Mediterranean large scale circulation, water mass formation and sea level low frequency variability

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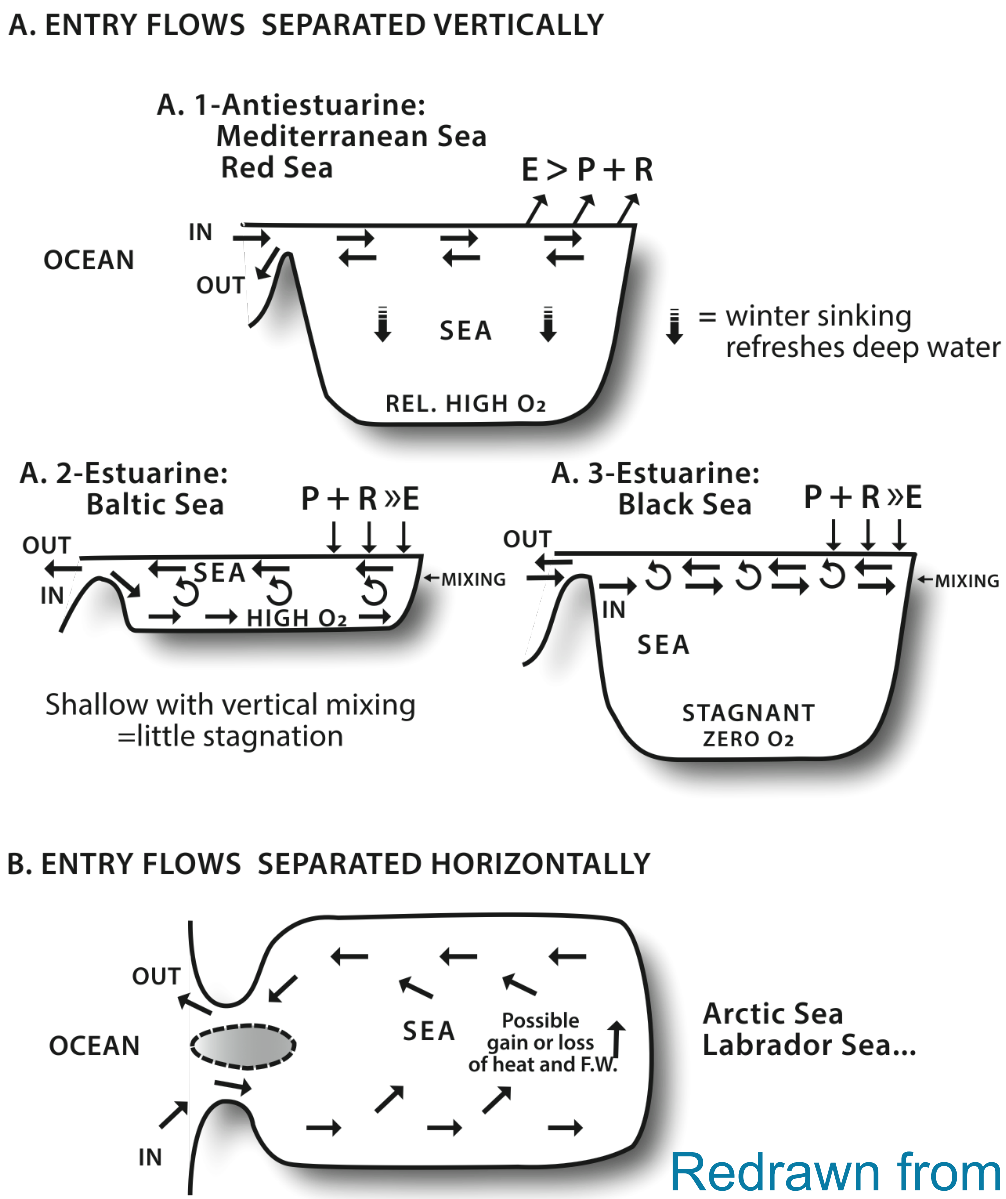
Outline

- A general theory of semi-enclosed sea circulation after Knudsen (Cessi, Pinardi and Lyubartsev, J.Phys. Ocean, 2014)
- The high resolution reconstruction of the Mediterranean Sea climate: 20 and 60 years re-analyses allows to pose new scientific questions:
  - What is the mean and decadal variability of the circulation? Pinardi et al., Progress in Oceanography, 2015
  - The changing characteristics of deep water masses and water mass formation rates
  - What causes the mean sea level trend in the Mediterranean Sea? Pinardi et al., Jour. Climate, 2014
- General remarks

Semi-enclosed seas: vertical circulation



Vigorous circulation in the whole water column

Almost stagnant circulation in the deep parts

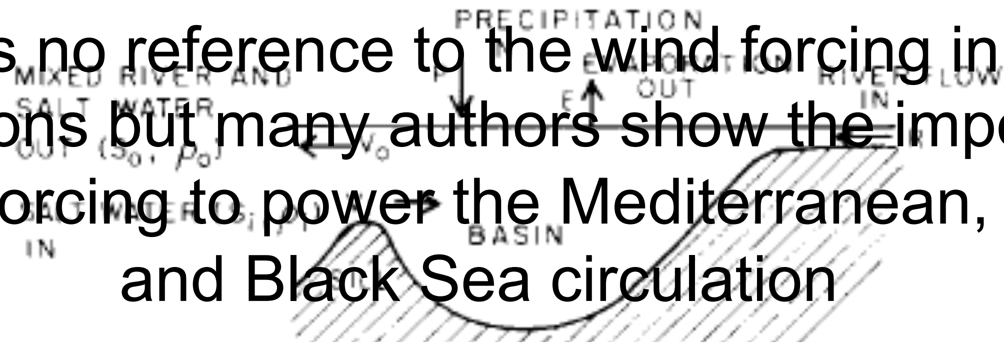
Why this difference?

Redrawn from Pickard and Emery, 1982

Semi-enclosed Seas: the Knudsen relations

- Classically, the Knudsen relations (Knudsen 1900) are used to explain the qualitative distinction between the estuarine and antiestuarine vertical circulation at the strait on the basis of the water and salt conservation

- There is no reference to the wind forcing in such explanations but many authors show the importance of wind forcing to power the Mediterranean, Baltic and Black Sea circulation



Thus proper energy equations
for semi-enclosed seas
with two layer fluxes at the Strait are required
in order to classify and understand what
powers the circulation

A general theory of semi-enclosed sea circulation (Cessi et al., 2014)

- Volume average energetics of semi-enclosed seas: different from global ocean because of flux at the Strait

$$\partial_t \langle \frac{u^2+v^2}{2} - zb \rangle = \int_A \frac{\boldsymbol{\tau} \cdot \boldsymbol{u}_s}{\rho_o}\, dx\, dy + F + \langle \kappa_v b_z \rangle - \langle \nu (|\nabla_h u|^2 + |\nabla_h v|^2) \rangle$$

$$- \langle \nu_v (u_z^2 + v_z^2) \rangle - \int_{OB}\!\!\int \left[\nu \frac{\nabla (u^2+v^2)}{2} \right] \cdot \hat{\boldsymbol{n}}\, dz\, dl + D\,,$$

$$F \equiv - \int_{OB}\!\!\int \left(\frac{u^2+v^2}{2} + \frac{p}{\rho_o} - z\, b \right) \boldsymbol{u} \cdot \hat{\boldsymbol{n}}\, dz\, dl\,,$$

$$D \equiv - \int_{OB}\!\!\int \kappa z \boldsymbol{\nabla}_h b \cdot \hat{\boldsymbol{n}}\, dz\, dl\,.$$

?

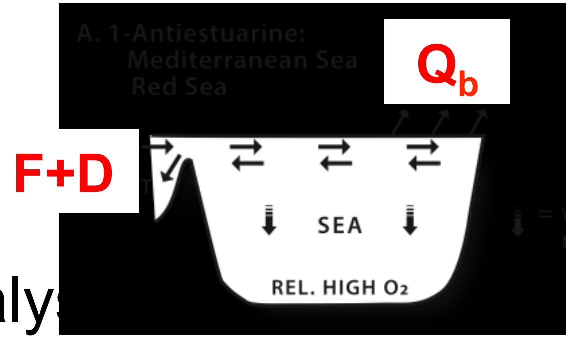
A general theory of semi-enclosed sea circulation (Cessi et al., 2014)

- For two-layer flows at the Strait, where h_1 is the interface and G the composite Froude #:

$$F = -h_1 \left(\int_A Q_b \, dx \, dy - \partial_t \langle b \rangle - \frac{D}{h_1} \right) \left[\frac{G^2}{2} \frac{h_2(h_2^2 - h_1^2)}{h_2^3 + h_1^3} + 1 \right] .$$

- For Mediterranean, Black and Red Sea G~0.2 so that:

$$\boxed{F + D \approx -h_1 \left[\int_A Q_b \, dx \, dy - \partial_t \langle b \rangle \right]}$$



- The theory is verified by the re-analy

A general theory of semi-enclosed sea circulation (Cessi et al., 2014)

- Thus in conclusion the energy equation for semi-enclosed seas with two layer flow at the Strait is:

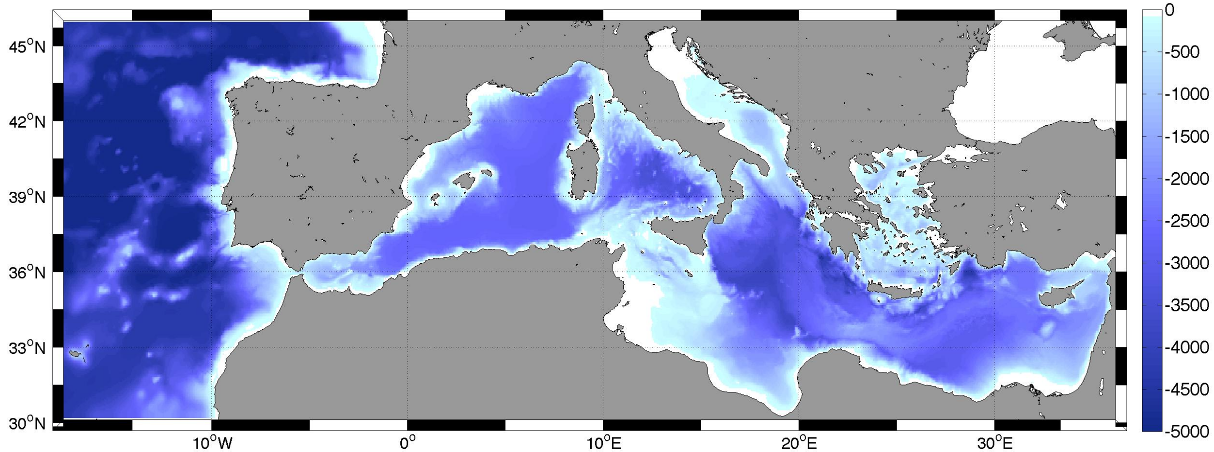
$$\partial_t \langle \frac{u^2+v^2}{2} \rangle - \langle (z+h_1)\, b_t \rangle \approx -h_1 \int_A Q_b \, dx\, dy + \int_A \frac{\boldsymbol{\tau} \cdot \boldsymbol{u}_s}{\rho_o} \, dx\, dy + \langle \kappa b_z \rangle$$
$$- \langle \nu (|\nabla u|^2 + |\nabla v|^2) \rangle - \langle \nu_v (u_z^2 + v_z^2) \rangle - \int_{OB} \int \nu \frac{\nabla (u^2+v^2)}{2} \cdot \hat{\boldsymbol{n}} \, dz\, dl \, .$$

Sea name	$V^{-1}\int_A Q_b \, dx\, dy$ ms^{-3}	$V^{-1}F$ m^2s^{-3}	h_1 m	$(V\rho_o)^{-1}\int_A \boldsymbol{\tau}\cdot\boldsymbol{u}_s \, dx\, dy$ m^2s^{-3}	V m^3
Mediterranean	-4.36×10^{-12}	7.80×10^{-10}	179	1.12×10^{-9}	3.28×10^{15}
Black (*)	1.04×10^{-11}	-3.11×10^{-10}	30	3.60×10^{-10}	5.47×10^{14}
Red	-2.72×10^{-11}	2.72×10^{-9}	100	1.23×10^{-10}	2.11×10^{14}
Baltic	5.87×10^{-11}	-7.04×10^{-10}	12	9.15×10^{-9}	1.89×10^{13}

- Semi-enclosed seas circulation energy depends on the balance between wind stress and buoyancy inputs

The new paradigm to study ocean climate variability: the reanalysis

- Re-analysis gives an optimal estimate of the ocean state using observations and numerical models to be used for fundamental studies and applications
- In the Mediterranean Sea we have two different re-analyses:
  - A short term one, 1987-2012, forced with high resolution, high accuracy atmospheric re-analyses (ERA-INTERIM)
  - A longer term one, 1958-2012, forced with lower resolution non-assimilative atmospheric model fields (AMIP)



The 1985-2012 re-analysis

- Data assimilation scheme: 3Dvar (Dobricic and Pinardi,2008) with daily updates and FGAT
- QC ‘raw’ observations:
  - 1985-2007 observations: CTD, XBT,BT MBT, ARGO
  - Along track satellite SLA from 1992 to today, all available satellites (ERS-1/2, T/P, Envisat, Jason1,2)
  - Satellite SST L4 gridded product
- Numerical model:
  - OPA code, 1/16 x 1/16 deg resolution, 72 levels
  - Climatological 9 river runoff
  - ECMWF ERA-INTERIM forcing, 6hr fields, all fluxes interactive, observed SST relaxation
  - Atlantic box open boundary conditions with climatological fields
  - CMAP monthly mean precipitation data set

The 1958-2012 Mediterranean Sea Reanalysis Reconstruction (RR)

Atmospheric and hydrological forcing:

Global AMIP 1900-2020 atmospheric forcing (Cherchi et al, 2007) ~ 1.125 °

Monthly mean climatological CMAP precipitation

Monthly mean climatological river runoff

Surface heat flux correction as a relaxation to monthly mean Hadley Center SST

Ocean General Circulation Model:

NEMO implicit free surface, 1/16 x 1/16 and 72 unevenly spaced levels. Atlantic box lateral open boundary condition: Mercator monthly mean fields

Assimilation scheme:

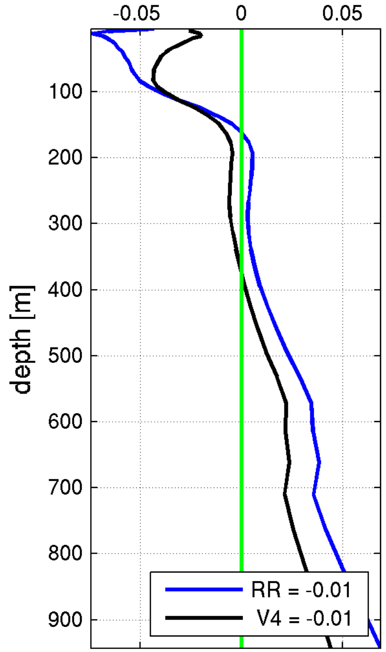
3D Variational scheme (Dobricic and Pinardi, 2008)

Observations:

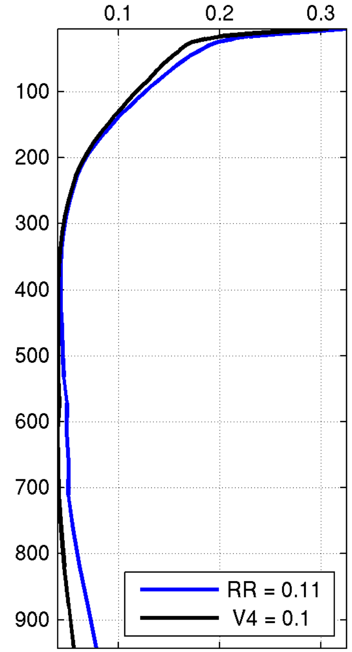
- **All T/S *in-situ* profiles**
- **Multi-satellite along track SLA**
- **Hadley Center reconstructed SST**

Comparison between Myocean reanalysis (1987-2012) and RR (1955-2012)

Salinity Misfit BIAS



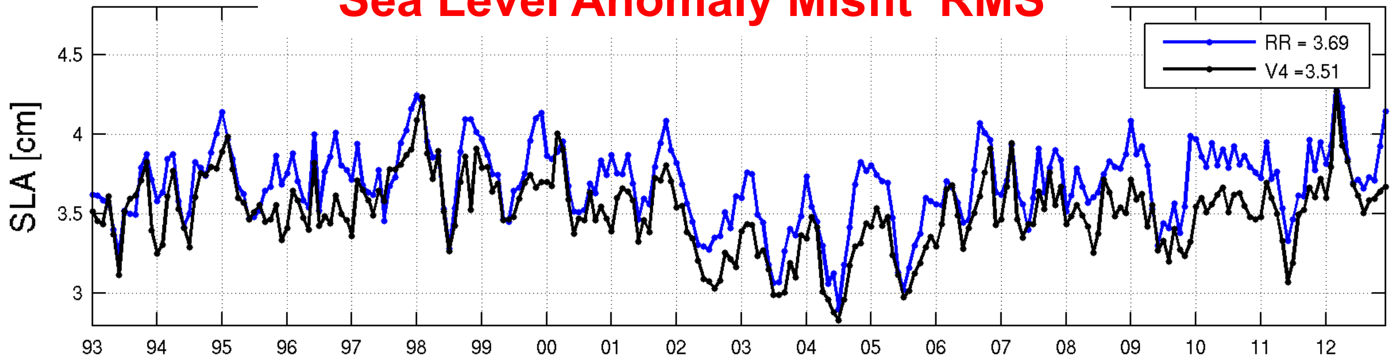
Salinity Misfit RMS



Blue=RR

Black: MyOcean

Sea Level Anomaly Misfit RMS

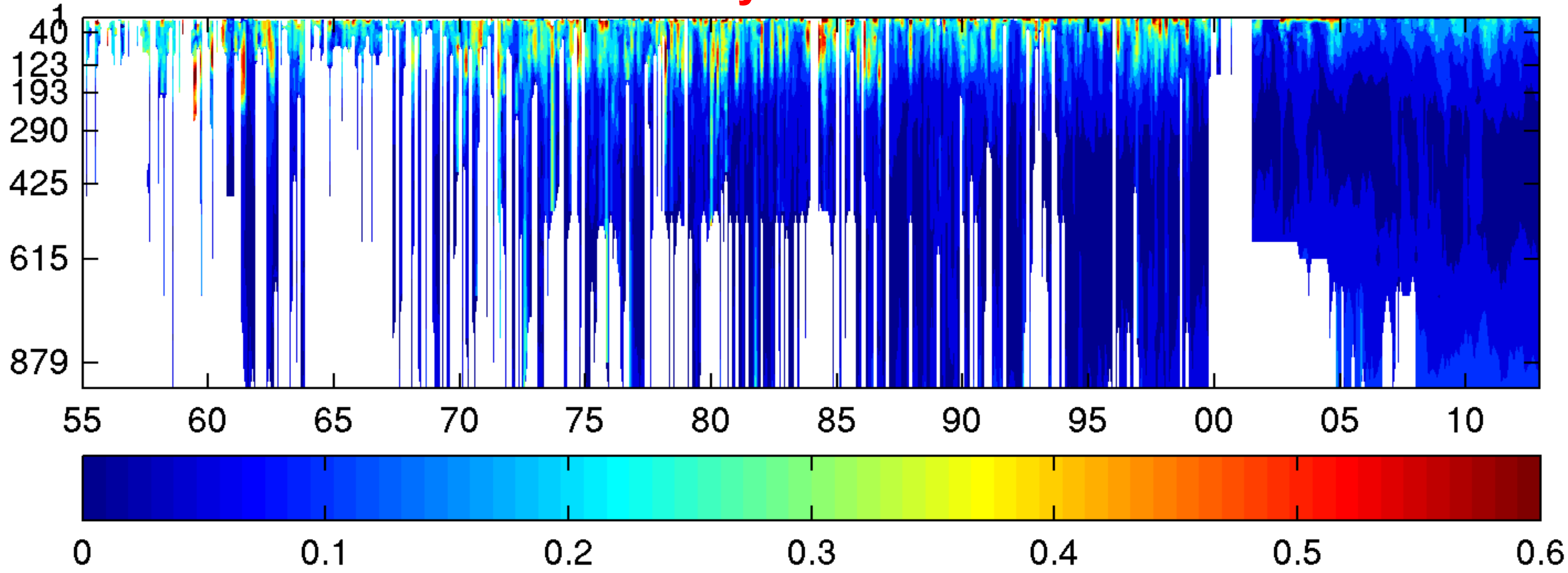


RR Salinity Accuracy (1955-2012)

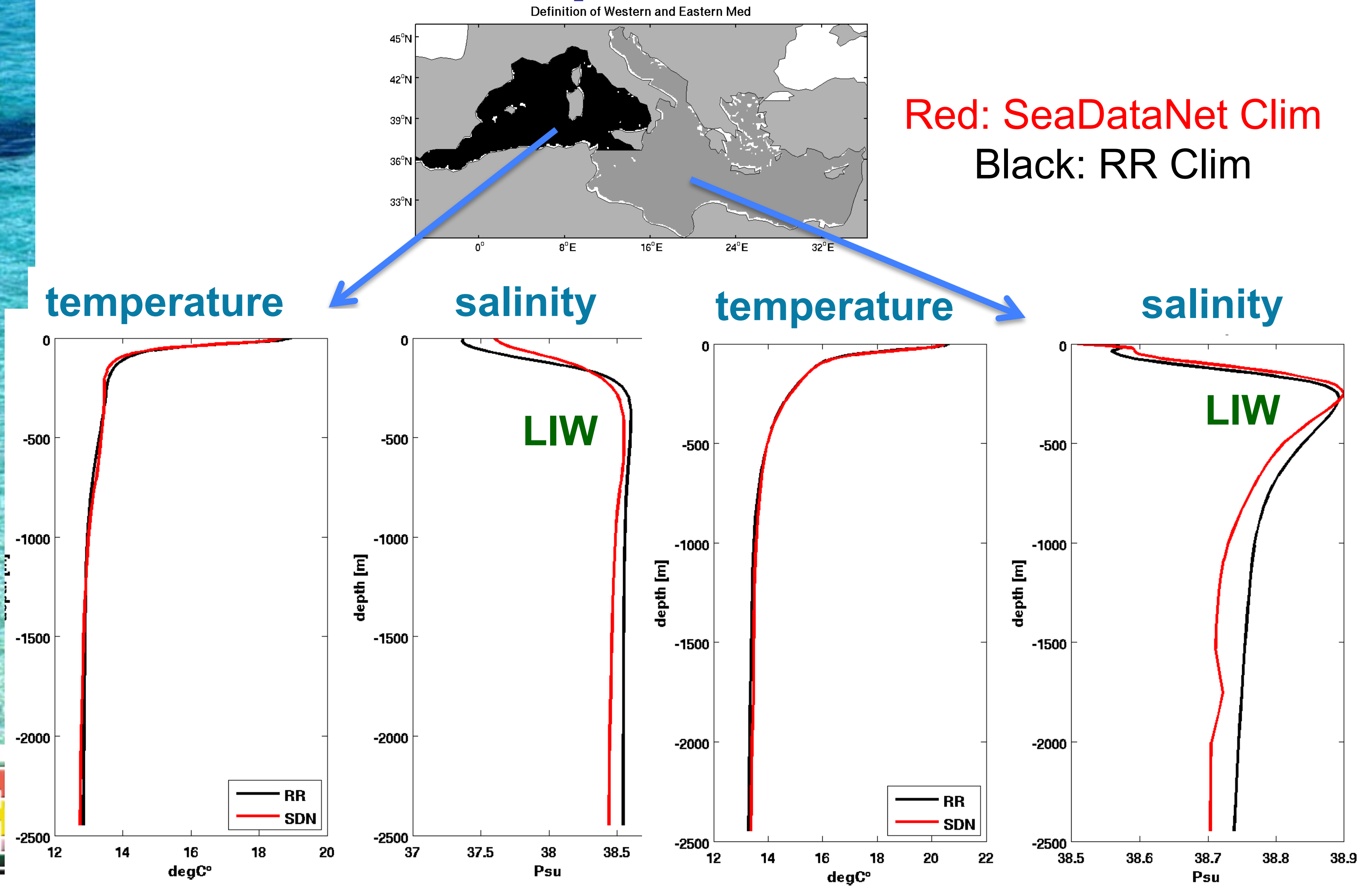
misfit = obs - model   statistics

ARGO era

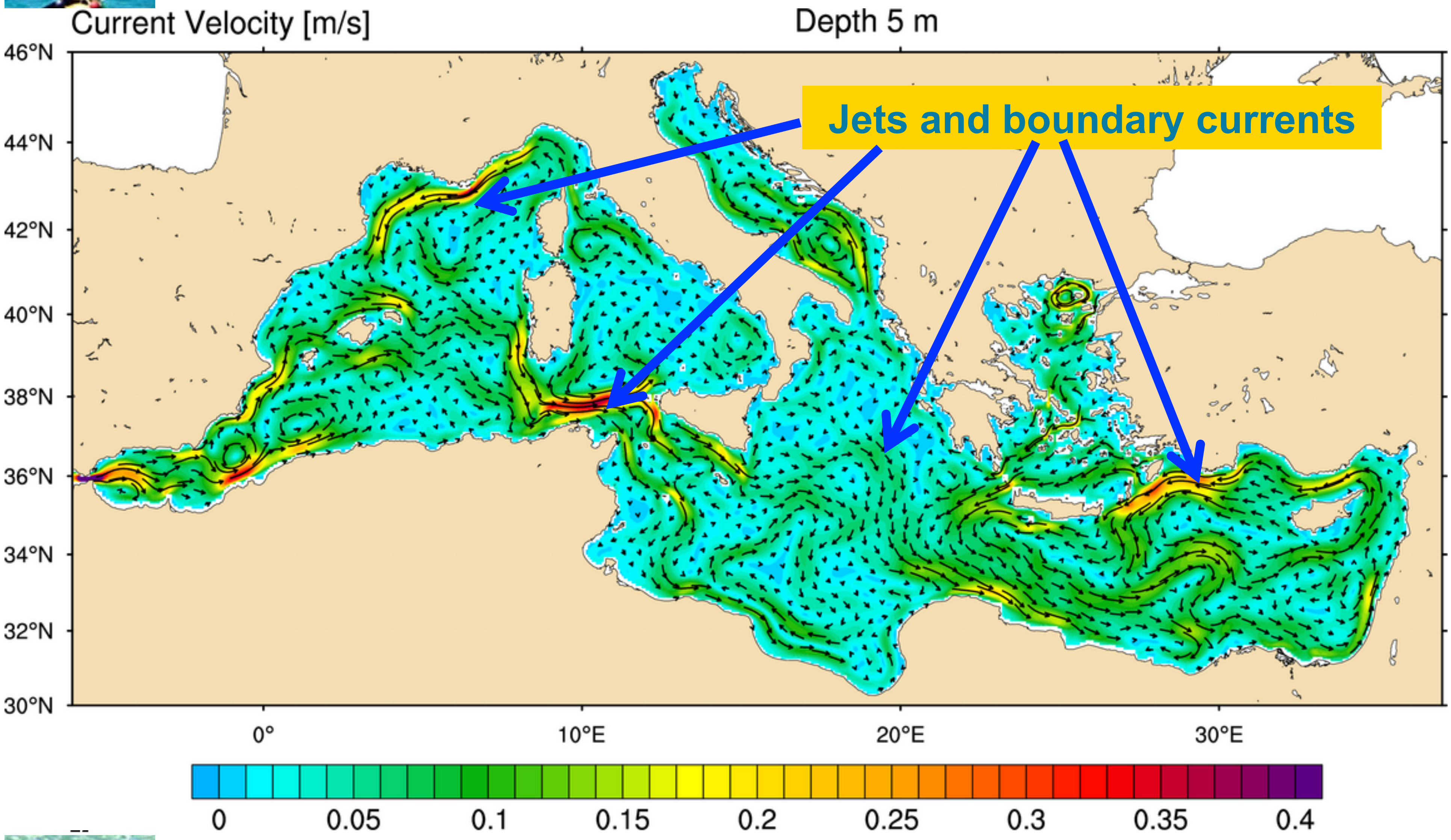
Salinity Misfit RMSE



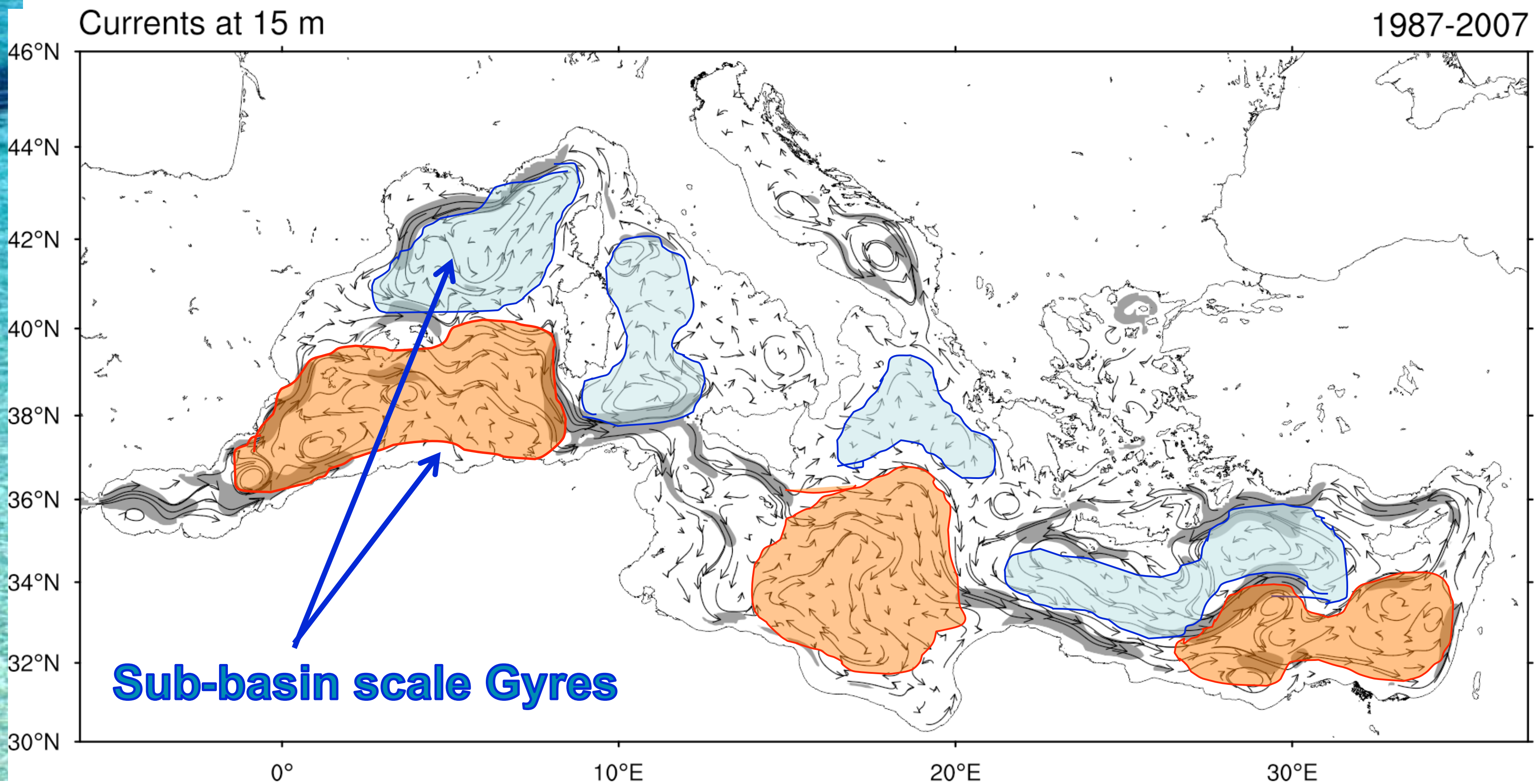
The thermohaline structure of the two sub-basins: comparison with SeaDataNet



The 1987-2007 *surface* mean circulation from re-analysis



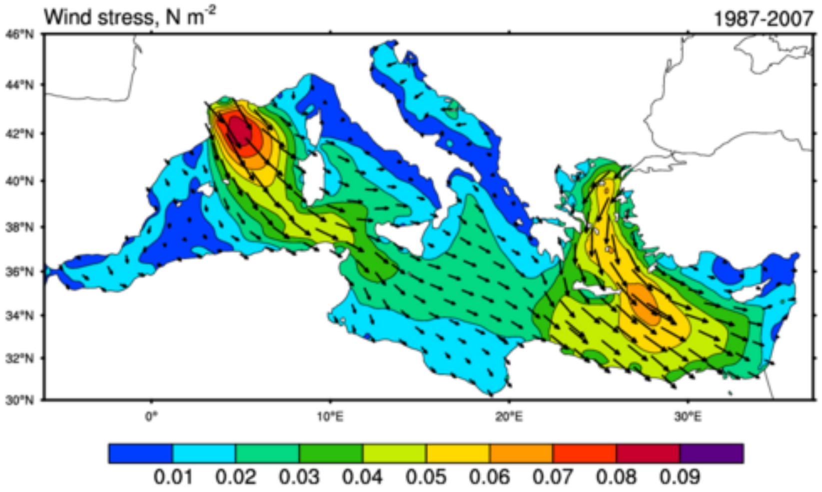
The 1987-2007 mean circulation: the 'gyre' structure



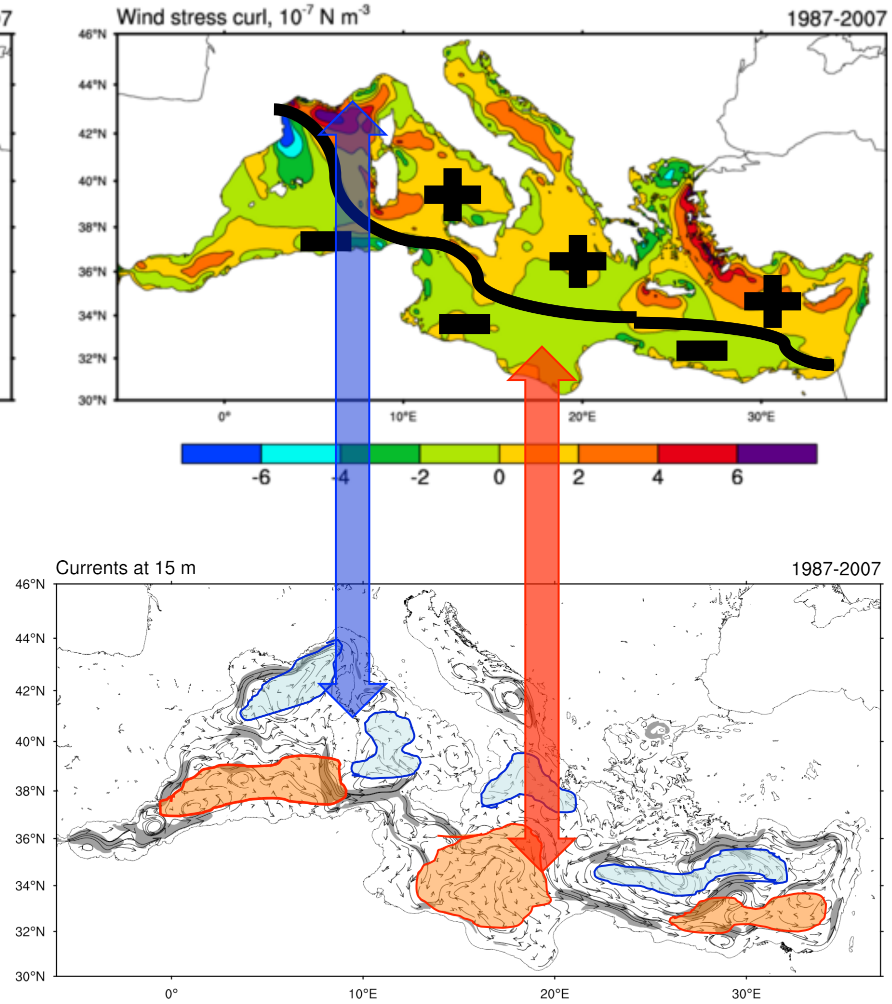
Grey shaded areas have velocities larger than 10 cm s^{-1}

The time-mean general circulation is connected to the wind stress curl structure

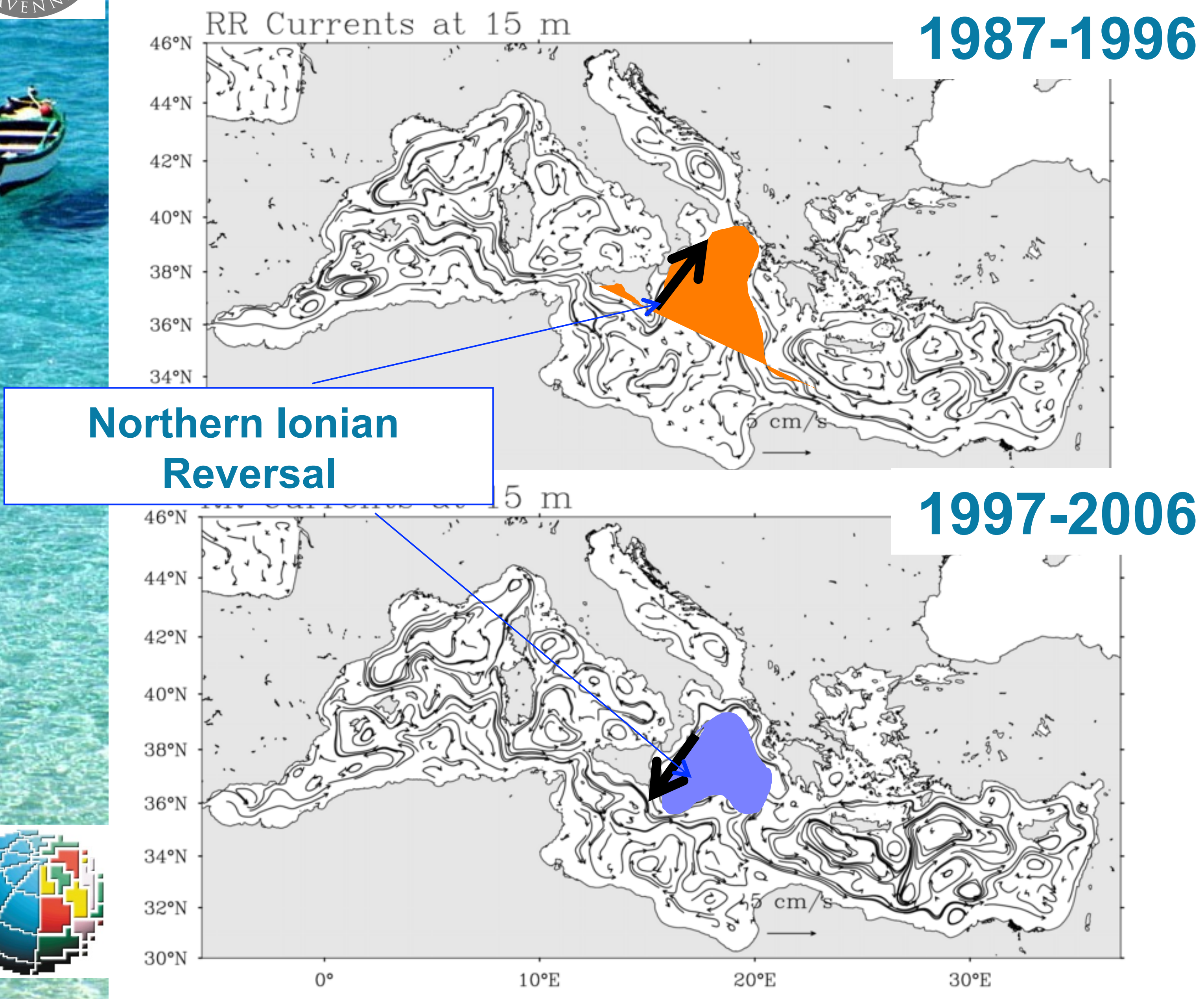
Wind Stress and amplitude



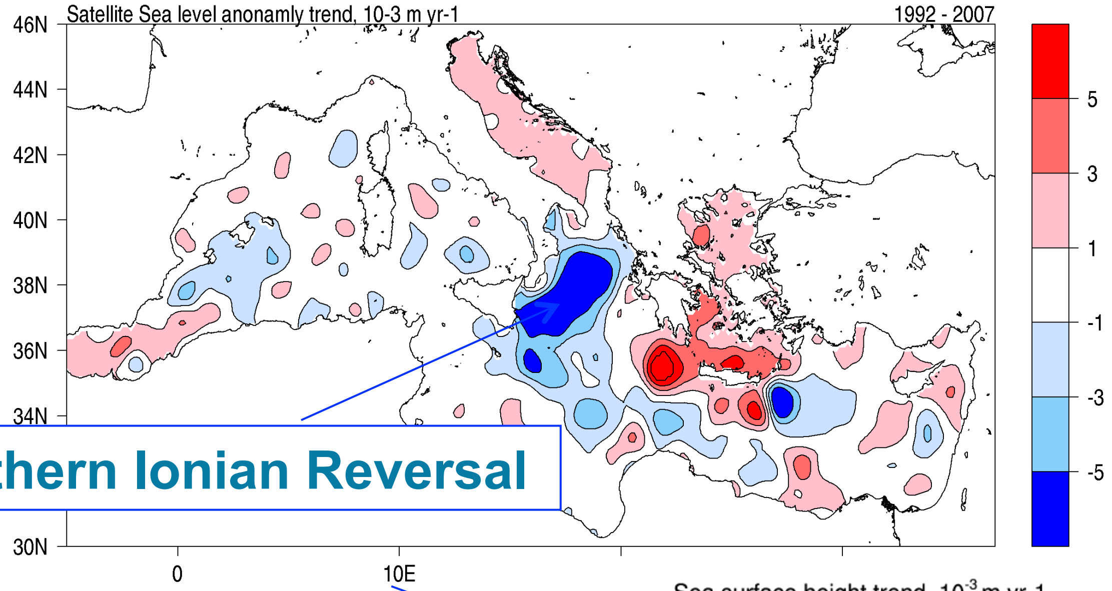
Wind Stress curl



The decadal circulation variability 1987-2007



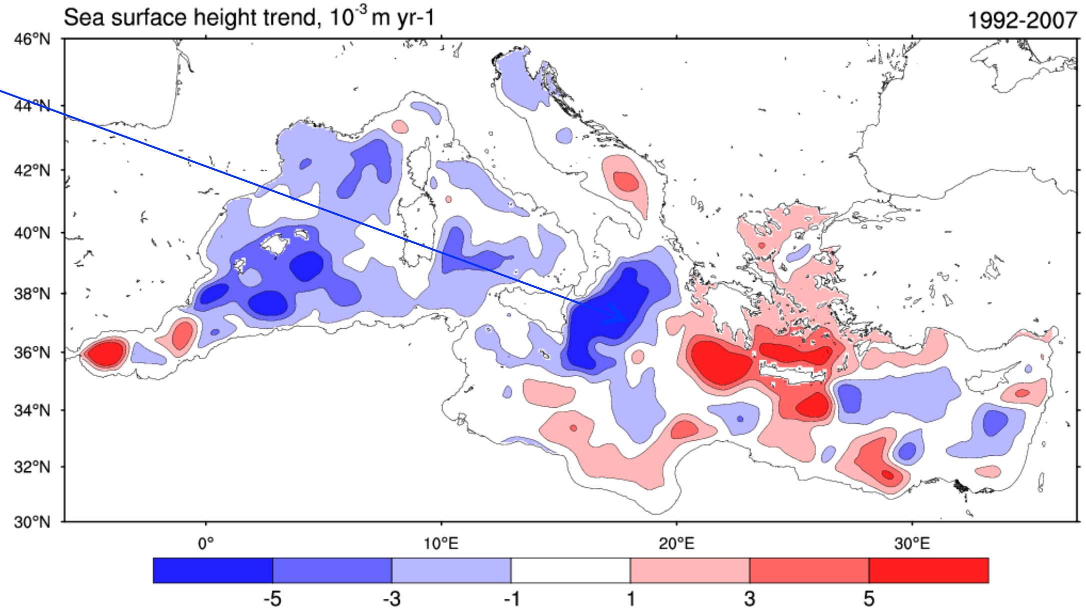
The Northern Ionian Reversal is evident in sea level trends 1992-2007



Northern Ionian Reversal

SLA

Re-analysis

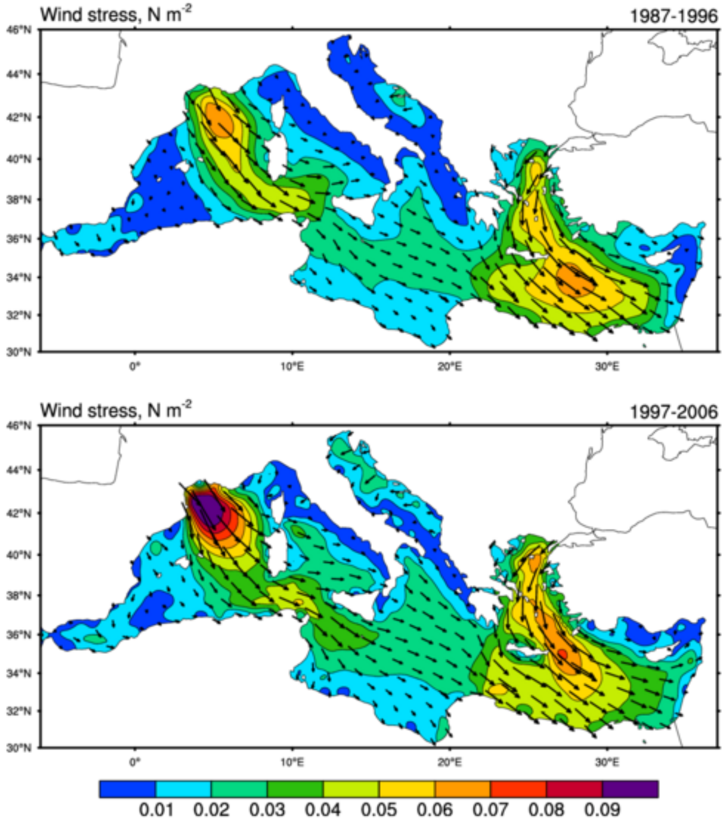


The northern Ionian reversal phenomenon: related to wind stress curl changes

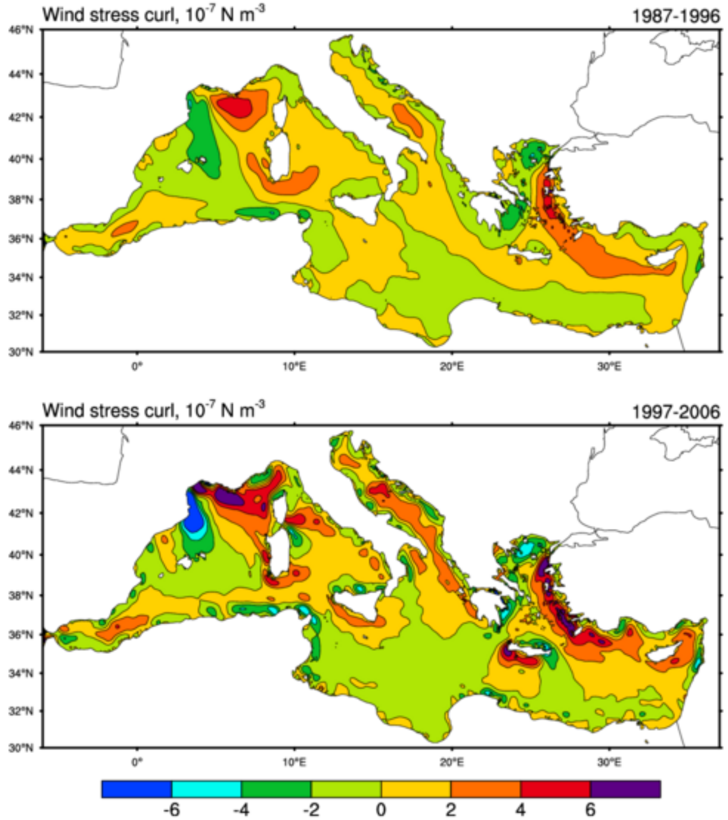
1987-1996 Relaxation of winds period

1997-2006 Large winds period

Wind stress



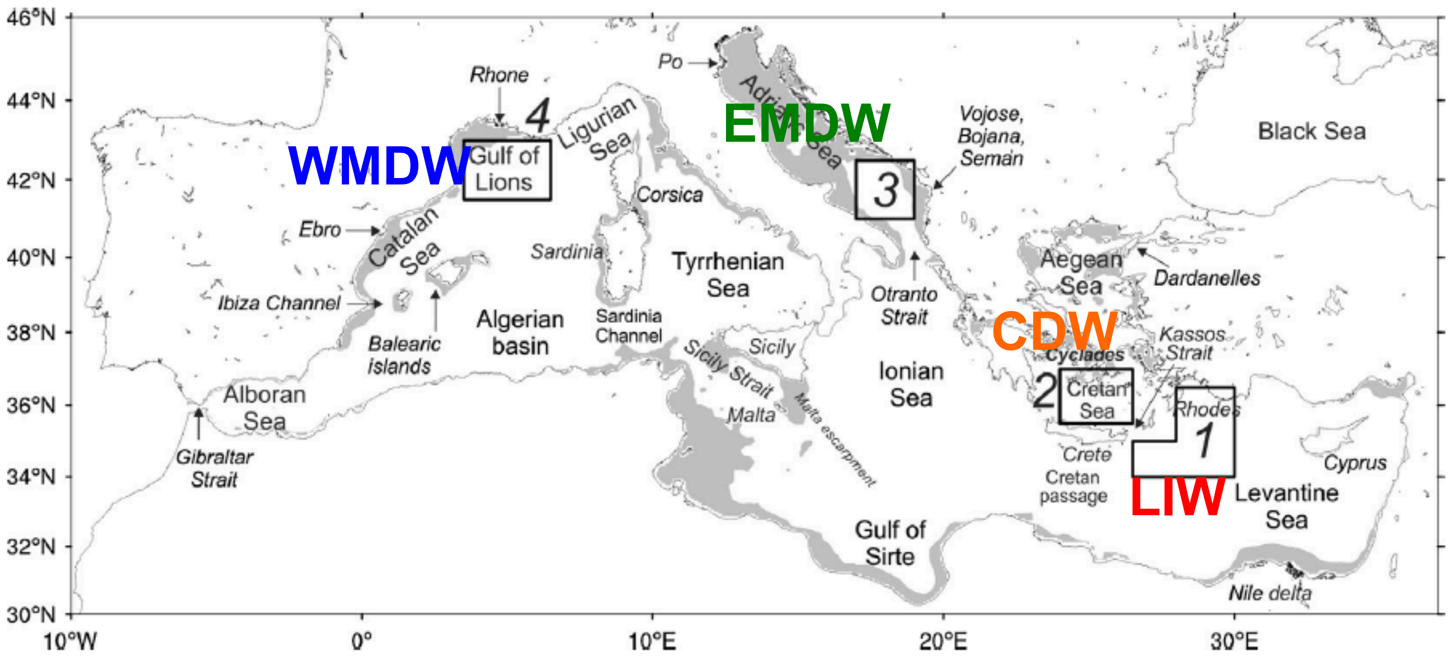
Wind stress curl



Water mass formation rates: what are the decadal variations?

Potential density thresholds for the Water Mass Formation (WMF) rate computations in each of the four regions of Fig. 1. Units are kg m^{-3}.

Areas	Water mass acronym	Density thresholds for WMF rate
1	LIW-LDW	28.95/29.10
2	CDW	29.00/29.10
3	EMDW	29.10/29.20
4	WMDW	29.00/29.10



Water mass formation rates: what are the decadal variations?

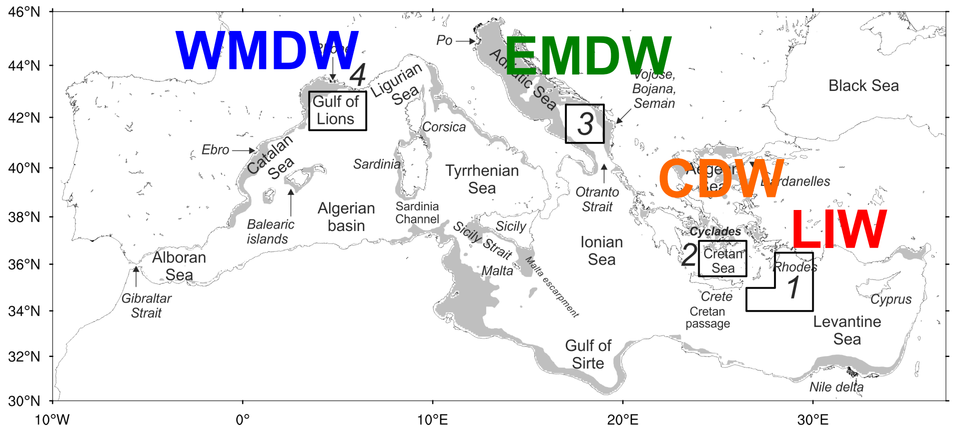
Four major events:

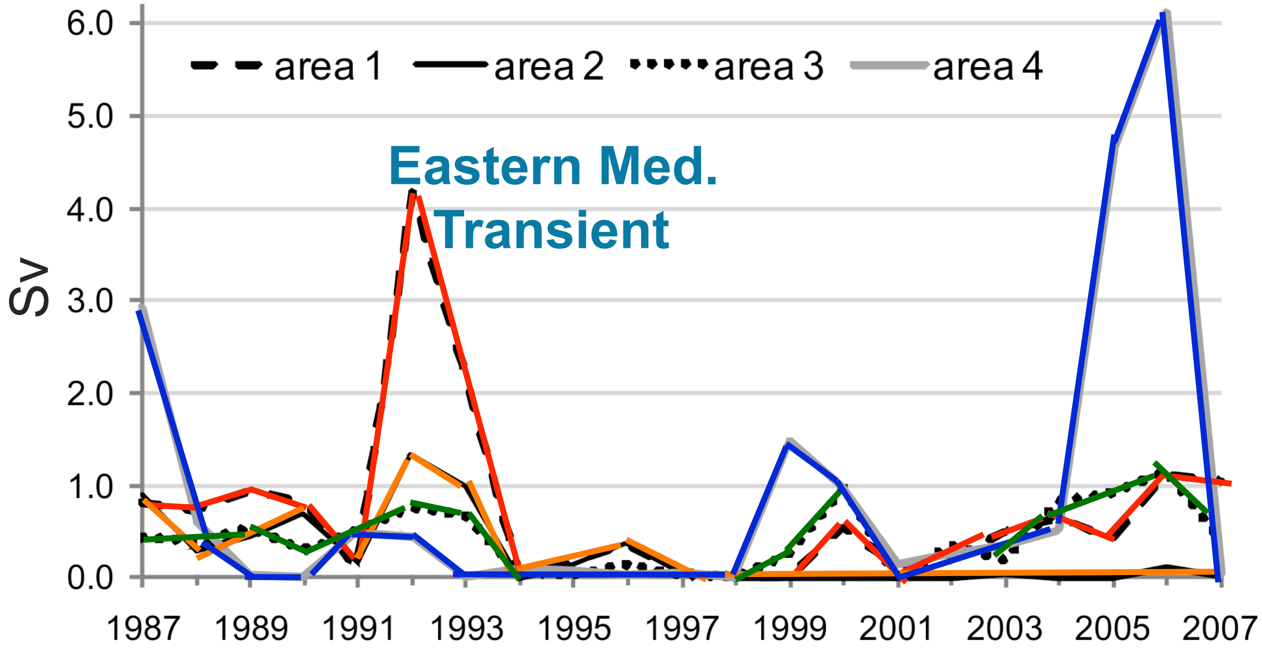
1) 1987 for WMDW

2) 1992-1993 for LIW, CDW and EMDW

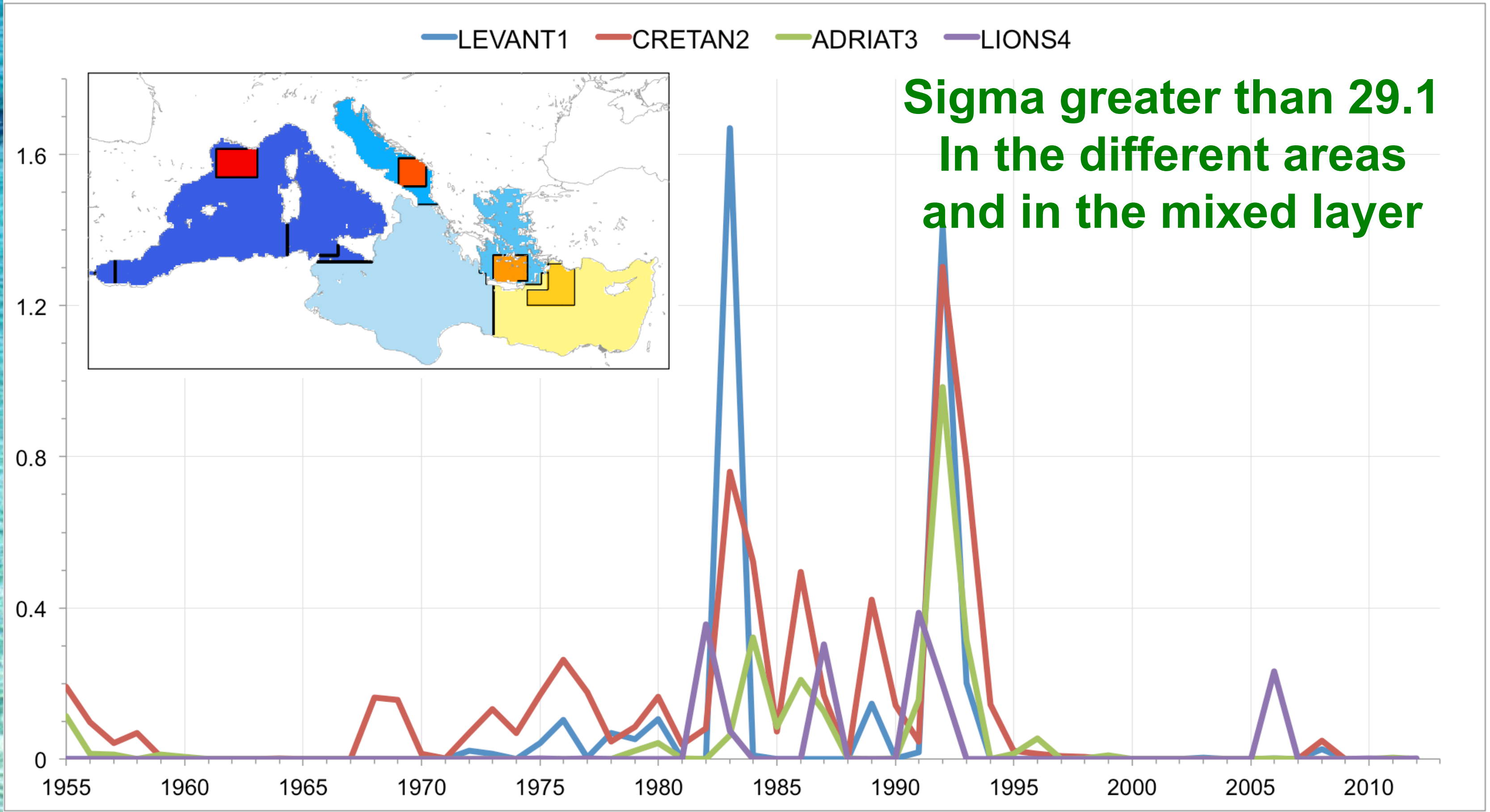
3) 1999-2000 for WMDW and EMDW

4) 2005-2006 WMDW, EMDW and LIW





Water Mass Formation Rates in the past 60 years

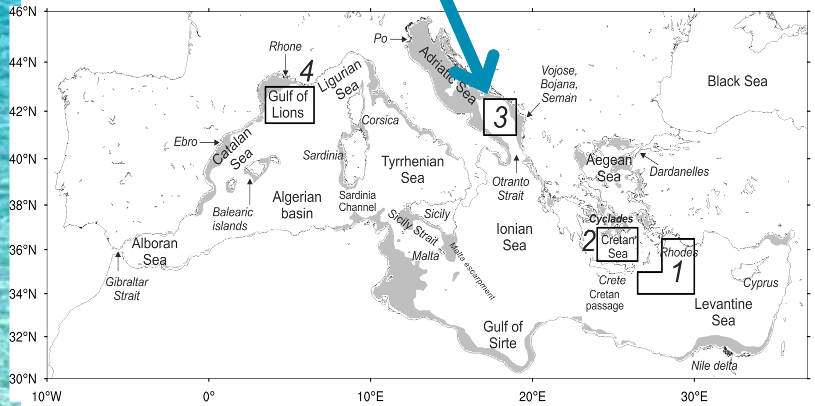


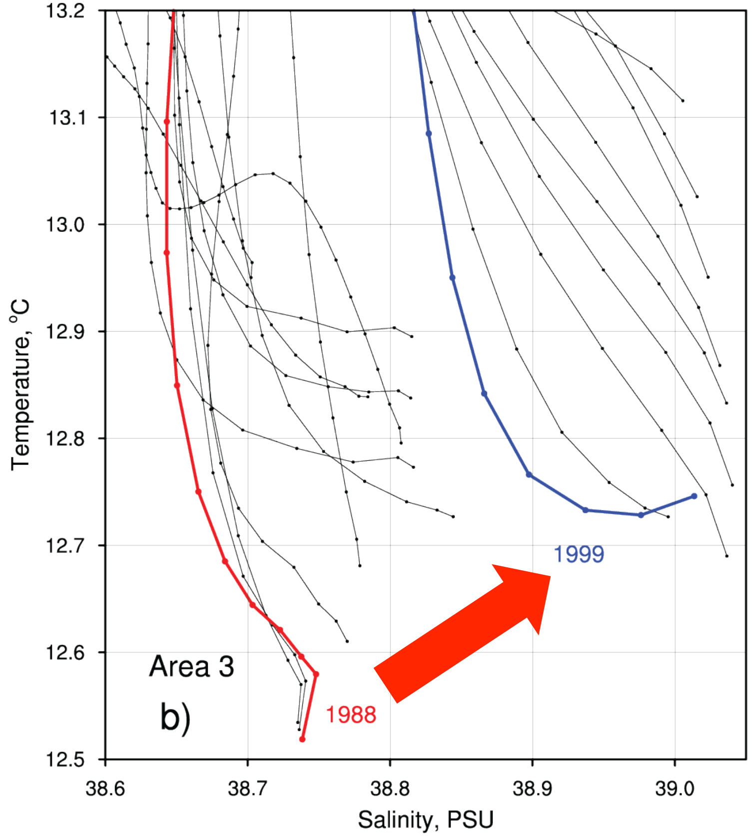
Period 1980-1995 anomalous in the last 60 years for Water mass formation rates

How did the deep water mass T,S characteristics change in the two decades?

Mean T,S diagram in the Adriatic Sea area

Adriatic Sea area, EMDW





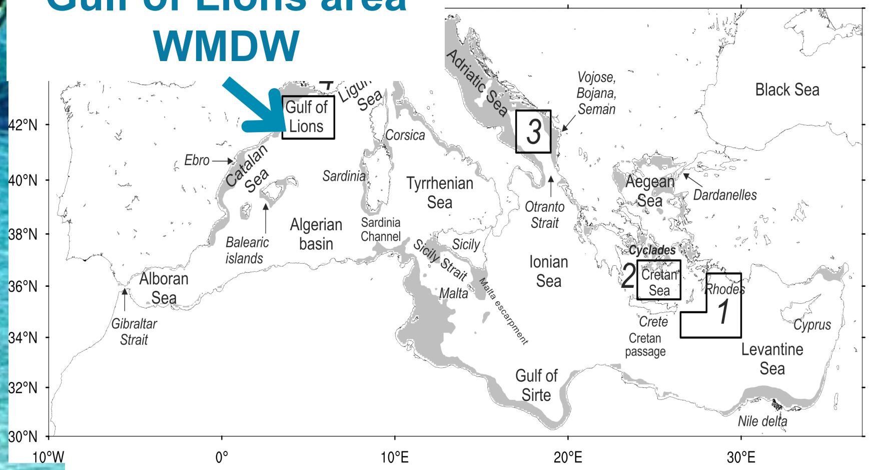
EMDW:

Warming ~ 0.2 /decade

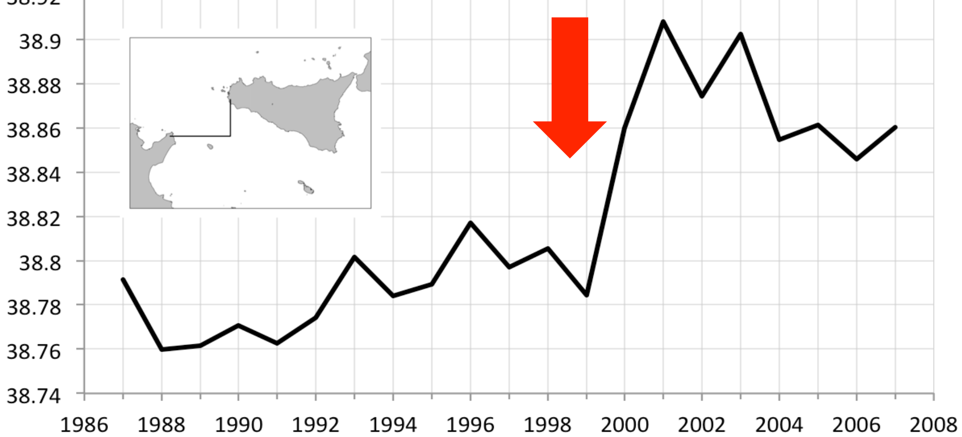
Salting ~ 0.3 /decade

How did the deep water mass T,S characteristics change in the two decades?

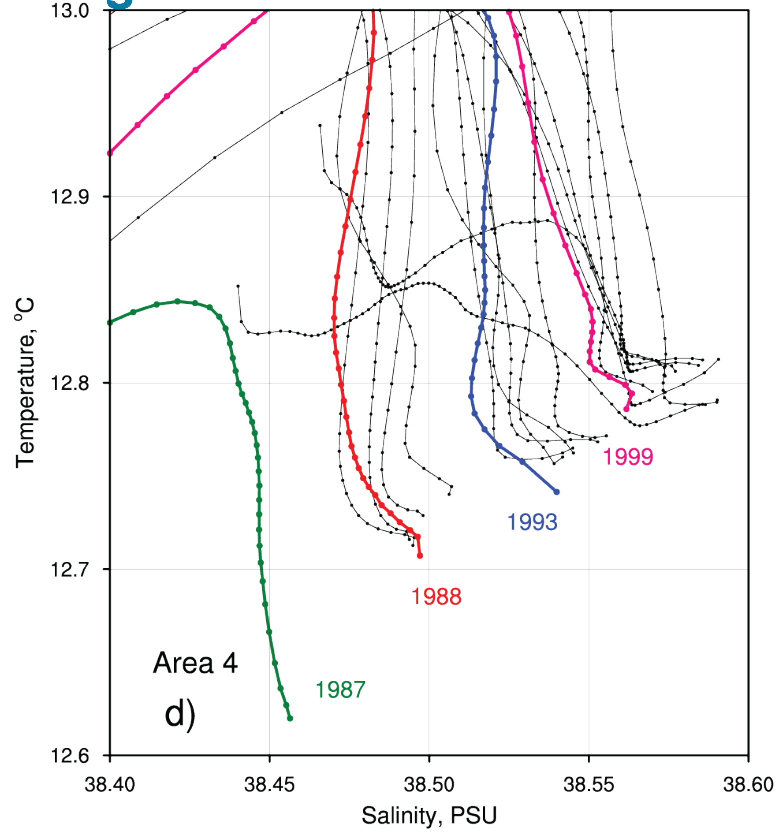
Gulf of Lions area WMDW



SALT at SICILY STRAIT:
EMT ARRIVED ONLY IN 1999



T,S diagram for Gulf of Lions area



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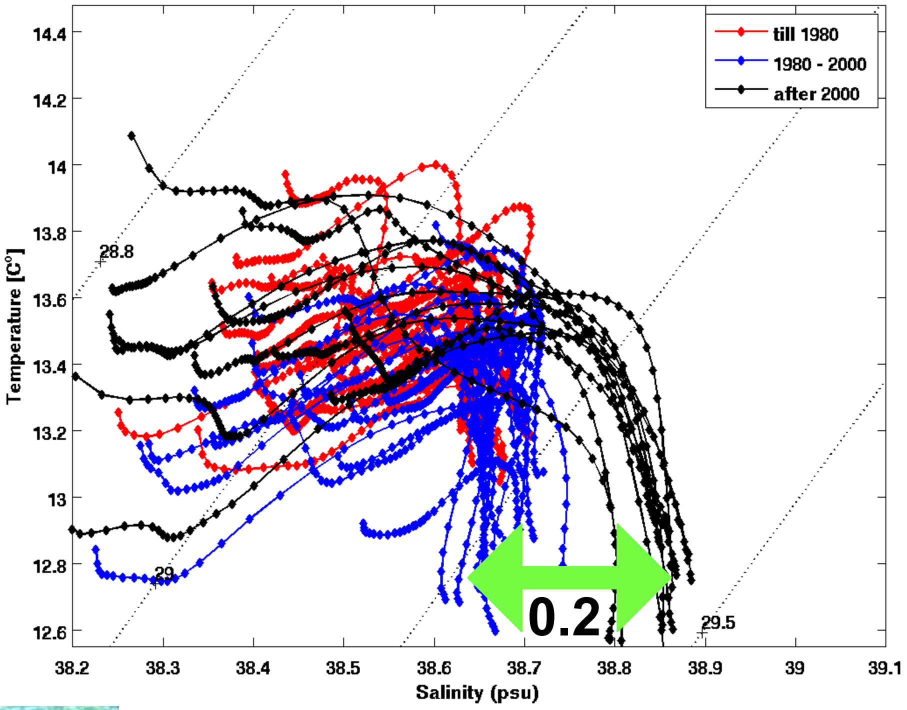
WMDW:
Warming ~ 0.1 /decade

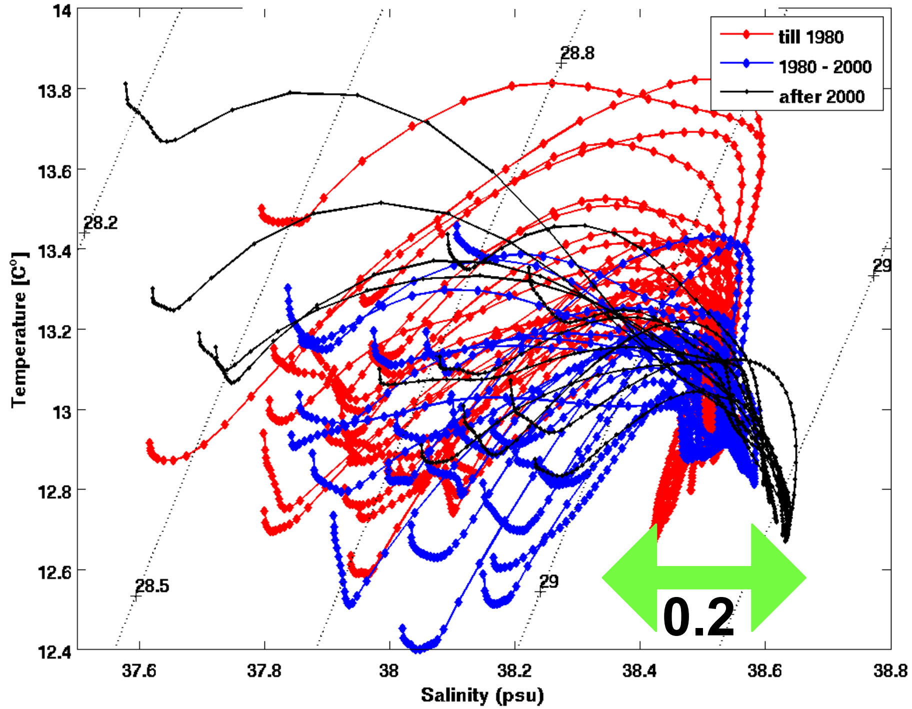
Salting ~ 0.1 /decade

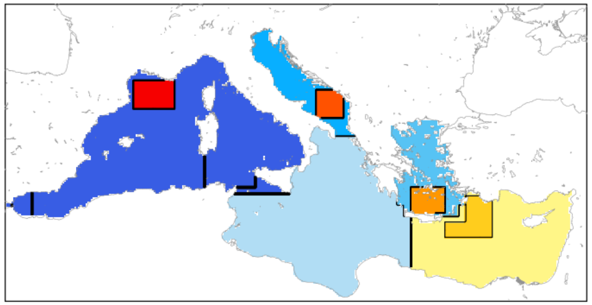
Deep salinity increase in the Deep Water Formation areas

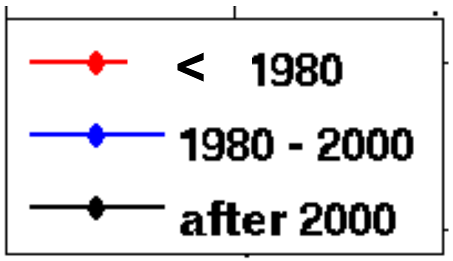
Southern Adriatic annual T-S diagram



Gulf of Lions annual T-S diagram



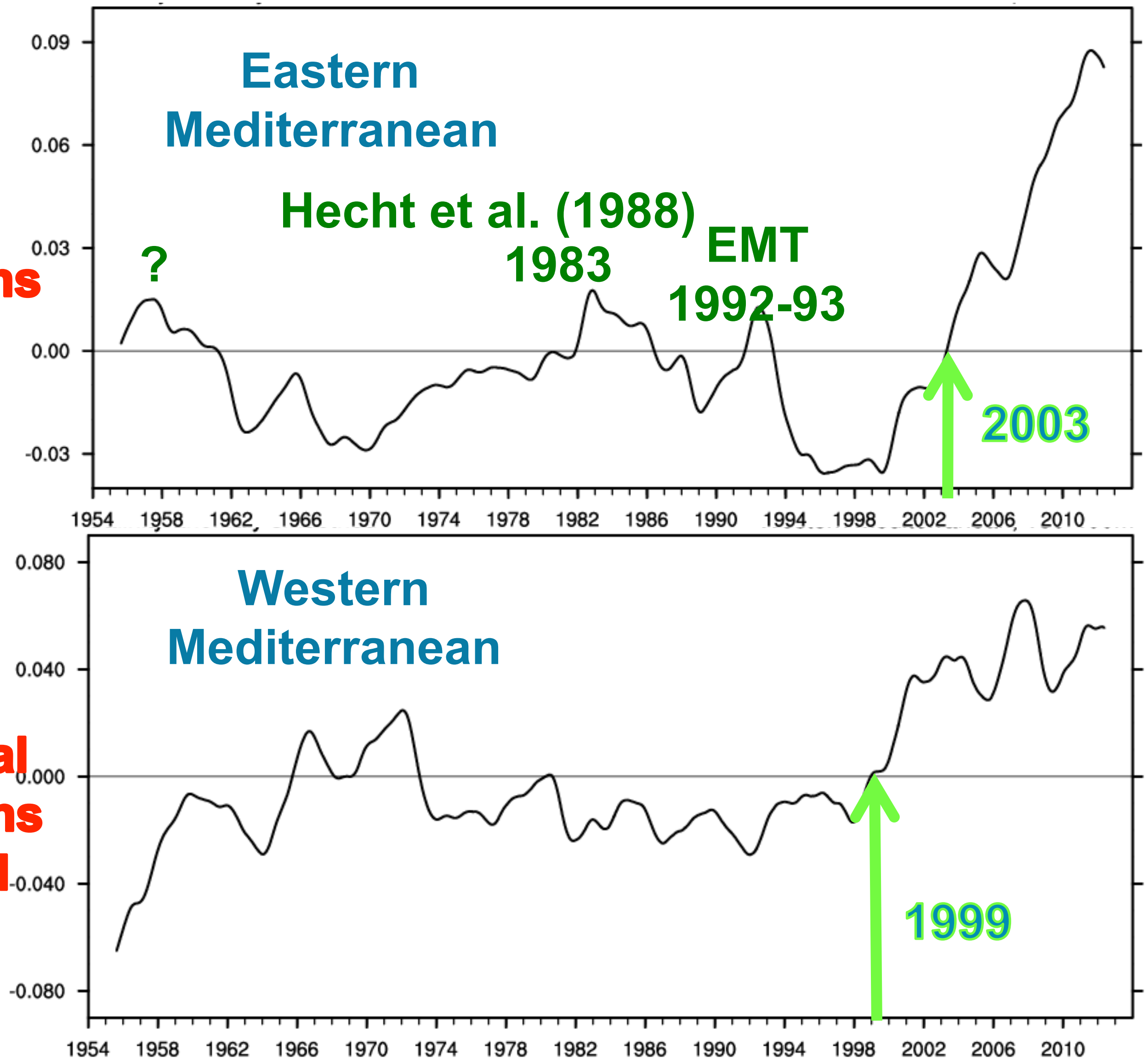




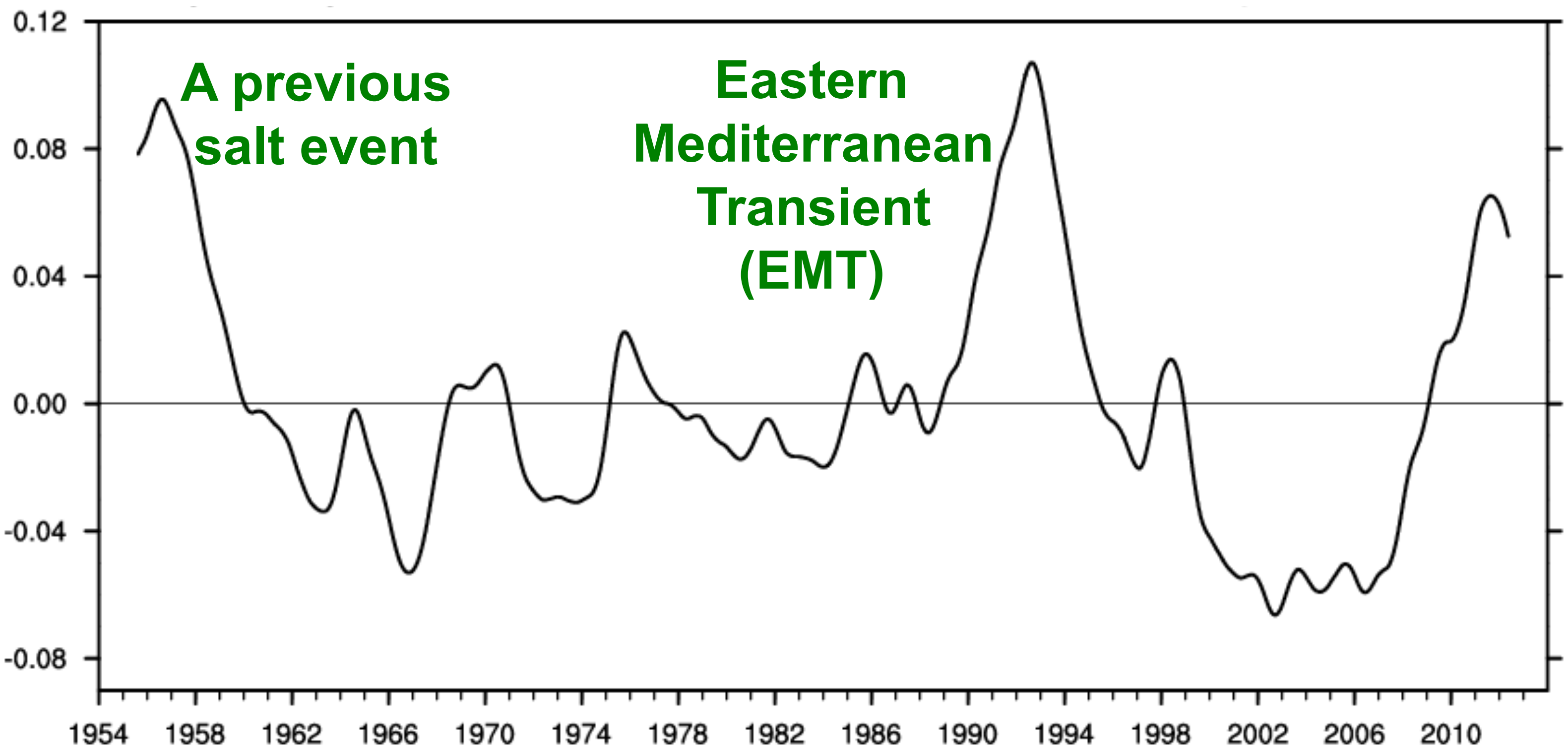
Salinity anomalies 1: 150-400 m Eastern and Western Mediterranean

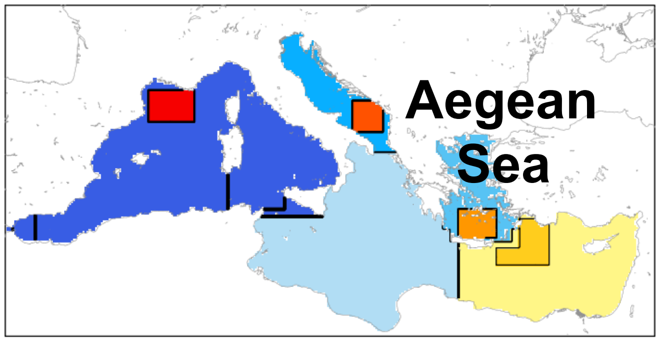
Decadal fluctuations

Interannual Fluctuations and trend

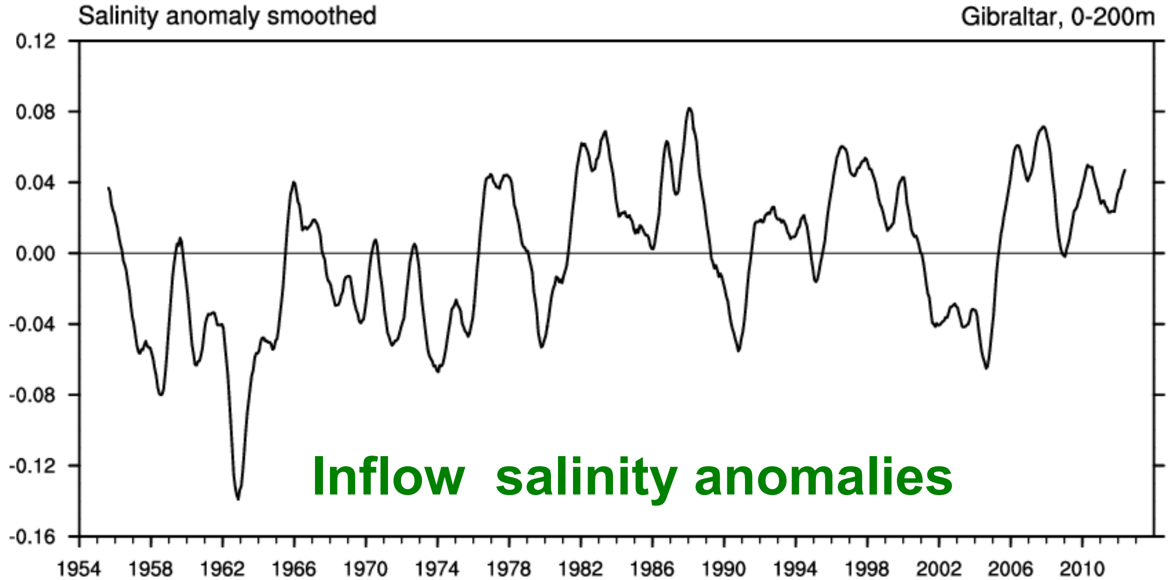


Salinity anomalies 2: 150-400 m in the Aegean Sea

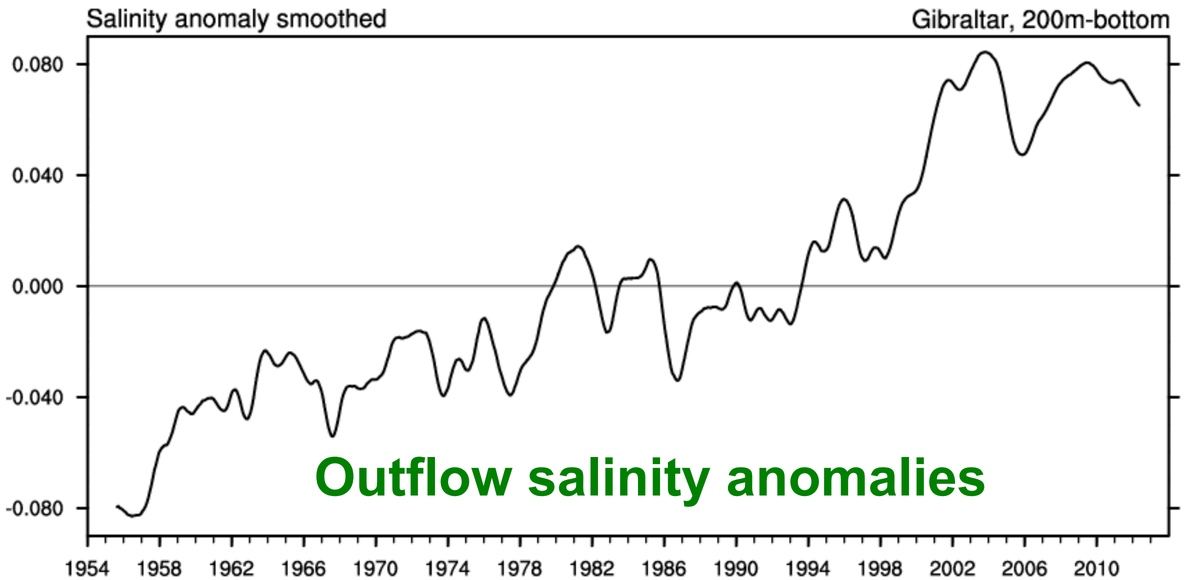




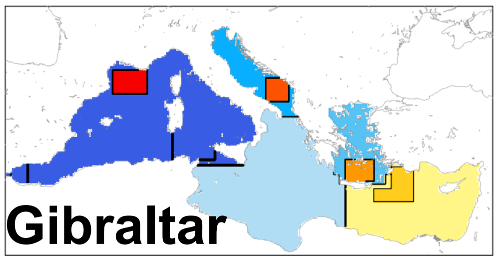
Salinity anomalies 3: the Gibraltar Strait inflow/outflow system



Interannual fluctuations



Trend



Gibraltar Strait

Intermediate conclusions

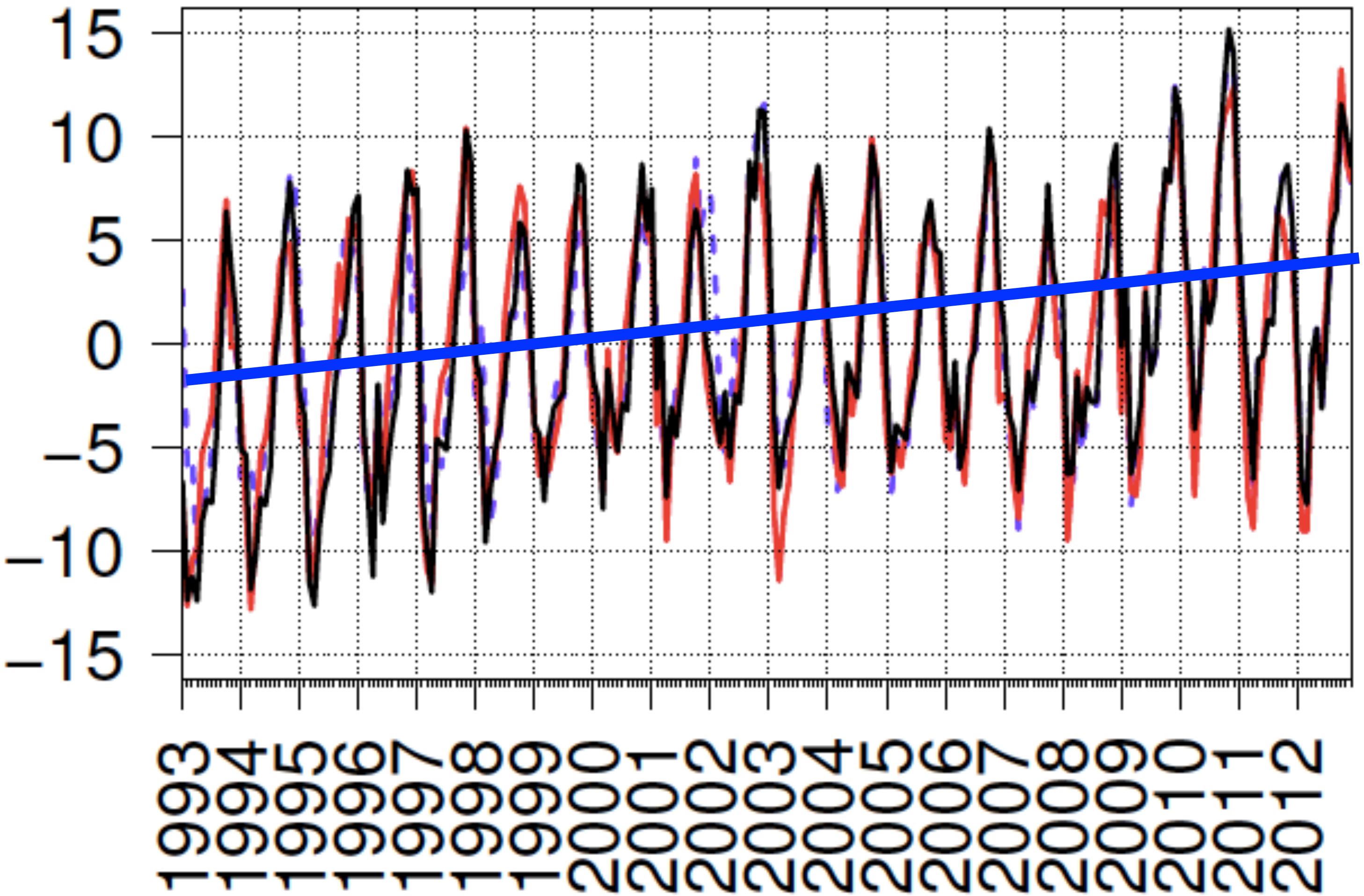
- New 58 years reanalysis reconstruction data set has been produced of a comparable quality to 20 years more accurate reanalysis
- The Levantine Intermediate Layer (LIW) anomalies have a decadal variability signal in the eastern and interannual+trend time scales in the western Mediterranean
- Increase of salinity in deep layers of different sub-areas of the basin is connected to the EMT: another high salinity event could have occurred in the 50s in the Aegean Sea
- The 1980-1995 Deep Water Mass Formation events unique in the 58 years time series

How did the mean Mediterranean sea level change in the past 20 years?

- Global ocean estimate
  - Church et al. (2011): 3.2 ± 0.4 mm year-1
  - Church et al. (2004) from reconstruction (100 years): 1.8 ± 0.3 mm year-1
- Mediterranean Sea estimate
  - Calafat and Jorda' (2011): 1.8 ± 0.3 mm year-1
  - Calafat and Gomis (2009) from reconstruction (100 years): 0.7 ± 0.2 mm year-1
- Why are so different? What is the mean sea level trend due to in the Mediterranean?

The Mean Sea Level in the Med

2.44 ± 0.5 mm year-1
last evaluation Bonaduce et al., 2015



Tide gauges and satellite altimetry

The mean sea level trend in the Med Sea: what is it due to?

The Mediterranean *Mean* sea level $\langle \eta \rangle_R = \frac{1}{A} \iint_A \eta \, dA$ **equation**

$$\frac{d\langle \eta_R \rangle}{dt} = -\left\langle \nabla \cdot \left[(H+\eta)\vec{\bar{u}} \right] \right\rangle_R - \langle q_W \rangle_R \quad \textbf{MASS}$$

$$= \mathit{Gibraltar\ net\ trans} - \mathit{waterflux}$$

$$+ \frac{1}{\rho_f} \left\langle \alpha_T \frac{Q}{C_W} \right\rangle - \left. \frac{\rho_o \beta \langle S_o q_W \rangle_R}{\rho_f} \right|_R - \frac{1}{\rho_f} \left\langle \int_{-H}^{\eta} \nabla \cdot \left(K_H \nabla \tilde{\rho} \right) \right\rangle \quad \textbf{STERIC}$$

$$+ \mathit{steric\ terms}\ (\mathit{thermosteric} + \mathit{halosteric} + \mathit{density\ adv.\ at\ Gib.})$$

where $q_W = E - P - \frac{R}{F_M} - M_G$

Pinardi et al., J.Clim, 2014

How do we compute the steric terms in an incompressible model?

$$
\begin{aligned}
\frac{d\langle\eta\rangle}{dt} &= -\frac{T_r}{\Omega} - \langle q_w\rangle - \frac{\rho_f}{\rho_0}\langle\beta S_0 q_w\rangle + \frac{1}{\rho_0}\langle\alpha_T \frac{Q}{C_w}\rangle - F_\rho \\
&= \quad (1) \quad\quad (2) \quad\quad\quad (3) \quad\quad\quad\quad (4) \quad\quad\quad (5)
\end{aligned}
$$

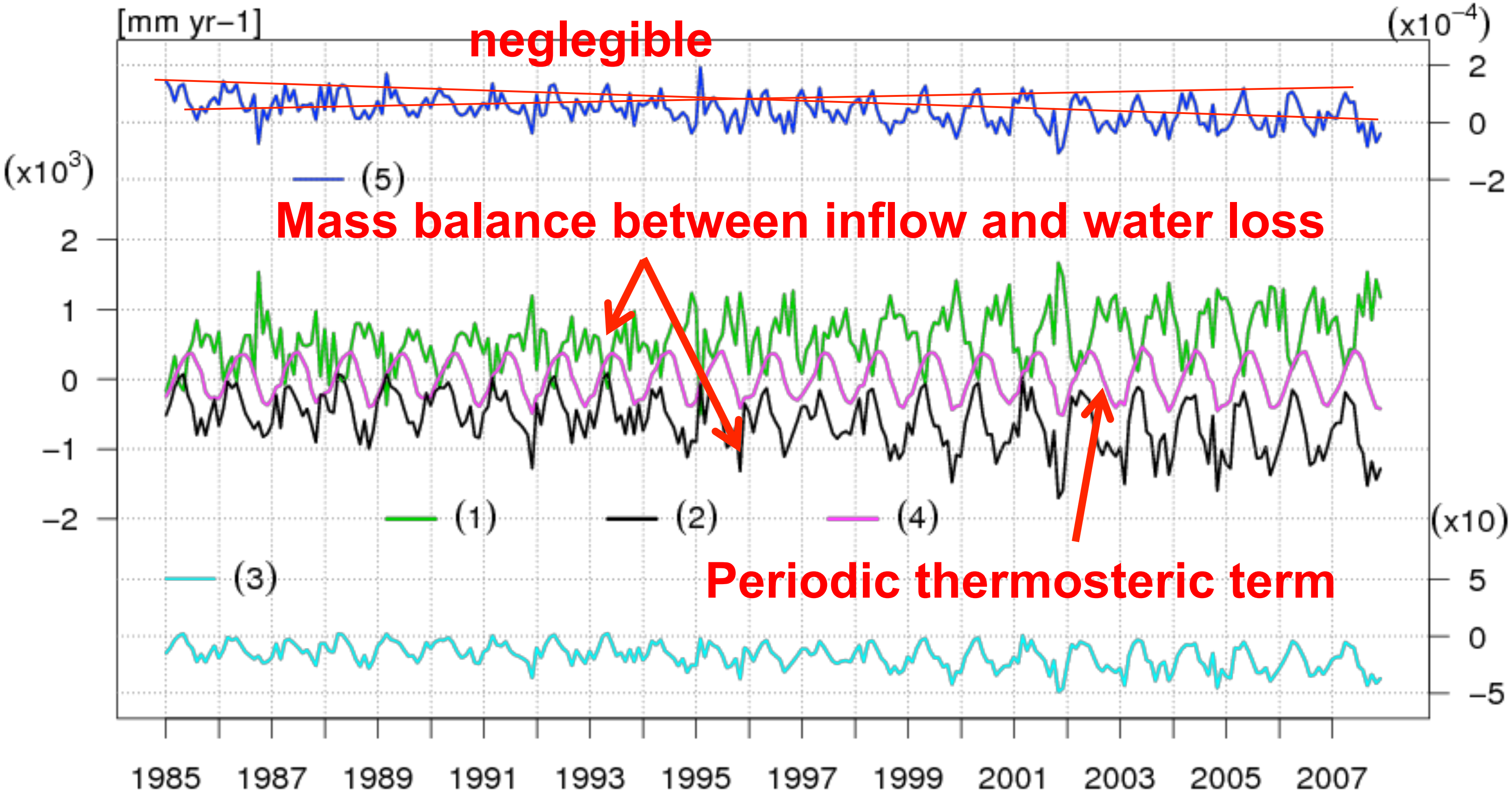
Following Mellor and Ezer (1995) the solution is approximately the linear superposition of two separate problems

$$
\begin{aligned}
\langle\eta\rangle &= \langle\eta_i\rangle + \langle\eta_s\rangle \\
\frac{d\langle\eta_i\rangle}{dt} &= -\frac{T_r}{\Omega} - \langle q_w\rangle \\
\frac{d\langle\eta_s\rangle}{dt} &= -\frac{\rho_f}{\rho_0}\langle\beta S_0 q_w\rangle + \frac{1}{\rho_0}\langle\alpha_T \frac{Q}{C_w}\rangle - F_\rho
\end{aligned}
$$

The mean sea level trend for the Mediterranean case: the re-analysis case

$$\frac{d\langle \eta_R \rangle}{dt} = -\left\langle \nabla \cdot \left[(H+\eta)\vec{\bar{u}} \right] \right\rangle_R - \langle q_W \rangle_R - \left\langle \frac{\rho_o \beta \langle S_o q_W \rangle_R}{\rho_f} \right\rangle_R + \frac{1}{\rho_f} \left\langle \alpha_T \frac{Q}{C_W} \right\rangle - \frac{1}{\rho_f} \left\langle \int_{-H}^{\eta} \nabla \cdot \left(K_H \nabla \tilde{\rho} \right) \right\rangle$$

$$= (1) + (2) + (3) + (4) + (5)$$

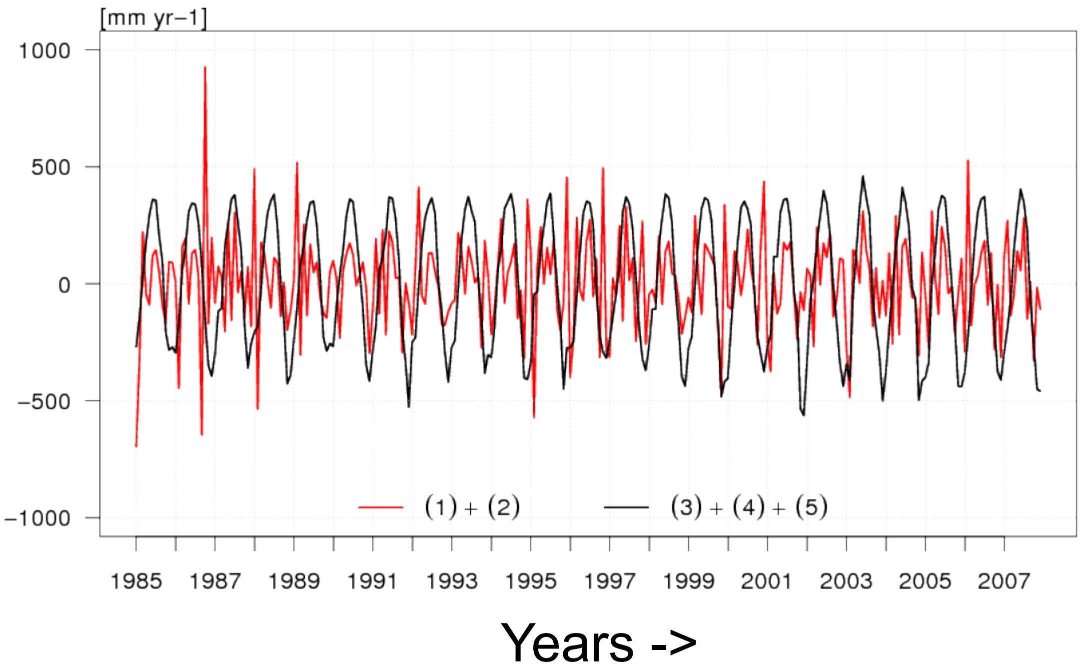


The mean sea level trend for the Mediterranean case: the re-analysis case

$$\frac{d\langle\eta_R\rangle}{dt} = -\left\langle \nabla\cdot\left[\left(H+\eta\right)\vec{\bar{u}}\right]\right\rangle_R - \left\langle q_W\right\rangle_R - \left\langle\frac{\rho_o\beta\left\langle S_o q_W\right\rangle_R}{\rho_f}\right\rangle_R + \frac{1}{\rho_f}\left\langle\alpha_T\frac{Q}{C_W}\right\rangle - \frac{1}{\rho_f}\left\langle\int_{-H}^{\eta}\nabla\cdot\left(K_H\nabla\tilde{\rho}\right)\right\rangle$$

$$= \quad (1) \quad + \quad (2) \quad + \quad (3) \quad + \quad (4) \quad + \quad (5)$$

$$\frac{d\langle\eta_R\rangle}{dt}\,(mm\,yr^{-1})$$



Sea level tendency in the Mediterranean Sea is due to:
mass terms (1+2) stochastic forcing
and (3+4+5) periodic steric terms

Final remarks

- The Mediterranean Sea is powered equally by buoyancy and wind work rate forcings
- Energetics shows that estuarine and anti-estuarine circulation strength is connected to the sign of the net buoyancy forcing
- The Mediterranean Sea mean circulation is structured around ‘cyclonic and anticyclonic gyres’ and, as in the North Atlantic, they are wind vorticity driven
- The decadal variability is dominated by the Northern Ionian reversal phenomenon between 1987-1996 and 1997-2006: which other time did it occur? On-going work

Final remarks

- In the Mediterranean, water mass formation rates show high production ‘events’: warming and salting of EMDW associated with EMT while WMDW gradual and consistent for the past 20 years
- Mediterranean Mean Sea Level dominated by the asynchronous response of Gibraltar to surface water fluxes, resulting in a stochastic forcing term that will control the trend