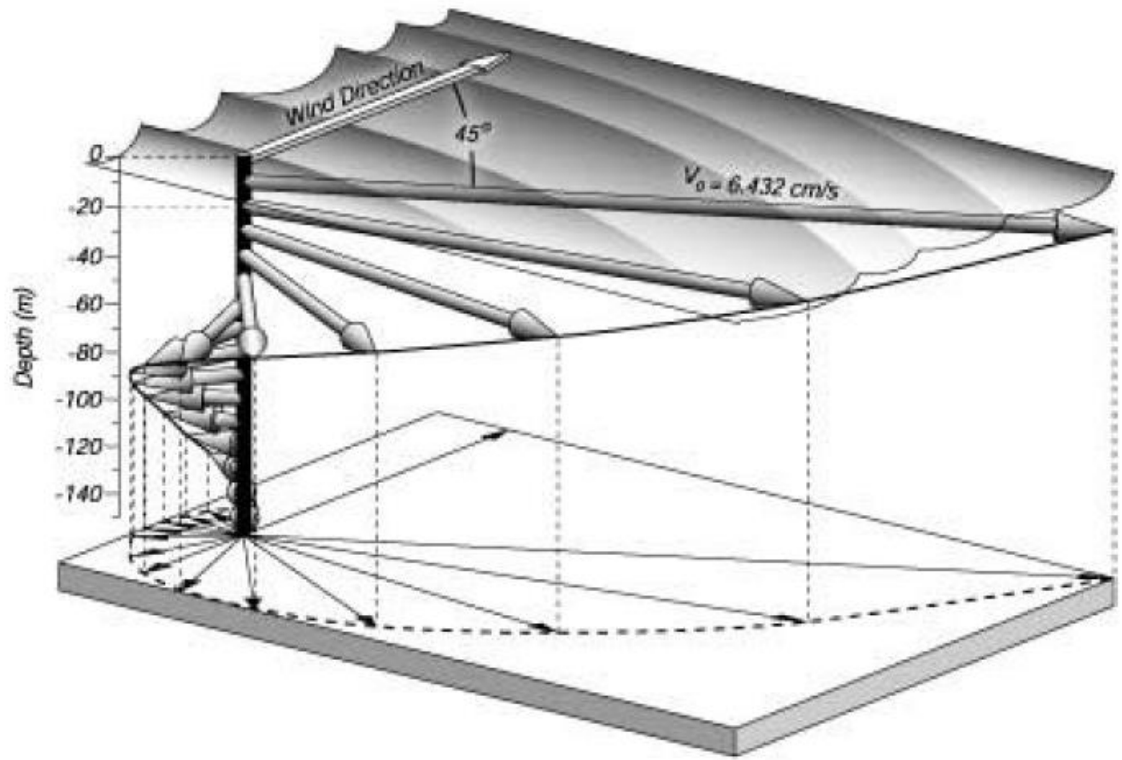


Ekman flow

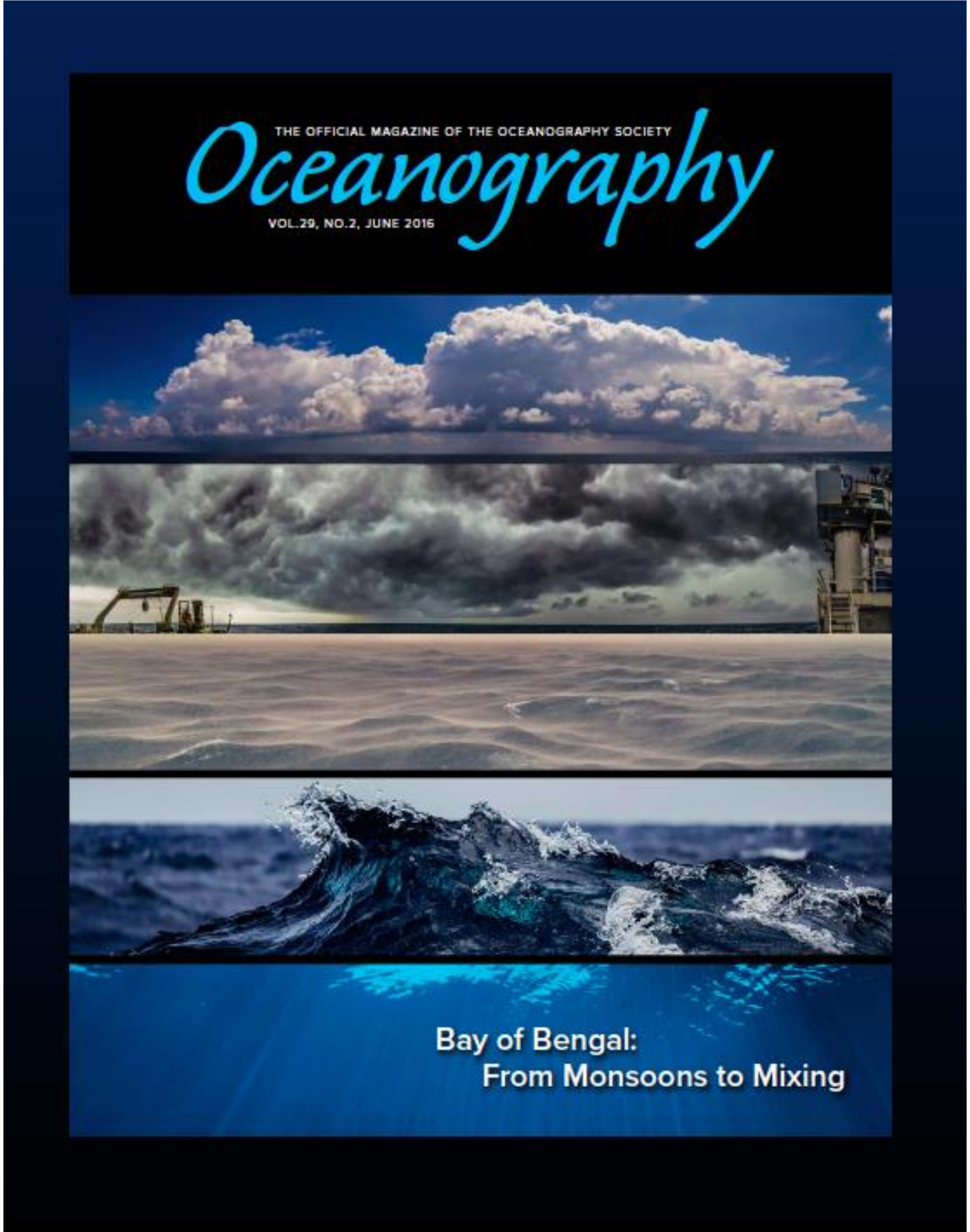
Steady state momentum equation

$$\frac{1}{\rho}\frac{\partial \tau^x}{\partial z}+fv=0$$

$$\frac{1}{\rho}\frac{\partial \tau^y}{\partial z}-fu=0$$



Ekman current generated by 10m/s wind at 35°N. Stewart (2008)



Vol. 29
June 2016

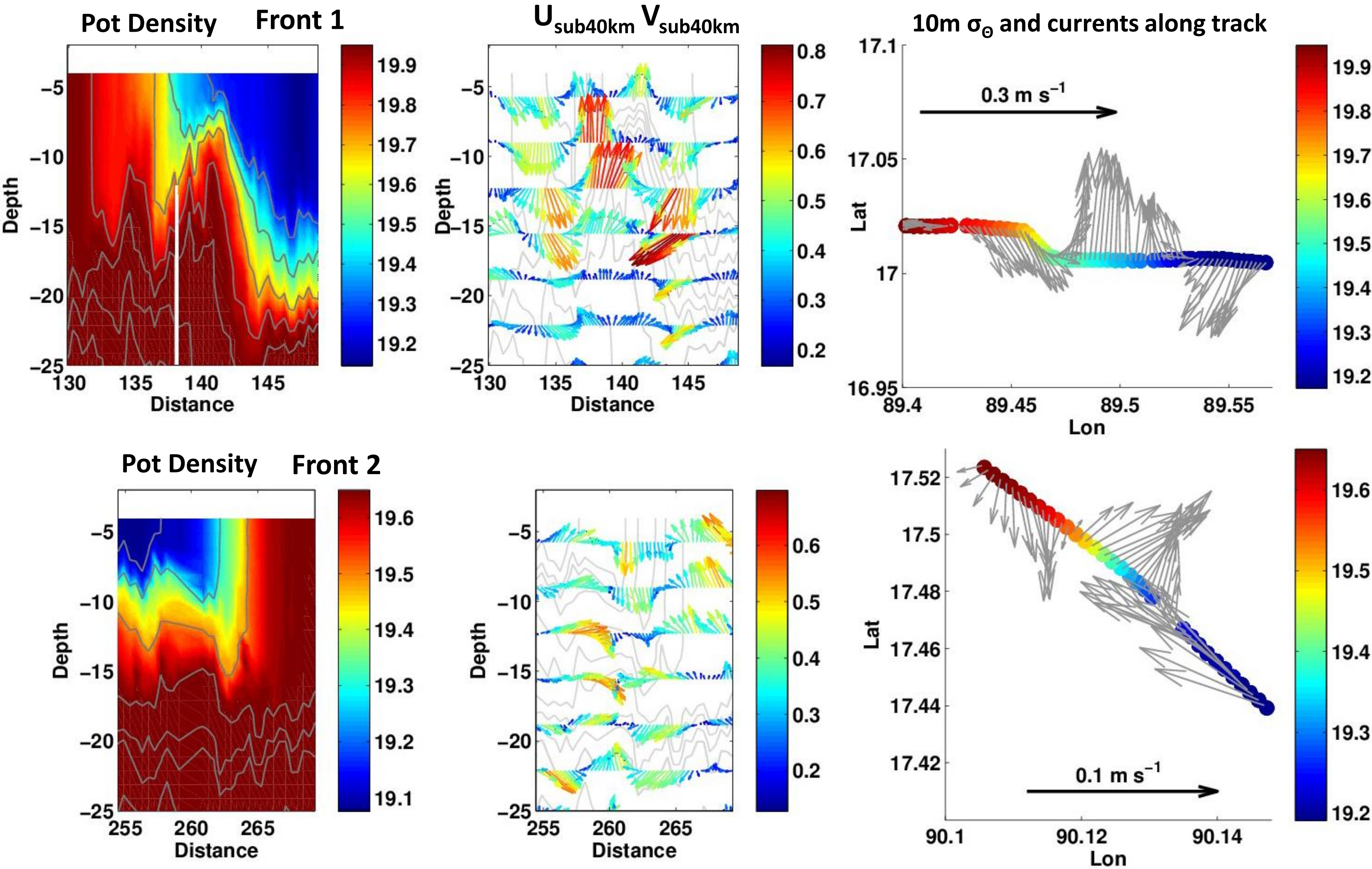
MODERN OBSERVATIONAL PHYSICAL OCEANOGRAPHY

UNDERSTANDING THE GLOBAL OCEAN

CARL WUNSCH

Frontal Jets

Rossby No ζ/f 1.5



Rossby number Ro = U/fL or ζ/f

U and L are velocity and length scales,

Coriolis frequency f = 2Ωsinθ; ζ relative vorticity

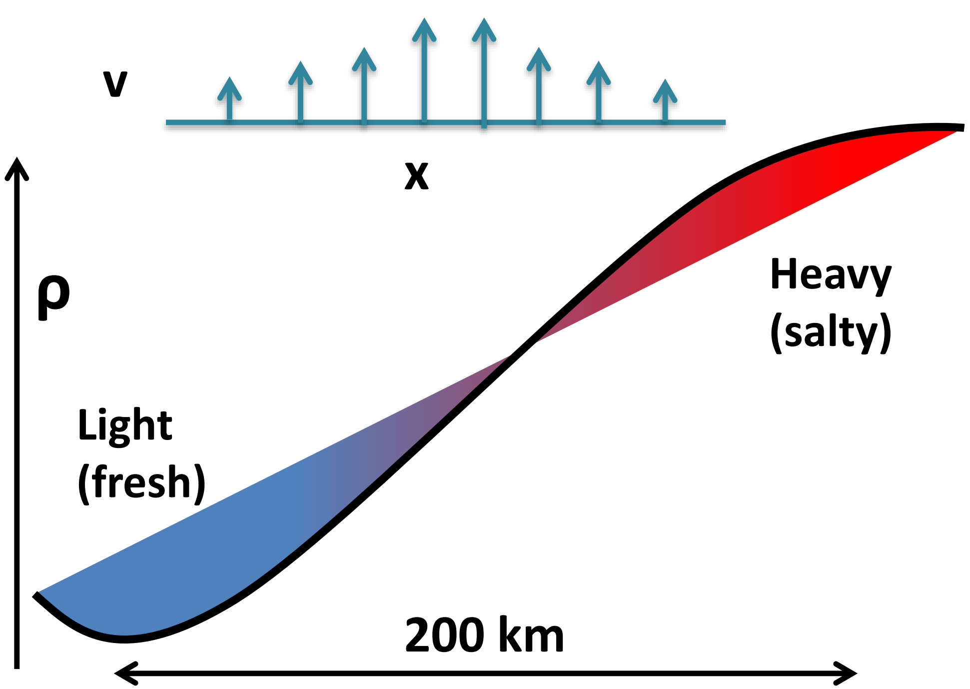
Thermal wind balance

$$-f\frac{\partial v}{\partial z} = g\frac{\partial \rho}{\partial x}$$

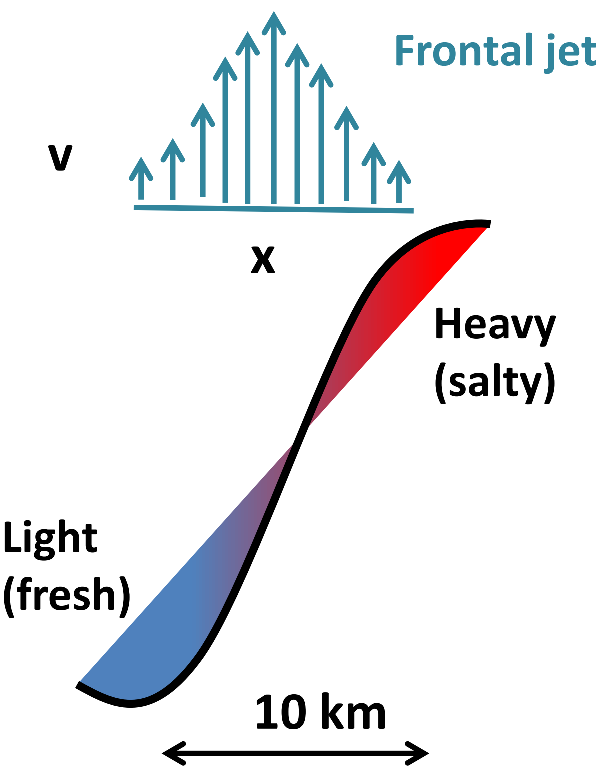
$$f\frac{\partial u}{\partial z} = g\frac{\partial \rho}{\partial y}$$

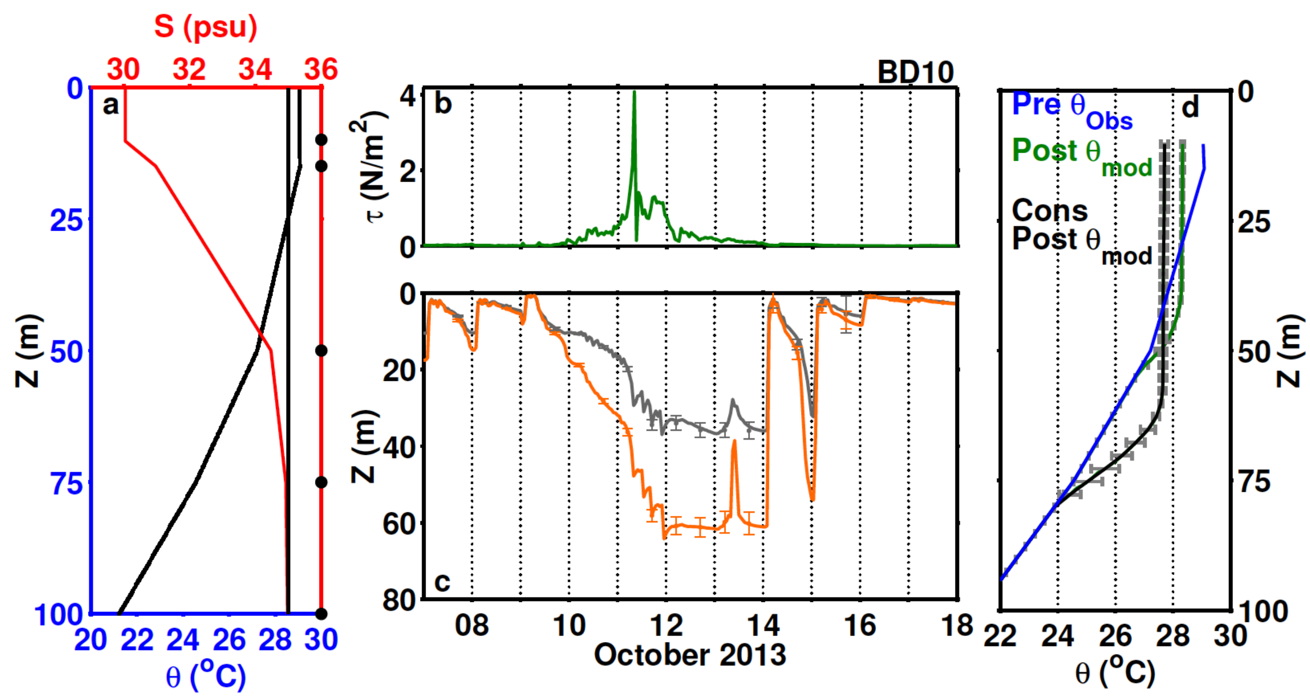
u and v are eastward and northward velocity

Mesoscale – order 100 km
Ro << 1 ; weak lateral shear



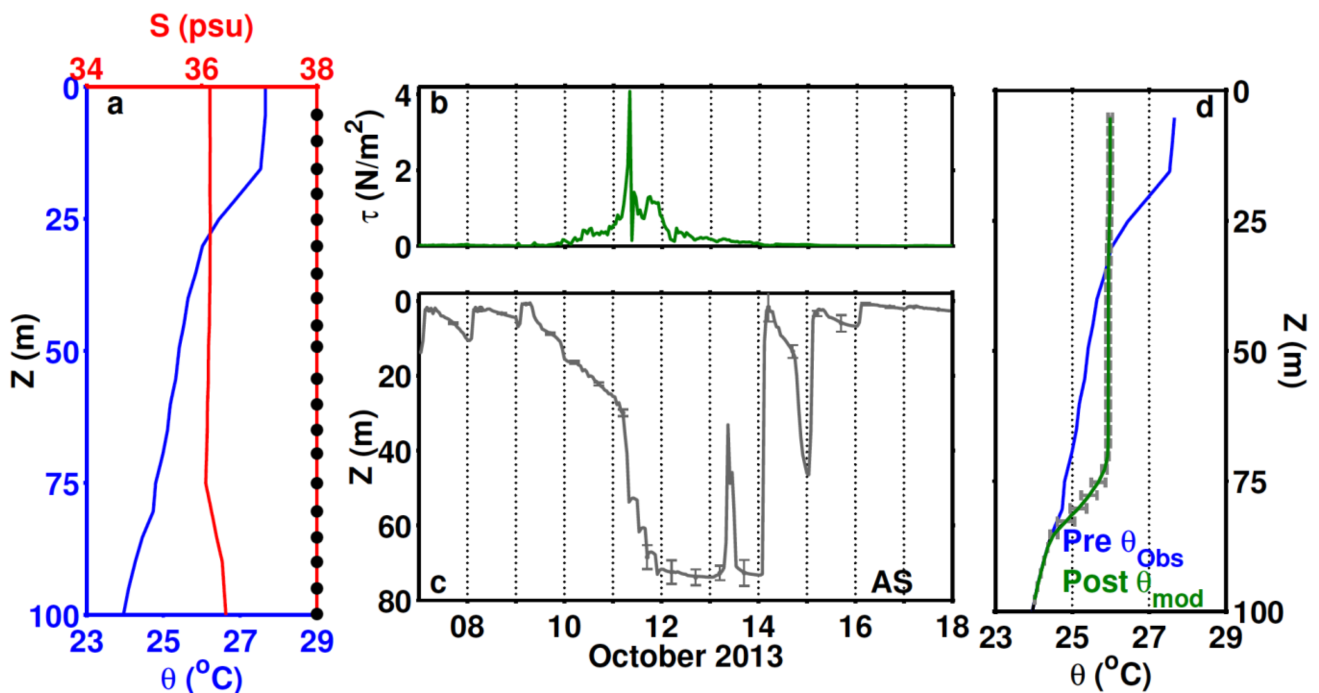
Submesoscale – order 10 km
Ro ~ O(1); high lateral shear

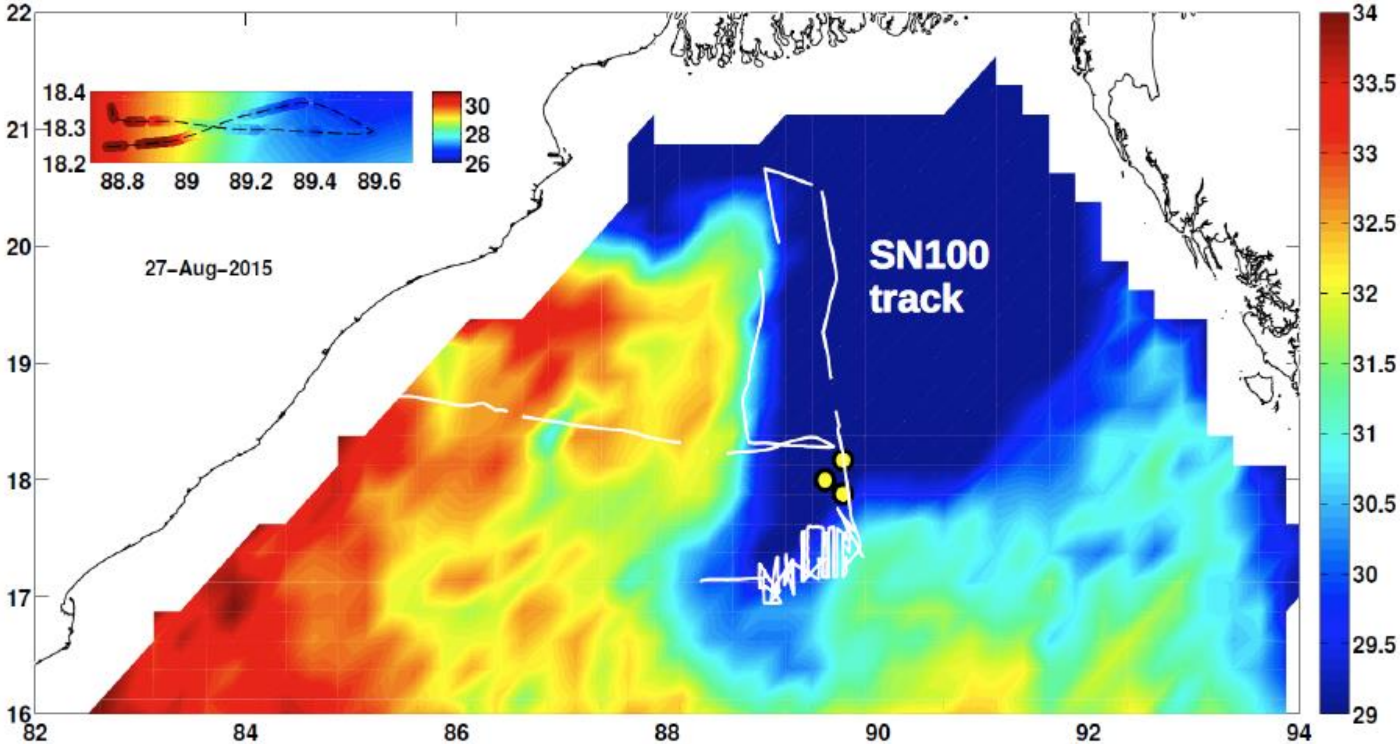


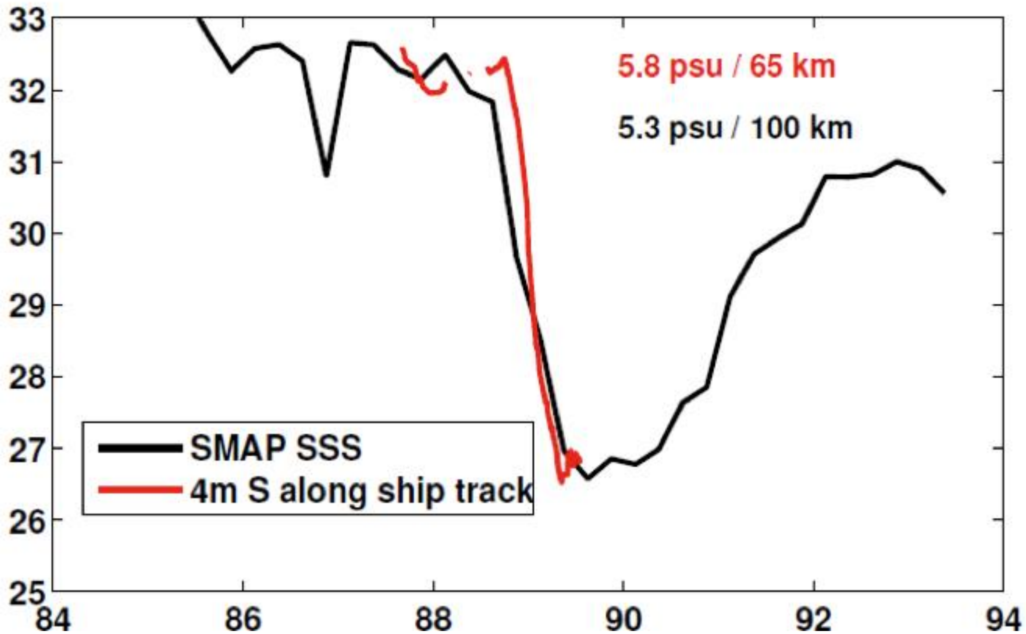


Effect of salinity stratification on MLD deepening and SST cooling

If cyclone Phailin passed over the Arabian sea, SST cooling would be 2.5 times larger







On 50 km scale, the satellite data underestimates SSS gradient by a factor of 2

EKMAN spiral

- Suggested by Nansen, after observations of ice drift .
- First theory of the wind driven flow

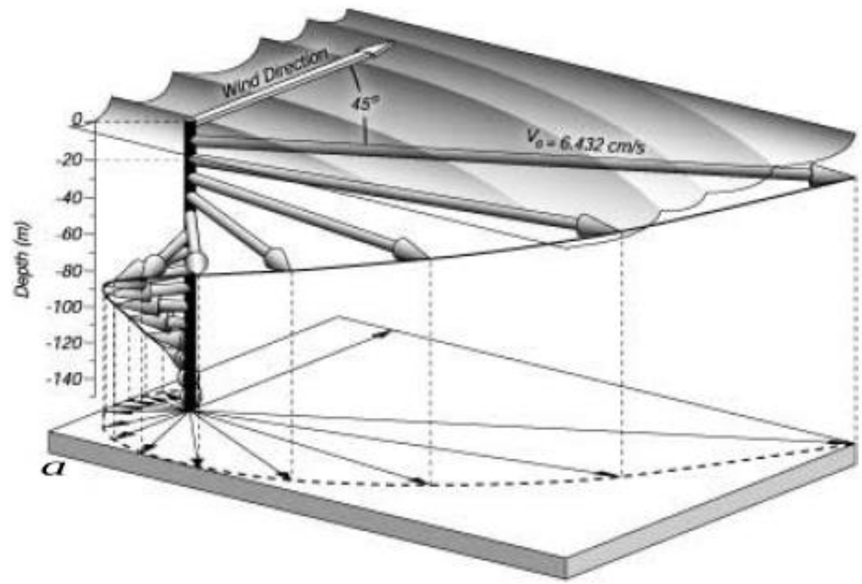
Soln

$$u = V_0 \exp az \sin\left(\frac{\pi}{4} - az\right)$$

$$v = V_0 \exp az \cos\left(\frac{\pi}{4} - az\right)$$

$$V_0 = \frac{T}{\sqrt{\rho^2 f A_z}}$$

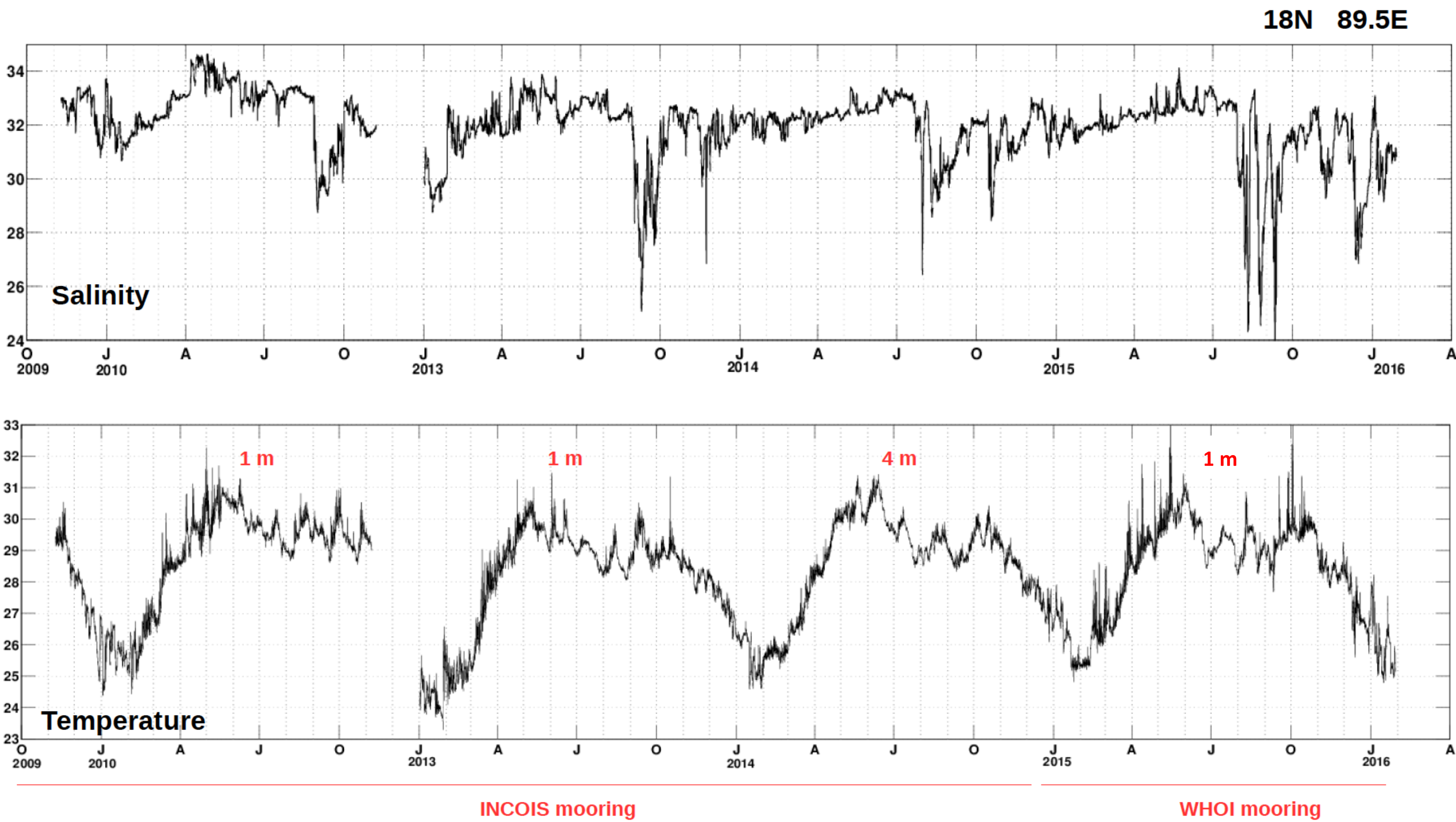
$$a = \sqrt{\frac{f}{2A_z}}$$



Ekman current generated by 10m/s wind at 35°N. Stewart (2008)

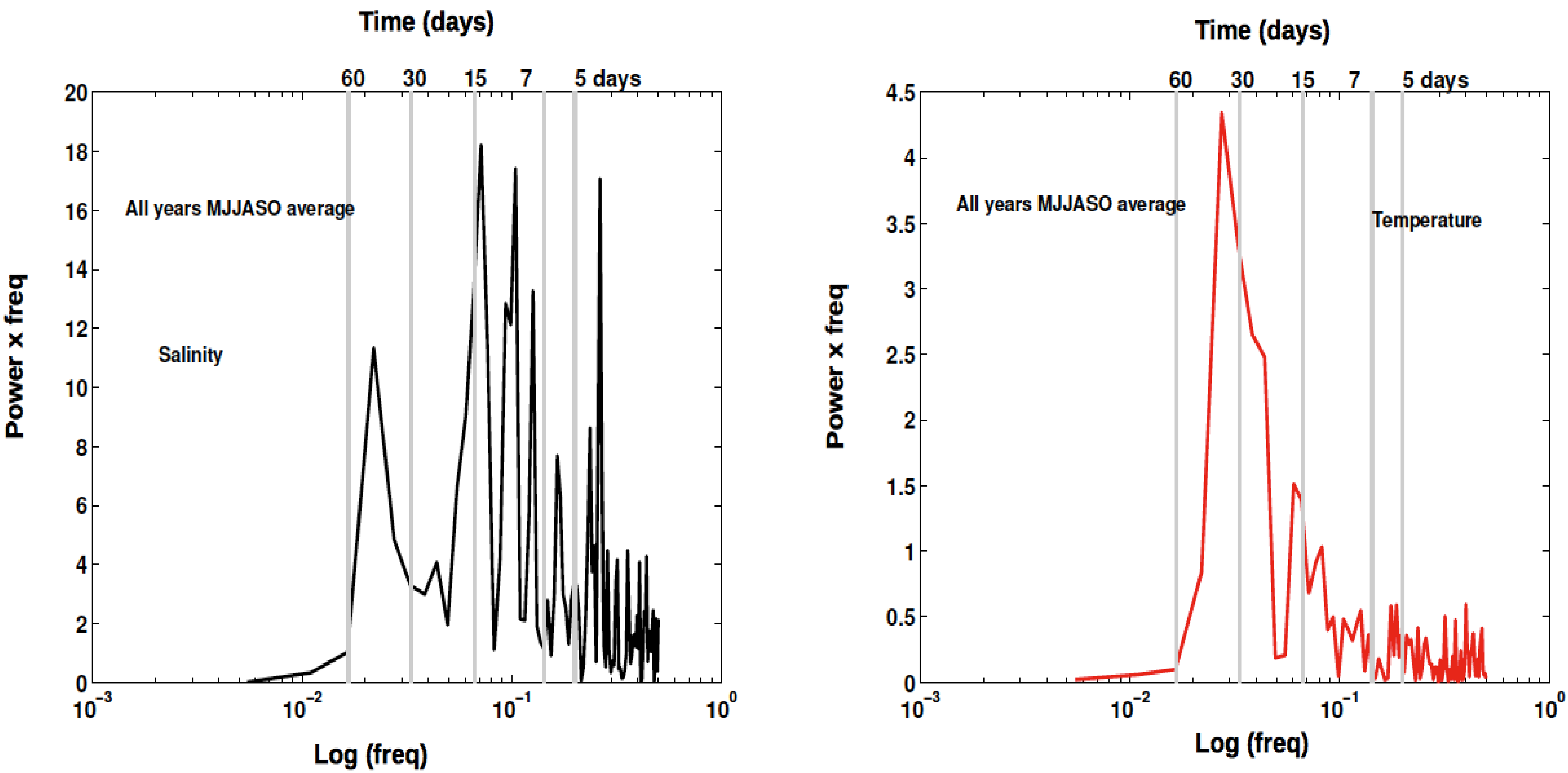
- Constant eddy viscosity A_z .
- Ekman depth a

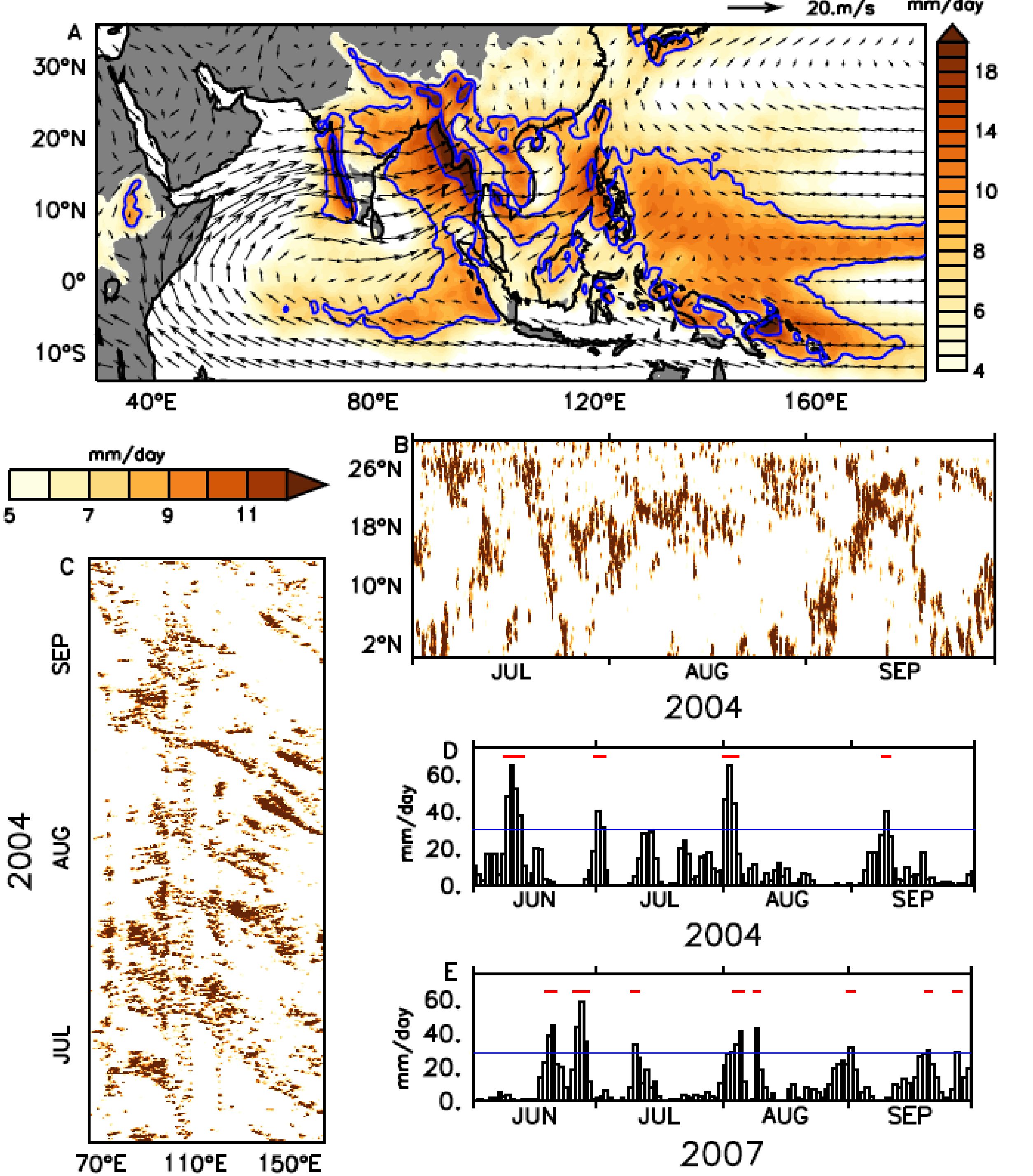
Hourly T/S observations from north Bay of Bengal moorings



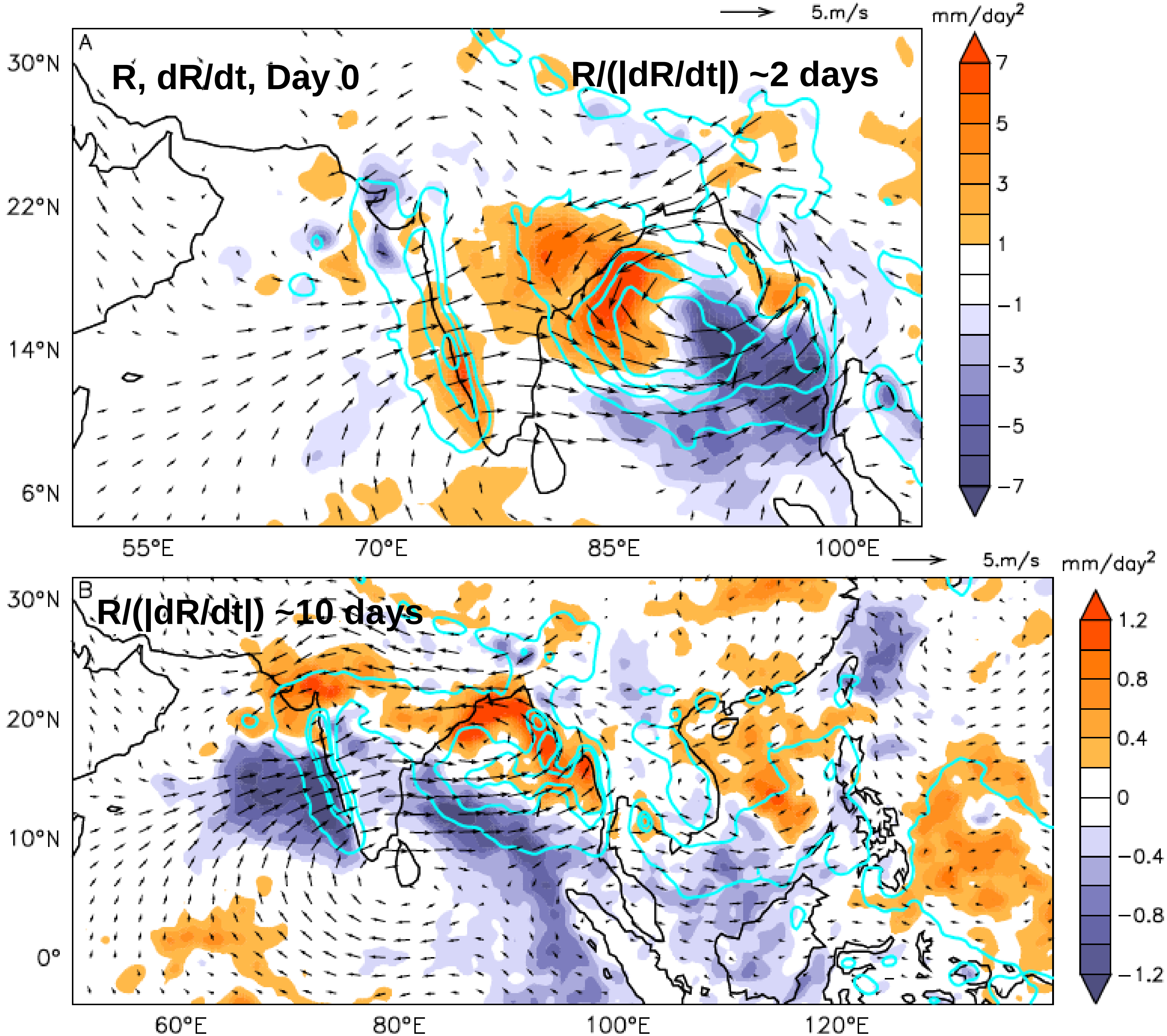
Variance-preserving spectra of sub-60 day mooring S (left) and T (right)

MJJASO average for 2010, 2013, 2014 and 2015

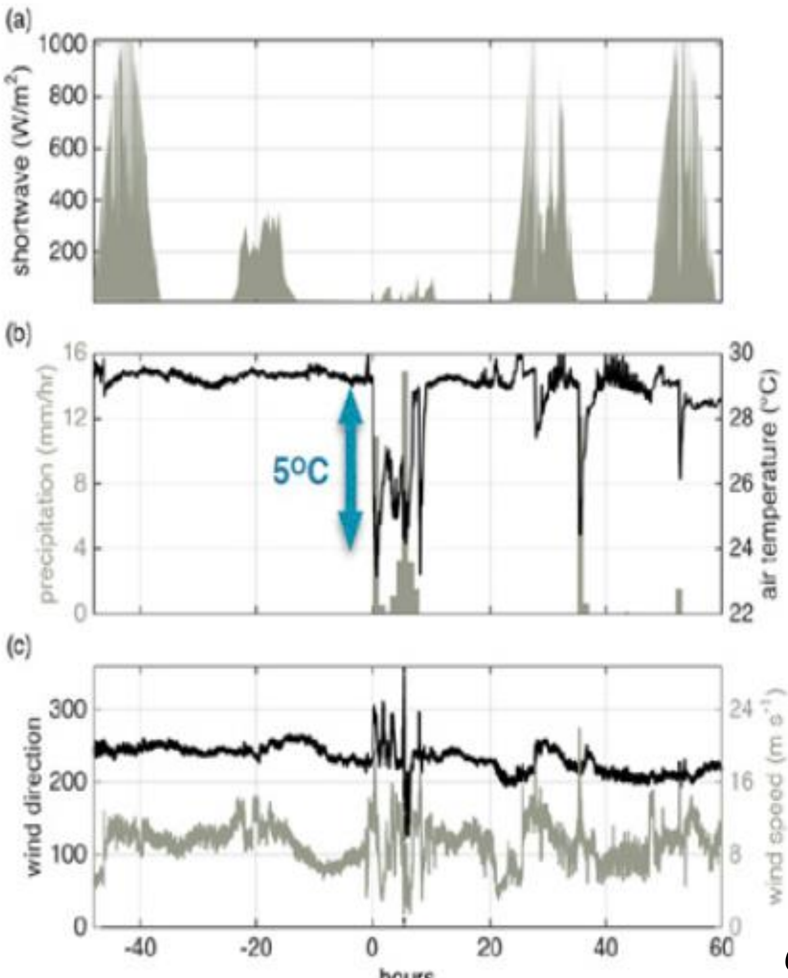


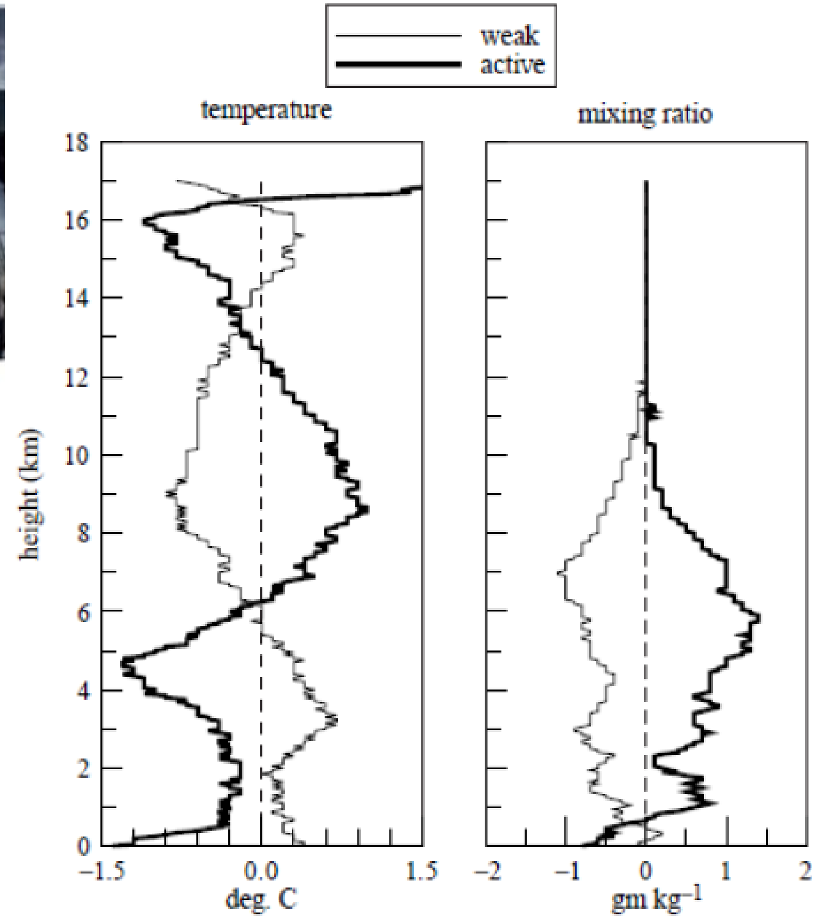


A
20.m/s
mm/day
30°N
20°N
10°N
0°
10°S
40°E
80°E
120°E
160°E
4
6
8
10
14
18
mm/day
5
7
9
11
B
26°N
18°N
10°N
2°N
JUL
AUG
SEP
2004
C
SEP
AUG
JUL
2004
70°E
110°E
150°E
D
mm/day
60.
40.
20.
0.
JUN
JUL
AUG
SEP
2004
E
mm/day
60.
40.
20.
0.
JUN
JUL
AUG
SEP
2007



A
R, dR/dt, Day 0
R/(|dR/dt|) ~2 days
5.m/s
mm/day2
7
5
3
1
−1
−3
−5
−7
30°N
22°N
14°N
6°N
55°E
70°E
85°E
100°E
B
R/(|dR/dt|) ~10 days
5.m/s
mm/day2
1.2
0.8
0.4
0
−0.4
−0.8
−1.2
30°N
20°N
10°N
0°
60°E
80°E
100°E
120°E

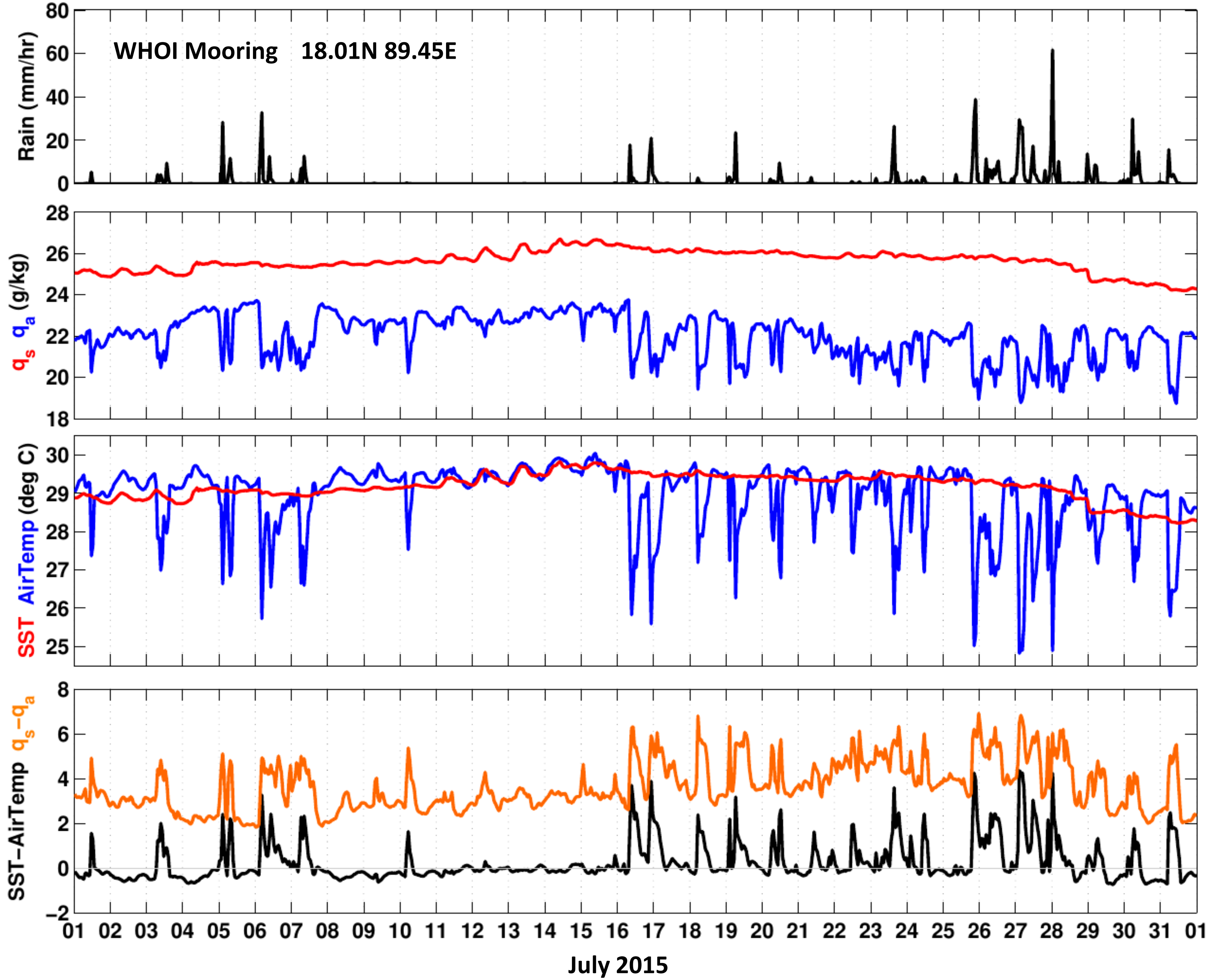




5-day ave. "Active" "Weak" T, q profiles
17.5N 89E BOBMEX July-August 1999

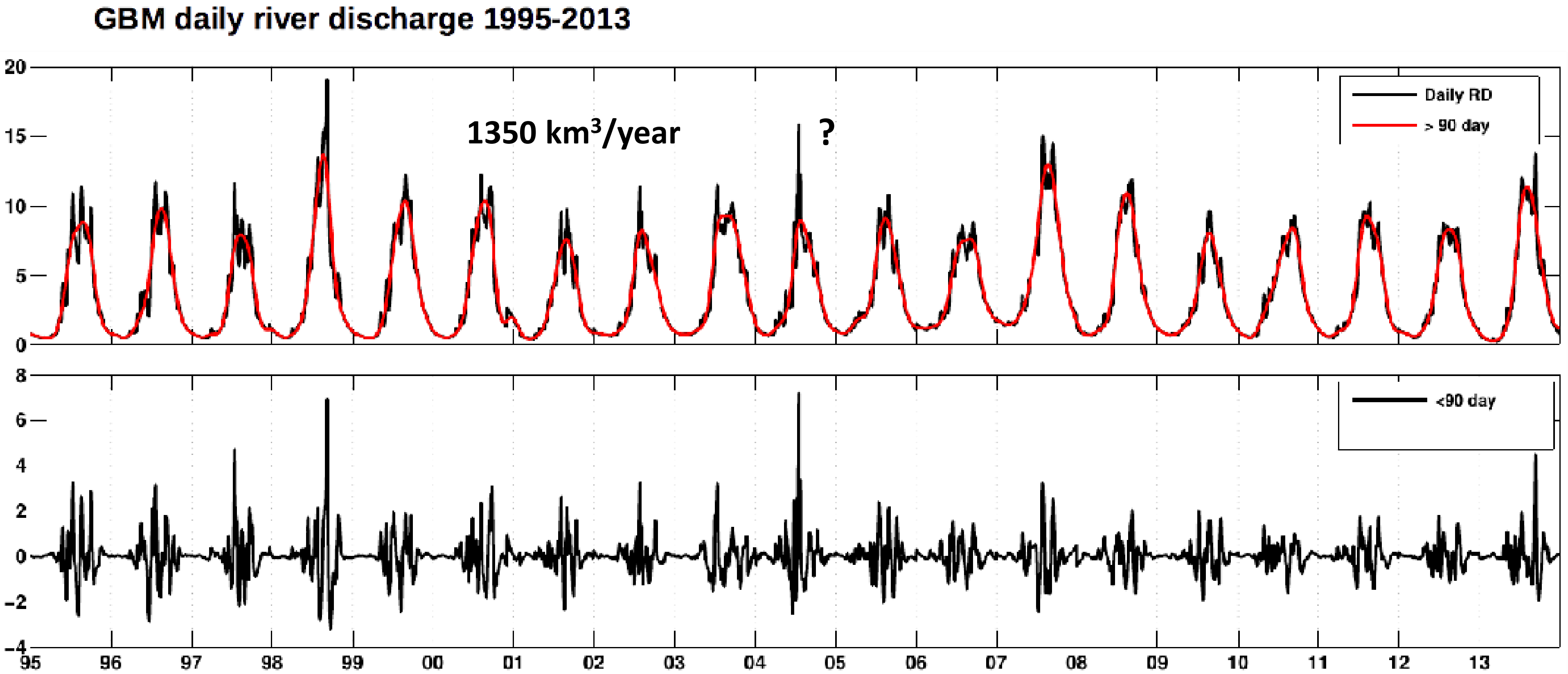
Bhat 2003

Courtesy: Emily Shroyer (OSU) San (SIO)



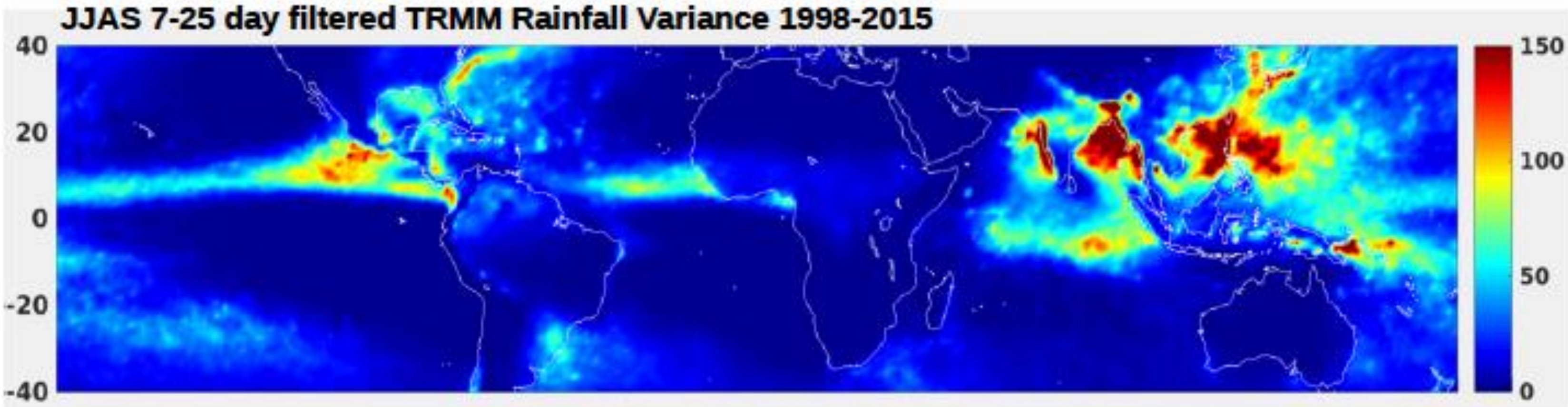
WHOI Mooring 18.01N 89.45E
Rain (mm/hr)
q_s q_a (g/kg)
SST AirTemp (deg C)
SST−AirTemp q_s−q_a
July 2015

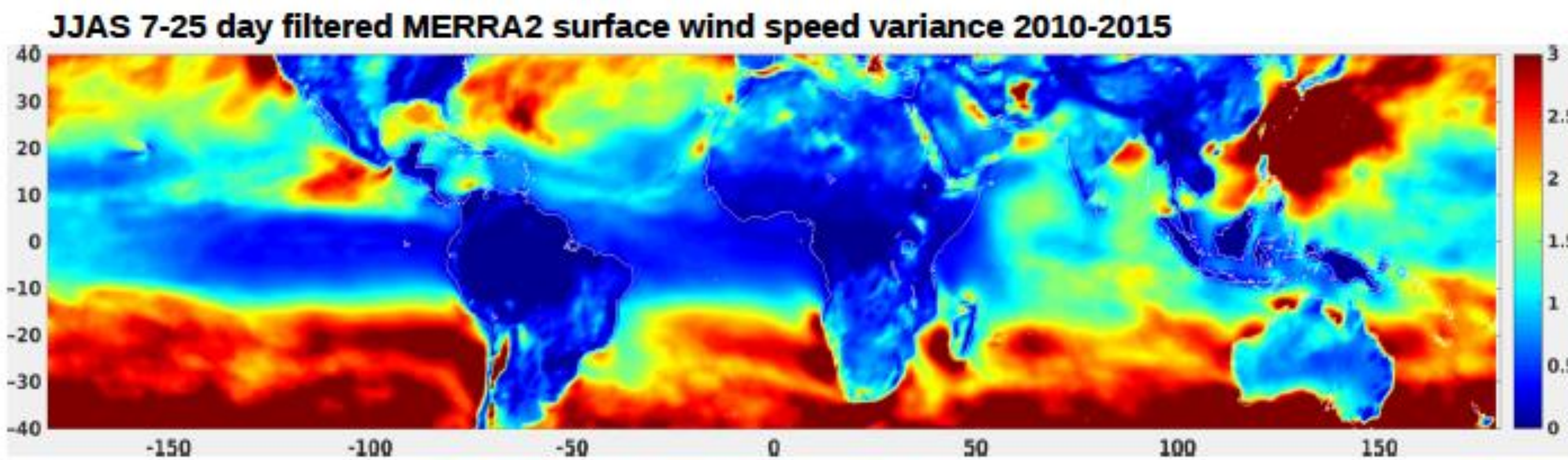
Ganga-Brahmaputra-Meghna river daily discharge to Bay of Bengal (km^3/day)



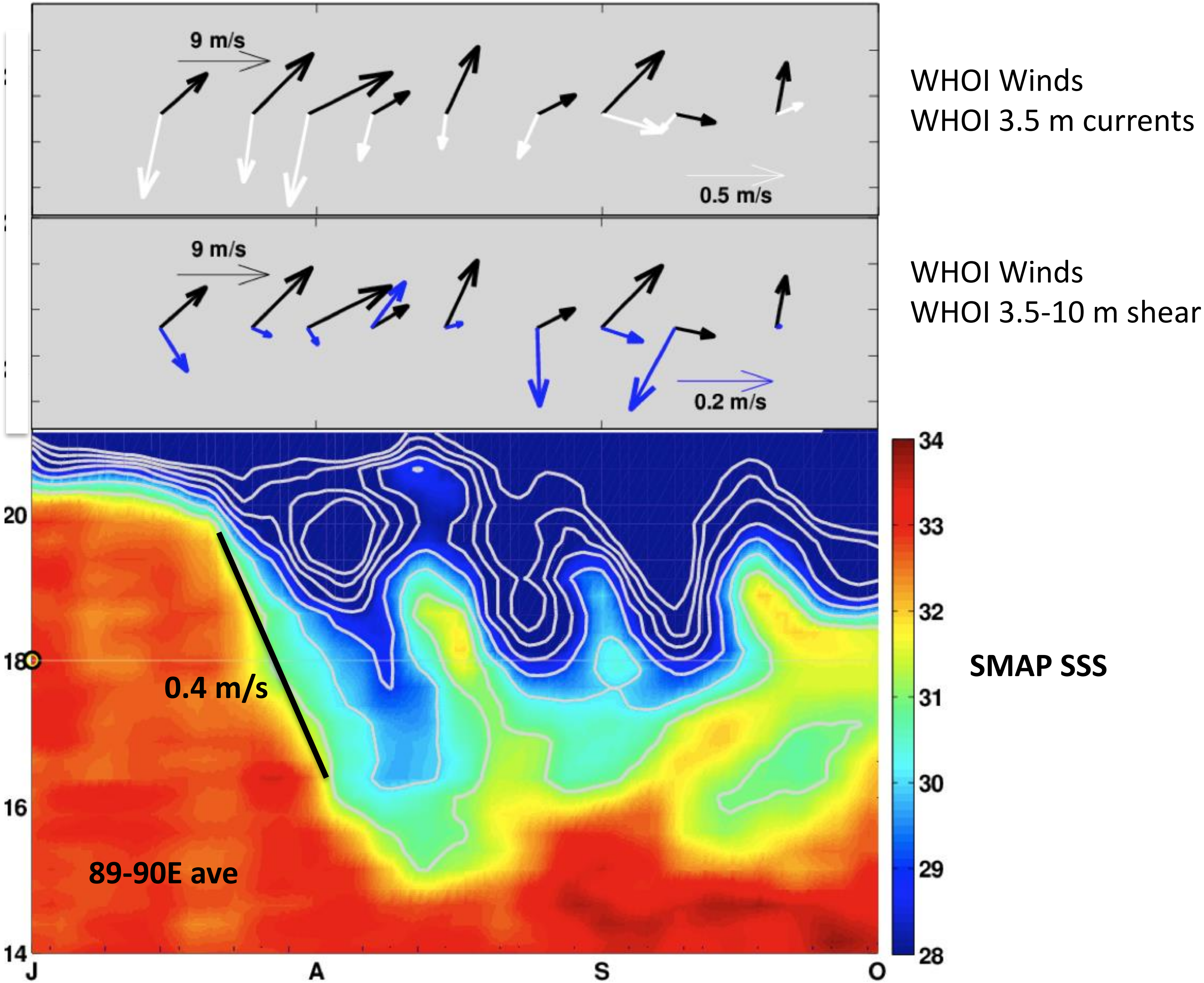
Gauges Hardinge (Ganga), Bahadurabad (Brahmaputra) - merged with satellite altimetry

Fabrice Papa and collaborators

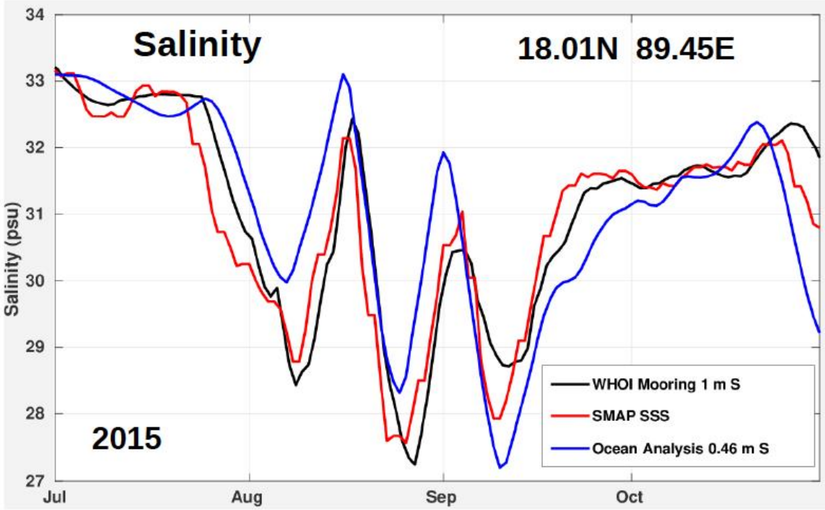




Quasi-biweekly mode (7-25 day) is the dominant mode of subseasonal variability in the Indo-West Pacific region but not in the western Equatorial Atlantic.


9 m/s
0.5 m/s
WHOI Winds
WHOI 3.5 m currents
9 m/s
0.2 m/s
WHOI Winds
WHOI 3.5-10 m shear
20
18
16
14
0.4 m/s
89-90E ave
J
A
S
O
34
33
32
31
30
29
28
SMAP SSS

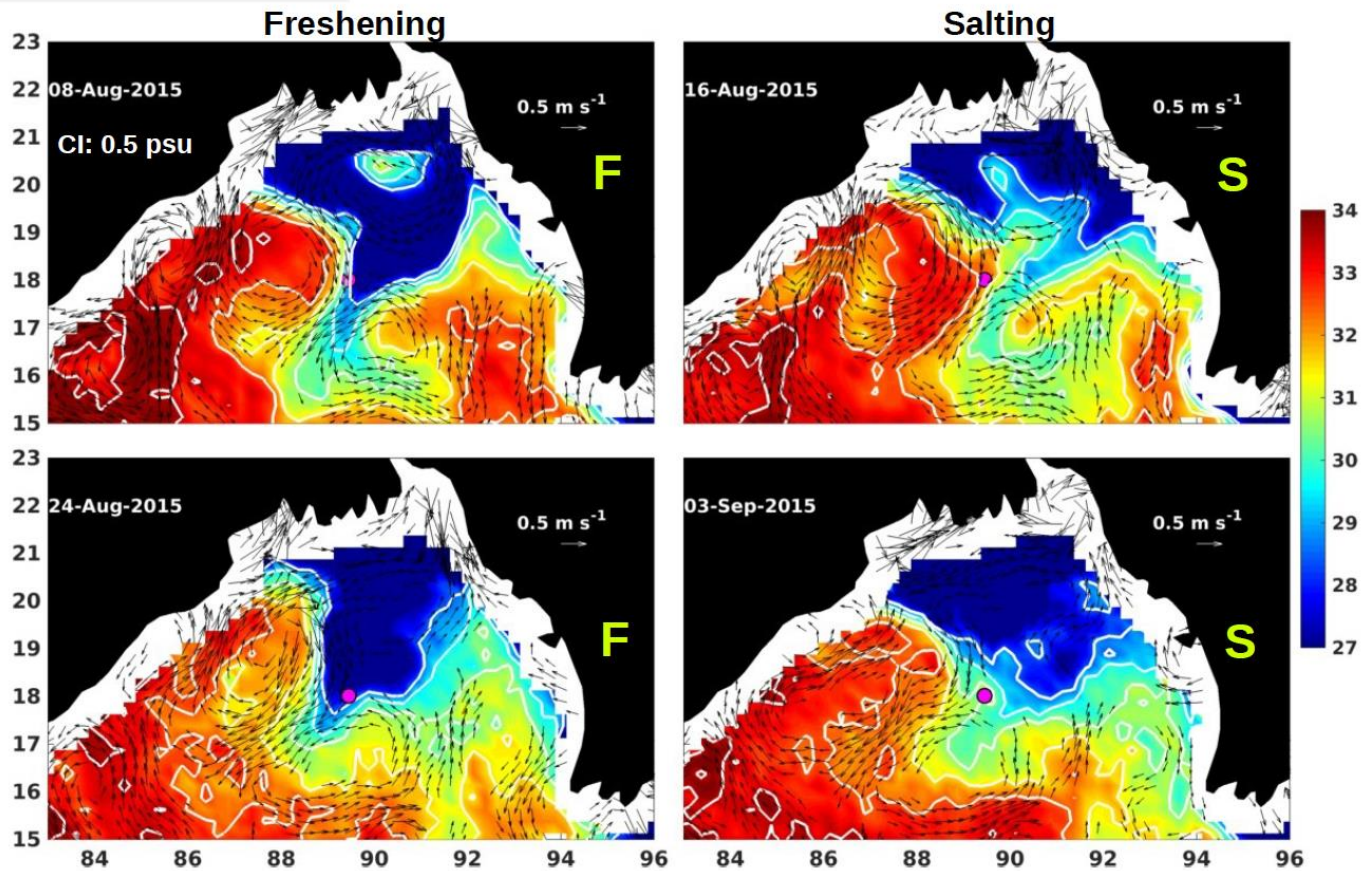
Ganga-Brahmaputra river water in the Bay of Bengal



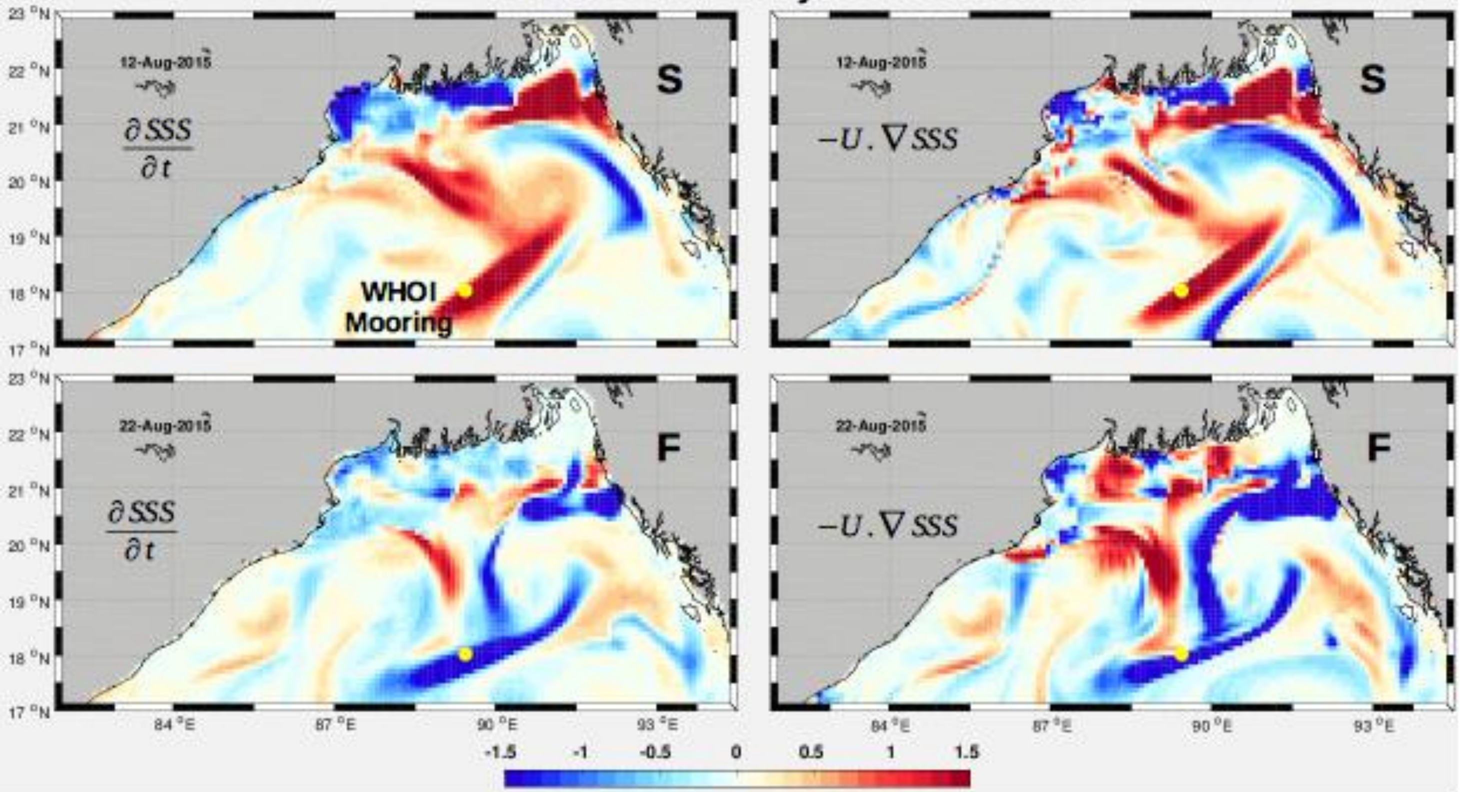
Quasi-biweekly variability in SSS from mooring, satellite and ocean analysis.

SMAP SSS (color), AVISO geostrophic velocity (vectors), WHOI Mooring (dot)

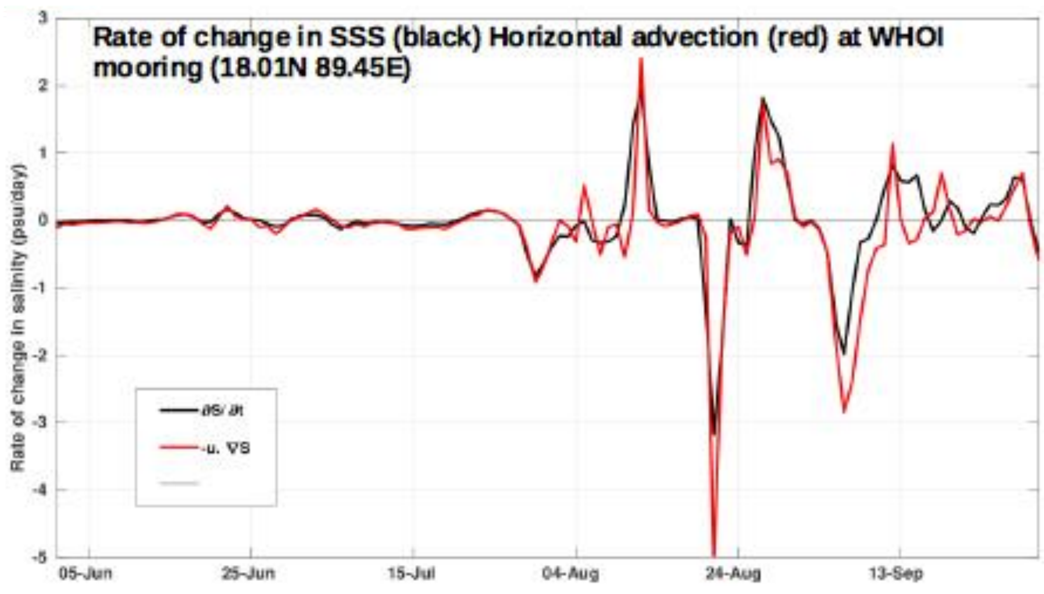
Two episodes of freshening (F) and salting (S) at the mooring



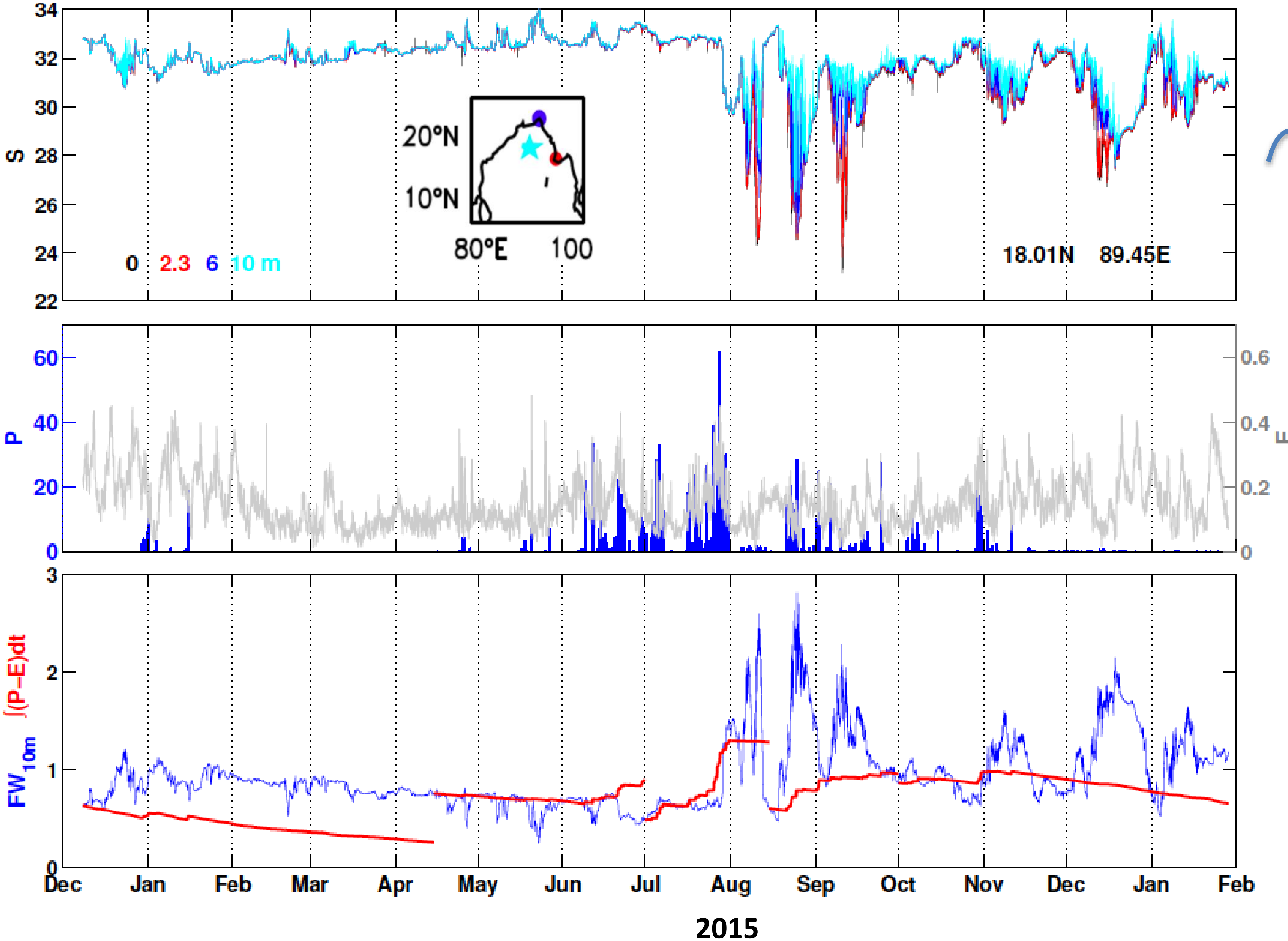
Global Ocean Analysis Forecast data



Ocean Analysis indicates that the subseasonal variability in SSS is mainly due to horizontal advection by the mesoscale eddy flow and the wind-driven shallow Ekman flow.



River water in the Bay of Bengal

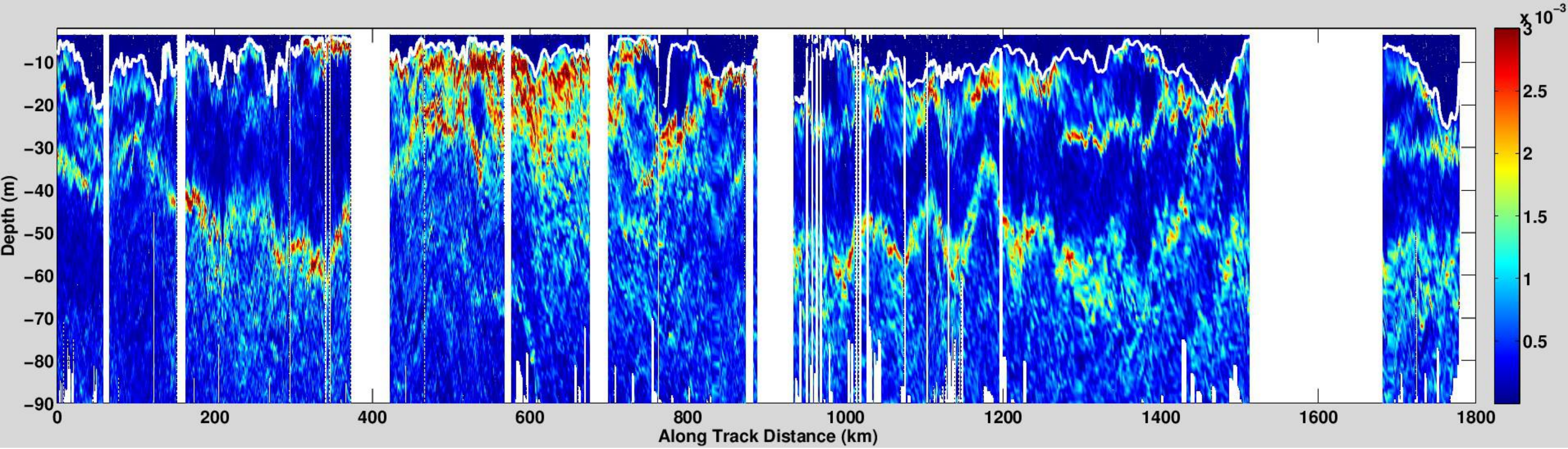


Pulses of river water at the mooring in summer and winter
Note persistence of river water for three seasons

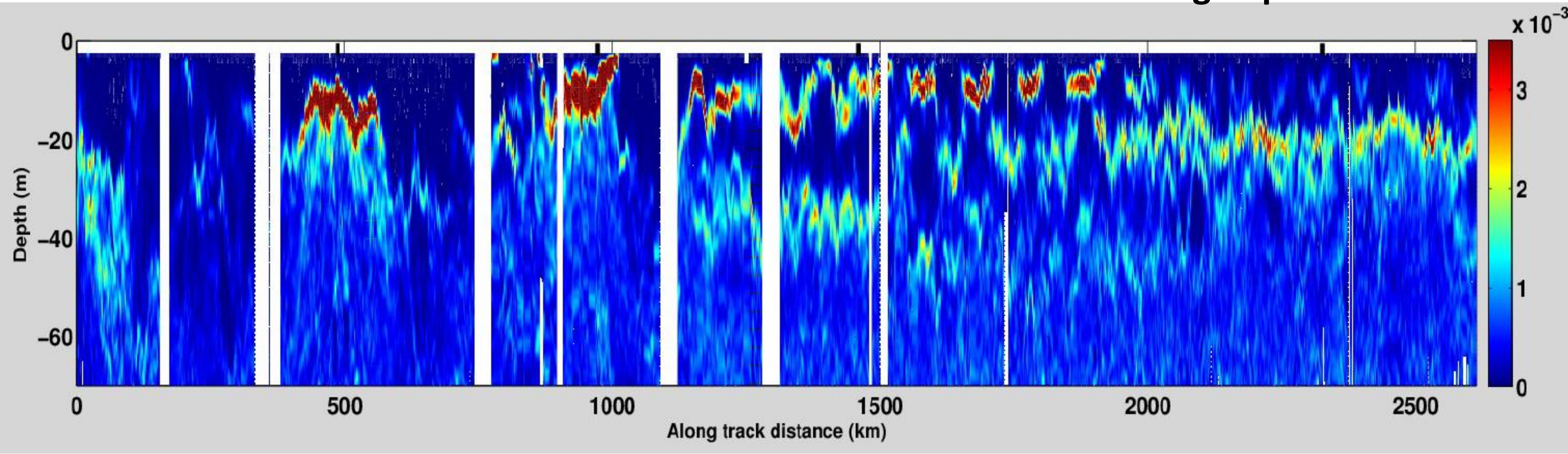
Sengupta *et al.* 2016

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

Aug-Sep 2014



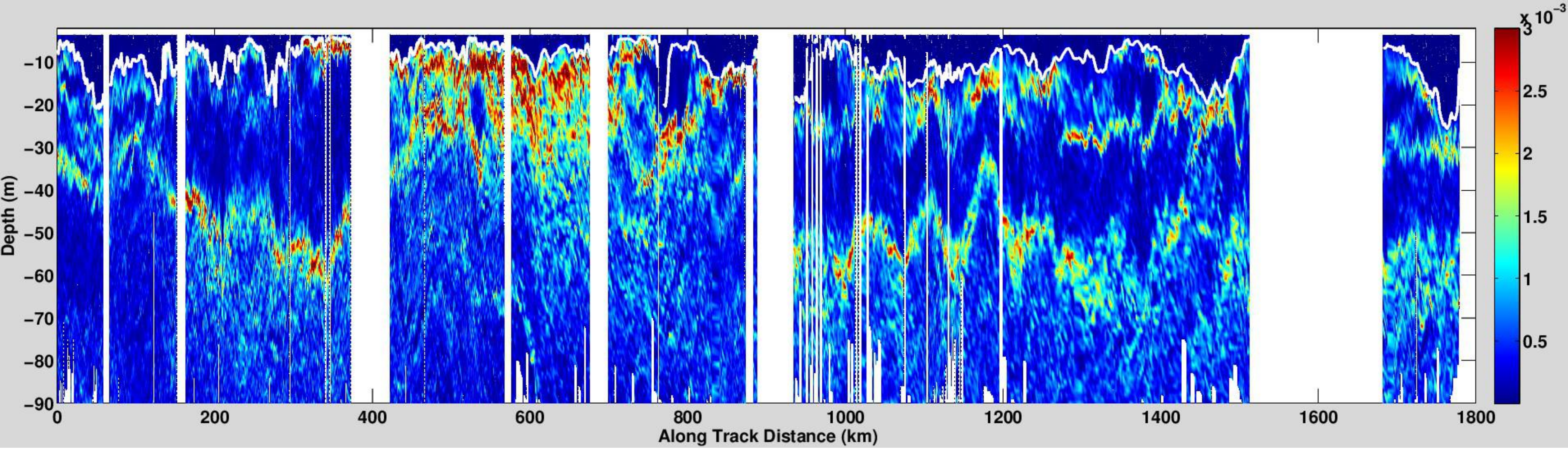
Aug-Sep 2015

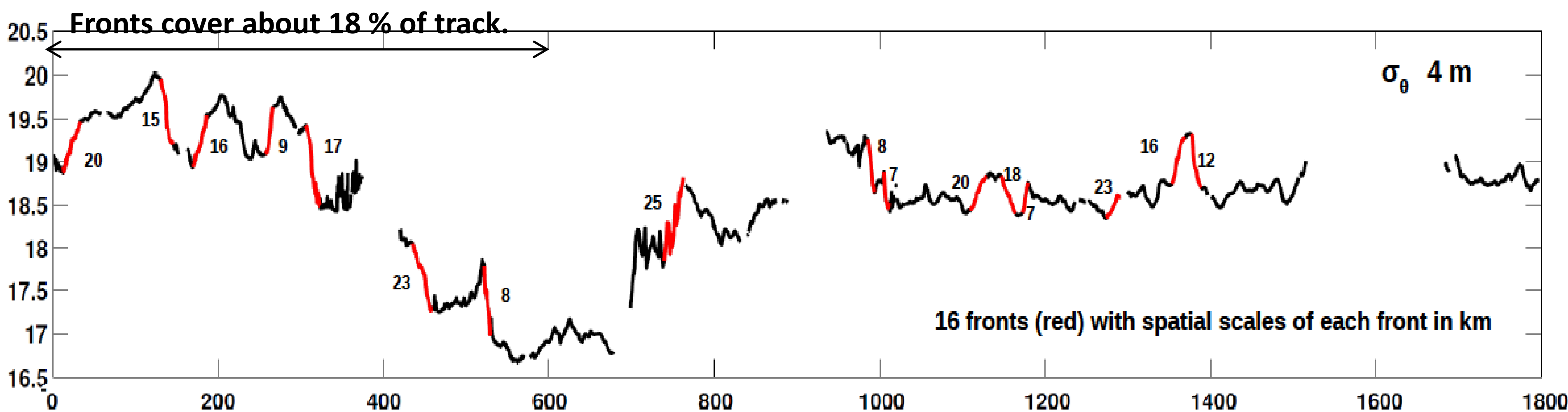


Two ship experiments

Stratification $N^2 = -g/\rho\ (d\rho/dz)$

Aug-Sep 2014

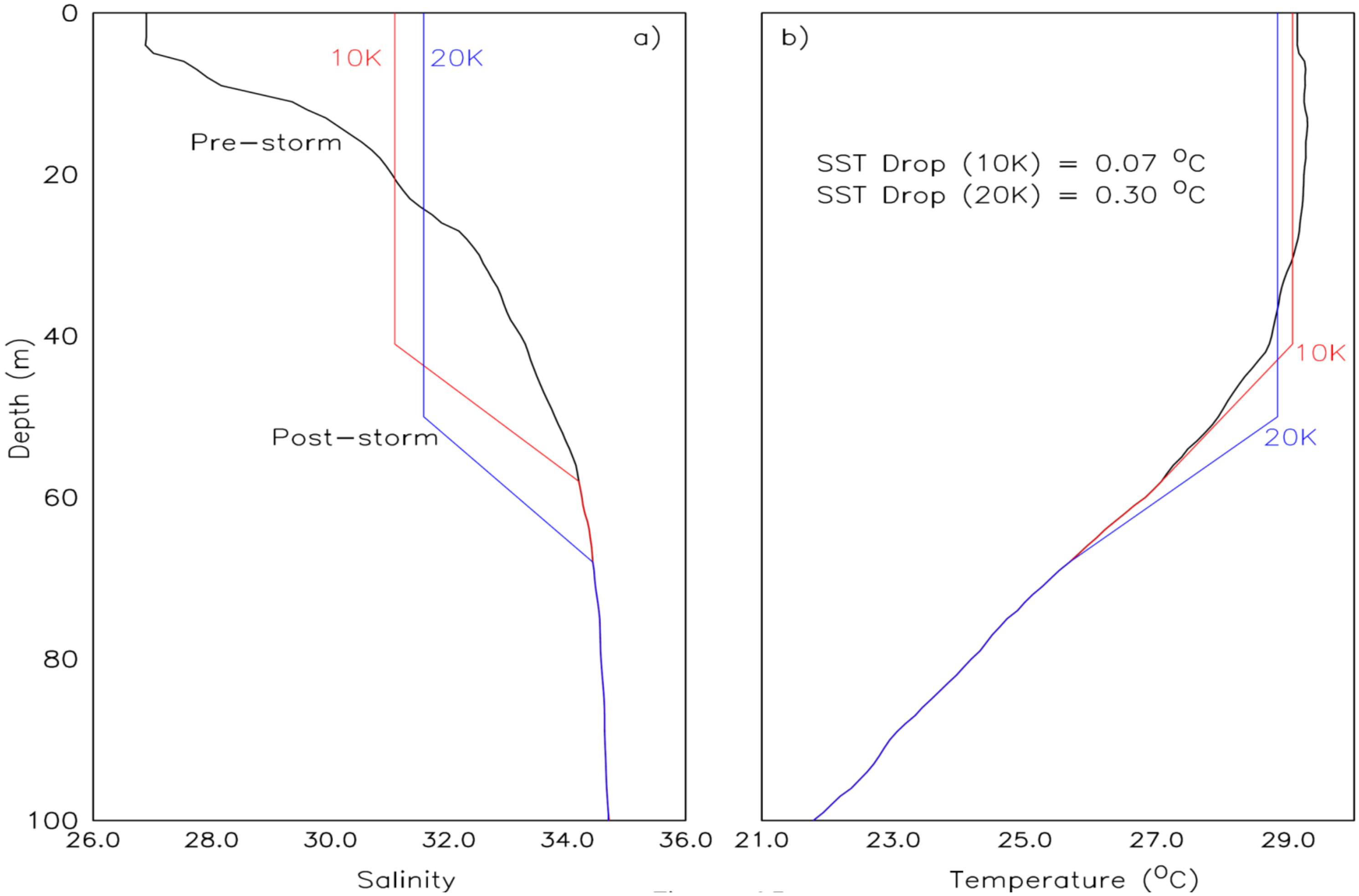




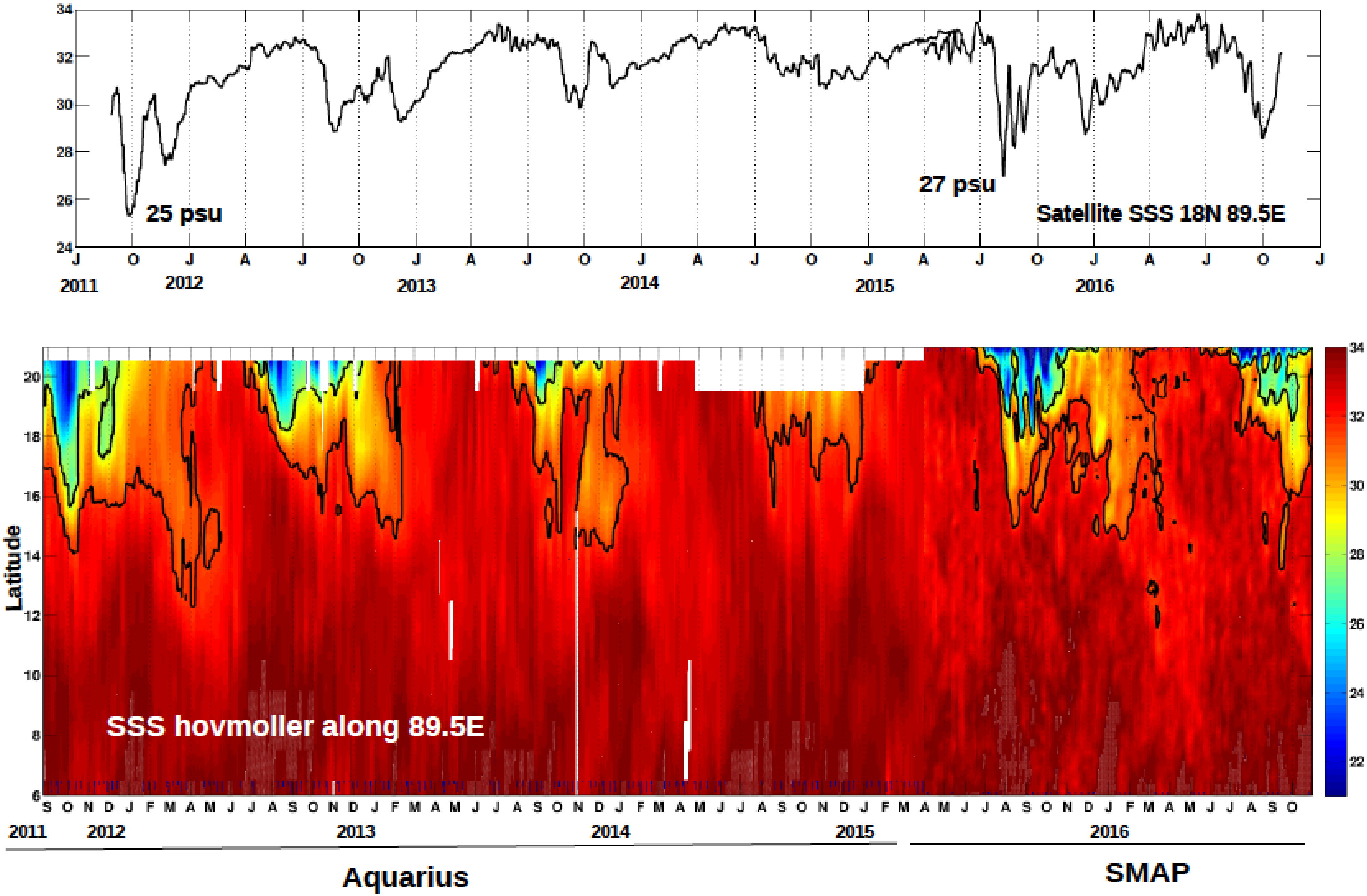
2014-15: 30 major salinity dominated fronts Scales 3-50 km, sizes 0.3- 3 kg/m^3

> 10 km data gaps blank

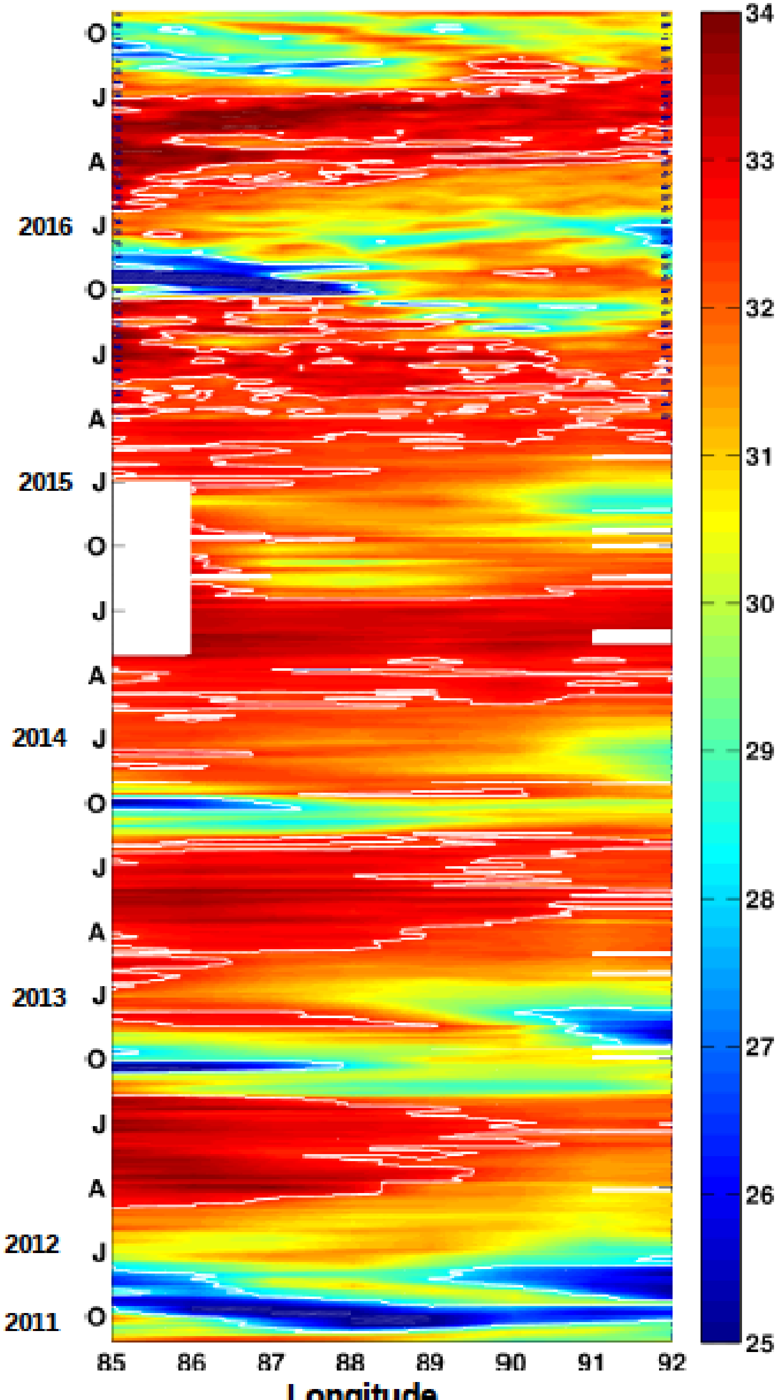
Interleaving, deeper halocline: Last year's river water ?



Post-monsoon cyclones don’t cool the north Bay of Bengal

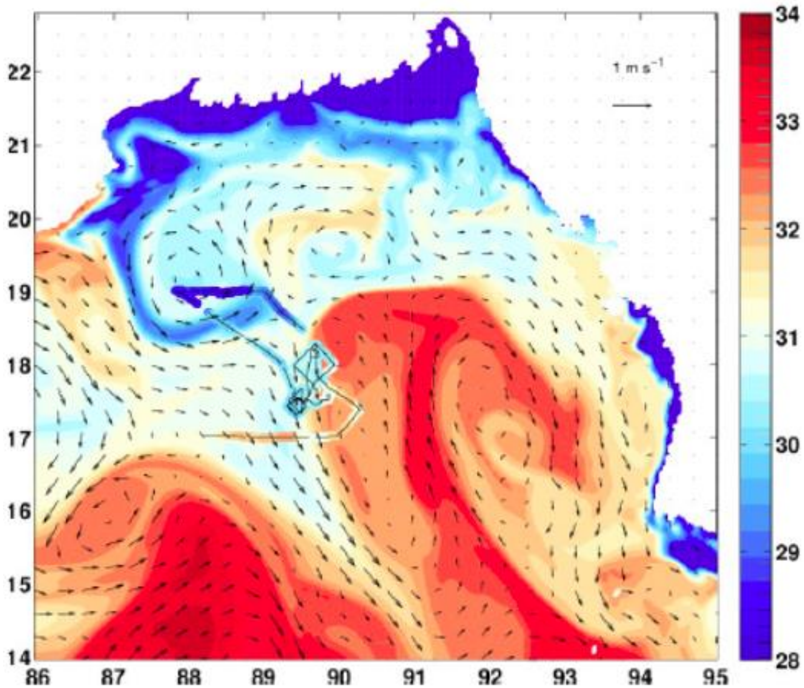


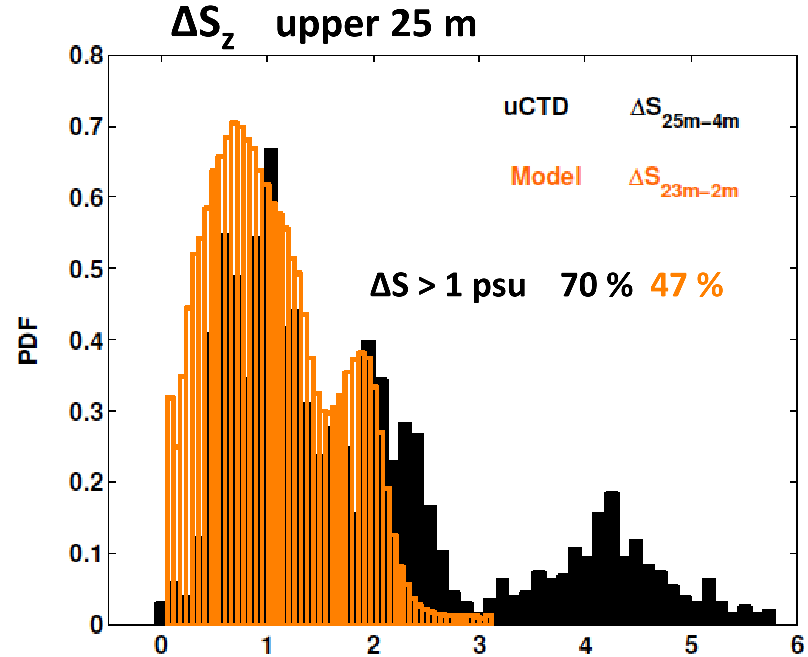
2011 and 2015 are very fresh years

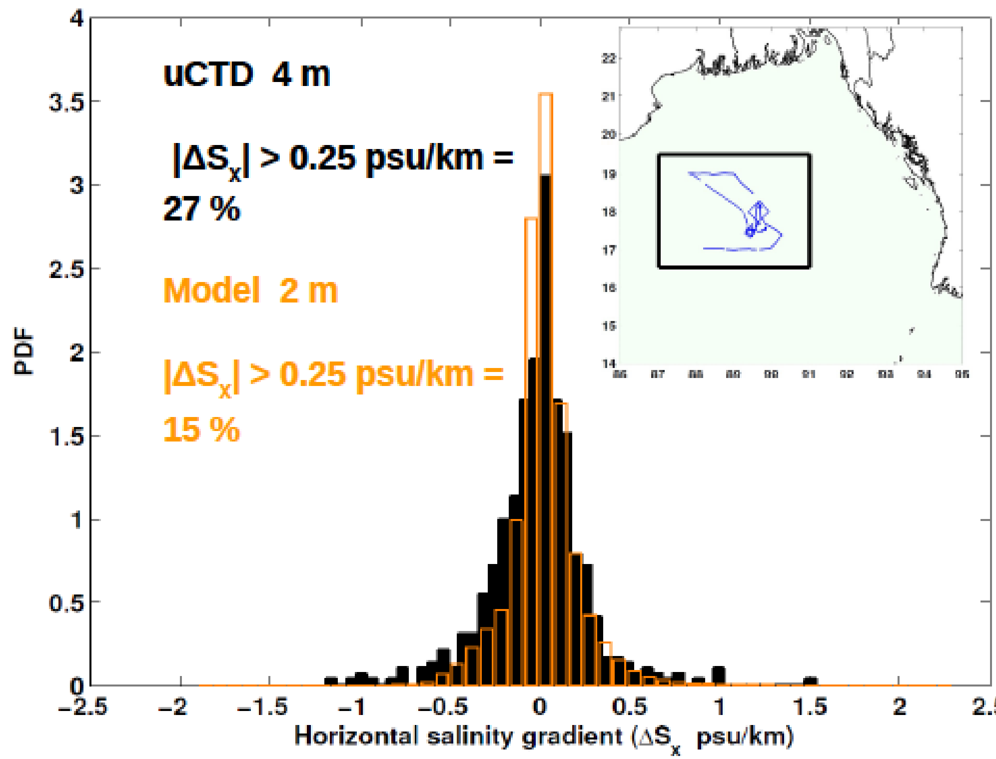


SSS hovmoller along 18N

3 km ROMS 16 Aug-6 Sep 2014







Bay of Bengal Regional Ocean Model

1/32º   50 sigma levels   Two-eq turbulence model
I.C. from data-assimilating HYCOM on 16 Aug 2014
Forcing 3-hourly MERRA fluxes, hourly model fields

Courtesy: Harper Simmons, U. Alaska