From Grand Combin to an Upwelling Bay: the Ría de Vigo

Miguel Gilcoto

Grand Combin?

Grand Combin?

A mountain range located in the Switzeland-Italy border

GRAND COMBIN SUMMER SCHOOL

Aspetti fondamentali della meccanica dei fluidi geofisici ed ambientali

Problèmes fondamentaux de la méchanique des fluides géophysiques et environmentaux

Fundamental problems in geophysical and environmental fluid mechanics

Course 2001

The fluid dynamics of coastal seas, closed basins and lakes

St. Oyen (Aosta) - June 13-23, 2001

Directors: Peter Davies (Univ. Dundee, UK), Joel Sommeria (CNRS, Grenoble).

http://www.to.isac.cnr.it/grandcombin/aosta2001/

http://www.to.isac.cnr.it/grandcombin/aosta2001/participants.html

GRAND COMBIN SUMMER SCHOOL

Course 2001

The fluid dynamics of coastal seas, closed basins and lakes

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http://www.to.isac.cnr.it/grandcombin/aosta2001/participants.html

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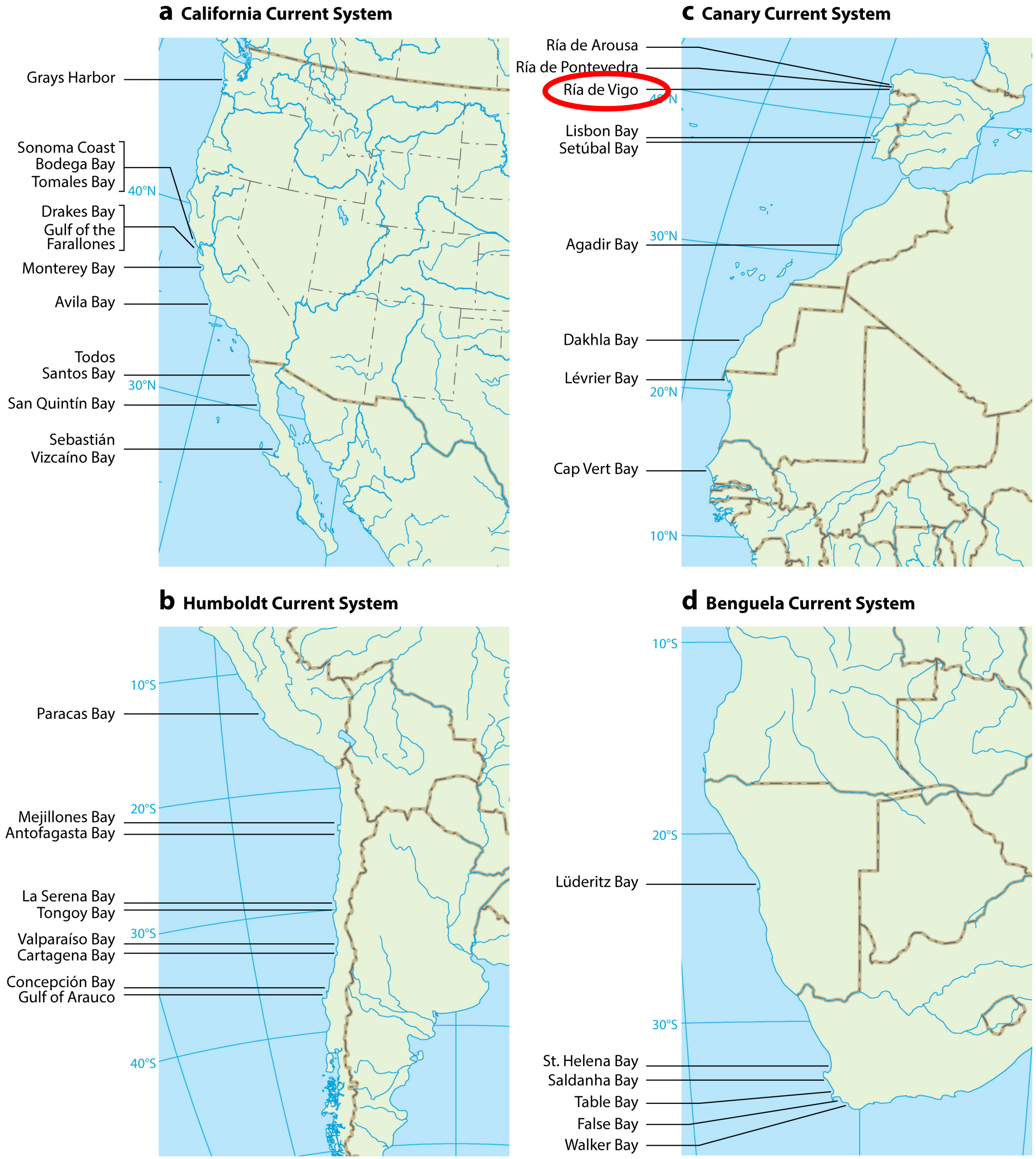
Upwelling bays?



Annual Review of Marine Science

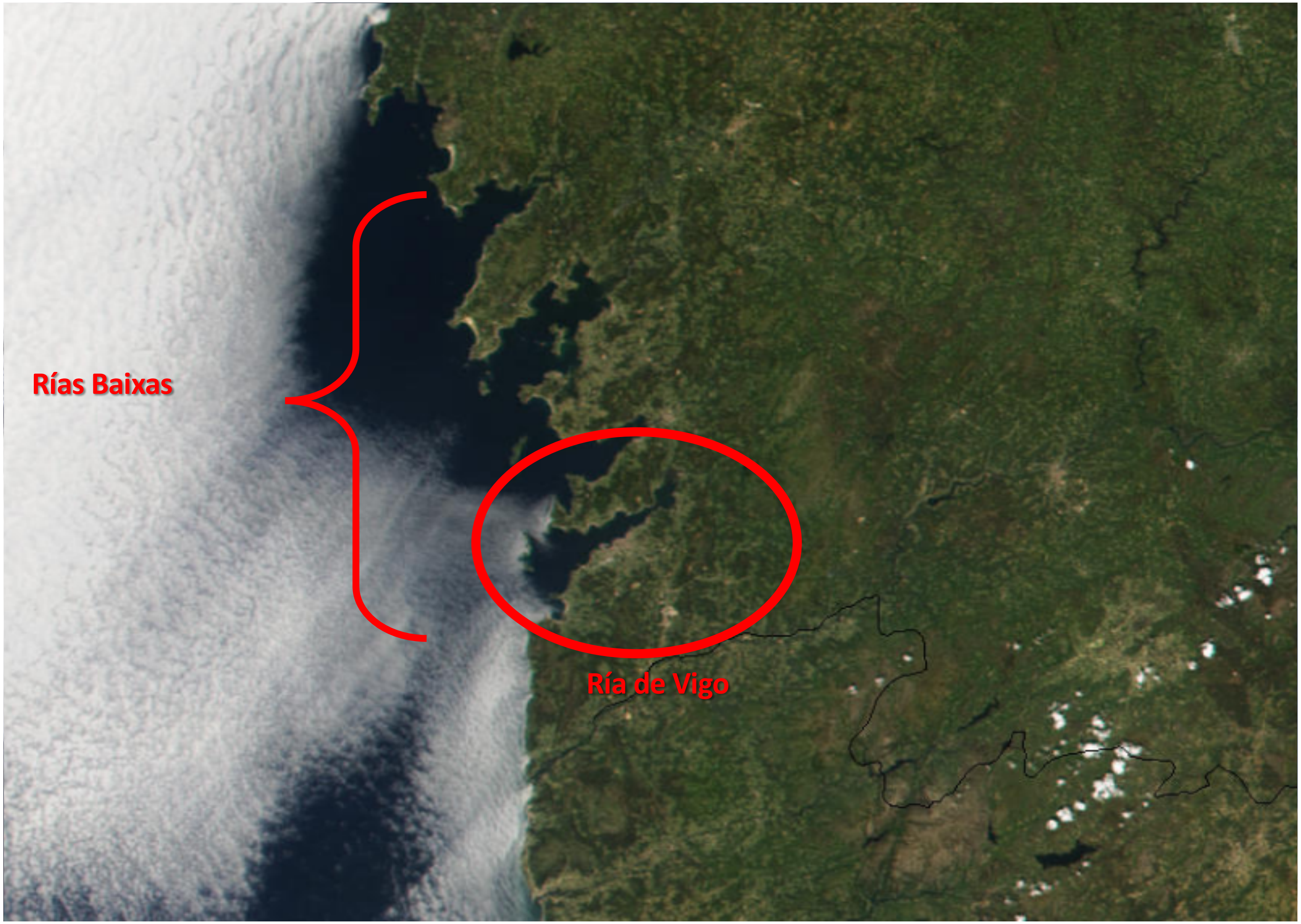
Upwelling Bays: How Coastal Upwelling Controls Circulation, Habitat, and Productivity in Bays

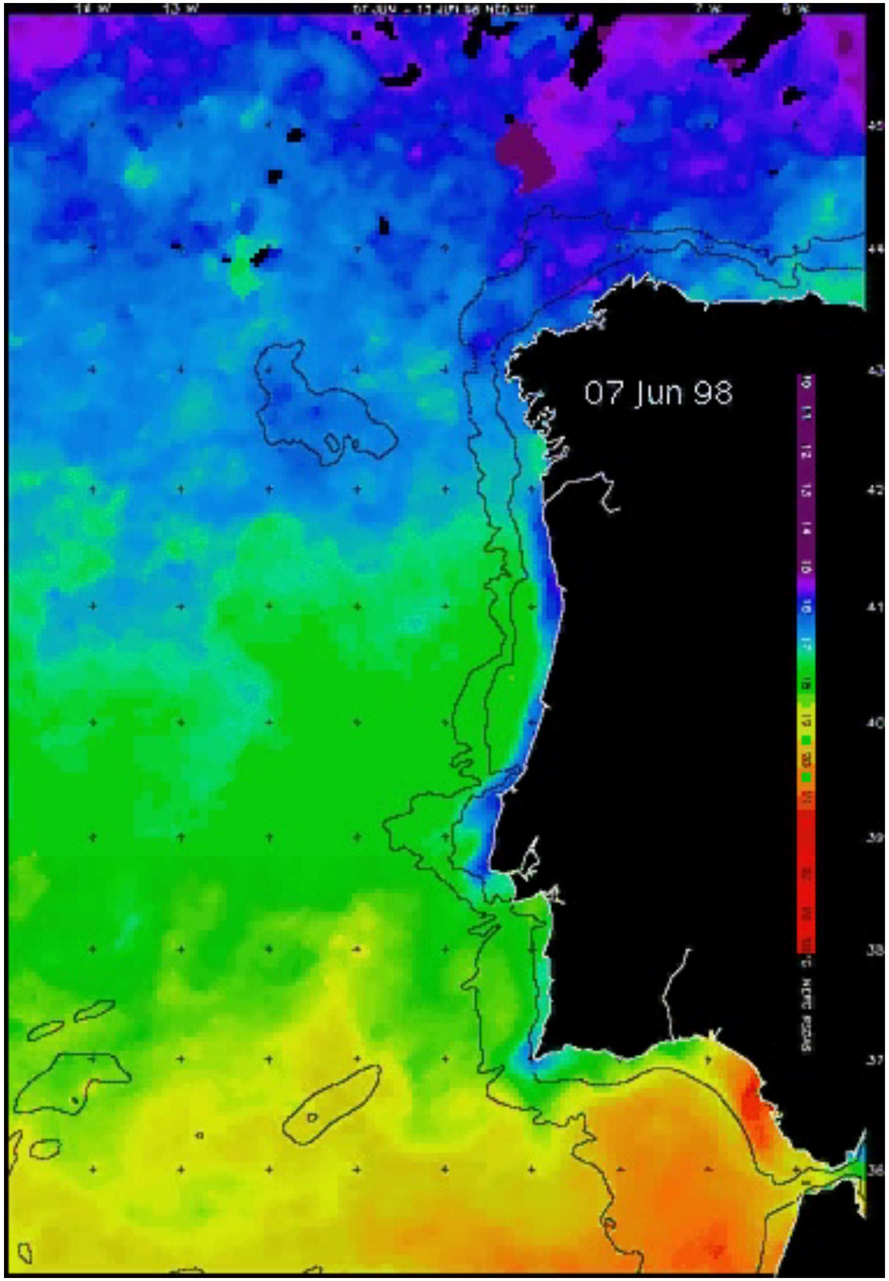
John L. Largier[1,2]

[1]Department of Environmental Science and Policy, University of California, Davis, California 95616, USA

[2]Coastal and Marine Sciences Institute, University of California, Davis, Bodega Bay, California 94923, USA; email: jlargier@ucdavis.edu

Largier JL. 2020.
Annu. Rev. Mar. Sci. 12:415–47


Rías Baixas
Ría de Vigo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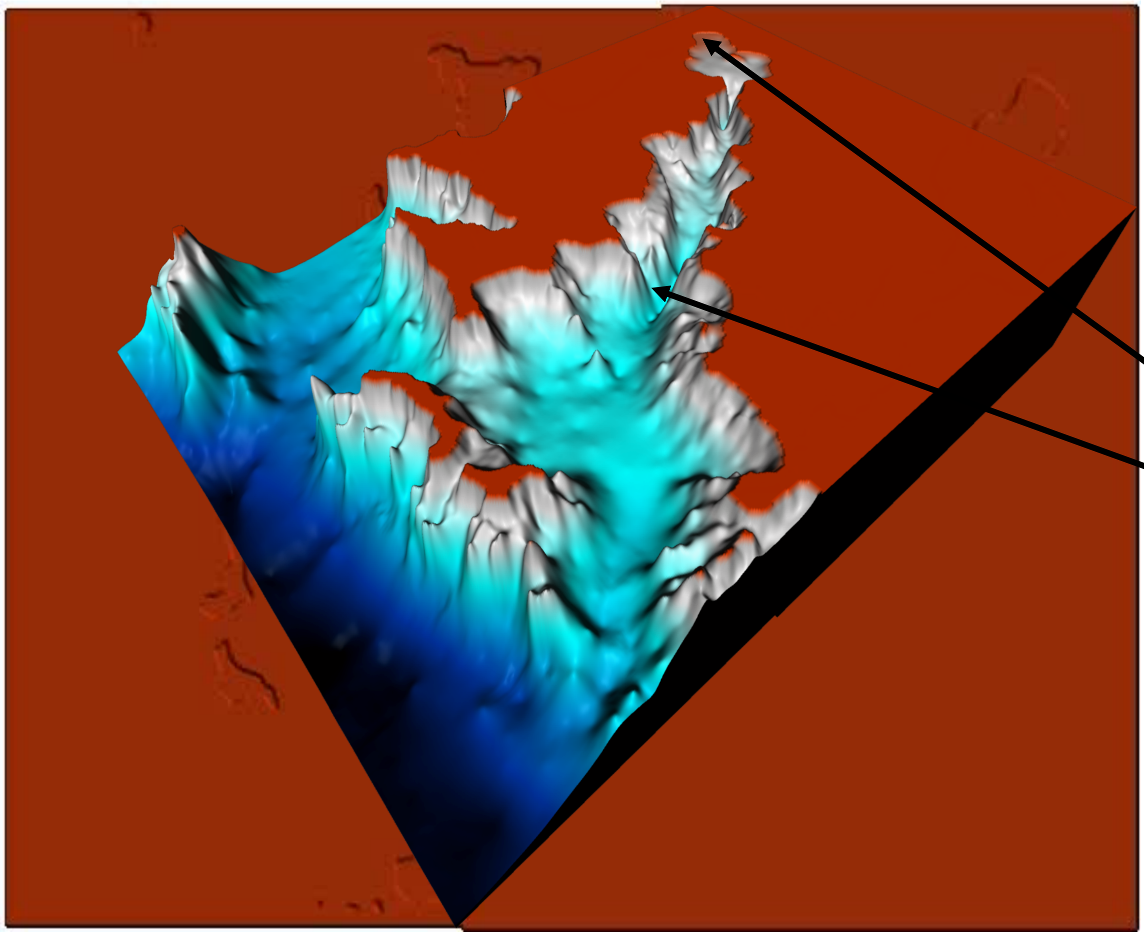

- Geologically: Drowned valley.
- River at the head of the ria (max. ~100 m^3/s).
- V-Shaped bathymetry

  20m average depth

  45m maximum

  60m at South Mouth

- **A partially-mixed estuary**

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- Therefore the Ria de Vigo is an estuary.
- It should show estuarine, gravitational, circulation described by:

$$u(z)=\frac{3\cdot Q_R}{h\cdot L_y}\cdot\left[\frac{z}{h}-\frac{1}{2}\cdot\left(\frac{z}{h}\right)^2\right]+\frac{1}{48}\cdot\frac{g}{\rho\cdot K}\cdot\frac{\partial\rho}{\partial x}\cdot h^3\cdot\left[-\frac{6\cdot z}{h}+15\cdot\left(\frac{z}{h}\right)^2-8\cdot\left(\frac{z}{h}\right)^3\right]$$

Bidirectional flow

- Therefore the Ria de Vigo is an estuary.
- It should show estuarine, gravitational, circulation described by:

$$\frac{\partial \rho}{\partial x} = -4{\cdot}10^{-4}\ \mathrm{kg{\cdot}m^{-4}}$$

$$L_y = 3000\ \mathrm{m}$$

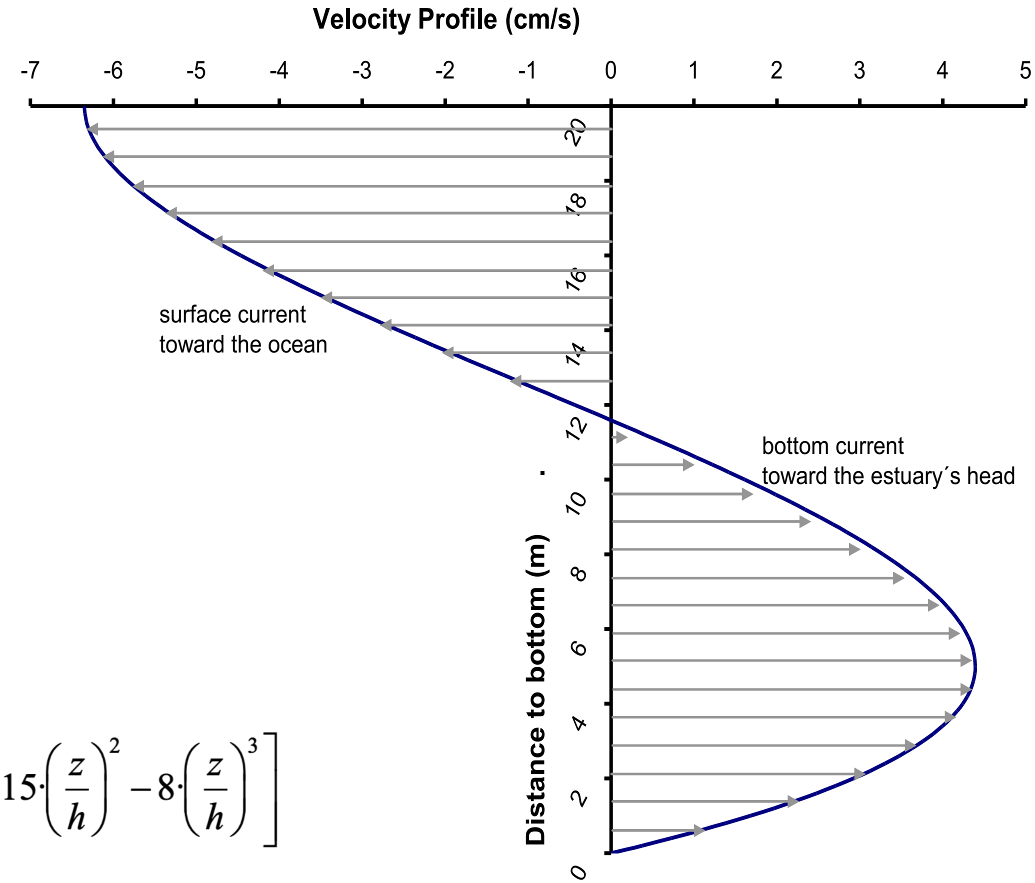
$$K = 10^{-2}\ \mathrm{m^2{\cdot}s}$$

$$h = 20\ \mathrm{m}$$

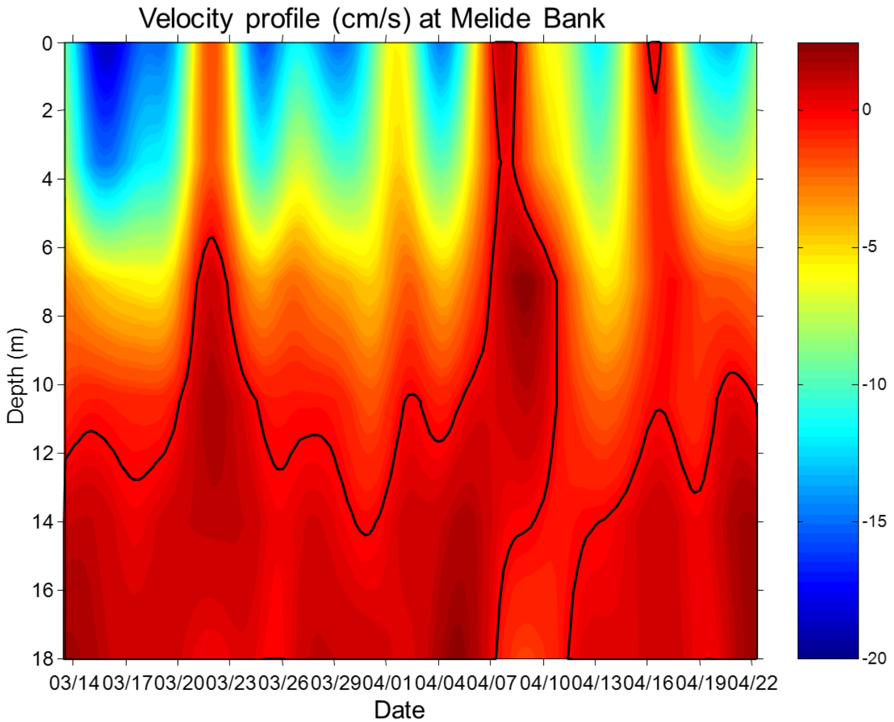
$$\rho = 1025\ \mathrm{kg{\cdot}m^3}$$

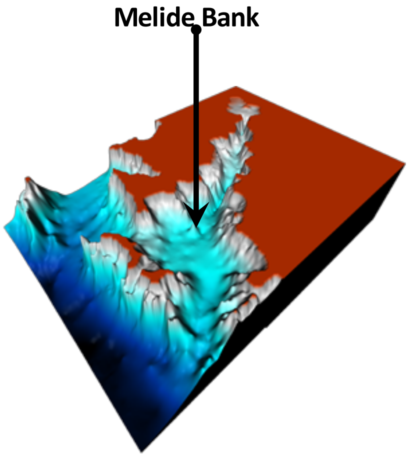
$$Q_R = 10\ \mathrm{m^3{\cdot}s^{-1}}$$

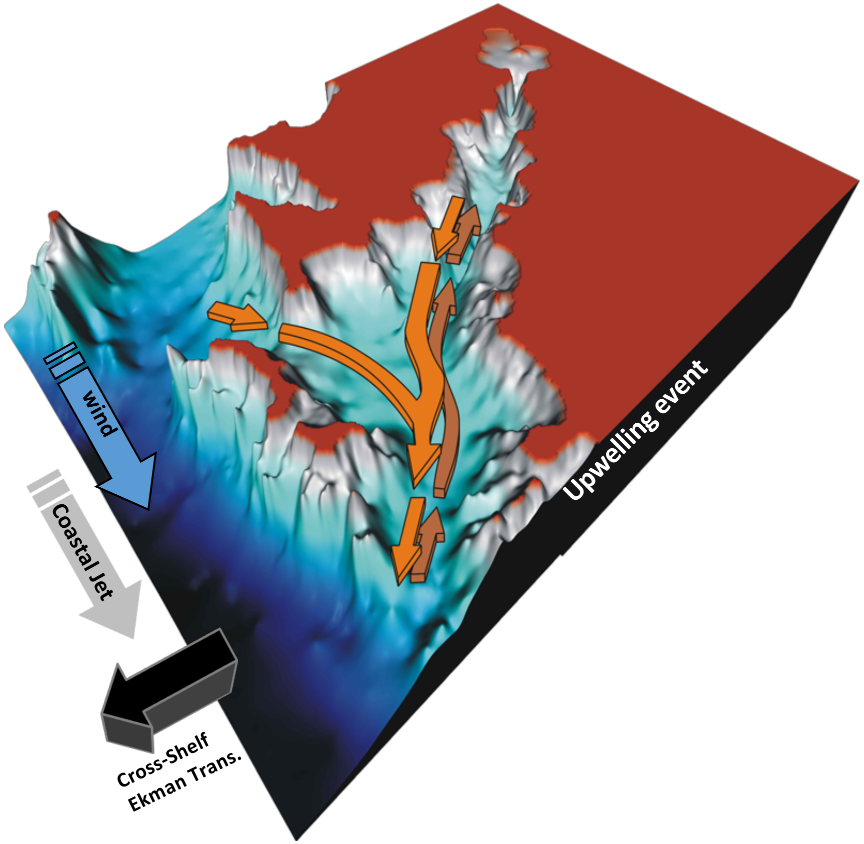
$$u(z) = \frac{3{\cdot}Q_R}{h{\cdot}L_y}{\cdot}\left[\frac{z}{h} - \frac{1}{2}{\cdot}\left(\frac{z}{h}\right)^2\right] + \frac{1}{48}{\cdot}\frac{g}{\rho{\cdot}K}{\cdot}\frac{\partial \rho}{\partial x}{\cdot}h^3{\cdot}\left[-\frac{6{\cdot}z}{h} + 15{\cdot}\left(\frac{z}{h}\right)^2 - 8{\cdot}\left(\frac{z}{h}\right)^3\right]$$

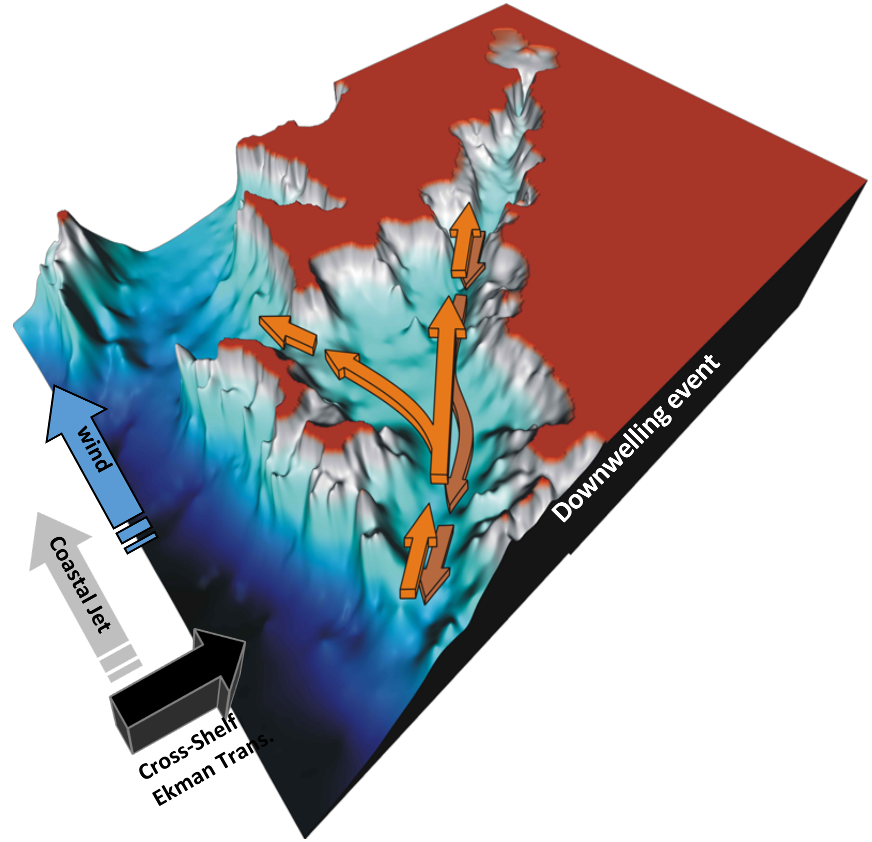


- But, the observational data tell us other, more complicated, story:









Souto, C., M. Gilcoto, L. Fariña-Busto, and F.F. Pérez (2003)
Modelling the residual circulation of a coastal embayment affected by wind driven upwelling: circulation of the Ría de Vigo (NW Spain).
Journal of Geophysical Research, 108(C11), 3340-3358.

Gilcoto, M., P. C. Pardo, X. A. Álvarez-Salgado, and F. F. Pérez (2007)
Exchange fluxes between the Ría de Vigo and the shelf: A bidirectional flow forced by remote wind
Journal of Geophysical Research, 112(C06), 21.

Barton, E. D., J. L. Largier, R. Torres, M. Sheridan, A. Trasviña, A. Souza, Y. Pazos, and A. Valle-Levinson (2015)
Coastal upwelling and downwelling forcing of circulation in a semi-enclosed bay: Ria de Vigo
Progress in Oceanografy, 134, 173-189.

STRAMIX Project

Vertical Profiles of Currents

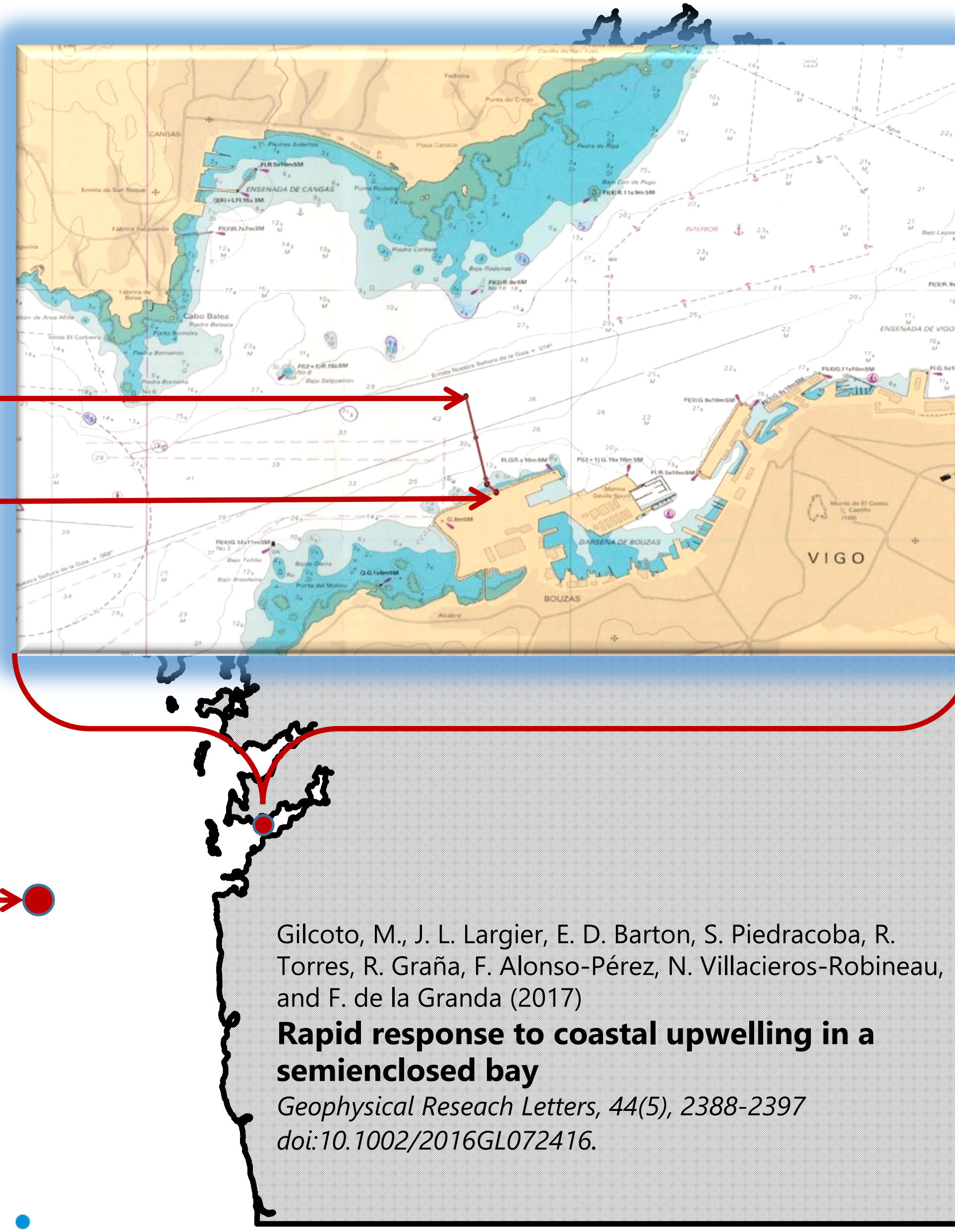
RDI ADCP (IIM-CSIC)
Sampling Frequency: 2 Hz
Time Span: 20.Jun.2013-13.Ago.2014
Coverage: 93.76%

Local Winds

Bouzas Meteo Station (IIM-CSIC)
Sampling Frequency: 1 Minute
Time Span: 01.Jan.2013-31.Dec.2014
Coverage: 96.77%

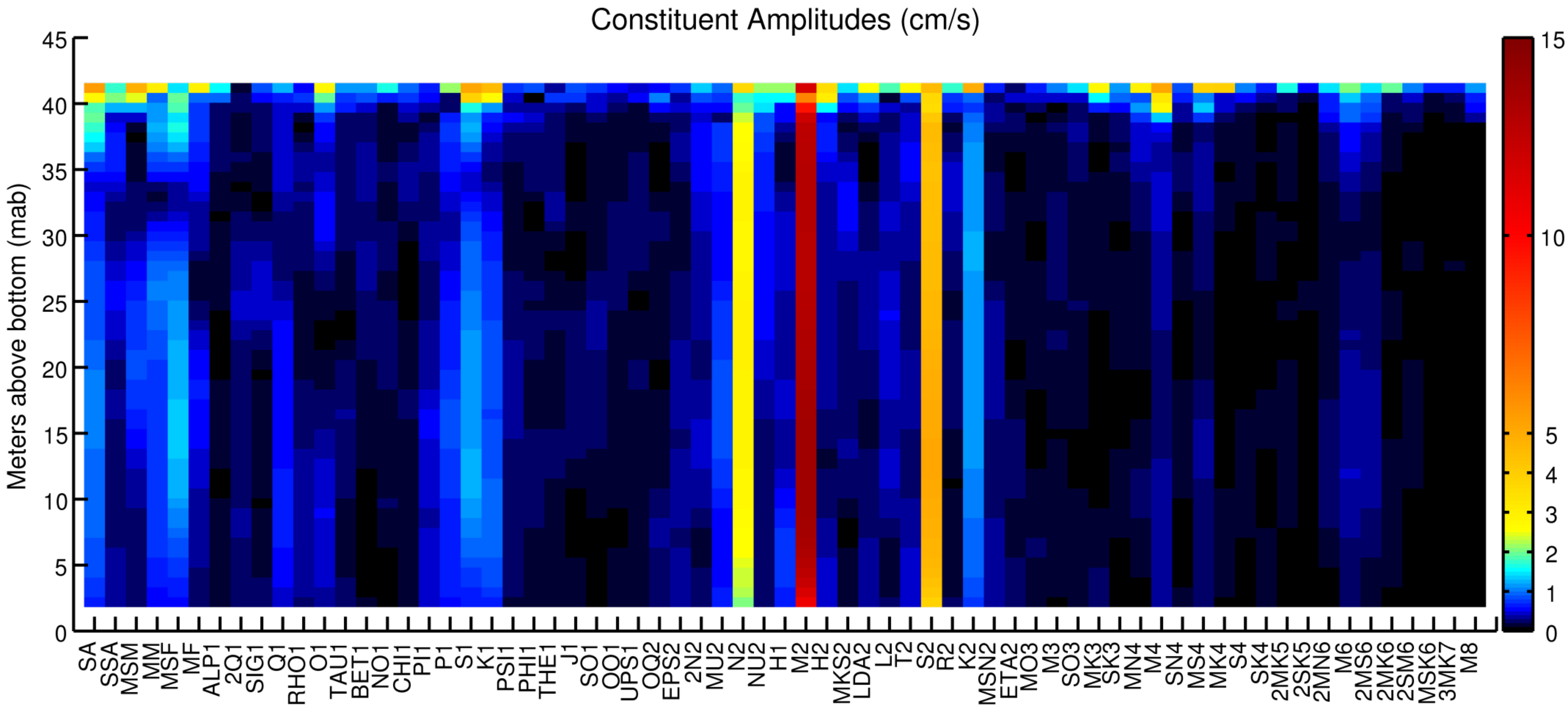
Remote Winds

Silleiro Buoy (Puertos del Estado)
Sampling Frequency: 1Hour
Time Span: 01.Jan.2013-31.Dec.2014
Coverage: 82.20%



Gilcoto, M., J. L. Largier, E. D. Barton, S. Piedracoba, R. Torres, R. Graña, F. Alonso-Pérez, N. Villacieros-Robineau, and F. de la Granda (2017)
Rapid response to coastal upwelling in a semienclosed bay
Geophysical Reseach Letters, 44(5), 2388-2397
doi:10.1002/2016GL072416.

Tidal Harmonic Analysis: complete set of constituents



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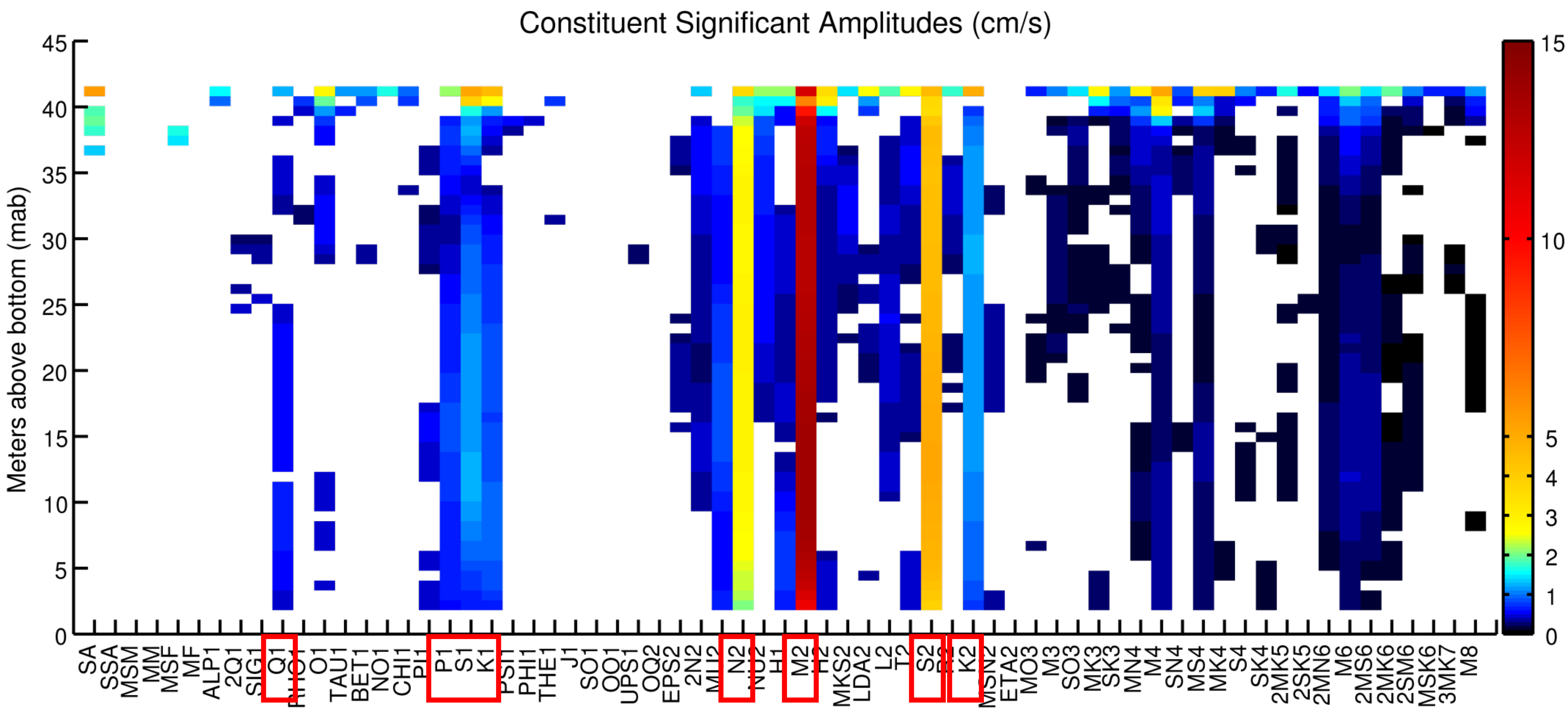
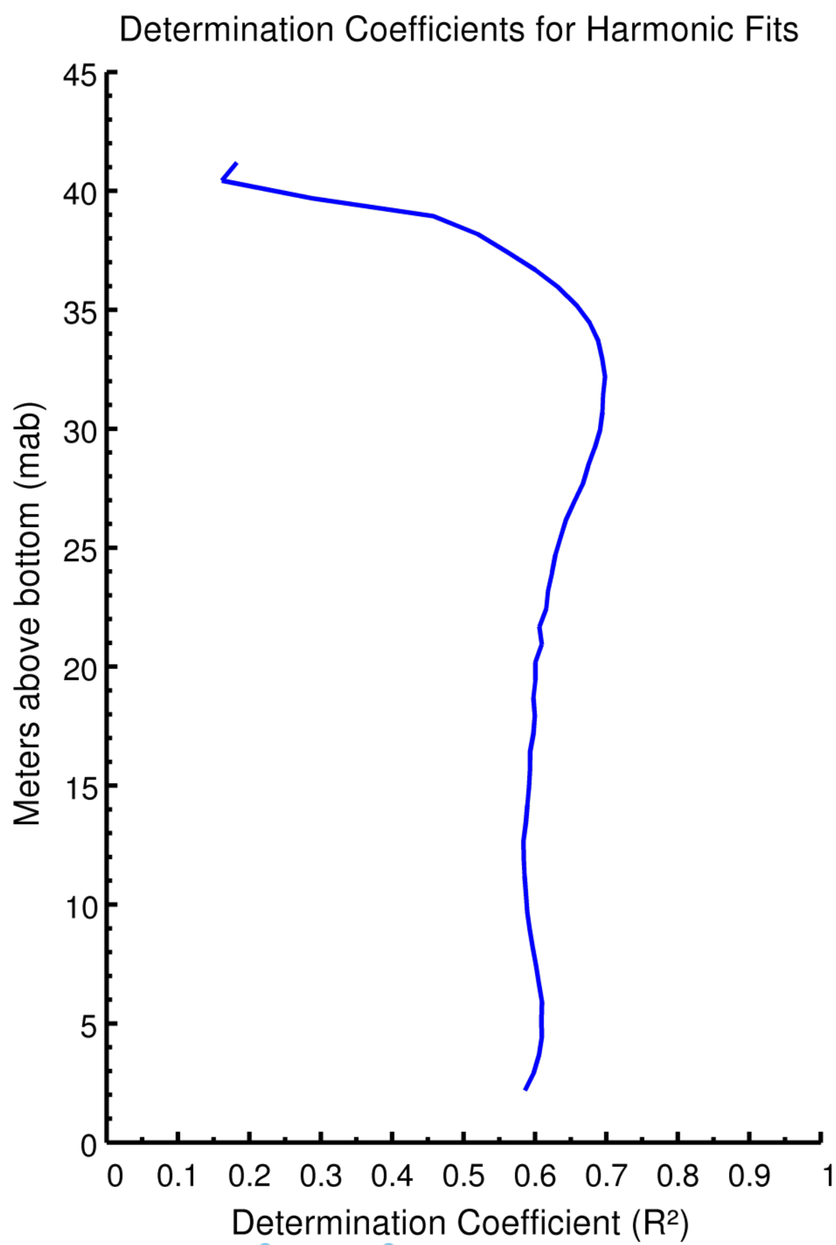
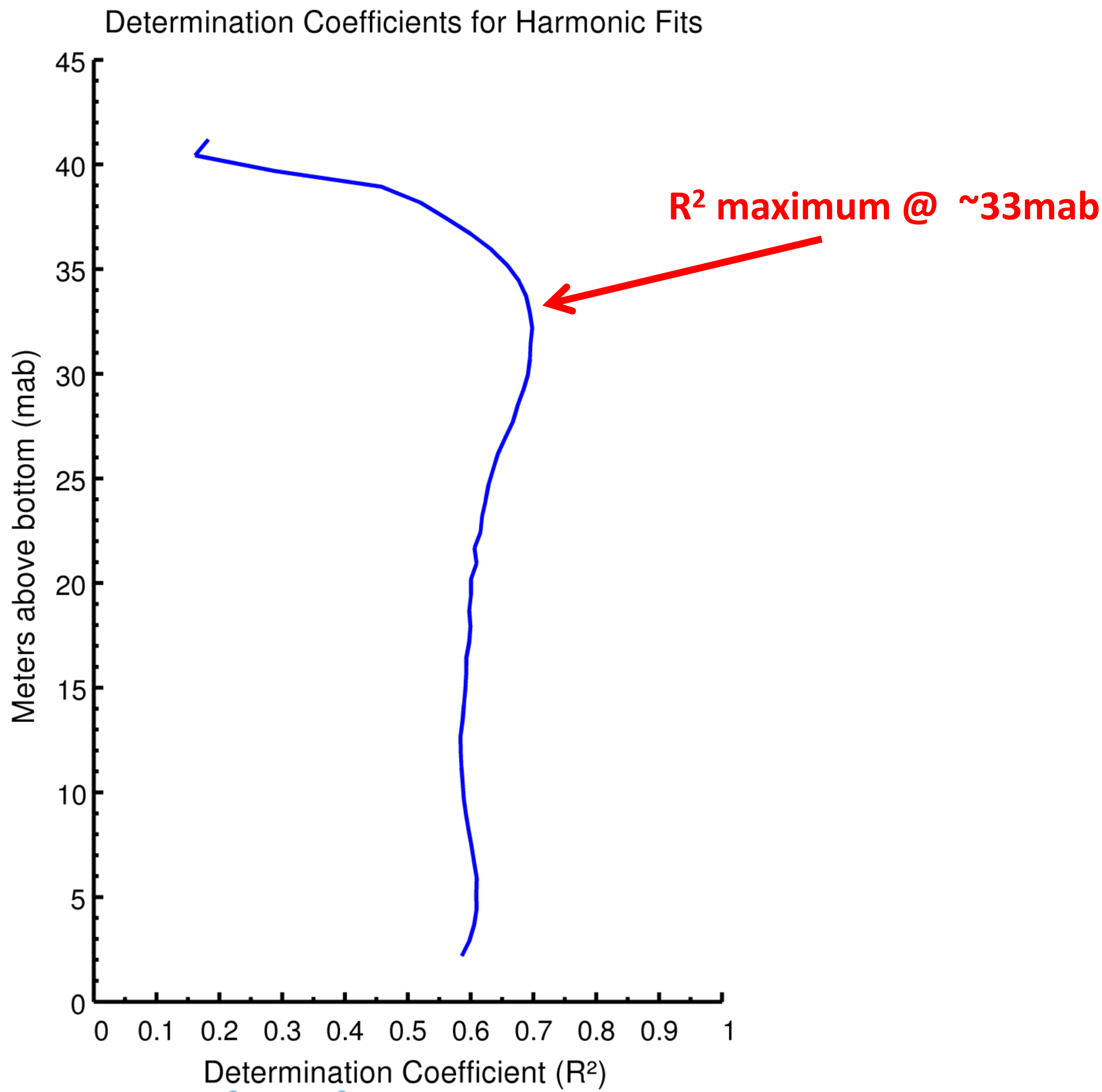
Tidal Harmonic Analysis: only SNR>2 constituents



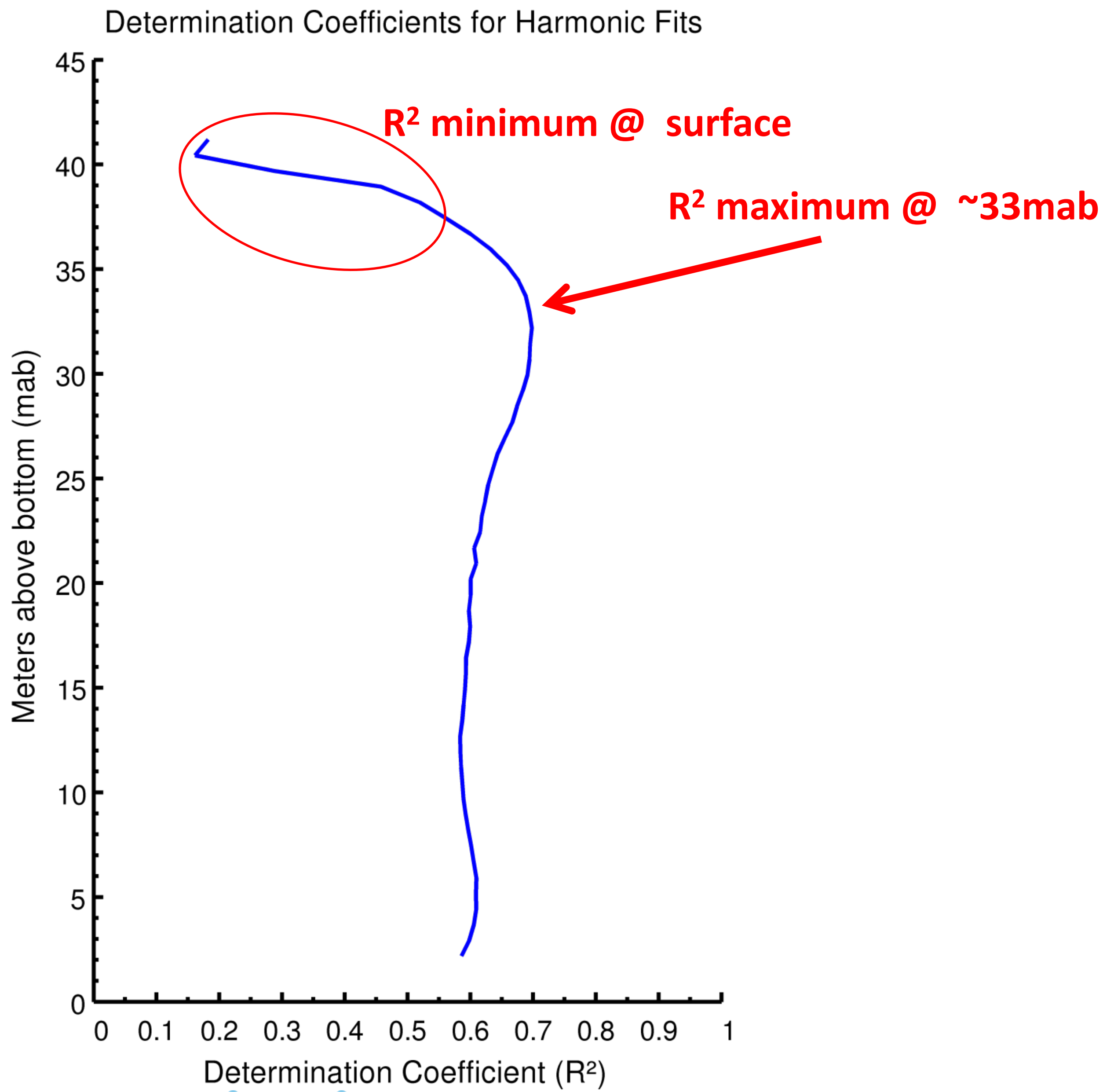


Determination Coefficients for Harmonic Fits
Meters above bottom (mab)
45
40
35
30
25
20
15
10
5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Determination Coefficient (R²)

Tidal Harmonic Analysis: vertical distribution of R^2



Tidal Harmonic Analysis: vertical distribution of R^2



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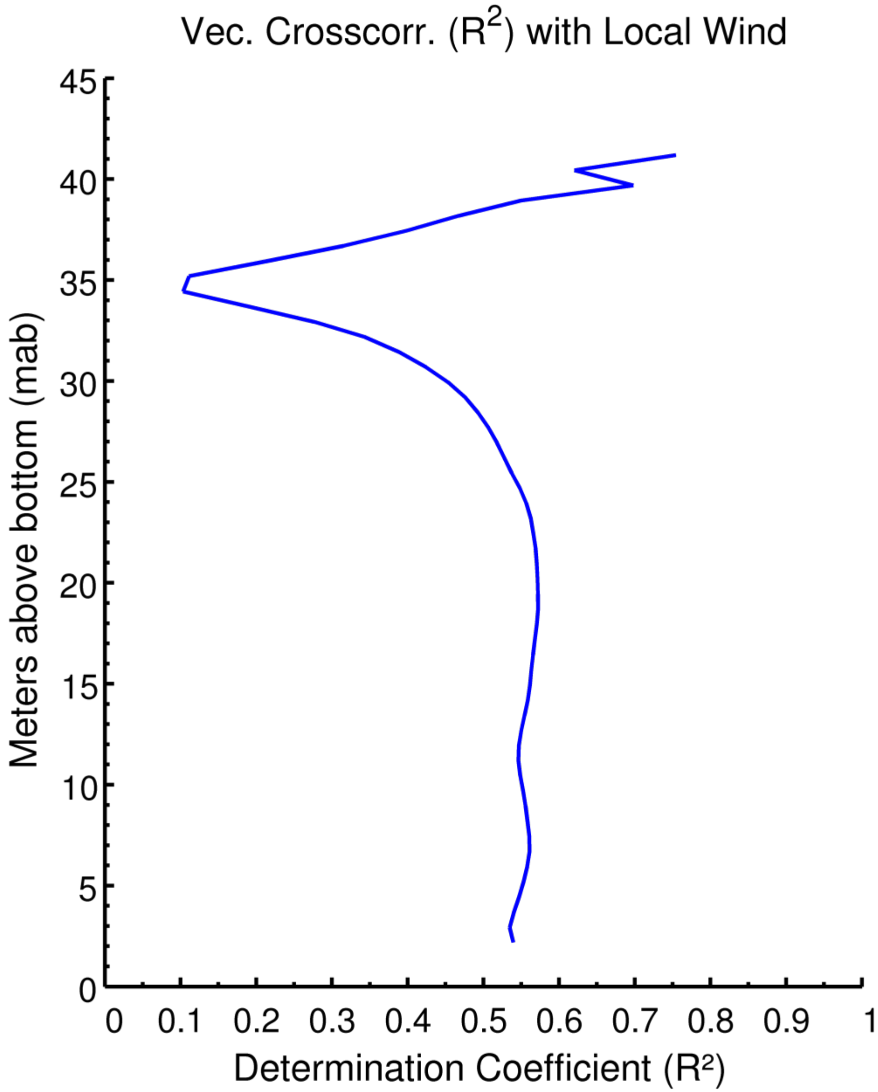
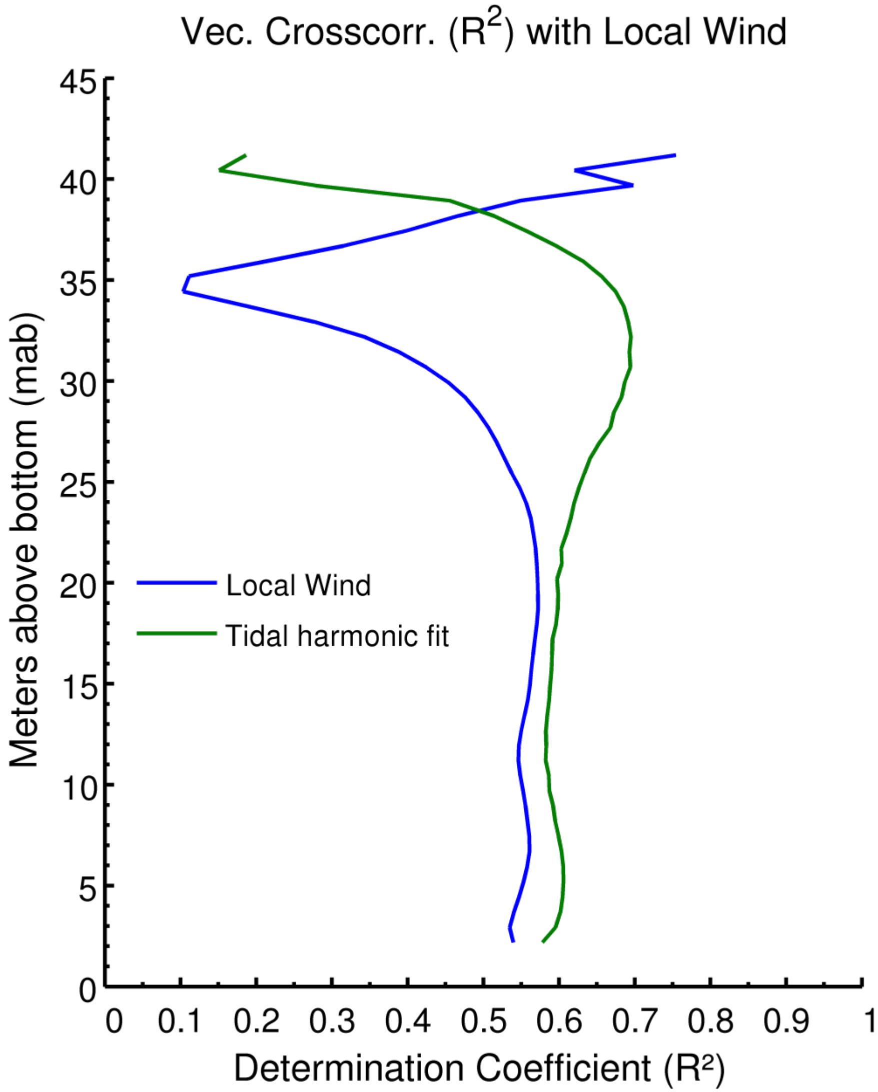
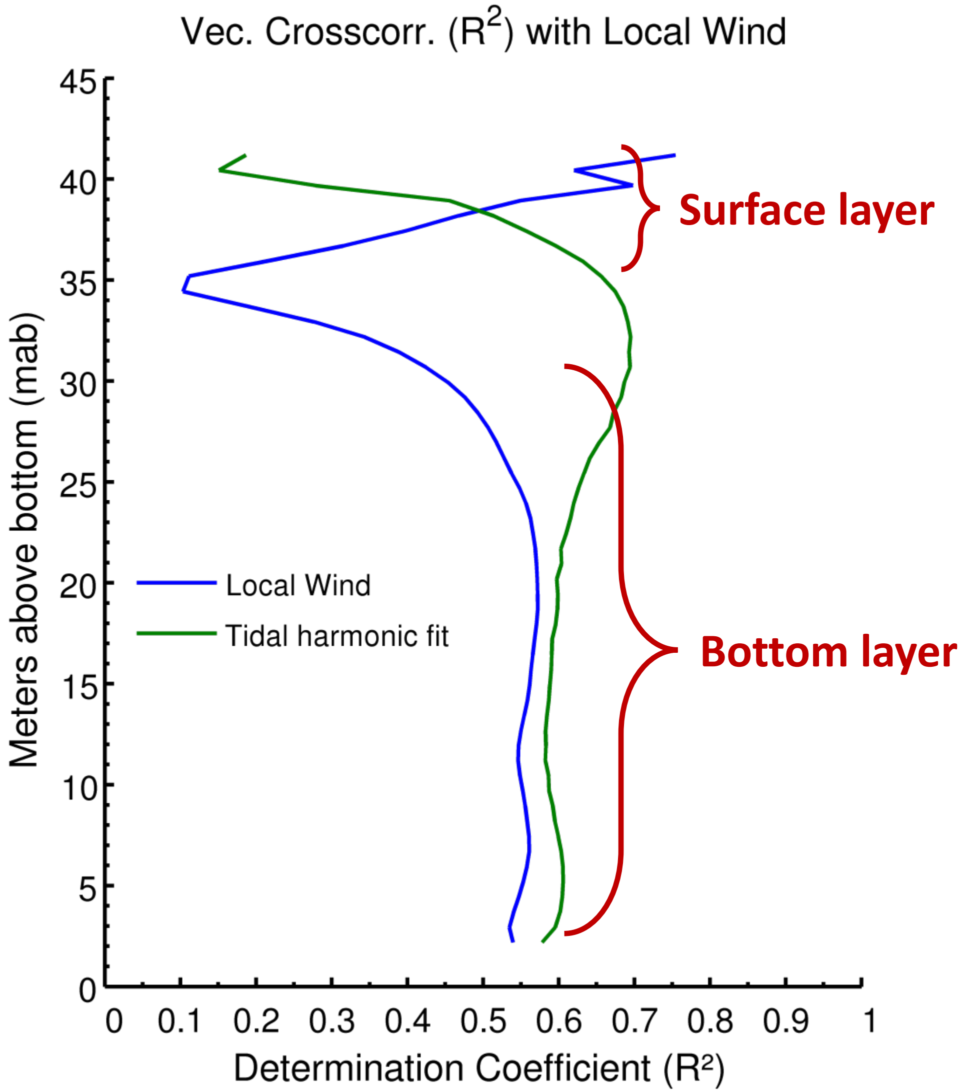
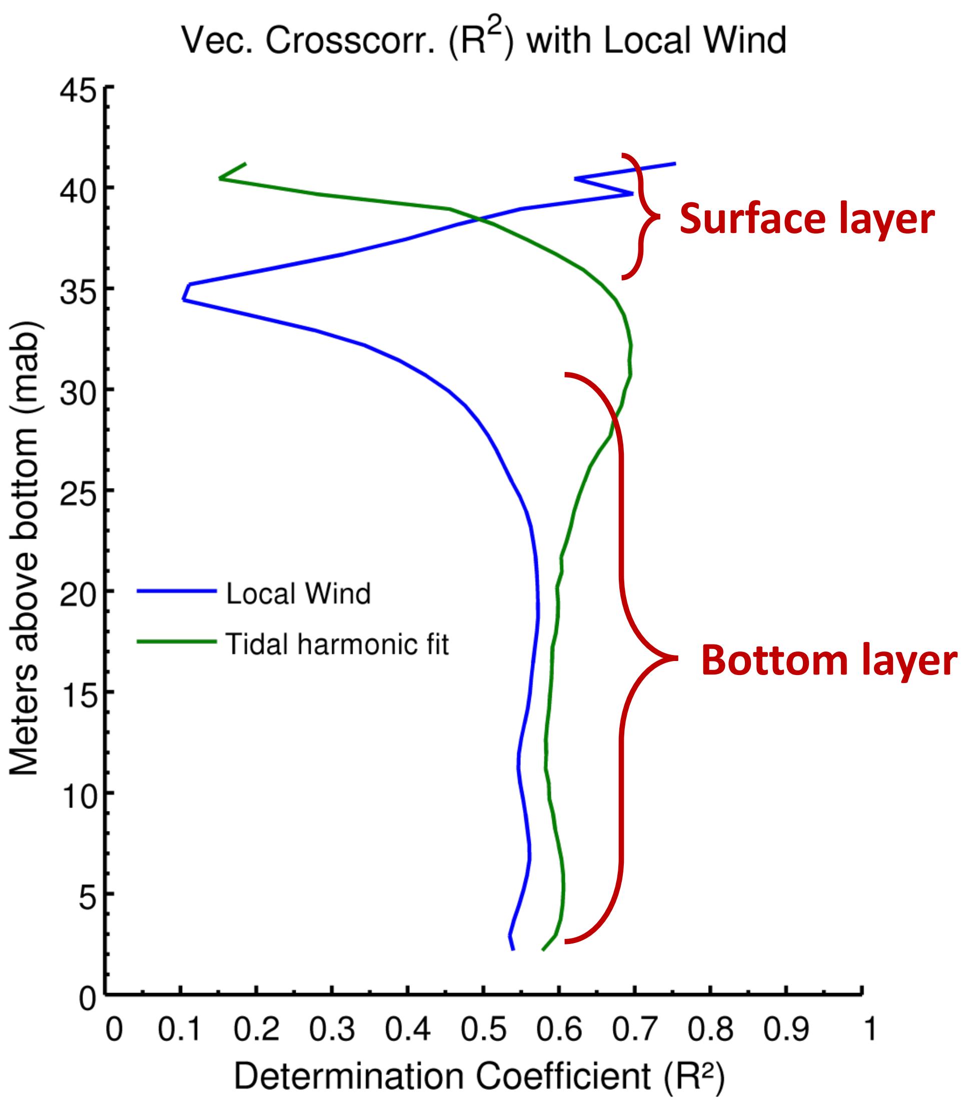

Vec. Crosscorr. (R^2) with Local Wind
Meters above bottom (mab)
45
40
35
30
25
20
15
10
5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Determination Coefficient (R^2)



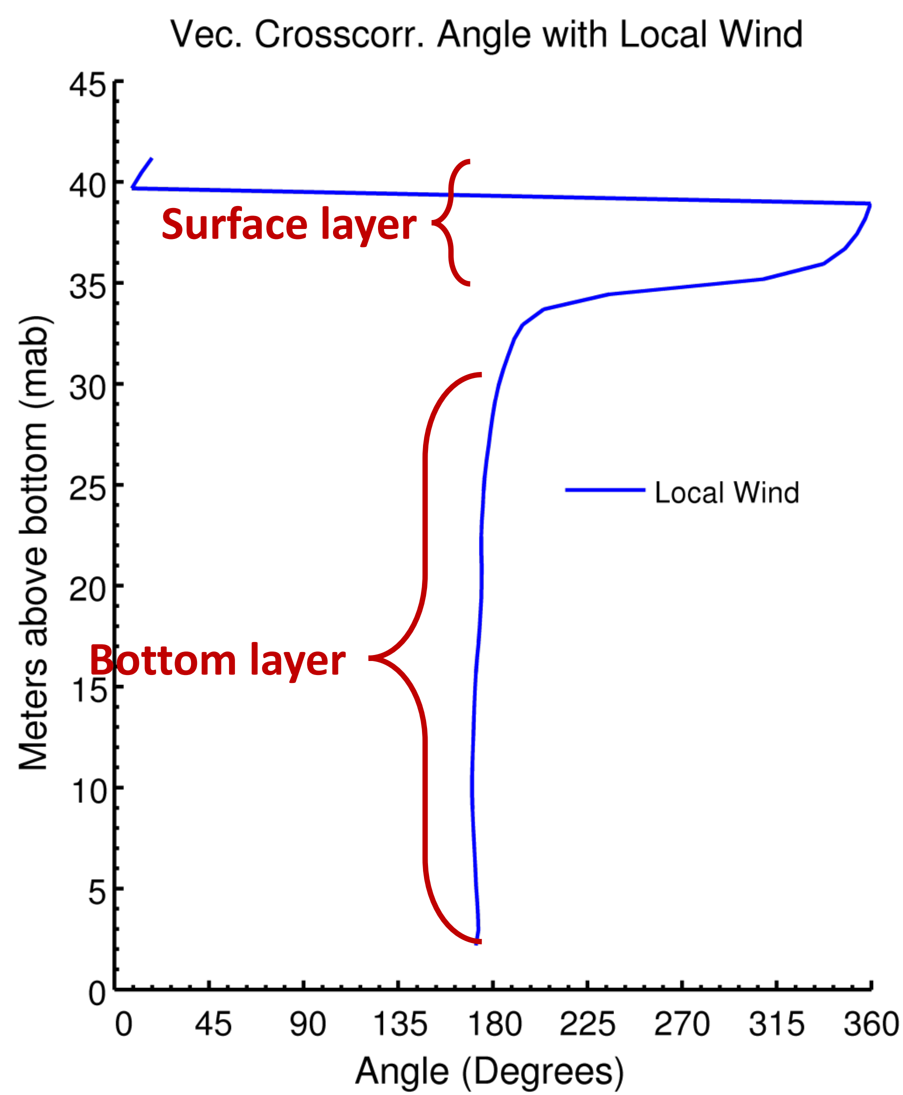
Vec. Crosscorr. (R^2) with Local Wind
Meters above bottom (mab)
Determination Coefficient (R^2)
Local Wind
Tidal harmonic fit
0
5
10
15
20
25
30
35
40
45
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

APHYS

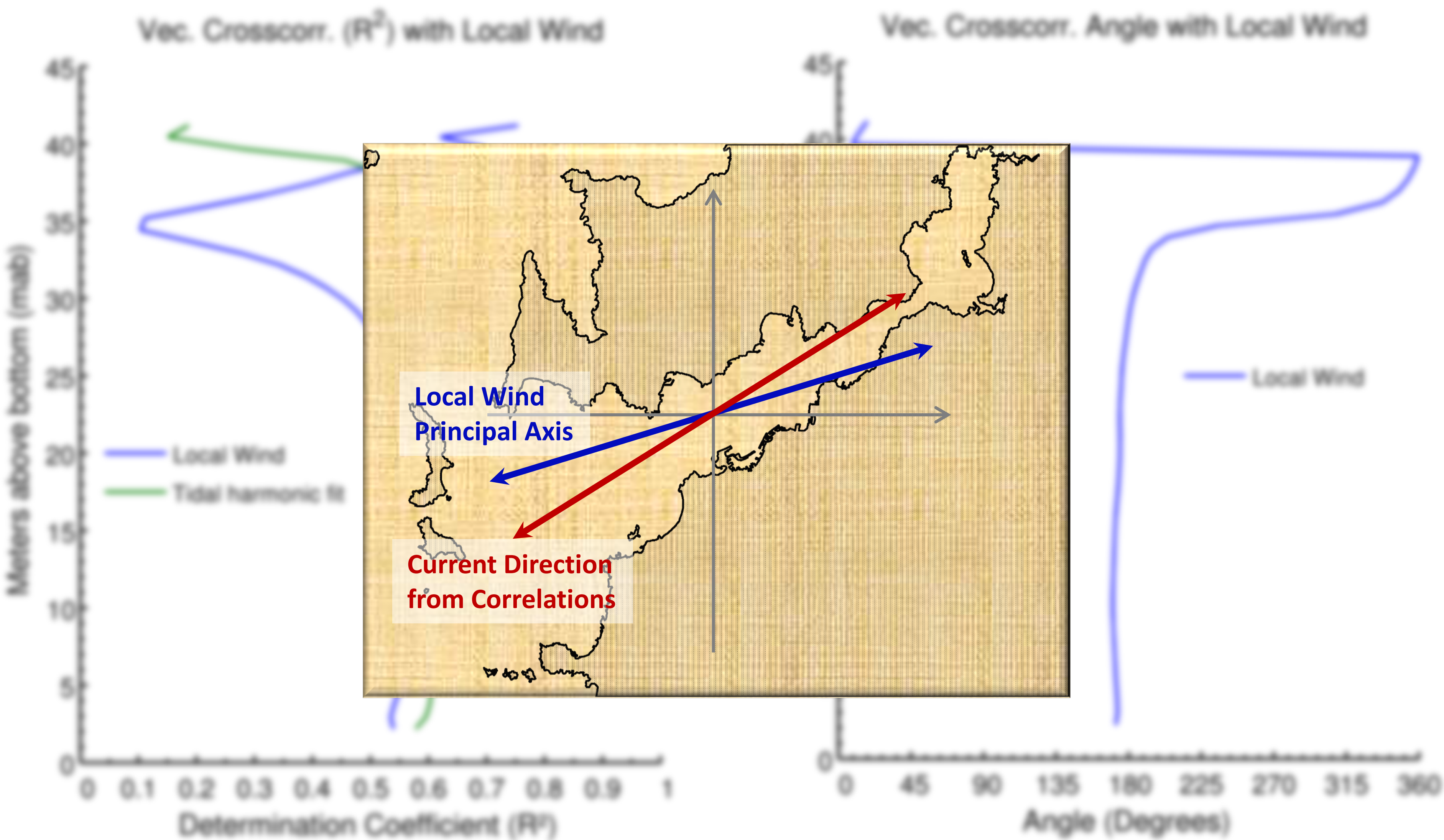

Vec. Crosscorr. (R^2) with Local Wind
Meters above bottom (mab)
0
5
10
15
20
25
30
35
40
45
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Determination Coefficient (R^2)
Local Wind
Tidal harmonic fit
Surface layer
Bottom layer

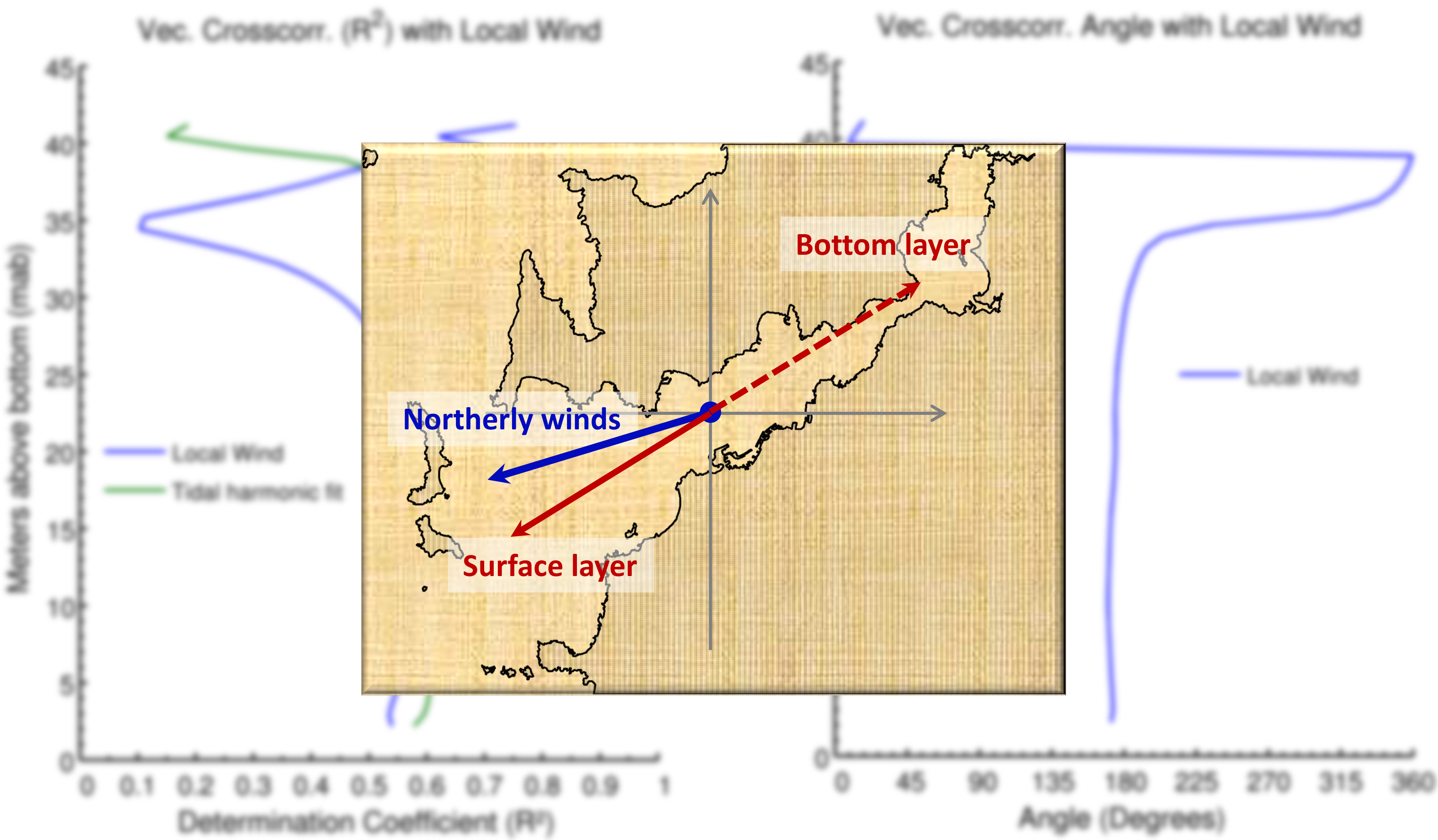


Vec. Crosscorr. (R2) with Local Wind
Meters above bottom (mab)
Determination Coefficient (R²)
Local Wind
Tidal harmonic fit
Surface layer
Bottom layer

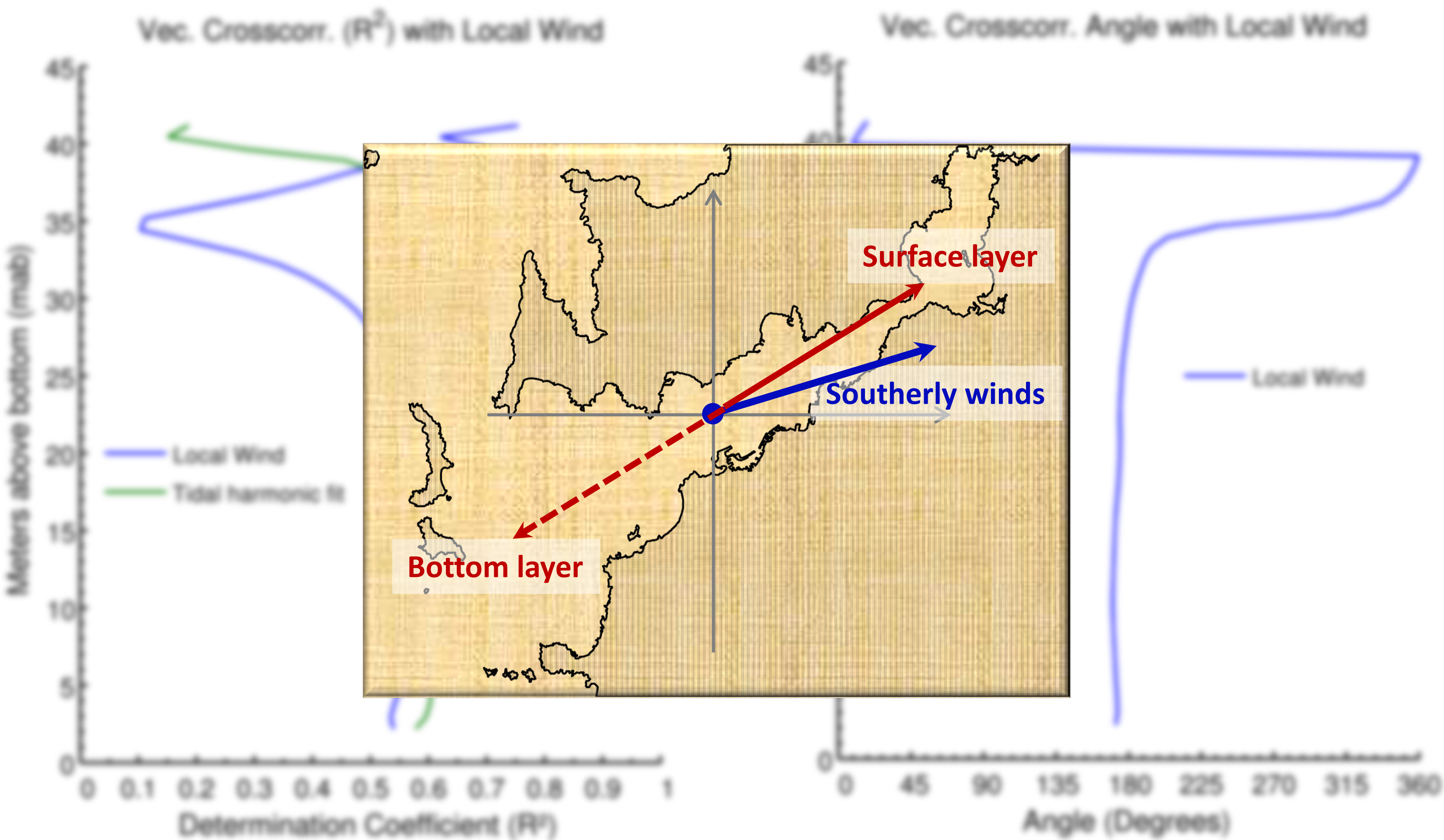


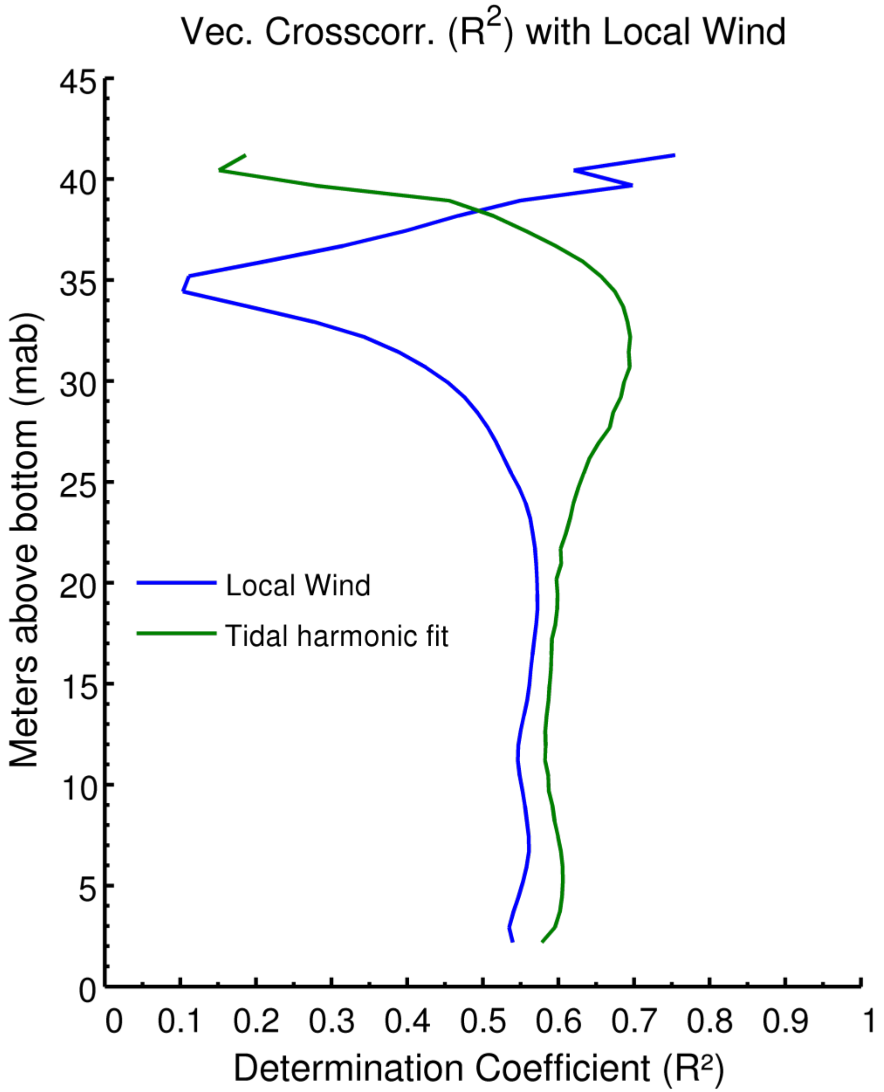
Vec. Crosscorr. Angle with Local Wind
Meters above bottom (mab)
Angle (Degrees)
Local Wind
Surface layer
Bottom layer


Vec. Crosscorr. (R^2) with Local Wind
Meters above bottom (mab)
Determination Coefficient (R^2)
Local Wind
Tidal harmonic fit
Vec. Crosscorr. Angle with Local Wind
Angle (Degrees)
Local Wind
Local Wind Principal Axis
Current Direction from Correlations

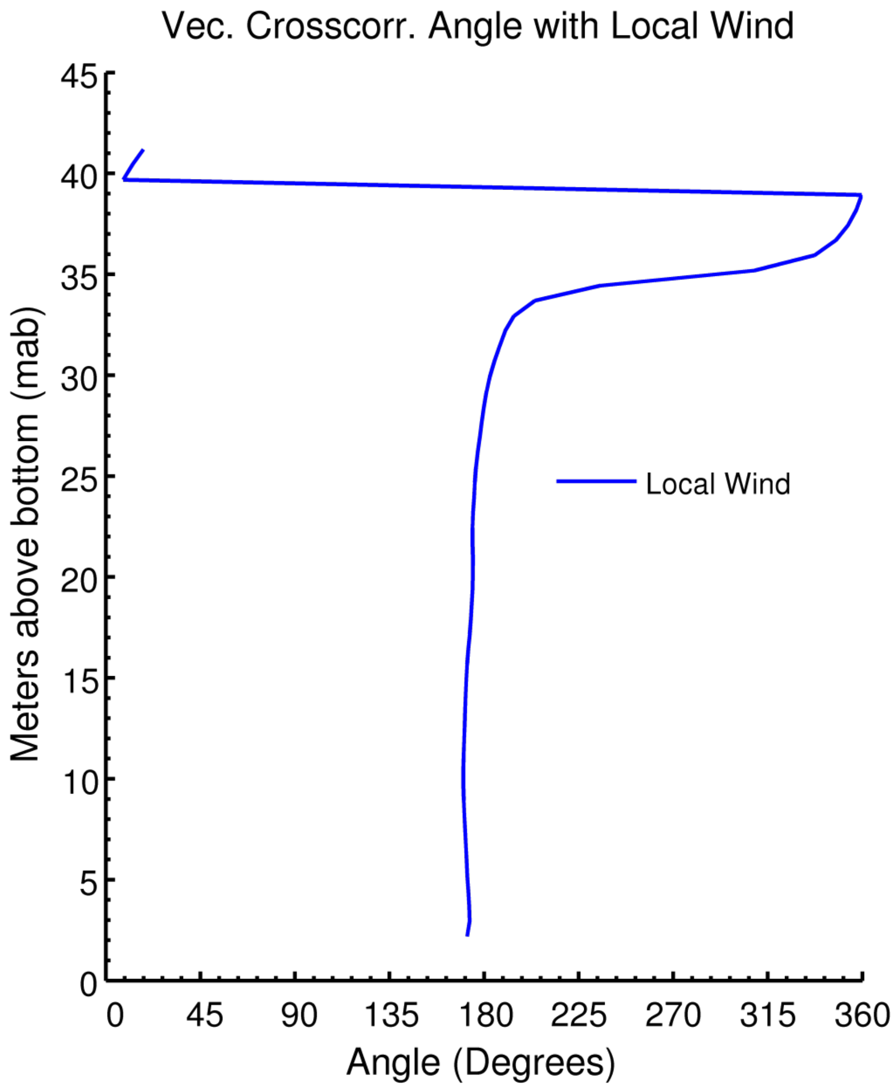


Vec. Crosscorr. (R^2) with Local Wind
Meters above bottom (mab)
Determination Coefficient (R^2)
Local Wind
Tidal harmonic fit
Vec. Crosscorr. Angle with Local Wind
Angle (Degrees)
Local Wind
Bottom layer
Northerly winds
Surface layer

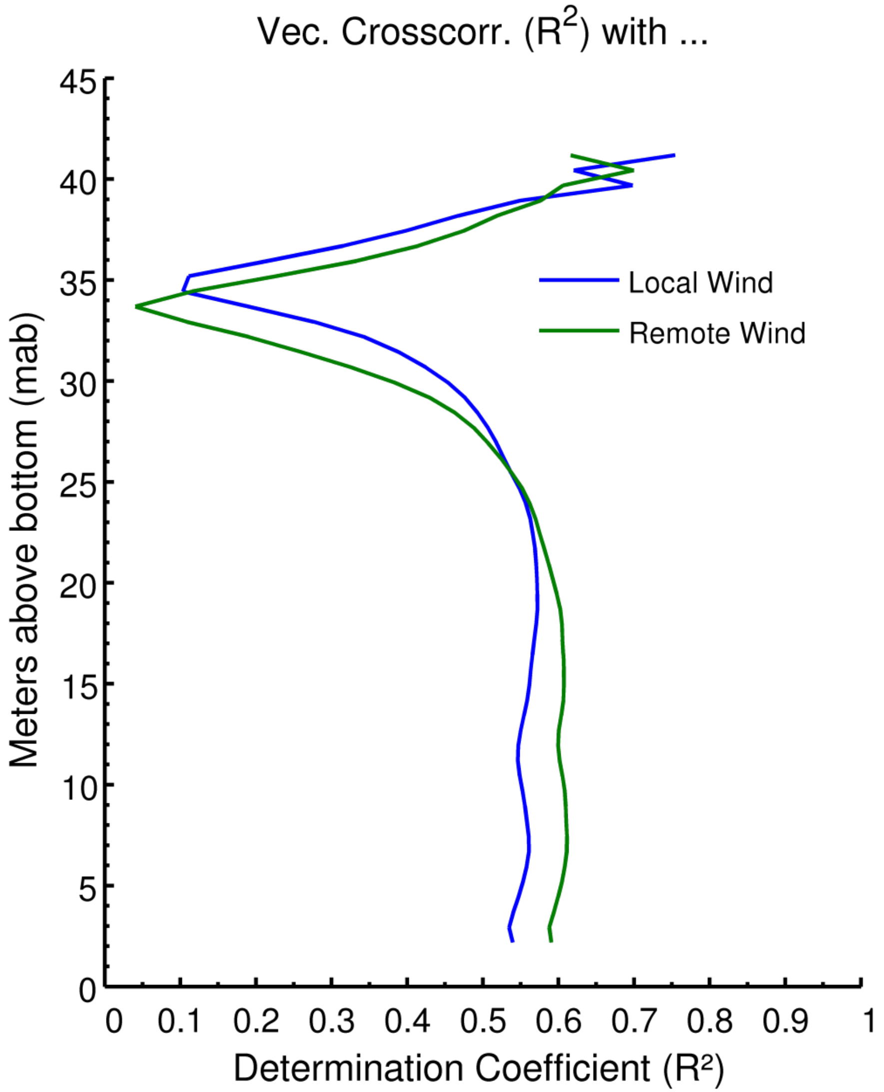

Vec. Crosscorr. (R²) with Local Wind
Meters above bottom (mab)
Local Wind
Tidal harmonic fit
Determination Coefficient (R²)
Vec. Crosscorr. Angle with Local Wind
Local Wind
Angle (Degrees)
Surface layer
Southerly winds
Bottom layer

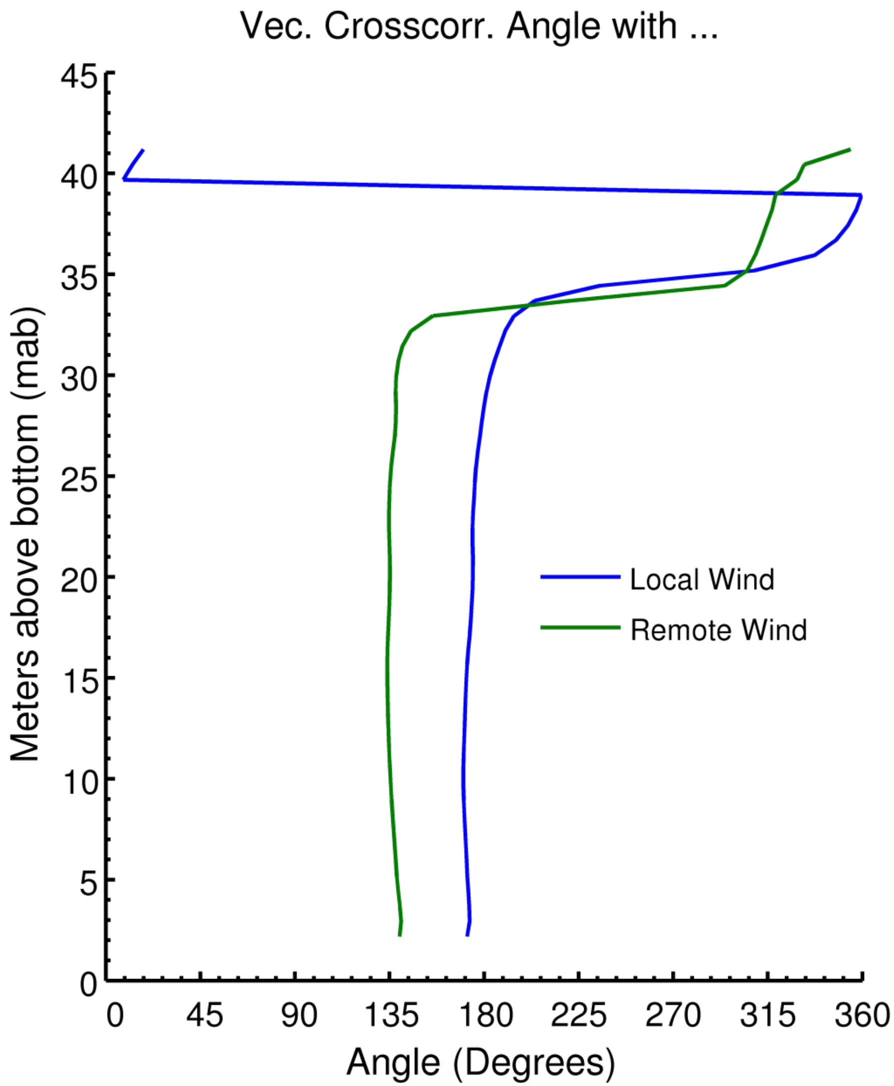


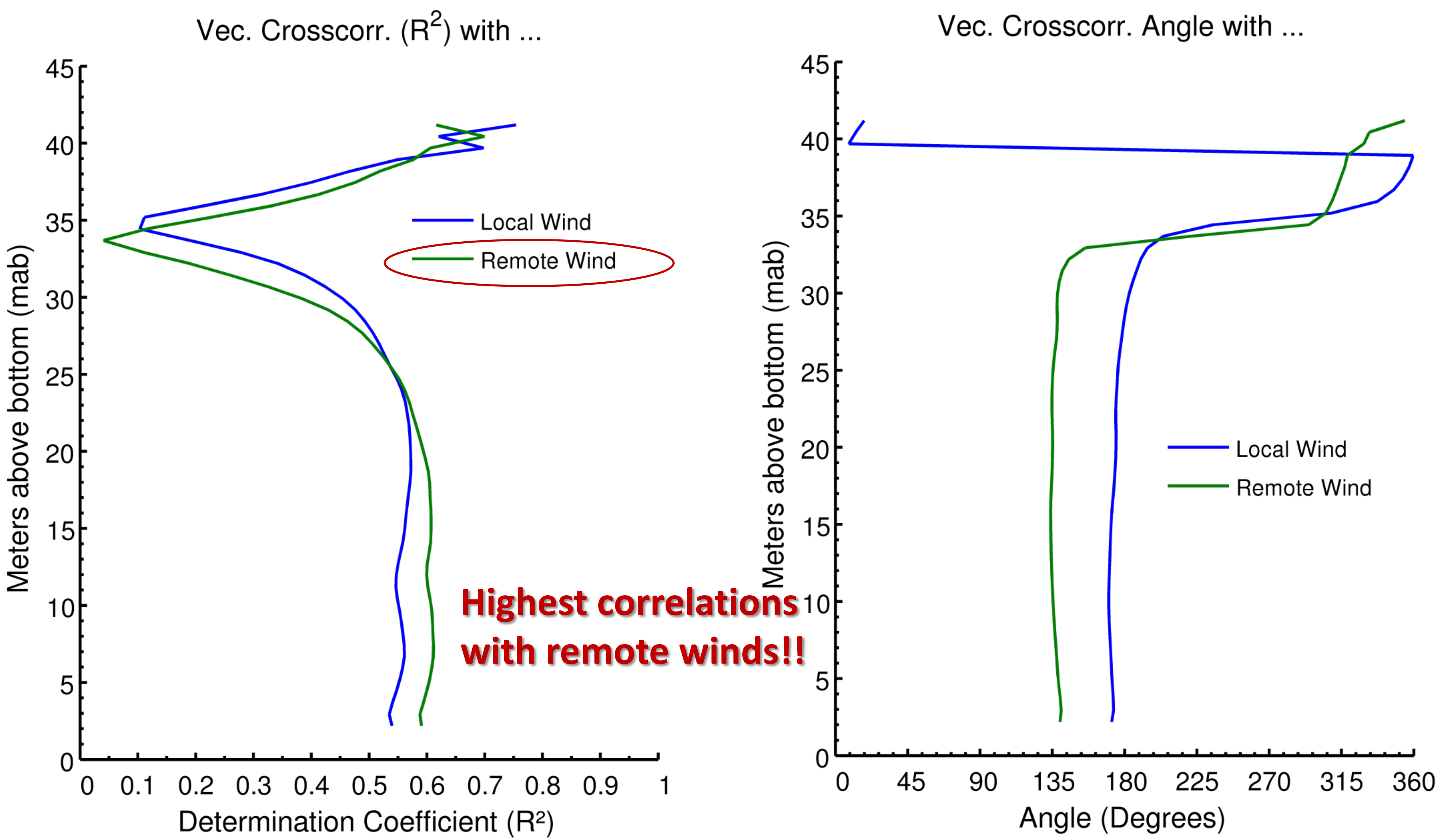
Vec. Crosscorr. (R^2) with Local Wind
Meters above bottom (mab)
Determination Coefficient (R²)
Local Wind
Tidal harmonic fit
0
5
10
15
20
25
30
35
40
45
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



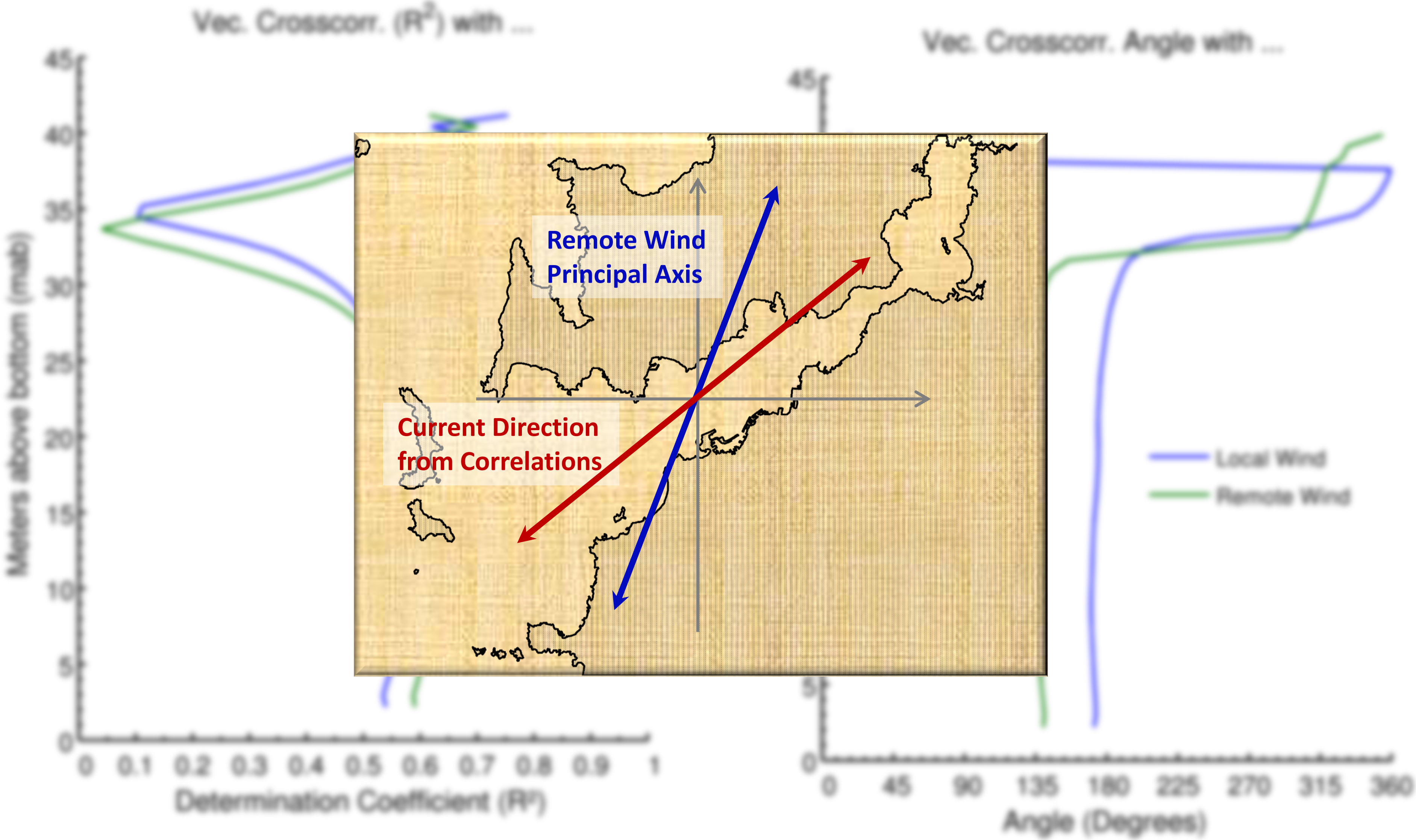
Vec. Crosscorr. Angle with Local Wind
Meters above bottom (mab)
Angle (Degrees)
Local Wind
0
5
10
15
20
25
30
35
40
45
0
45
90
135
180
225
270
315
360

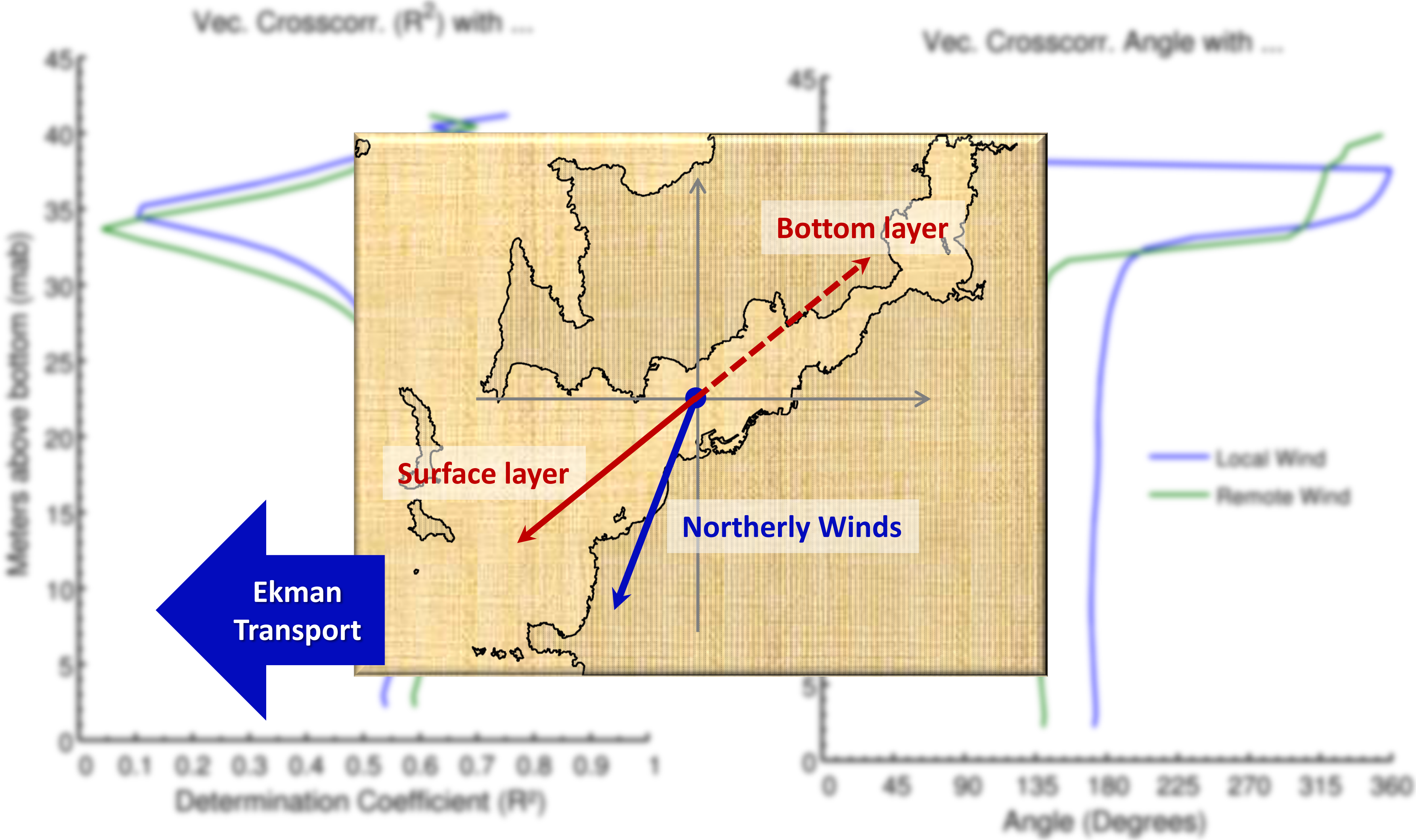

Vec. Crosscorr. (R^2) with ...
Meters above bottom (mab)
Determination Coefficient (R^2)
Local Wind
Remote Wind
0
5
10
15
20
25
30
35
40
45
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

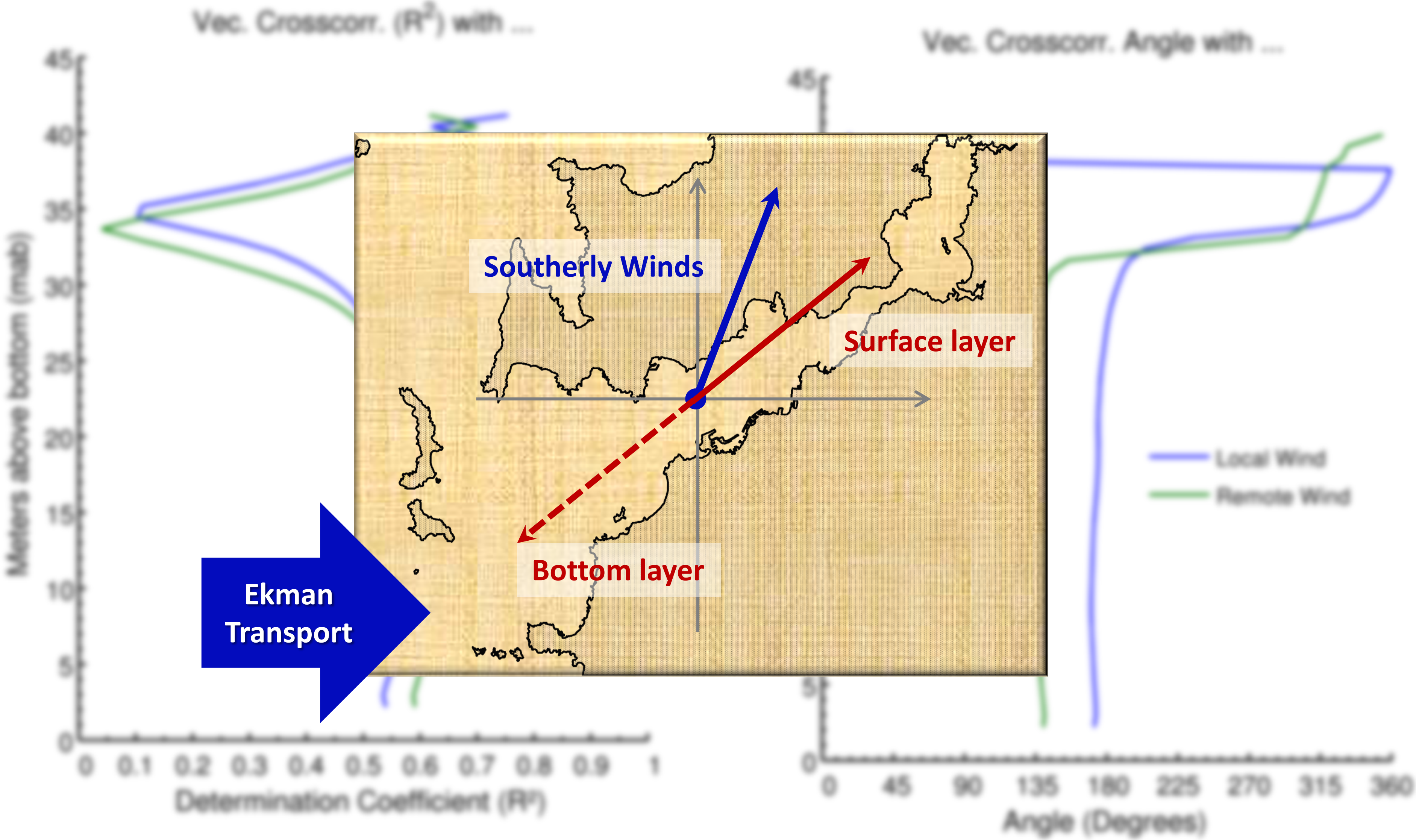

Vec. Crosscorr. Angle with ...
Meters above bottom (mab)
Angle (Degrees)
Local Wind
Remote Wind
0
5
10
15
20
25
30
35
40
45
0
45
90
135
180
225
270
315
360

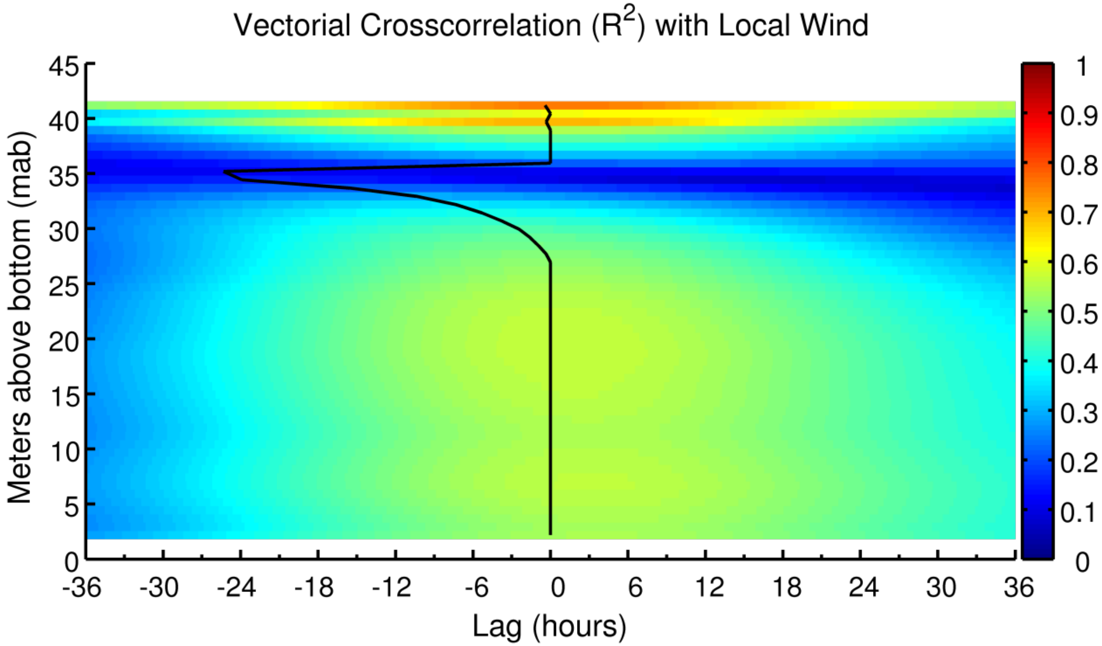


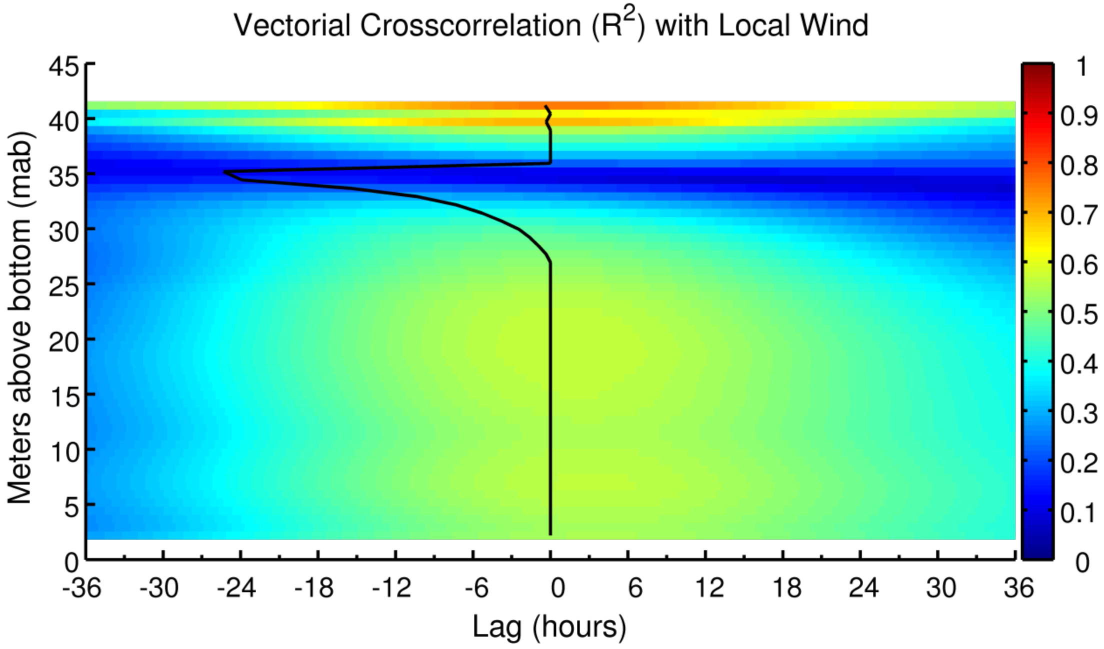
Highest correlations with remote winds!!


Vec. Crosscorr. (R^2) with ...
Vec. Crosscorr. Angle with ...
Meters above bottom (mab)
Determination Coefficient (R^2)
Angle (Degrees)
Local Wind
Remote Wind
Remote Wind
Principal Axis
Current Direction
from Correlations

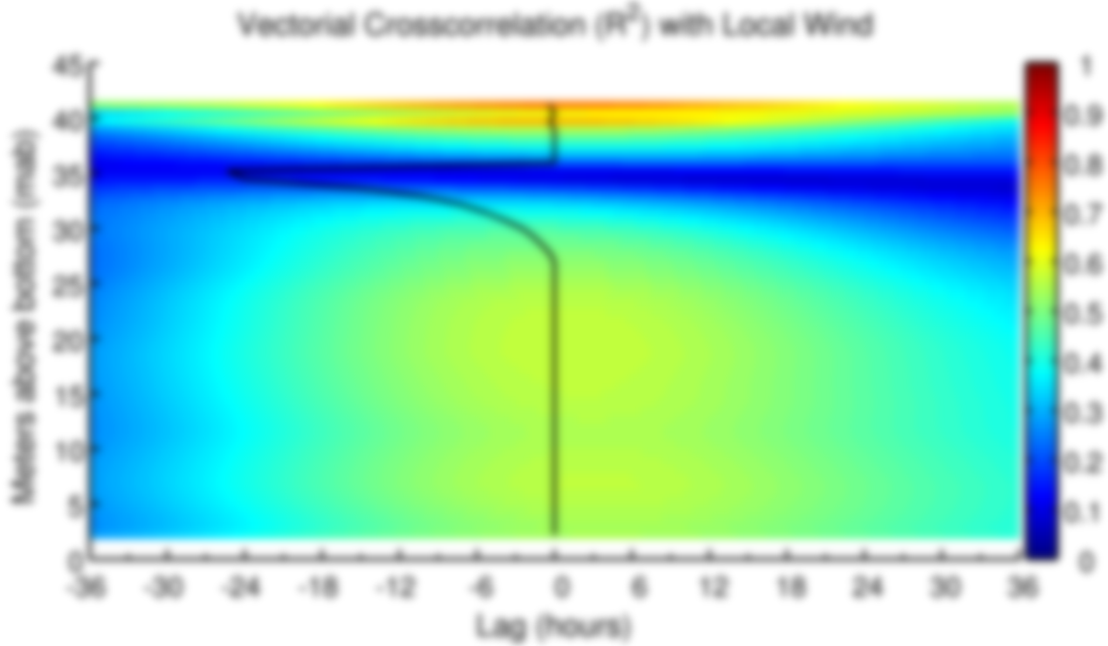

Vec. Crosscorr. (R^2) with ...
Vec. Crosscorr. Angle with ...
Meters above bottom (mab)
Determination Coefficient (R^2)
Angle (Degrees)
Local Wind
Remote Wind
Bottom layer
Surface layer
Northerly Winds
Ekman Transport


Vec. Crosscorr. (R^2) with ...
Vec. Crosscorr. Angle with ...
Meters above bottom (mab)
Determination Coefficient (R^2)
Angle (Degrees)
Local Wind
Remote Wind
Southerly Winds
Surface layer
Bottom layer
Ekman Transport

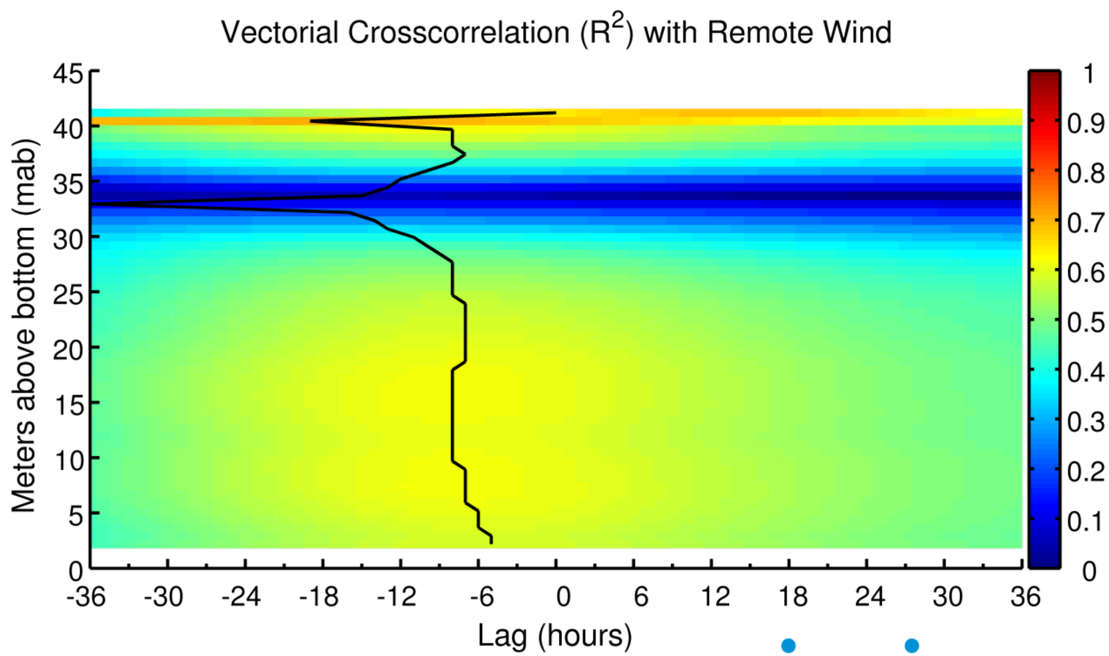

Vectorial Crosscorrelation (R^2) with Local Wind
Meters above bottom (mab)
Lag (hours)
45
40
35
30
25
20
15
10
5
0
-36
-30
-24
-18
-12
-6
0
6
12
18
24
30
36
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0



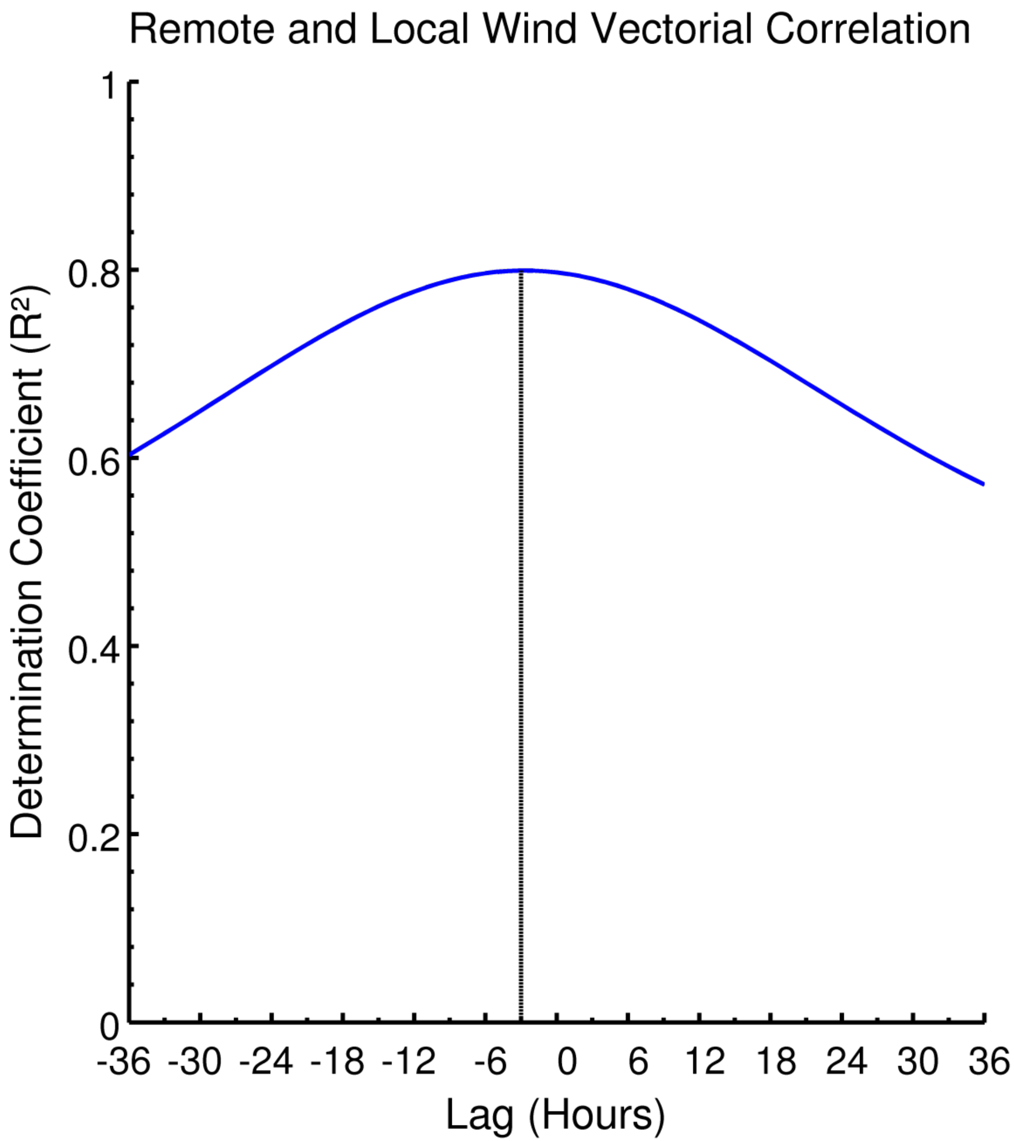
There is no lag between local winds and residual currents!!



There is no lag between local winds and residual currents!!



There are 6-8 hours of lag between remote winds and residual currents!!



There is no lag between local winds and residual currents!!

There are 3 hours of lag between remote winds and local winds!!

When a low or high pressure comes from the Atlantic it takes 3 hours in travelling from Silleiro Buoy to Vigo.

And 3-5 hours later, the Ekman transport will be driving the residual circulation of the ria.

There are 6-8 hours of lag between remote winds and residual currents!!

CSIC

APHYS EPFL

1. The analysis of long time series reinforces the idea of residual circulation as a bidirectional flow driven by coastal upwelling.

1. The analysis of long time series reinforces the idea of residual circulation as a bidirectional flow driven by coastal upwelling.

2. The Ría de Vigo response to coastal upwelling is quite rapid:

   - In just 6-8 hours the Ria is feeling the remote wind effects.

   - But the response through the local wind is felt some 3-5 hours before.

If the Ría de Vigo is so influenced by Coastal Upwelling then:

Is it a partially mixed estuary?

Dataset

Meteo

Finisterre St
Vigo Airport St
Bouzas St

Air temperature
Relative humidity
Wind velocity
Cloudiness
Rainfall

Hydrography

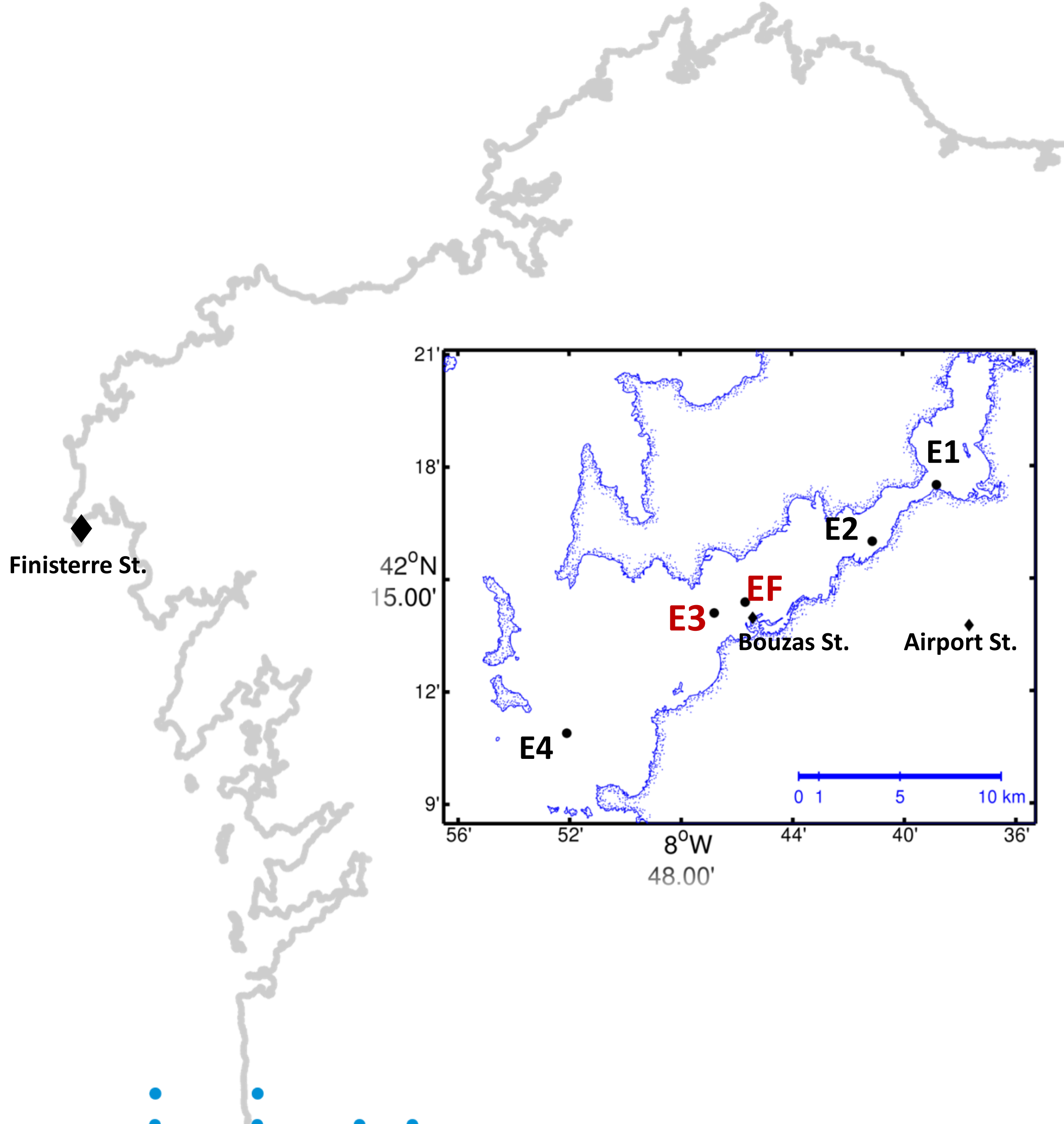
E1, E2, E3, E4

Temperature
Salinity
Pressure

Currents

EF and E3

HF Radar, ADCP



Processing

Dataset

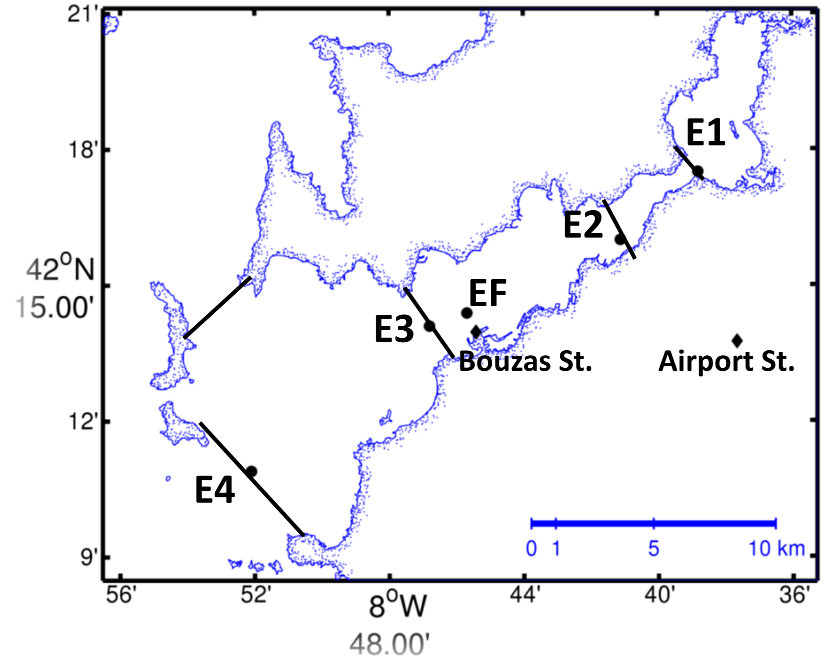
Seasonal fit (least squares):

$$Var = A_0 + A_2 \cdot cos\left(\frac{2 \cdot \pi}{T_1} + F_1\right) + A_2 \cdot cos\left(\frac{2 \cdot \pi}{T_2} + F_2\right)$$

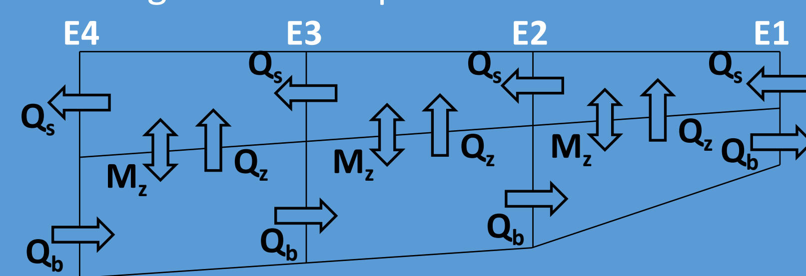
Stratification ,Anomaly of Potential Energy (APE, ø)

$$\phi = \frac{1}{h}\int_{-h}^{0} z \cdot g \cdot (\rho - \overline{\rho})dz$$

$$\overline{\rho}=\frac{1}{h}\int_{-h}^{0}\rho \, dz$$



- two layer
- non-steady
- Volume, temperature and salt conservation
- weighted least squares solution



Processing

Adimensional Numbers

1. Hansen & Rattray

Hansen, D. V., and M. J. Rattray (1966), New dimensions in estuary classification, Limnology and Oceanography, 11(3), 319-326.

Stratification Parameter

$$\frac{\Delta_z S}{S_0}$$

Circulation Parameter

$$\frac{u_s}{U_f}$$

2. Geyer & MacCready

Geyer, W. R., and P. MacCready (2014), The Estuarine Circulation, Annu. Rev. Fluid Mech., 46(1), 175-197.

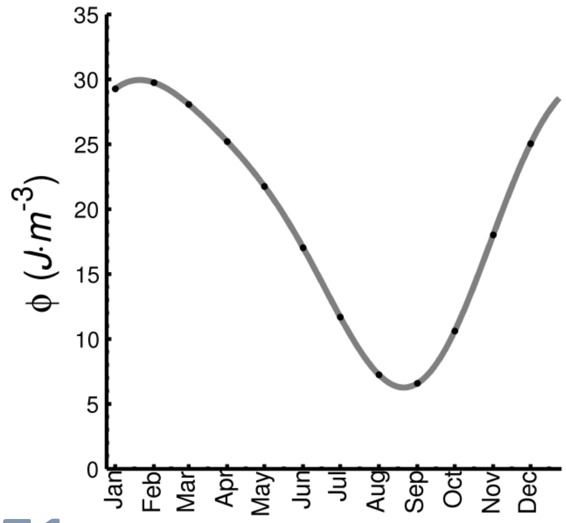
Froude Freshwater Number

$$Fr_f = \frac{U_f}{\sqrt{g' \cdot H}}$$

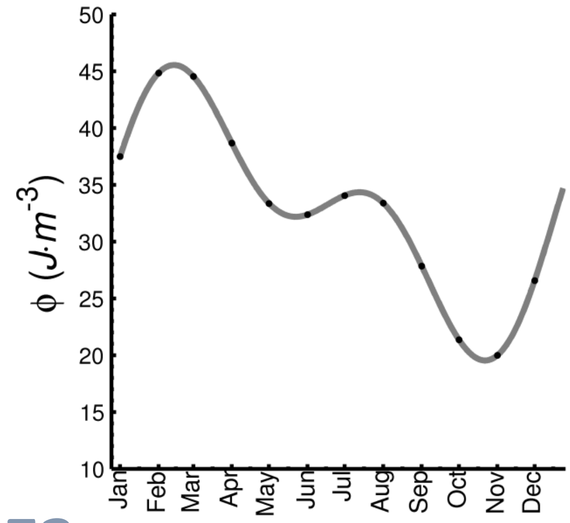
Mixing Number

$$M = \frac{C_D \cdot {U_T}^2}{\omega_T \cdot N \cdot H^2}$$

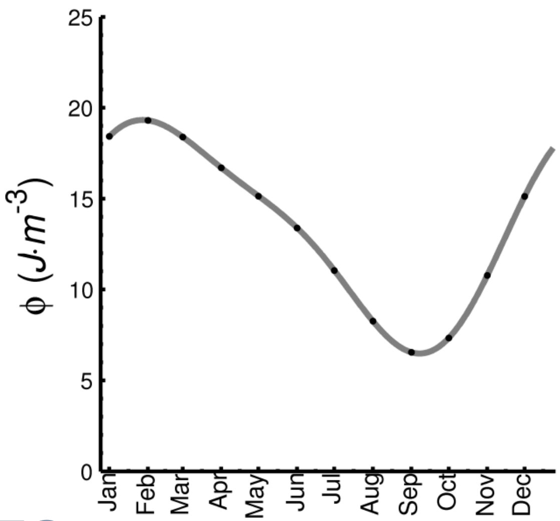
Results



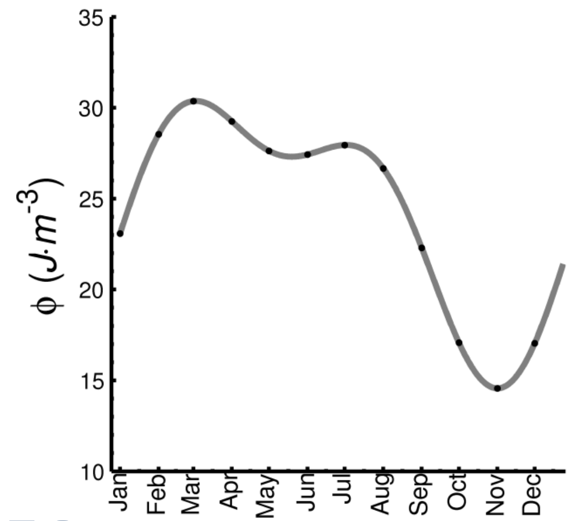
E1



E3

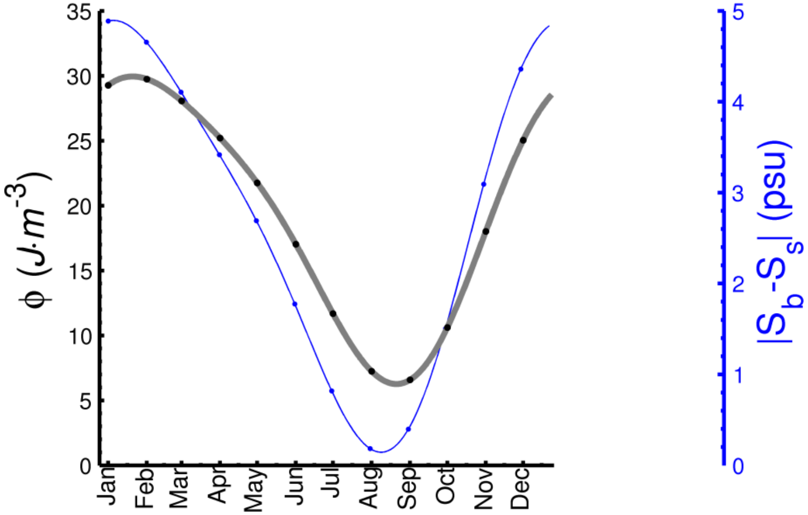


E2

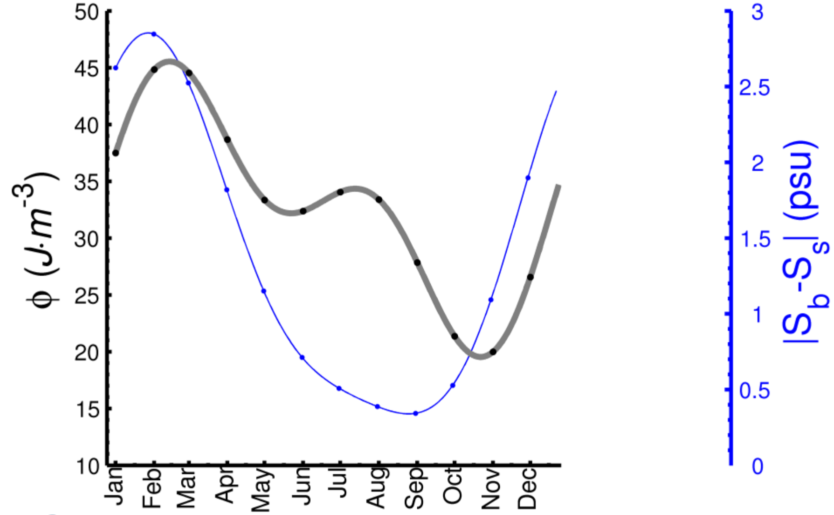


E4

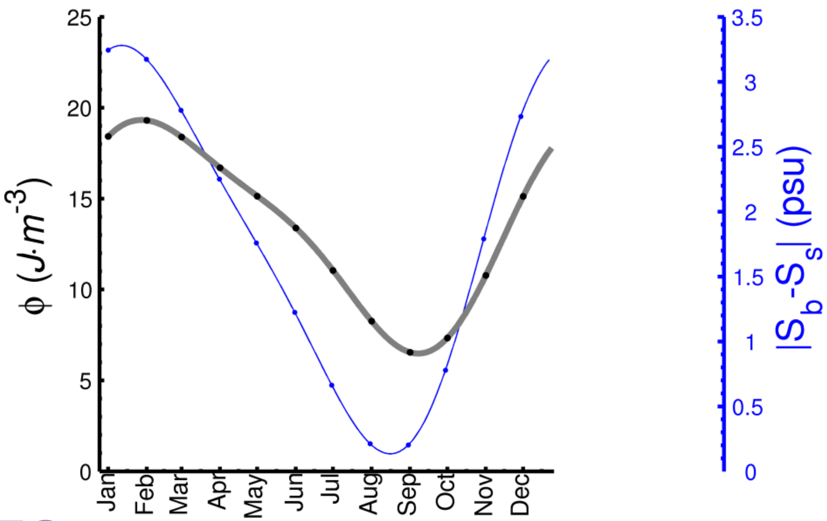
Results



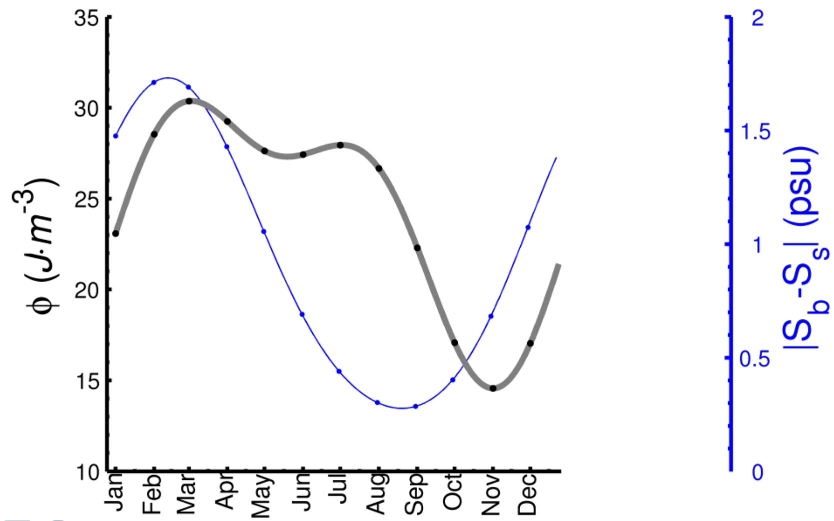
E1



E3

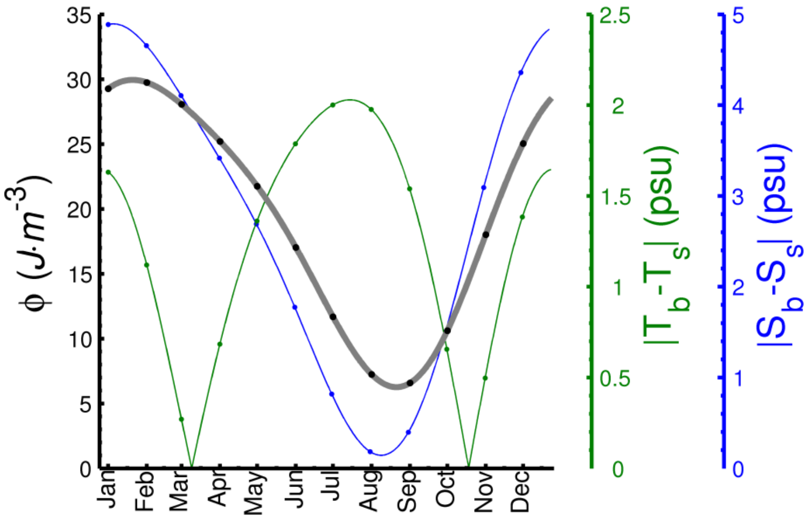


E2

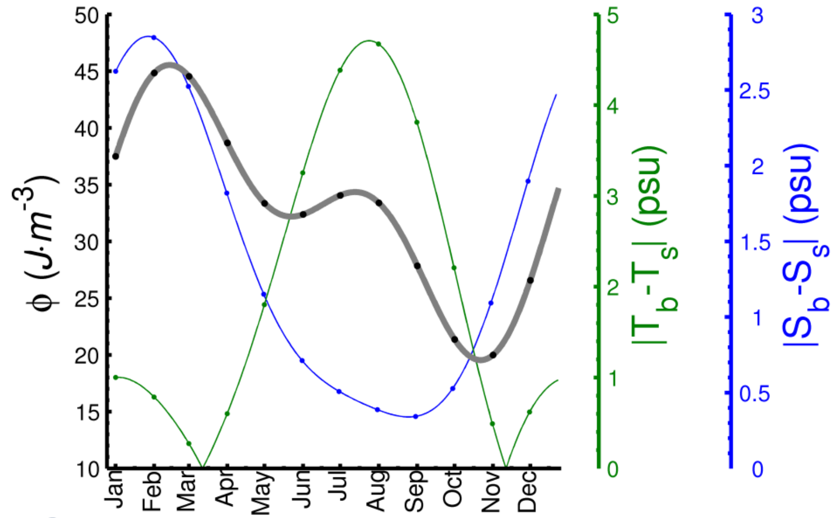


E4

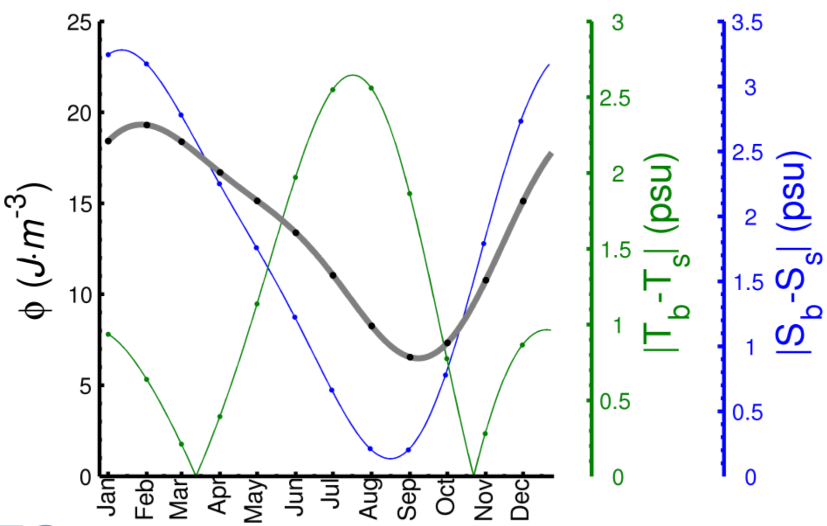
Results



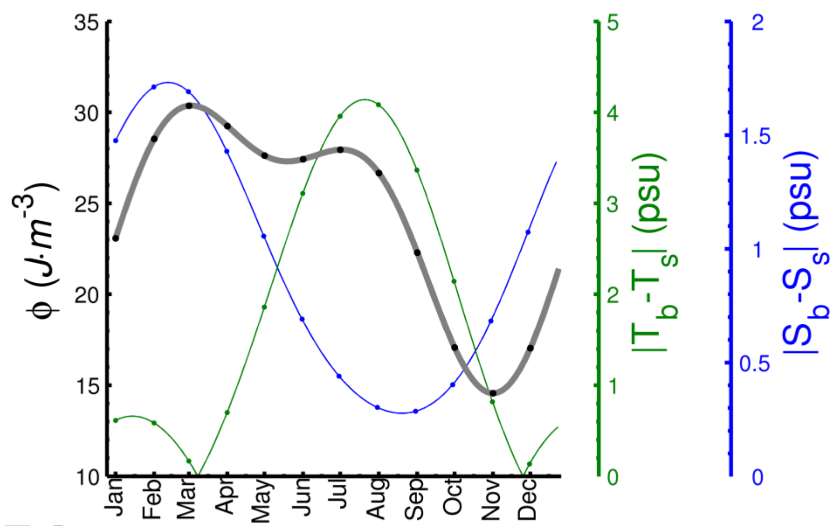
E1



E3



E2

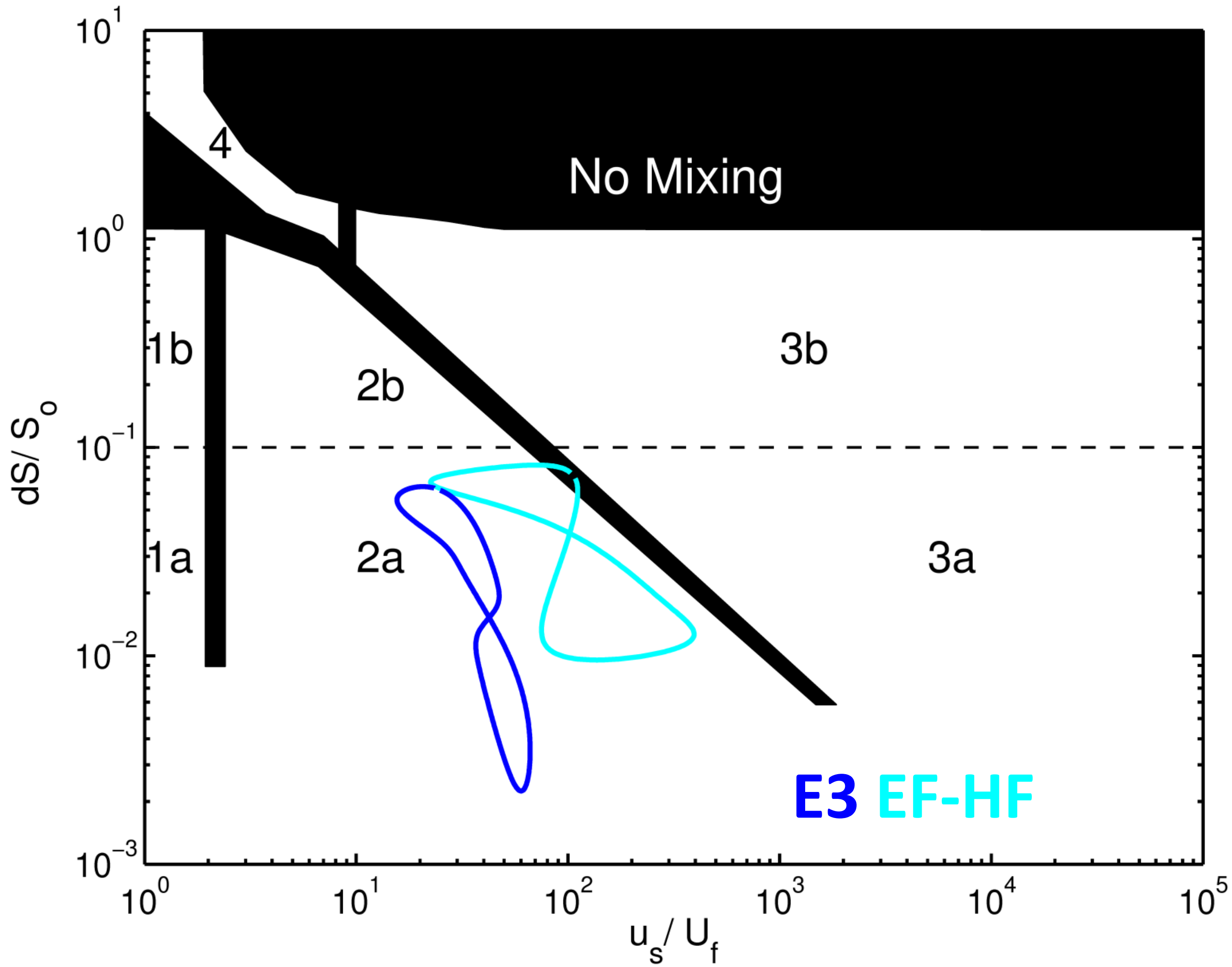


E4

CSIC

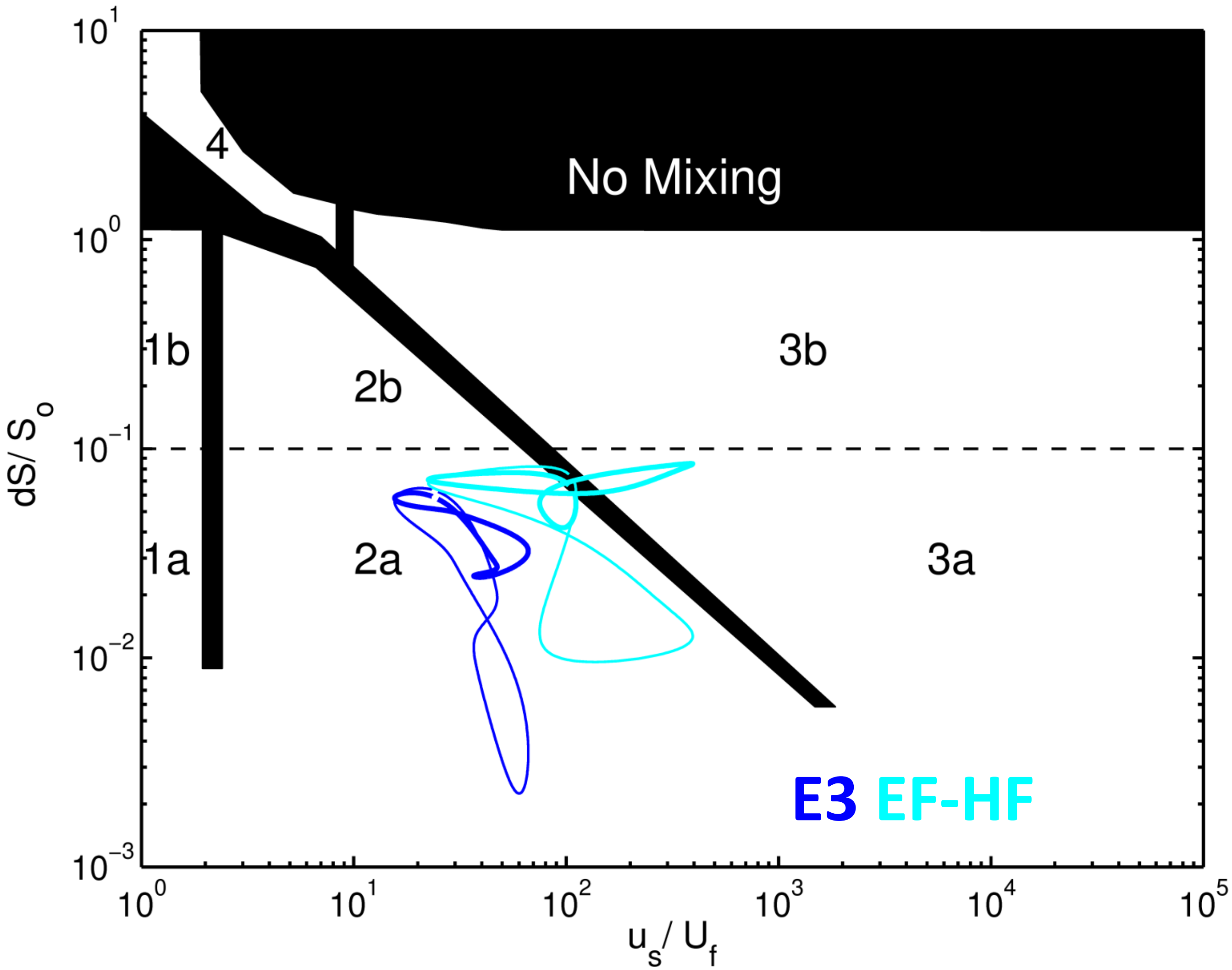
APHYS EPFL

Results



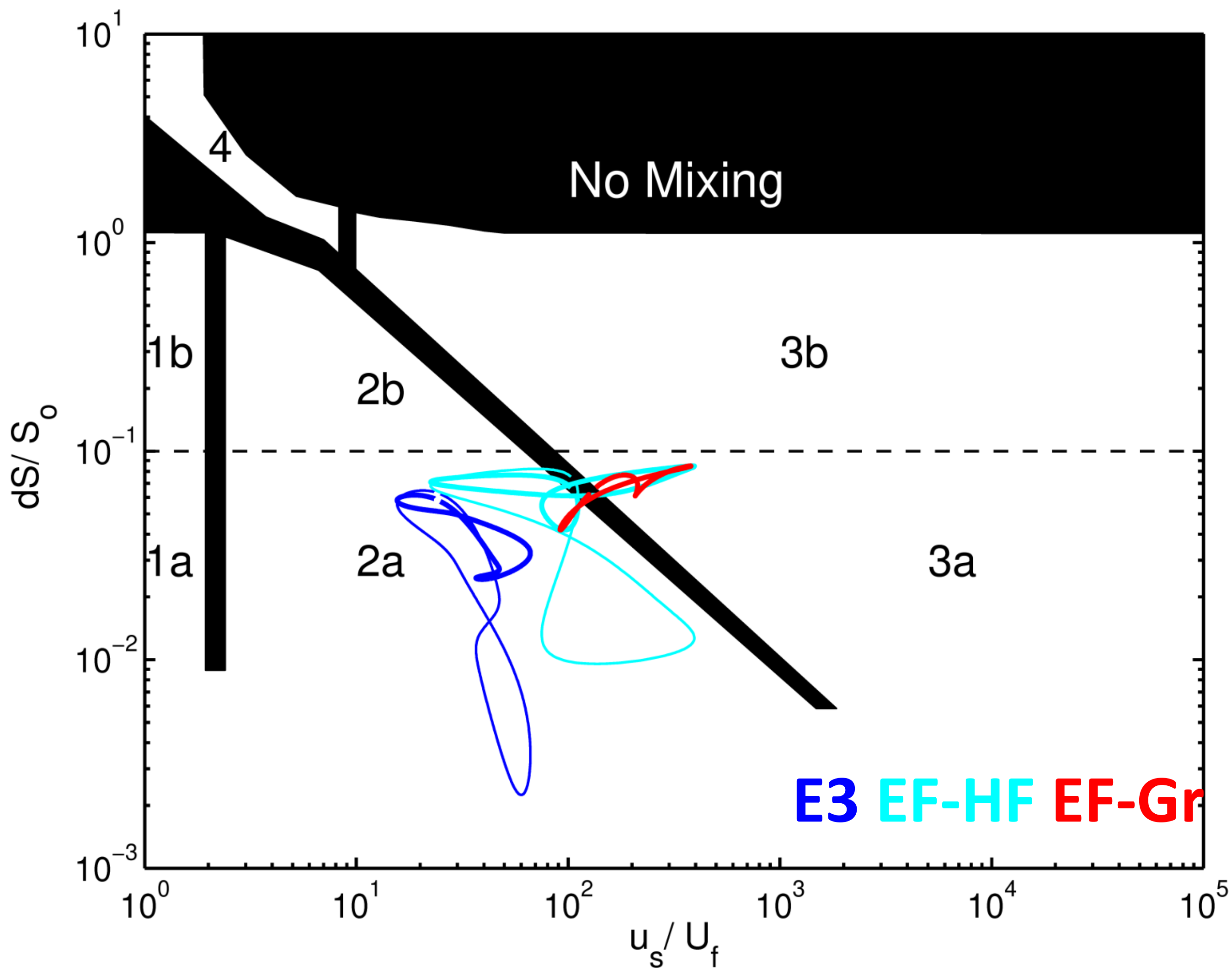
No Mixing
4
1b
2b
3b
1a
2a
3a
dS/ S$_o$
u$_s$/ U$_f$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
E3 EF-HF

Results



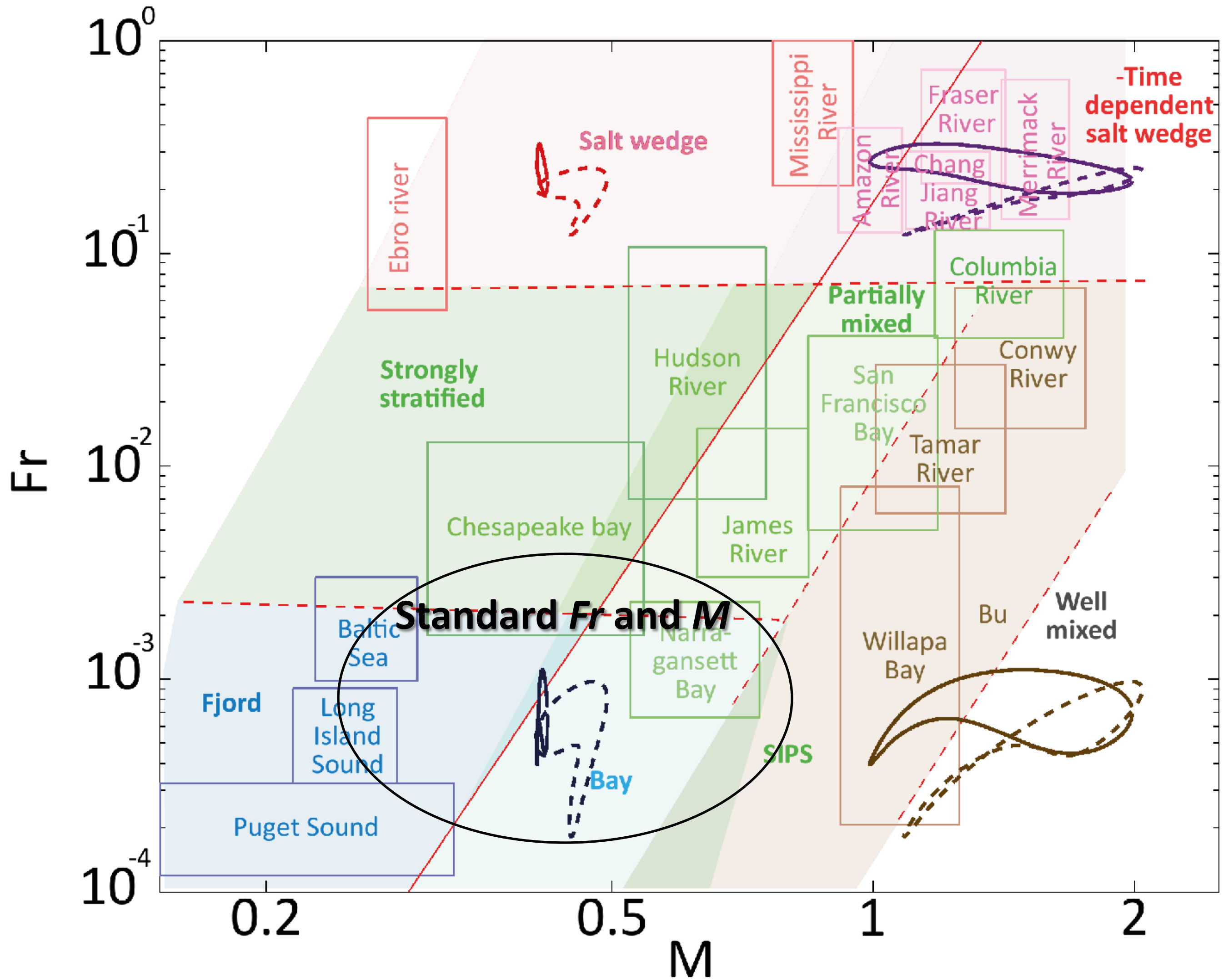
No Mixing
4
1b
2b
3b
1a
2a
3a
E3
EF-HF
dS/ S_o
u_s/ U_f
10^1
10^0
10^-1
10^-2
10^-3
10^0
10^1
10^2
10^3
10^4
10^5

Results



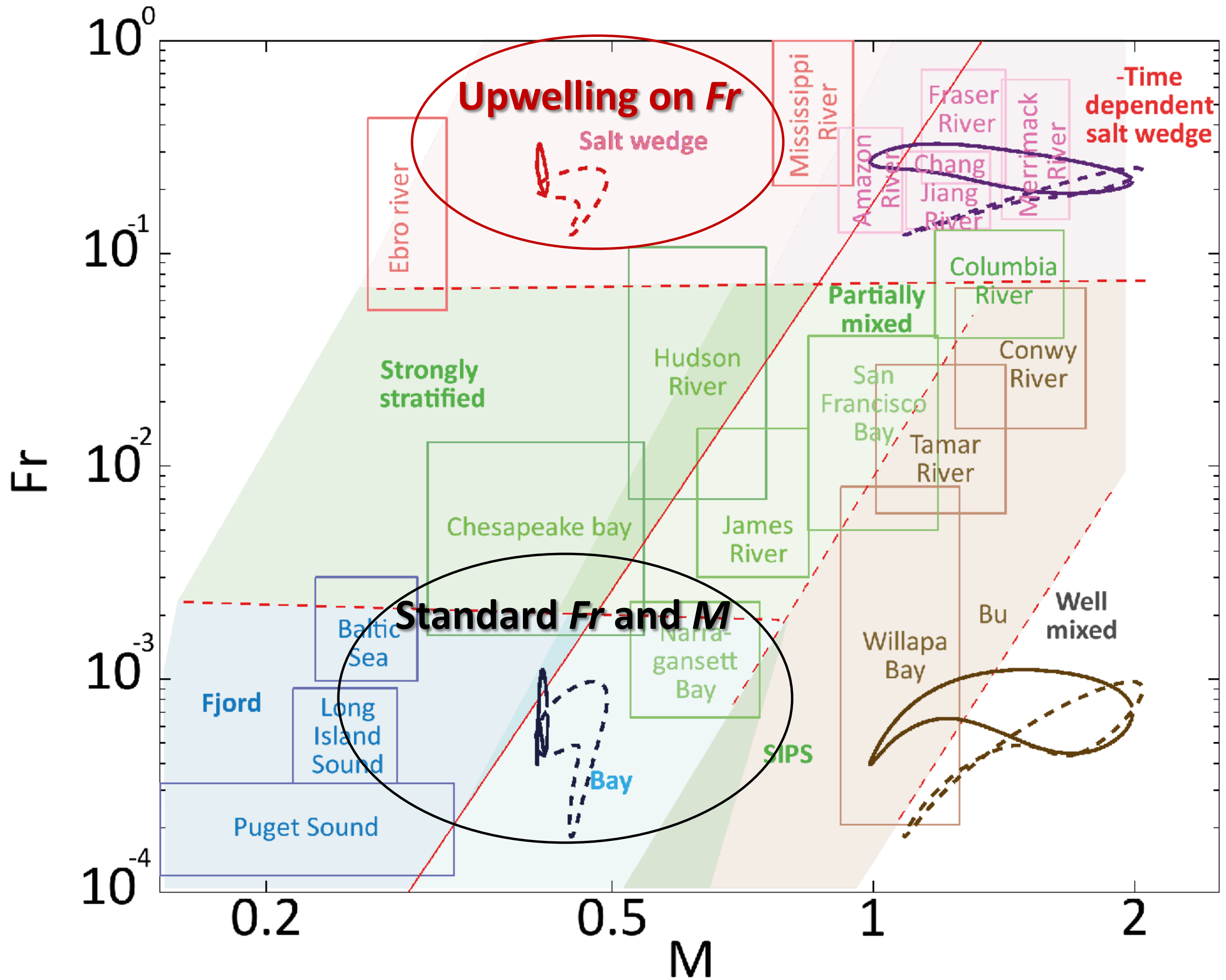
No Mixing
4
1b
2b
3b
1a
2a
3a
dS/ S_o
u_s/ U_f
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^0
10^1
10^2
10^3
10^4
10^5
E3 EF-HF EF-Gr

Results



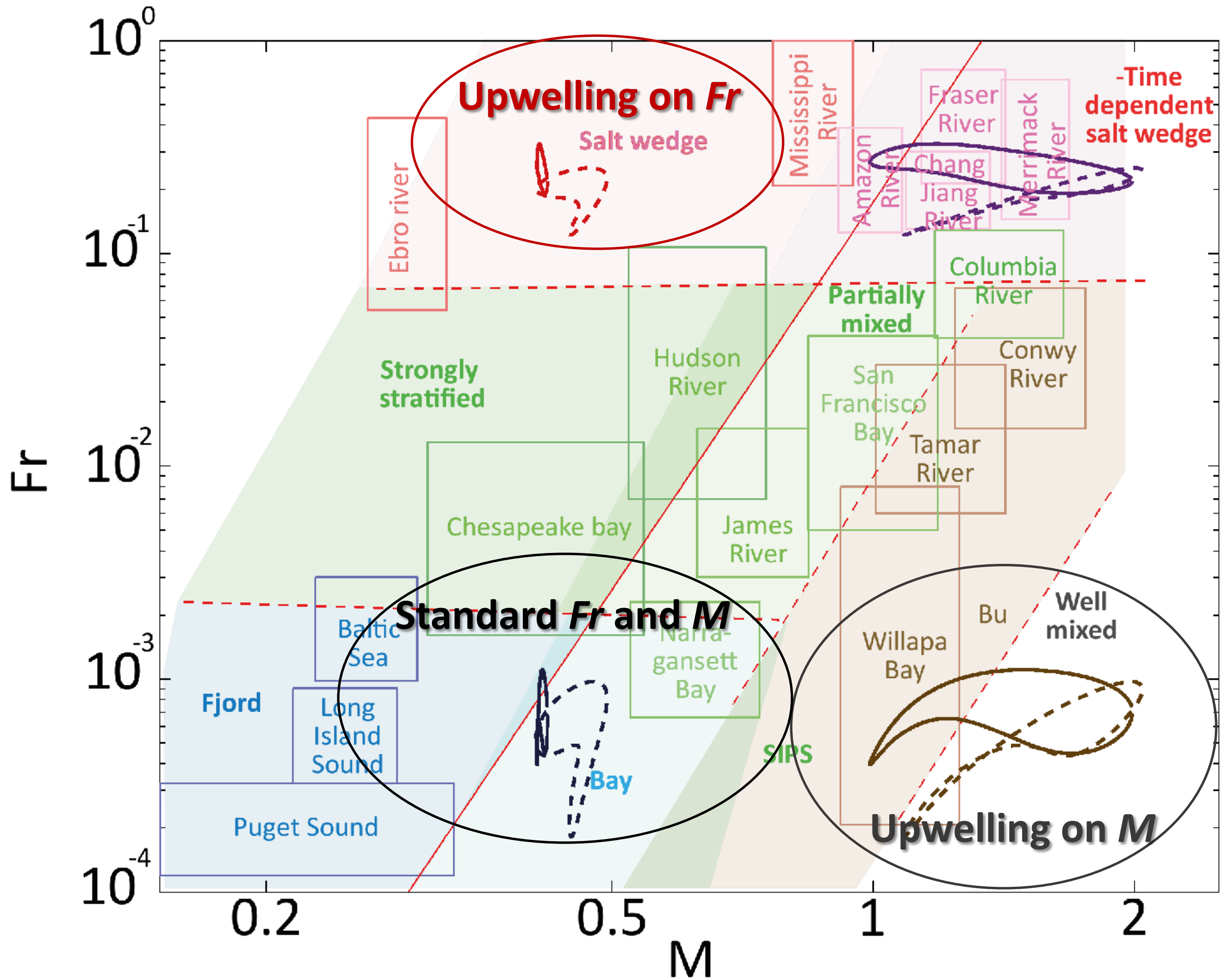
Fr
M
Ebro river
Salt wedge
Mississippi River
Amazon River
Fraser River
Chang Jiang River
Merrimack River
-Time dependent salt wedge
Columbia River
Partially mixed
Strongly stratified
Hudson River
San Francisco Bay
Conwy River
Tamar River
Chesapeake bay
James River
Standard *Fr* and *M*
Baltic Sea
Narra-gansett Bay
Willapa Bay
Bu
Well mixed
Fjord
Long Island Sound
Bay
SIPS
Puget Sound

Results

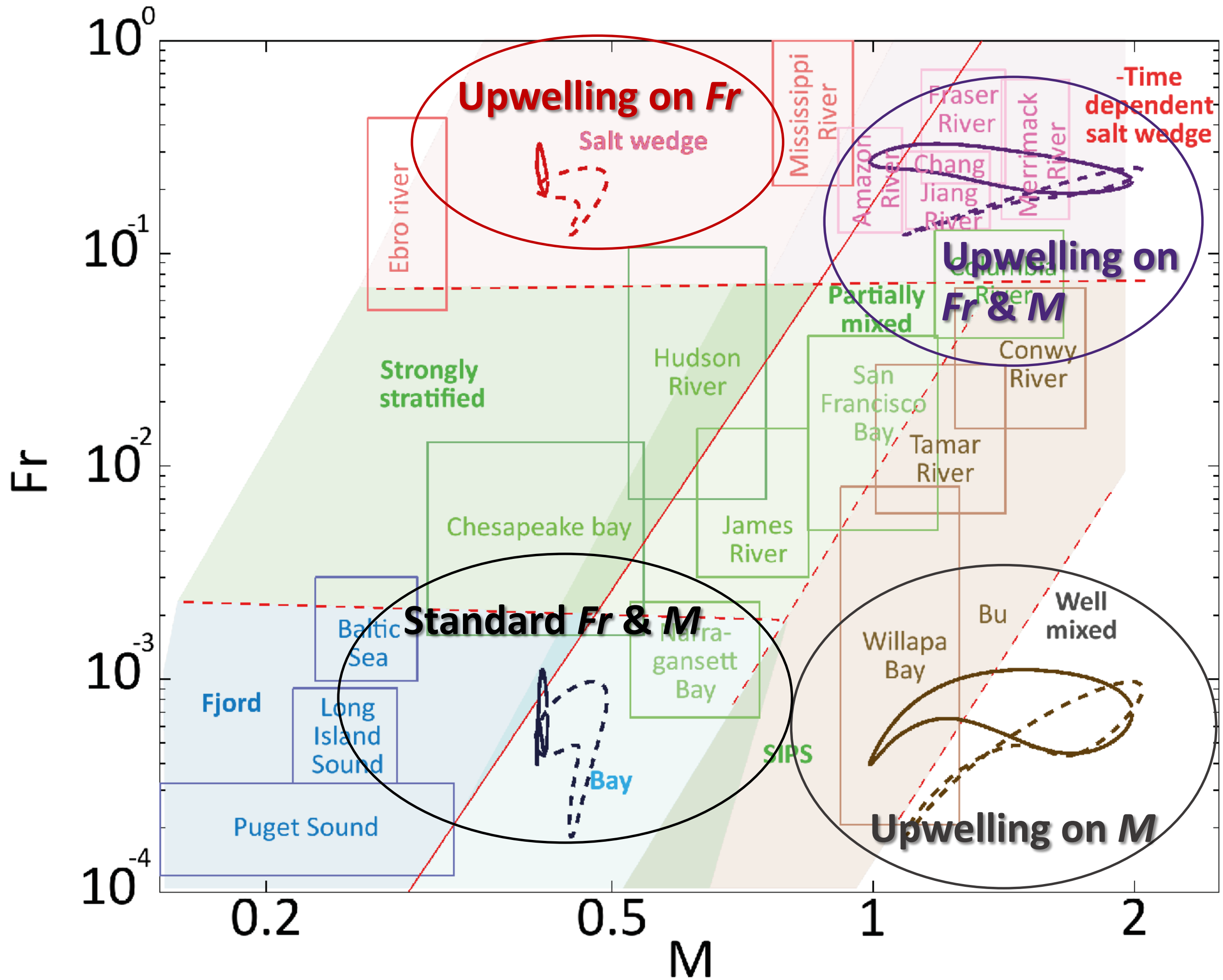


Upwelling on Fr
Salt wedge
Standard Fr and M
-Time dependent salt wedge
Ebro river
Mississippi River
Amazon River
Fraser River
Chang Jiang River
Merrimack River
Columbia River
Partially mixed
Strongly stratified
Hudson River
San Francisco Bay
Conwy River
Tamar River
Chesapeake bay
James River
Willapa Bay
Bu
Well mixed
Baltic Sea
Narra-gansett Bay
Fjord
Long Island Sound
Bay
SIPS
Puget Sound
Fr
M

Results

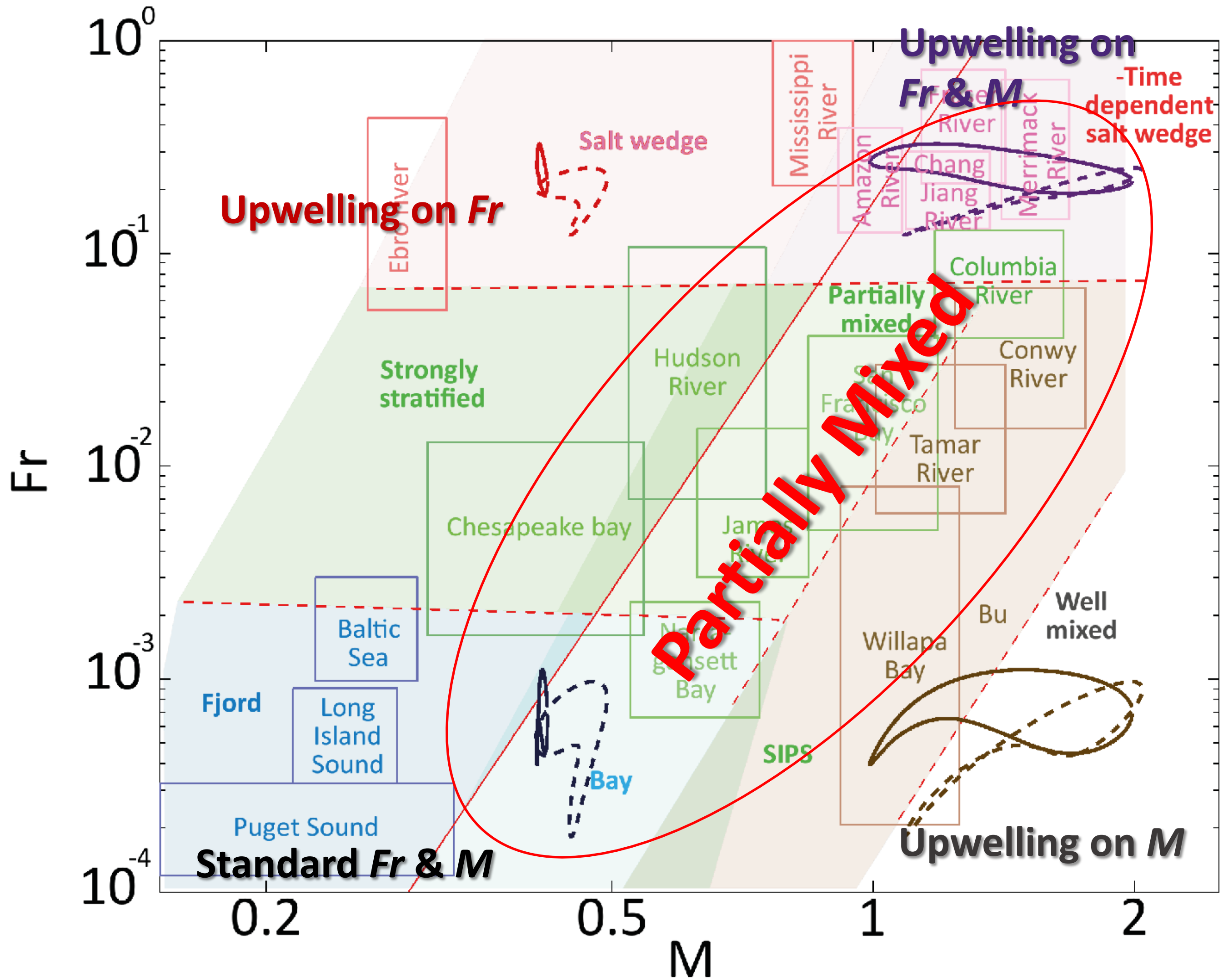

Upwelling on Fr
Salt wedge
Mississippi River
Ebro river
Amazon River
Fraser River
Chang Jiang River
Merrimack River
-Time dependent salt wedge
Columbia River
Partially mixed
Strongly stratified
Hudson River
San Francisco Bay
Conwy River
Tamar River
Chesapeake bay
James River
Standard Fr and M
Baltic Sea
Narra-gansett Bay
Well mixed
Bu
Willapa Bay
Fjord
Long Island Sound
Bay
SIPS
Puget Sound
Upwelling on M
Fr
M
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.2
0.5
1
2

Results



Upwelling on Fr
Salt wedge
Ebro river
Mississippi River
Fraser River
Amazon River
Chang Jiang River
Merrimack River
-Time dependent salt wedge
Upwelling on Fr & M
Columbia River
Partially mixed
Strongly stratified
Hudson River
San Francisco Bay
Conwy River
Tamar River
Chesapeake bay
James River
Standard Fr & M
Baltic Sea
Narra-gansett Bay
Fjord
Long Island Sound
Puget Sound
Bay
SIPS
Willapa Bay
Bu
Well mixed
Upwelling on M
Fr
M
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.2
0.5
1
2

Results



Fr
M
Upwelling on Fr & M
-Time dependent salt wedge
Salt wedge
Upwelling on Fr
Mississippi River
Ebro River
Fraser River
Amazon River
Chang Jiang River
Merrimack River
Columbia River
Partially mixed
Hudson River
Strongly stratified
Conwy River
San Francisco Bay
Tamar River
Partially Mixed
Chesapeake bay
James River
Narragansett Bay
Baltic Sea
Willapa Bay
Well mixed
Fjord
Long Island Sound
Bay
SIPS
Puget Sound
Standard Fr & M
Upwelling on M

Conclusions

As with many estuaries, it is **difficult to define the estuarine classification of the Ría de Vigo**, even on seasonal time scales.

In summer, **salinity is not the best proxy** for estimating the stratification and mixing seasonal cycles of the ría.

Upwelling modulations must be taken into account on the seasonal cycles of stratification and mixing to obtain a sounded estuarine classification of the ría.

The most probable circulation regimes are those falling between time-dependent salt-wedge and bay-fjord, i.e **partially mixed estuary**

Current & future research lines

Mainly second order forcings of residual circulation:

Vertical (turbulent) mixing

Modulation of tidal cycles of turbulent dissipation by coastal upwelling (Bieto et al., 2018)

Change of vertical M_2 ellipticity as proxy for stratification (in prep.)

Waves

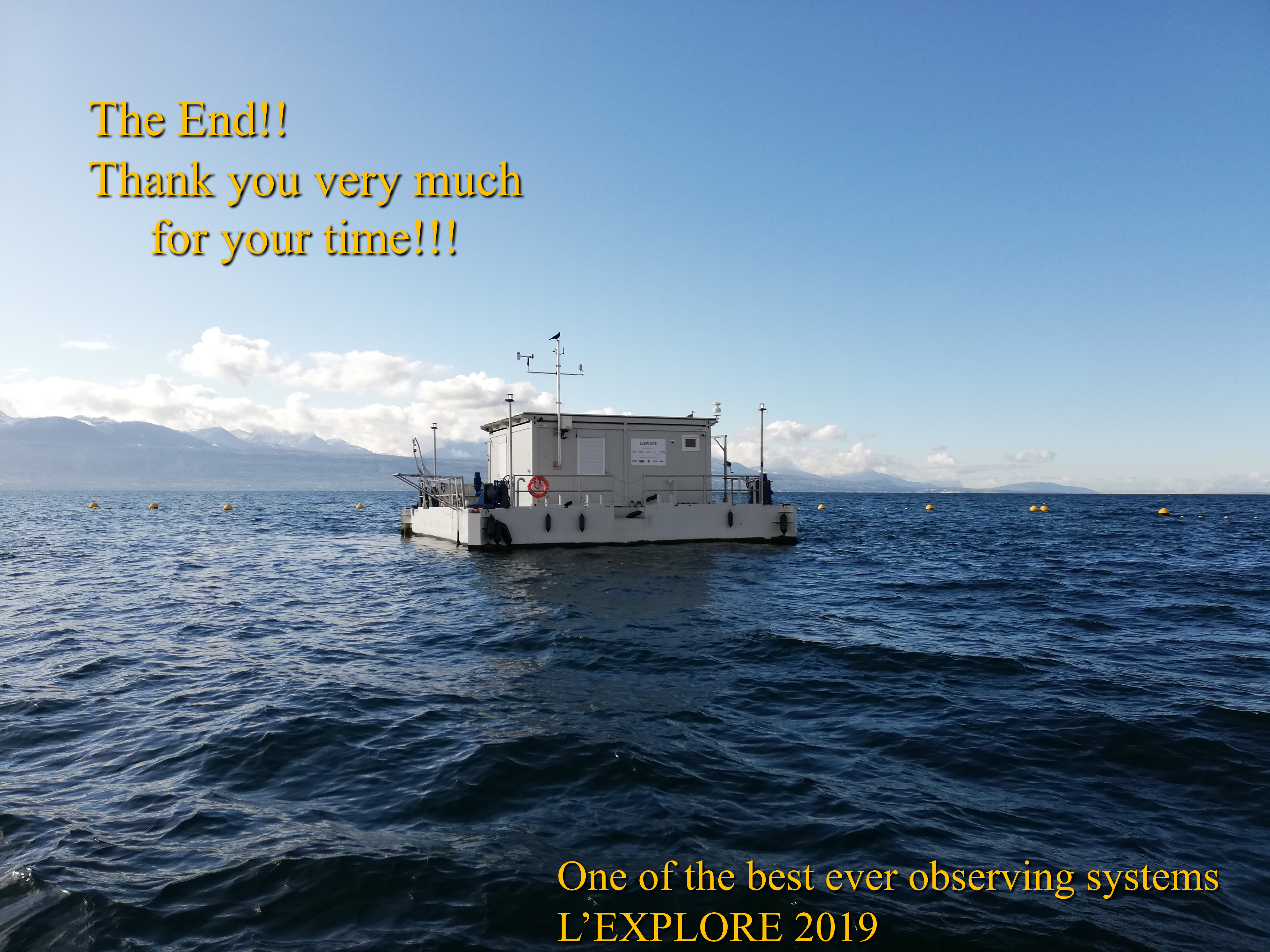
Stokes transport contribution to residual currents (in prep.)

Influence of waves induced turbulence (bottom)

Lagrangian description

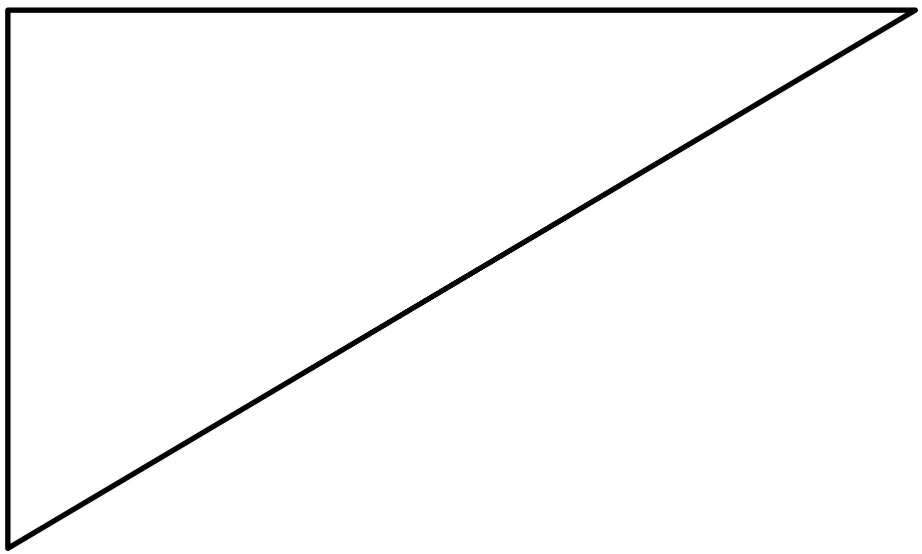
Ready to release 50 GPS/GPRS drifters in the ría


The End!!
One of the very first Observing Systems
Lethbridge Diving Machine 1715


The End!!
Thank you very much
for your time!!!
One of the best ever observing systems
L'EXPLORE 2019

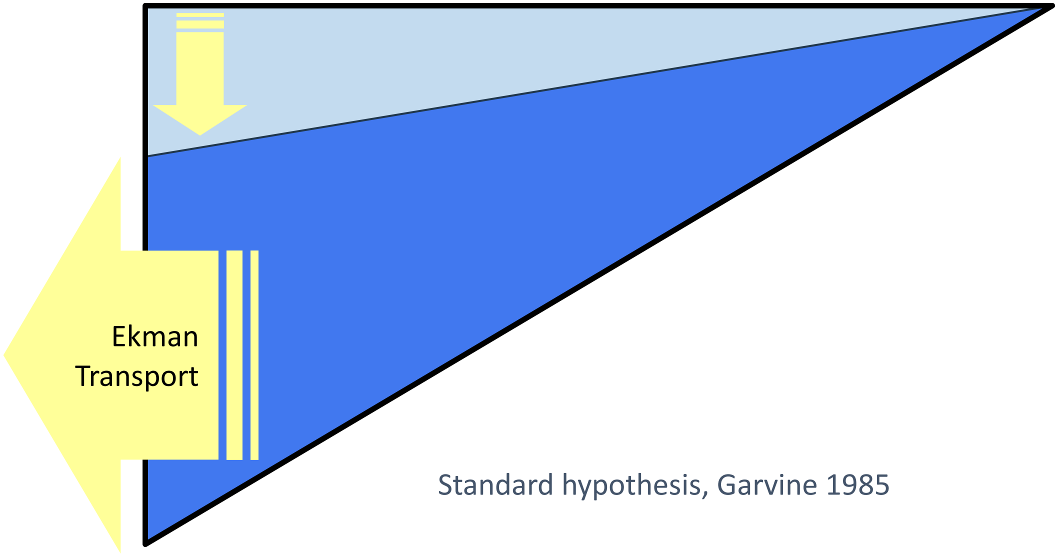
9. Barotropic bidirectional flow theory

- Former conclusions drive to the *Barotropic bidirectional flow forced by remote wind* of Gilcoto et. al. 2007
- We can compere it with the standard hypothesis of *unidirectional flow* for shallow estuaries of Garvine, 1985



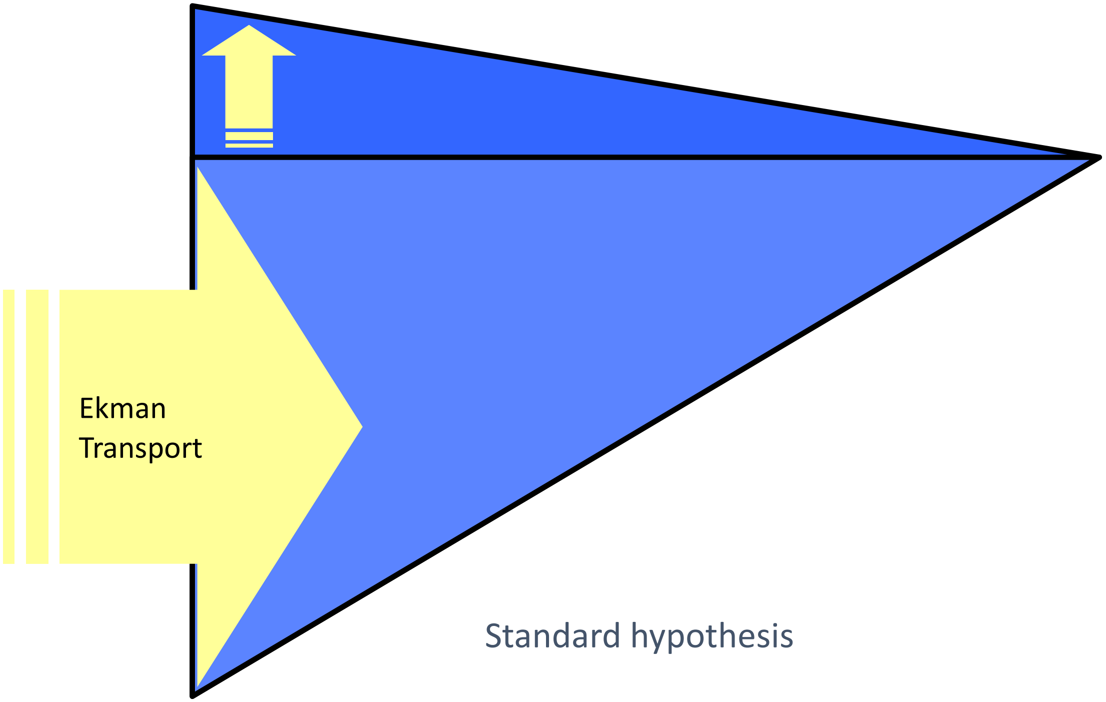
Garvine, R.W., 1985. A simple model of estuarine subtidal fluctations forced by local and remote wind stress. Journal of Geophysical Research 90 (C6), 11945-11948.

Unidirectional flow under an **upwelling** event

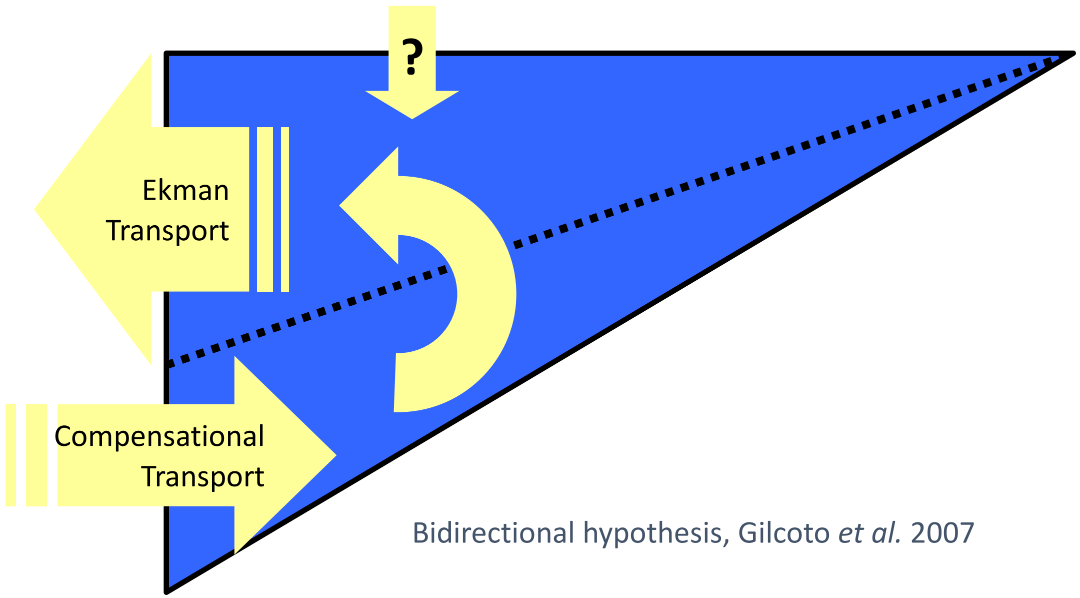


Standard hypothesis, Garvine 1985

Unidirectional flow under a **downwelling** event

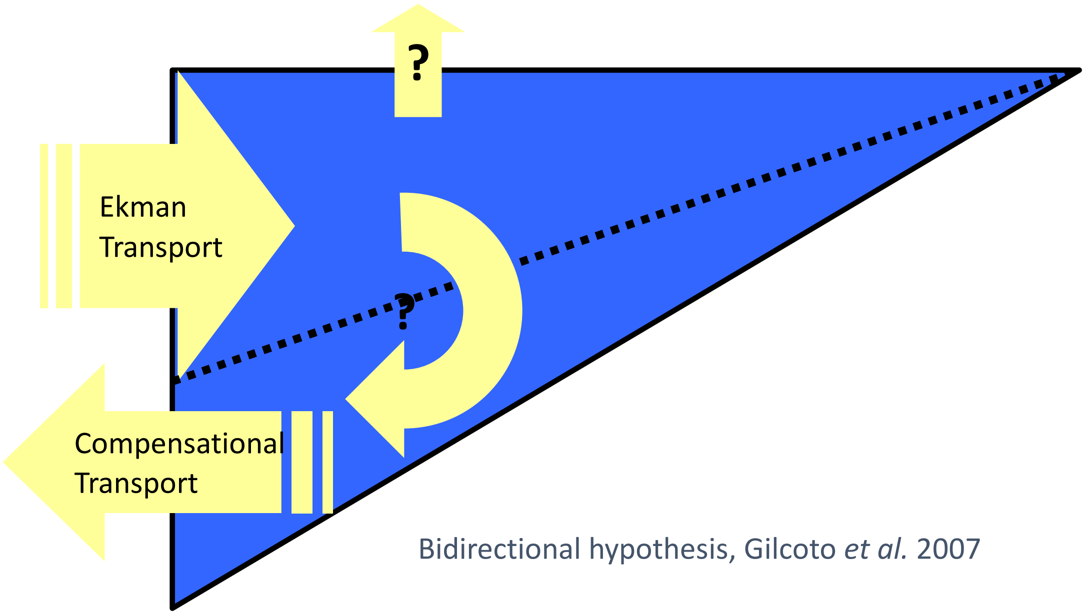


<u>**Bidirectional** flow under an **upwelling** event</u>



Bidirectional hypothesis, Gilcoto *et al.* 2007

<u>Bidirectional</u> <u>flow under a</u> **<u>downwelling</u>** <u>event</u>



Bidirectional hypothesis, Gilcoto *et al.* 2007