The influence of mesoscale eddies of the Arabian Sea on the slope currents of Red Sea and Persian Gulf outflow water

Pierre L'Hegaret, Leo Lacour and Xavier Carton,
LPO/UBO, Brest, France
Remy Baraille and Stephanie Correard
SHOM/CMO, Toulouse, France

Outline

- General characteristics of the region
- The mesoscale eddies and their effects at depth
- A seasonal dipole in the Northern Sea of Oman and its influence on the PGW outflow
- Study of a submesoscale lens off Ras al Hadd (from Physindien 2011 data)
- Conclusions and openings

université de bretagne occidentale

I. General characteristics of the region

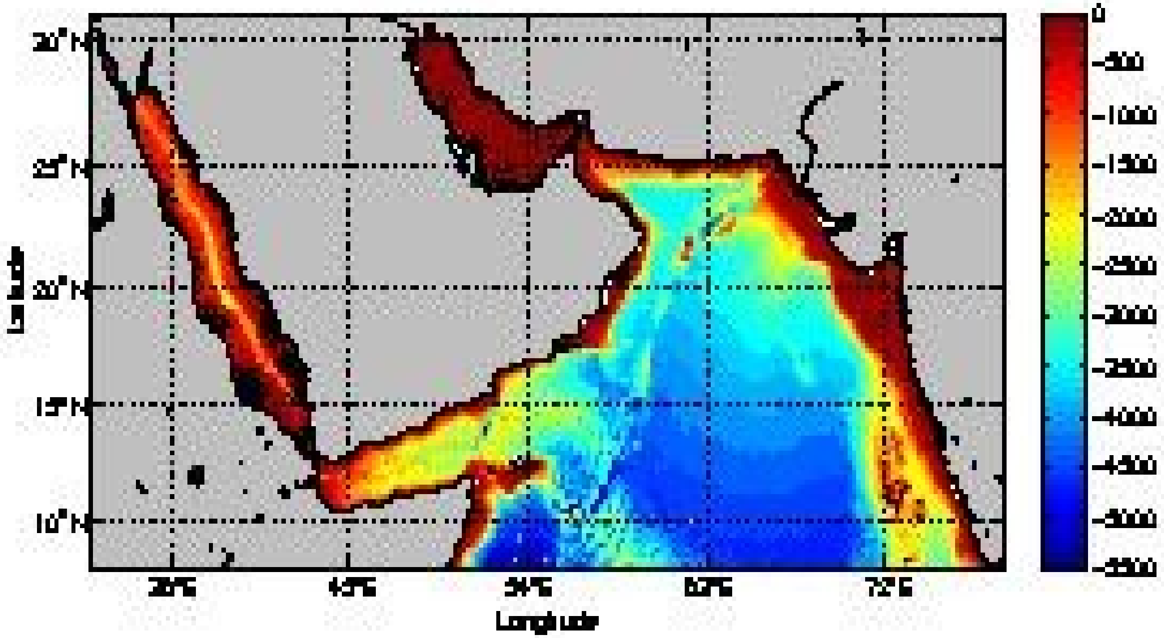


Figure 1: Model bathymetry

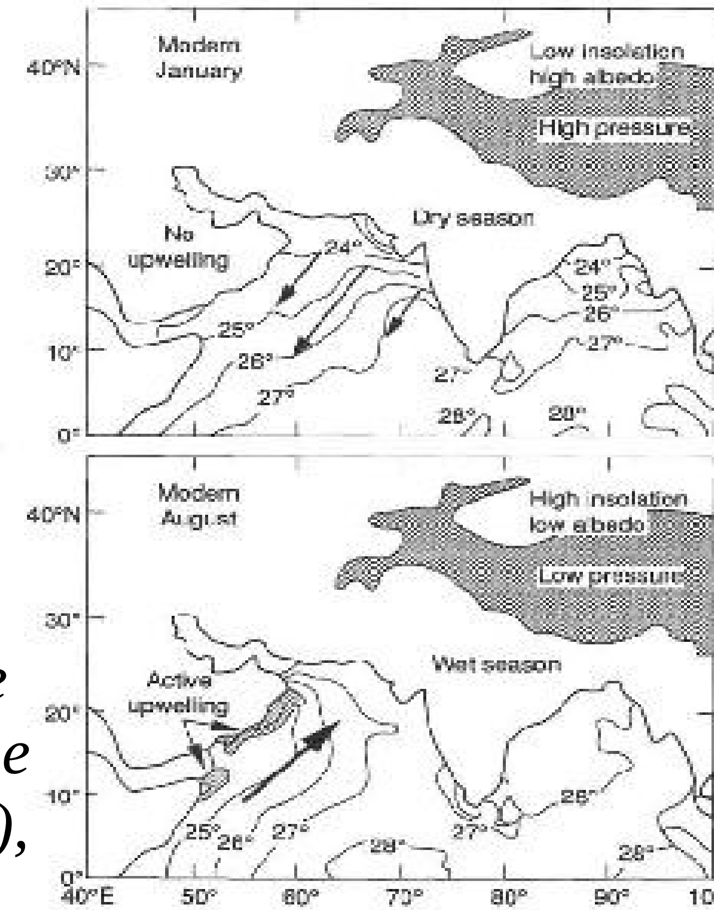


Figure 3. Seasonal changes in the boundary conditions of monsoonal circulation in the northern Indian Ocean and in Asia. Upper: During the northeastern monsoon in modern January. Lower: During the southwestern monsoon in modern August. Shaded area is the Tibetan Plateau and the Himalaya. Arrows denote wind directions; sea surface temperatures are given in °C. During the southwestern monsoon, upwelling offshore Somalia and Oman (shaded pattern) lowers the sea surface temperatures to between 22° and 24°C. Redrawn after Prell (1984a).

Shallow regions lie in the Persian Gulf, along the Coasts of Indian and in the Red Sea (except on the Central axis). The Arabian Sea (the Gulf of Aden), and the Gulf of Oman are deep.

The monsoon winds reverse in April and in October (approx); the summer monsoon creates Upwellings along Somalia and Oman

I.1 Geographic distribution of water masses

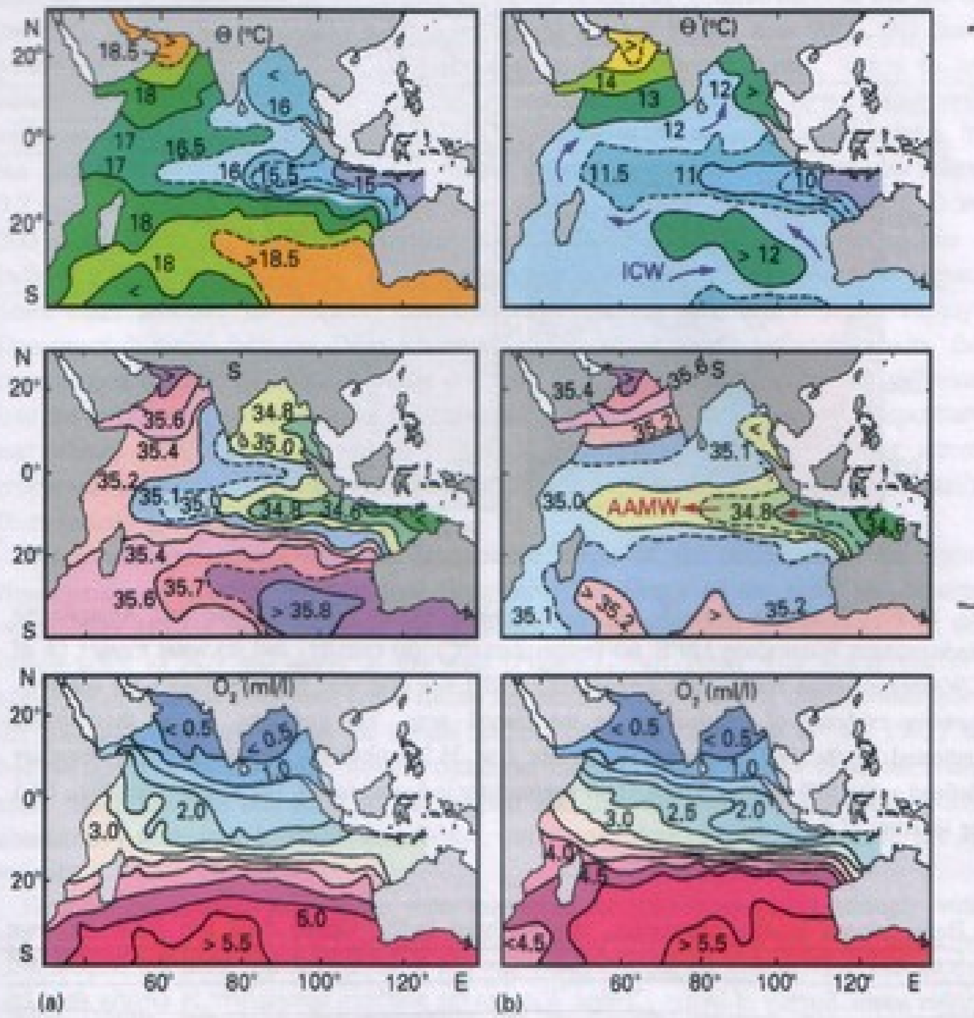


Fig. 12.9. Annual mean temperature (°C), salinity, and oxygen (ml/l) in the thermocline on isopycnal surfaces. (a) On the σ_θ surface 25.7, located in the depth range 150 - 200 m, (b) on the σ_θ surface 26.7, located in the depth range 300 - 450 m. Arrows indicate the movement of ICW and AAMW. After You and Tomczak (1993)

* at 150-200m depth : ICW, PGW, BBW ; they (or their influence) can be found again at 350-400m

* very strong E-W contrast in T and S north of the Equator

* influence of cold and fresh AAMW

* deeper RSW (600-1000 m), along the African coast

I.2 General circulation at the surface

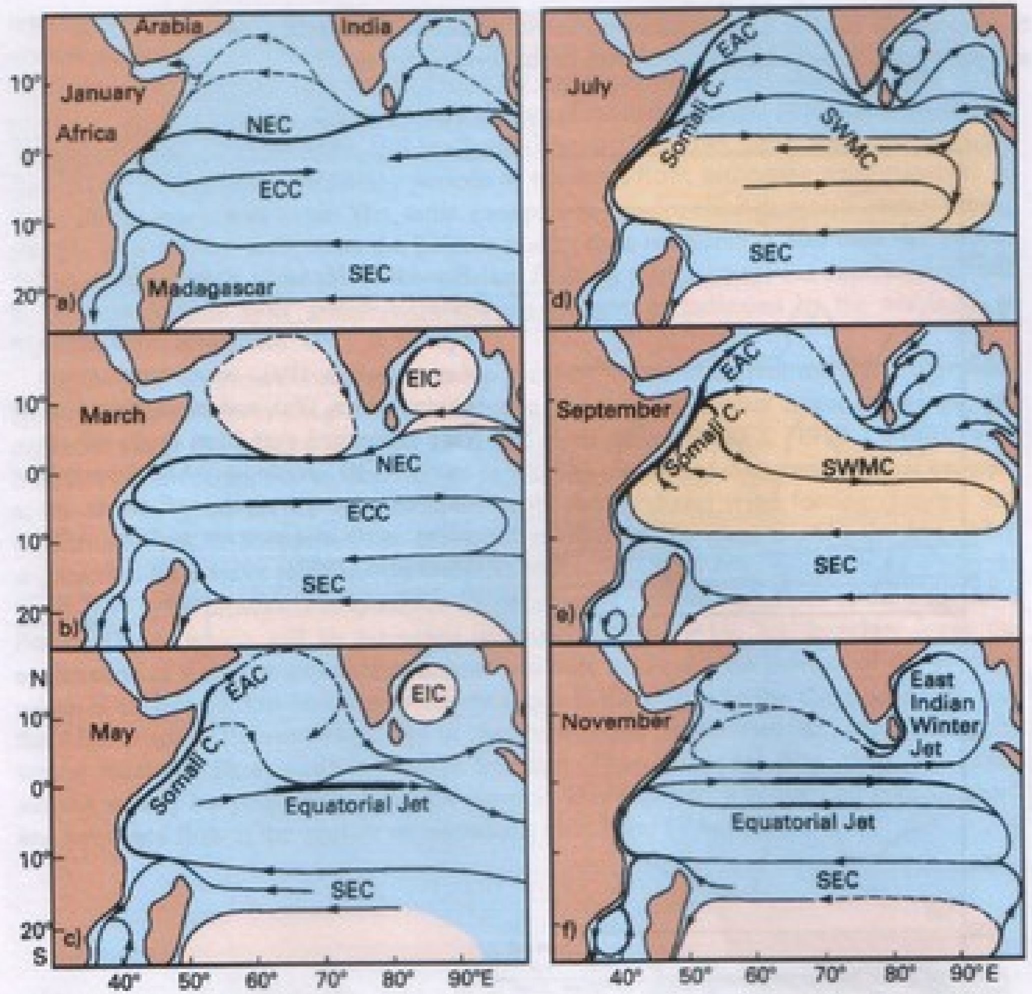
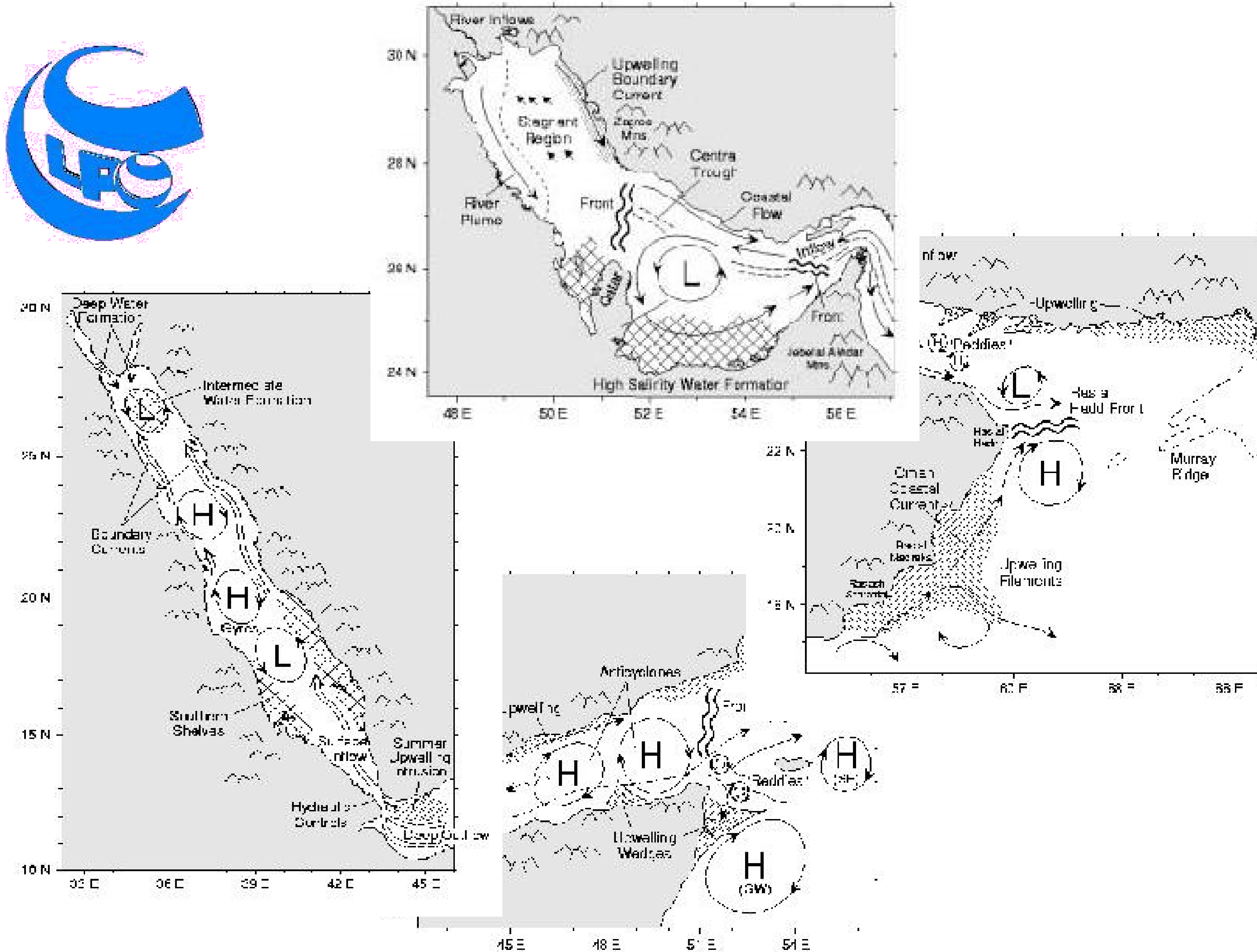


Fig. 11.4. Surface currents in the northern Indian Ocean as derived from ship drift data. SEC: South Equatorial Current, NEC: North Equatorial Current, ECC: Equatorial Countercurrent, SWMC: Southwest Monsoon Current, EAC: East Arabian Current, EIC: East Indian Current. Adapted from Cutler and Swallow (1984).

* from November to February, the circulation in the Arabian Sea is complex but it has cyclonic branches

* in summer the circulation is mostly anticyclonic, the Somali current is intense and is accompanied by the Great Whirl (AC eddy)

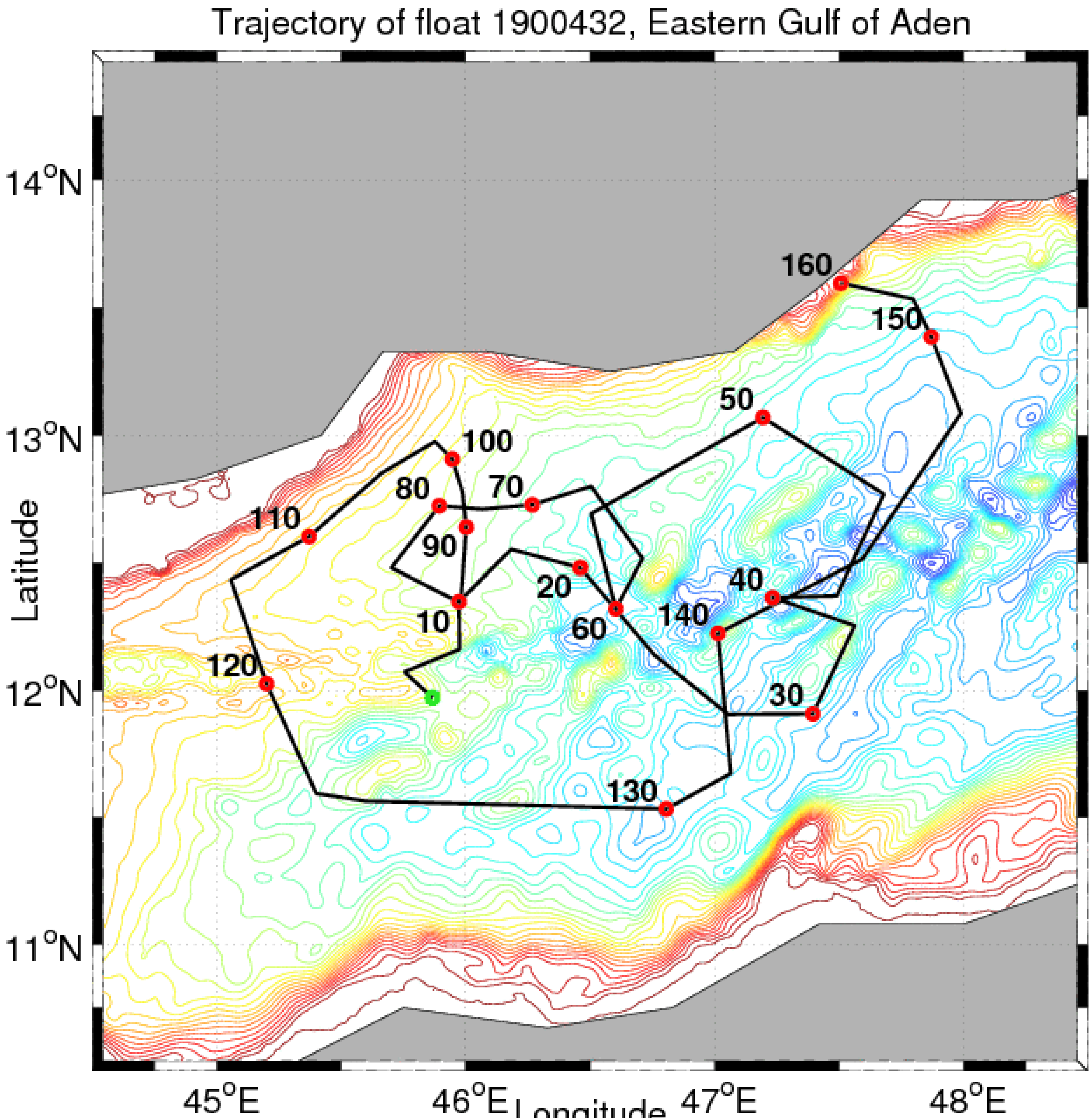
I.3 Main mesoscale phenomena in the region (summer)



II. The mesoscale eddies and their effects at depth

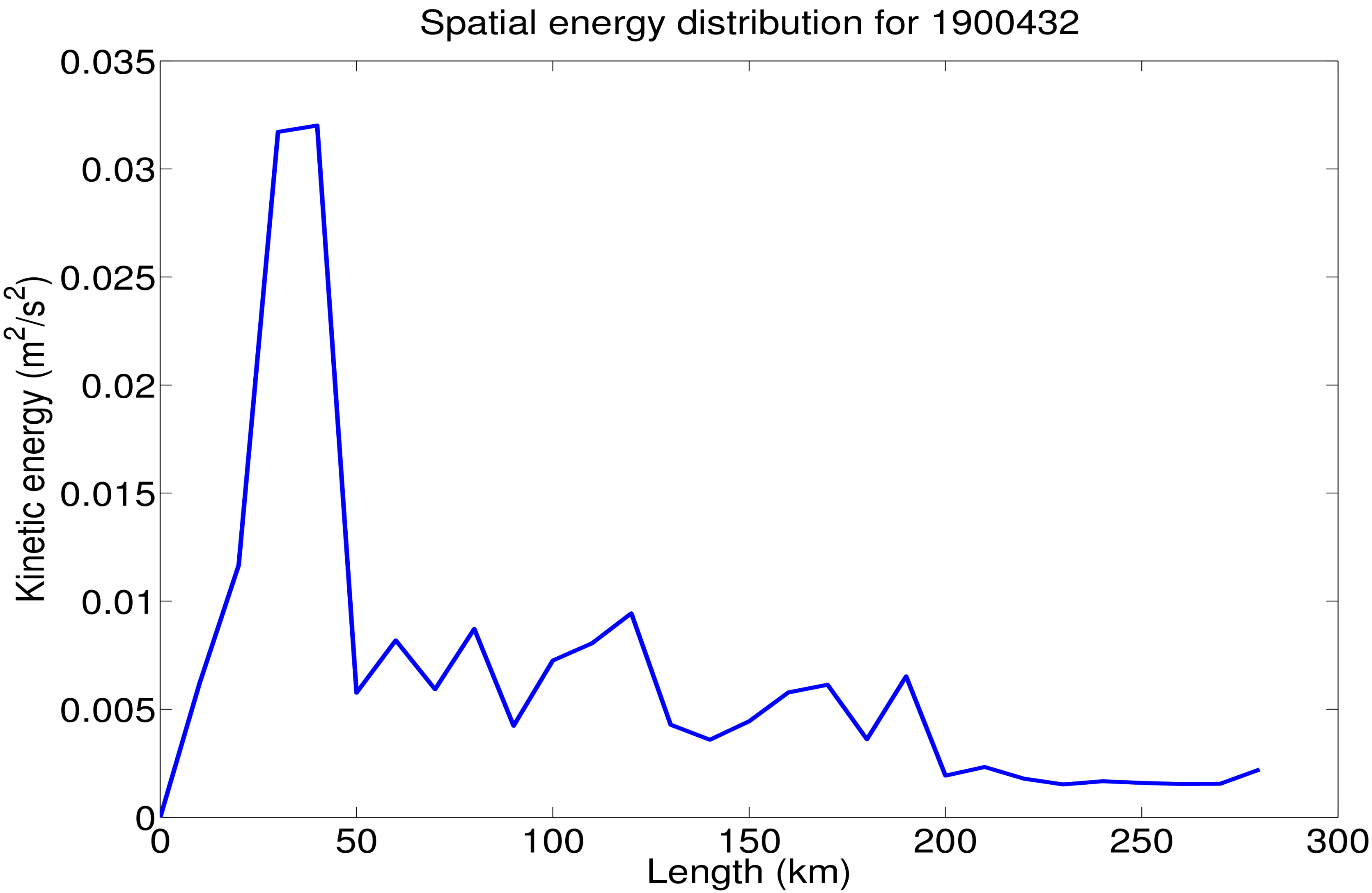
We use ARGO float data and satellite altimetry to characterize the relation between the surface mesoscale circulation and the motions at depth. ARGO floats are profiling floats with a parking depth of 700 or 1000 m and profiling from 2000 m depth to the surface every 5 to 10 days).

II.1 Float 1900432 in the Gulf of Aden :
(a) trajectory over bathymetry

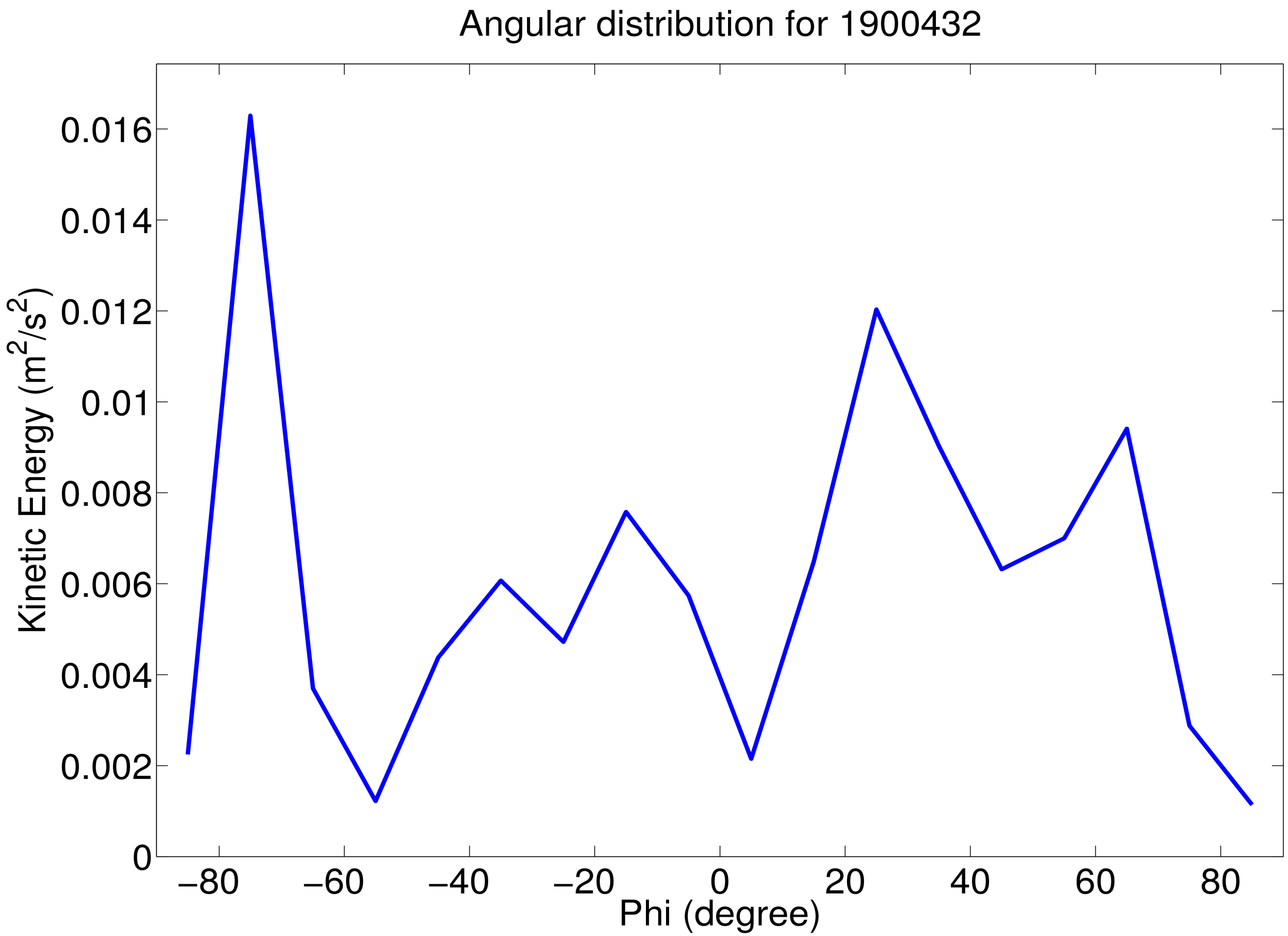


1) clearly an along-gulf motion
2) superimposed loops
3) relation with surface dynamics or bathymetry ?
4) thermohaline structure and relation with motion ?

(b) EKE distribution vs (cumulative) displacement (float 1900432)

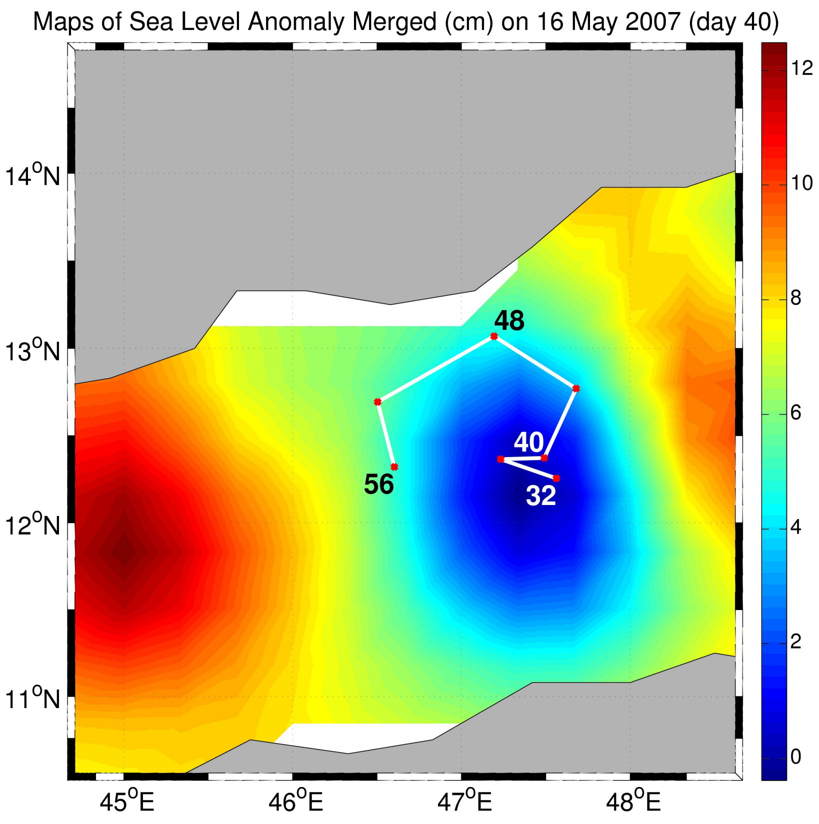


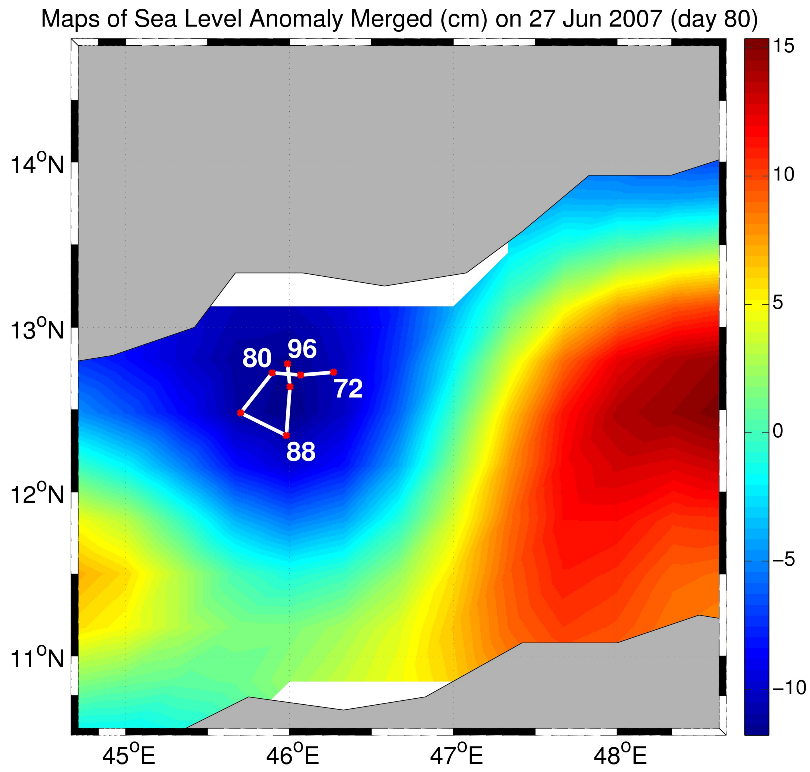
(c) EKE distribution vs direction (0 degree = East-West)



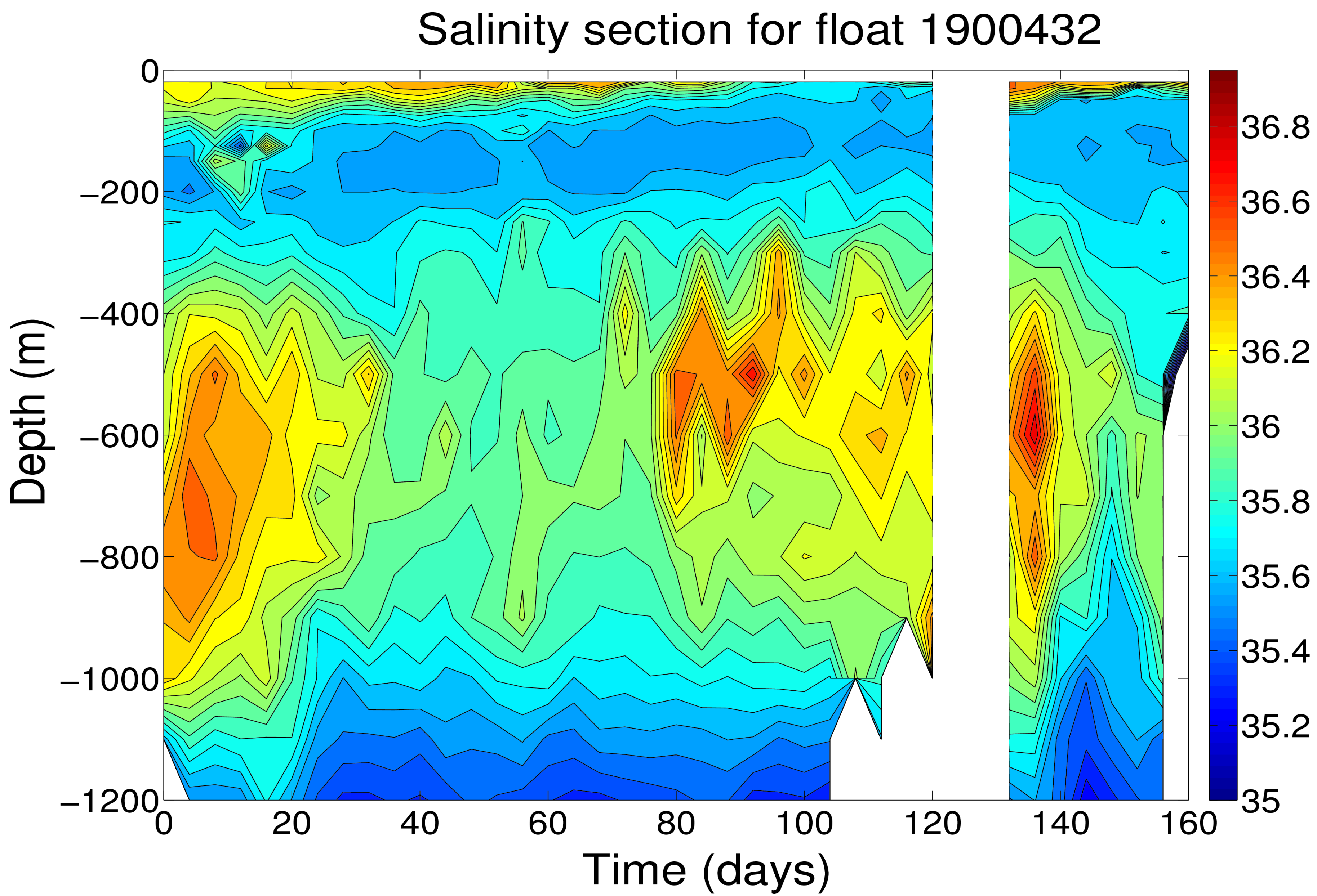
(d) Correlation between altimetry and motions at 1000 m depth

Correlation implies a deep reaching dynamical signature and a relatively barotropic character of the eddies





(e) Salinity section along the float trajectory



(f) Analysis of float 1900432

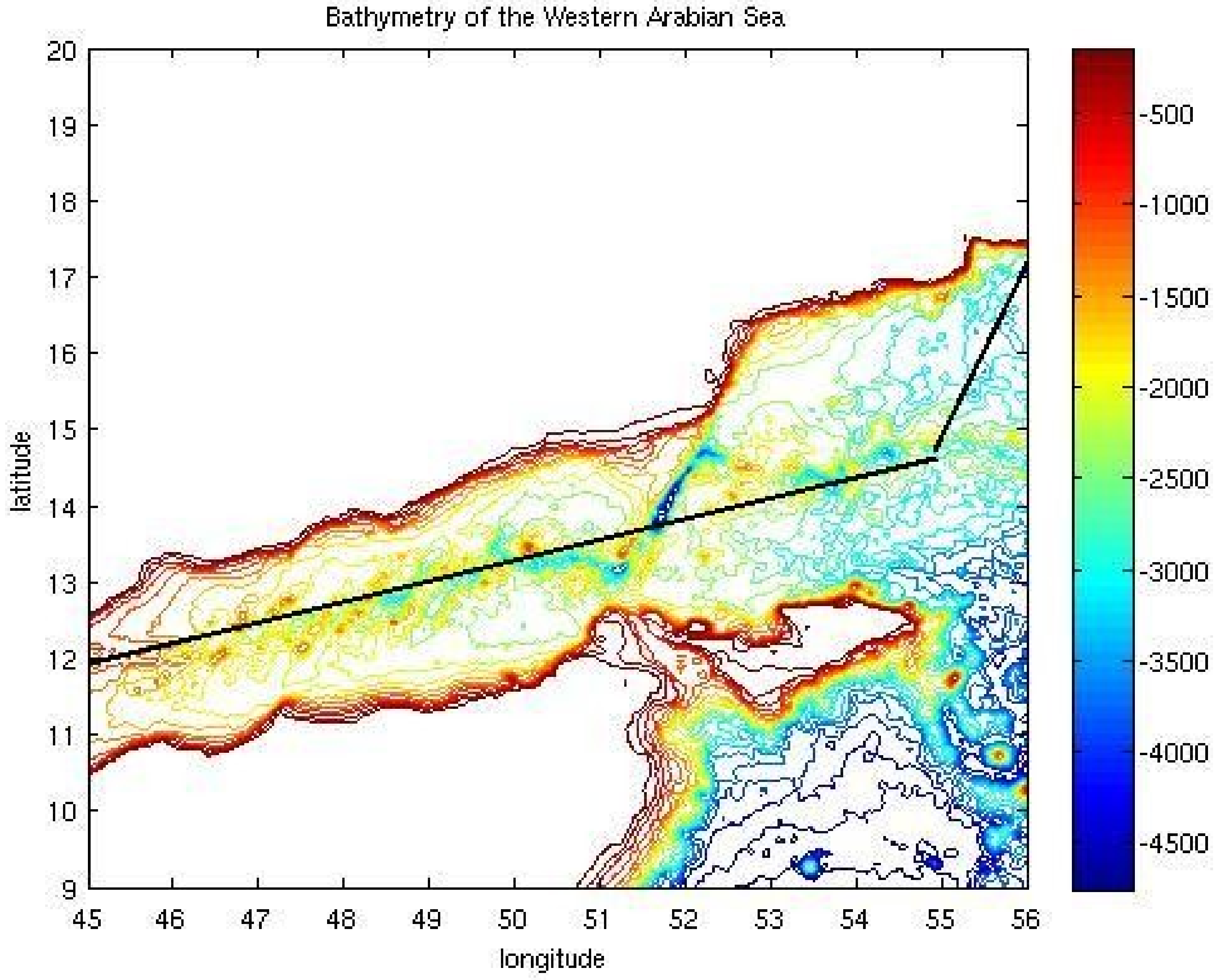
The mesoscale eddies have a barotropic character and carry fresh ICW into the Gulf of Aden

Maximum salinity at 1000 m depth lies to the west and thus near the straits of Bab el Mandeb – the T and S gradients are well correlated with climatology (nor shown here).

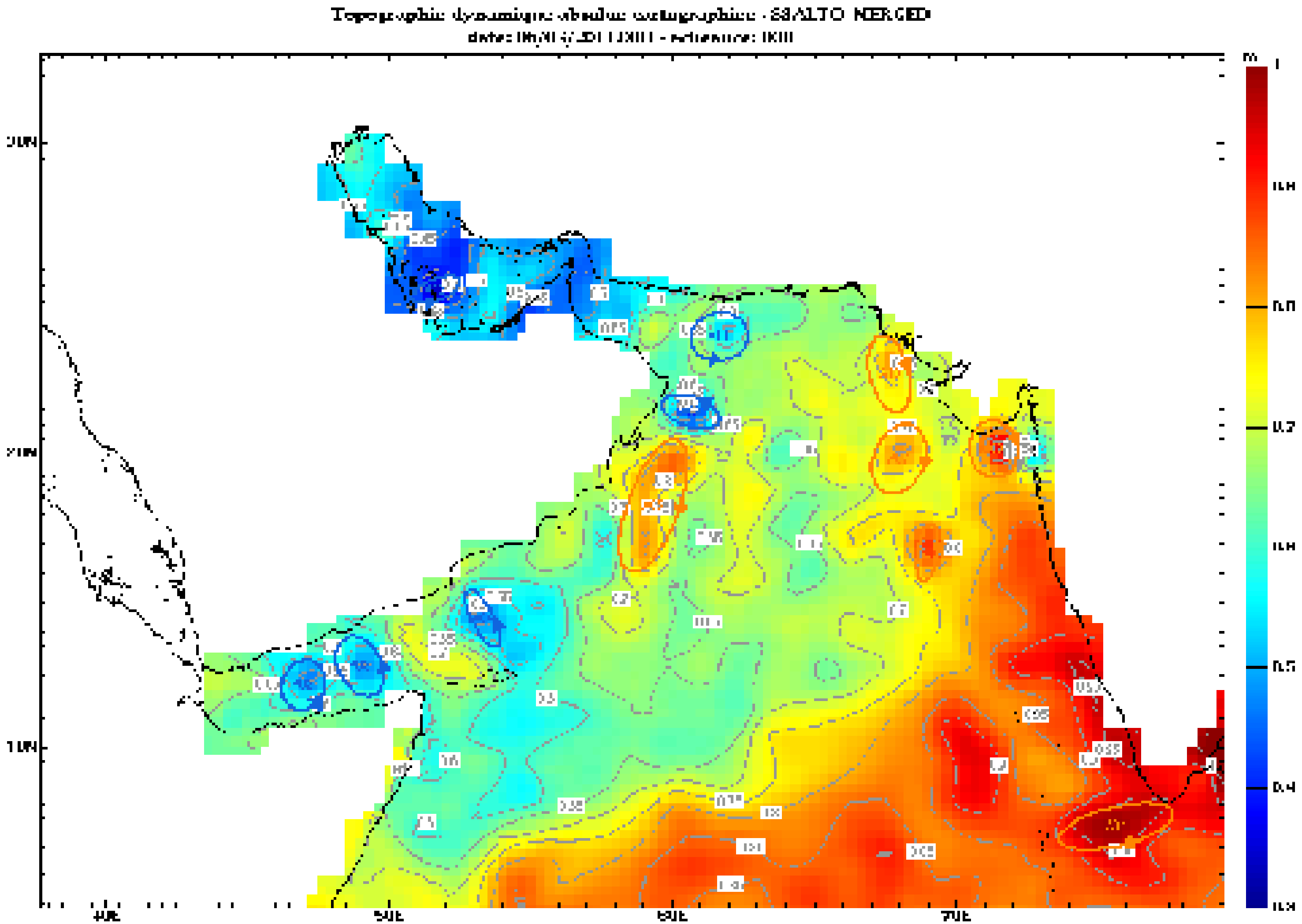
Salty filaments are advected along N-S axes across the Gulf

These events occur at several seasons and for several years at least

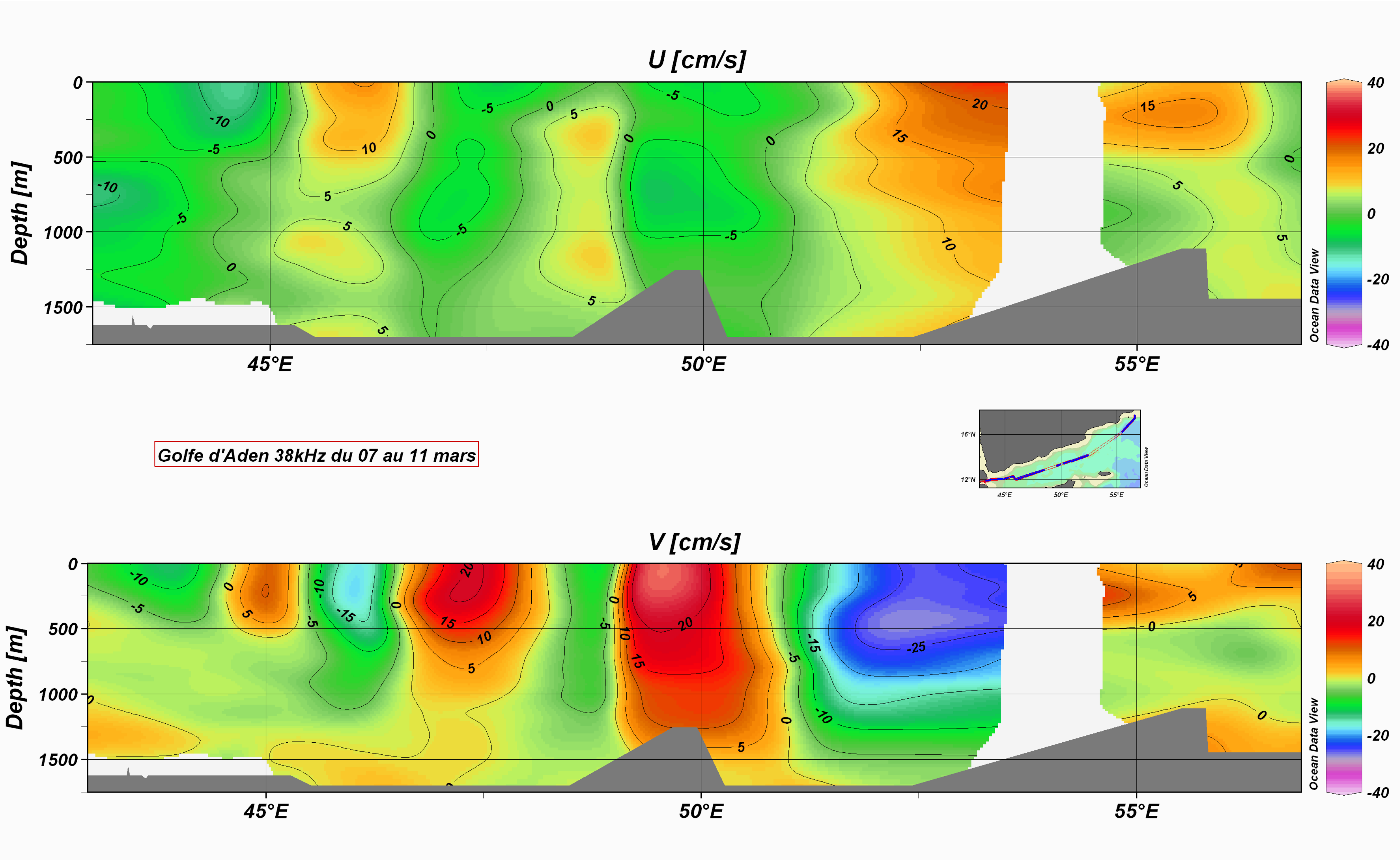
II.2 XBT-XCTD-VMADCP transect across the Gulf of Aden - Physindien 2011



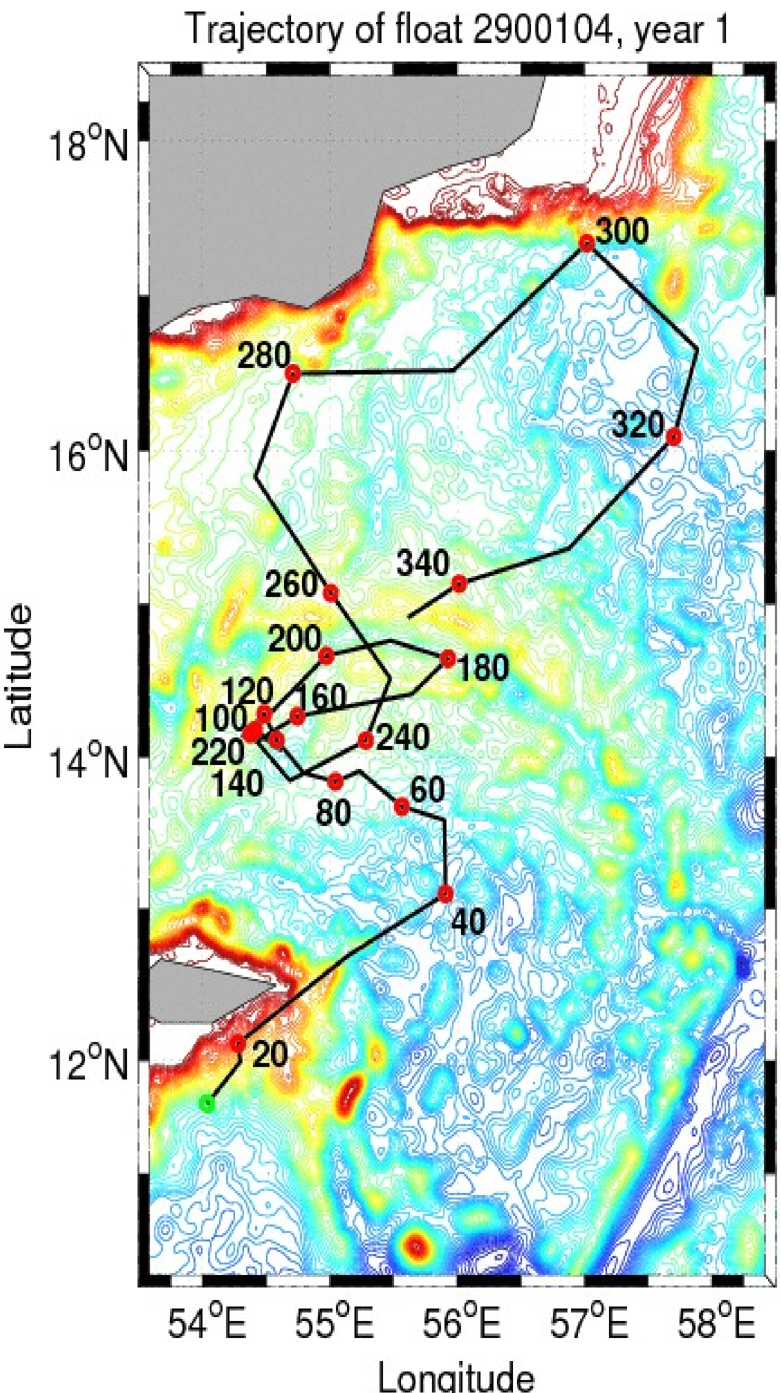
II.2.a Satellite altimetry map at the time of Physindien 2011



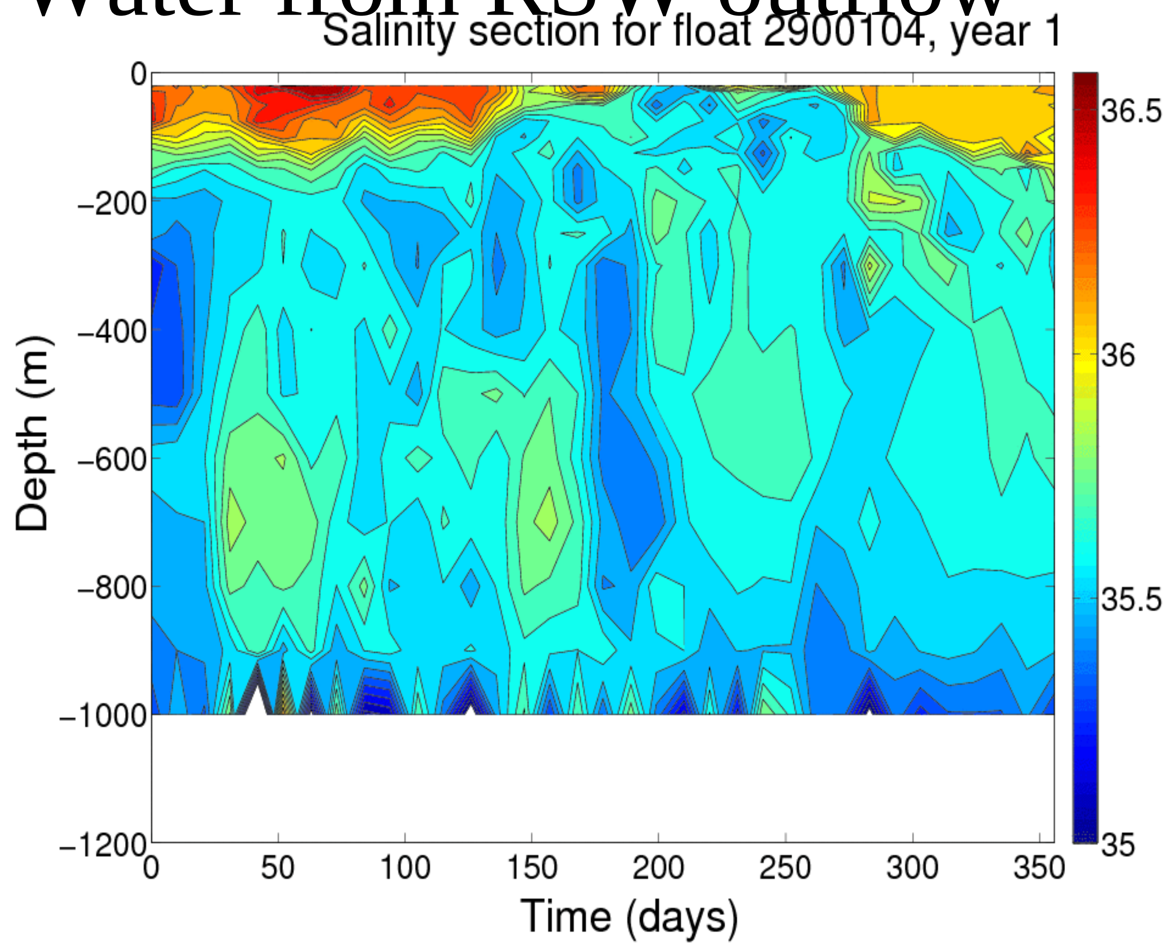
II.2.b VMADCP currents along the Gulf of Aden section of Physindien 2011



II.3 Analysis of float 2900104 (year 1)

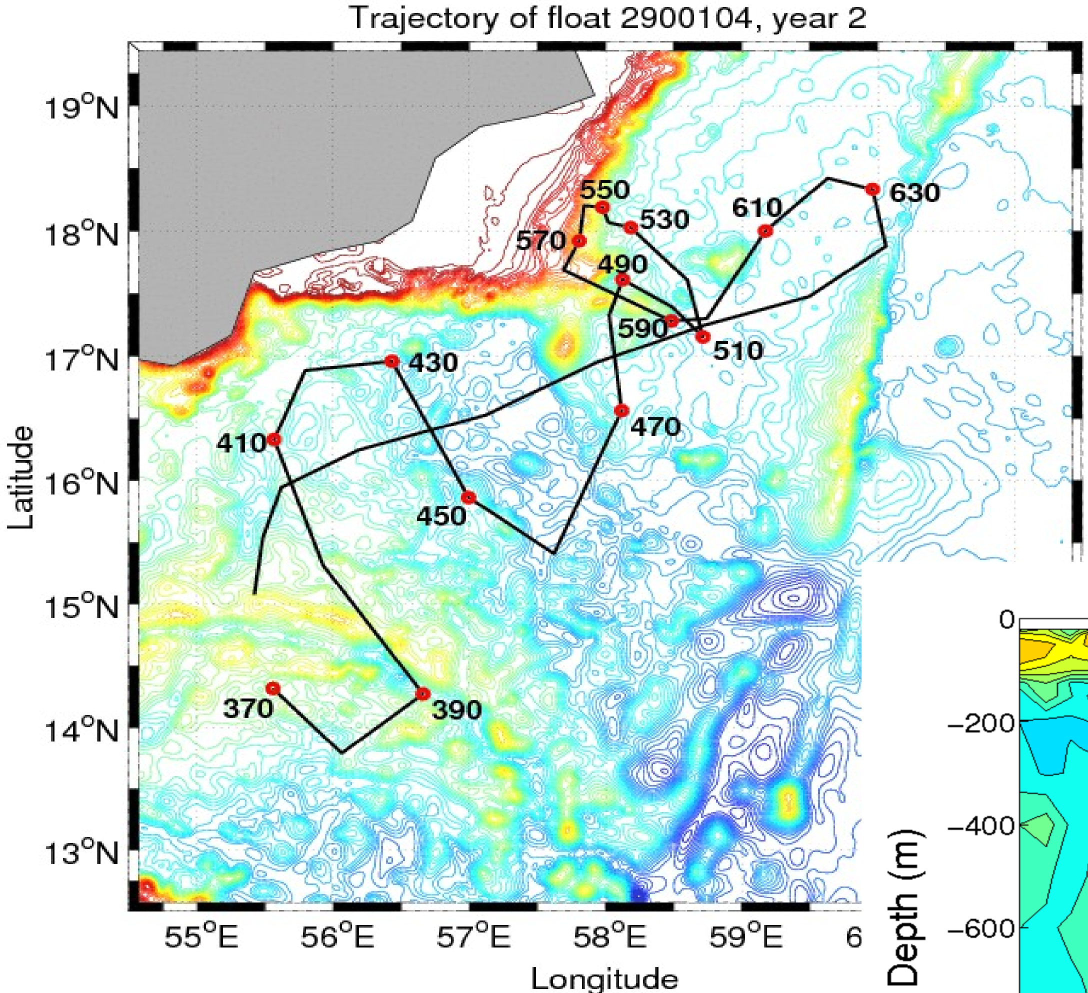


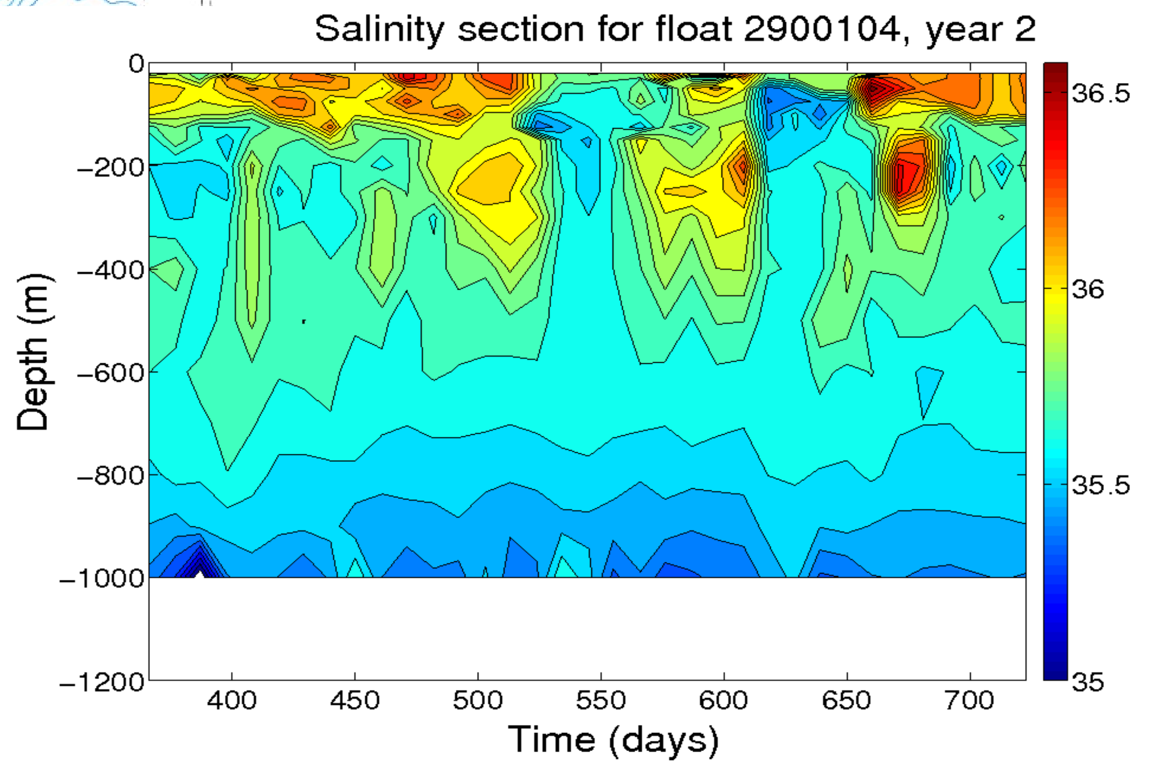
Offshore patches of RSW (Days 40 and 150). Existence of surface dipoles extracting Water from RSW outflow



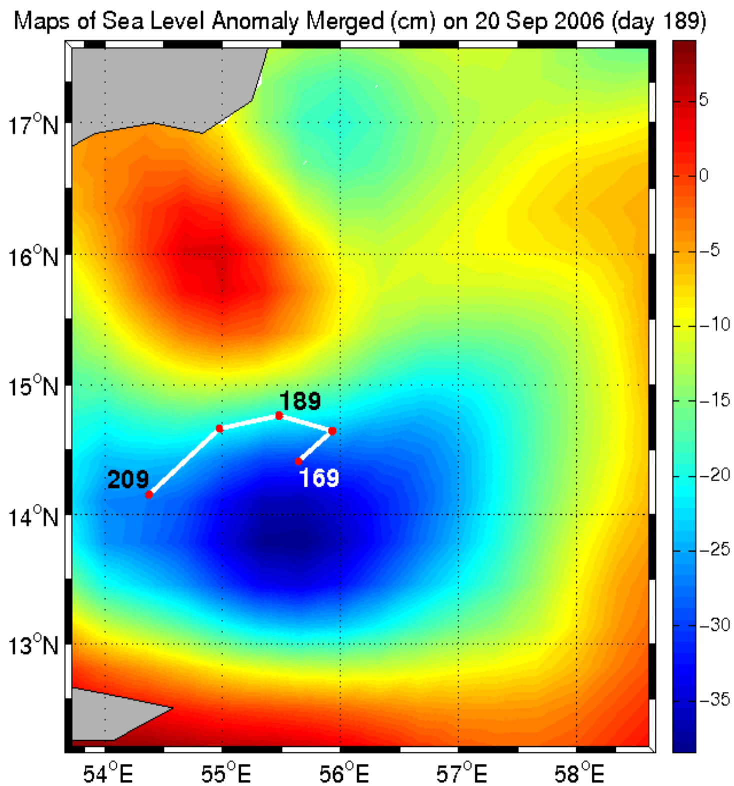
II.4 Analysis of float 2900104 (year 2)

Float trajectory and S Anomalies (PGW)

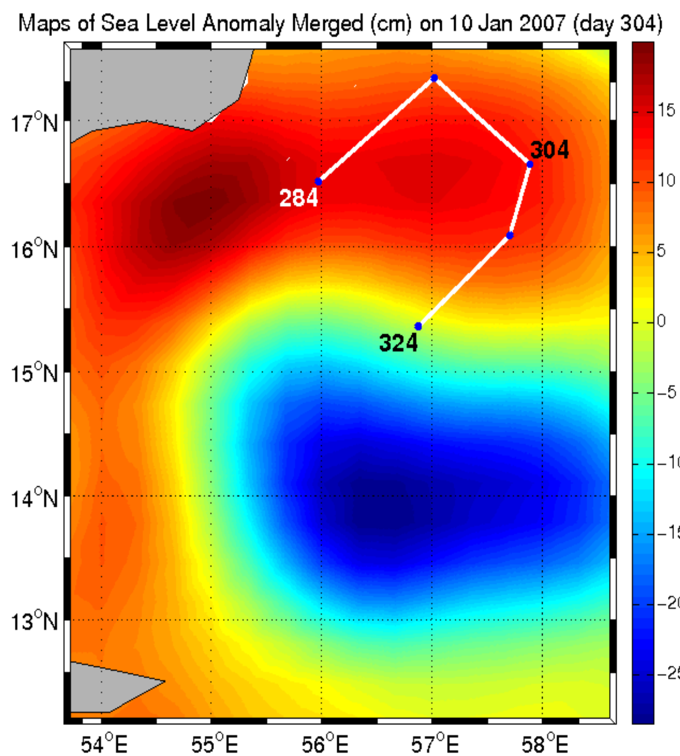




II.4 Analysis of float 2900104 (year 2)



Correlation of float motion
With altimetric maps
(dipoles)



Summary of part 2

Both in the Gulf of Aden, near Socotra or south of Oman, the deep floats roughly follow the surface mesoscale circulation ; submeso or meso scale patches of salty water are found far offshore

The presence of dipoles, which can extract water from the coastal outflows, is often observed

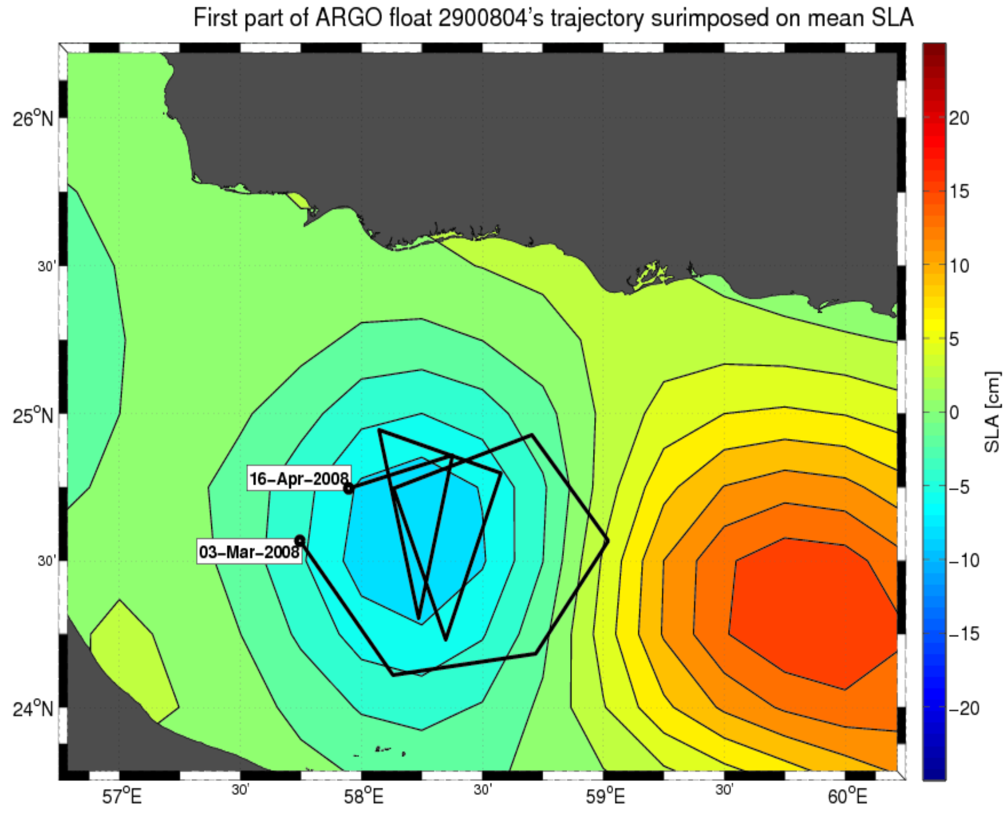
We will now show the correlation between a dipole and PGW extraction from the coast, in the northern Sea of Oman

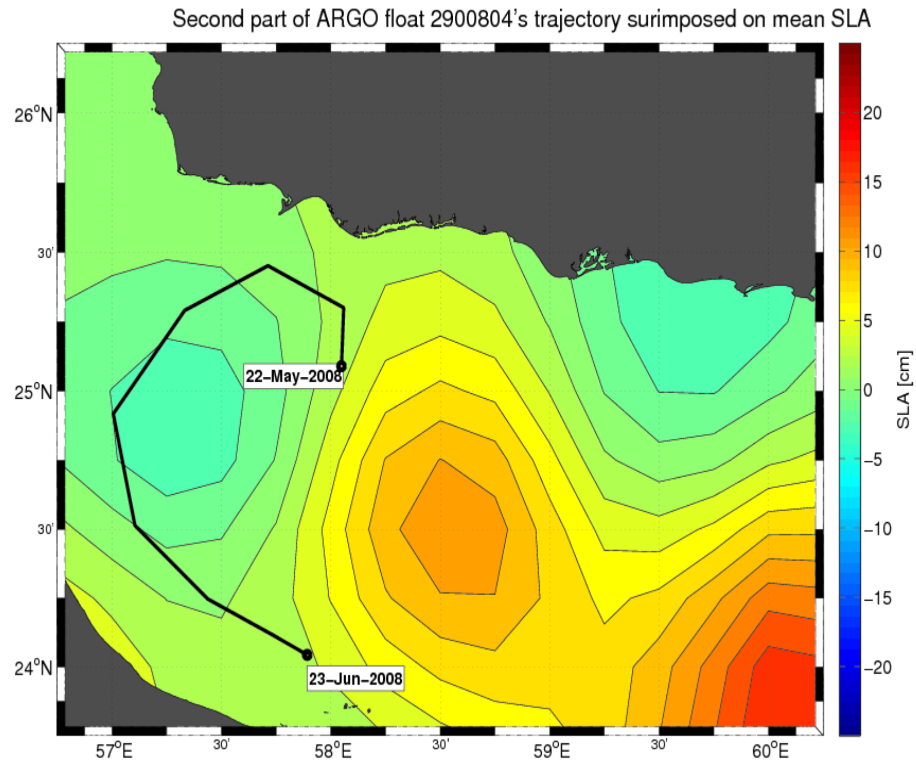
III. A seasonal dipole in the Northern Sea of Oman and its influence on the PGW outflow

Here again we use ARGO float data and satellite altimetry to put in evidence The mesoscale (and smaller-scale) motions above and near the PGW outflow in the northern Sea of Oman

ARGO float trajectories and T,S recordings show that PGW can be extracted from the slope current during spring by the action of mesoscale surface dipoles. The evolution of PGW, the extraction mechanism and the origin of the dipole are studied here.

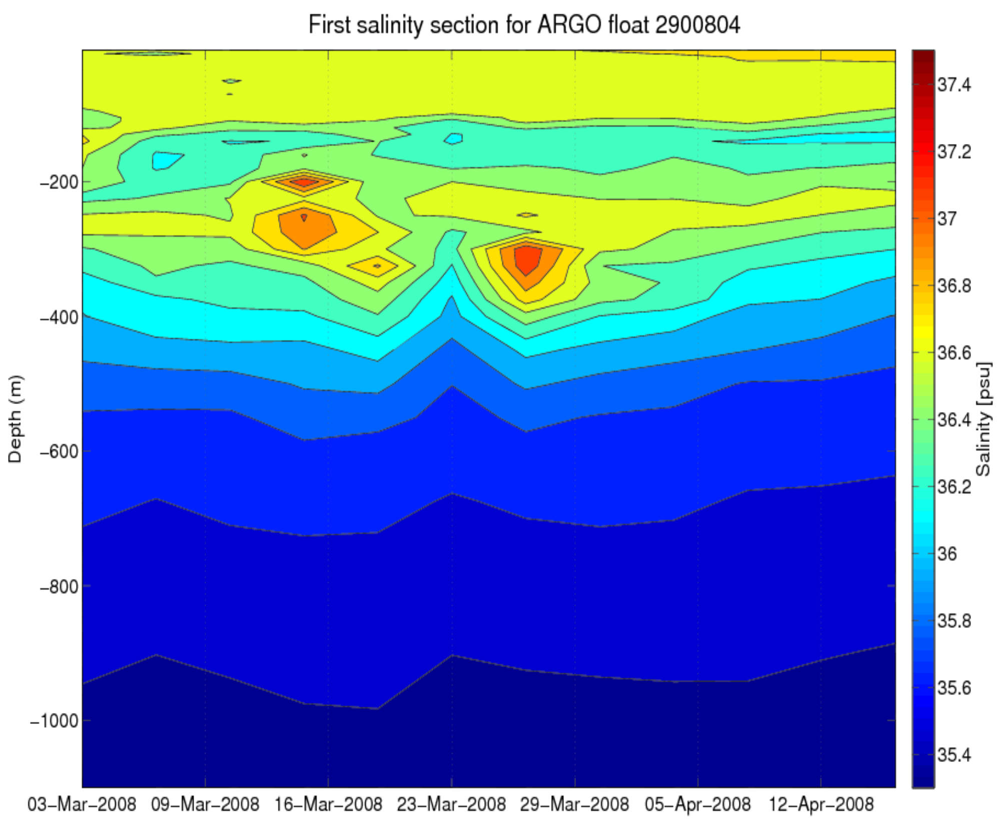
III.1 Analysis of Argo float 2900804 in the northern Sea of Oman (March 3- April 4, 2008 and May 22 -

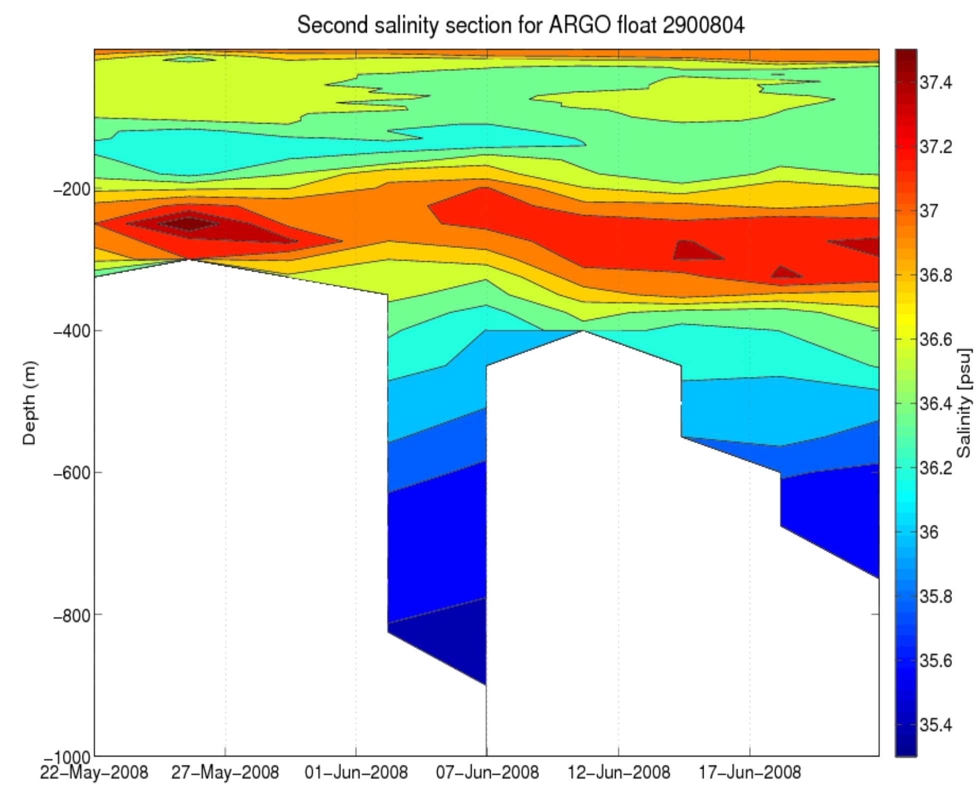




III.1 Analysis of Argo float 2900804 in the northern Sea of Oman (March 3- April 4, 2008 and May 22 -

in 2011-2012



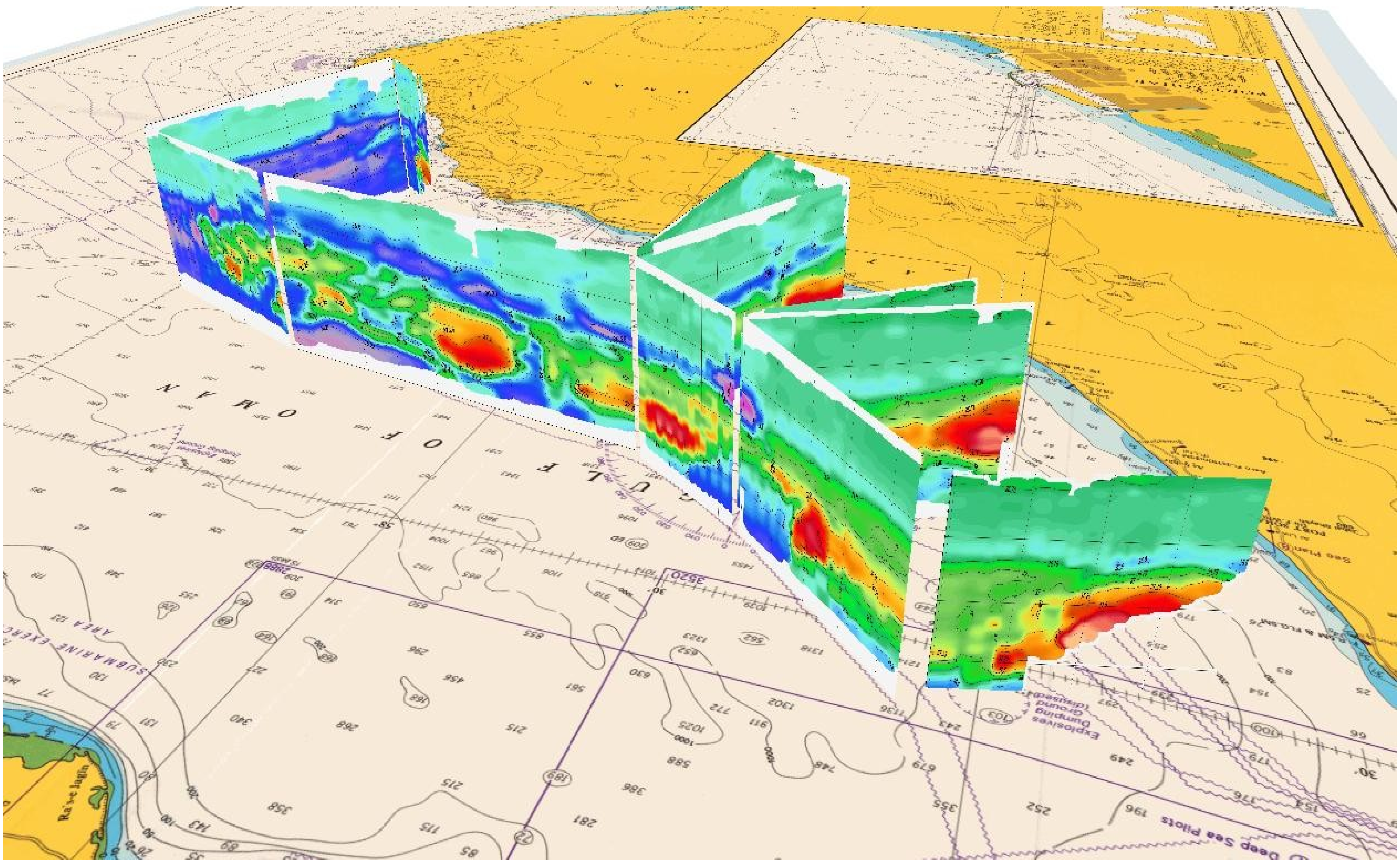


III.2 Argo float data analysis

Satellite altimetry and several float trajectories indicate the presence of a dipole in the northern part of the Sea of Oman in 2008, 2011, 2012 (but also in 1994, 95,97, 98, 2005, 2007 from altimetry)

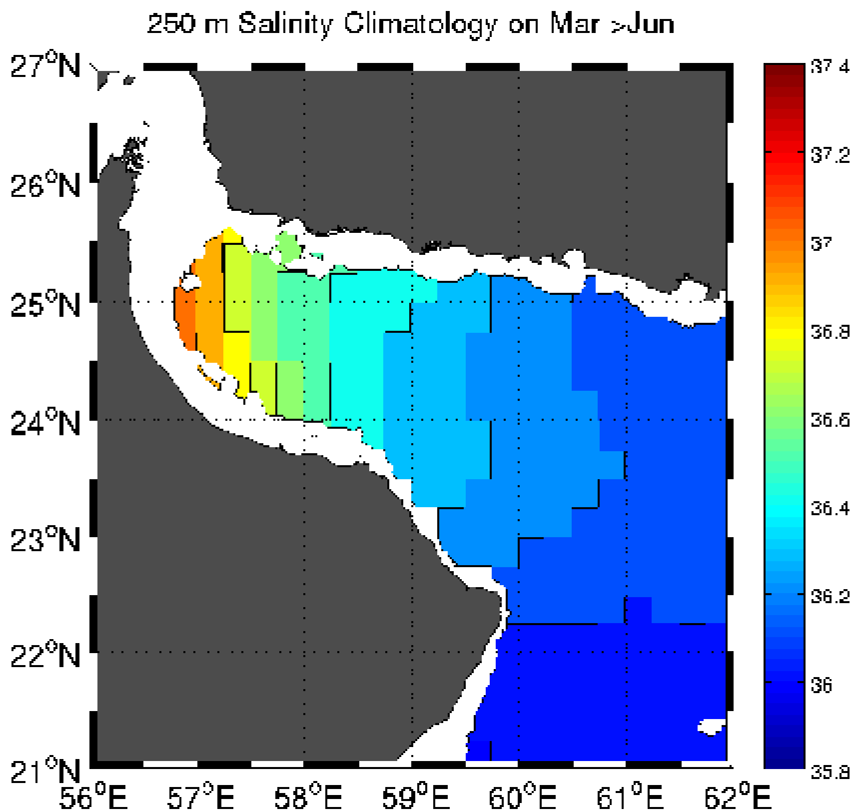
This dipole extracts PGW from the coast of Oman. This PGW recirculates along the coast of Iran either cyclonically to the West or anticyclonically to the East. It can be carried away to the coast of Pakistan where it is again expelled offshore.

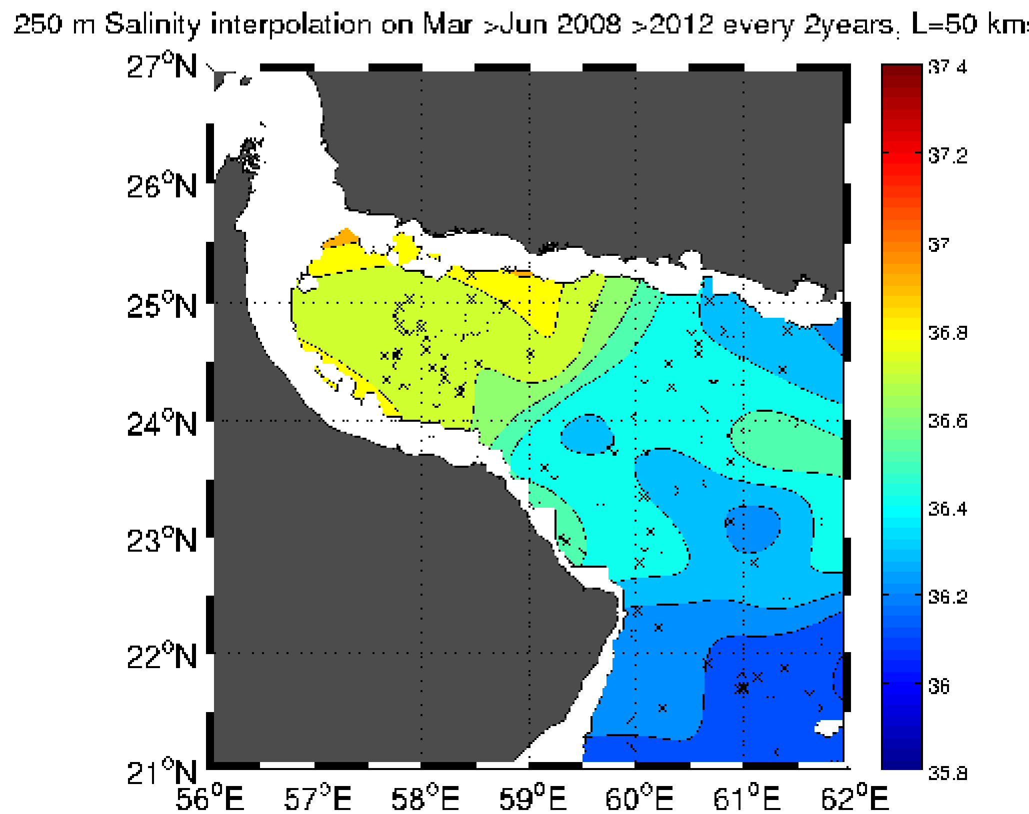
III.3 confirmation of the existence of small fragments of PGW in the middle of the Sea of Oman : axial section of salinity in the Sea of Oman (Physindien 2011, March)



III.4 What is the result of PGW ejection ?

Compare S maps at 250 m depth from climatology and from Argo float data



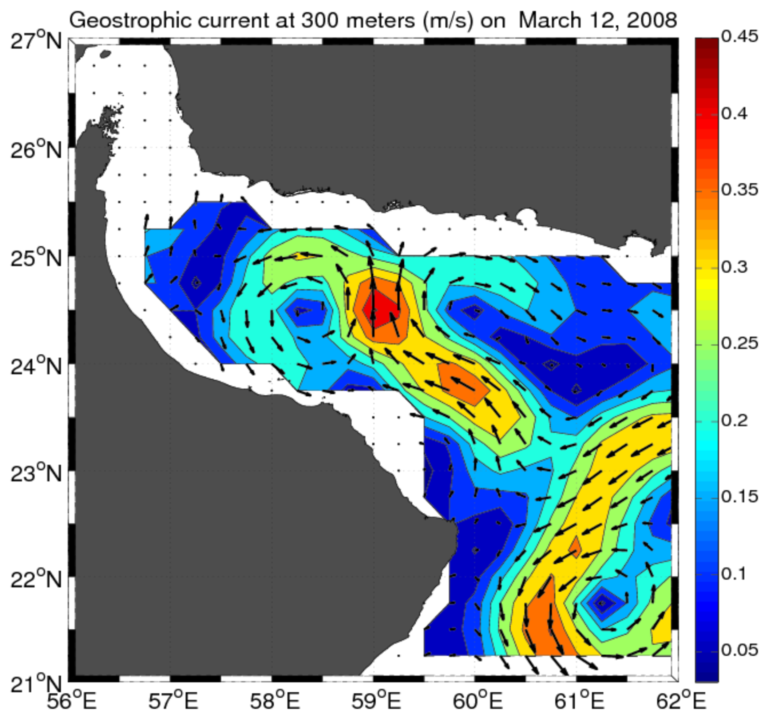


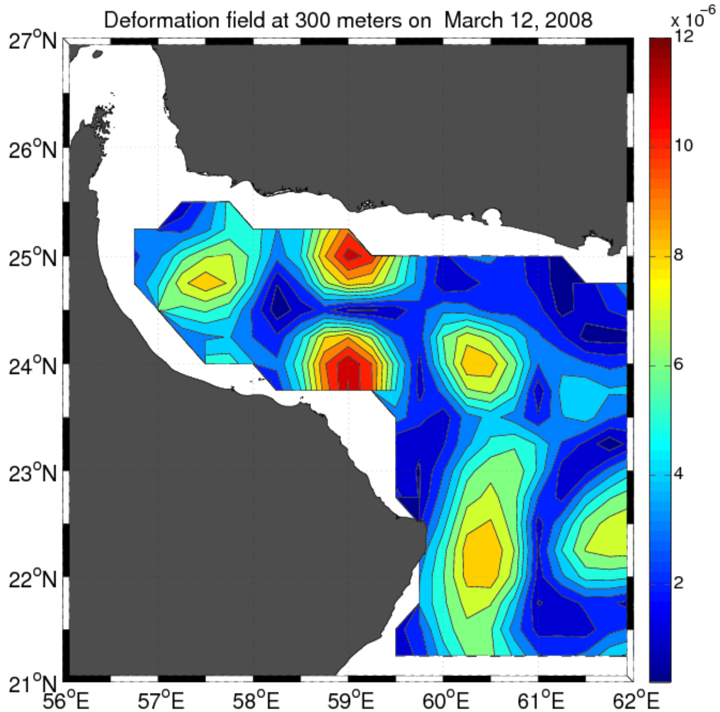
III.5 how does the dipole extract PGW

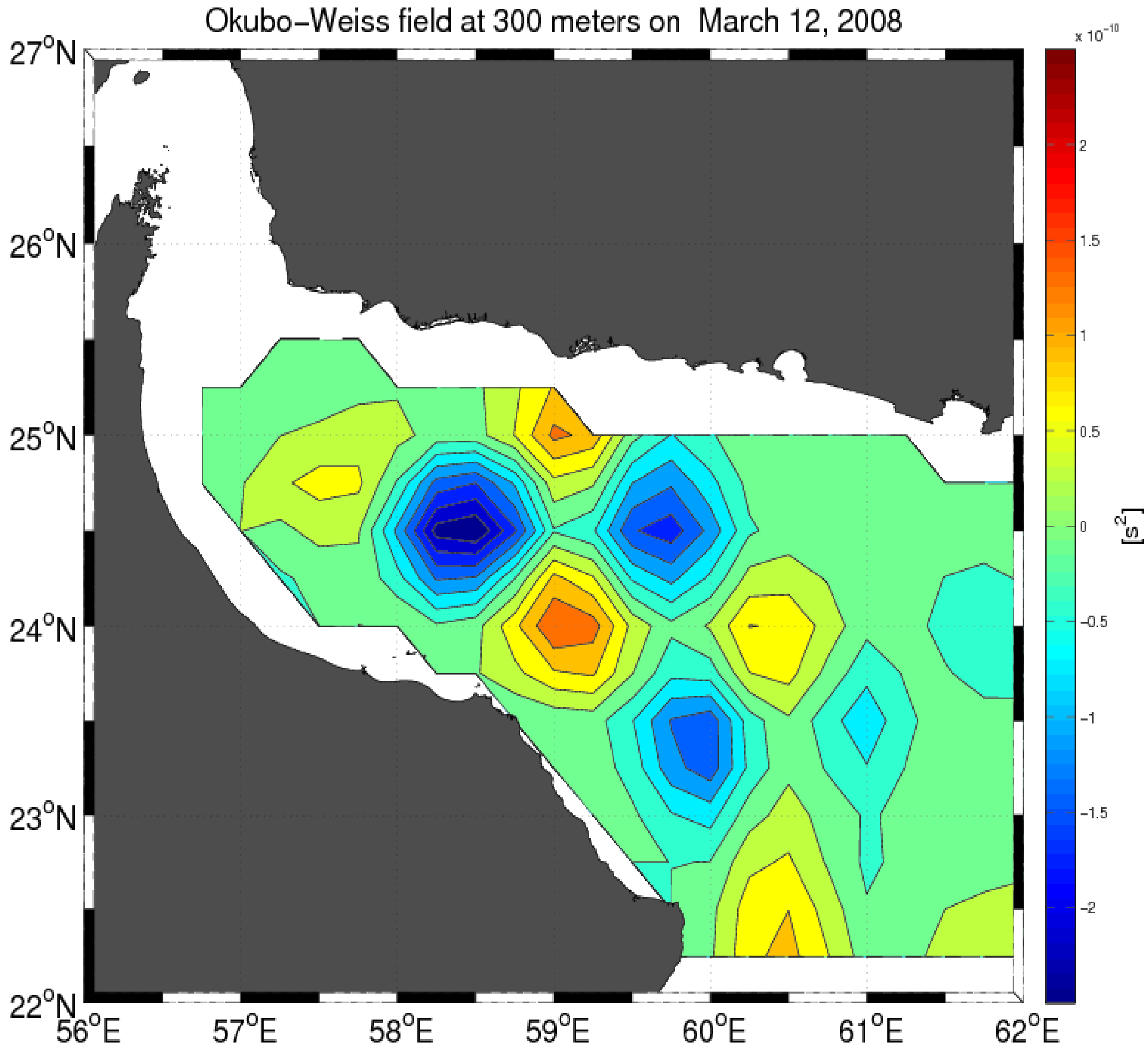
from the coastal current ?

Compute deformation and Okubo Weiss maps for deep currents

(obtained from altimetric surface currents + thermal wind)

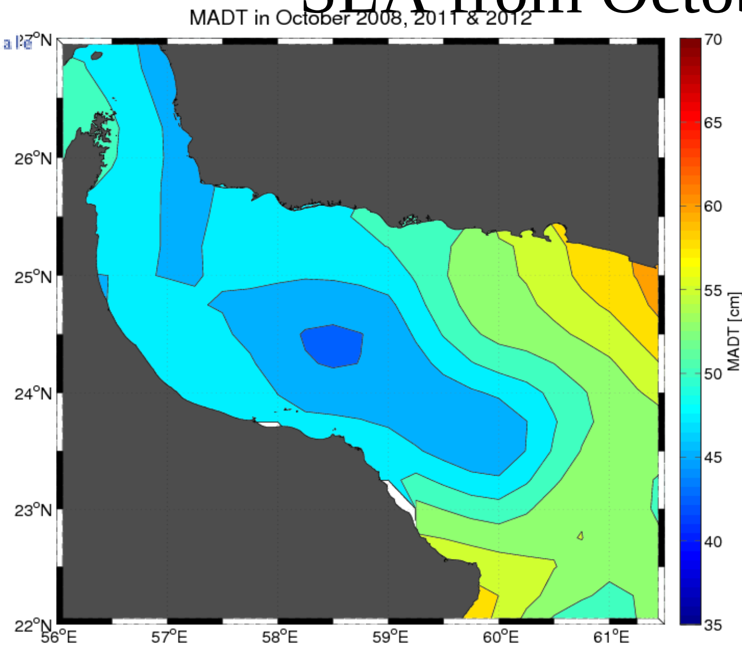


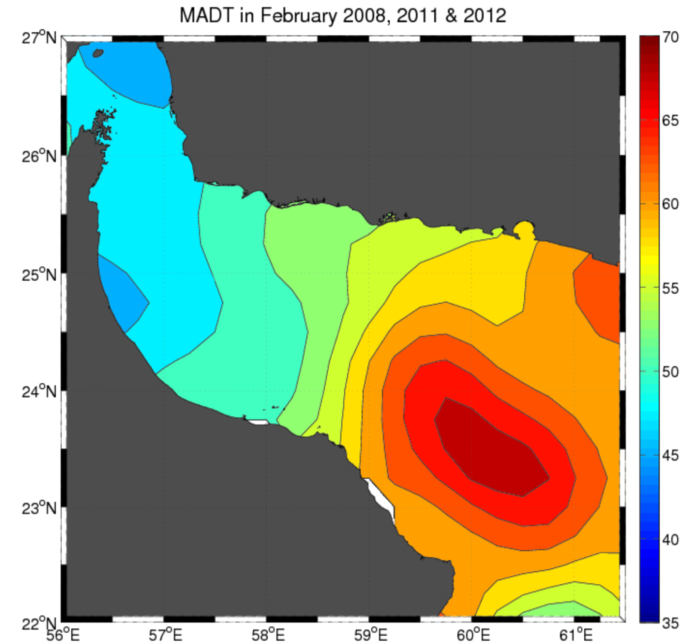


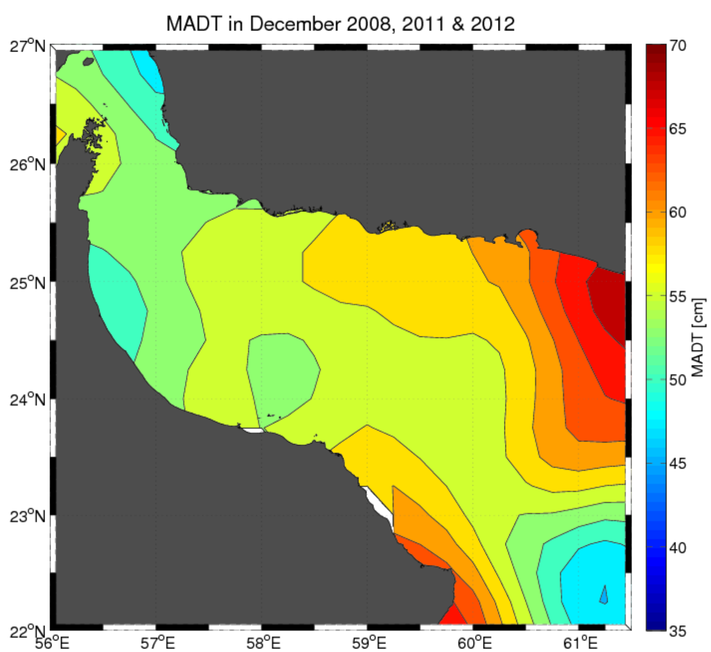


Okubo−Weiss field at 300 meters on March 12, 2008
27°N
26°N
25°N
24°N
23°N
22°N
56°E
57°E
58°E
59°E
60°E
61°E
62°E
x 10^−10
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
[s^2]

III.6 where does the dipole come from ? Evolution of monthly SLA from October to February (/2 months)



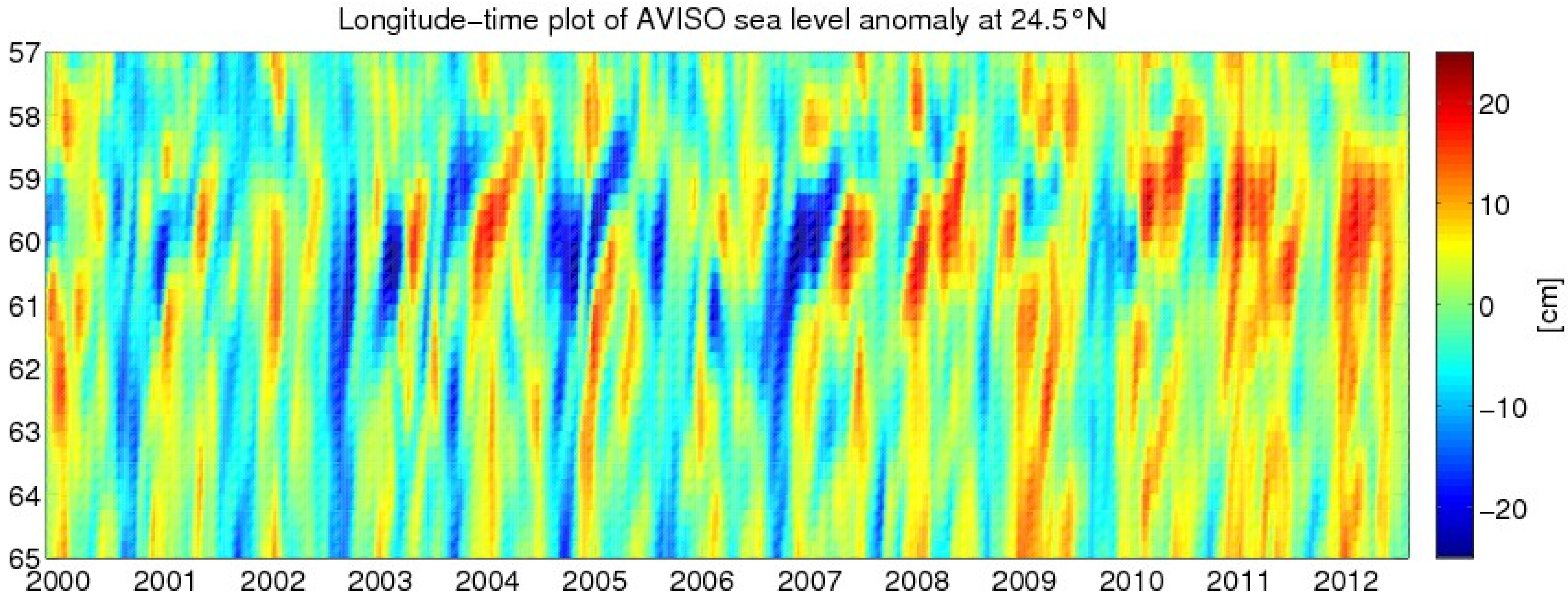




Clearly the cyclonic patch pre-exists in fall, and the anticyclonic patch grows in winter near the mouth of the Sea of Oman

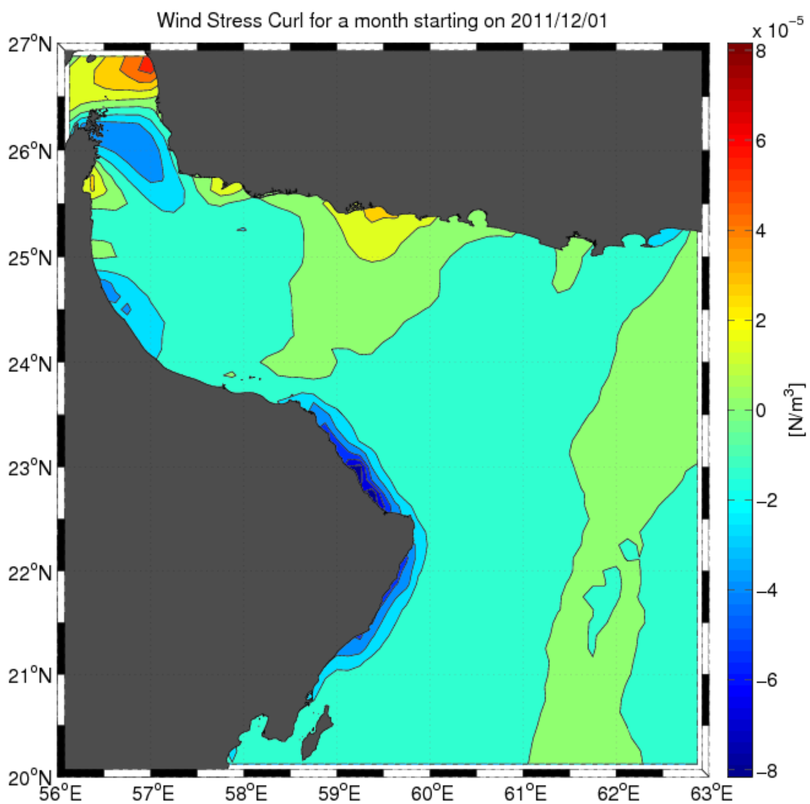
III.6 Existence or a long baroclinic RW

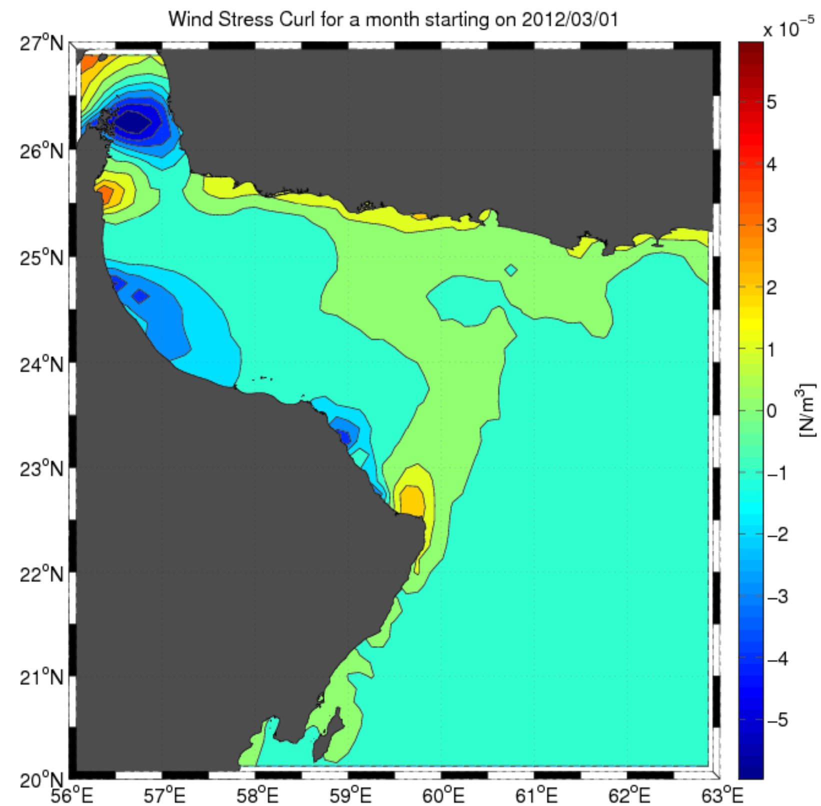
at 24.30N



A Rossby Wave with wavelength ~ 500 km and phase speed 2.5 cm/s propagates along 24.30N and brings positive SSH near 60E at the end of winter. This SSH is intensified there

III.6 Influence of the wind on the AC patch





The area of intensified SSH corresponds to the area of strong negative wind stress curl ; this negative curl moves into the Sea of Oman in early spring

III.7 Summary of part 3

A mesoscale dipole exists in spring in the northern Sea of Oman

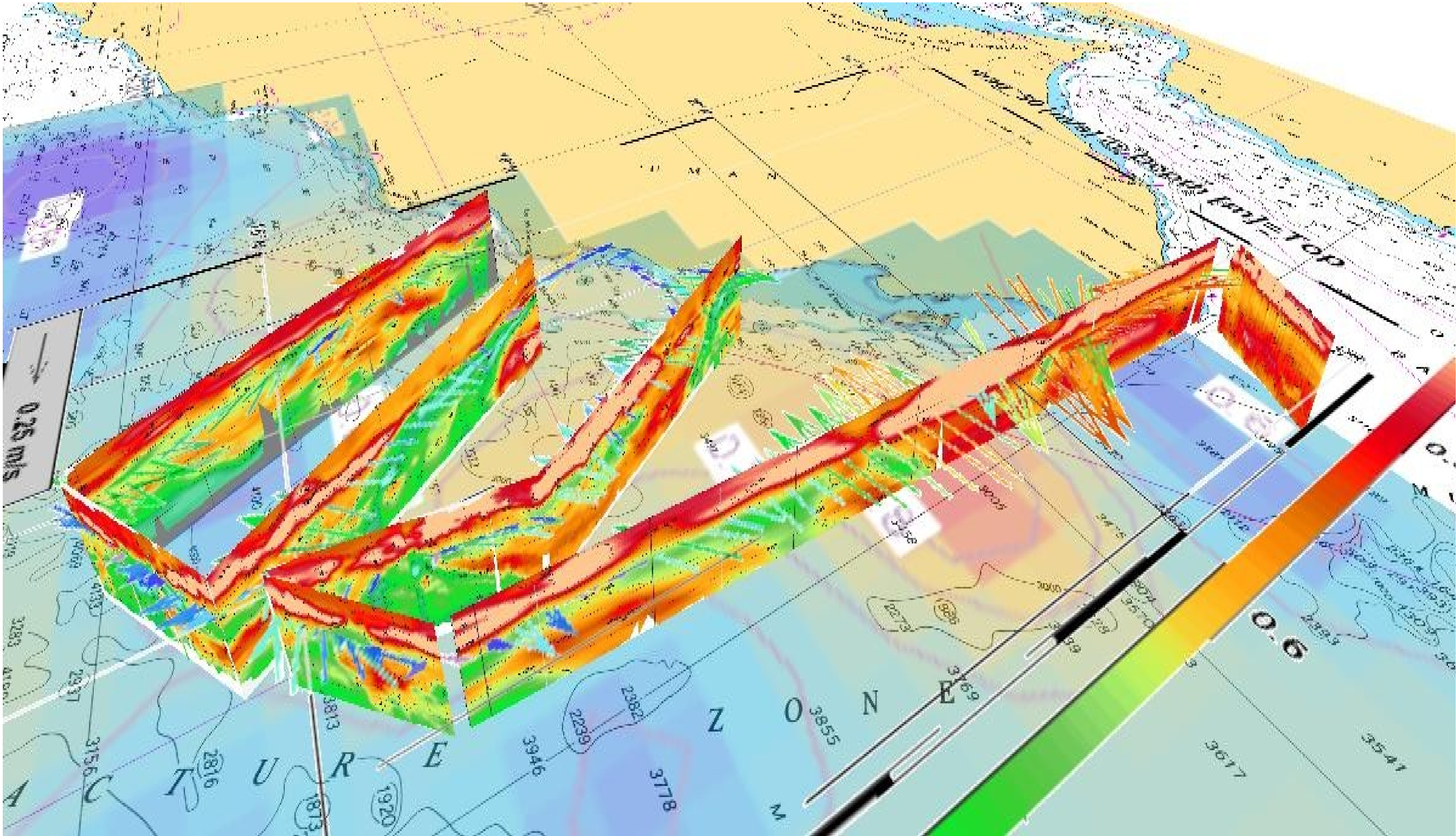
It extracts PGW from the coastal outflow under the form of submesoscale fragments

PGW is carried away along the coasts of Iran and Pakistan and is further expelled offshore by mesoscale eddies

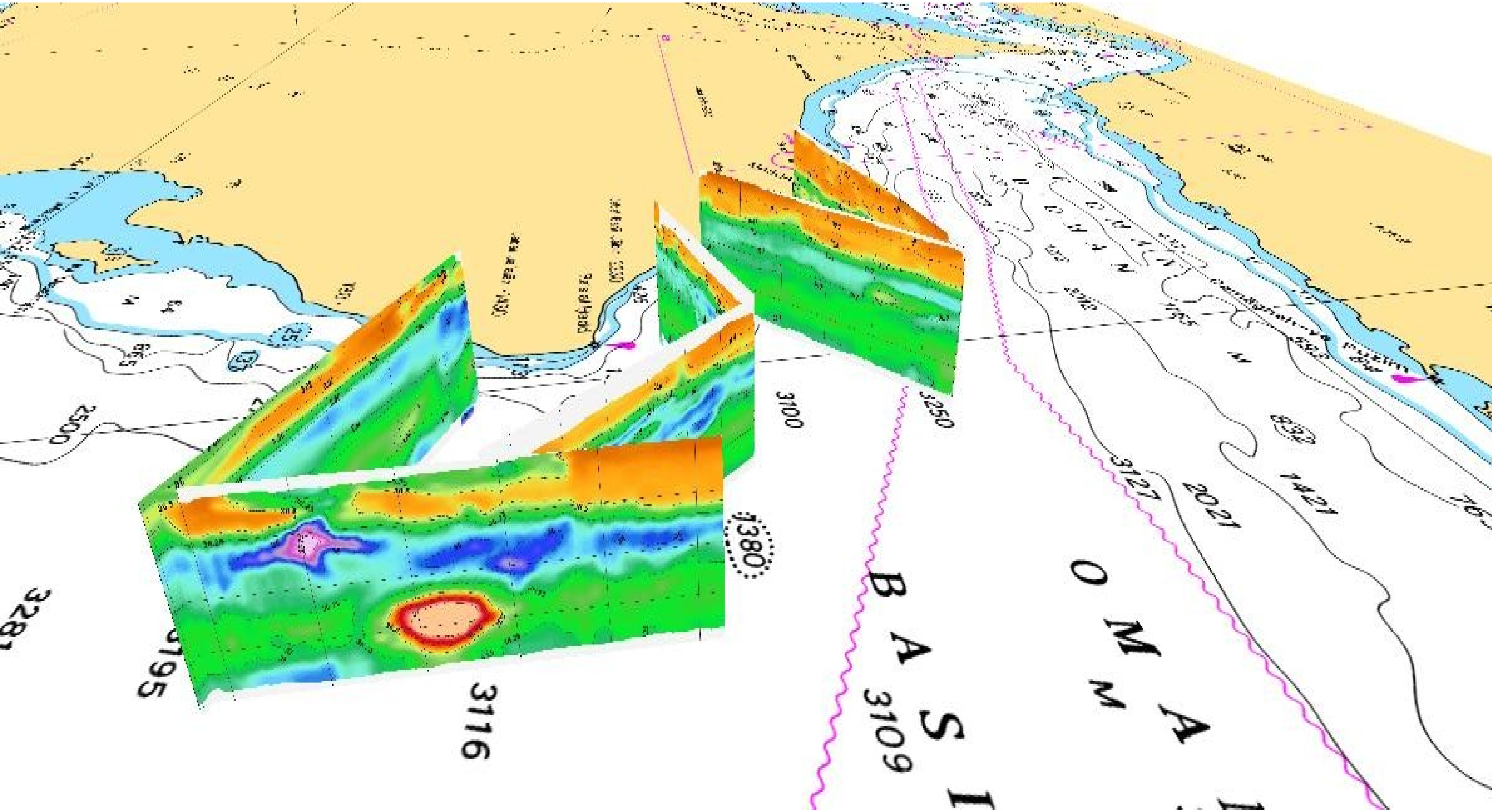
The deformation created by the dipole at the depth of PGW is well characterized by a jet which allows this extraction

The origin of the dipole lies in a pre-existent cyclonic circulation associated with an anticyclonic pole ; this pole is created by a long RW intensified by local winds

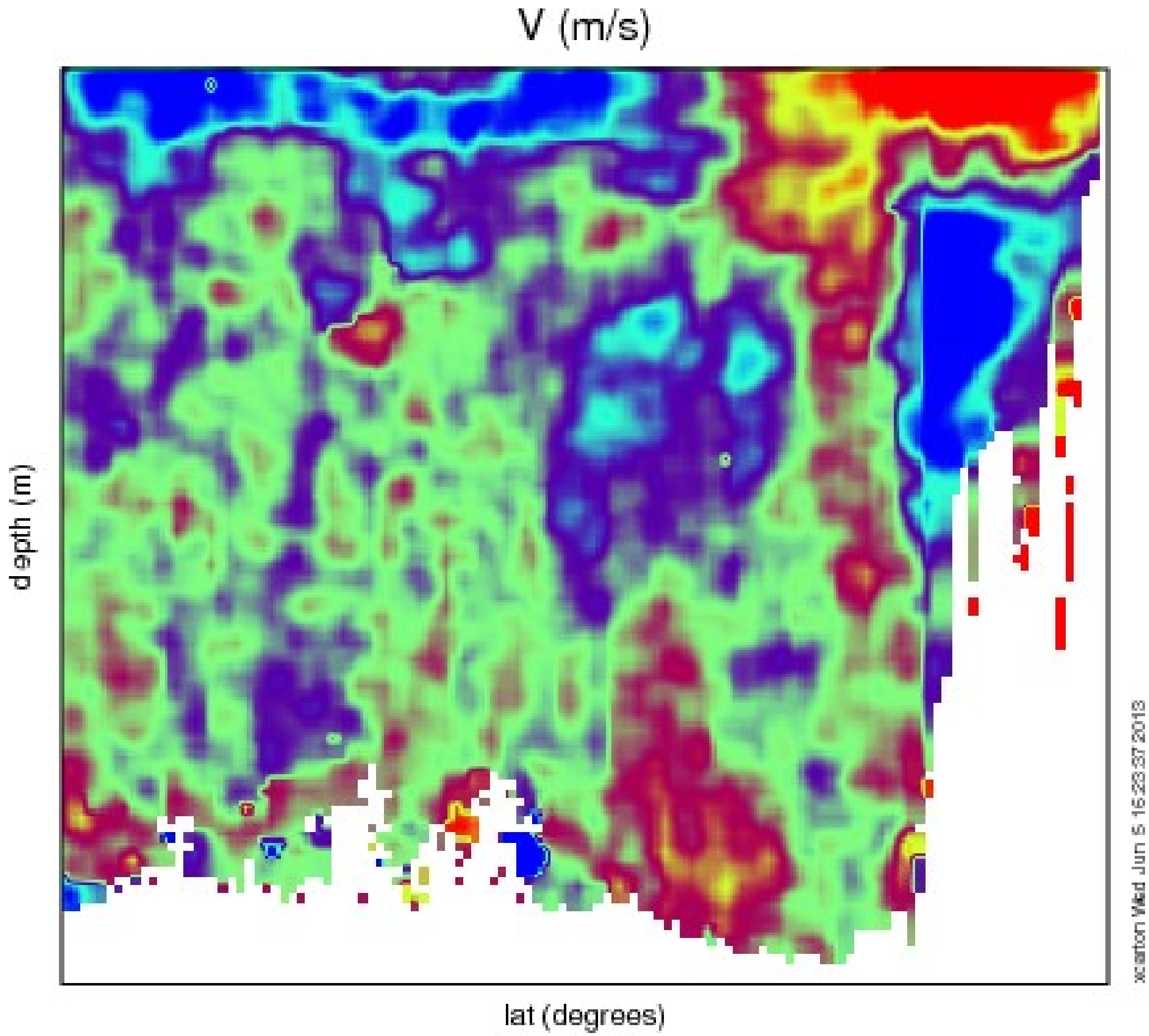
IV. Study of a submesoscale lens off Ras al Hadd (data of Physindien 2011)



université de bretagne occidentale

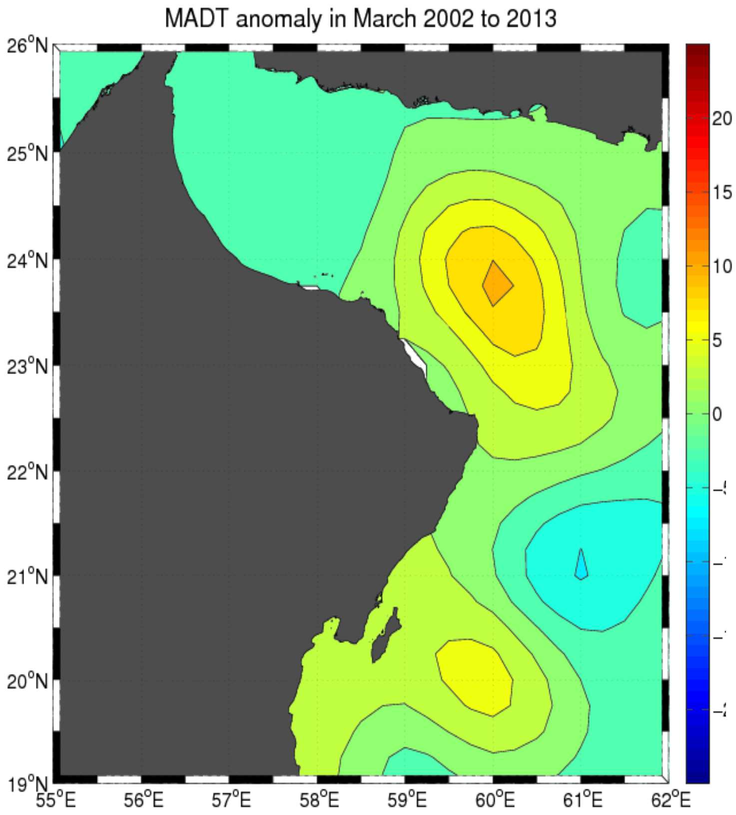


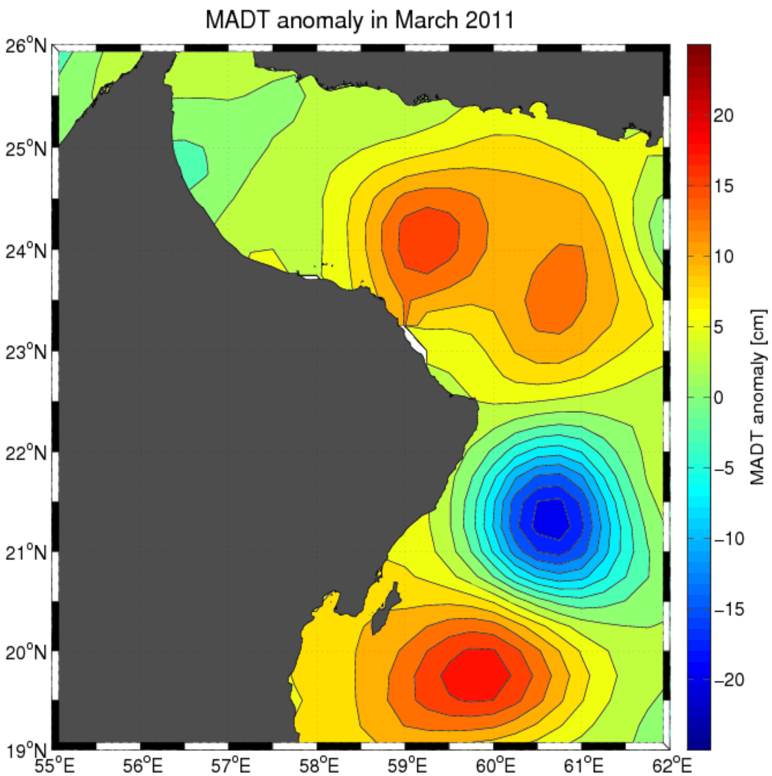
IV.1 PGW slope current section



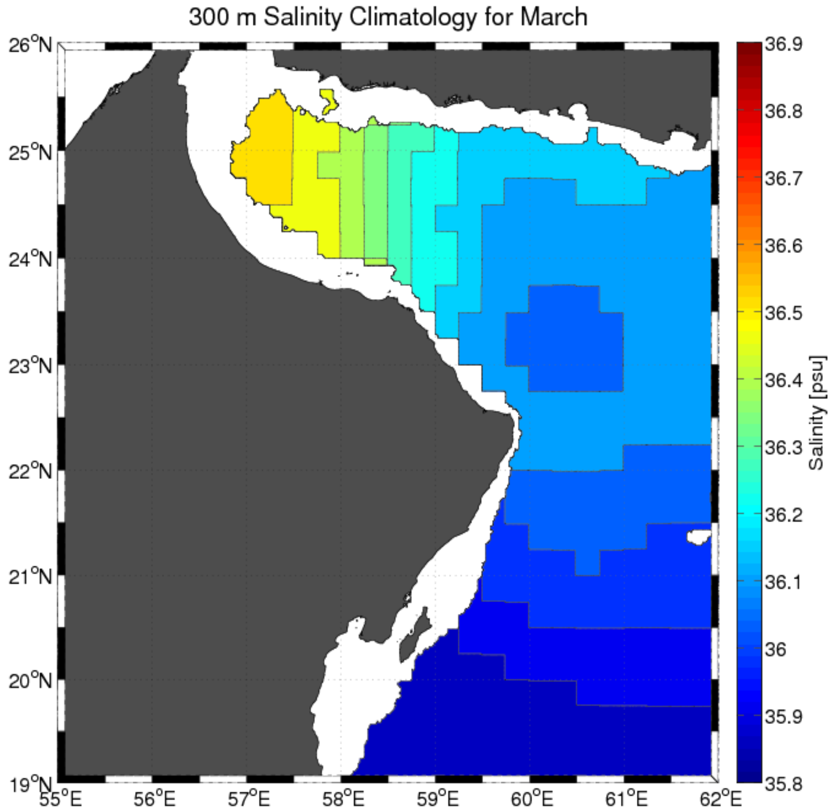
Range of V: -50 to 50 m/s
Range of lat: 15.6855 to 18.1319 degrees
Range of depth: -1703.48 to -39.48 m
Frame 178 in File V_section.nc

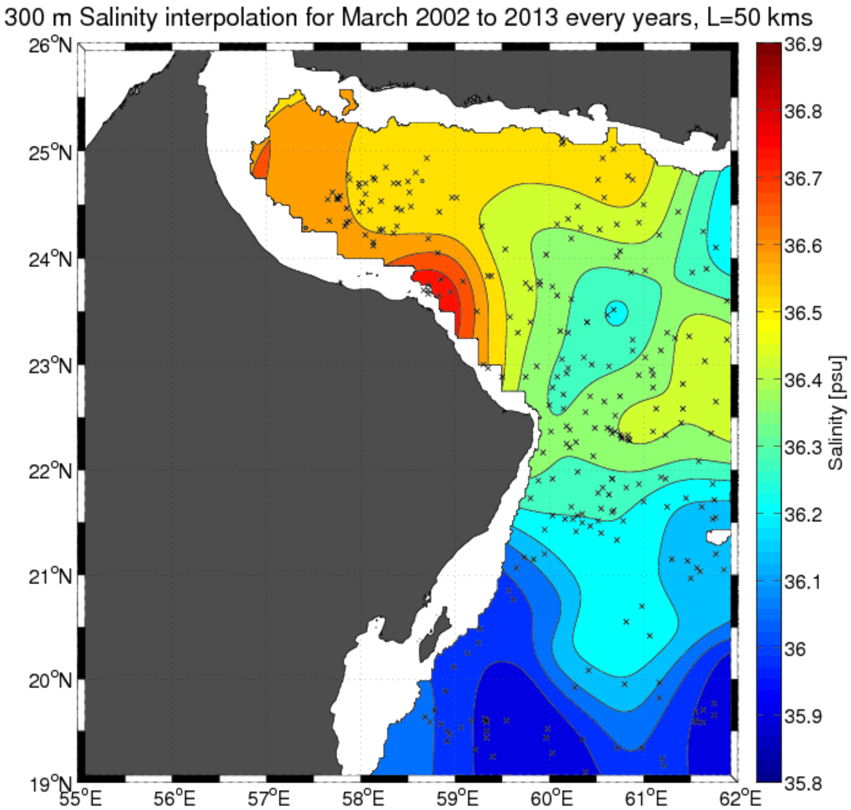
IV.2 MADT anomaly in March 2002-2011 and in March 2011



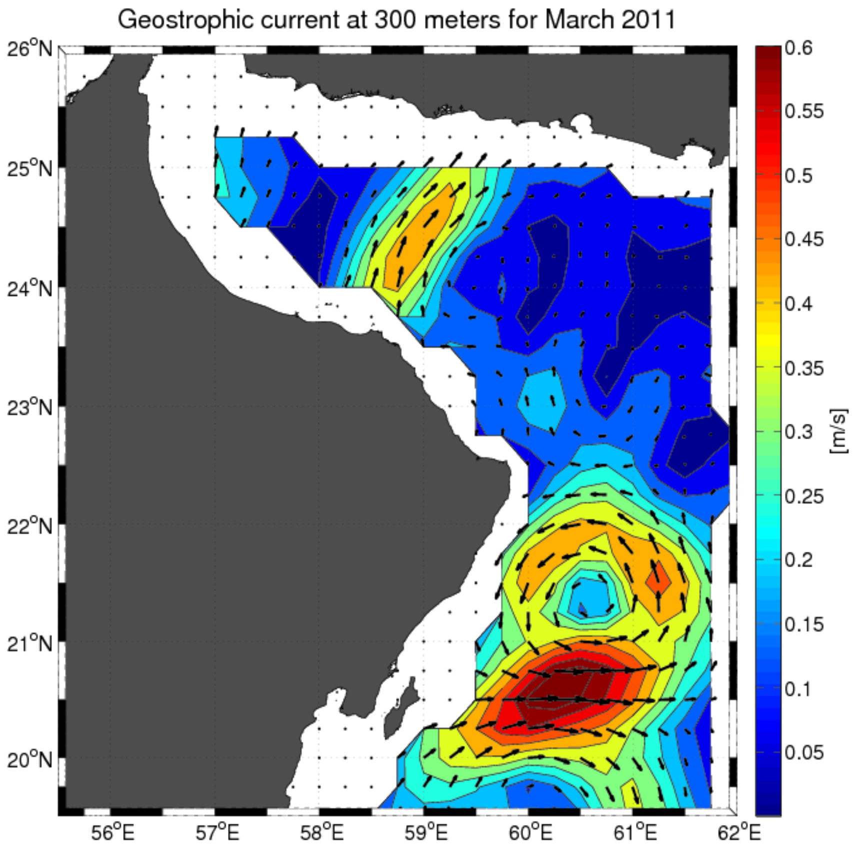


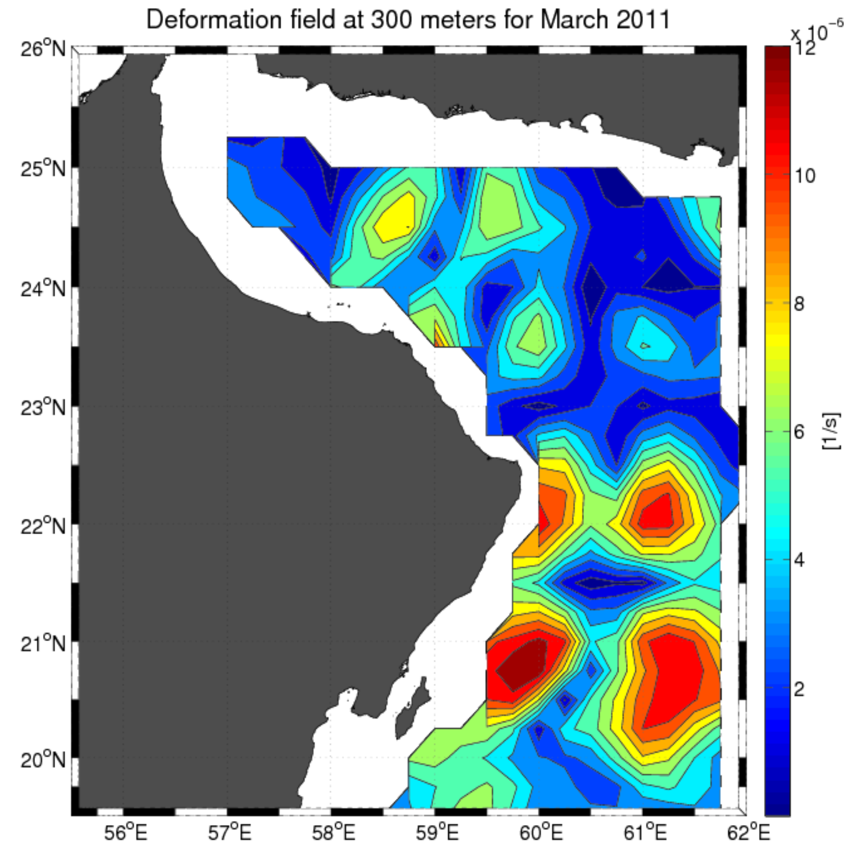
IV.3 Salinity at 300 m depth in climatology and in Argo float data



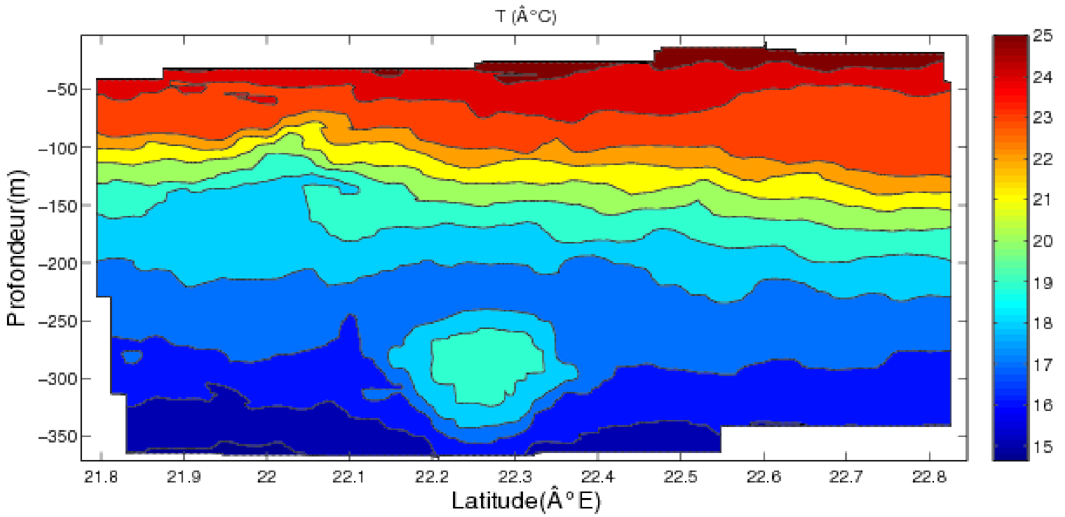


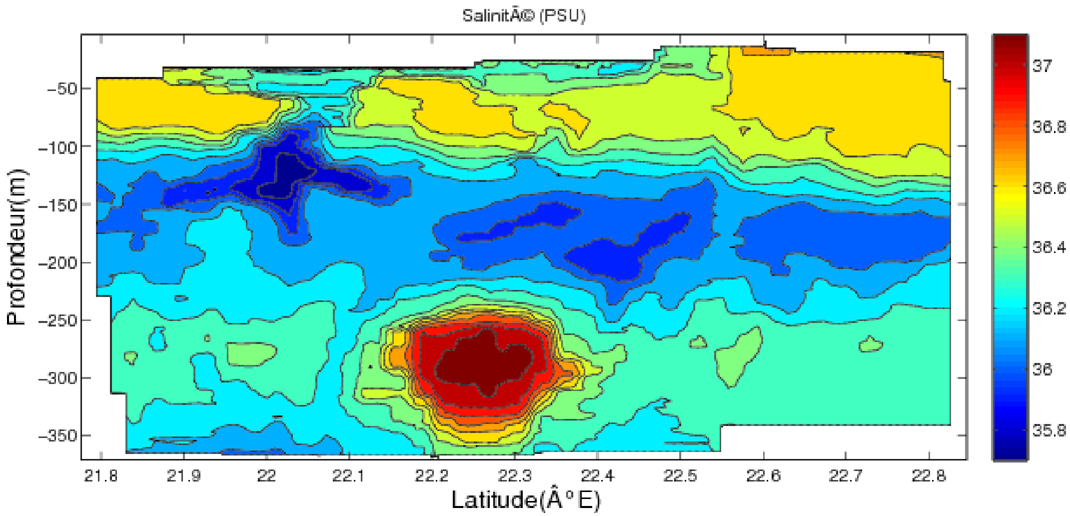
IV.4 Geostrophic currents and deformation at 300 m depth in March 2011



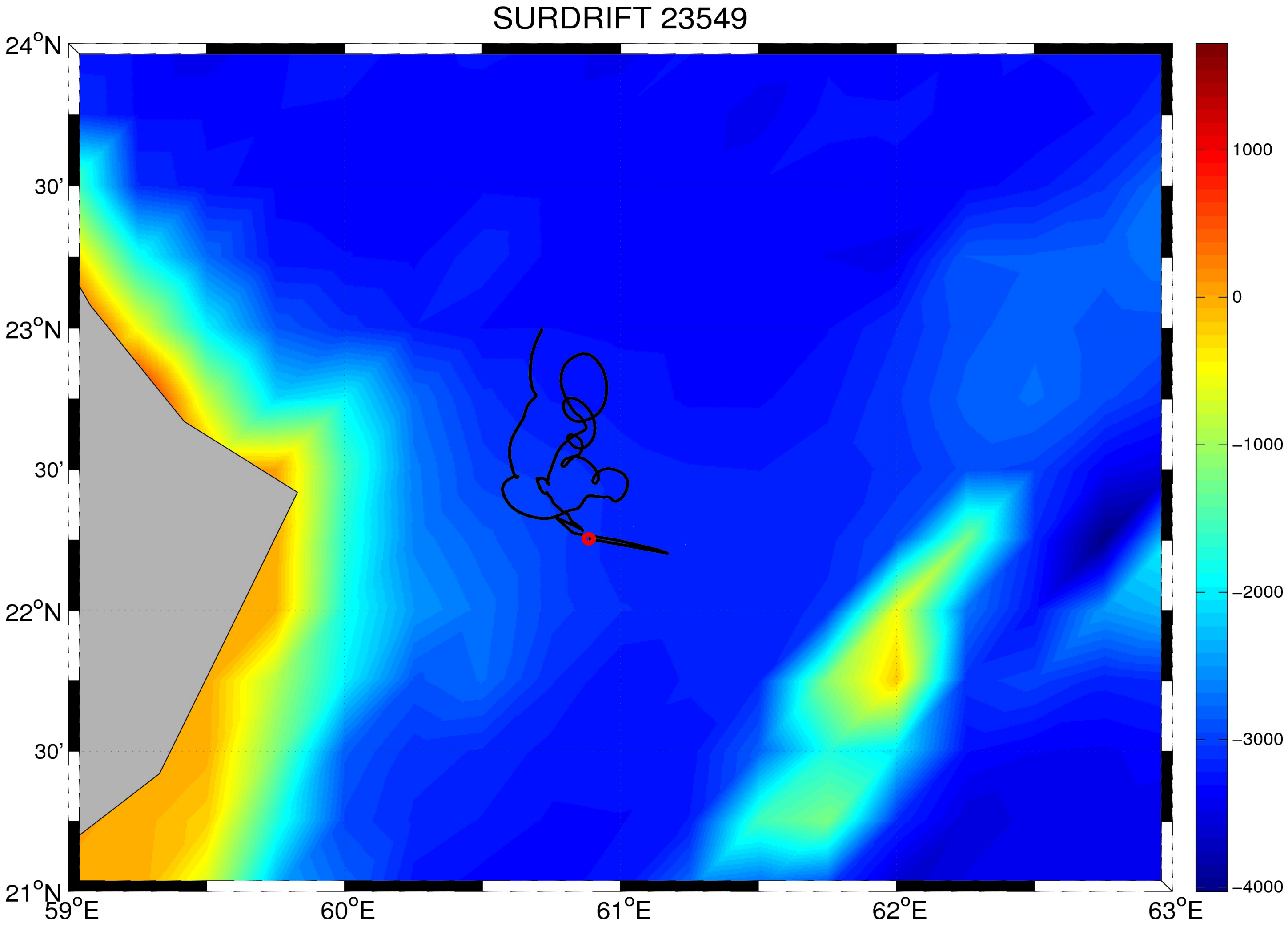


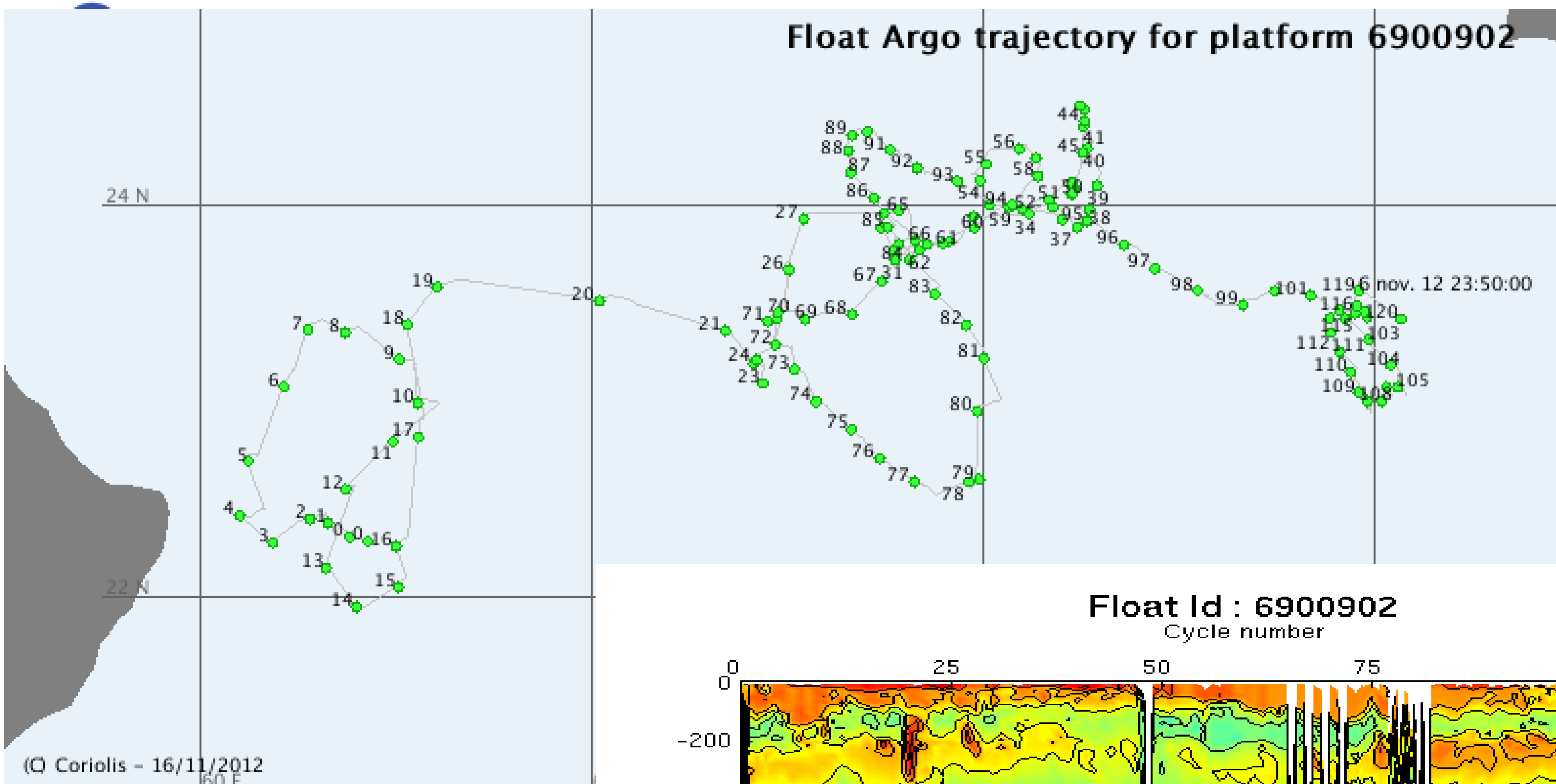
IV.5 The anticyclonic lens of PGW in March 2011

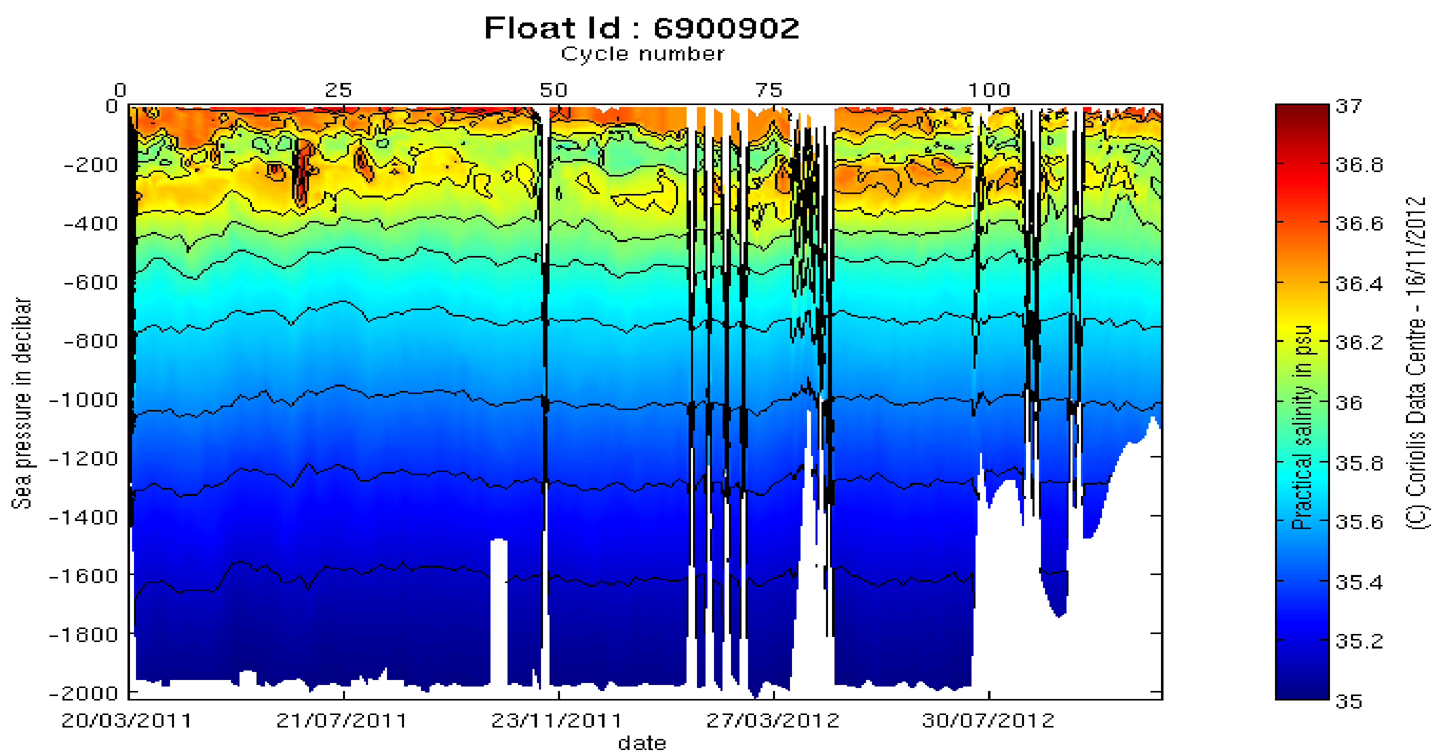




Surdrift trajectory (initially seeded in the lens eddy – 250 m cable)




Float Argo trajectory for platform 6900902
24 N
22 N
60 E
116 nov. 12 23:50:00
(C) Coriolis - 16/11/2012


Float Id : 6900902
Cycle number
0
25
50
75
100
Sea pressure in decibar
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
20/03/2011
21/07/2011
23/11/2011
27/03/2012
30/07/2012
date
Practical salinity in psu
37
36.8
36.6
36.4
36.2
36
35.8
35.6
35.4
35.2
35
(C) Coriolis Data Centre - 16/11/2012

V. Conclusions

- Argo float, satellite altimetry and in situ data of the Physindien experiment have shown the existence of many mesoscale eddies in the northern Arabian Sea.
- The marginal seas (RS, PG) export salty waters along the coasts of Somalia and of Oman
- Mesoscale eddies in isolation, or under the form of dipoles, can extract this salty water from the coastal currents, and form submesoscale fragments

V. Conclusions

In particular, it has been shown that RSW can be expelled into the Gulf of Aden by the deep reaching mesoscale eddies ; this participates in the mixing of RSW with ICW. Fragments of RSW are found offshore Socotra

There exists a seasonal dipole in the Northern Sea of Oman, which extracts PGW from the coastal current. This dipole is formed from the local circulation and from a RW intensified by wind.

A similar situation was observed in 2011 off Ras al Hadd ; a submesoscale lens eddy of PGW was formed.

Thank you for your attention