Gulf of Tehuantepec: Coastal Dynamics and its interaction with the eastern Tropical Pacific ocean

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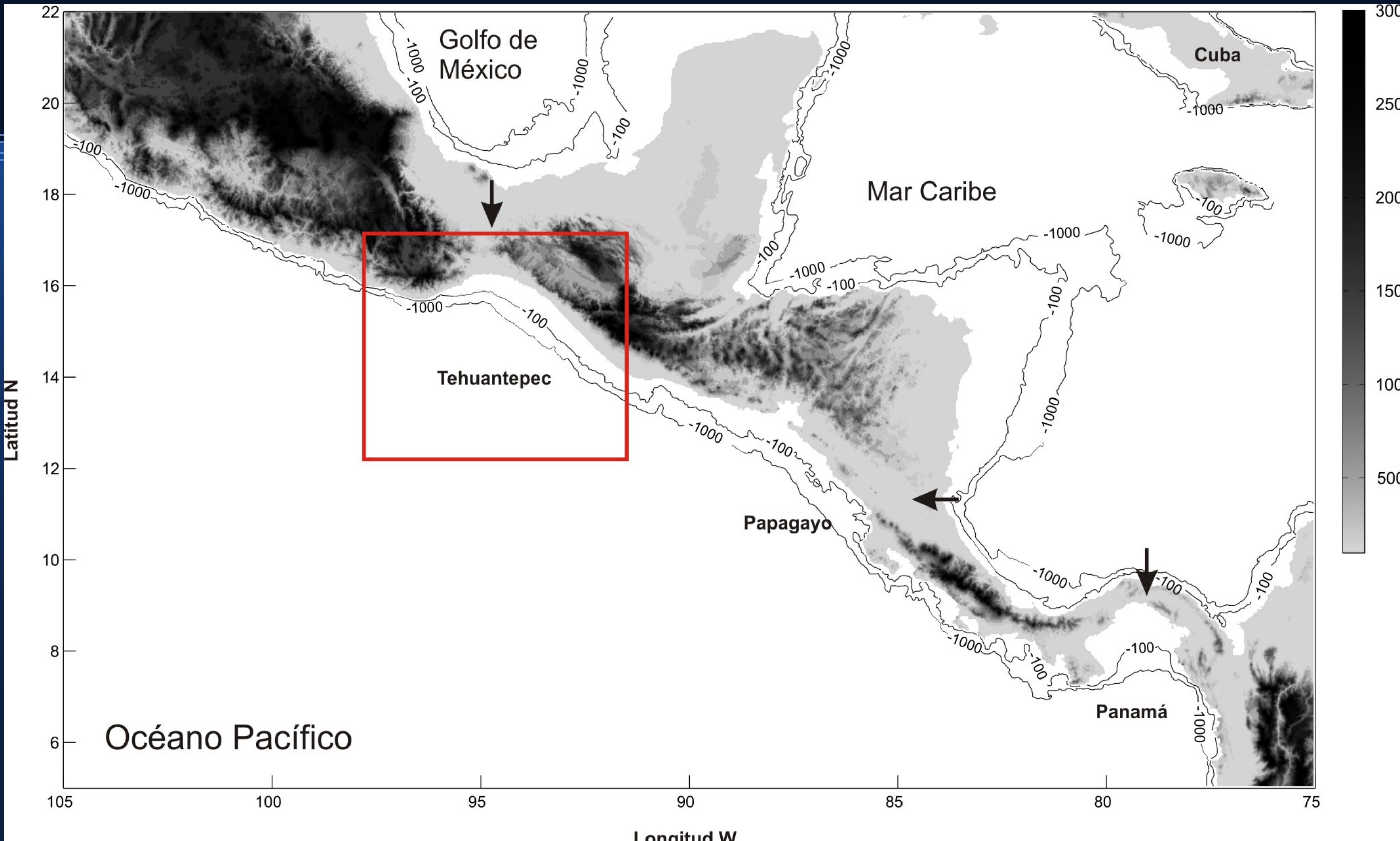
1. Study area



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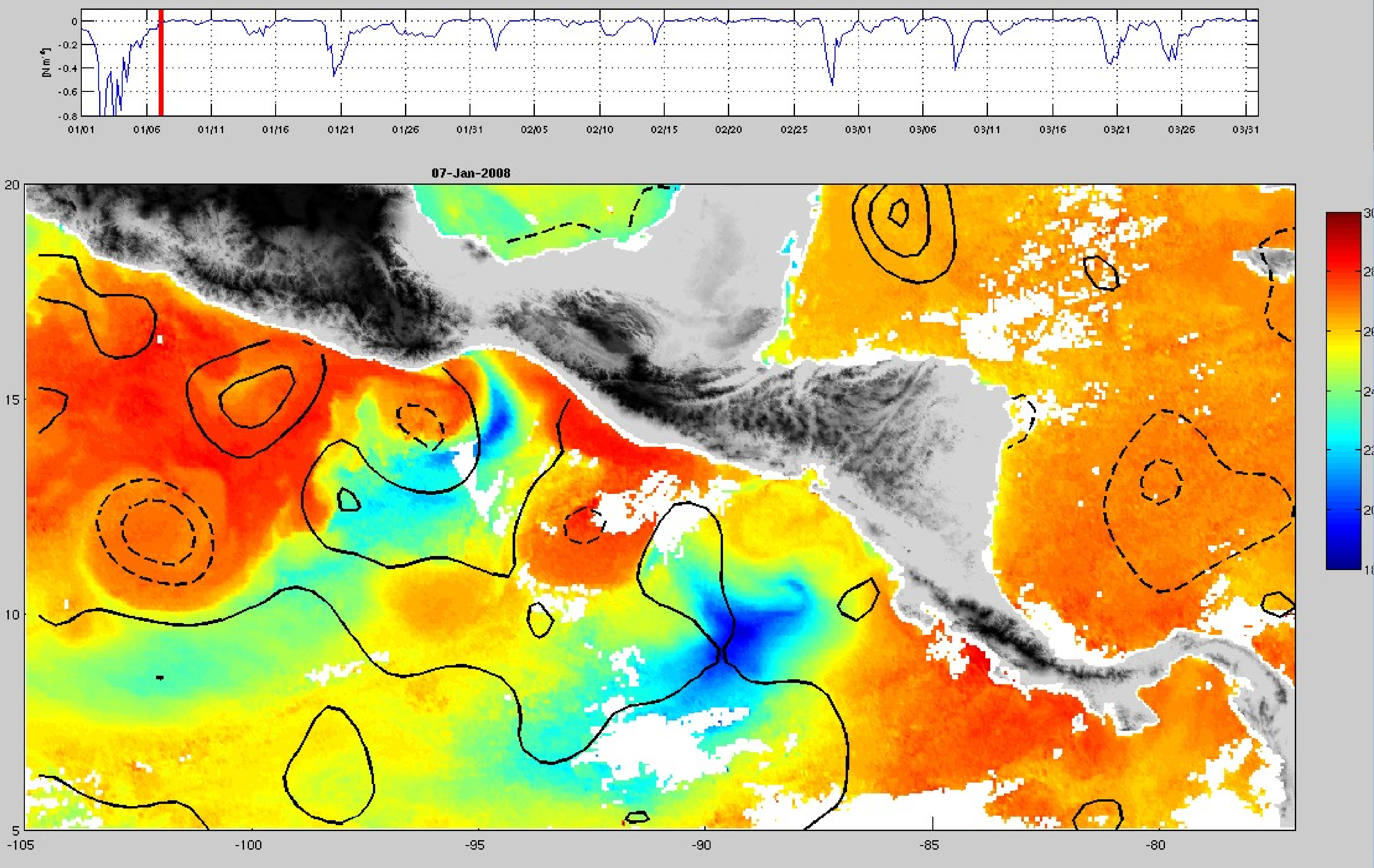

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2. Motivation

- The dynamics of coastal circulation in absence of wind, and the role of geostrophic currents, are unknown

- Coarse resolution of satellite products difficult the study of nearshore processes

- In-situ observations (CTD, moorings) are difficult to conduct due to strong winds

High Frequency Radars were used since they are robust oceanographic instruments capable of remotely achieving uninterrupted, high resolution, surface current measurements under strong wind conditions.

3. Outline

- Data
- High Frequency Radars: Data calibration using ship echoes
- Coastal circulation under weak wind conditions
- Ageostrophic and geostrophic coastal circulation
- Evidence of coastal-shelf arrested waves
- Conclusions

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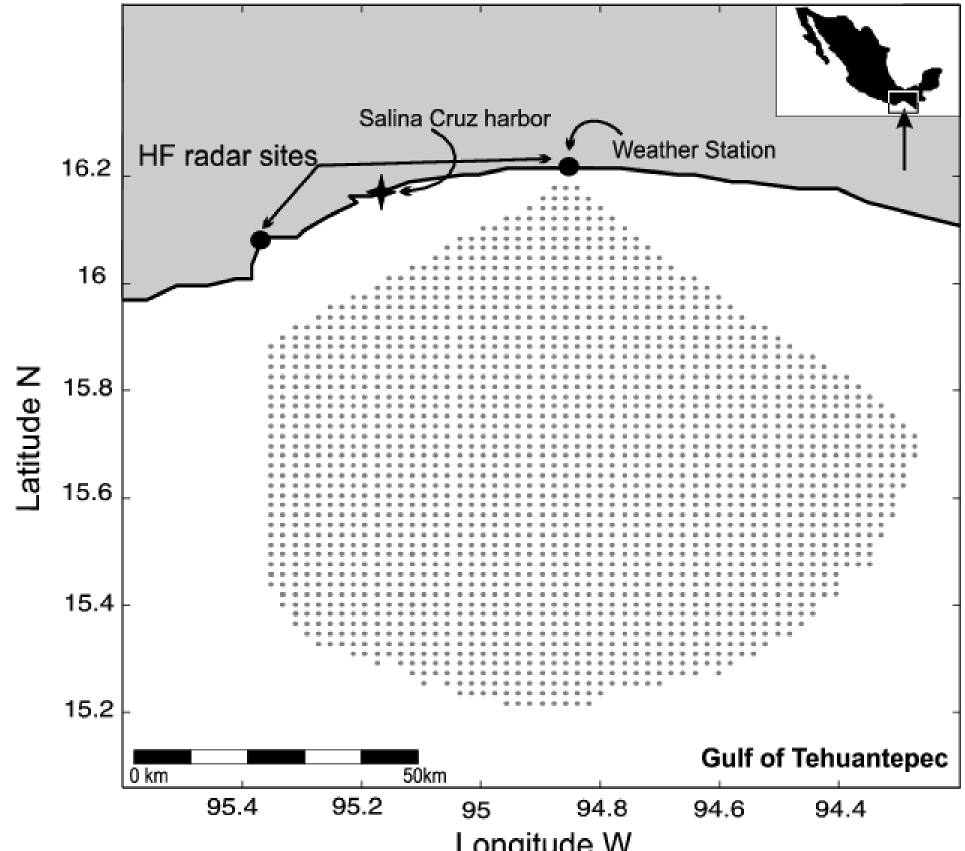
4. HFR Data



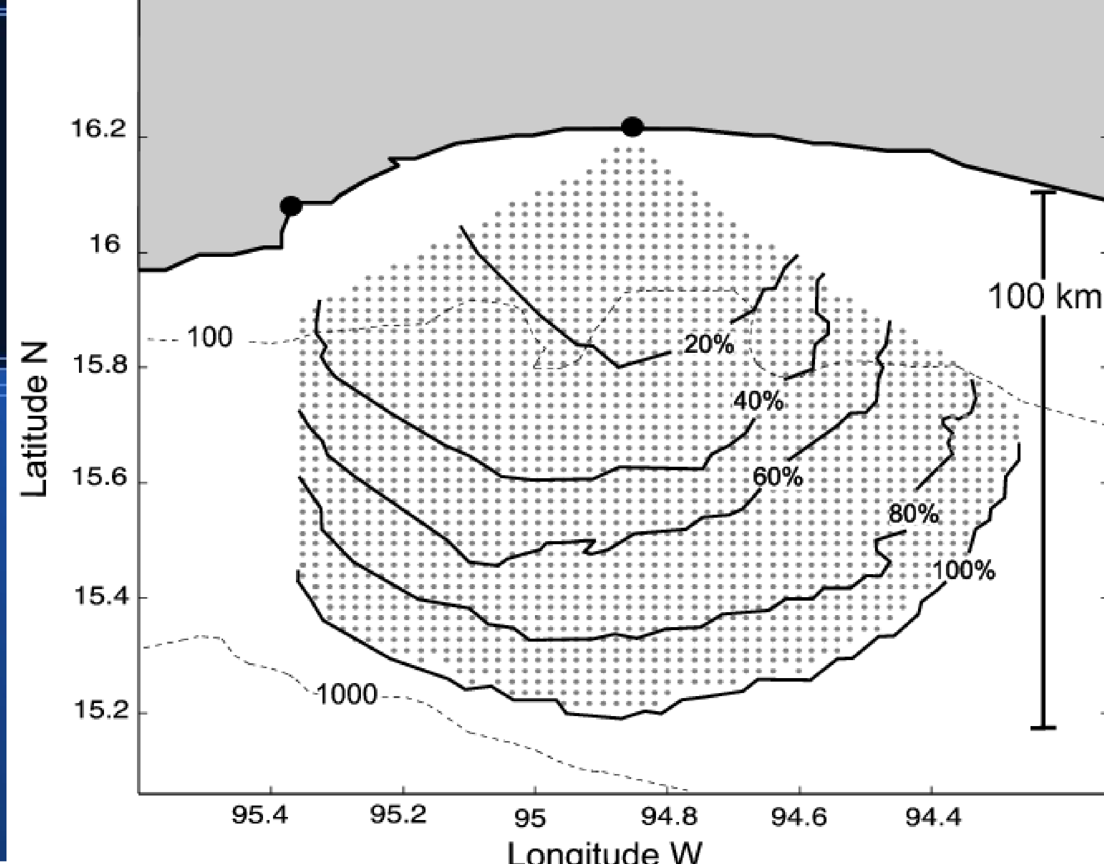
Spatial resolution of 1.5 km
Sampling every 30 min
Coverage of 50x100 km

HFR Data

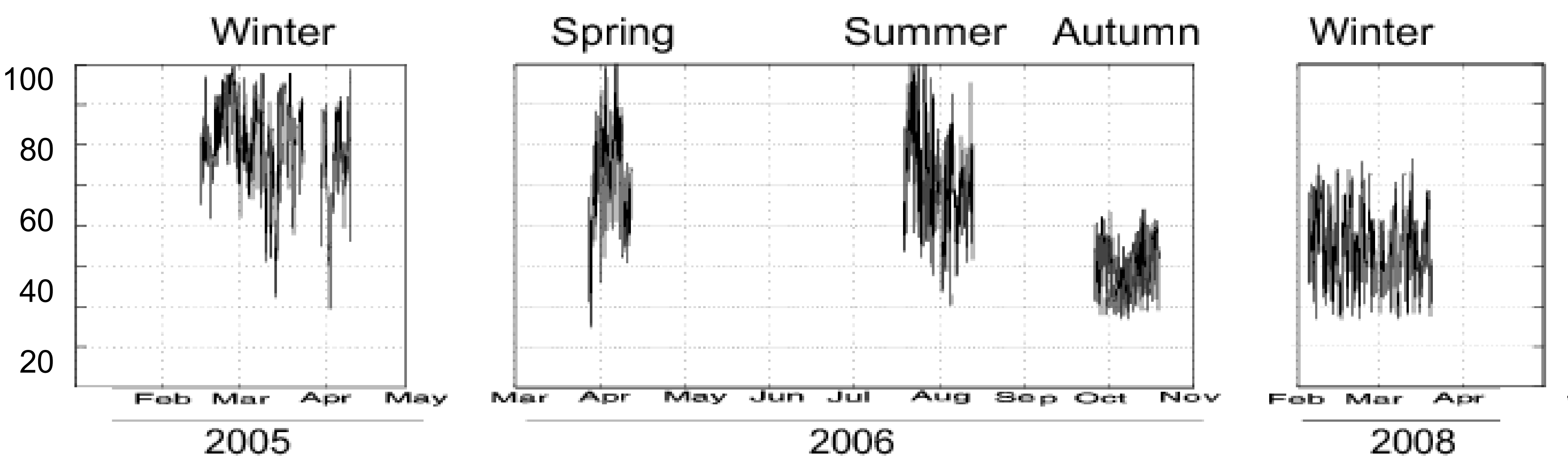
HFR-measured currents were sampled in diferent seasons,

Each data set was about 30 – 60 days long.

Full coverage was up to 100 km offshore



% of data coverage



Additional data

-Thermistor chain (0.5 hr sampling, vertically spaced every 10 m or less)

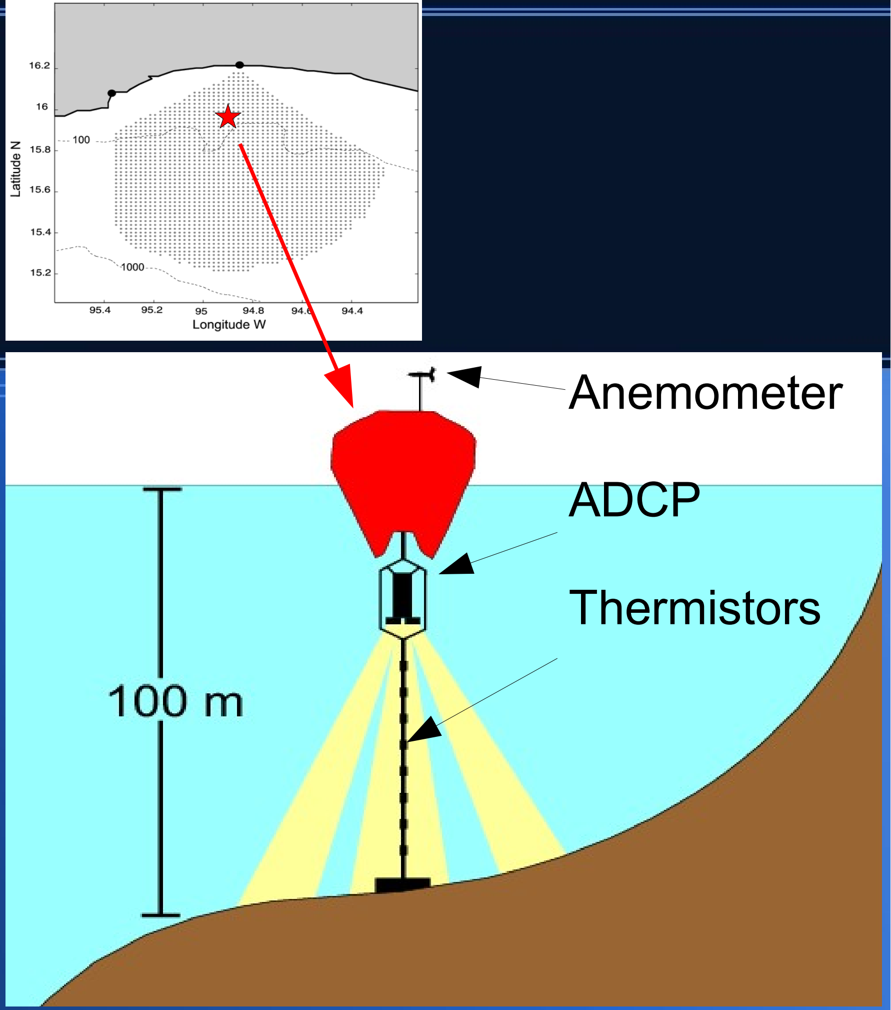
-600 kHz downward looking ADCP (0.5 hr)

-Coastal and at sea anemometers (0.5 hr sampling)

-CTD (summer of 2008)

-Satellite

SST **PODAAC** 1/16 degree hourly gridded product
SSH **AVISO** 1/3 degree daily gridded product
QuikSCAT **CCMP** 1/4 degree, 6 hourly gridded product



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Chapter I
High Frequency Radars: Beam steering calibrations using ships as reflectors

X. Flores-Vidal, P. Flament, C. Chavanne and R. Durazo

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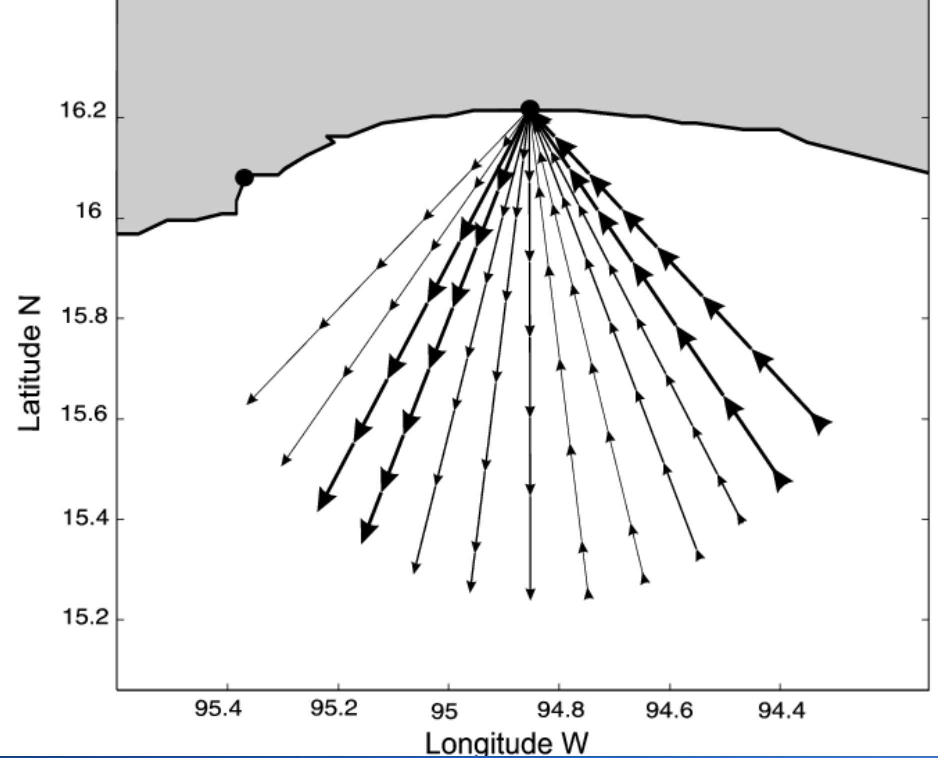
1. HFR basic principles

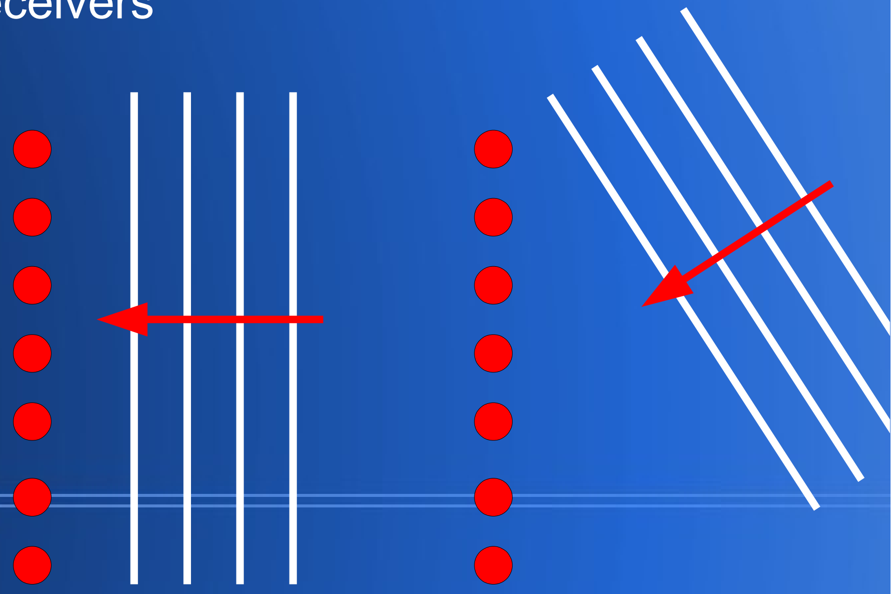
HFR measure surface currents relative to the HFR's position.

Radial resolution is achieved by modifying bandwith (in our case 100 kHz → 1.5 km)

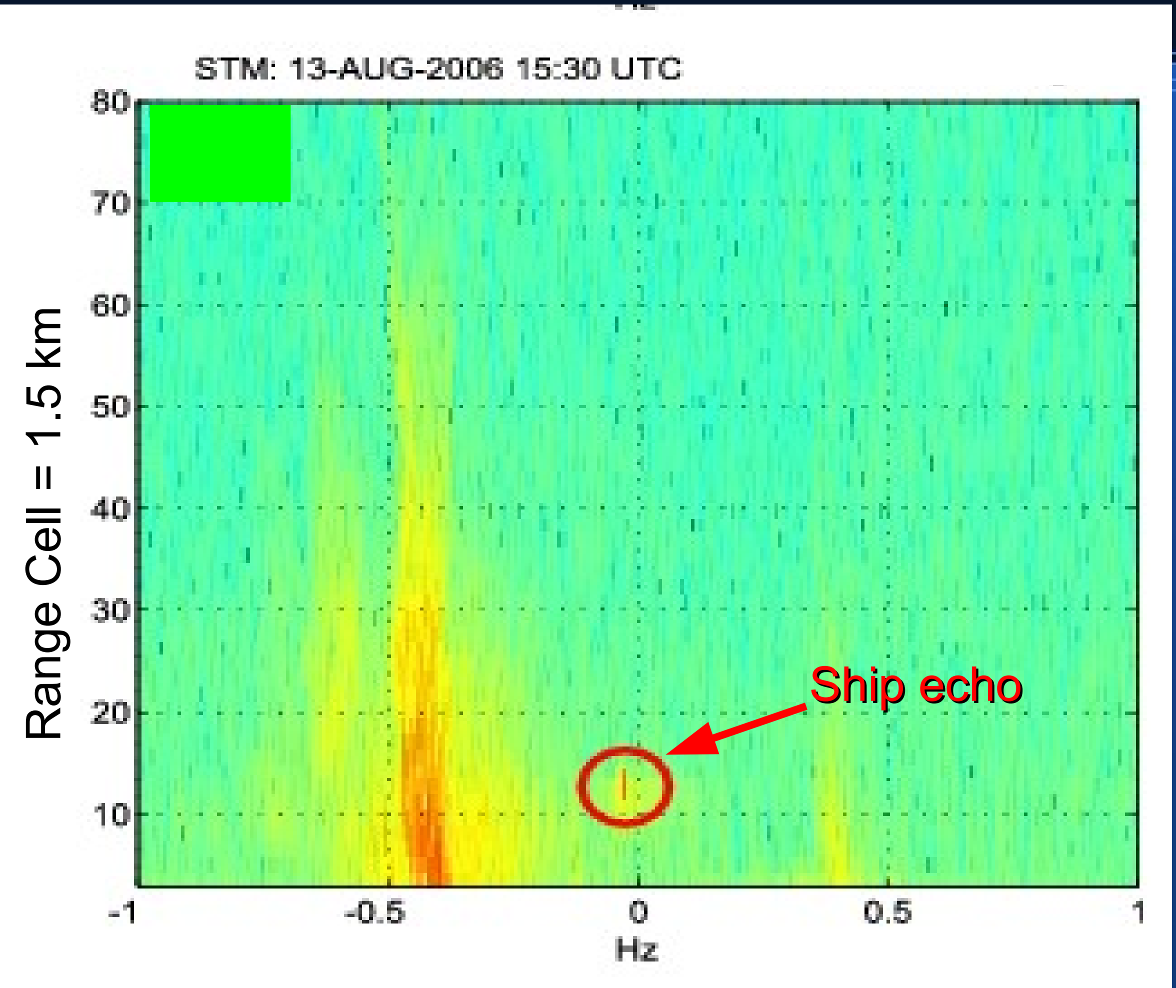
Angular resolution depends on the number of receivers or antennas in linear array (16 elements → ~ 7 degres)



Beam steering is achieved by inducing controlled phase variations directly on the receivers



2. Miss-calibrated phase problem



Backscatter power vs range cell, for a beam steered normal to the receivers linear-array

Heavy ship traffic in the region. Ships are "seen" as peaks on energy spectra

The direction of arrival or bearing and its phase are represented by vectors

$$\hat{S}_j = \pi \sin(\theta_j) \qquad \hat{\phi}_i = \pi \sin(\theta_i)$$

with j and i representing ships and antennas. The overdetermined problem can be stated as

$$P = \sum_j^M \sum_i^N (\phi_{i,j} - (i-1)\hat{S}_j - \hat{\phi}_i)$$

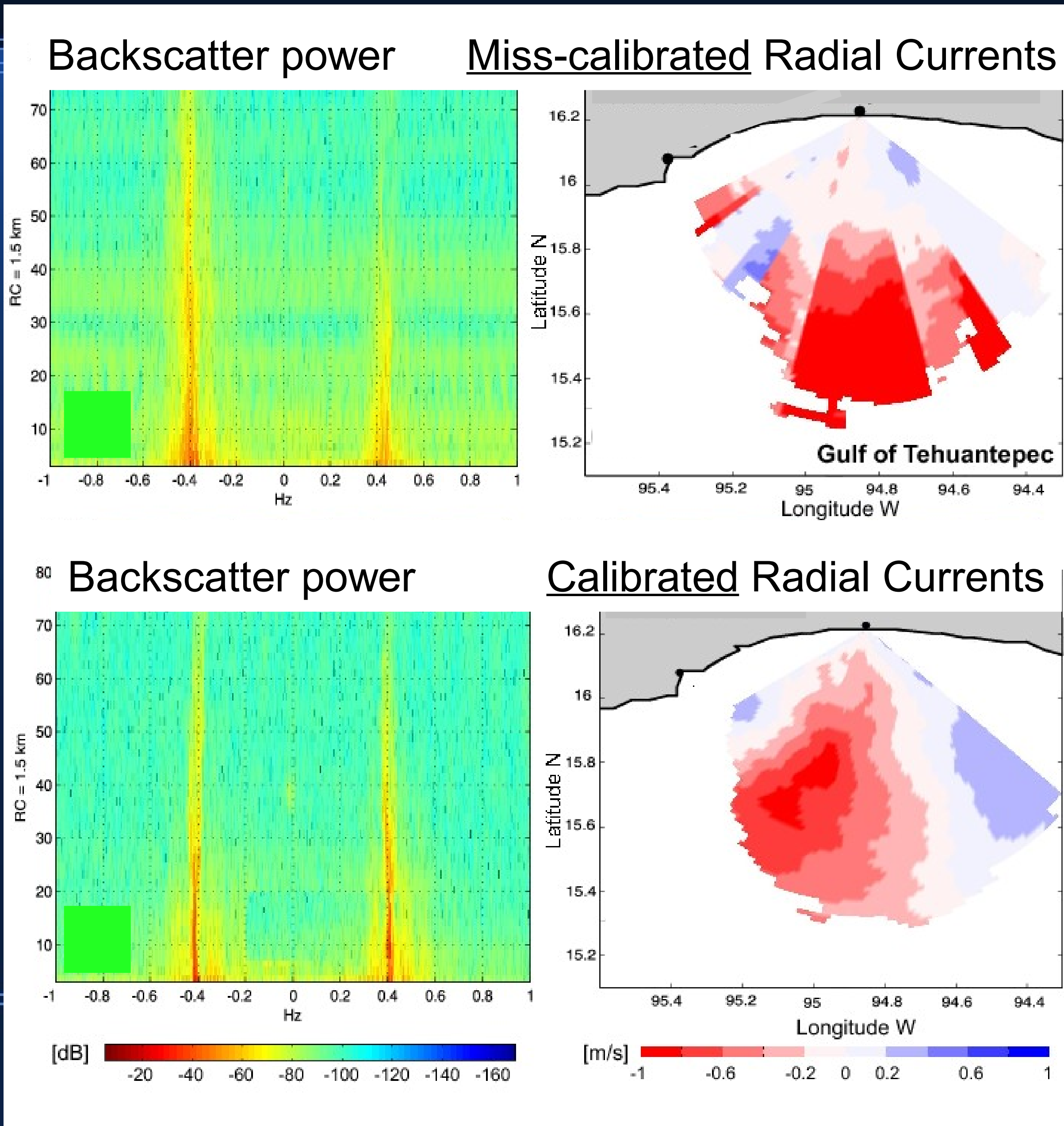
Where $\phi_{i,j}$ is the measured phase for every antenna and for every ship. The system is solved in the least squares sense

$$B = X^{-1} Y$$

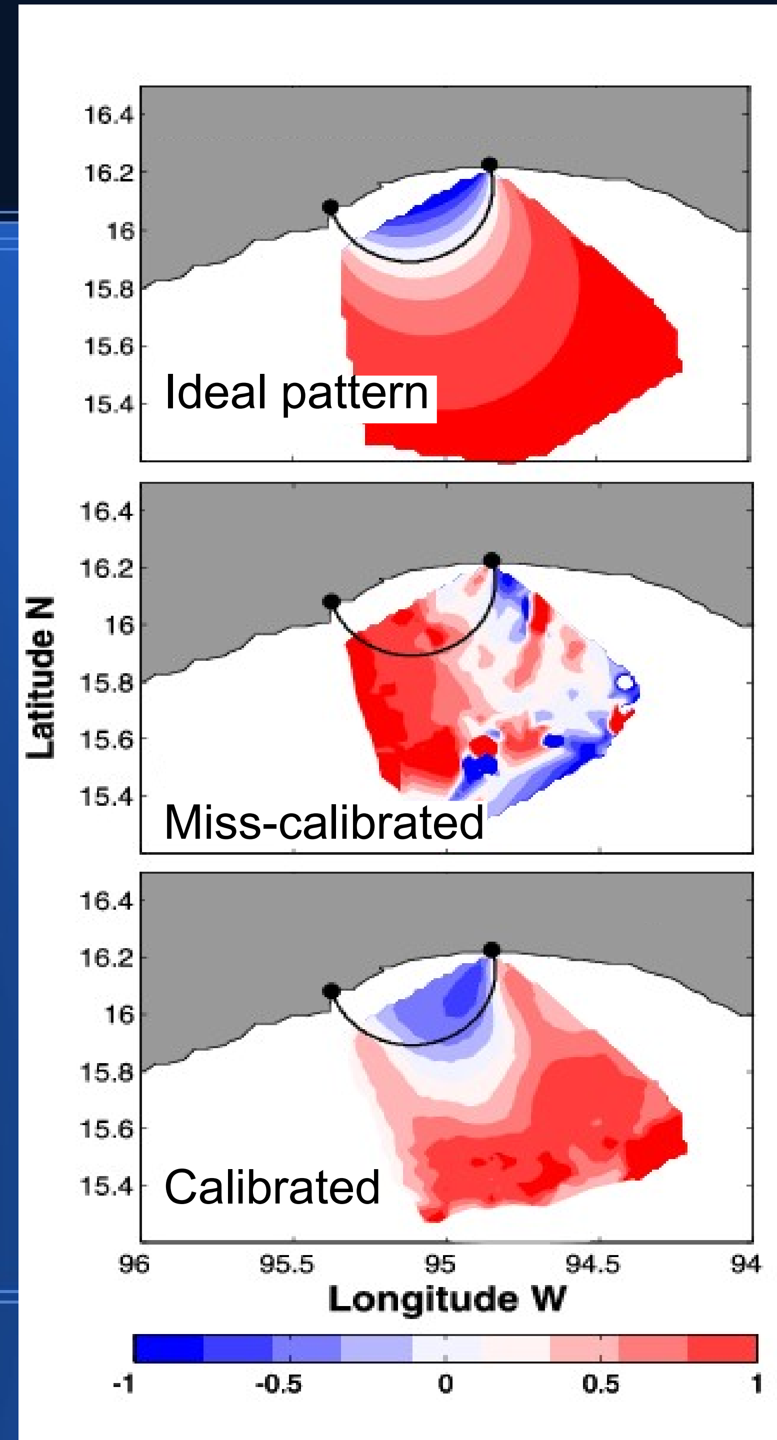
Where solution B represents phase at every antenna and the bearing for every ship.

3. Results

For a single file



Cross-correlation of two months of data



4. Chapter syntesis

- ✔ We developed and tested a robust statistical least square technique to calibrate phases on HFR linear array receivers
- ✔ This technique allowed us to make misscalibrated data usable for this study

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Chapter II
Coastal circulation under low wind conditions in the Gulf of Tehuantepec, Mexico: High Frequency Radar Observations

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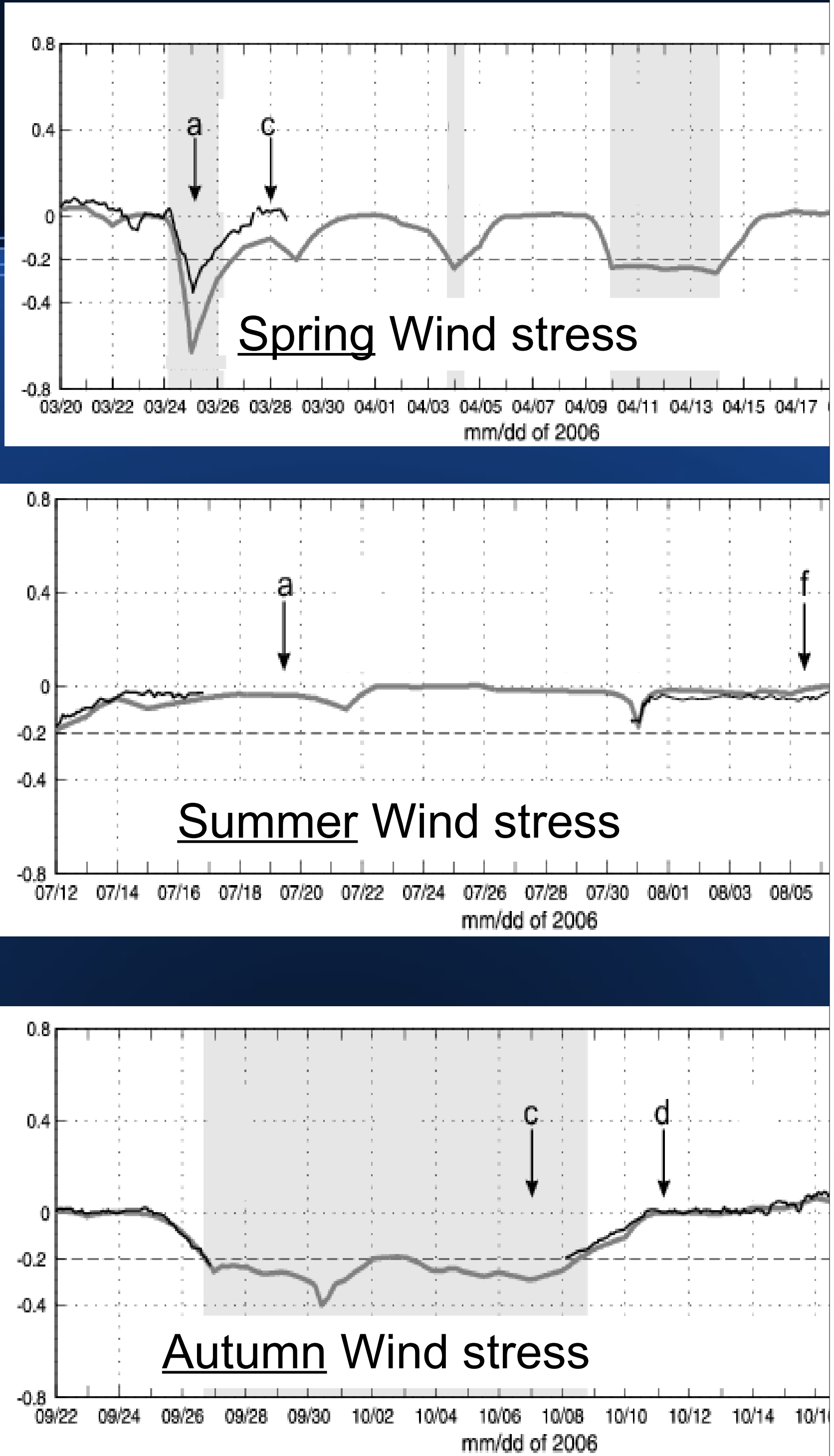
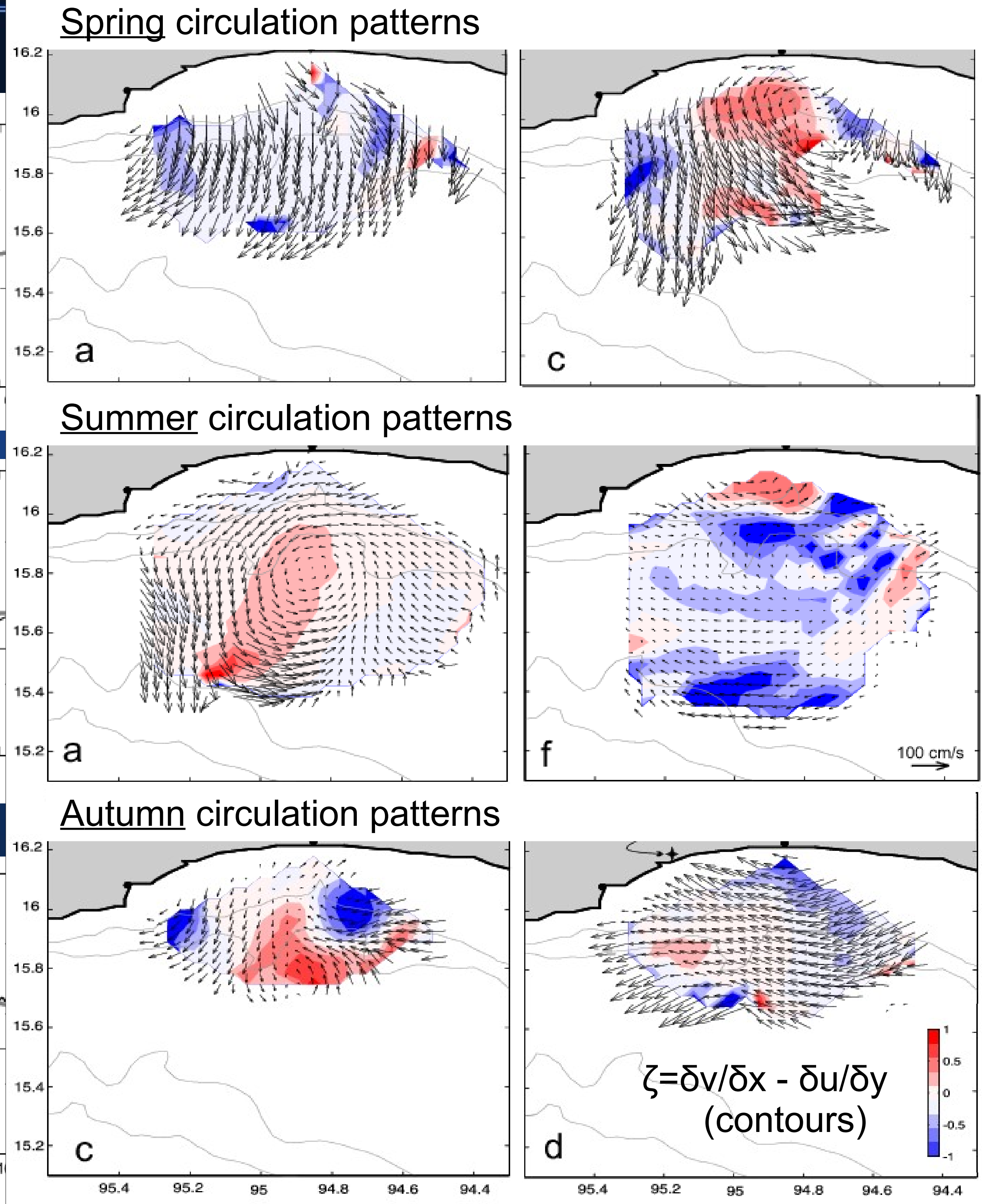
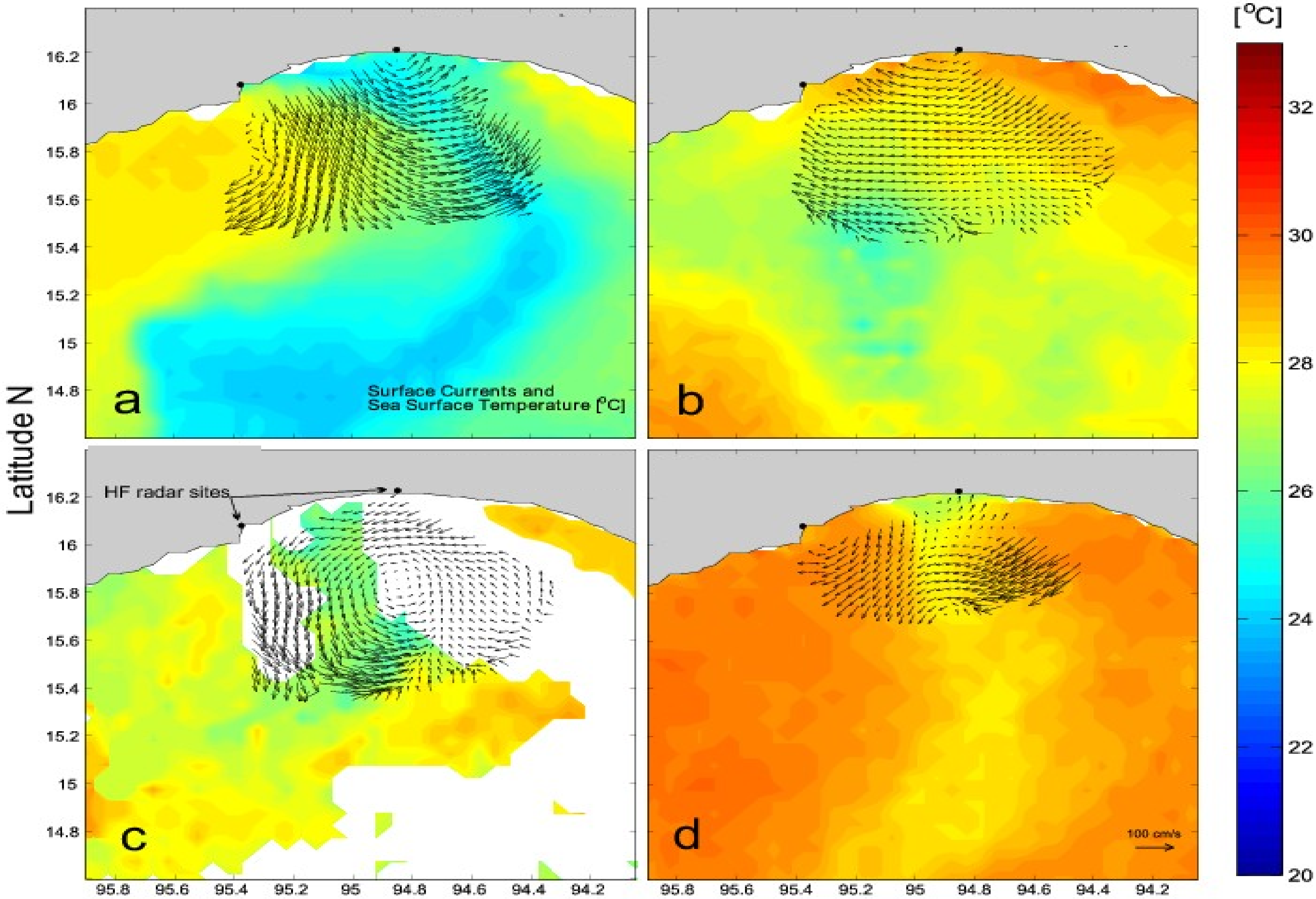
1. Seasonality of surface currents

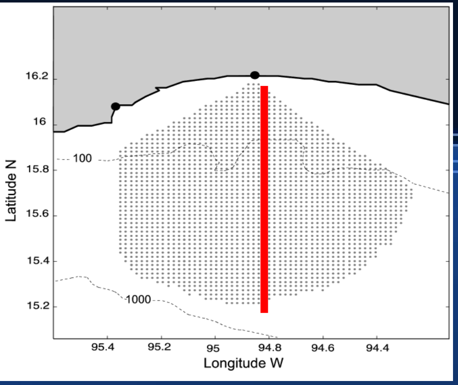


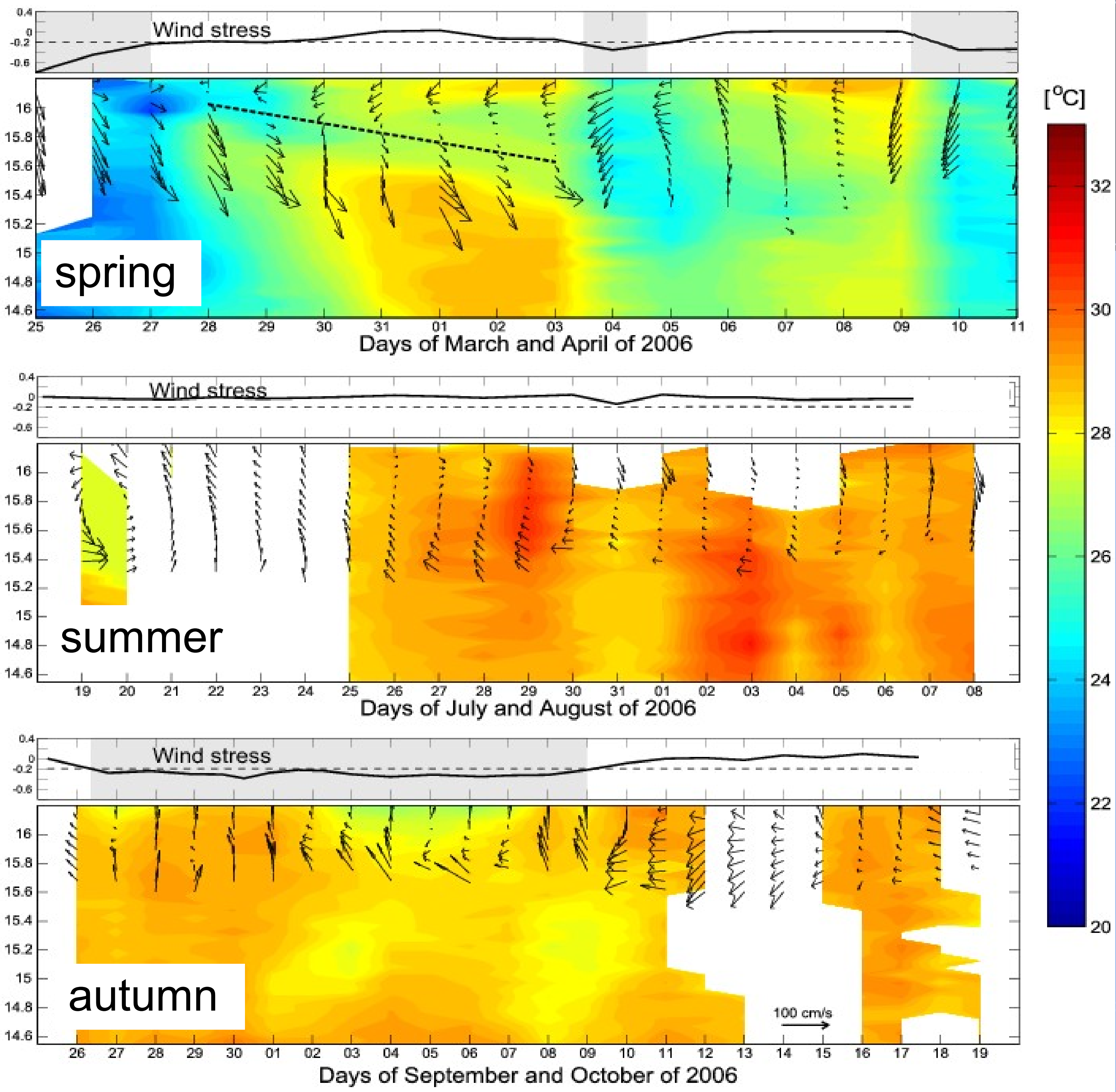


2. Typical current patterns and SST



3. Time variability over a transect





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4. Chapter synthesis

- ✔ A warm coastal current was persistently observed during spring and autumn
- ✔ In summer the coastal current displaced offshore
- ✔ Wind stress over 0.2 Nm^{-2} was able to modify SST field
- ✔ During weak wind conditions, cyclonic eddies were observed

With the purpose of identify the geostrophic contribution on the observed dynamics, we extracted the ageostrophic variability of the data.

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Chapter III
Ageostrophic and quasi-geostrophic circulation in the Gulf of Tehuantepec, México: HF Radio measurements.

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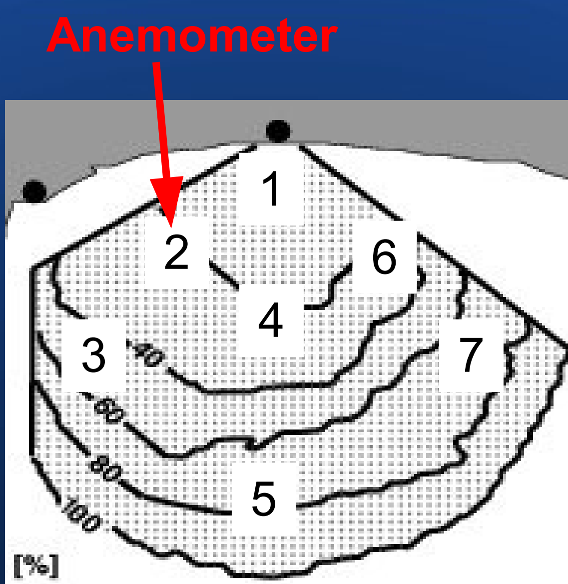
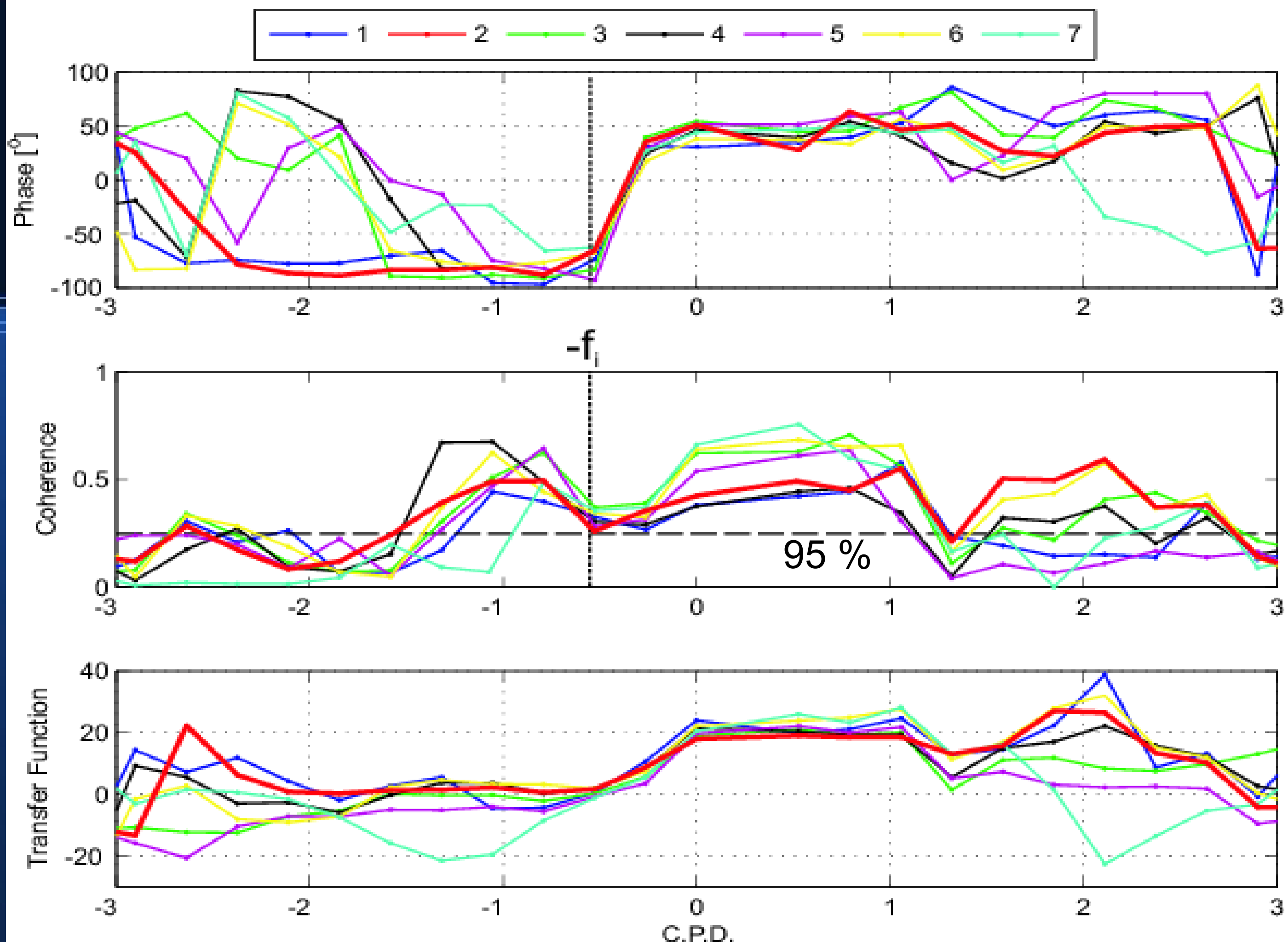
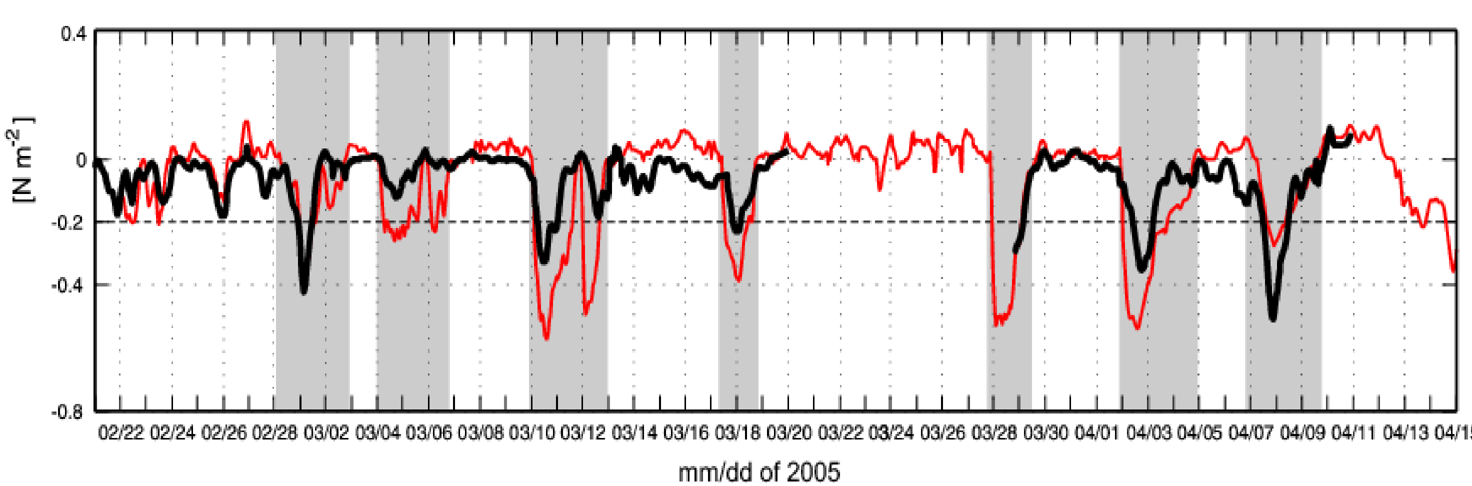
1. Transfer function or admittance analysis







Season	$\|H\|$	ϕ_c
Winter 2005	20	50
Spring 2006	21	48
Summer 2006	10	55
Autumn 2006	19	50
Winter 2008	20	50

2. Breaf dynamic review

Ekman theory establishes the relationship between wind and upper ocean velocity. The linearized momentum balance can be written as,

$$\frac{\partial \vec{U}(t,z)}{\partial t} + if\vec{U}(t,z) = -\frac{1}{\rho}\frac{\partial \tau(t,z)}{\partial z}$$

In the ocean, horizontal pressure gradients and vertical gradient of stress induced by the wind are the two main forces that accelerate fluid,

$$\frac{\partial U_p}{\partial t} - fV_p = -\frac{1}{\rho}\frac{\partial p}{\partial x} \quad ; \quad \frac{\partial V_p}{\partial t} + fU_p = -\frac{1}{\rho}\frac{\partial p}{\partial y} ,$$

$$U_E = \frac{\tau_y}{f\rho} \quad ; \quad V_E = \frac{-\tau_x}{f\rho} ,$$

Thus, surface ocean velocity can be expressed as the sum of the geostrophic and the Ekman (ageostrophic) contributions as,

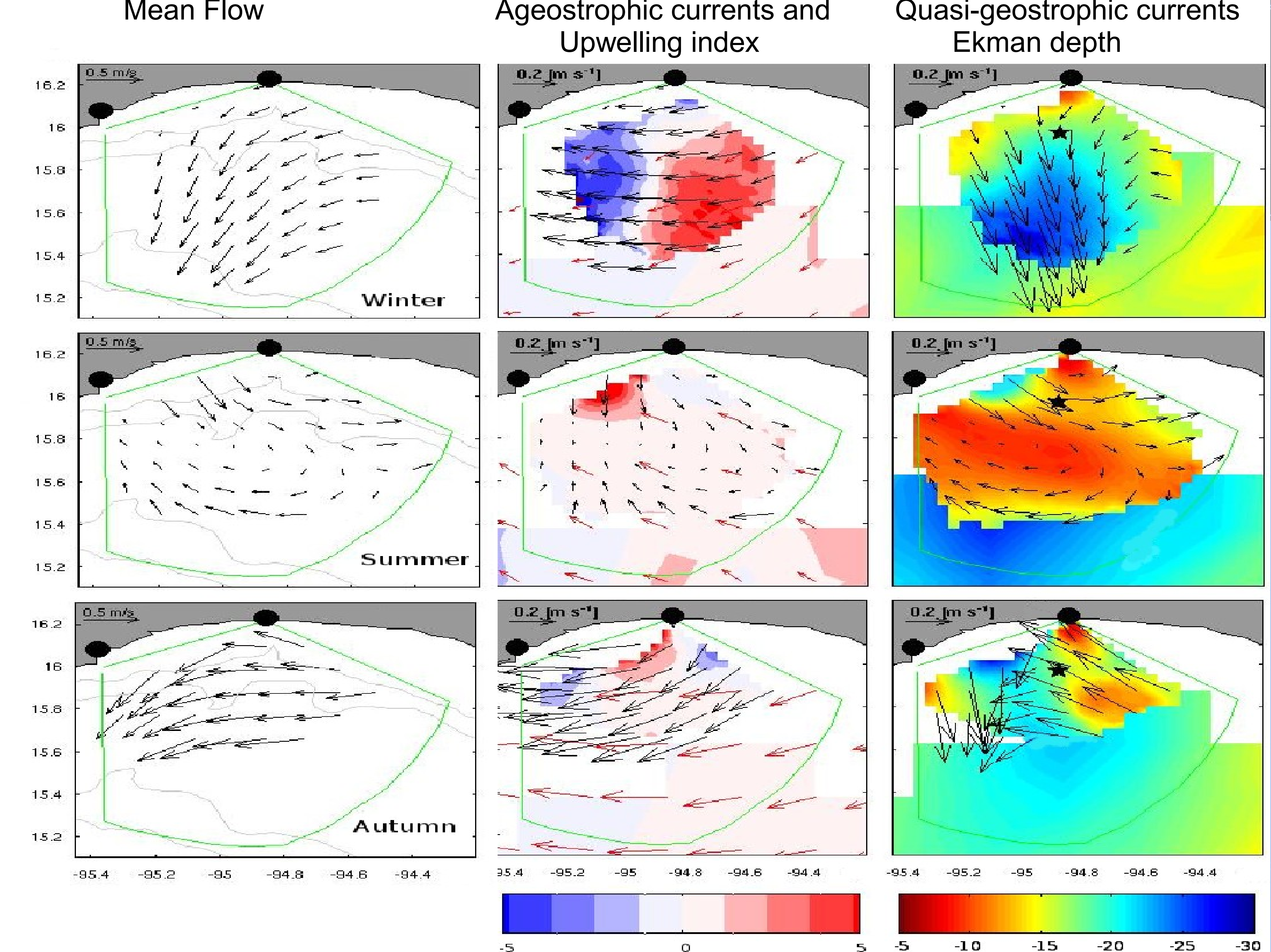
$$U = U_p + U_E + noise \quad ; \quad V = V_p + V_E + noise$$

Vertical integration of U_E and V_E (across the Ekman layer) gives the Ekman transport,

$$\frac{\partial \dot{U}_E}{\partial x} + \frac{\partial \dot{V}_E}{\partial y} = \frac{curl(\tau)}{f\rho}$$

and its divergence is defined as Ekman pumping (upwelling index).

Definition of Ekman layer depth H_E not only depends on wind stress but also on the vertical density gradient. We used $H_E = u_*/\beta f^{1/2}$, where $u_*^2 = \frac{|\tau|}{\rho}$, where $\beta \sim 0.065$



Mean Flow
Ageostrophic currents and Upwelling index
Quasi-geostrophic currents Ekman depth
0.5 m/s
0.2 [m s⁻¹]
Winter
Summer
Autumn
16.2
16
15.8
15.6
15.4
15.2
-95.4
-95.2
-95
-94.8
-94.6
-94.4
-5
0
5
-5
-10
-15
-20
-25
-30

4. Chapter synthesis

- ✔ The use of a transfer function allowed us the extraction of ageostrophic and quasi-geostrophic contributions
- ✔ The horizontal pressure gradient imposed by the wind during winter-spring drives quasi-geostrophic currents to the south, while its ageostrofic part is westward.
- ✔ Summer currents are geostrophically driven
- ✔ Although autumn was affected by relatively strong winds, the geostrophic westward current was persistent

What is the origin of this coastal current?

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Chapter IV
Evidence of coastal-shelf arrested waves in the Gulf of Tehuantepec

X. Flores-Vidal, R. Durazo, C. Chavanne, P. Flament
Tentative co-authors: Reyes C., Zavala L., Ocampo, J.

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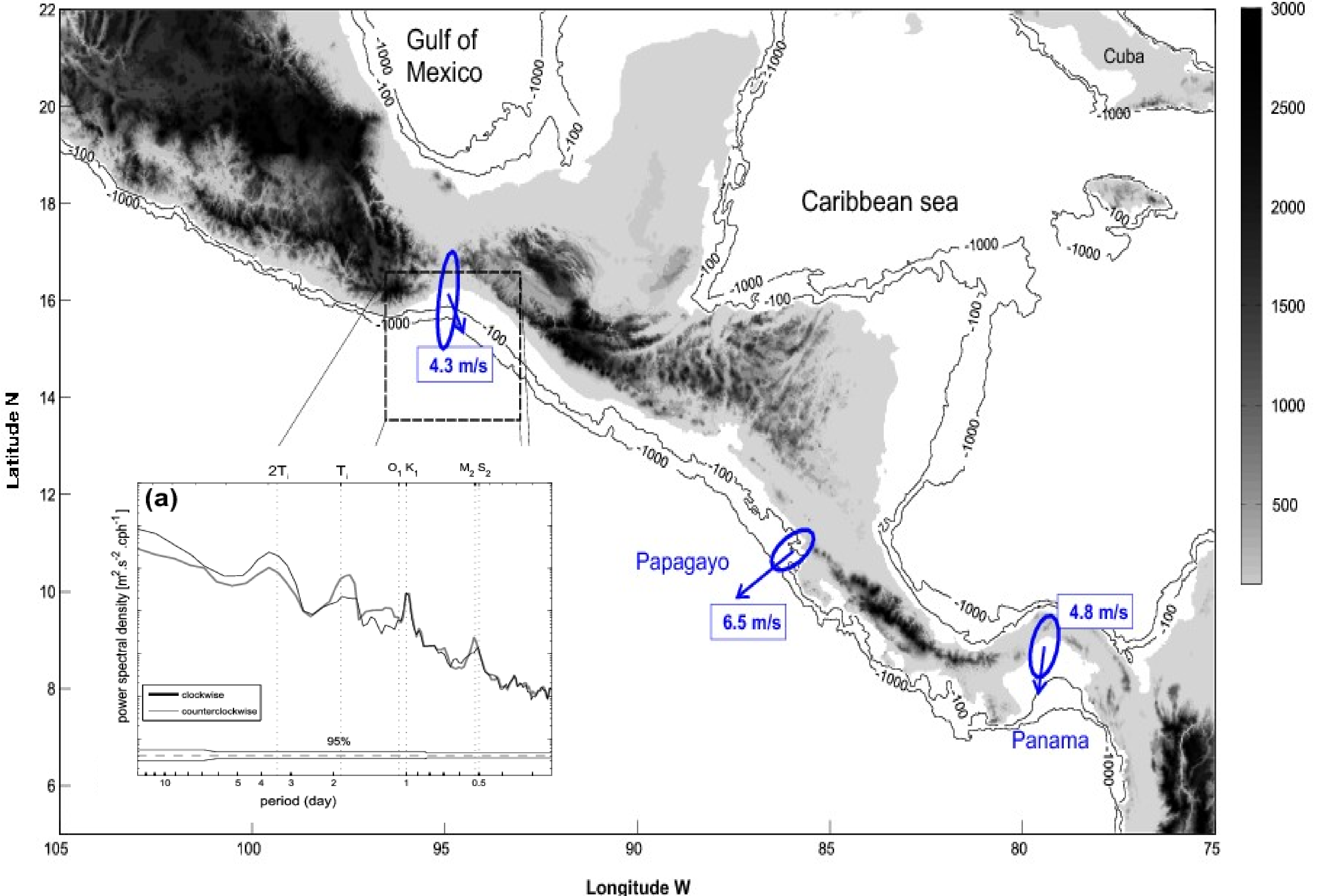
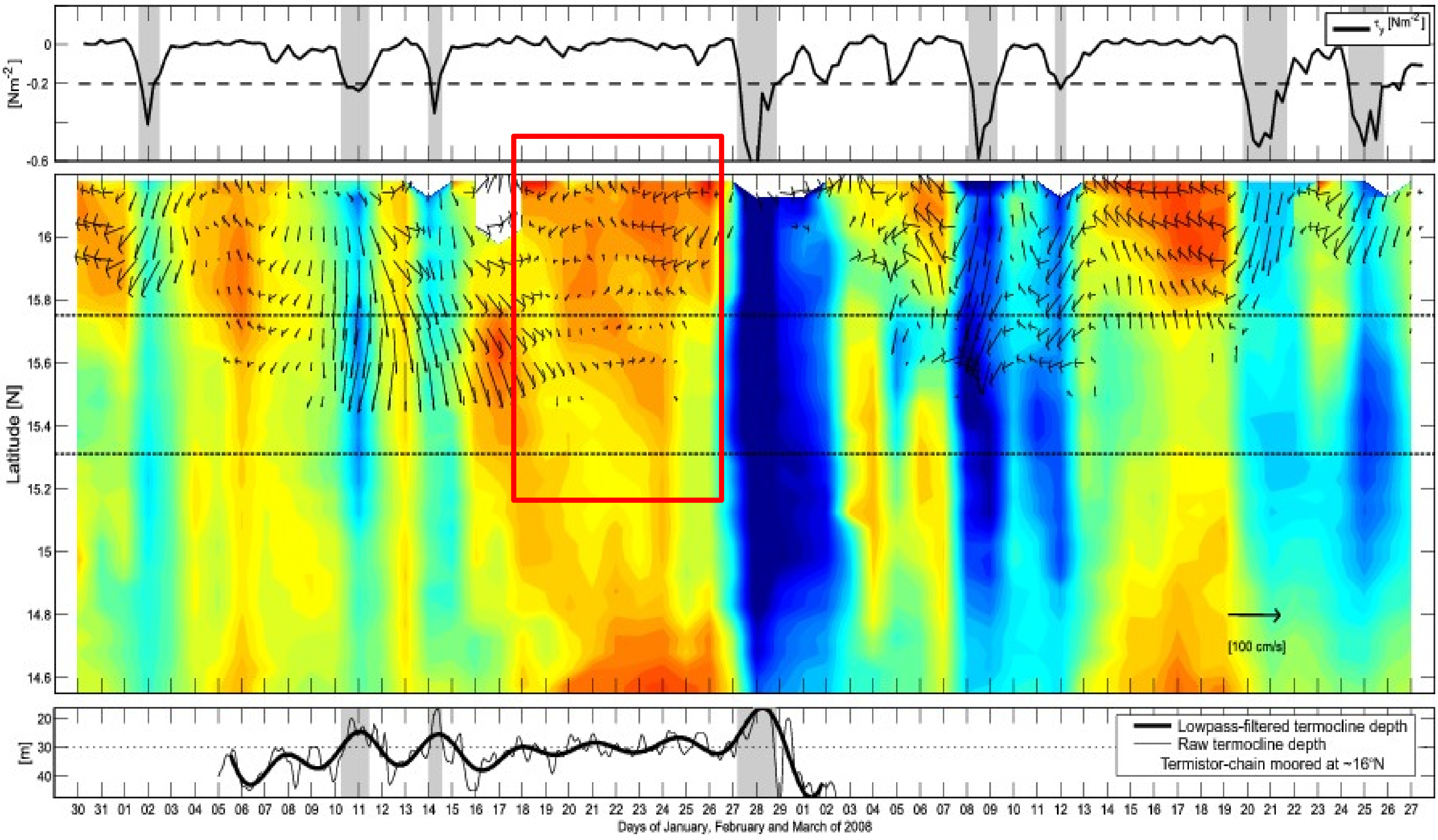
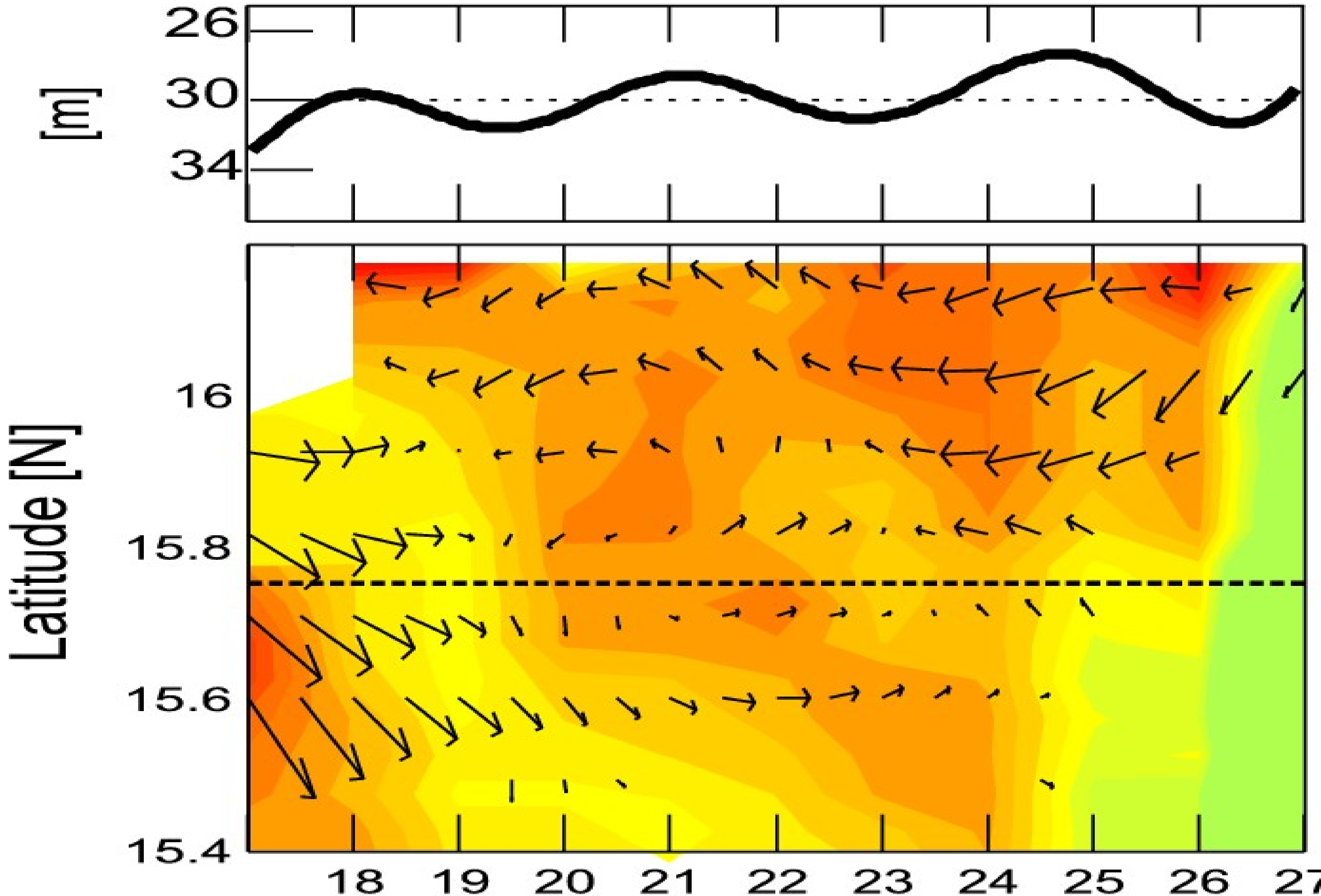
1. Gap winds statistics and surface currents power spectra



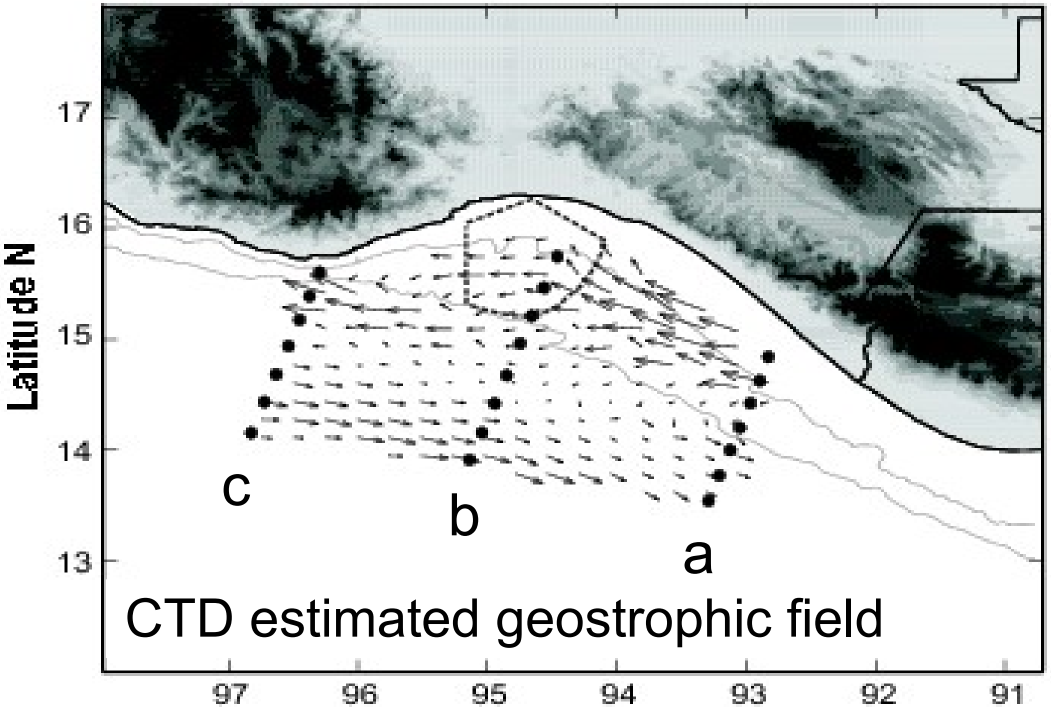
2. Variability over the transect

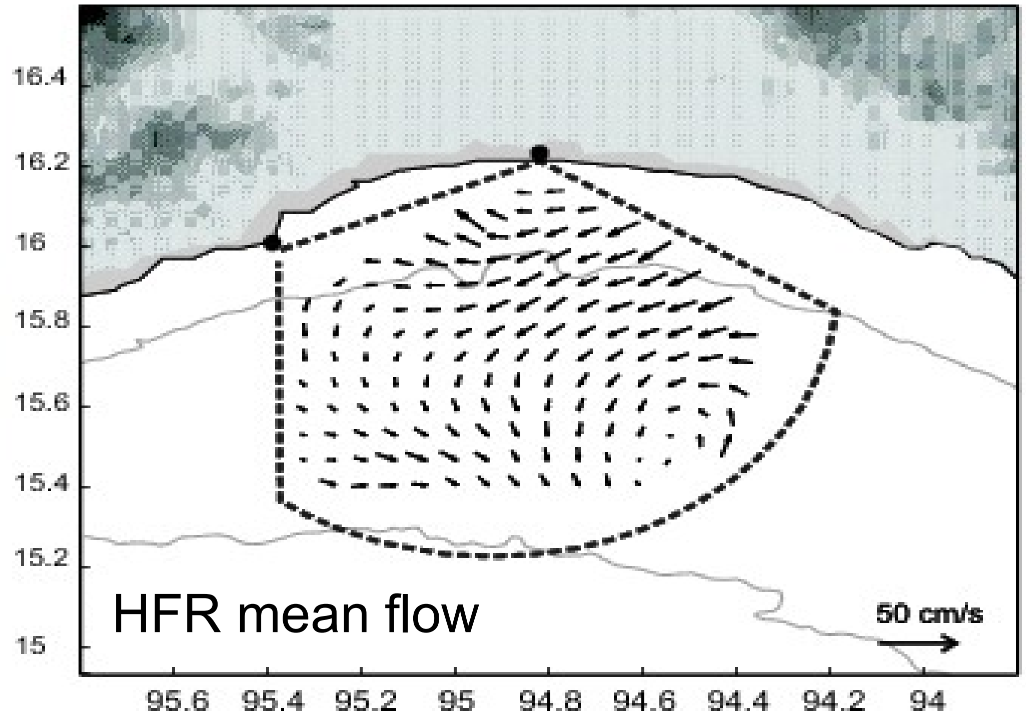


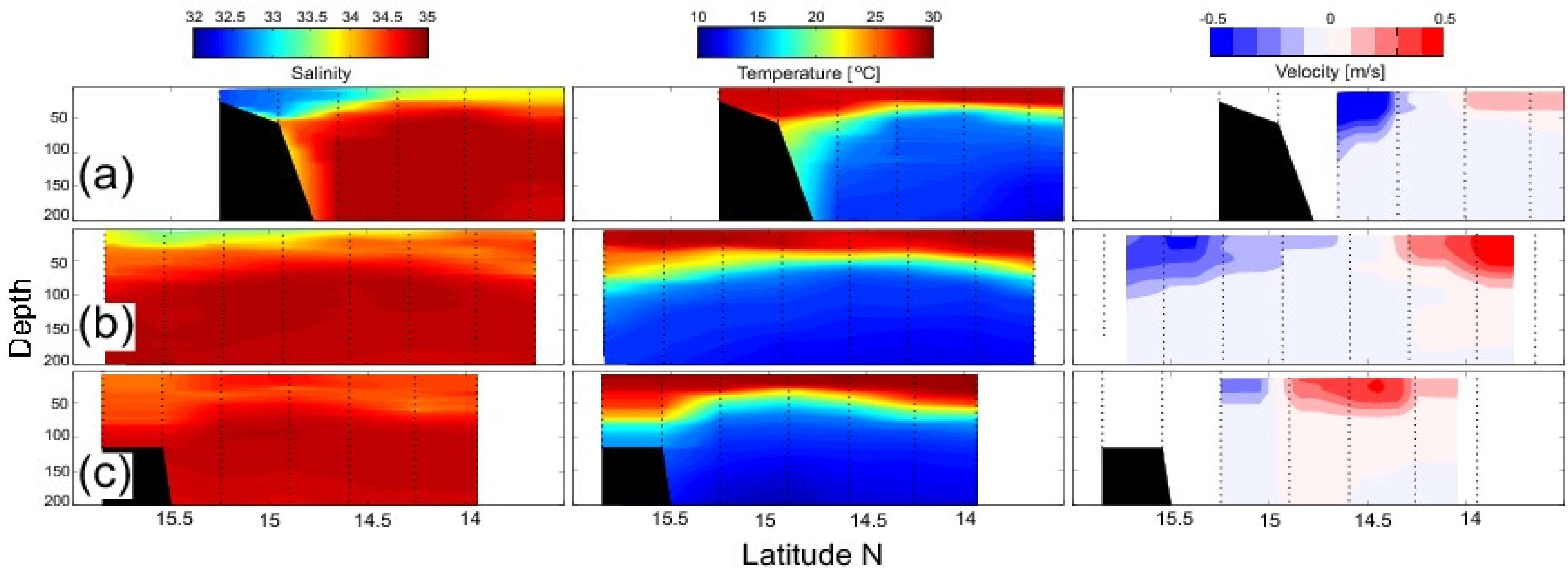


26
30
34
[m]
16
15.8
15.6
15.4
Latitude [N]
18
19
20
21
22
23
24
25
26
27

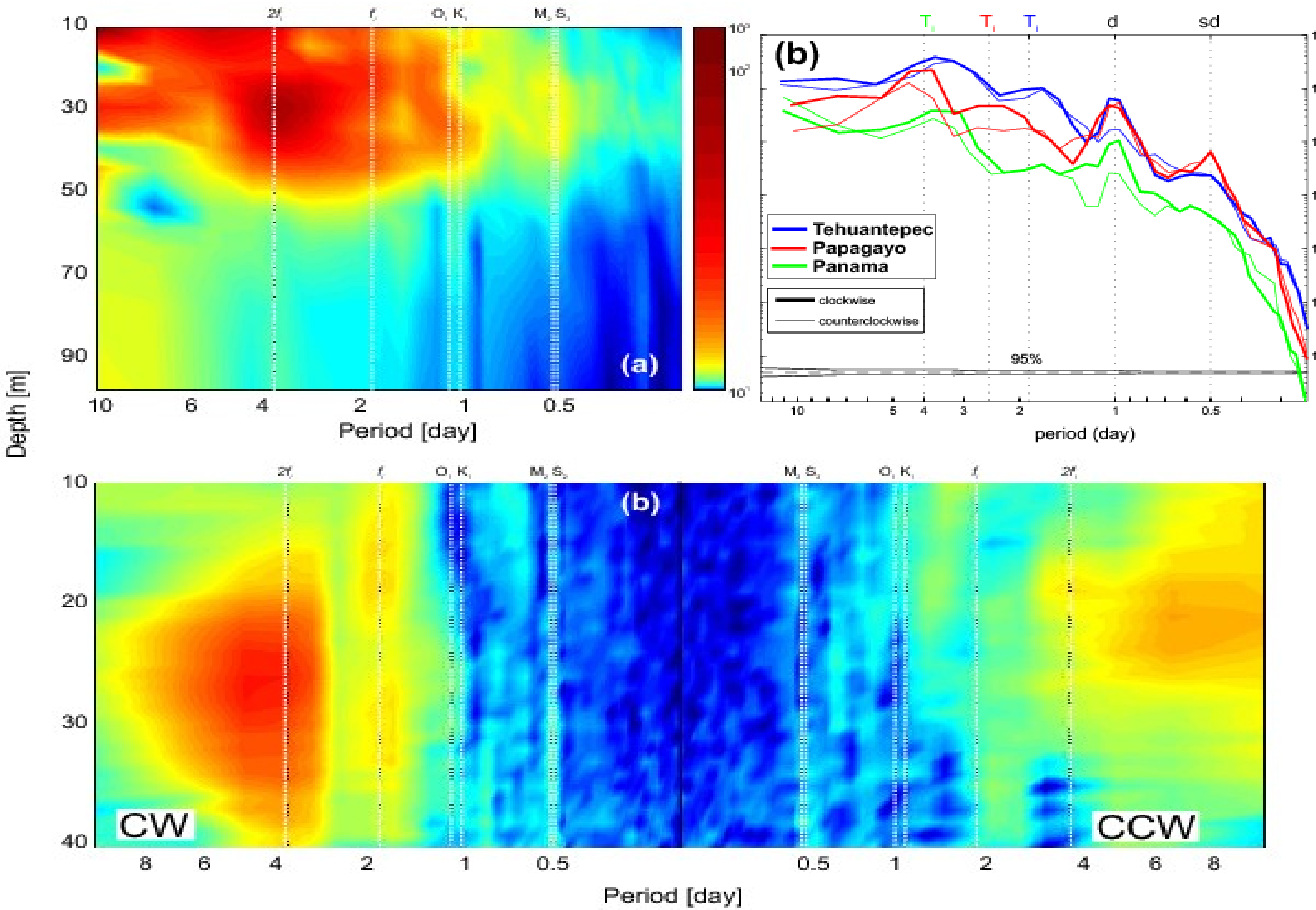
3. Geostrophic circulation







4. Spectral analysis: ADCP, thermistor-chain and wind at the three locations



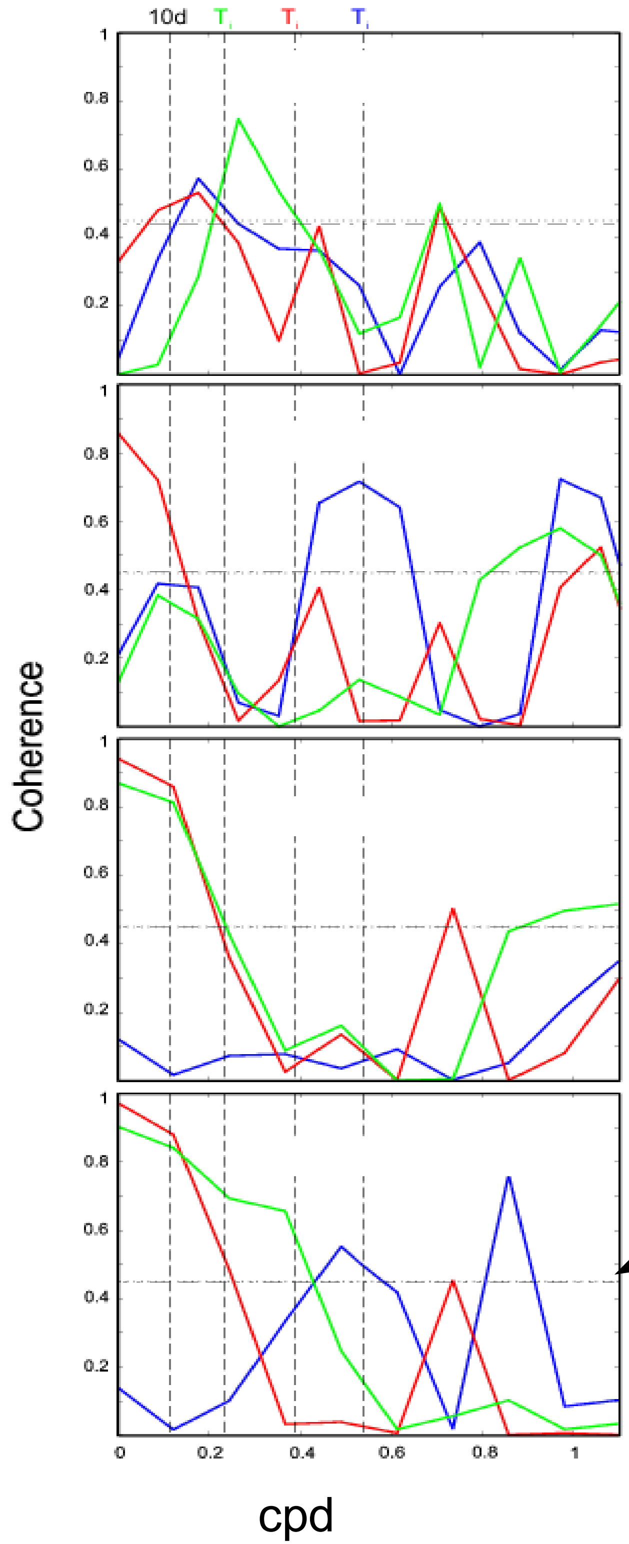
5. Coherence of cross-shore wind vs

Along-shore currents

Cross-shore currents

Sea surface temperature

Thermocline depth



95% confidence limit

6. Chapter synthesis

- ✔ The westward coastal current is restricted to the shelf and has a periodicity of ~ 4 days
- ✔ It is associated with warmer and less saline water
- ✔ It is barotropic at least over the continetal shelf
- ✔ The data suggest this coastal current behaves as a coastal arrested wave
- ✔ Coherence values shows that the origin of this coastal arrested waves may be the Gulf of Panamá.

Conclusions

1. A methodology to calibrate HFR using ships as reflectors was established

2. Circulation under low wind conditions (i.e. summer and autumn) was studied

3. We propose a value of 0.25 Nm^{-2} (~12 m/s) over which the wind-stress generates eddies. Thermocline pumping and cooling are also observed above this value

4. Poleward shelf arrested coastal currents composed by relatively warm and less saline water, were related to geostrophic variability

5. Coastal traped waves are proposed as the mechanism to explain the observed coastal current.

GRACIAS

-Dr. Reginaldo Durazo, quien ha impulsado el desarrollo de los HFR en México desde hace mucho tiempo

-Prof. Pierre Flament kindly invite me to collaborate at the Radar Laboratory of the University of Hawaii and trained me for about two years on field operations at Hawaii, China Sea, Bohol and Sulu seas, the Philippines and Taiwan.

-Al Dr. Francisco Ocampo, Julio Candela y Víctor Camacho por las revisiones y sugerencias realizadas a este trabajo.

-Dr. Cedric Chavanne, who kindly trained me on HFR postprocessing tools and had lots of ideas during data processing

-CONACYT, beca de posgrado 2006-2010, beca-mixta 2007

-Programa *POGO International Fellowship 2008*

-Personal académico y estudiantes de la Universidad del Mar, campus Puerto Ángel.

-Estación de Investigación Oceanográfica de la SEMAR en Salina Cruz, Oax.

-Los proyectos CONACYT ciencia básica U40822-F y 85108.

-UABC-FCM por la infraestructura y recursos adicionales mediante los programas 323, 341 y 361.

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apendix

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Remarks on HFR

Electromagnetic waves (EM) sent to the ocean are backscattered on surface waves of exactly half the radio wavelength. Since the ocean is covered by waves of many different wavelengths and directions (continuous spectrum), there are always trains of waves propagating toward and away from the transmitter. The return signal from either train will be Doppler-shifted by the wave velocity, which is known exactly by the gravity wave dispersion relationship.

$$c_p = \sqrt{\frac{2\pi g}{\lambda}\tanh(kH)}$$

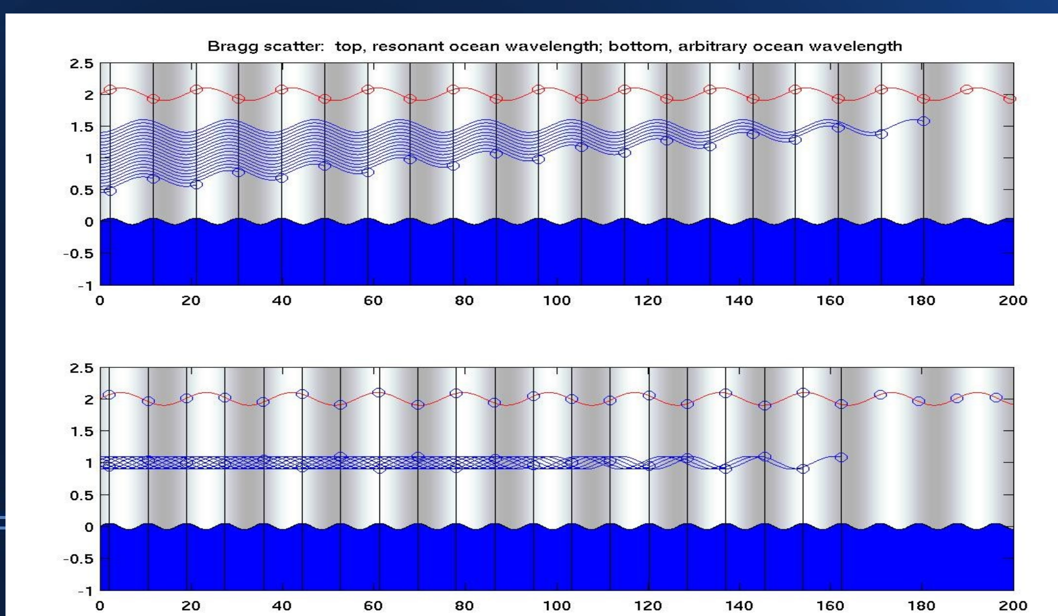
<-- Deep water (H > ½ λ)

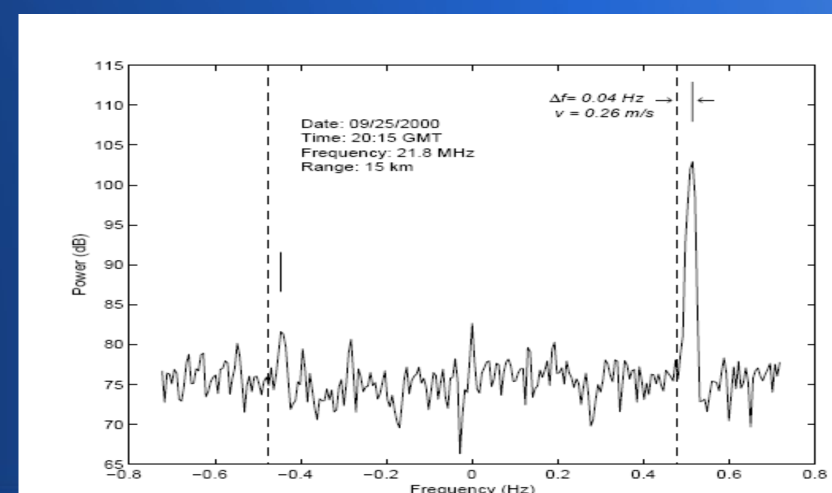
$$c_p = \sqrt{\frac{g\lambda}{2\pi}}$$

<-- Shallow water (H < ½ λ)

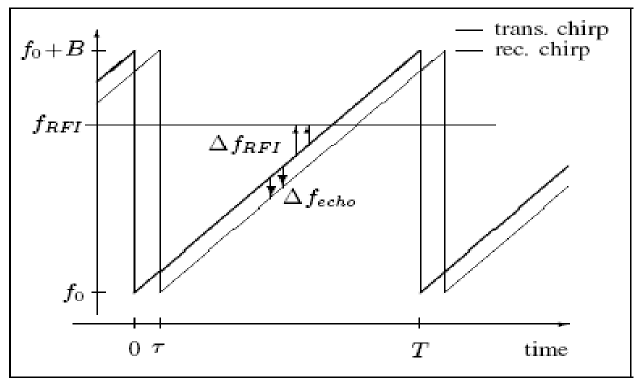
f=c/λ

V=Δf*λ





Range resolution can be obtained by "chirping" the signal, *i.e.* ramping the frequency on an interval of time T within a bandwith B. Typical bandwith are from 50 a 150 kHz. Such kind of signal modulation is known as FMCW (Frequency modulated continuous wave).



Spatial resolution is governed by the bandwidth of the chirps, and is defined as c/2B (*i.e.* B= 100 kHz --> 1.5 km)

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Complex analysis

$U(t) = u(t) + iv(t)$ Considering the velocity vector on its complex form

$$U(t) = \sum_{n=-\infty}^{+\infty} U_w e^{iwt}$$

we can define the Fourier transform for the angular velocity (omega).
where omega = 2πn/d and
d=is the length of the data record.

The angular pulsation (omega) will be an integral positive (CCW) or negative (CW), multiple of 2π/d. The coefficients U(omega) are computed from the sine and cosine Fourier coefficients of, U(t) and V(t), corresponding to the angular frequency,

$\sigma = |w|.$ [Gonella, 1972] .

Coherence

$$\gamma^2(w^\pm) = \frac{|\langle \tilde{U}_1 \tilde{U}_2^* \rangle|^2}{\langle \tilde{U}_1 \tilde{U}_1^* \rangle \langle \tilde{U}_2 \tilde{U}_2^* \rangle}$$

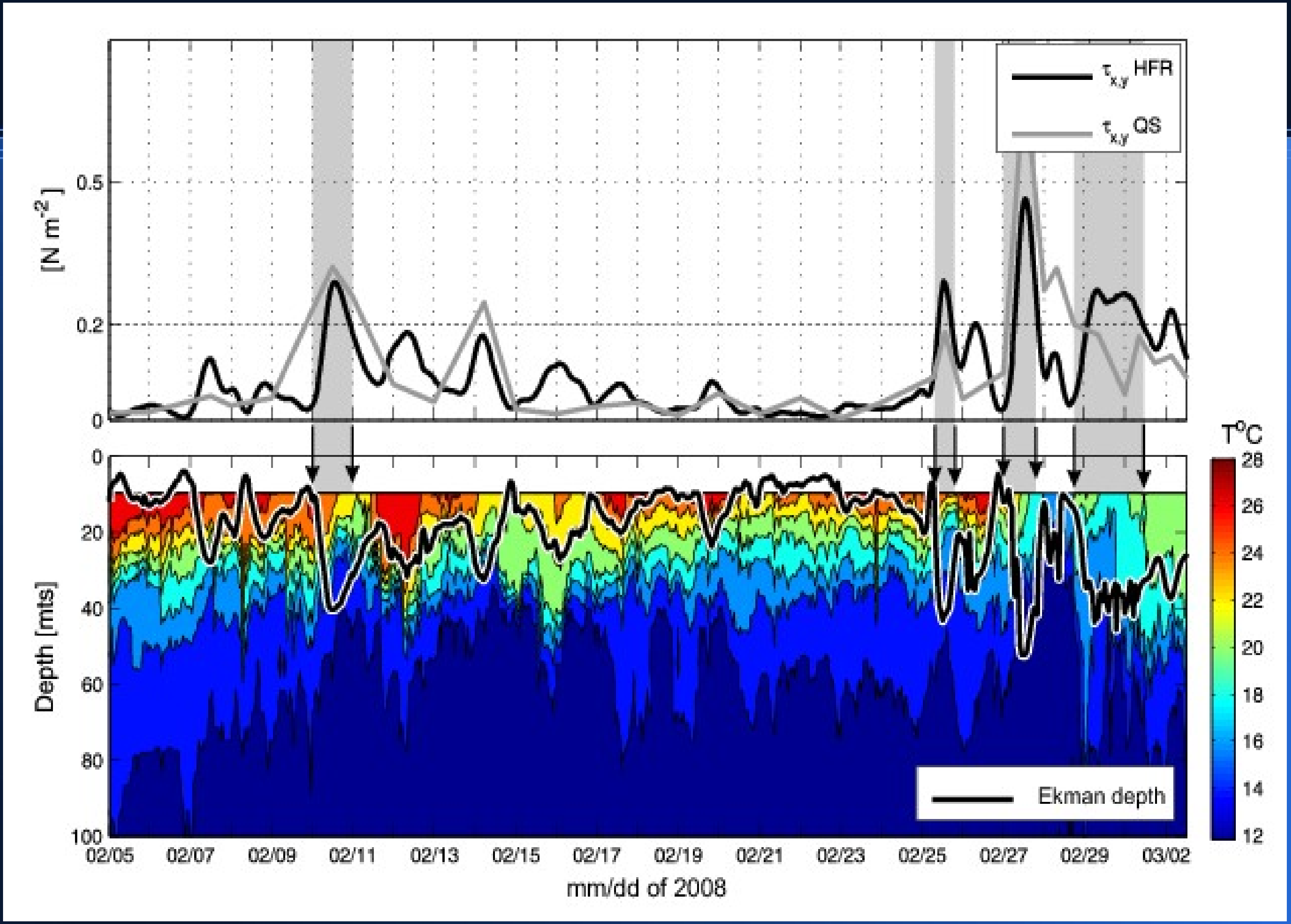
Phase

$$\phi_c(w^\pm) = \arctan\left[\frac{Im(\langle \tilde{U}_1 \tilde{U}_2^* \rangle)}{Re(\langle \tilde{U}_1 \tilde{U}_2^* \rangle)}\right]$$

Admittance (transfer function),

$$H(w^\pm) = \frac{\langle \tilde{U}_1 \tilde{U}_2^* \rangle}{\langle \tilde{U}_2 \tilde{U}_2^* \rangle}$$

where ~ designates the Fourier transform and * the complex conjugate.



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