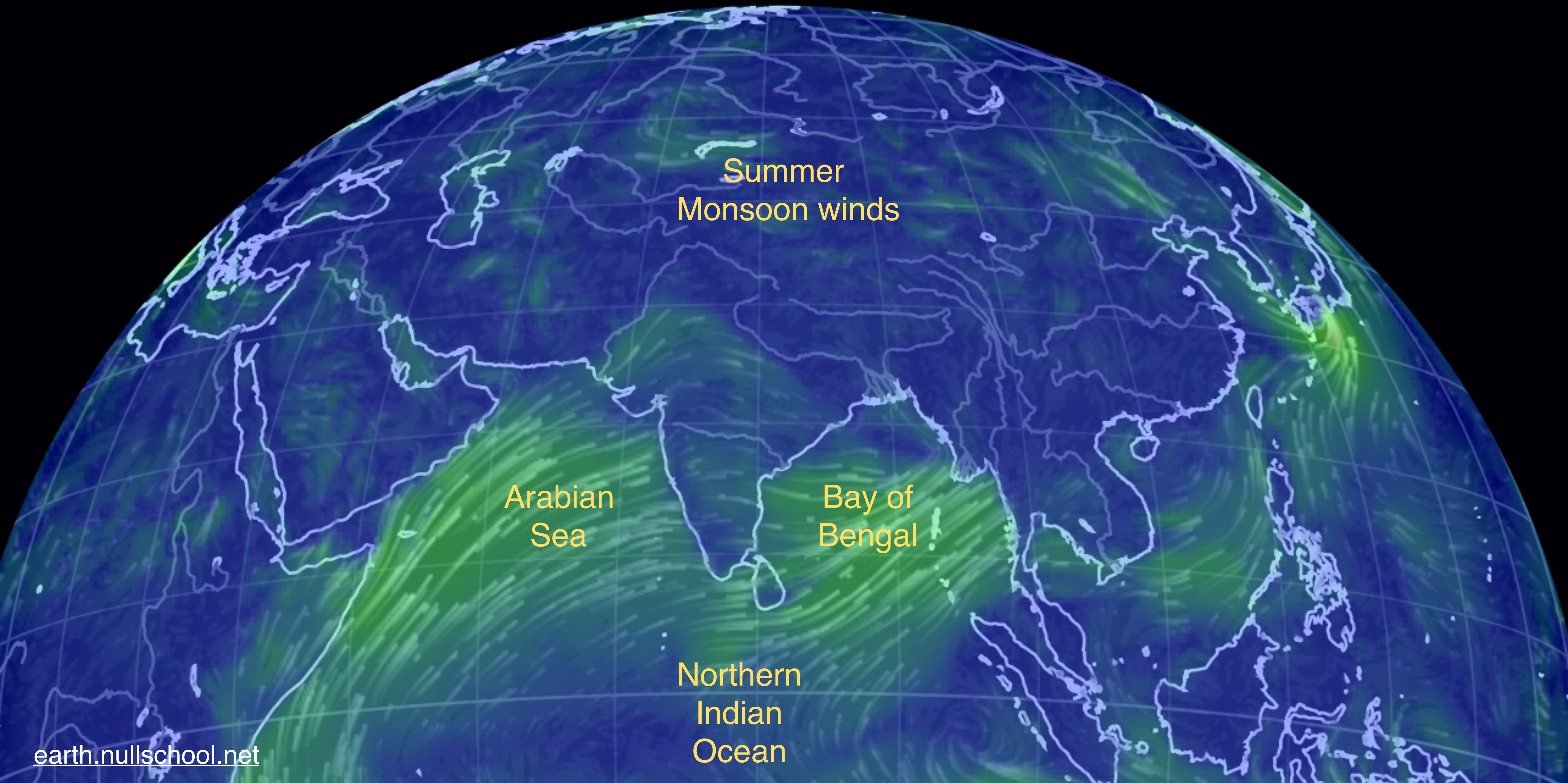
Boundary layers in the Bay of Bengal

ASIRI

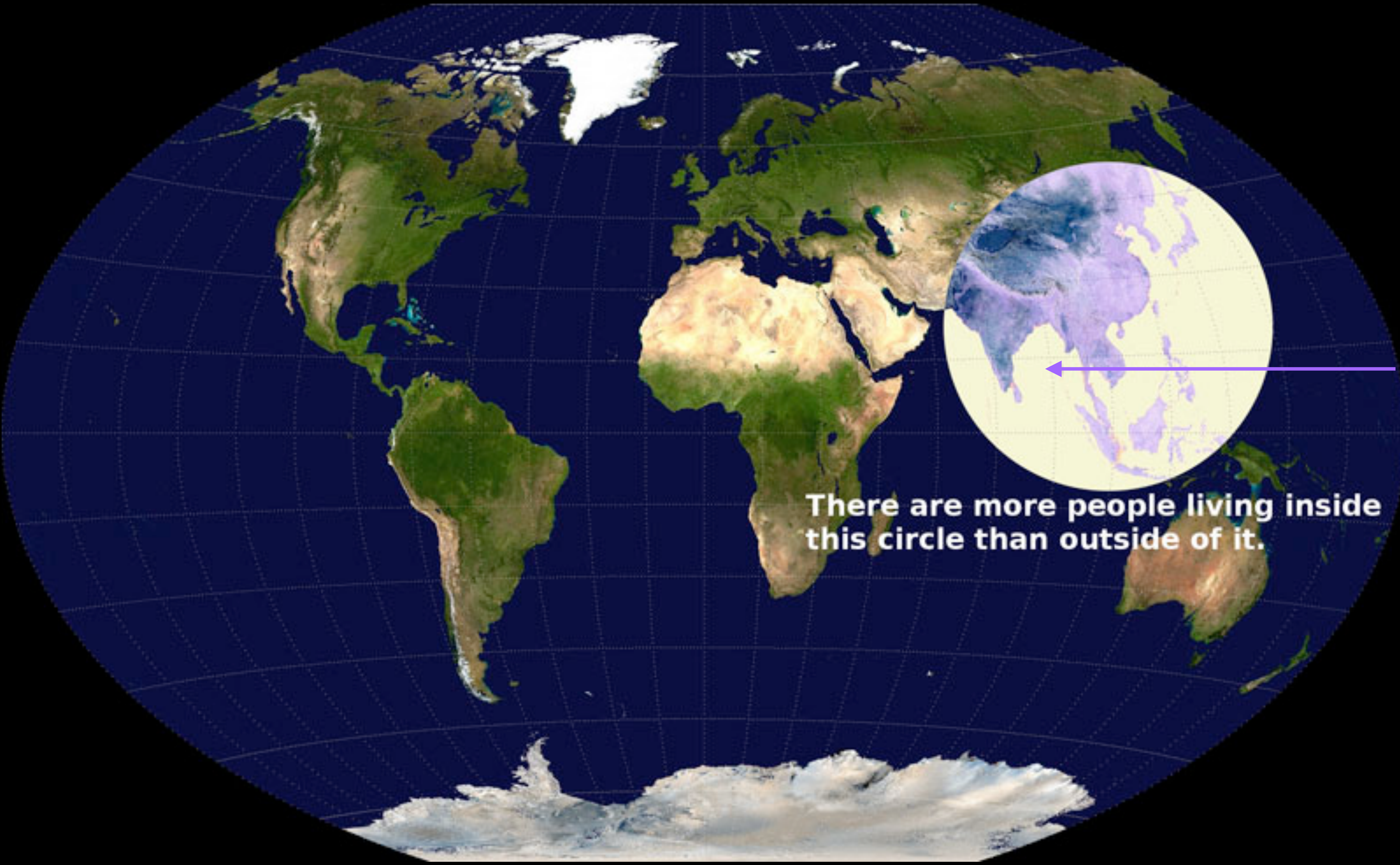
Amit Tandon

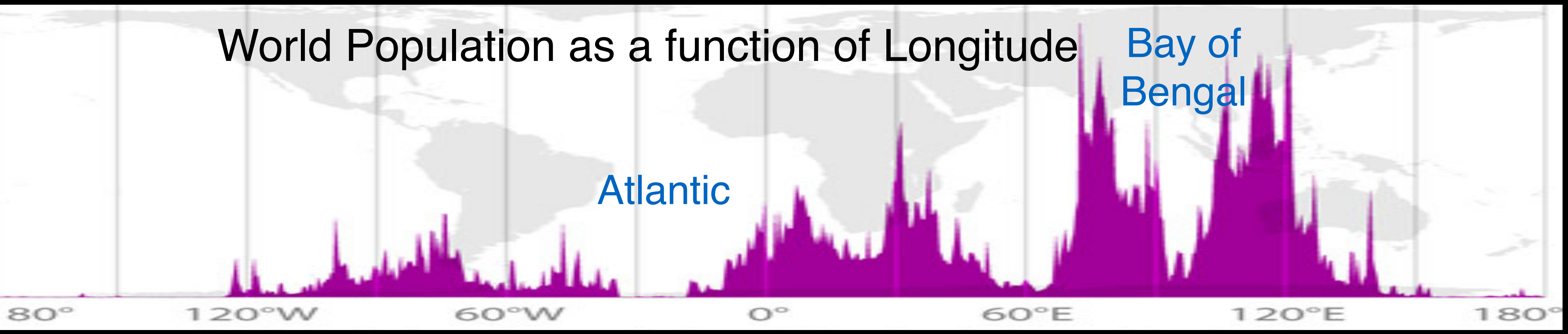
UMass Dartmouth



earth.nullschool.net

2.5 billion people depend on the Monsoon for water, food, economy



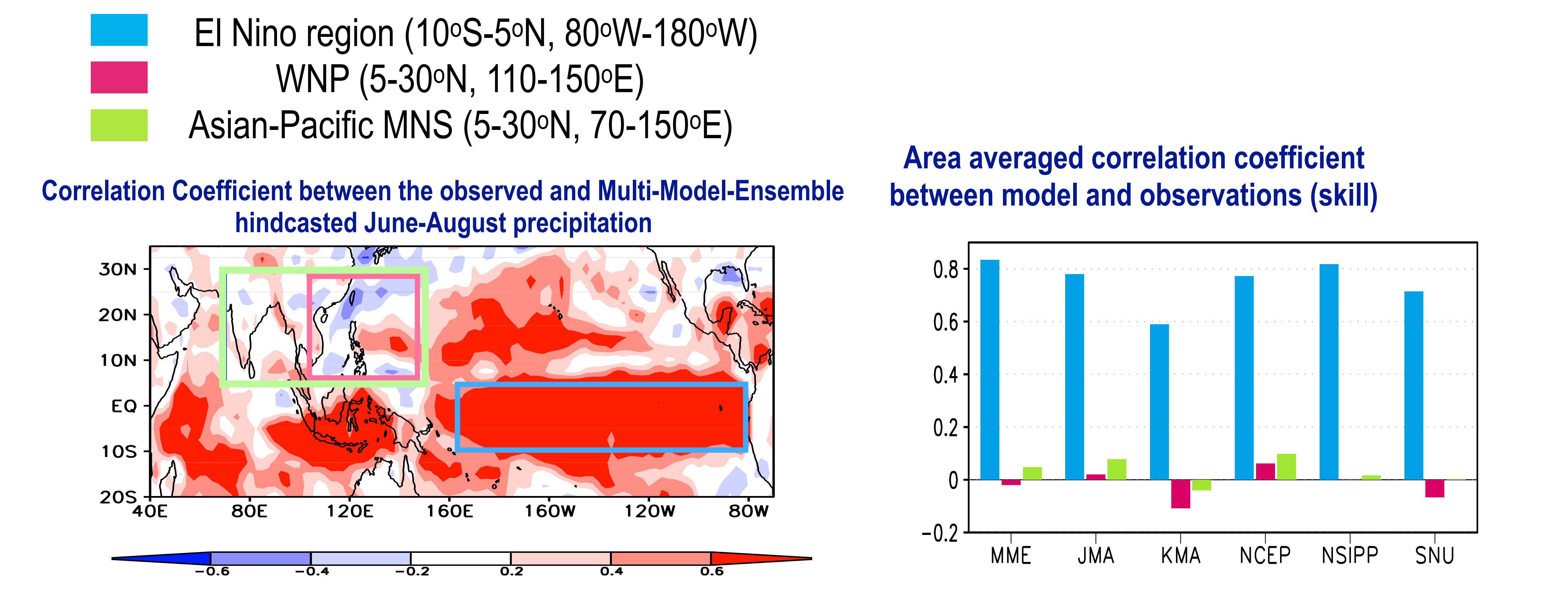


- Highest per capita impact of oceanic influence
- Largest human susceptibility to climate change.

Motivation for ASIRI

- Almost a third of the world's population depends on the South Asian Monsoon for water
- Climate models have difficulty in predicting the monsoons, particularly their sub-seasonal variability (active/break periods).
- The ocean supplies heat and moisture for the monsoon. Role of oceans is important, but in coupled models SST is too cold.
- Upper ocean structure, physical processes, and air-sea interaction affect the SST.
- The Bay of Bengal is strongly affected by freshwater from the monsoons. How does this modify oceanic processes?

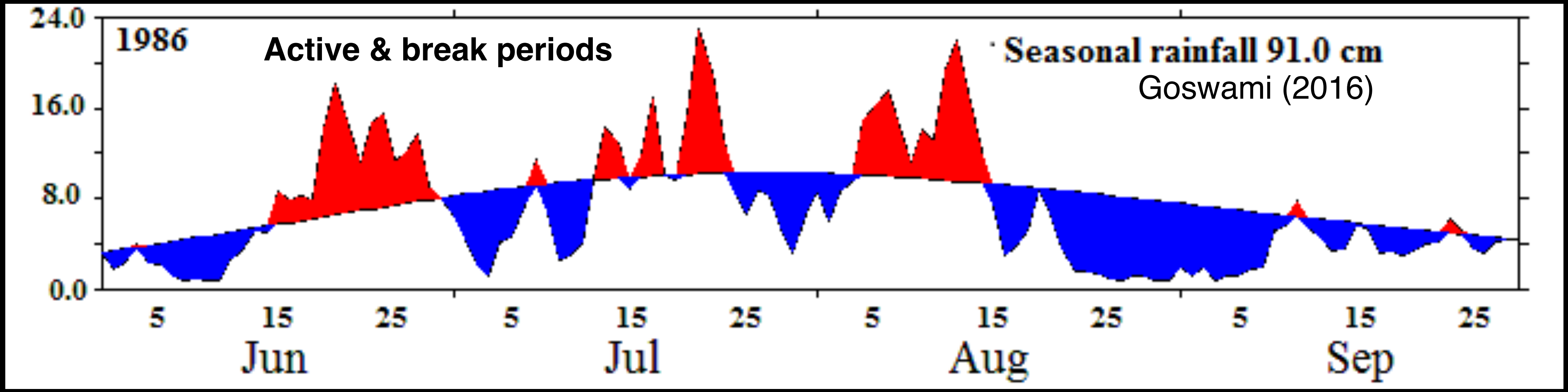
While forecast skill for precipitation is good for El-Nino region, it is very poor for the Asia-Western Pacific!



(Bin Wang, *et al.* 2005)

- ➡ Coupling of upper ocean with lower atmosphere is key to better prediction of tropical storms in this region.
- ➡ ONR motivation: Safety of ships at Sea, Active-Break periods of the Monsoon impact wave forecasts
- ➡ India MoES motivation: Better characterization of air-sea interaction is important to improve Monsoon forecasts

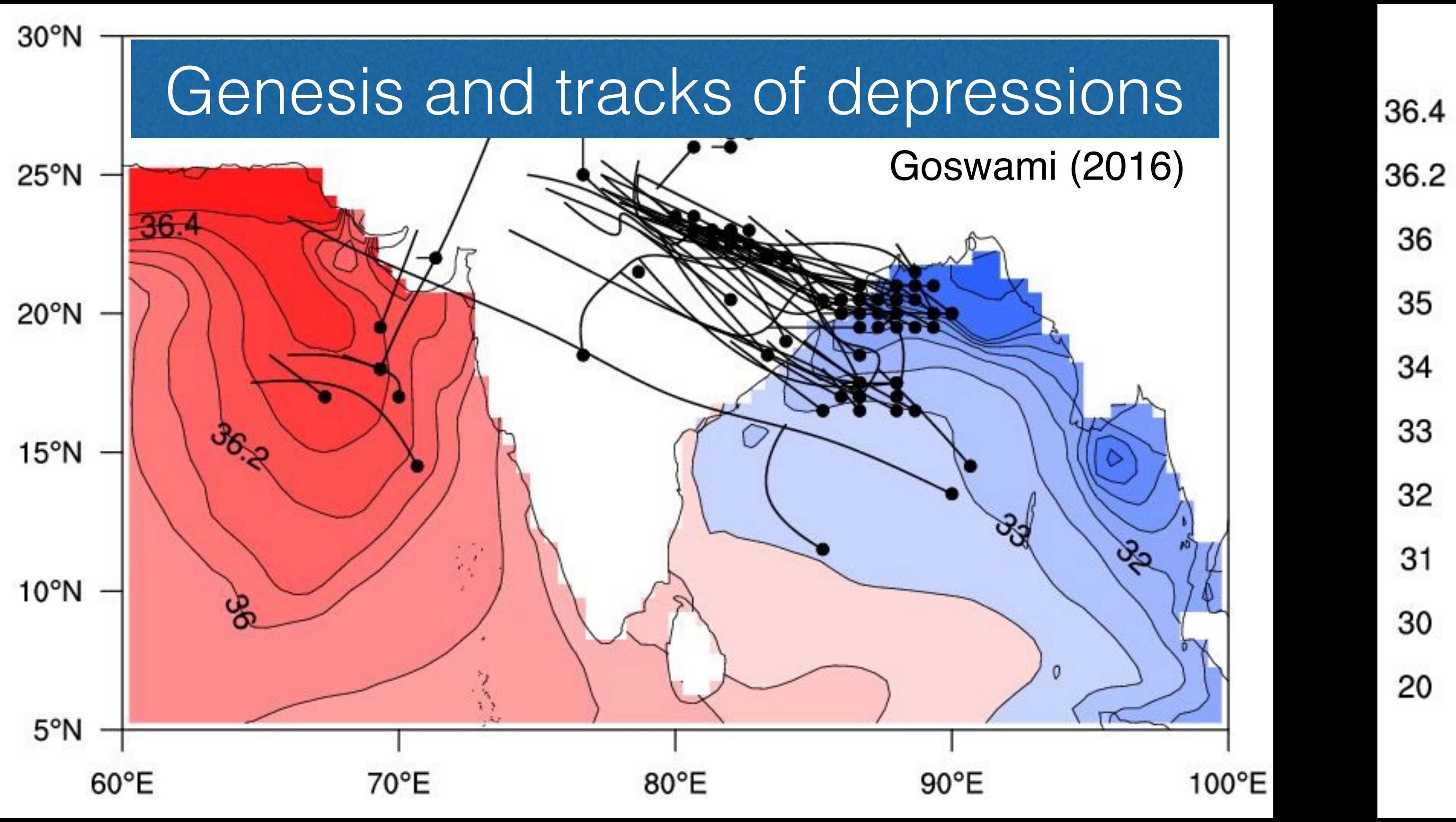
Monsoons: A challenge for prediction



1986 drought year

Why Bay of Bengal?

Why North Bay?



Weakness of coupled forecast models

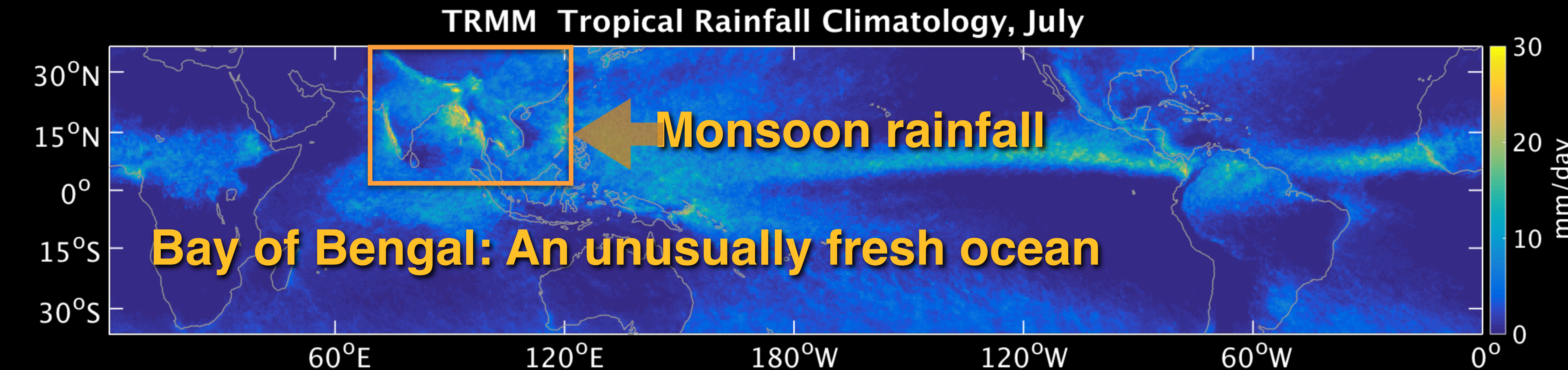
- Ocean is poorly represented
- Sea surface too cool, stratification weak
- Intra-seasonal variability not captured

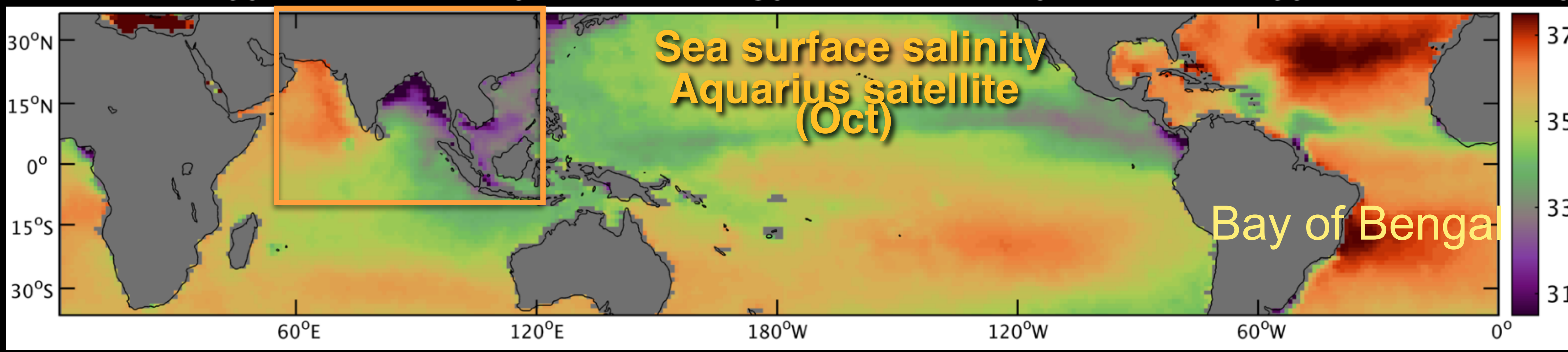
Ocean: What is affecting the monsoon forecasts?

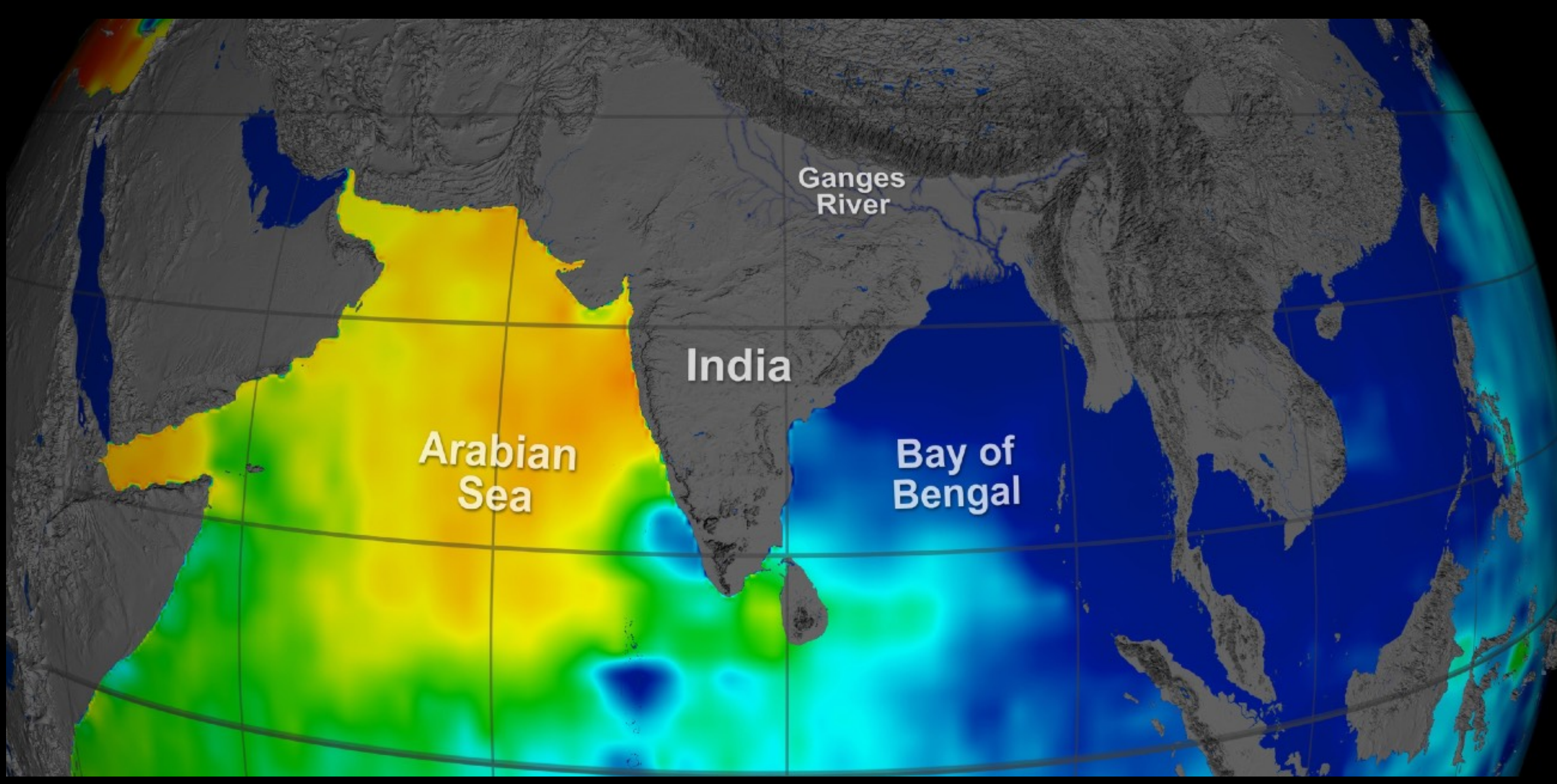
(1) Poorly known air-sea fluxes in the Bay.

(2) Unique ocean response, mixing and boundary layer physics in the region is not well understood and not captured by GCMs.

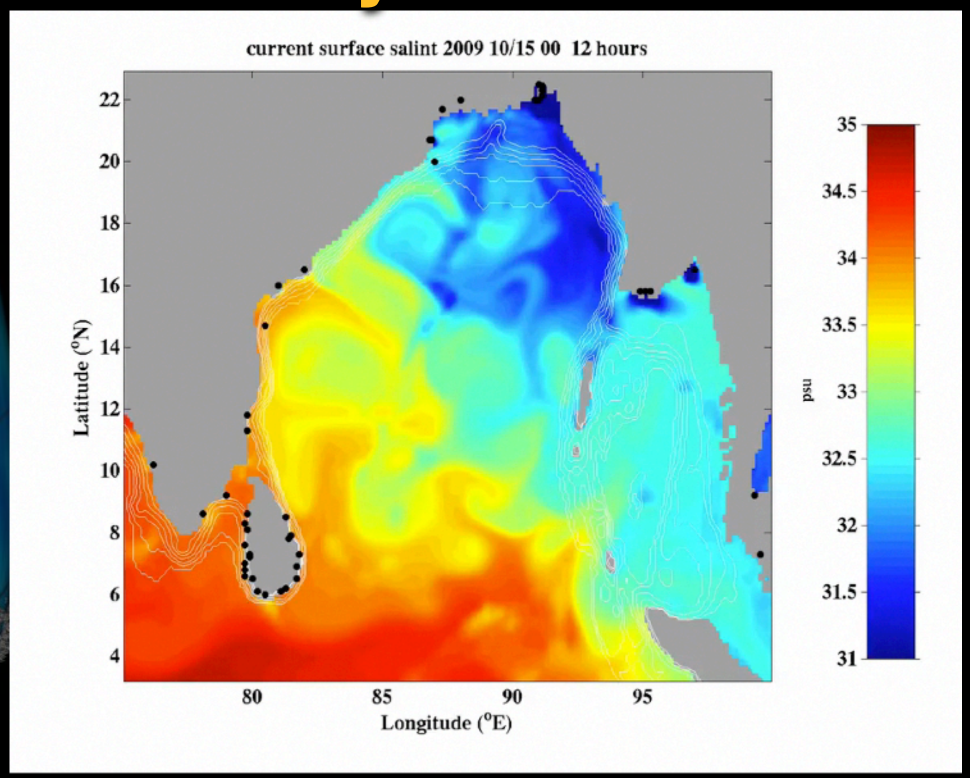
(Collection of papers by IITM Pune 2016)





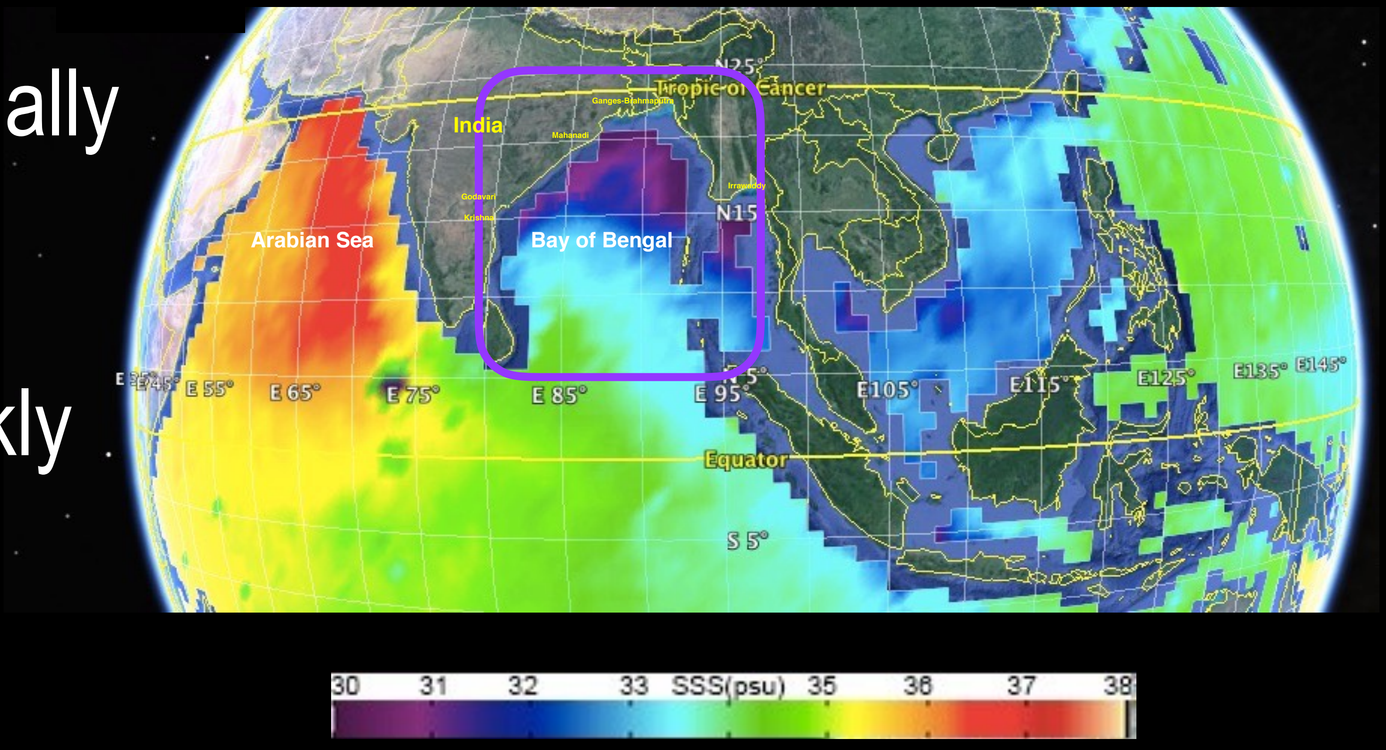


Salinity: NRL Model

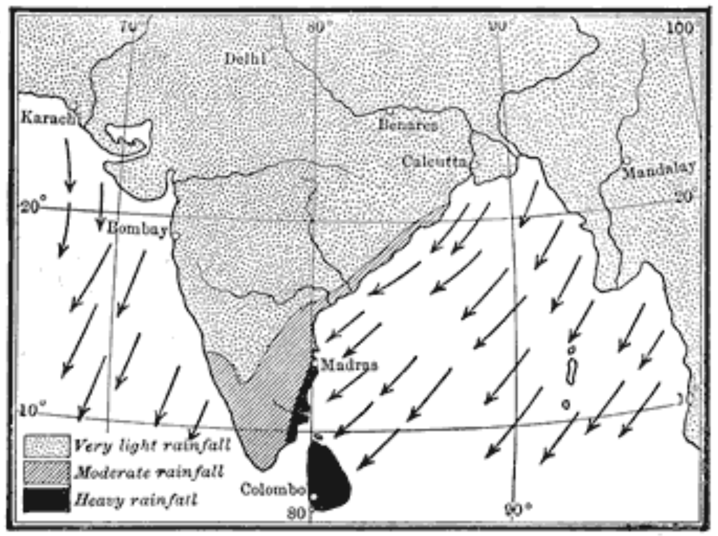


Bay of Bengal - anomalous ocean

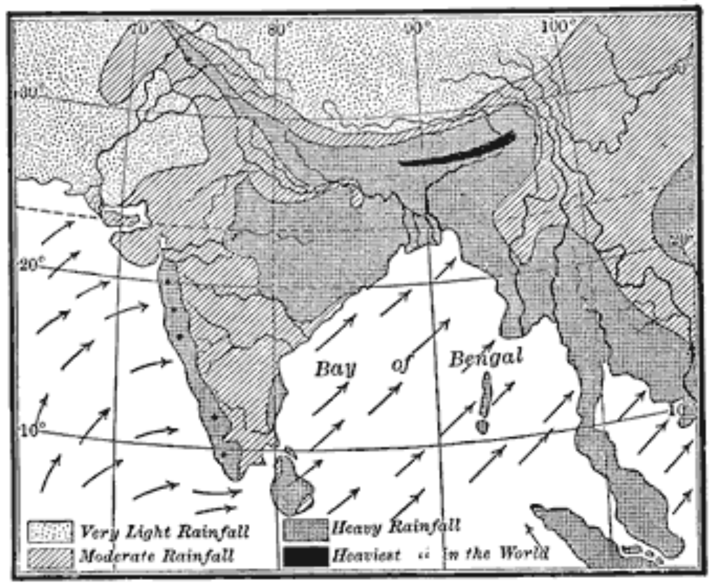
- Winds & Circulation reverse seasonally
- Extremely fresh
- Highly stratified, poorly ventilated
- Warm surface - SST responds quickly
- Air-sea fluxes ↗ FW runoff
- Oxygen minimum zone



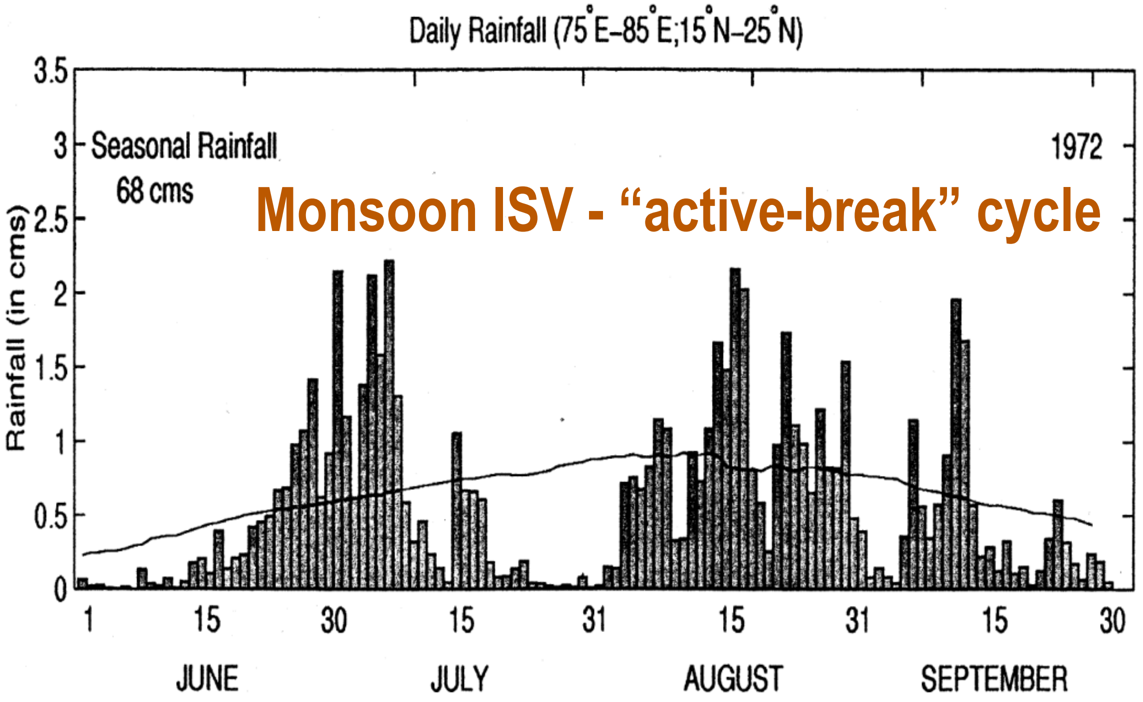
Surface salinity from the Aquarius satellite, Fall 2013



WINTER MONSOON WINDS



SUMMER MONSOON WINDS

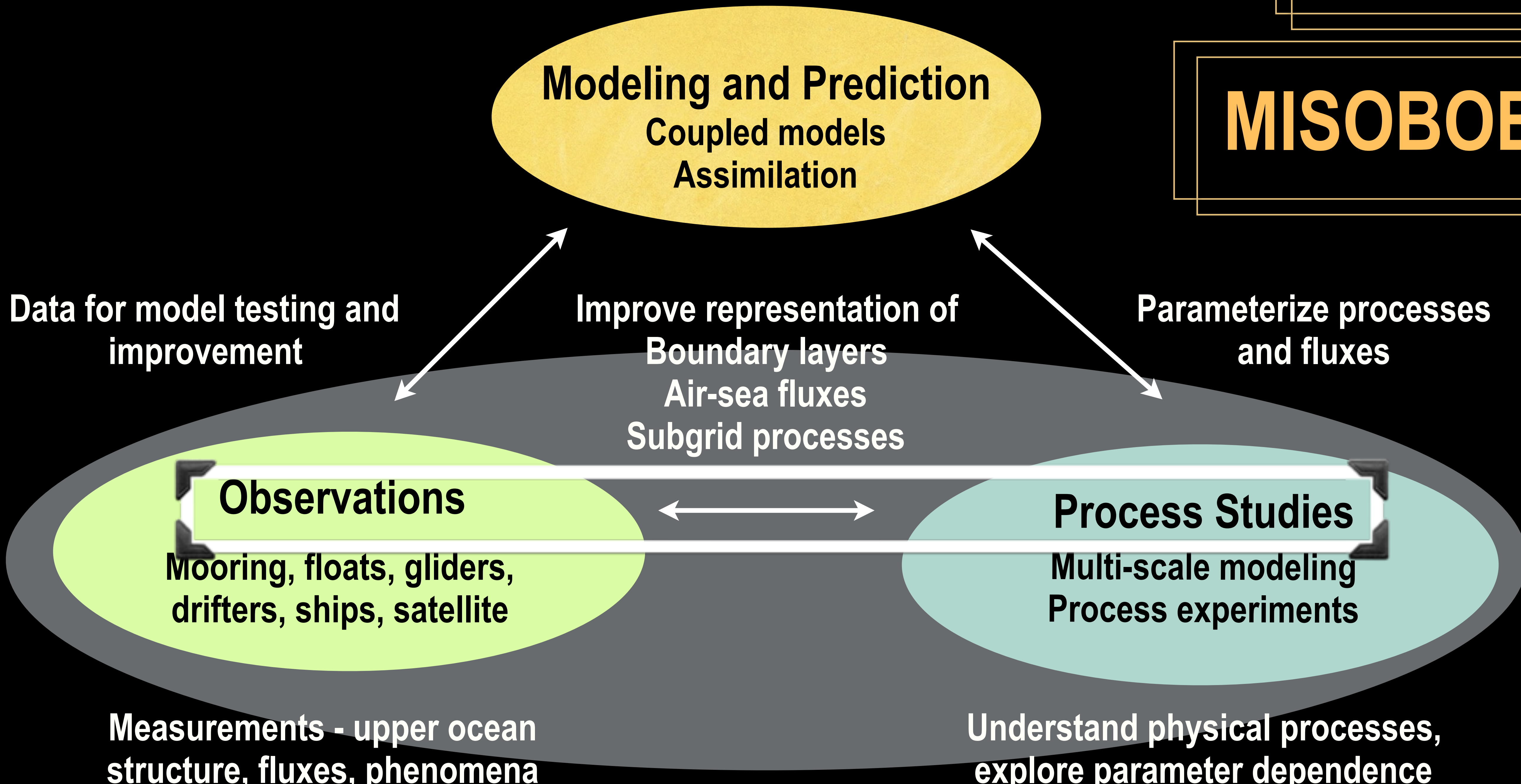


What sort of program ?

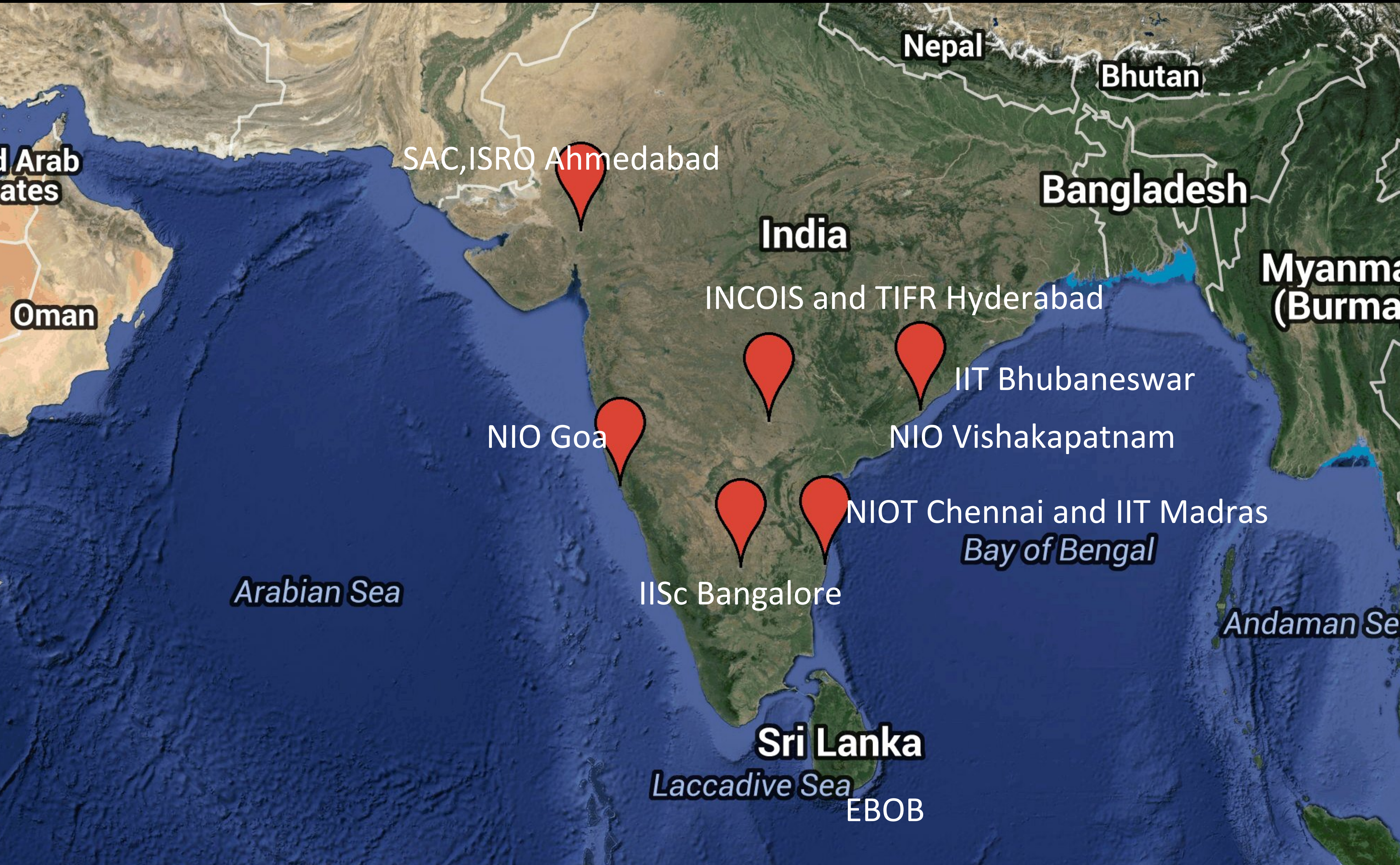
Toward improving the monsoonal forecast

ASIRI

MISOBOB



10 USA Institutions (about 20+ US PIs) and 8 Indian institutions (10+ Indian PIs) collaborating



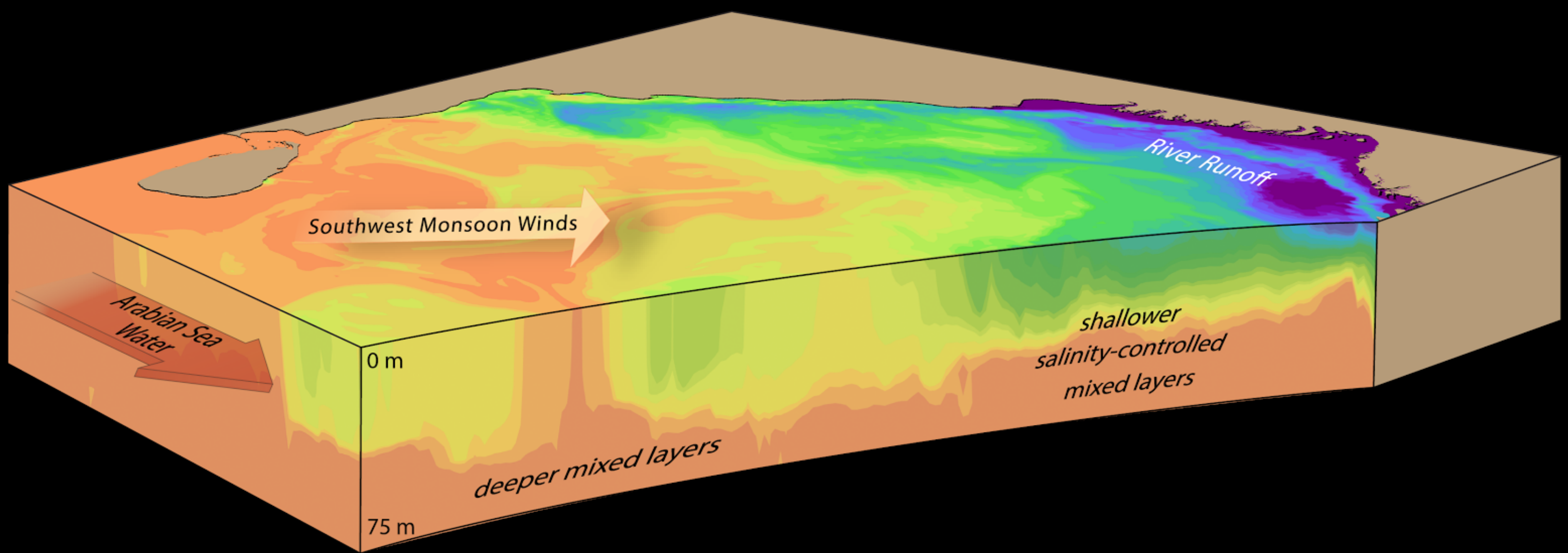
ASIRI – OMM: Observations Begin!

ASIRI

- Nov-Dec 2013.
  - Survey and **Process Experiment 1**: R/V Revelle with US and Indian teams; Cruise on Nidhi with Indian and US scientists
- **2014:**
  - Survey and Process Experiment 2: Pre-Monsoon observations with Indian scientists in international waters (June, R/V Revelle Chennai Port call)
  - July: Summer Workshop on Upper Ocean Physics in the Bay of Bengal; August 2014.
  - August: R/V Nidhi Monsoon cruise with Indian and US scientists
  - Nov.-Dec.: Flux mooring deployment from R/V Nidhi
- August-September 2015. Survey and Process Experiment 3: SW Monsoon Intensive Observational Period on US R/V Revelle and Indian ships.

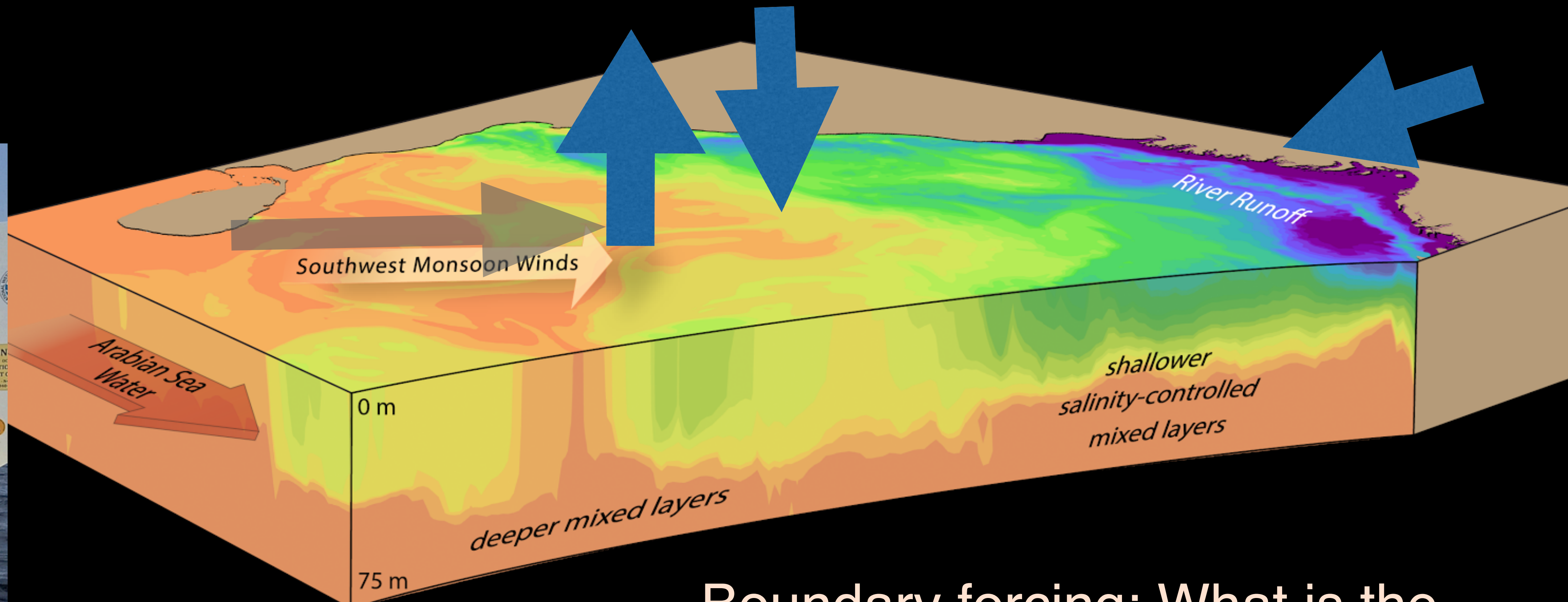
ASIRI: OBJECTIVES

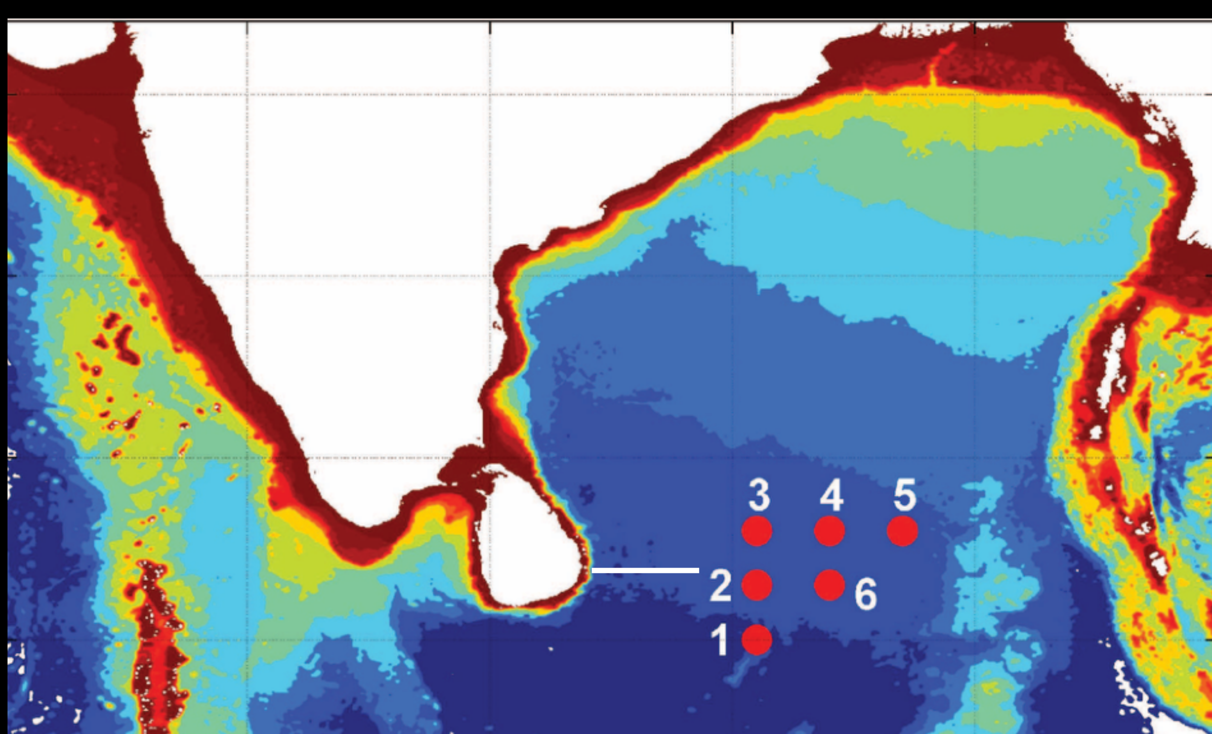
What is the role of freshwater and seasonality of forcing on the upper ocean structure and circulation of the Bay of Bengal?



1. Boundary forcing: What is the variability in air-sea flux and boundary inputs? How are they affected by (and affect) freshwater distribution? Will accurate boundary fluxes improve forecasting of upper ocean structure and evolution?
2. How are physical processes, such as 1-d wind-driven mixing, Ekman transport, mesoscale circulation (nominally already included in models) playing out in unusual ways here?
3. What sets the stratification (submesoscale mixing and/or re-stratification, episodic events like strong cyclones, internal wave breaking, or others) ?

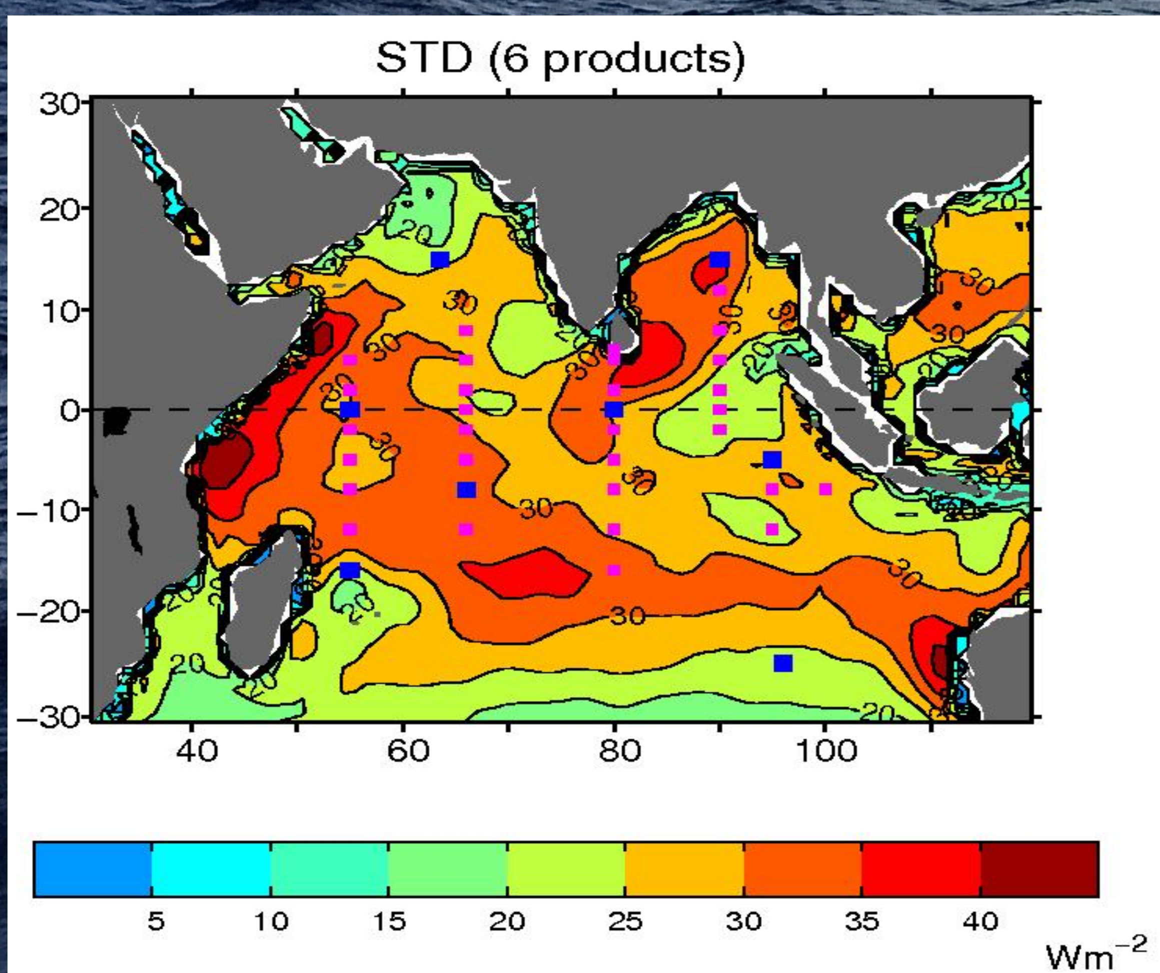
ASIRI: OBJECTIVES - 1





Boundary forcing: What is the variability in air-sea flux and boundary inputs? How are they affected by (and affect) freshwater distribution? Will accurate boundary fluxes improve forecasting of upper ocean structure and evolution?

Need for benchmark measurements of air-sea fluxes



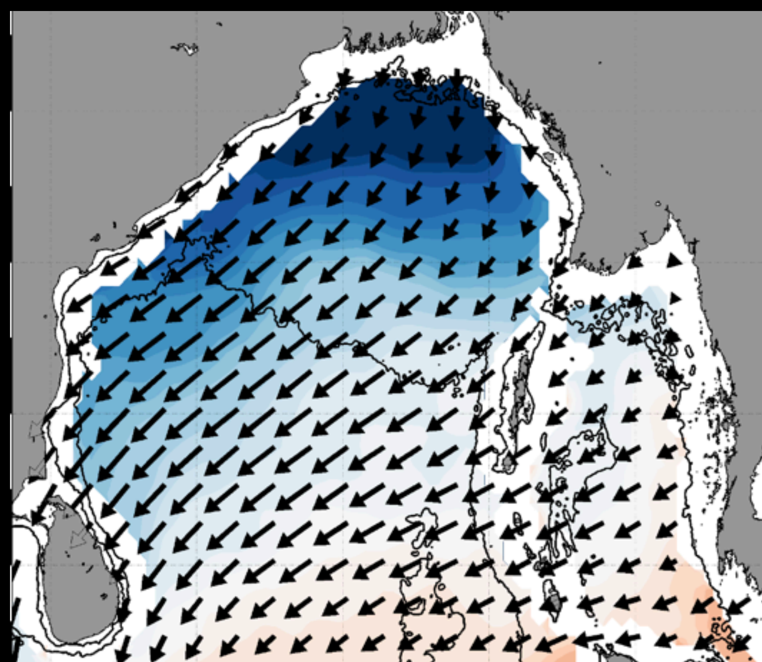
Lack of agreement in air-sea fluxes from different reanalysis products.

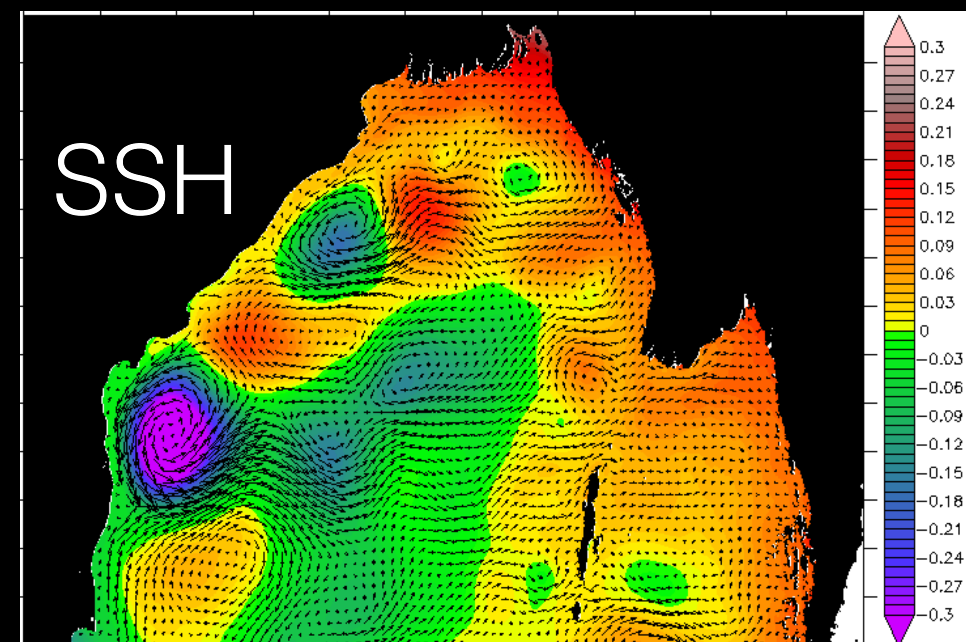
ASIRI: OBJECTIVES - 2

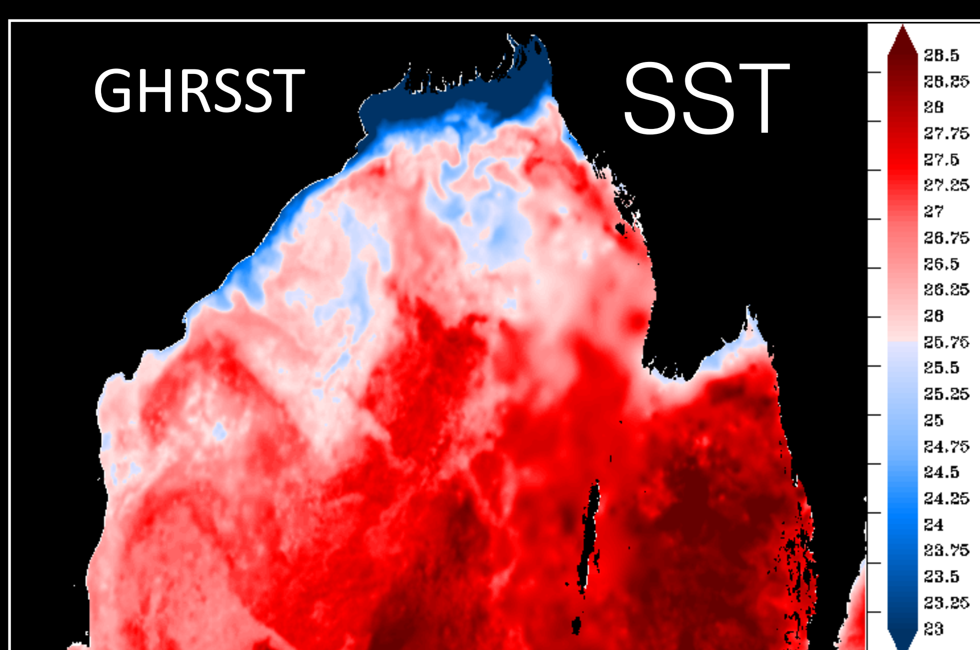
How are physical processes, such as 1-d wind-driven mixing, Ekman transport, mesoscale circulation (nominally already included in models) playing out in unusual ways here?

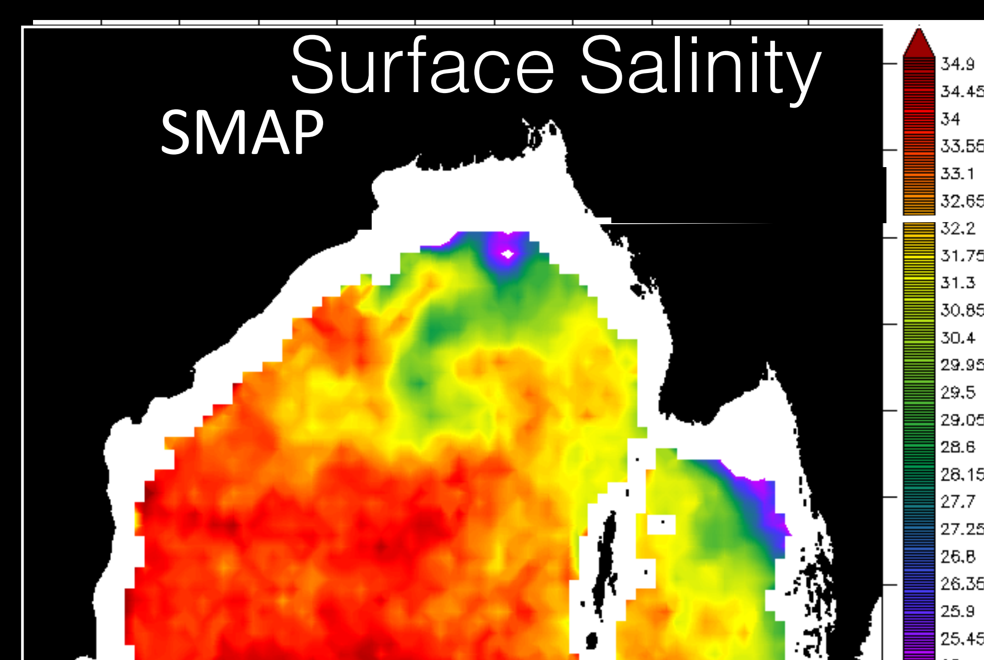
Winds

Winter







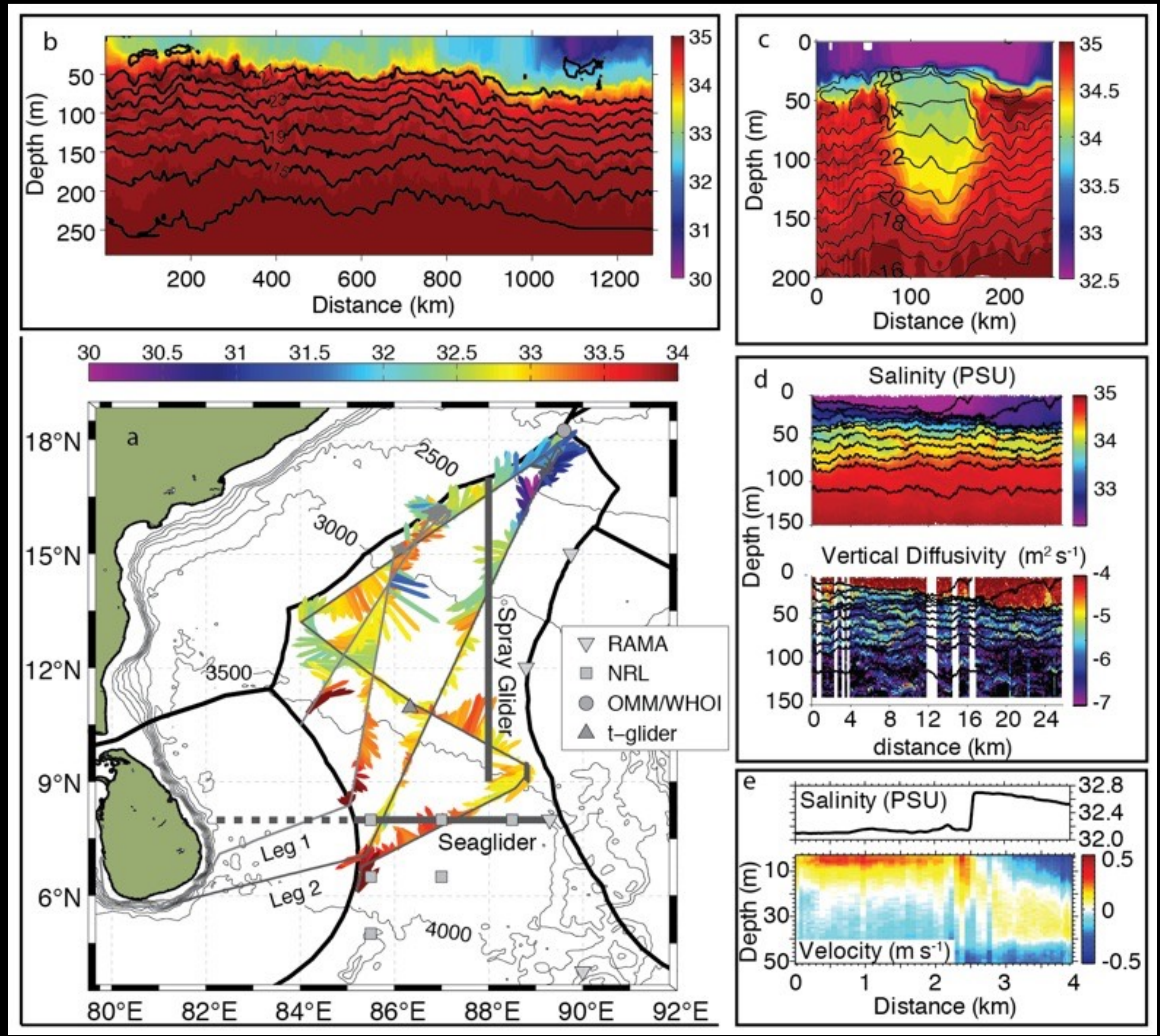


Sarma et al.

Observational Focus- Mapping the full-scale of Physical Processes at work in the Bay of Bengal

Instrumental & Observational Challenge

Our approach integrating moored time series, autonomous assets, & shipboard surveys with state of the art instrumentation



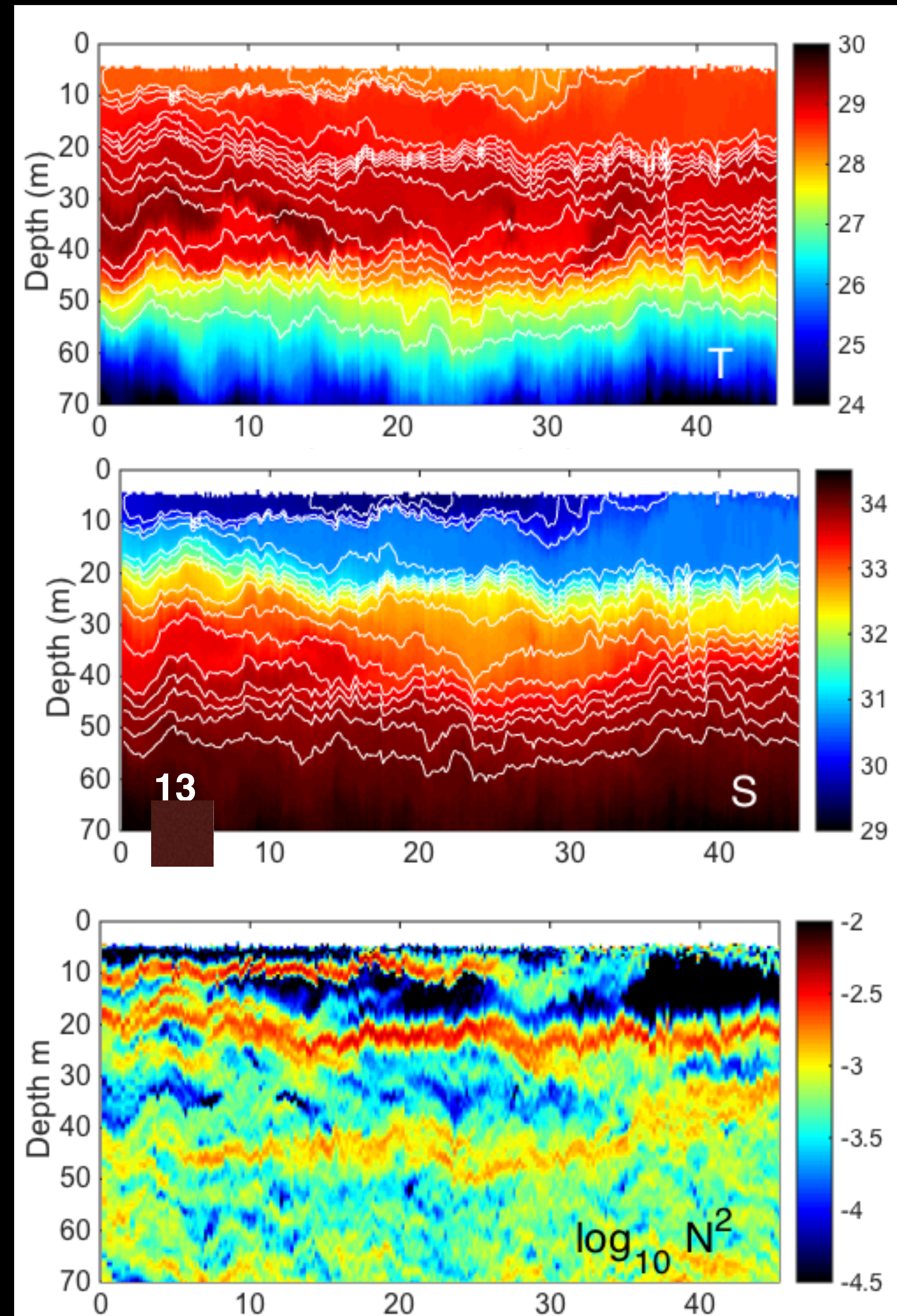
ASIRI: OBJECTIVES - 3

What sets the stratification (submesoscale mixing and/or re-stratification, episodic events like strong cyclones, internal wave breaking, or others) ?

T

S

N^2



Distance along track

ASIRI

Science Results: What we have learned? What improvements are possible for weather and ocean forecasting?

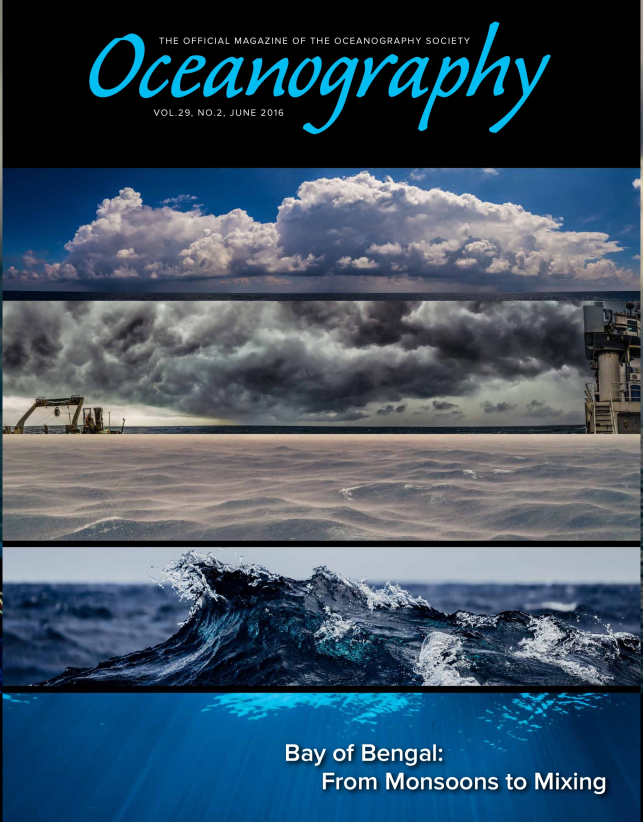
A. Large pools of sub-surface warm water in Barrier layers.

B. Microstructure and scalar mixing in the BoB.

C. What air-sea flux variations prediction models are missing - and why.

D. Interplay of mesoscale eddies, wind and the freshwater from rivers sets the multiple stratification layers.

E. Unprecedented near-surface process observations near fronts



ASIRI 2013-2017: Outcomes with International Collaboration in the region

MISO-BOB 2017-2021

Long term observatory

- Air-sea flux measurements + solar input
- Test bulk formulae, improve models
- Upper ocean vertical structure

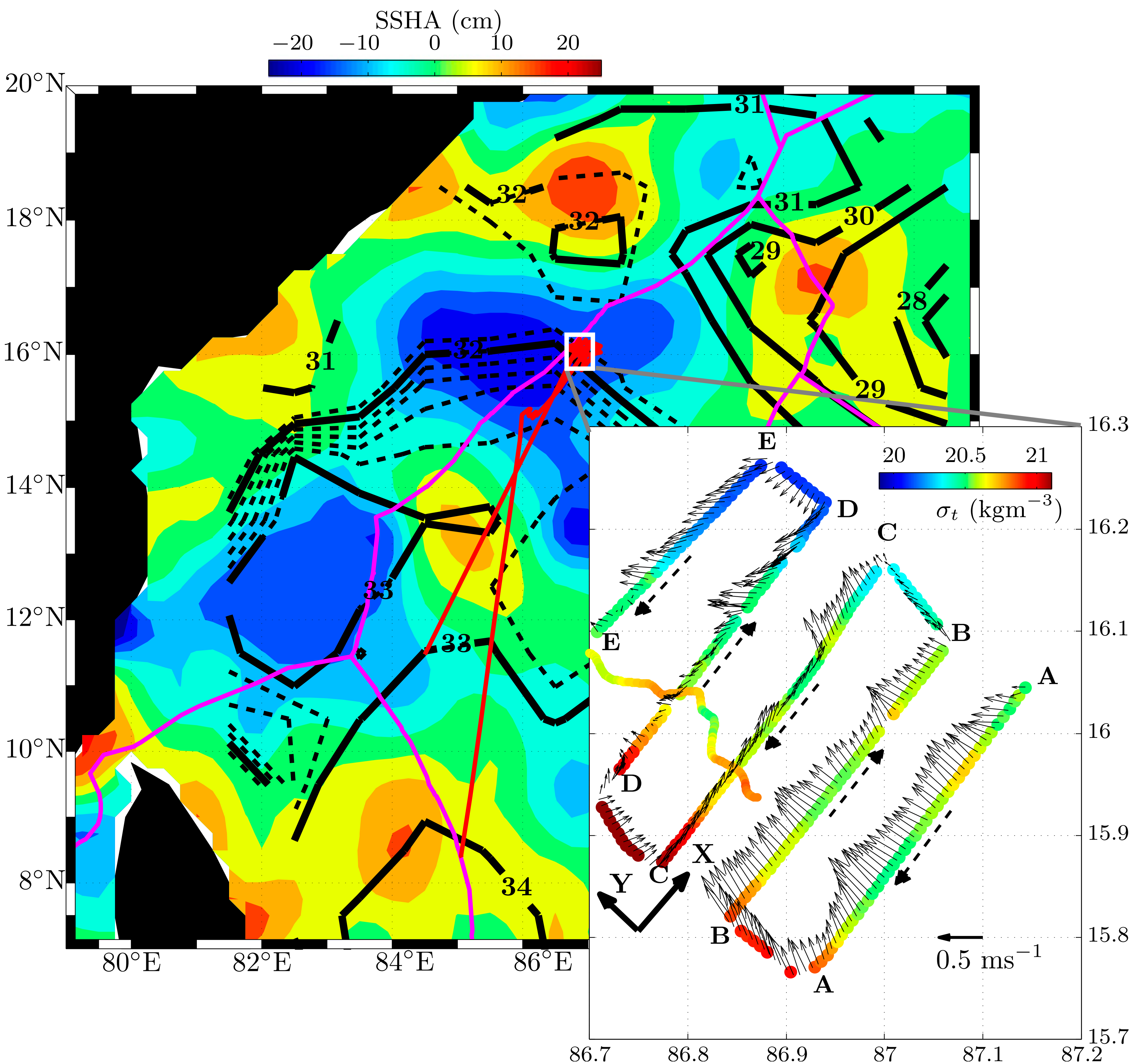
Measure mixing rates

- Relate to air-sea fluxes and stratification
- Test and improve parameterizations
- Improve upper ocean structure in models

Process modeling

- Understand freshwater dispersal mechanisms
- Understand mixing processes
- Estimate advection - test for seasonal variations

Central Bay Process Study: Nov, 2013



Aquarius salinity
+
CCAR SSHA

Mesoscale strain (OSCAR) ~ 0.15 f

0-10 m averaged potential density

UCTD resolution: 0.7-1.0 km
Duration of transects: 4-6 hrs

Ramachandran, Tandon *et al.* March 2018 JPO

Ramachandran, Tandon *et al.* March 2018 JPO

ADCP

Waterhouse

Lucas

Pinkel

Mackinnon

Wirewalker

Analysis

Ramachandran

Tandon

Shroyer

Weller

UCTD

Met. data

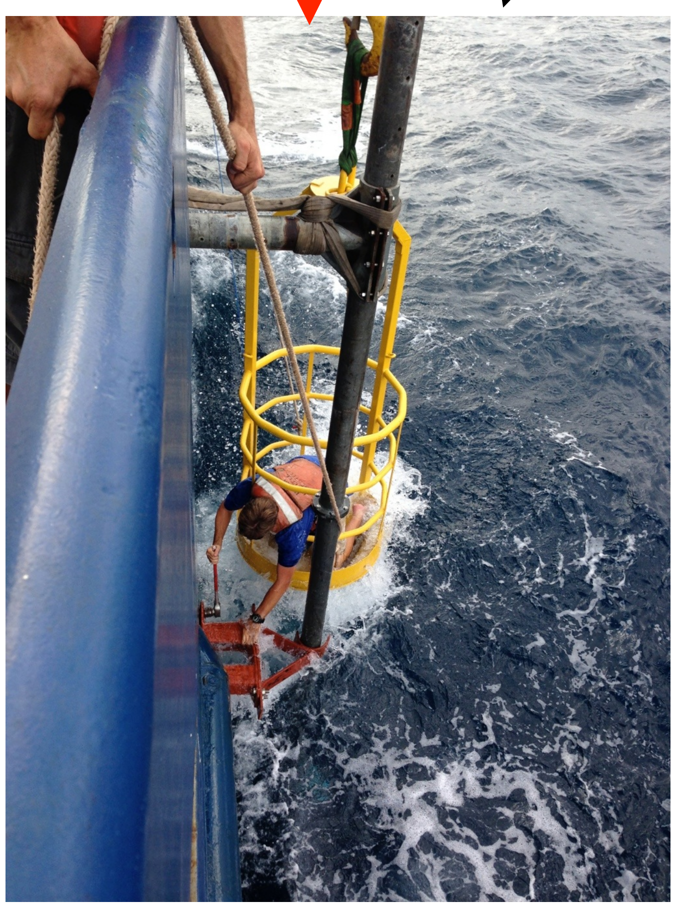
Nash

Farrar

Mahadevan

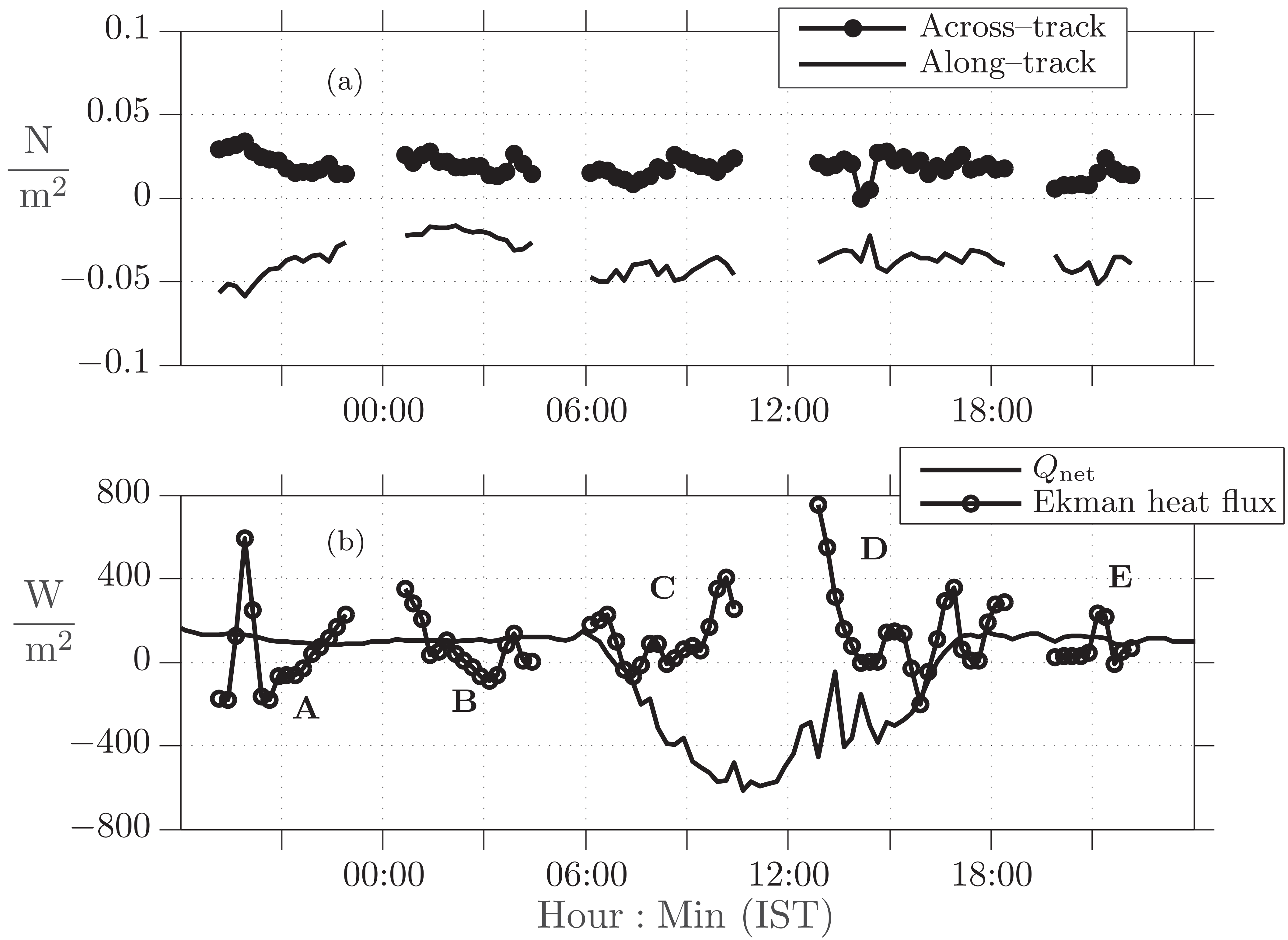
Measurements used in this study

- Underway CTD
- Standard shipboard through flow T & S
- Permanent sonars on the ship (4)
  - Side-pole ADCP + Pipestring ADCP

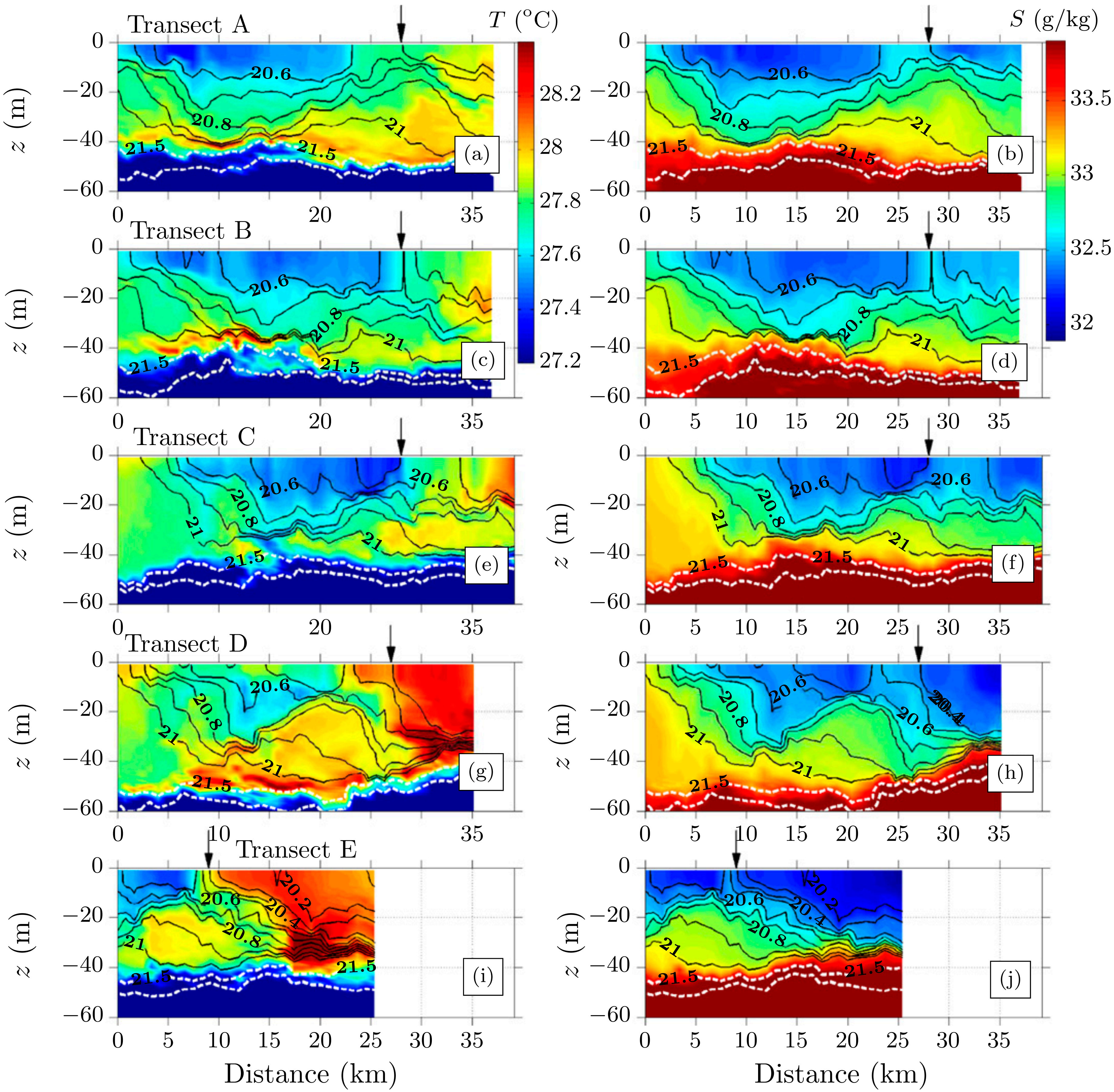


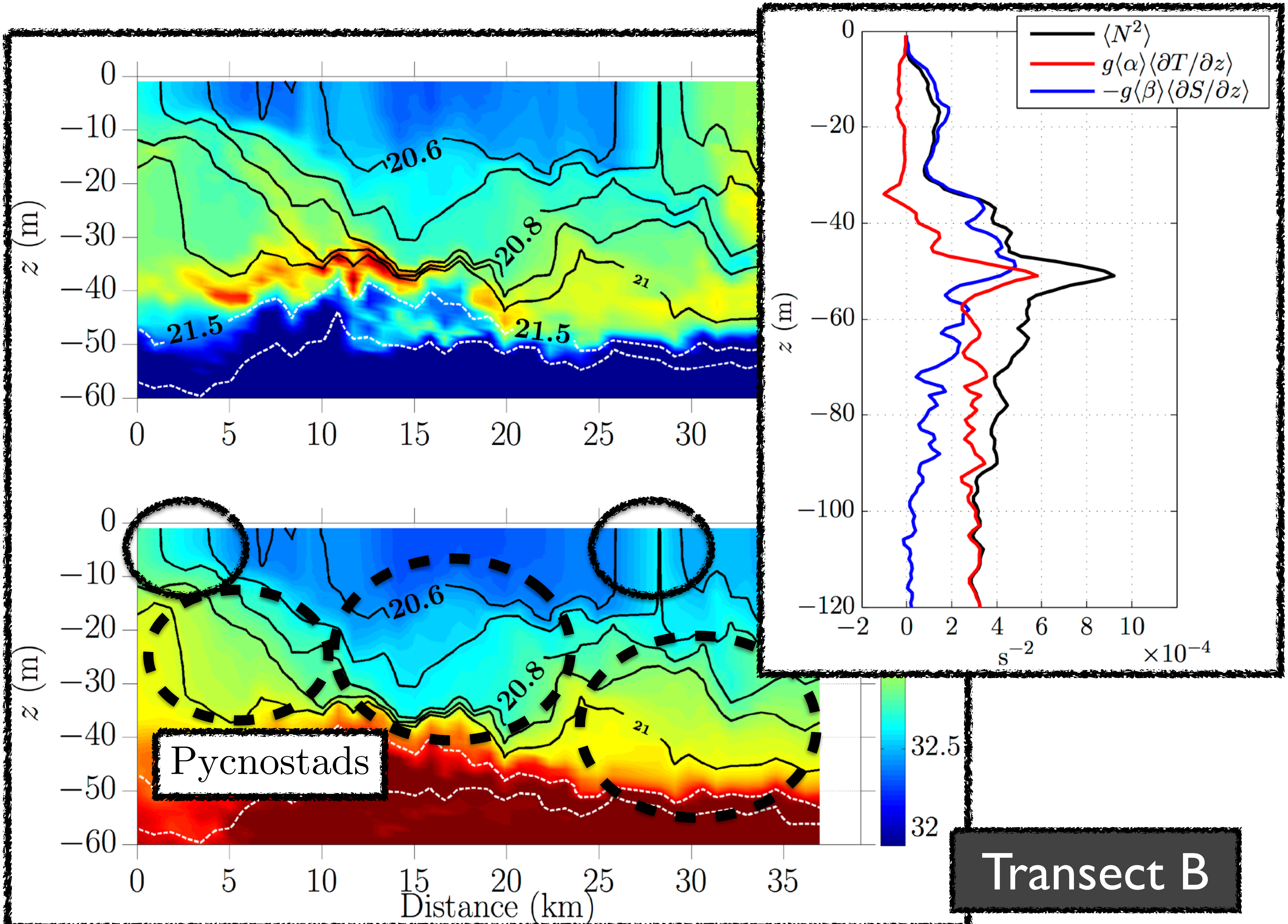
- Wirewalker
- Shipboard met. data

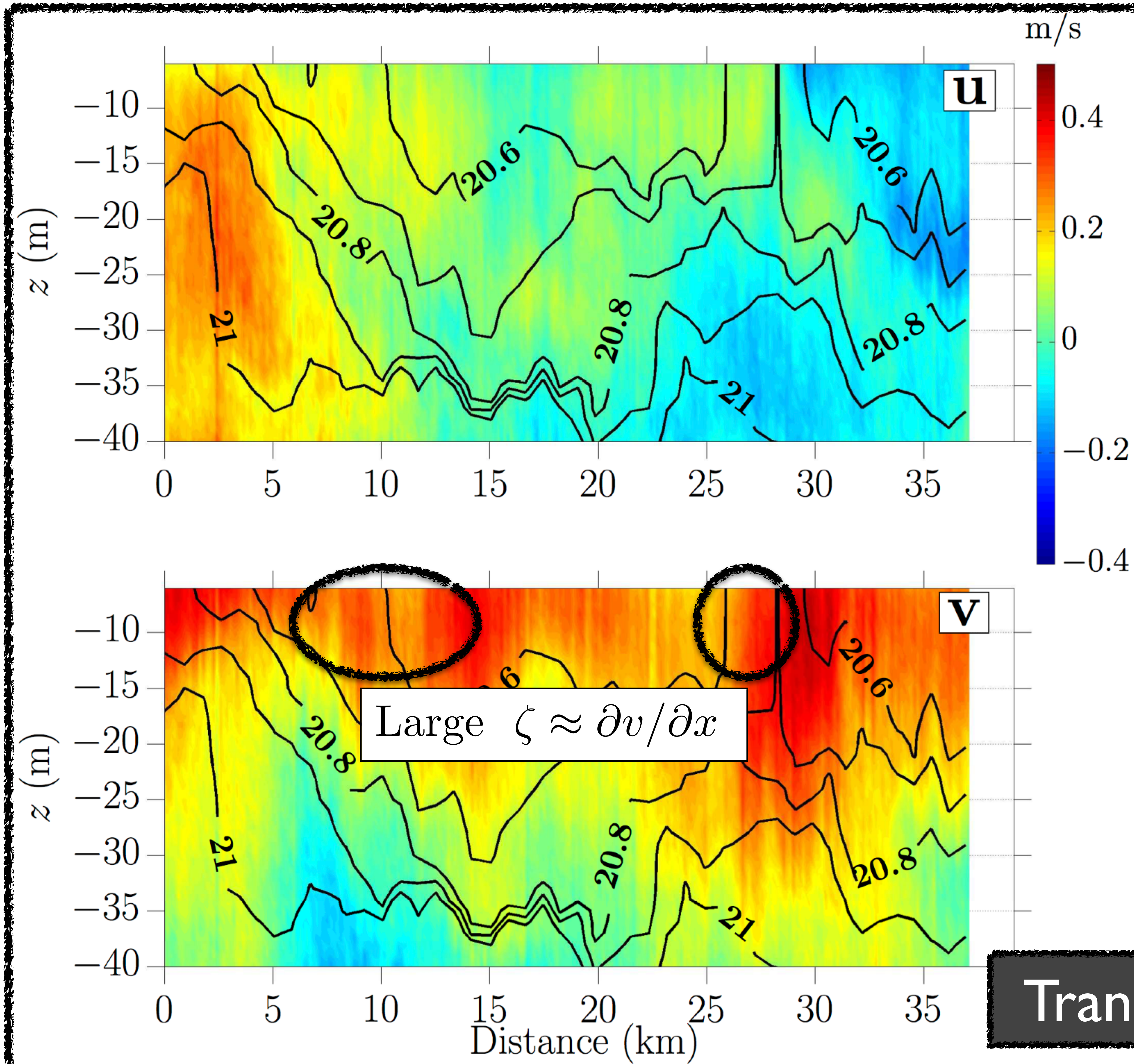
Surface Forcing



T and S sections for each of the transects

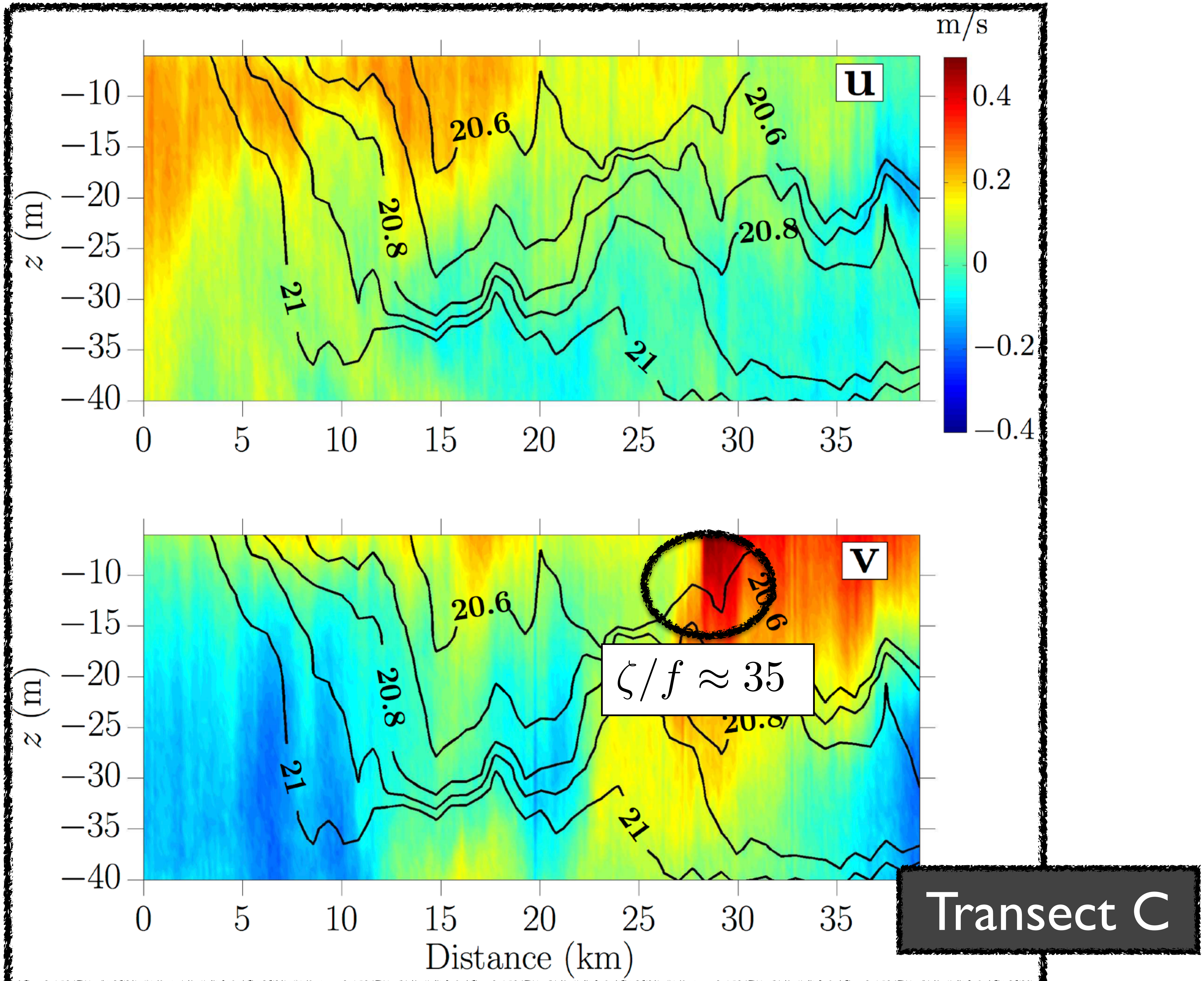



Pycnostads
Transect B
20.6
20.8
21
21.5
z (m)
Distance (km)
32.5
32
⟨N²⟩
g⟨α⟩⟨∂T/∂z⟩
−g⟨β⟩⟨∂S/∂z⟩
s⁻²
×10⁻⁴

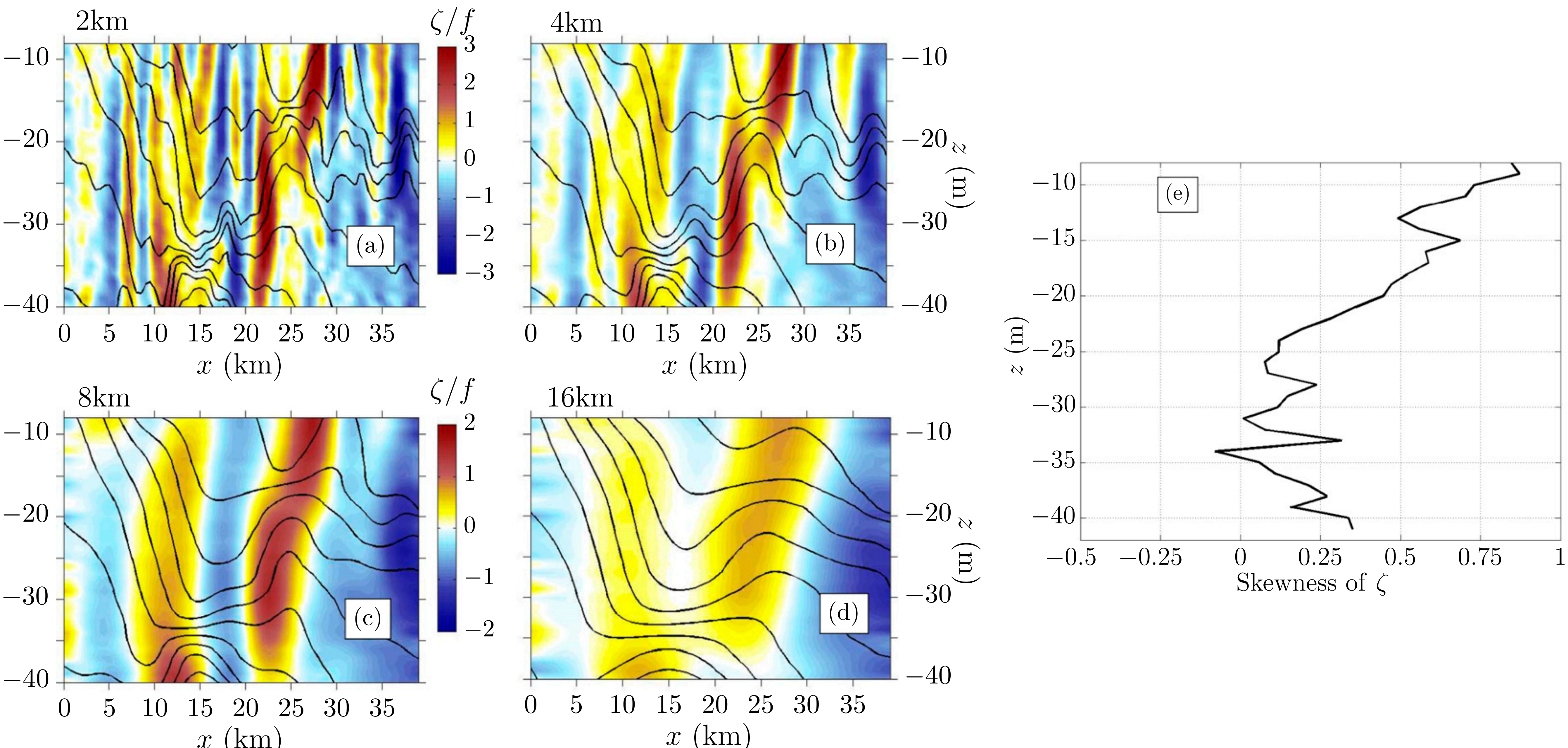


u
v
m/s
Large $\zeta \approx \partial v/\partial x$
z (m)
Distance (km)
20.6
20.8
21

Transect B


m/s
u
v
20.6
20.8
21
0.4
0.2
0
−0.2
−0.4
$\zeta/f \approx 35$
z (m)
Distance (km)
Transect C

Vorticity is O(f) with more structure emerging as scales get finer. Positively skewed



Transect C

Are these fronts in balance?

Geostrophy

For a linear regression model:

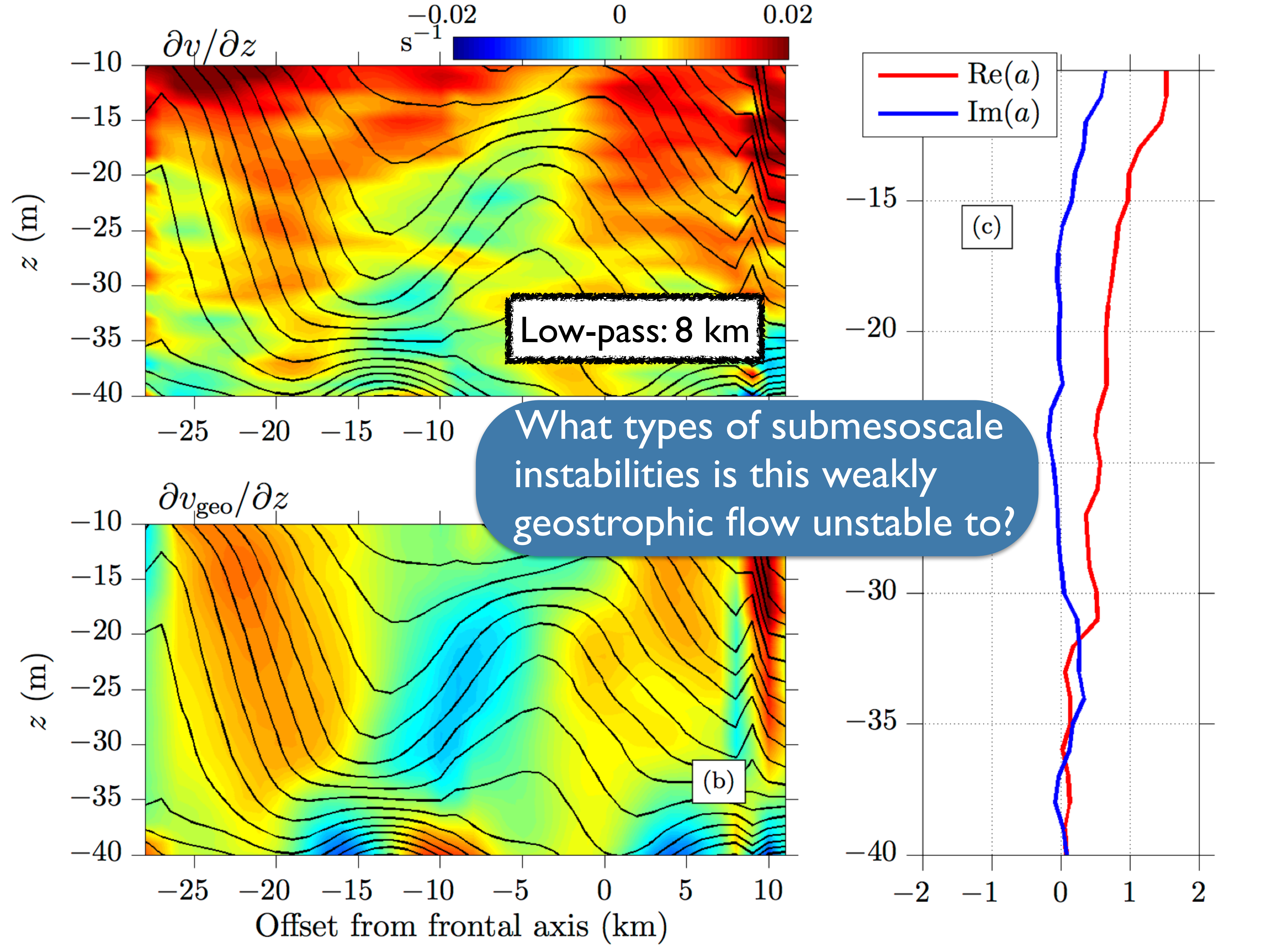
$$\widetilde{u}_z = a \, \frac{-ig}{f \rho_0} \, \nabla \rho$$

the smallest residual occurs when

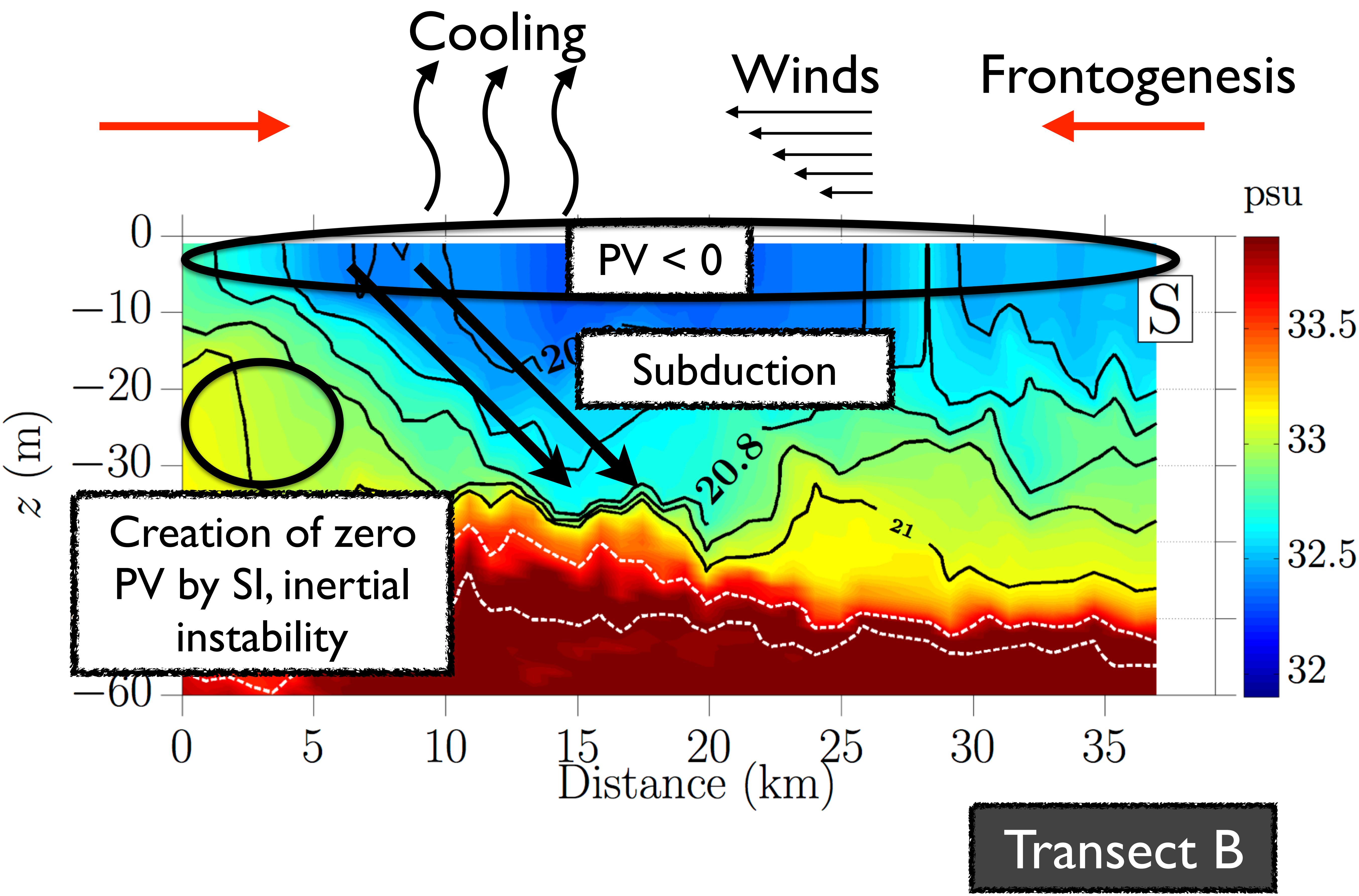
$$a = \frac{i f \rho_0}{g} \, \frac{\langle u_z \nabla \rho^* \rangle}{\langle \nabla \rho \nabla \rho^* \rangle}$$

For thermal-wind balance, $a = 1$

Rudnick and Luyten (1996)

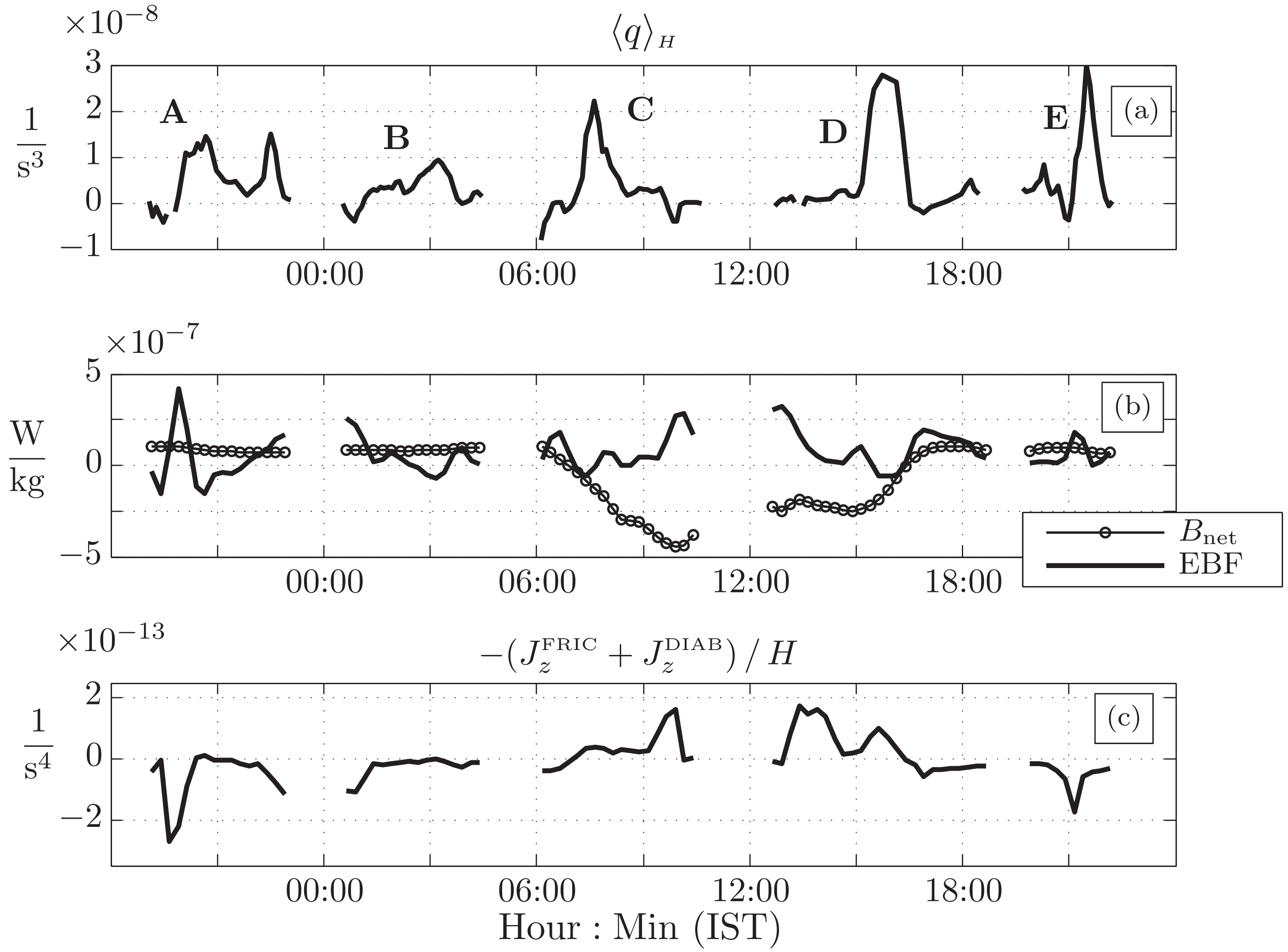


$\partial v/\partial z$
s^{-1}
−0.02
0
0.02
Low-pass: 8 km
z (m)
$\partial v_{\mathrm{geo}}/\partial z$
(b)
Offset from frontal axis (km)
Re(a)
Im(a)
(c)
What types of submesoscale instabilities is this weakly geostrophic flow unstable to?



Cooling
Winds
Frontogenesis
PV < 0
Subduction
Creation of zero PV by SI, inertial instability
S
psu
33.5
33
32.5
32
0
−10
−20
−30
−60
z (m)
0
5
10
15
20
25
30
35
Distance (km)
20.8
21
Transect B

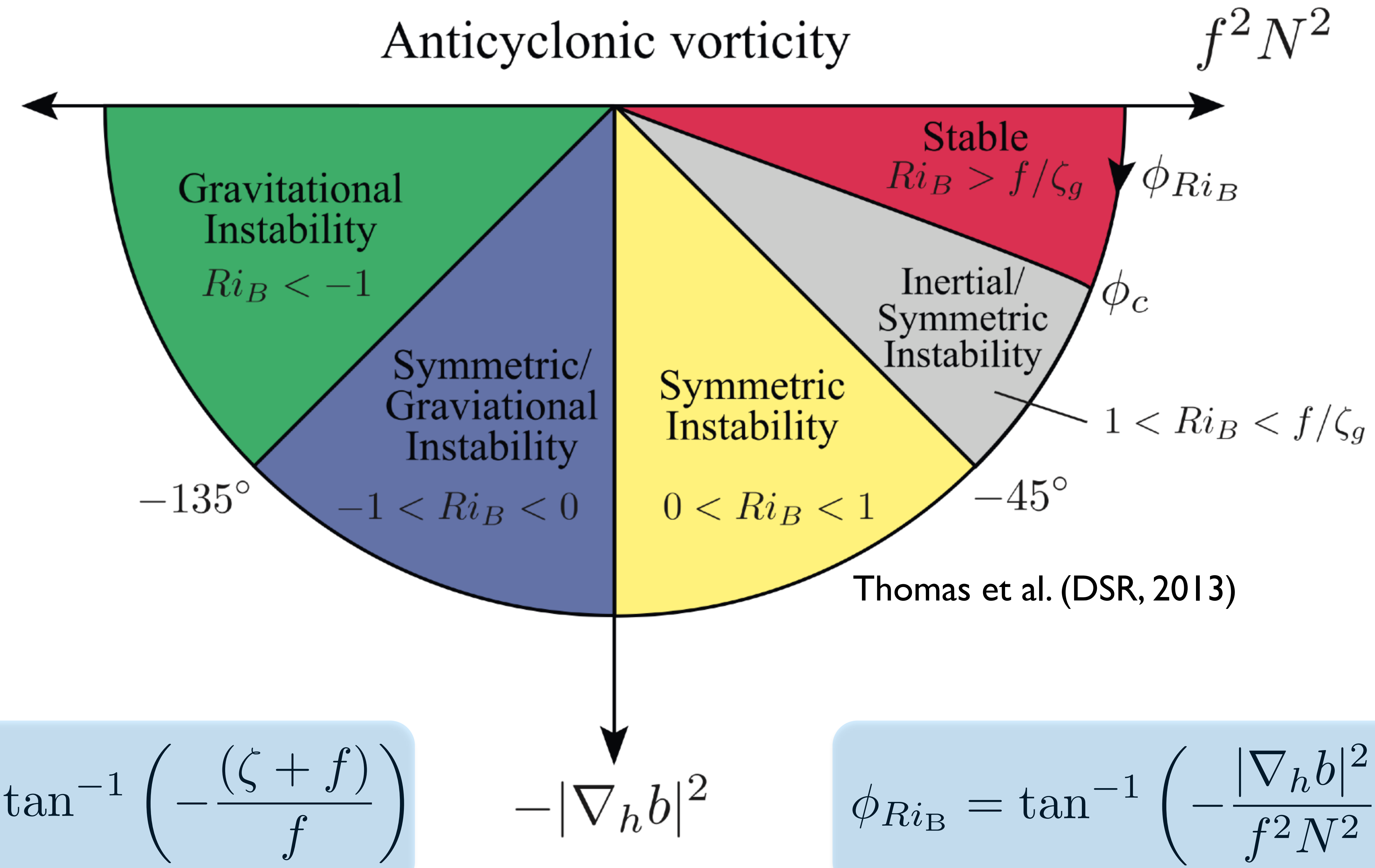
PV forcing and budget



$$\frac{\partial}{\partial t}\langle q\rangle_H = \frac{1}{H}\int_{-H}^{0}\frac{\partial q}{\partial t} = -\frac{1}{H}(J_z^{\mathrm{DIAB}} + J_z^{\mathrm{FRIC}})\Big|_{-H}^{0} - \frac{1}{H}(\ldots), \tag{8}$$

The changes in PV are large, and cannot be explained by surface forcing. These changes happen over a longer time scale than the survey (advected into the sampled volume)

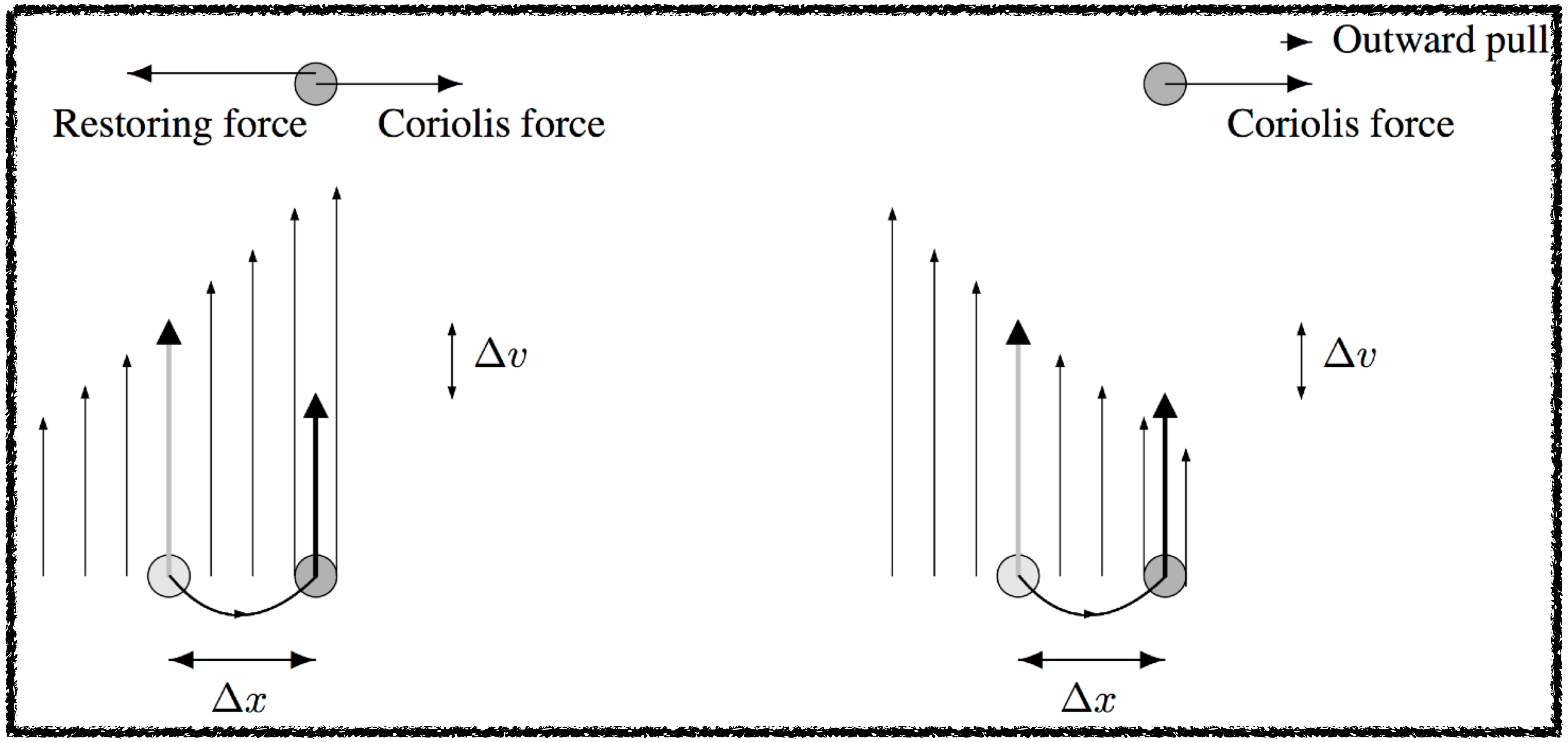
Potential instabilities when $fq < 0$



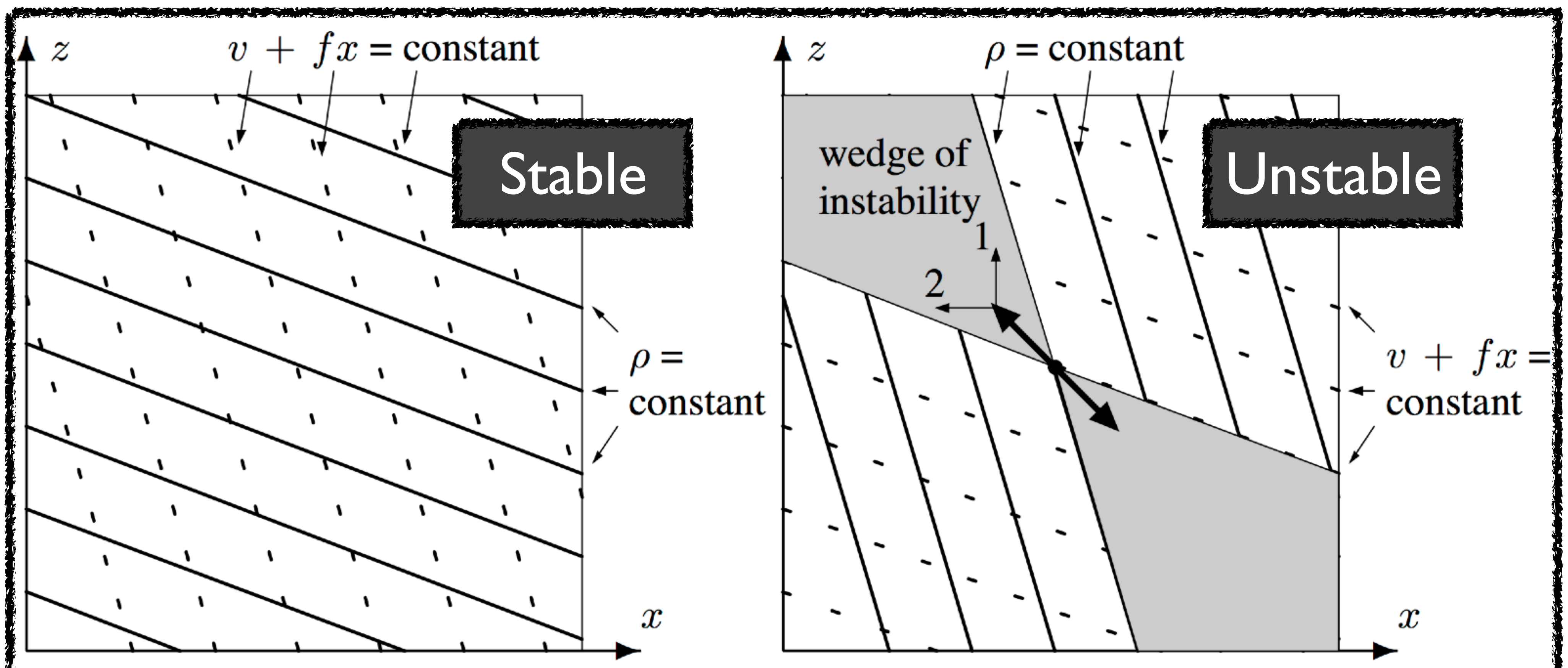
Thomas et al. (DSR, 2013)

$$\phi_c = \tan^{-1}\left(-\frac{(\zeta + f)}{f}\right)$$

$$\phi_{Ri_B} = \tan^{-1}\left(-\frac{|\nabla_h b|^2}{f^2N^2}\right)$$

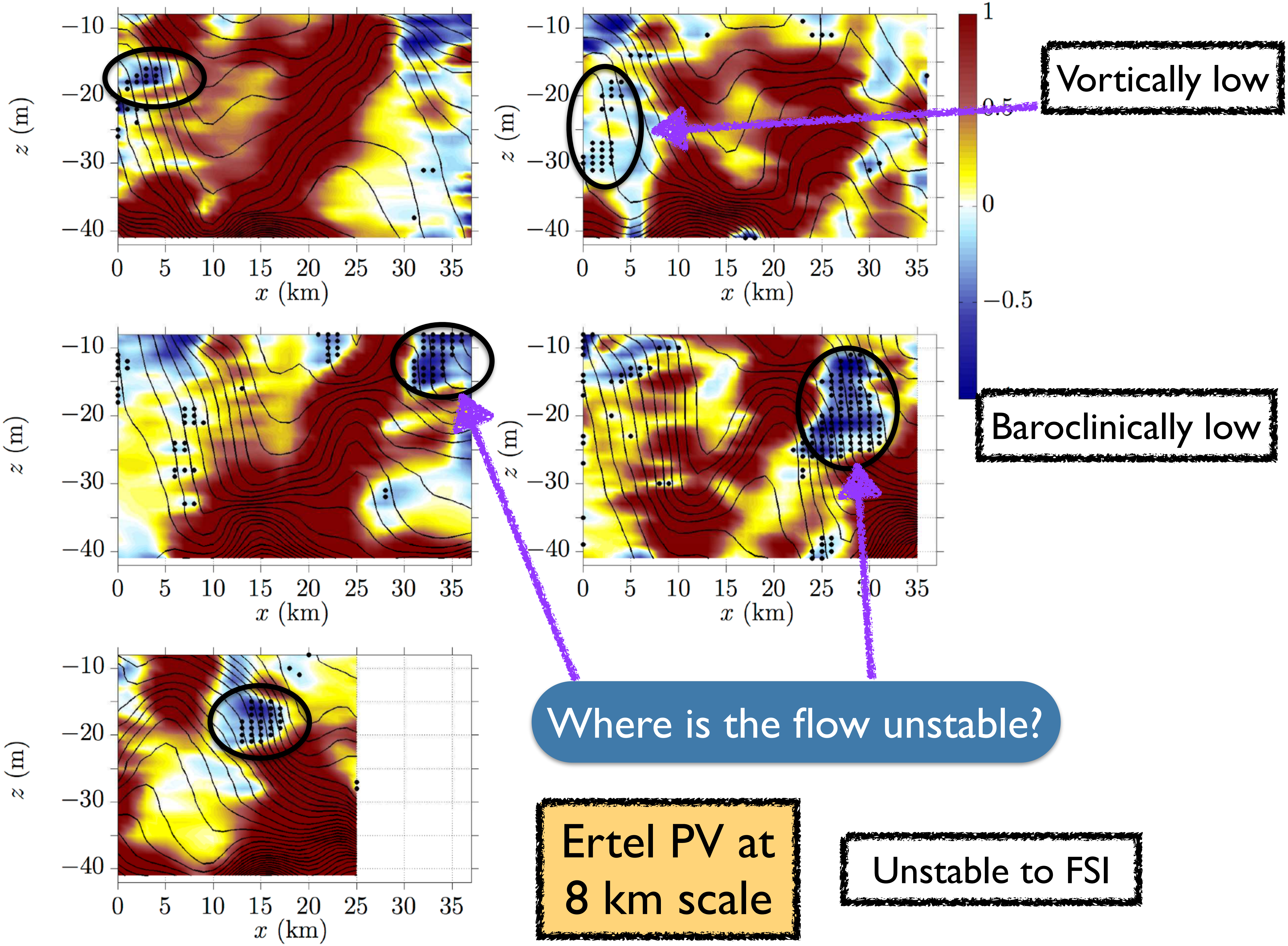


Inertial instability

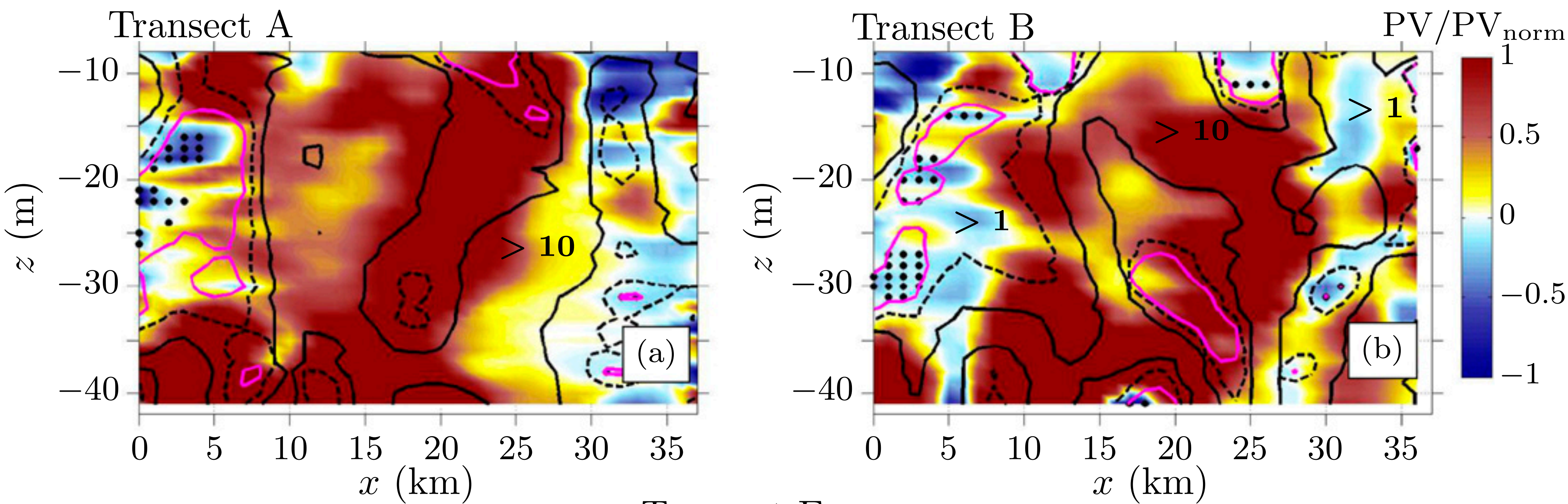


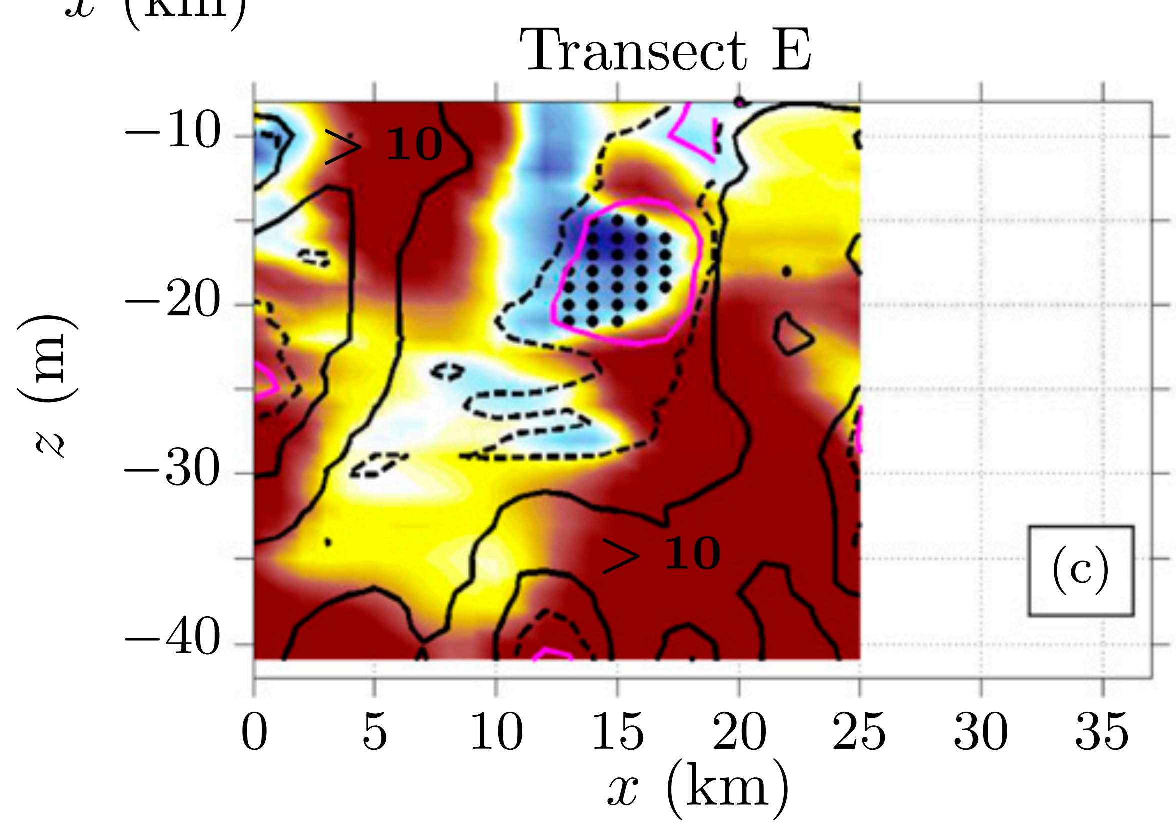
Symmetric instability

Cushman-Roisin and Beckers


Vortically low
Baroclinically low
Where is the flow unstable?
Ertel PV at 8 km scale
Unstable to FSI
z (m)
x (km)
1
0.5
0
−0.5

Normalized PV and balanced Ri = f^2N^2/M^4

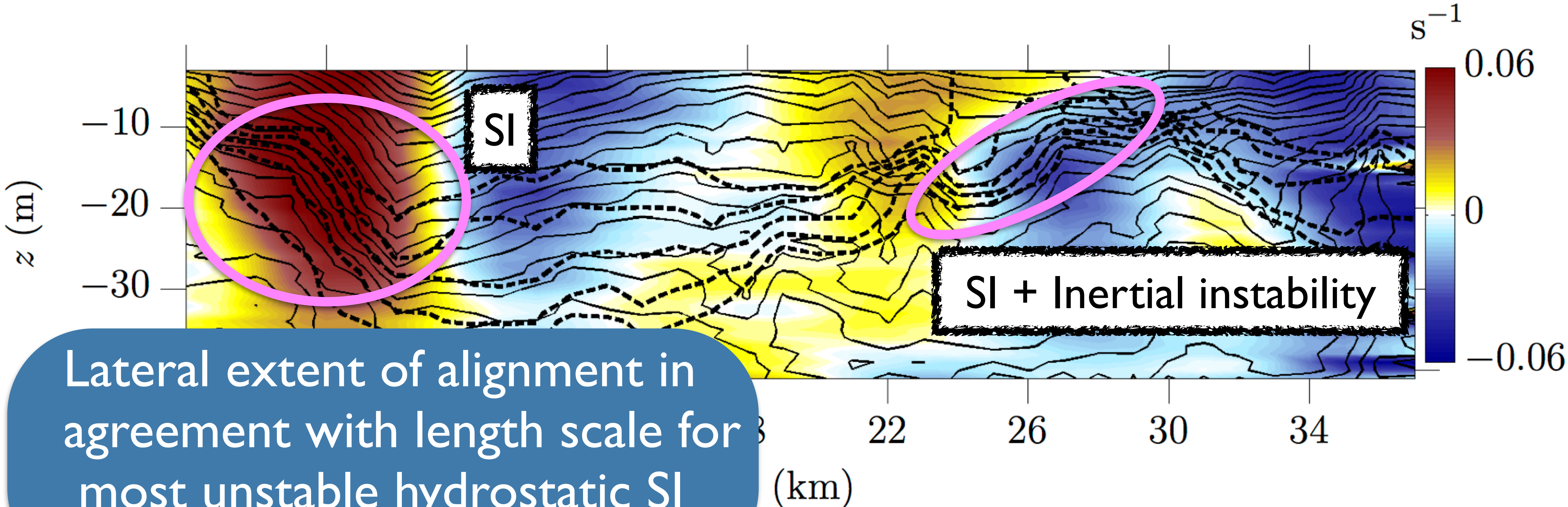




The presence of these regions with flow conditions close to neutral stability for FSI (Ri slightly larger than unity) in the vicinity of other regions where FSI might be active, is suggestive of the neutrally stable Ri resulting from earlier FSI events.

Transect A

$\partial M_{\mathrm{abs}}/\partial x \times 10^3$ (8 km scale)



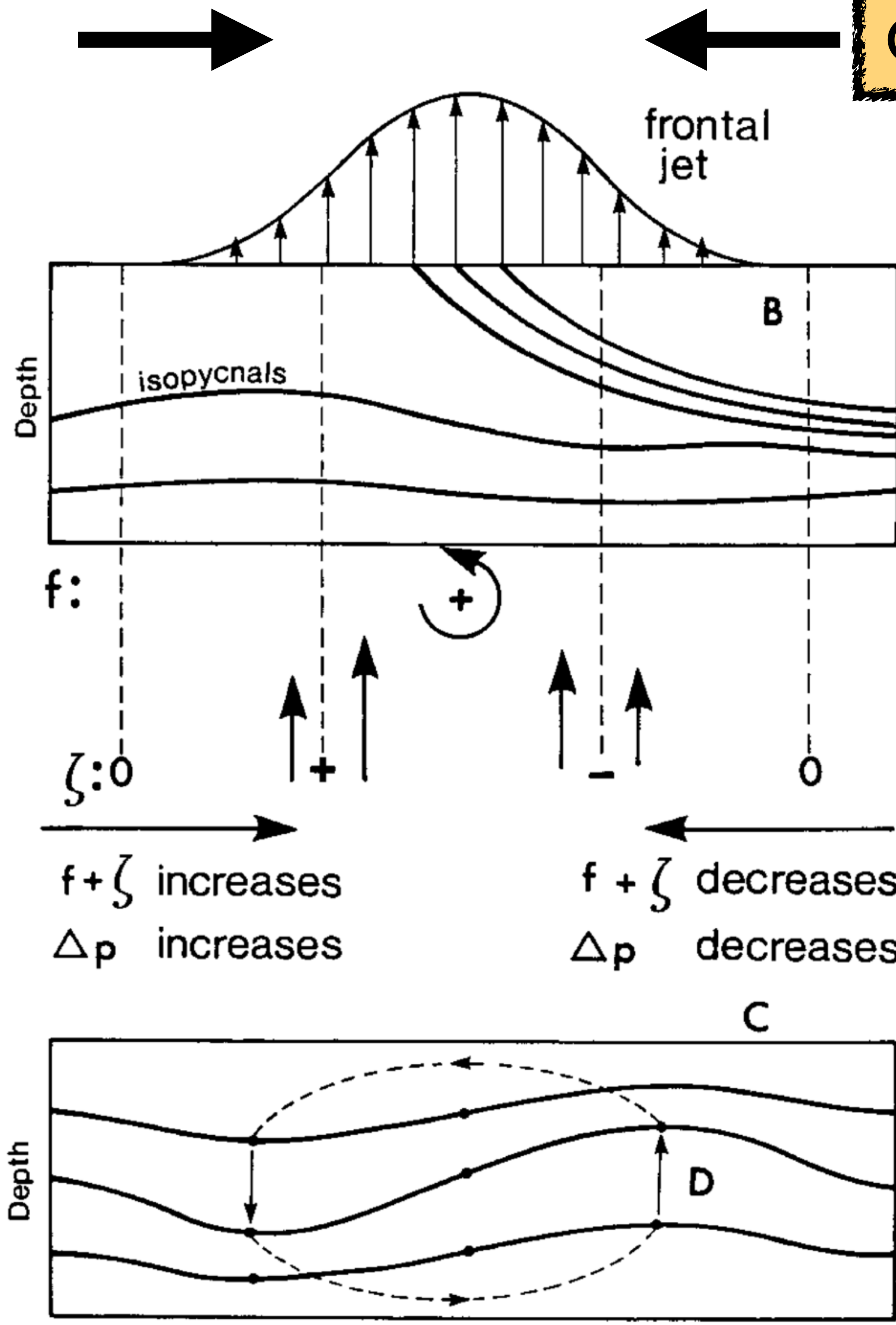
Lateral extent of alignment in agreement with length scale for most unstable hydrostatic SI mode

Symmetric instability: Alignment of contours of M_{abs} and density (2 km scale)

$$M_{\mathrm{abs}} = v + fx$$

$$\partial M_{\mathrm{abs}}/\partial x < 0 \implies \text{Inertial instability}$$

Contours are absolute momentum
Color: Gradient of absolute momentum (8km fields)



Confluent flow

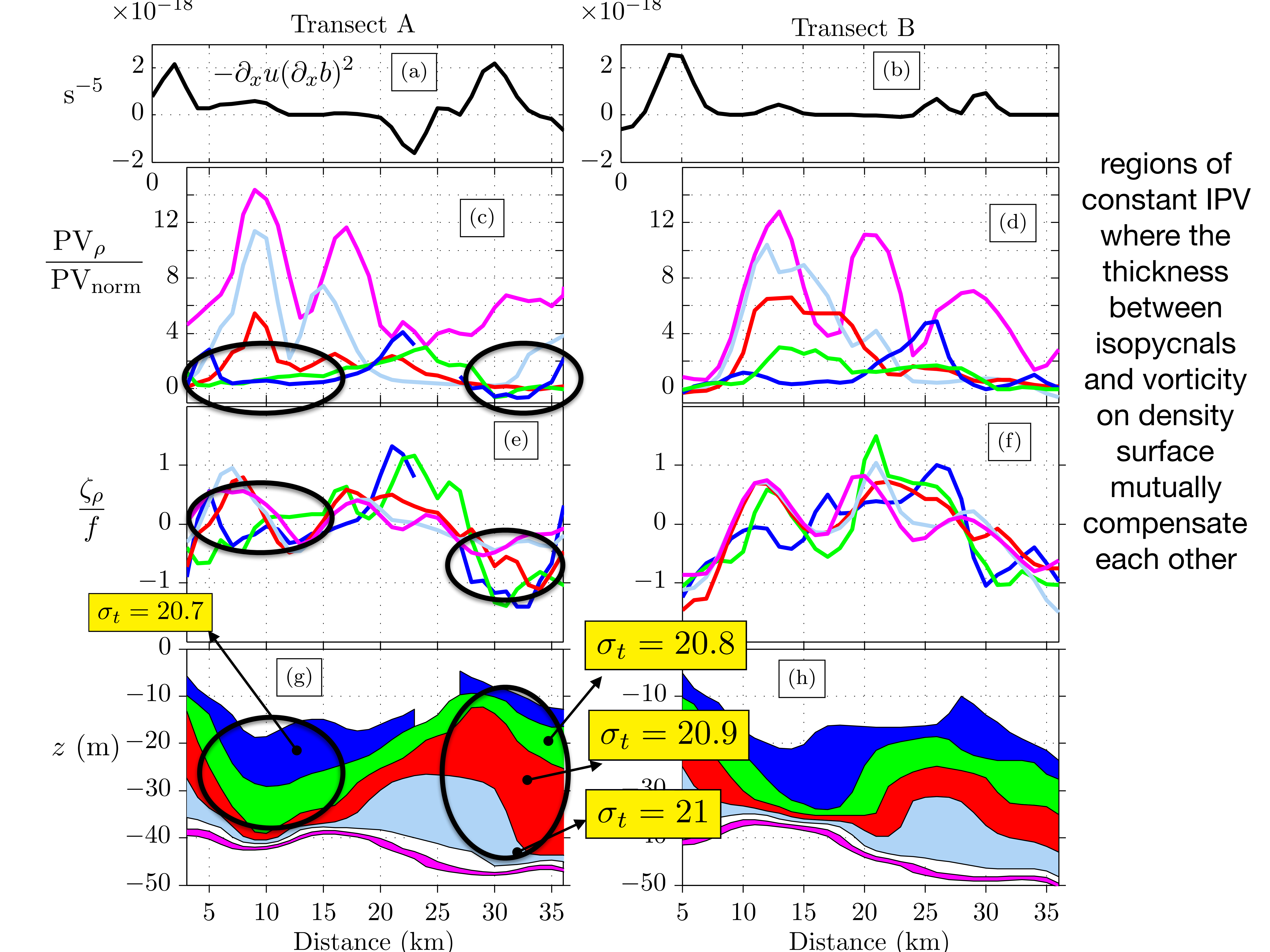
Isentropic PV

$$\mathrm{PV}_\rho = \frac{f + \zeta_\rho}{\Delta P}\frac{\delta\rho}{\rho}$$

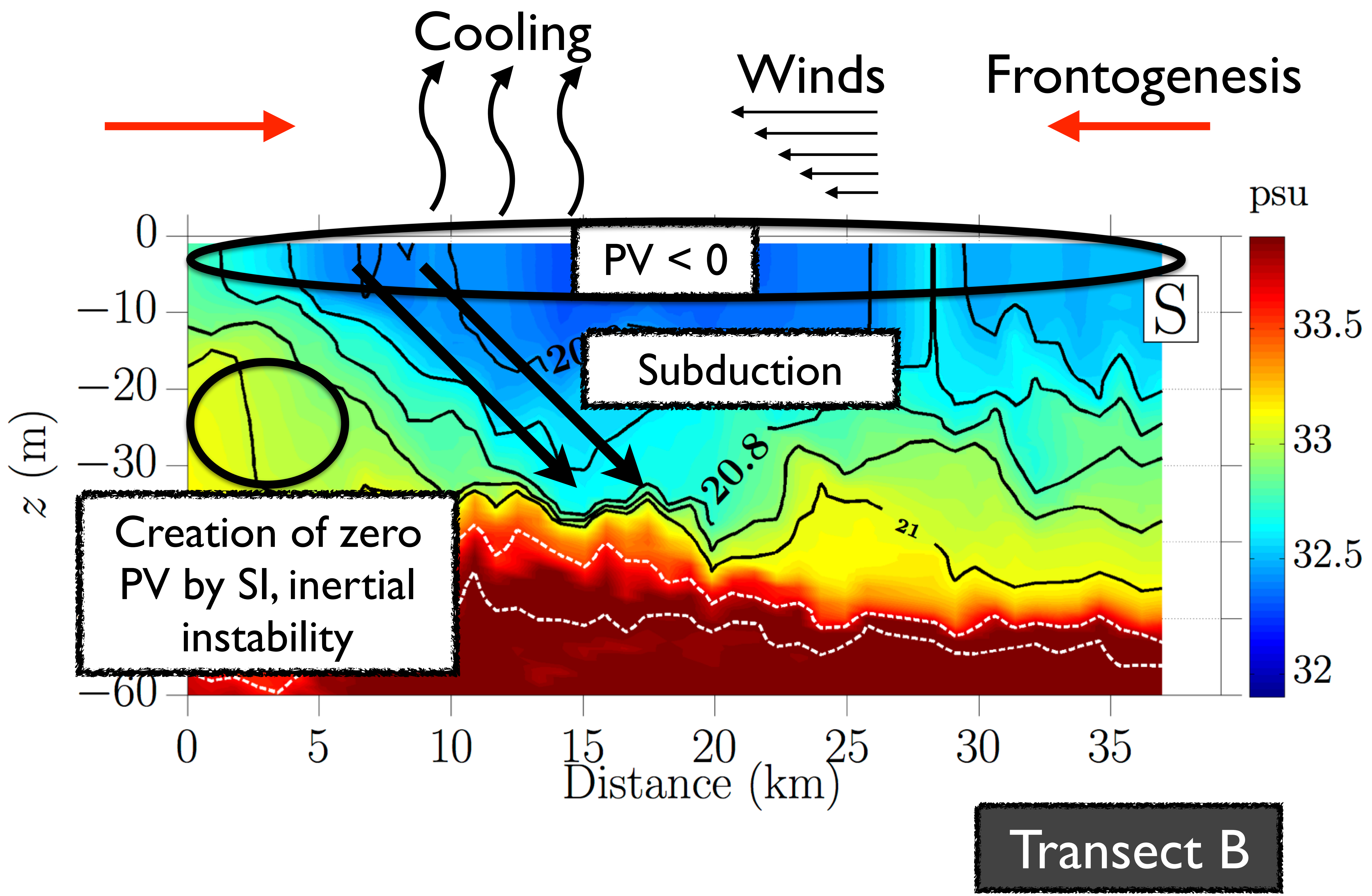
$$\zeta_\rho \approx \left.\frac{\partial v}{\partial x}\right|_\rho$$

We would like to see the imprint of lateral velocity gradients in the spatial variability of N^2

Pollard and Regier (1992).



$\times 10^{-18}$
Transect A
$\times 10^{-18}$
Transect B
$-\partial_x u(\partial_x b)^2$
(a)
(b)
s^{-5}
$\frac{PV_\rho}{PV_{norm}}$
(c)
(d)
$\frac{\zeta_\rho}{f}$
(e)
(f)
$\sigma_t = 20.7$
$\sigma_t = 20.8$
$\sigma_t = 20.9$
$\sigma_t = 21$
(g)
(h)
z (m)
Distance (km)
Distance (km)
regions of constant IPV where the thickness between isopycnals and vorticity on density surface mutually compensate each other



Cooling
Winds
Frontogenesis
PV < 0
Subduction
Creation of zero PV by SI, inertial instability
S
psu
33.5
33
32.5
32
20.8
21
0
−10
−20
−30
−60
z (m)
0
5
10
15
20
25
30
35
Distance (km)
Transect B

Summary

Fronts in the northern Bay are sharp, shallow and stratified.

Observations at a salinity front forced with downfront winds and moderate mesoscale frontogenesis show a range of submesoscale processes at play

- Negative Ertel PV, O(f) vorticity
- Symmetric instability, inertial instability

Below the top 10 m, isopycnal thickness and isentropic vorticity vary in lockstep

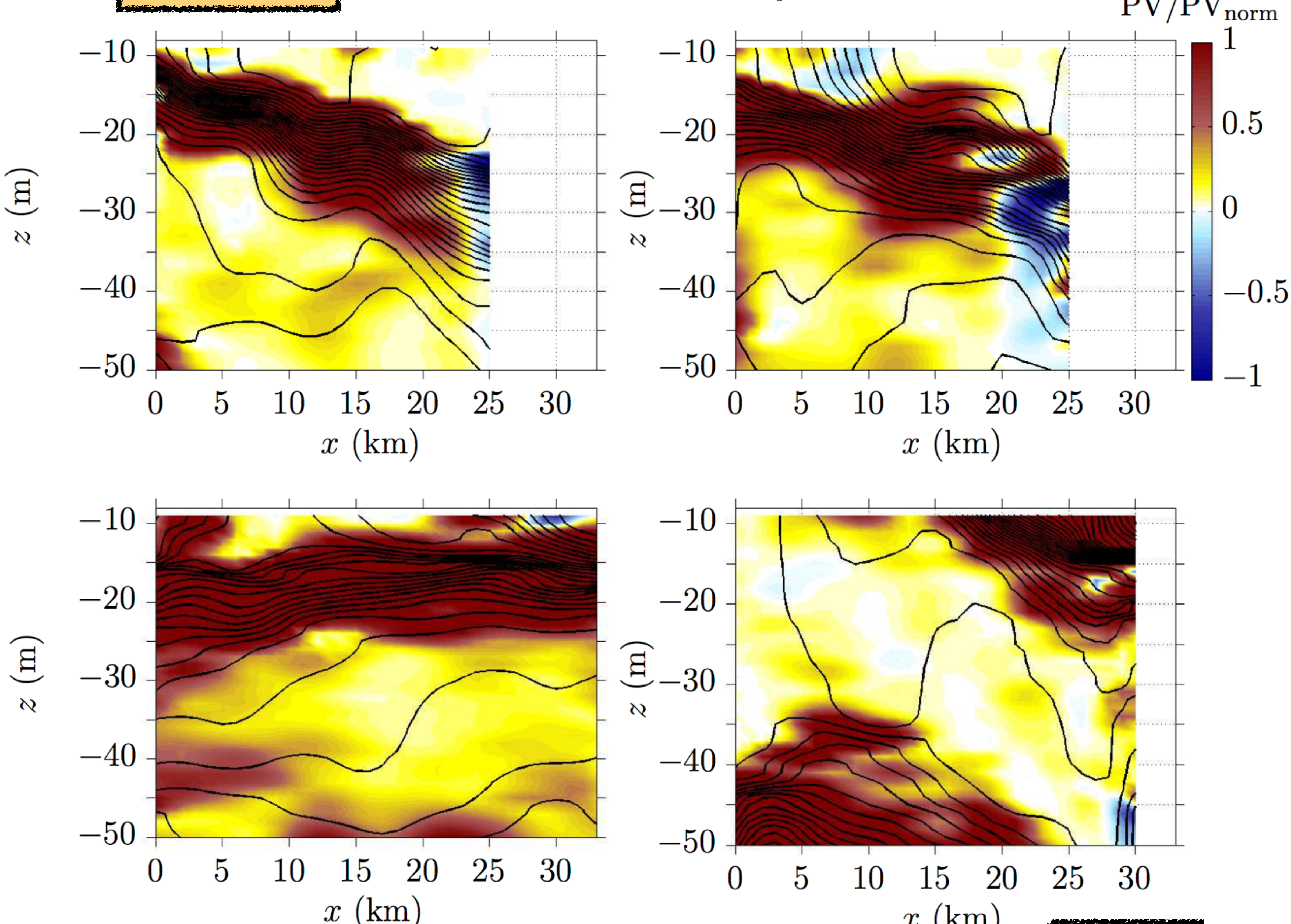
- Pycnostads with O(1-10 km) lateral scales.

Similar dynamical markers missing at a second process study in winter forced by upfront winds and weak frontogenesis.

2015 data analysis shows intriguing results (ongoing)

Was CBPS special?

Ertel PV



Upfront winds and weak strain at 17.3N