The recent warming of intermediate waters at the Eastern North Atlantic. Insights from a monthly hydrographical timeseries at the Bay of Biscay

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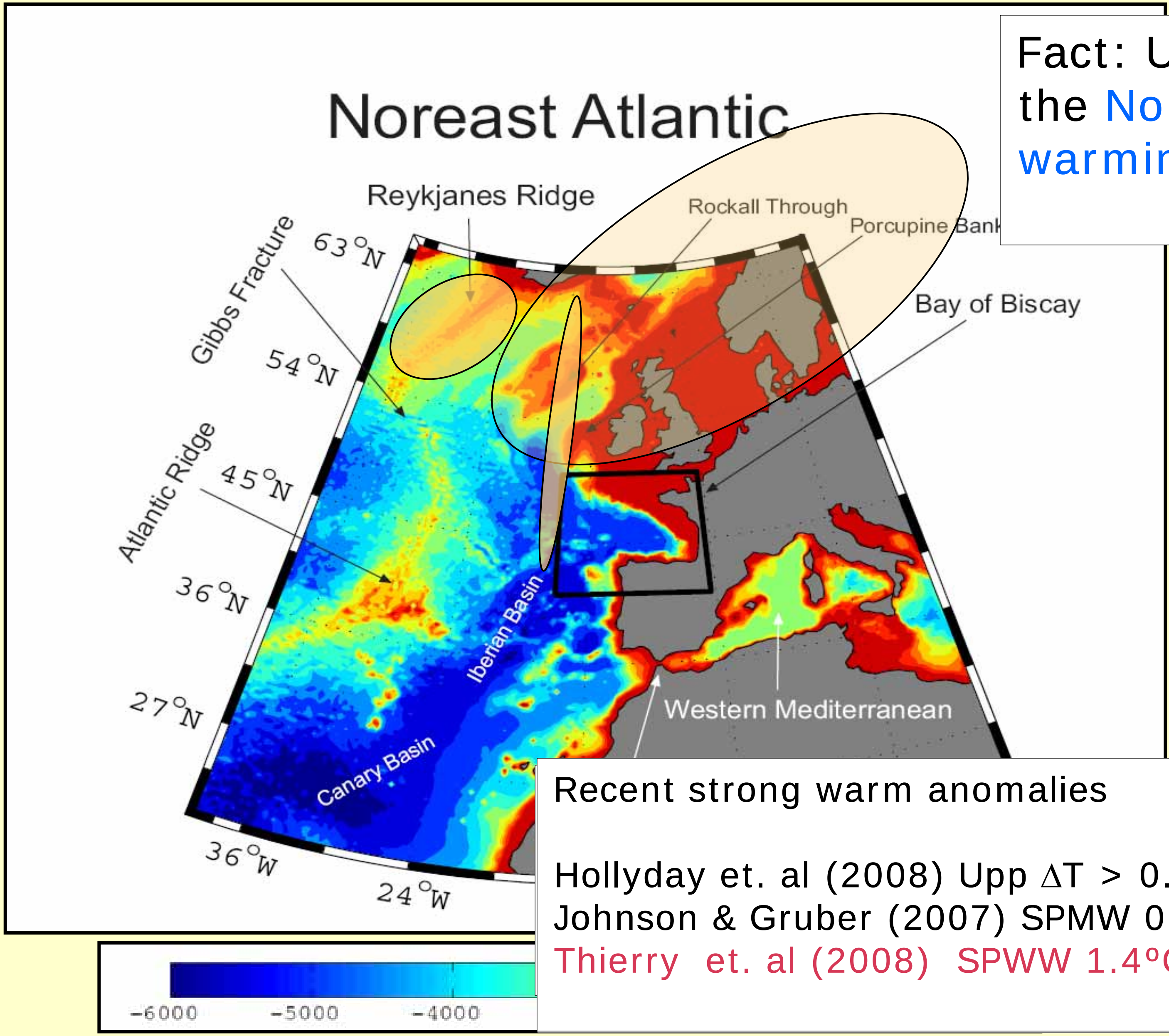
Effects of climate change on the world's oceans

2008 May 19-23, Gijón, Spain

Introduction. Warming in the Eastern North Atlantic

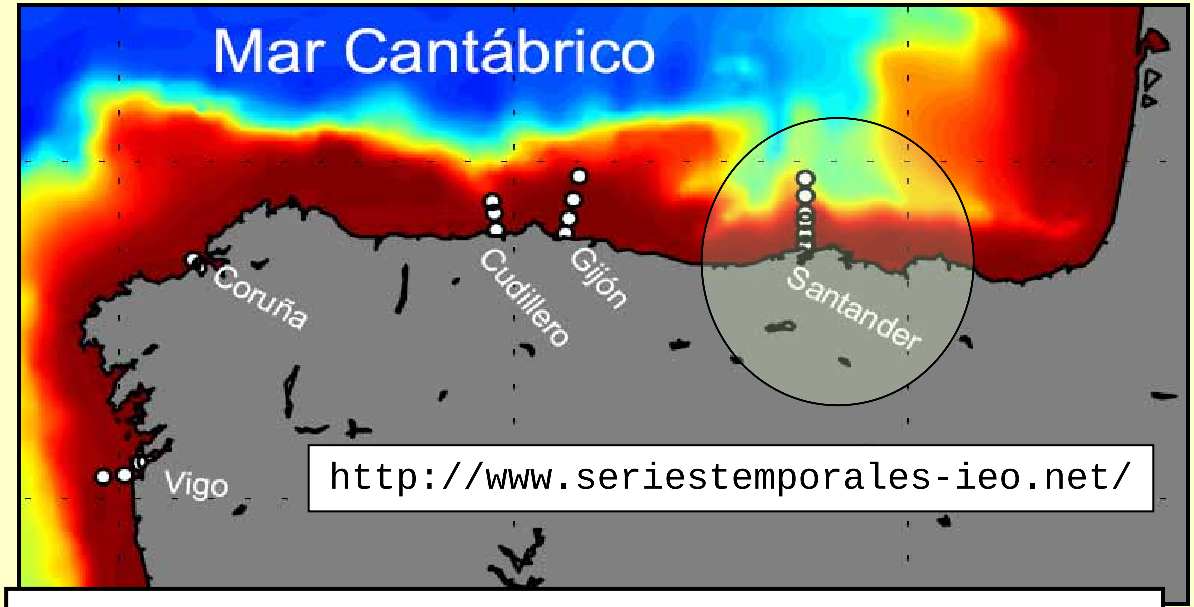


Fact: Upper layers of the North Atlantic are warming.

Recent strong warm anomalies

Hollyday et. al (2008) Upp $\Delta T > 0.1$°C from 2000
Johnson & Gruber (2007) SPMW 0.7°C 1993-2003
Thierry et. al (2008) SPWW 1.4°C 1996-2003

The Radiales Project. The Santander Standard Section



http://www.seriestemporales-ieo.net/

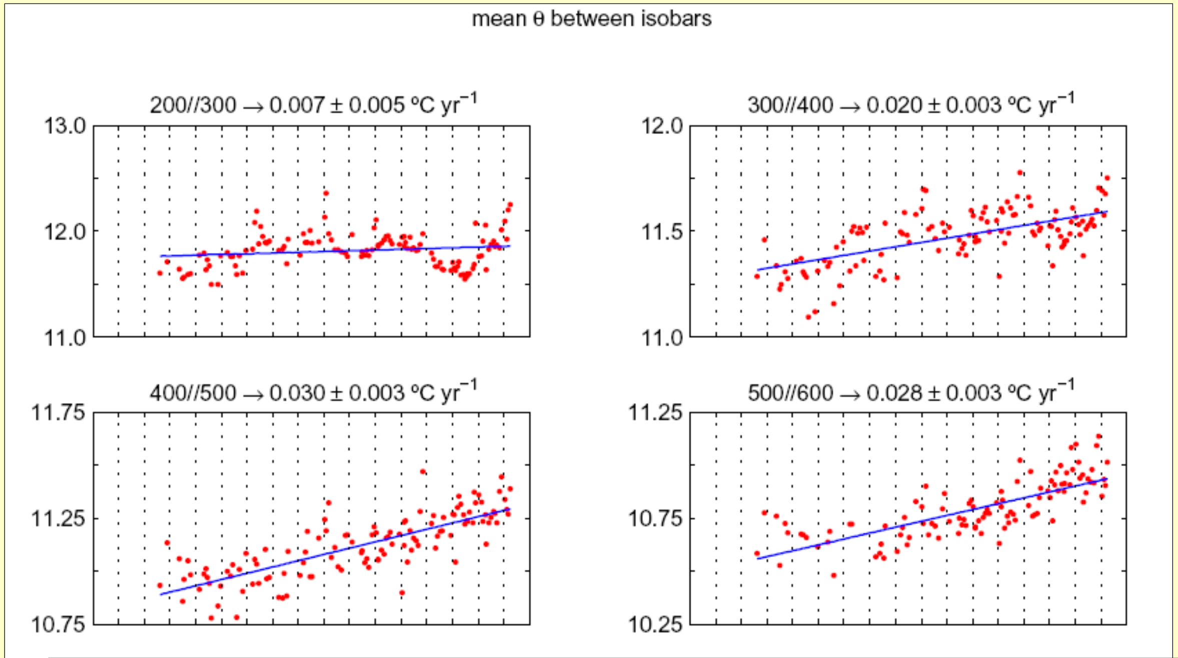
Radiales Project: Systematic sampling (hydrographical and biological in 8 standard sections around Spanish waters).

Monthly sampling in the Galician-Cantabrian area.

- Santander Section. 7 stations, 1 in the shelf break, two over the deep ocean (2400 and 2800)
- Small ship, sampling limited to 1000m depth (1500 from 2006).

High frequency timeseries of central water properties.

Sustained warming at all depths

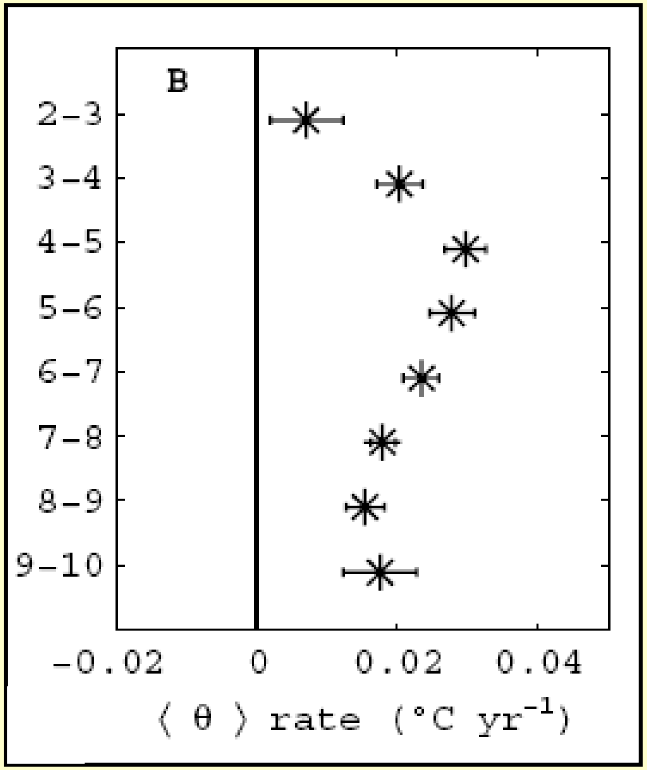


From early 90`s all water masses have warmed at rates 0.015-0.030 ºC/yr.

(0.020 ºC/yr on average. 0.30ºC in 15 years)

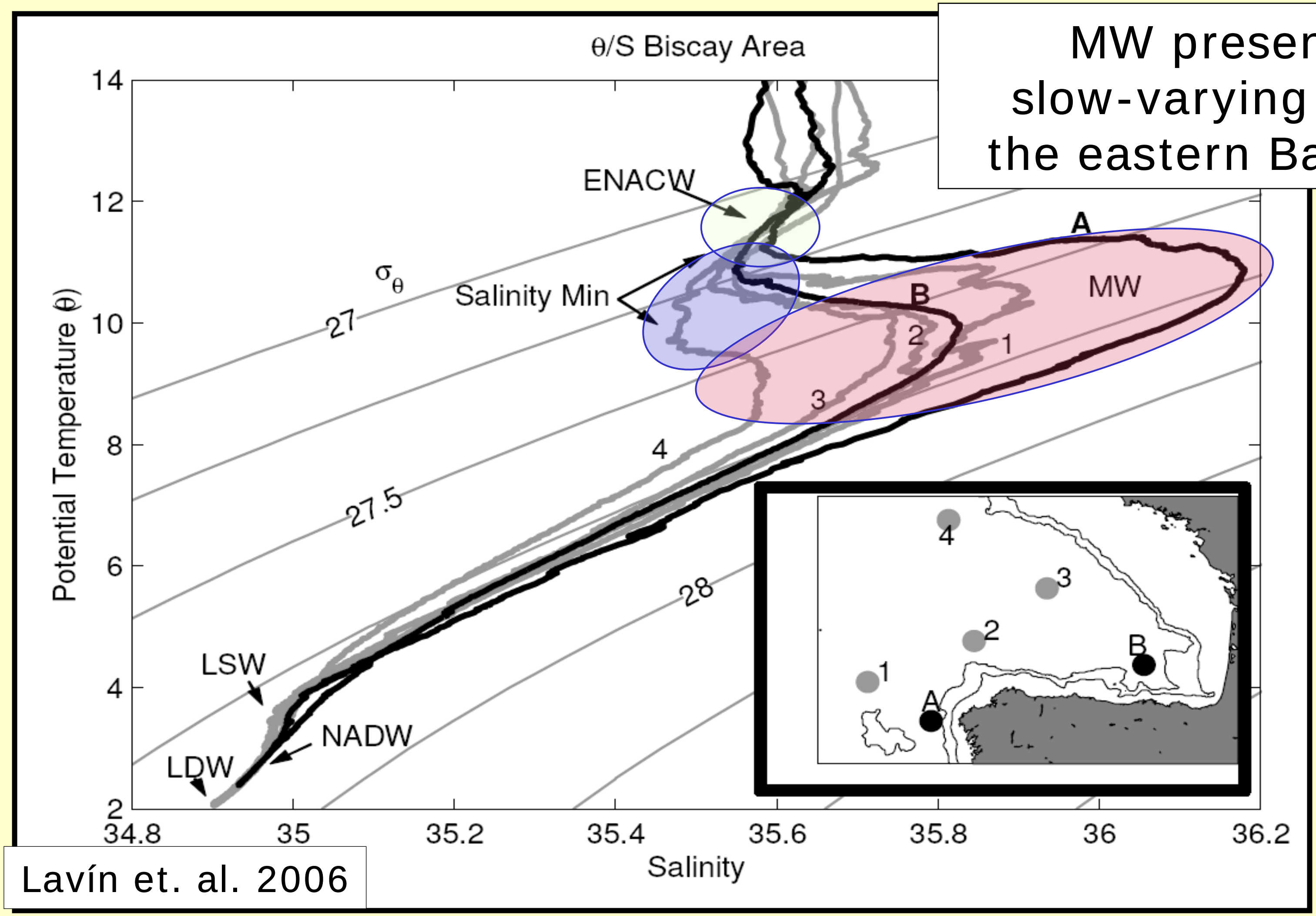
Different water masses (different sources and pathways) and different types of warming.

Possible to look to the interannual variability and strong shifts (climatic signals).



Water masses in the Bay of Biscay

East North Atlantic Central Water (ENACW). σ_θ~27.1-2 Pres ~ 350 dbar
Lower bound of ENACW (Sal Min). σ_θ~27.2-3 Pres ~ 500 dbar
Mediterranean Water (MW). σ_θ~27.3-27.6 Pres ~ 1000 dbar (core)



MW present a smooth slow-varying structure a the eastern Bay of Biscay

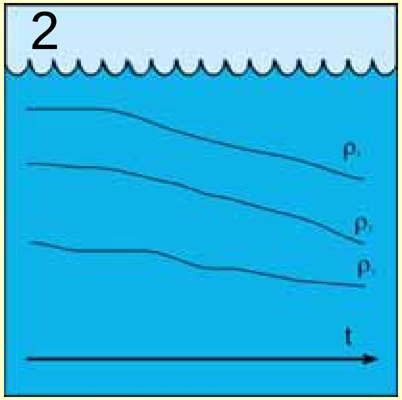
Lavín et. al. 2006

Quantifying water masses changes

It is possible to split changes at a fixed depth approximately in two main components (*Bindoff & McDougall 1994, Arbic & Owens, 2001*) :

1. Thermohaline properties variation at fixed isopycnal levels. *Pure Warming//Freshening.* [air-sea fluxes variability]
2. Variations due to vertical displacement of isopycnal levels. *Pure Heave.* [renewal rates, circulation changes]

Approximate expression:



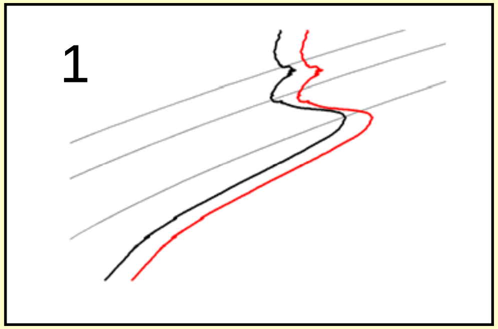
Heating at isobaric levels "isobaric change"

$$\left.\frac{\mathrm{d}\theta}{\mathrm{d}t}\right|_p = \left.\frac{\mathrm{d}\theta}{\mathrm{d}t}\right|_n - \left.\frac{\mathrm{d}p}{\mathrm{d}t}\right|_n \frac{\partial\theta}{\partial p}.$$

1

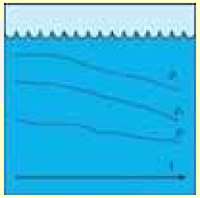
2

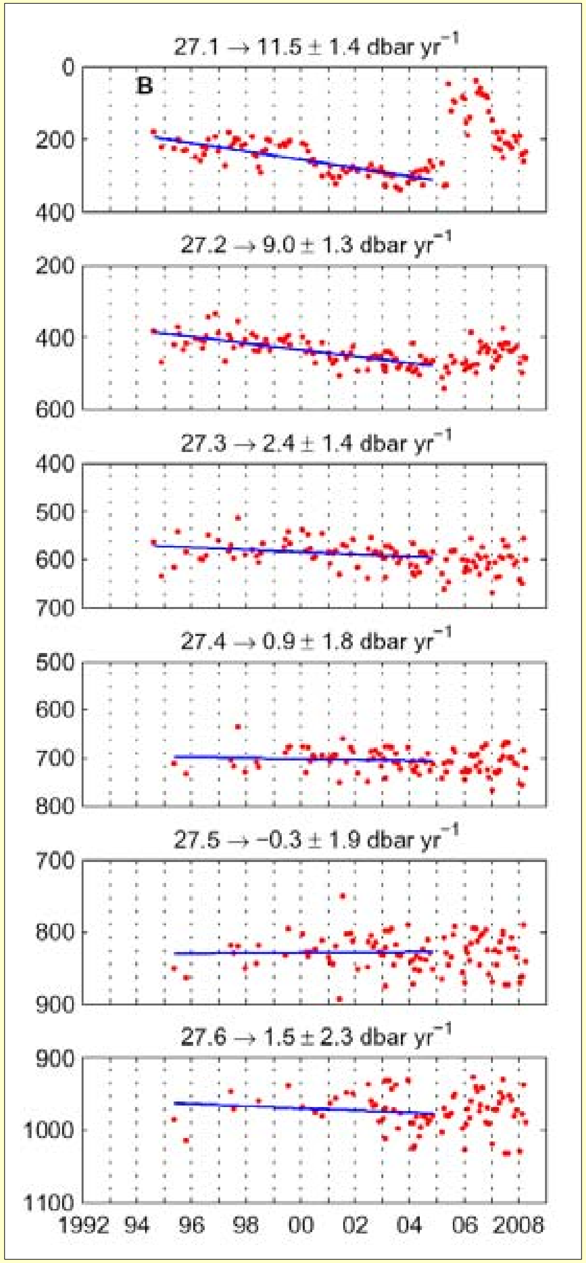
Heating at isopycnal levels "isopycnal change". Modification of the thermohaline structure of the water masses

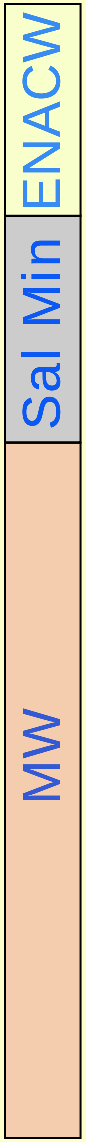


Heating due to isopycnal level displacement "heave". 'Same water types' but different proportions.

Isopycnal sinking (heave). St7



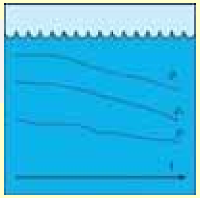


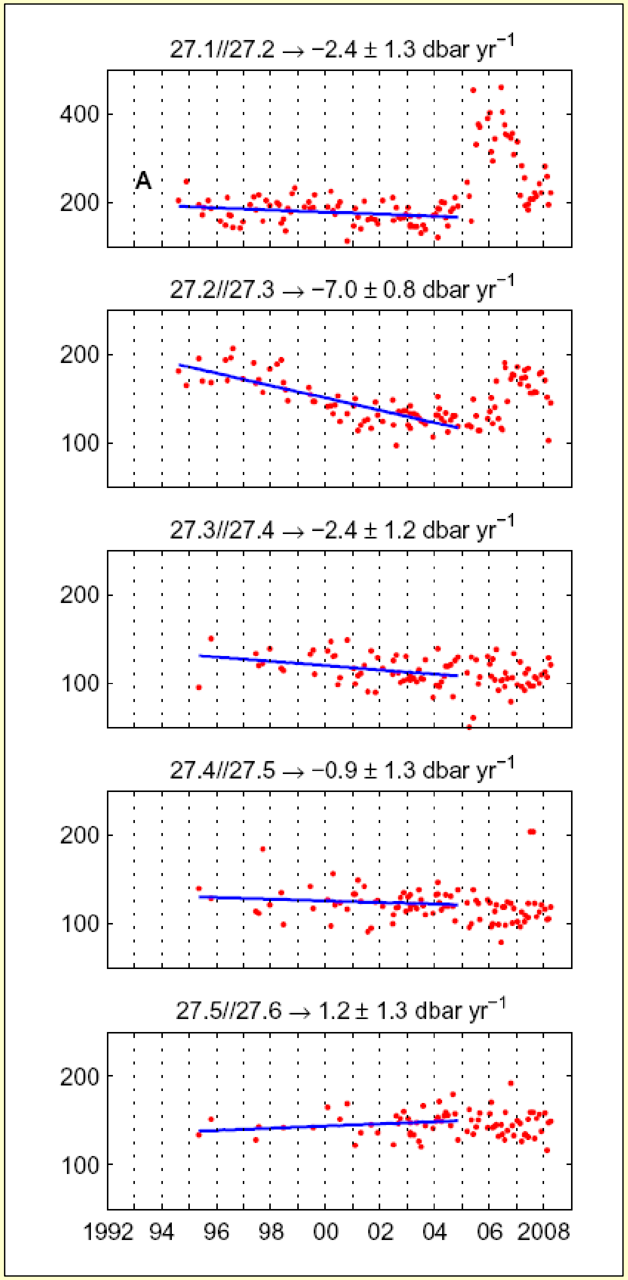


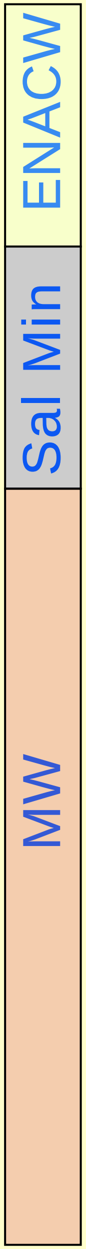
27.1-27.2 ⇨ Significant and progressive sinking until 2005.

27.3-27.6 ⇨ fairly stable

Thickness of the layers (heave). St7







ENACW

Sal Min

MW

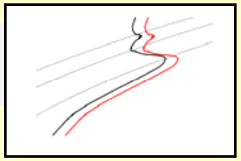
27.1// 27.2 ⇨ Stable (slight non-significant reduction). Sudden increase in 2005.

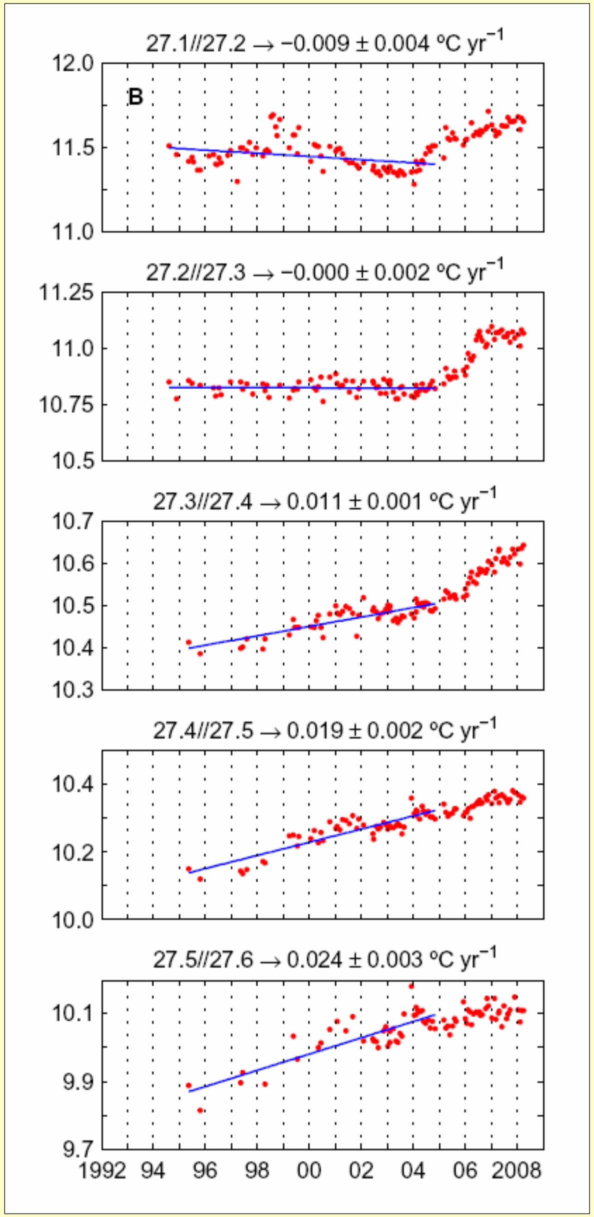
27.2// 27.3 ⇨ Strong reduction (~7 dbar yr^{-1}). Restoration in 2005.

27.3// 27.4 ⇨ Slight reduction

27.3-27.6 ⇨ fairly stable

Θ between isopycnals (isopycnal change), same for salinity!





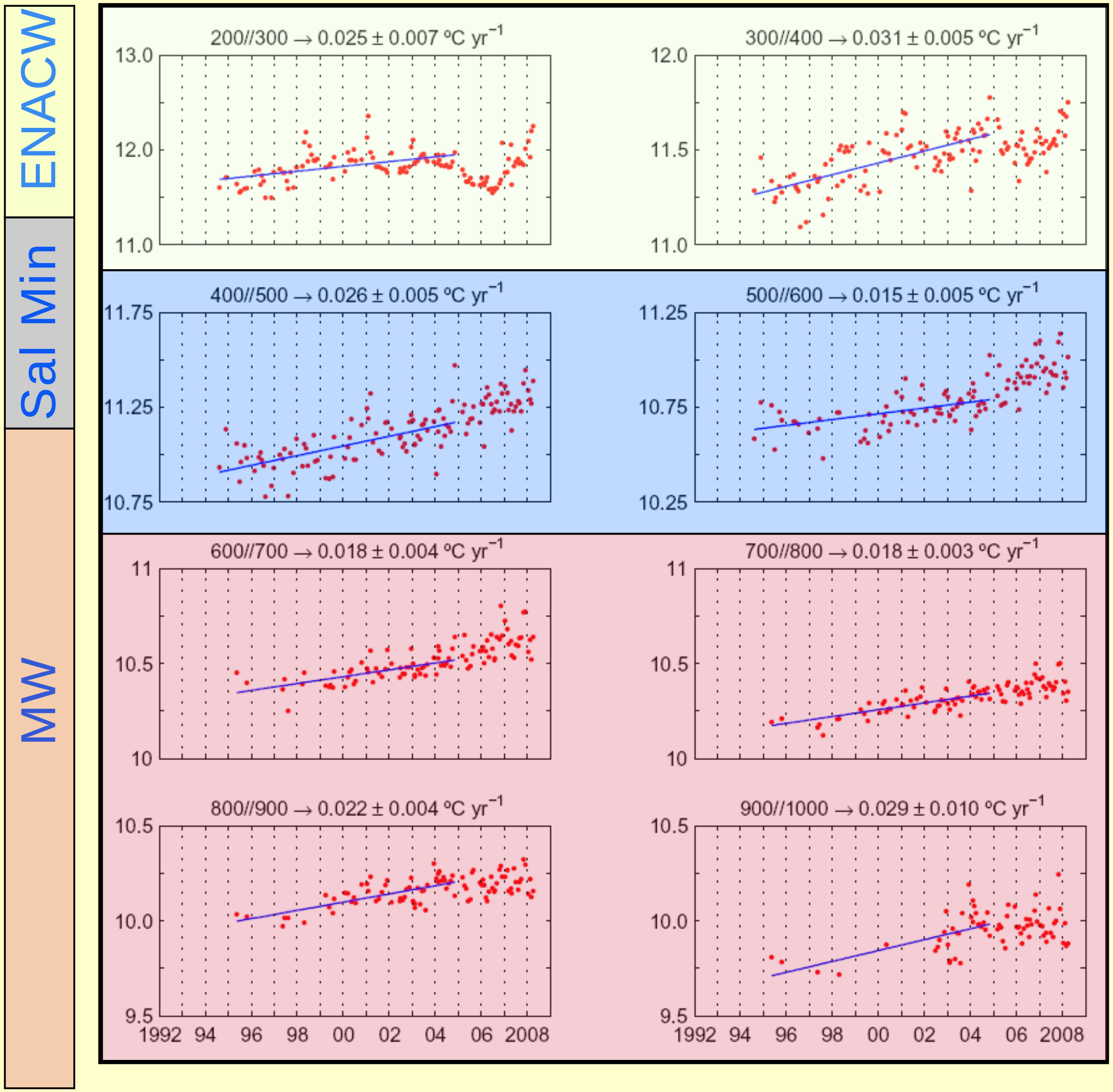
27.1//27.2 → -0.009 ± 0.004 °C yr^{-1}

27.2//27.3 → -0.000 ± 0.002 °C yr^{-1}

27.3//27.4 → 0.011 ± 0.001 °C yr^{-1}

27.4//27.5 → 0.019 ± 0.002 °C yr^{-1}

27.5//27.6 → 0.024 ± 0.003 °C yr^{-1}



ENACW

200//300 → 0.025 ± 0.007 °C yr^{-1}

300//400 → 0.031 ± 0.005 °C yr^{-1}

Sal Min

400//500 → 0.026 ± 0.005 °C yr^{-1}

500//600 → 0.015 ± 0.005 °C yr^{-1}

MW

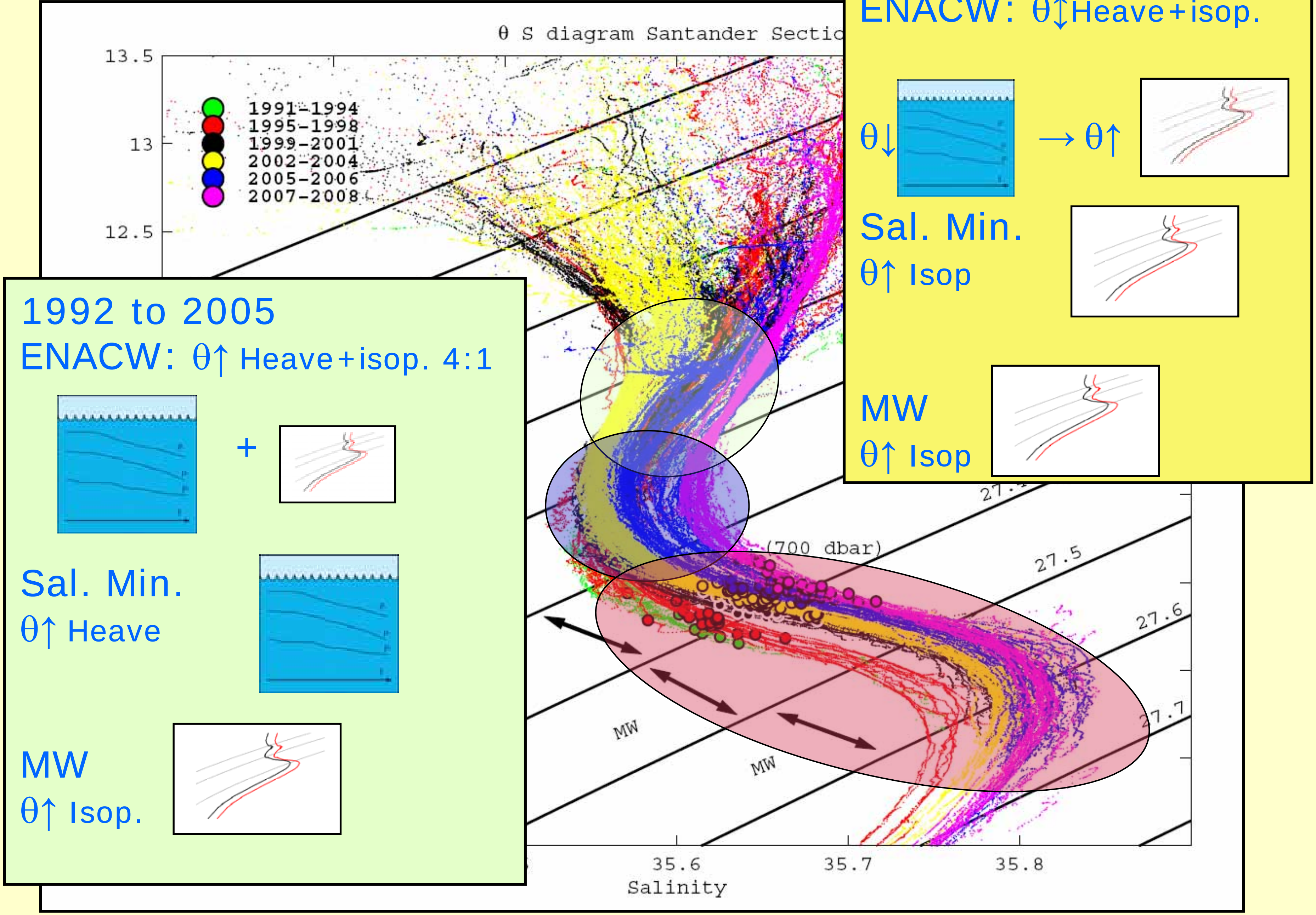
600//700 → 0.018 ± 0.004 °C yr^{-1}

700//800 → 0.018 ± 0.003 °C yr^{-1}

800//900 → 0.022 ± 0.004 °C yr^{-1}

900//1000 → 0.029 ± 0.010 °C yr^{-1}

Overall View, θS temporal evolution



1992 to 2005

ENACW: θ↑ Heave+isop. 4:1

+

Sal. Min.

θ↑ Heave

MW

θ↑ Isop.

2005 onwards

ENACW: θ↕Heave+isop.

θ↓ → θ↑

Sal. Min.

θ↑ Isop

MW

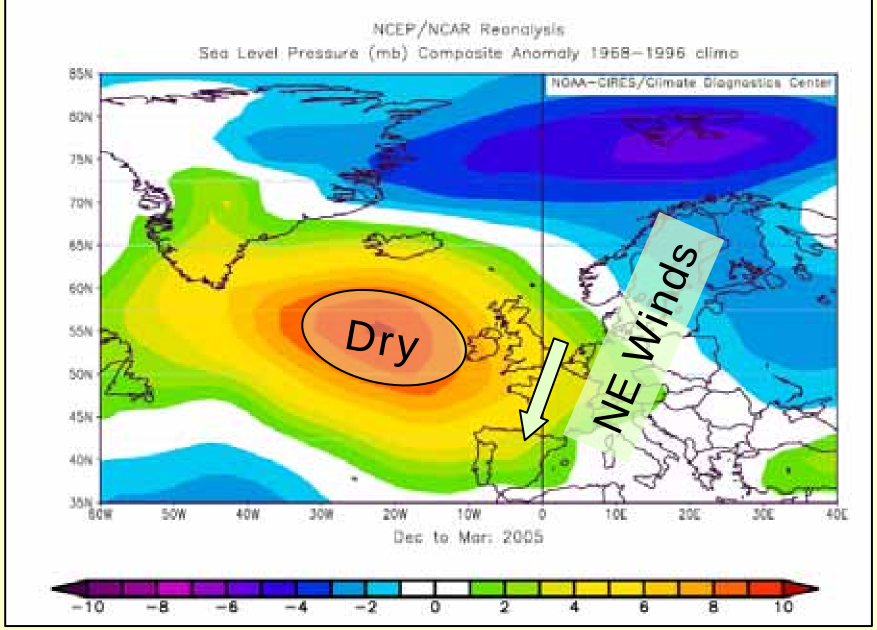
θ↑ Isop

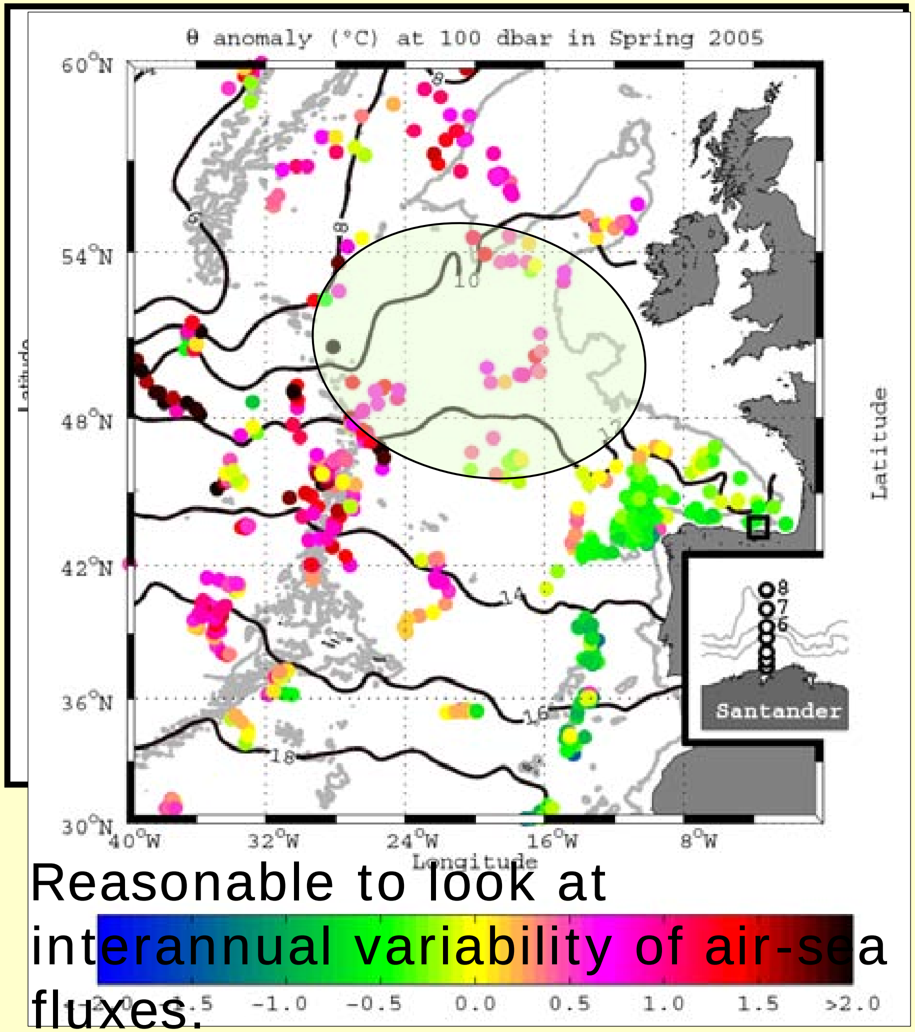
Interpretation of the changes. ENACW & Sal. Min.

Winter 2005 anomalous atmospheric pattern

ENACW is modal water formed by local winter deep convection.

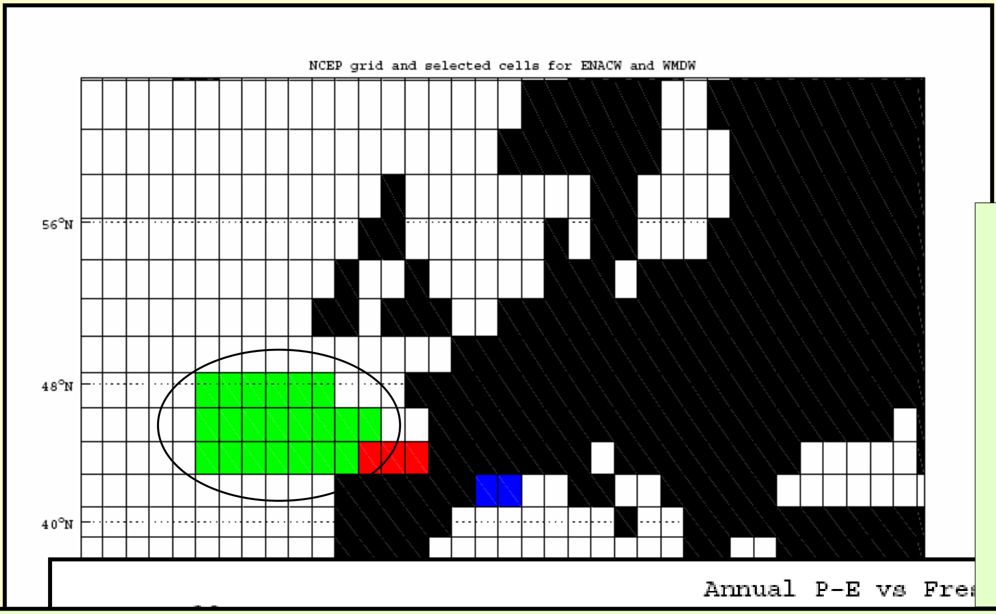
NCEP/NCAR Reanalysis Sea Level Pressure (mb) anomaly. Dec04-March05.





Reasonable to look at interannual variability of air-sea fluxes.

Interpretation of the changes. ENACW & Sal. Min.



Cells for air-sea fluxes calc.
NCEP/NCAR Reanalysis
`http://www.cdc.noaa.gov`

Winter [and yearly] air temperature always above average since early 90’s.

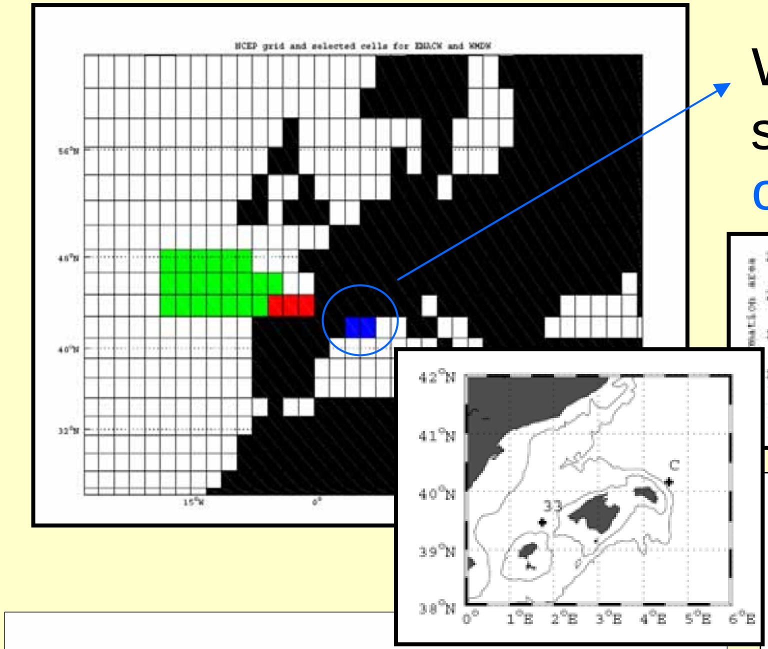
No trend in air-sea heat exchange.

From early 90’s to 2004:
ENACW modal water progressively more lighter (warm) 27.2 ⇨ 27.1

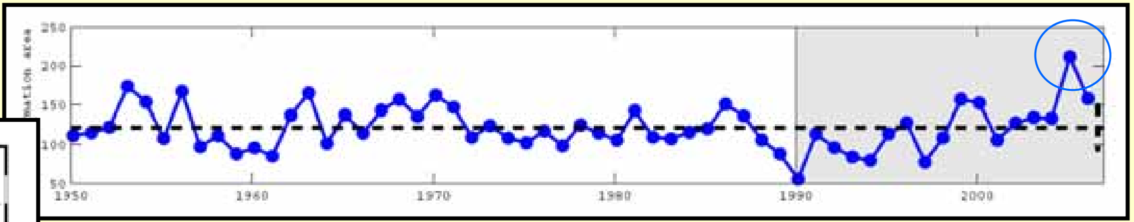
In 2005:
Local high heat loss + strong precipitation deficit. 27.1 ⇨ 27.2++ (warmer+saltier).

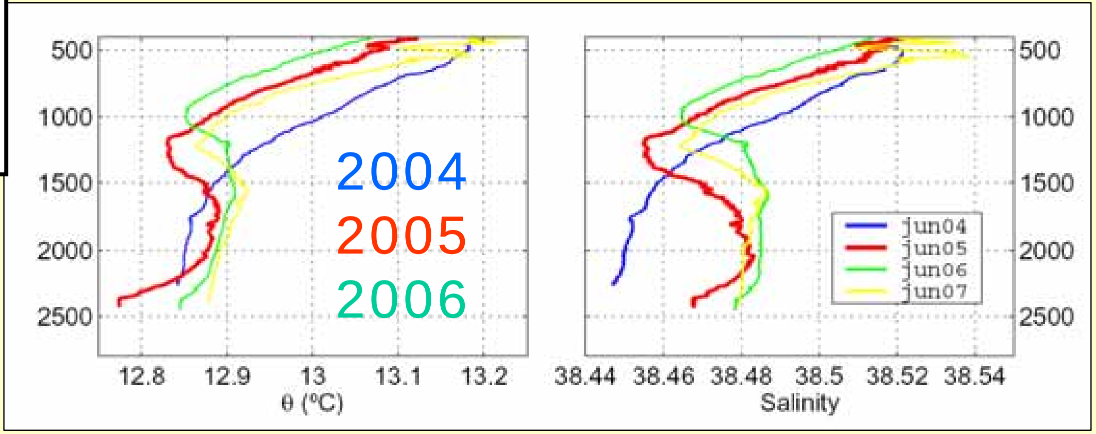
An isolated cooling + mixing event after years of heave transmitted downwards the warm anomaly (as isopycnal warming, i.e. within salt-increase).

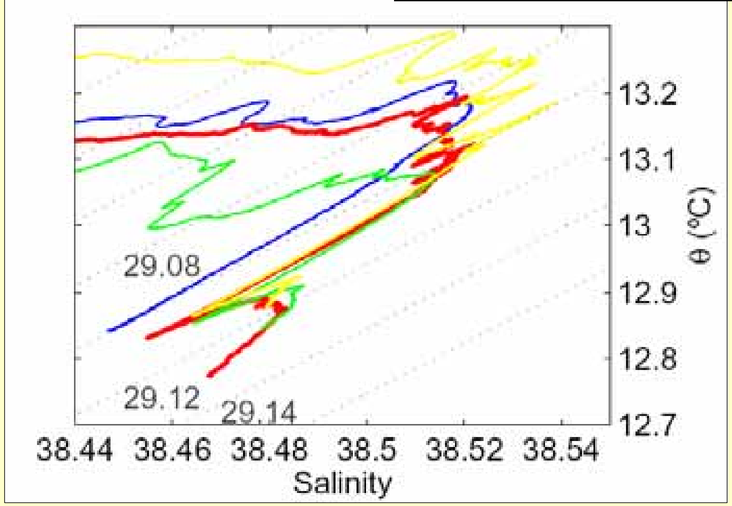
Western Mediterranean deep water formation: Parallelism.



Western Mediterranean (Deep Water source). Highest heat flux loss anomaly on record (Lopez-Jurado et. al. 2005).



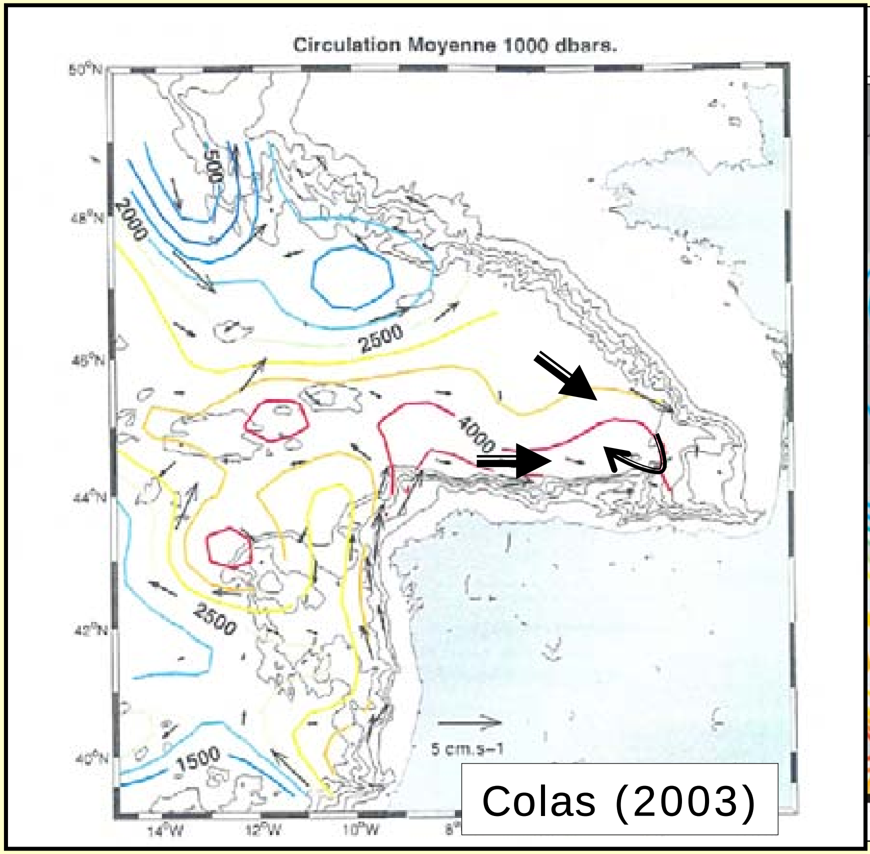




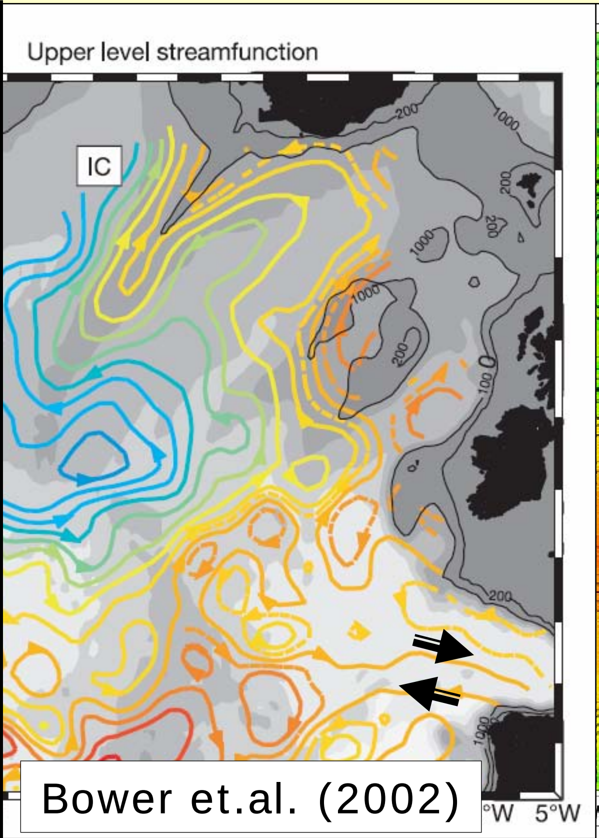
An isolated cooling + mixing event (deep water formation event) after years of sustained warming and salt-increase transmitted downwards the warm anomaly.

Tracking climatic signals at MW in the Bay of Biscay?

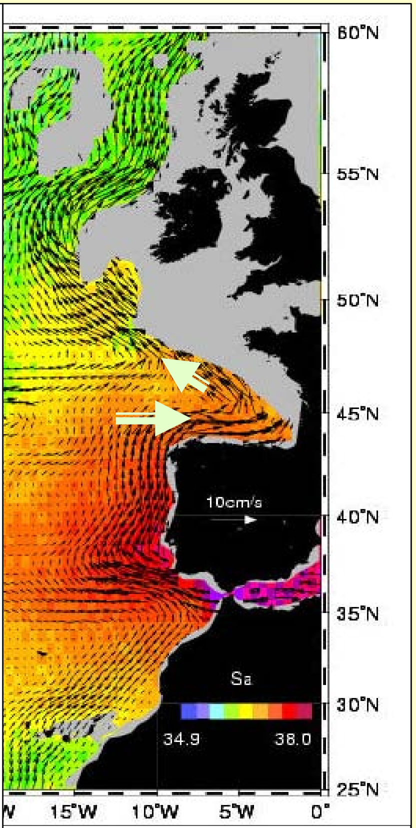
- MW have a clear pathway until the Galician Bank and less clear into the Bay of Biscay. MW at Biscay could take 15-25 months to reach Santander directly from the MW source, or could mainly come from the main reservoir.



Colas (2003)



Bower et.al. (2002)



Iorga & Lozier (1999)

Tracking climatic signals at MW in the Bay of Biscay?

➢MW have a clear pathway until the Galician Bank and less clear into the Bay of Biscay. MW at Biscay could take 15-25 months to reach Santander directly from the MW source, or could mainly come from the main reservoir.

➢MW changes during 90`s until 2005 did not come from mixing from above (i.e were advected).

➢MW forms at the Gulf of Cadiz (MOW+ENACW, 1:3, Baringer & Price 1997). Santander MW core contains about 40% of original.

➢90's to 2004 (at least) MOW warmed continuously (Millot et.al 2006), as ENACW did.

➢2005 onwards, MOW cooled (Lafuente et. al. 2007). Upper ENACW cooled while core and lower ENACW warmed (Santander results).

… suggest that the 2005 cooling event may have produced a signature at Santander MW.

Tracking climatic signals at MW in the Bay of Biscay?

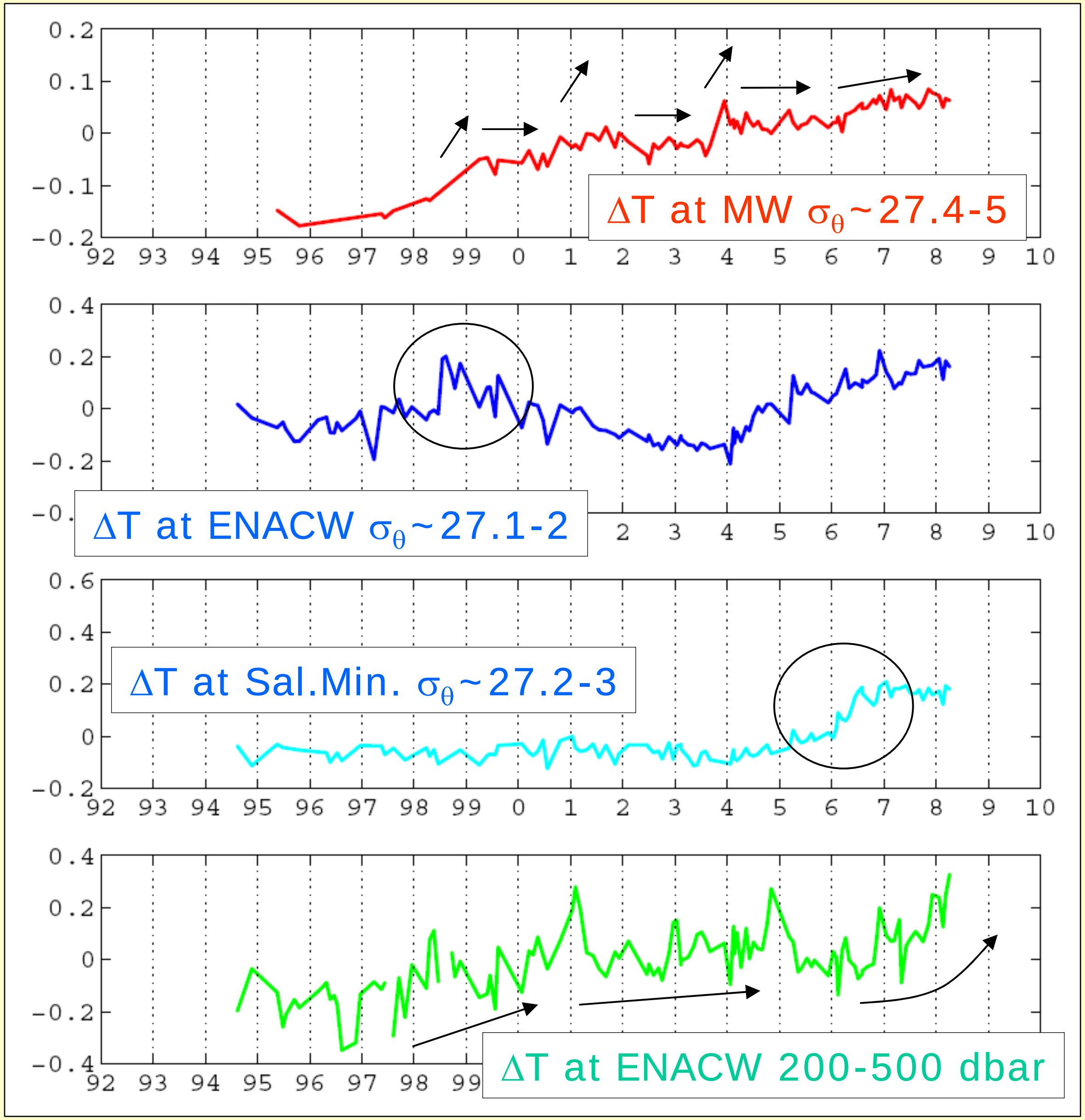
No signs of cooling at MW until 2008.

Warming at MW evolves as plateaus and steps not clearly correlated to shifts in Central Waters.

MW warming as:

a) The smoothed outcome of the continuous overall warming of its constituents.

b) The overall large-scale MW warming at the Eastern Atlantic reservoir.



Conclusions

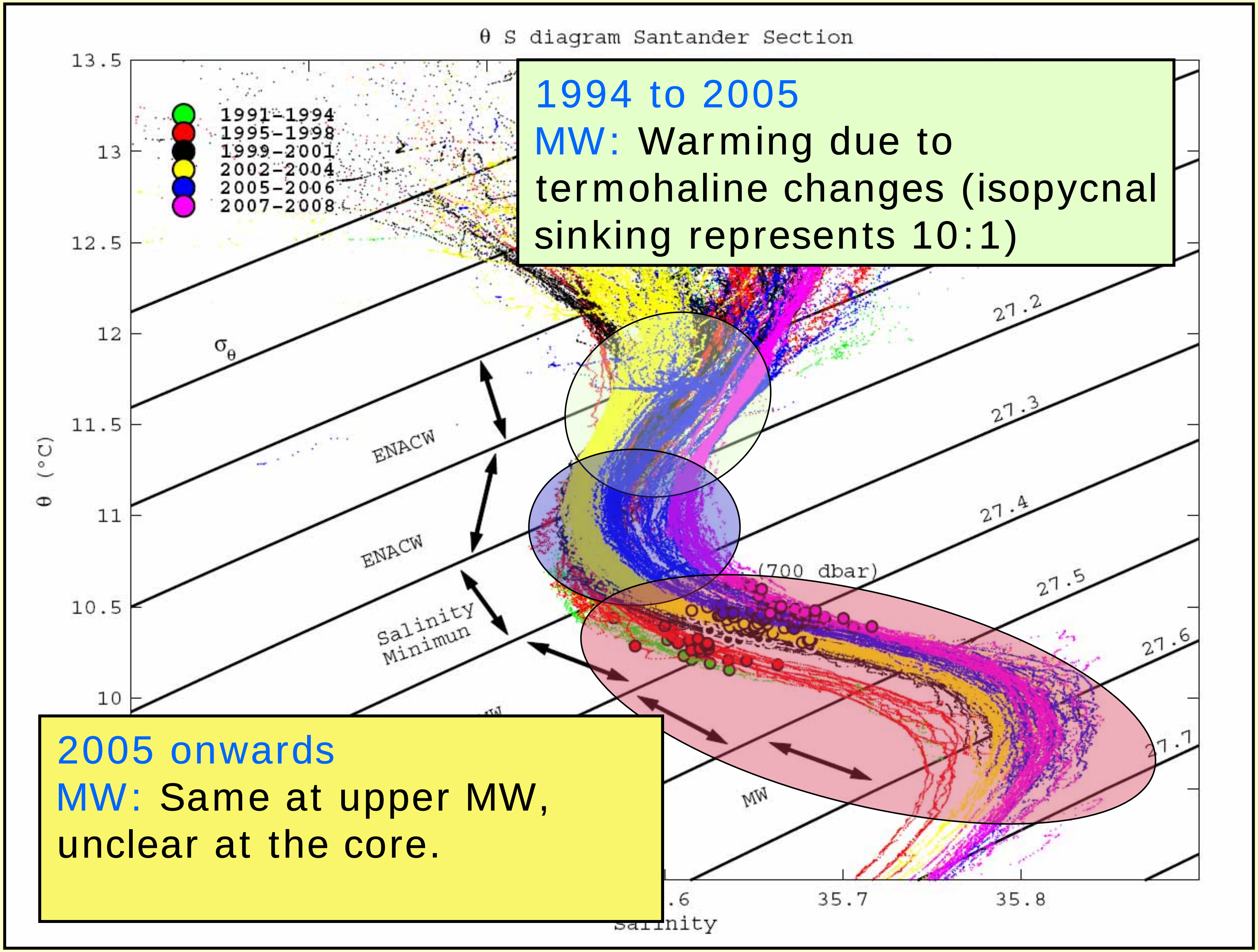
- Central waters down to 1000 m in the southern Bay of Biscay have suffered strong and progressive modifications from early 90’s, with the effect of a generalized warming at all levels at rates from 0.015 ºC yr^{-1} to 0.030ºC yr^{-1}.

- Central waters variability are well correlated with local air-sea fluxes. (We could blame global warming for this ‘local warming’ as far as we blame global warming for decades of high temperatures).

- Winter 2005 provided a strong local cooling. The effect was the isopycnal warming of deep levels fairly stable until then (at most warming by heave). Western Mediterranean experimented something similar.

- MW at the Bay of Biscay continues a progressive warming and salinity increase (density compensating) without a tight response to short-term climatic signals.

Overall View



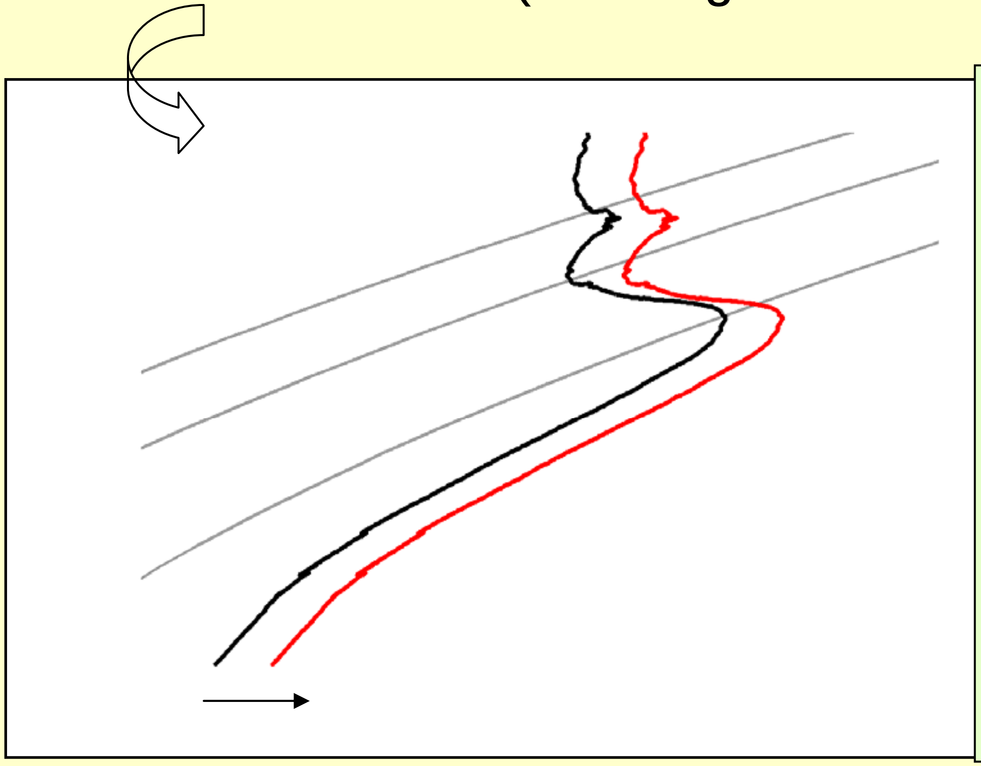
1994 to 2005
MW: Warming due to termohaline changes (isopycnal sinking represents 10:1)

2005 onwards
MW: Same at upper MW, unclear at the core.

Quantifying water masses changes

Water masses analysis: Two natural components:

1. Effective modification of the thermohaline structure of the water masses (θS diagram alteration).



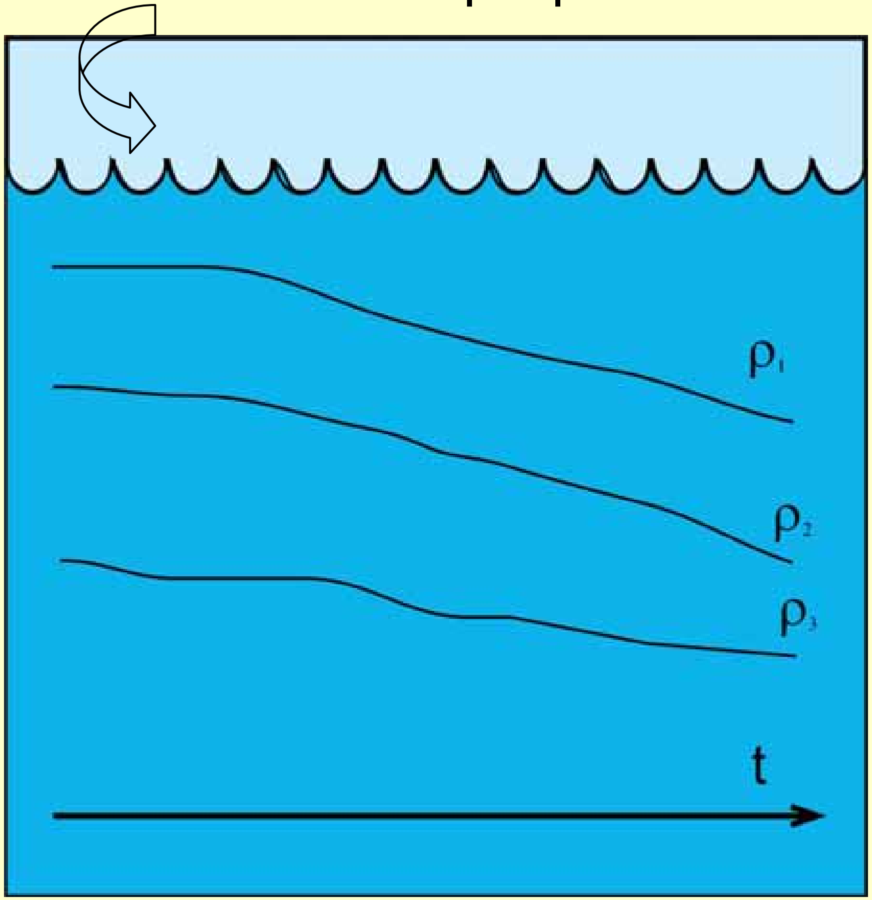
Related to heat and freshwater fluxes at the formation areas.

water formed is ‘different’

Quantifying water masses changes

Water masses analysis: Two natural components:

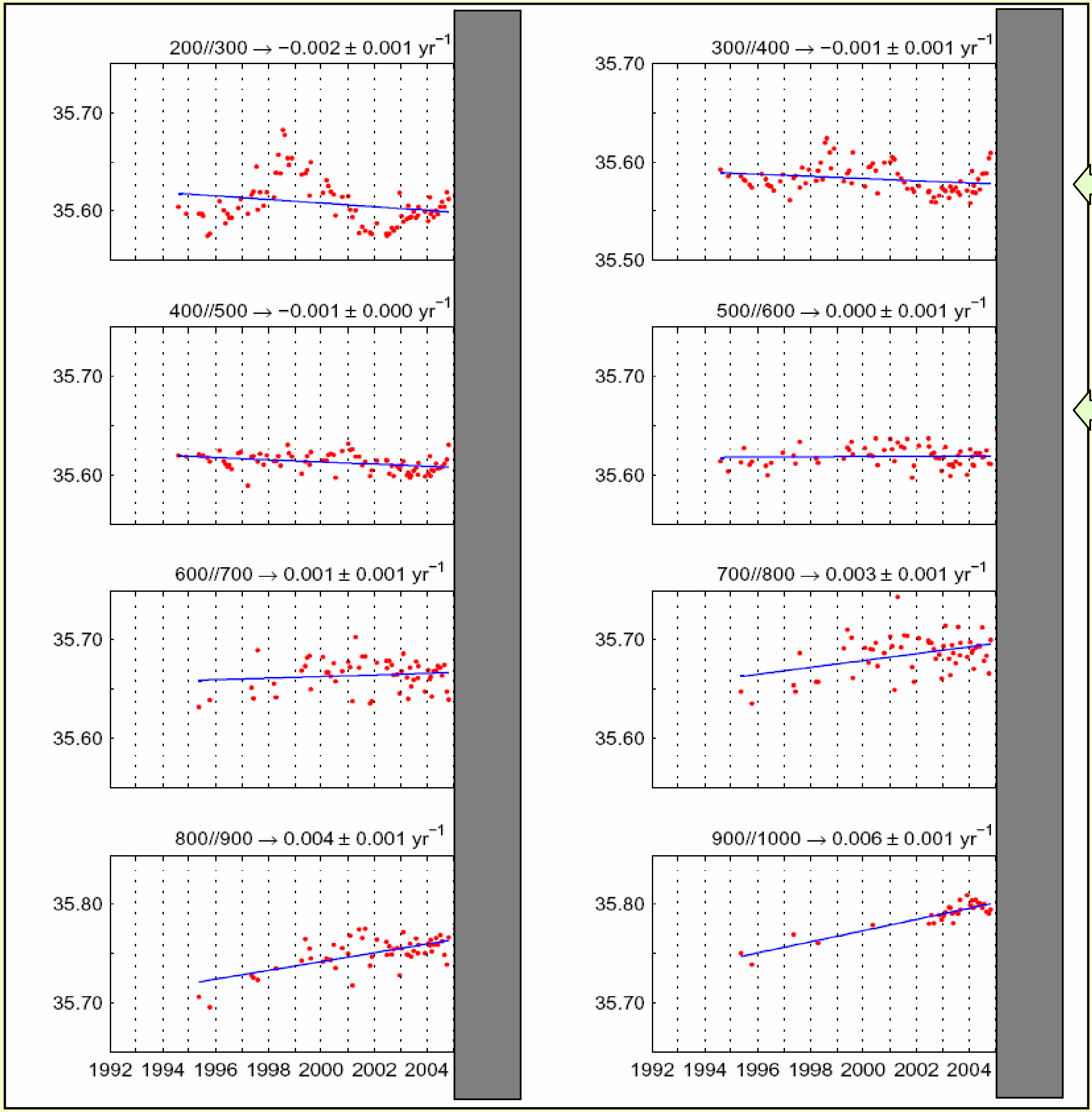
2. Vertical displacement of isopycnal levels without changes in water masses properties.



Related to variations in renewal rates or circulation changes.

‘Same water types’ but different proportions.

Salinity between isobars (st7)



200//400 ⇨ Strong interannual variability

400//600 ⇨ No salinity change

Salinity increase below 400 dbar (first time observed)

600//1000 Progressive increase