# Sea level changes in marginal seas: The Mediterranean as an example

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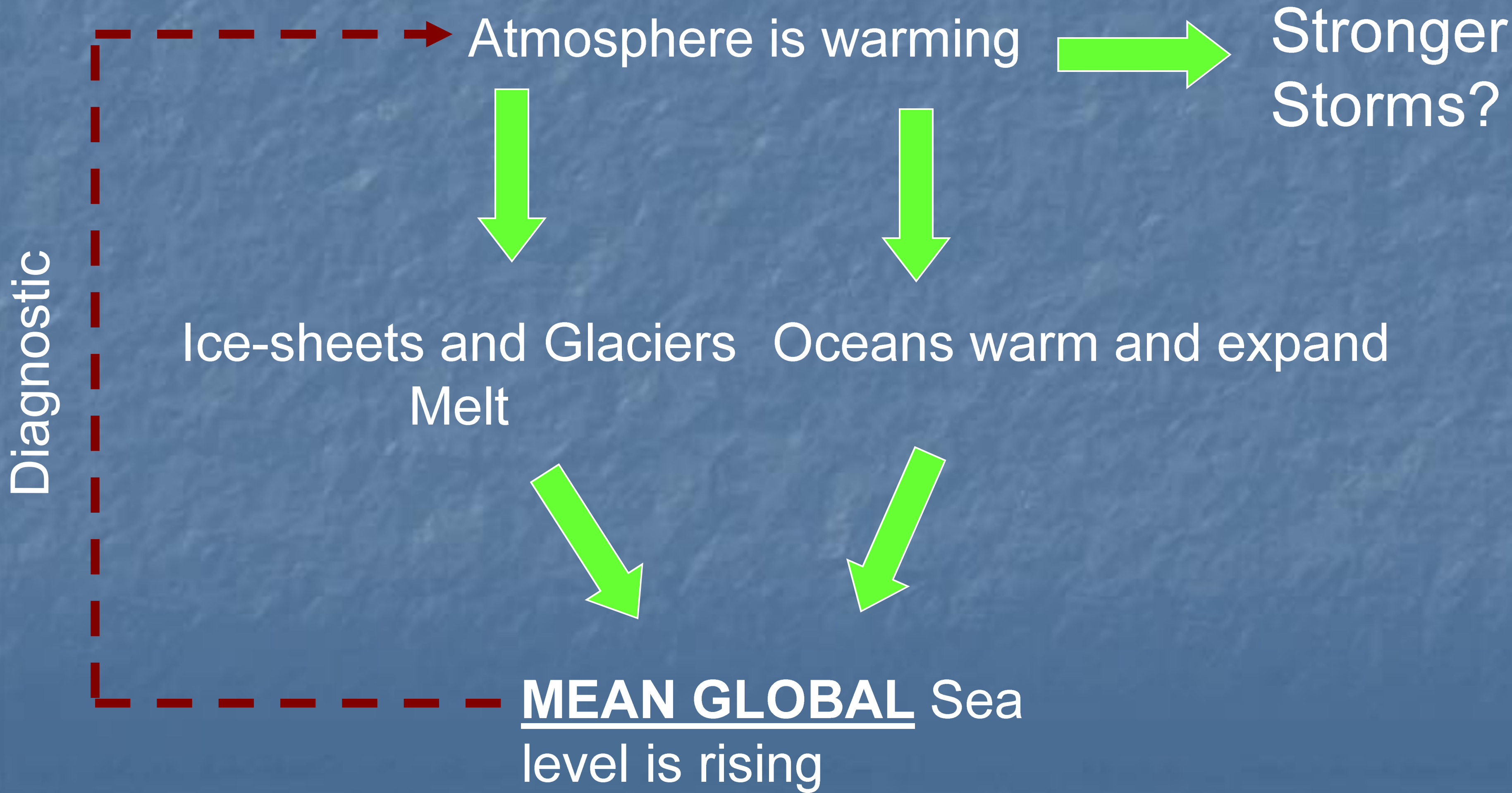
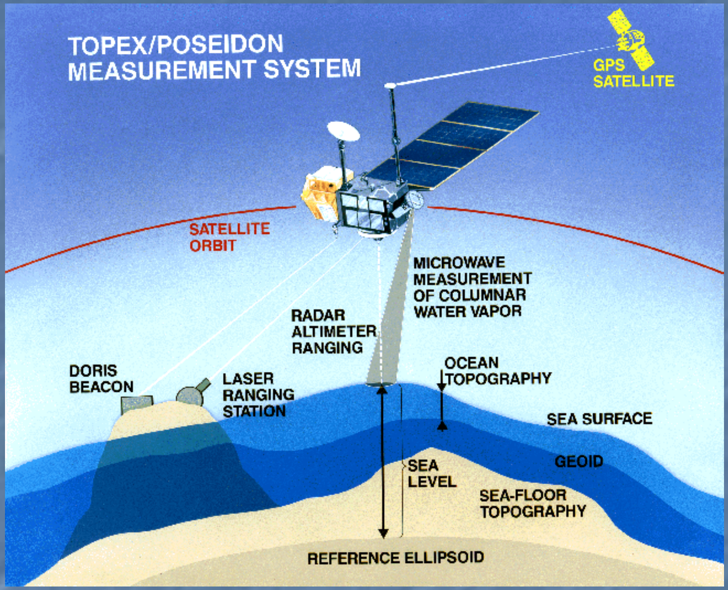
# Why is sea level change important?

- A diagnostic of climate change
  - More appropriate globally
  - Regionally informative for mass addition
- Coastal impacts
  - Mean change
  - Inter-annual variability
  - Seasonality
  - Extremes
  - Tidal range

# Why is sea level rise important?



# How do we measure sea level?




## Satellite Altimetry

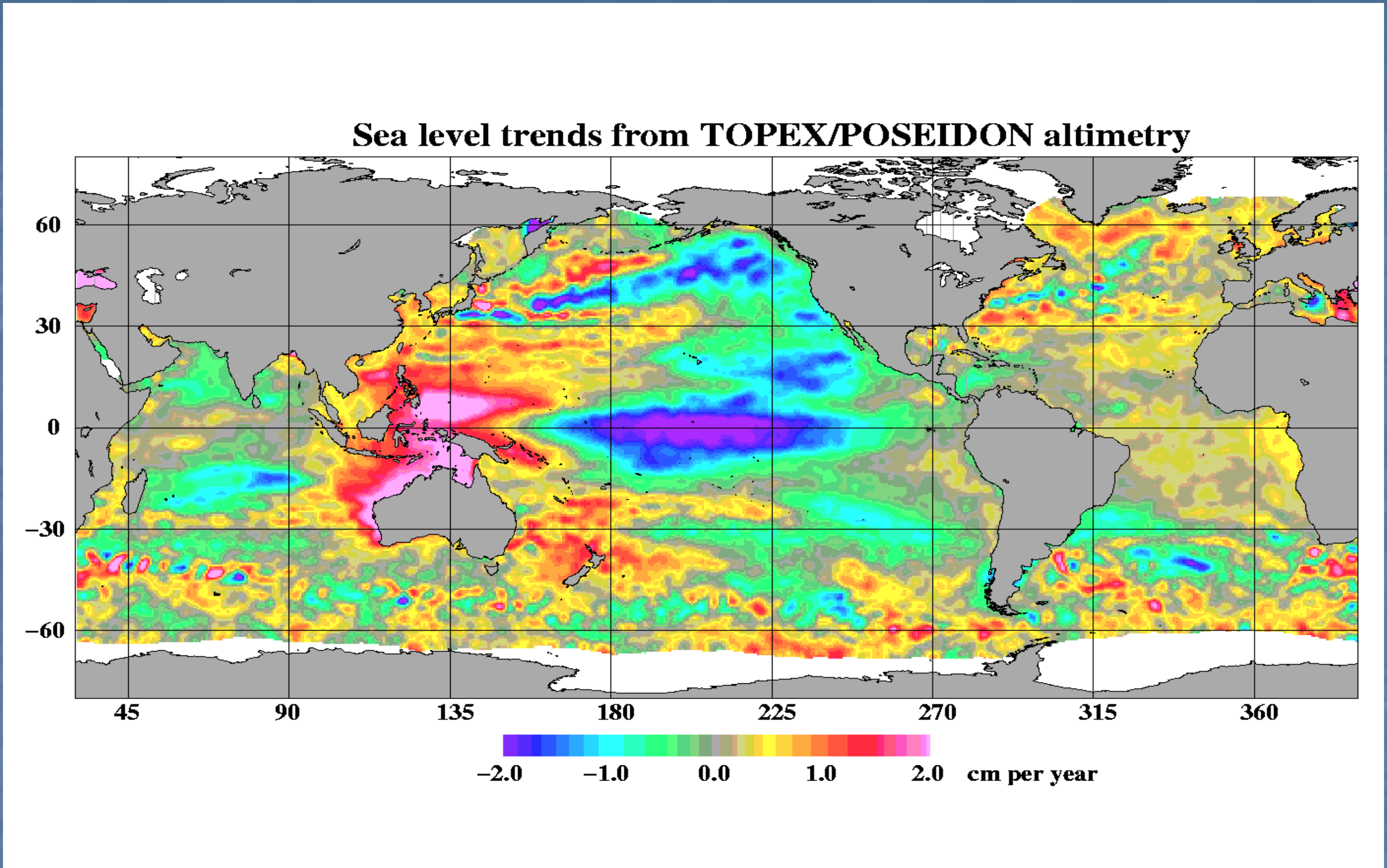
-since 1993
-nearly global
-doesn’t work near the coast

-3-8 cm  accuracy of measurement
-repeat measurement ~10 days or longer
-need of extensive corrections

## Tide - gauges

-since 1800
-point values
-coastal only
-accuracy ~ 1cm
-~min, typically 1hr values reported
-Corrections for land movements needed

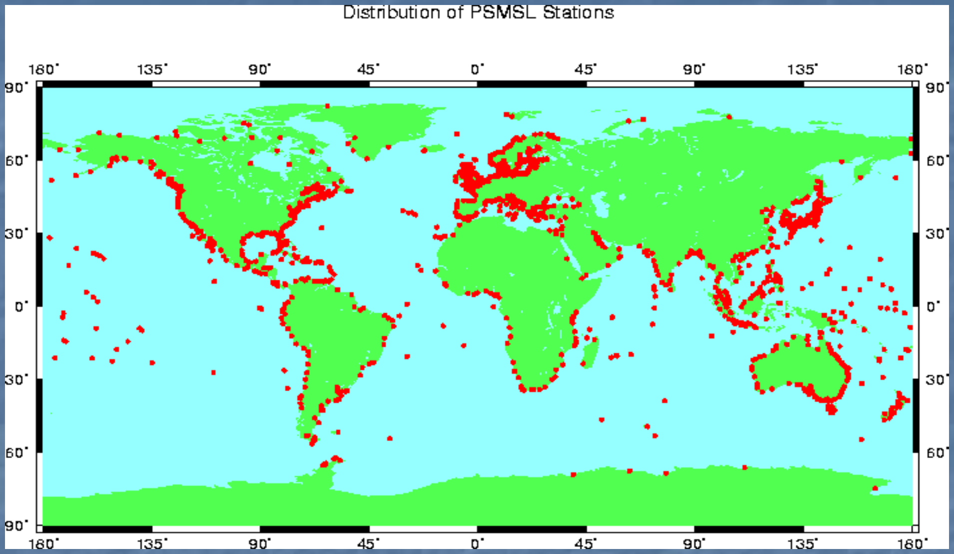
# Global Sea level rise: does it mean anything?

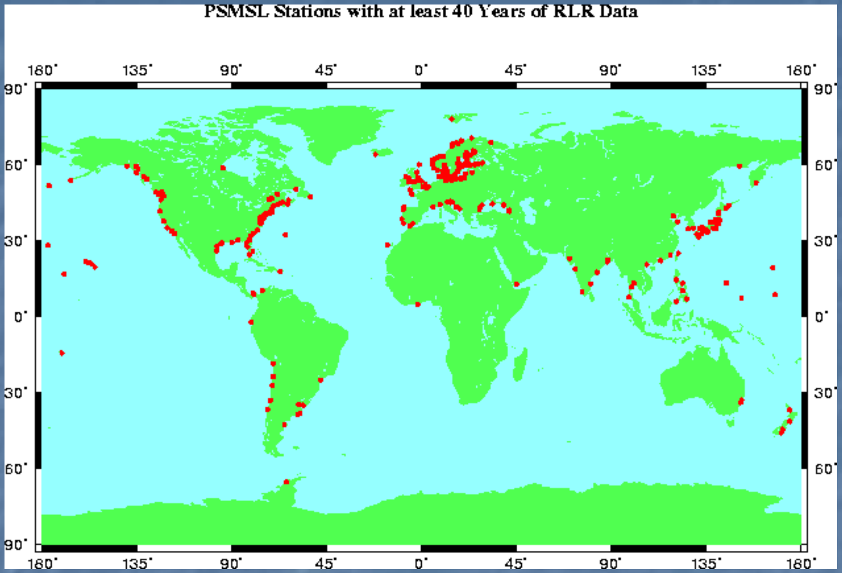



Global trend ~ 3.2 mm/yr (1993-2010)

"Local" trends in error by up to 2 mm/yr (estimated by comparison of missions)- EGU 2012

# Where do we measure sea level?




- Less than 10 tide-gauges longer than 120 years

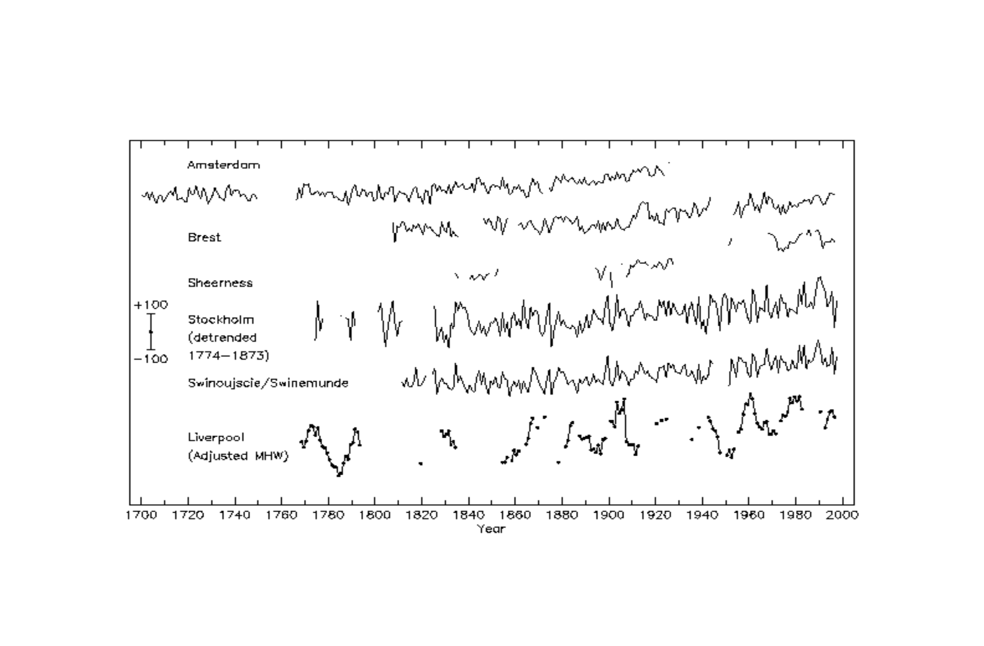
-around 170 longer than 40 years

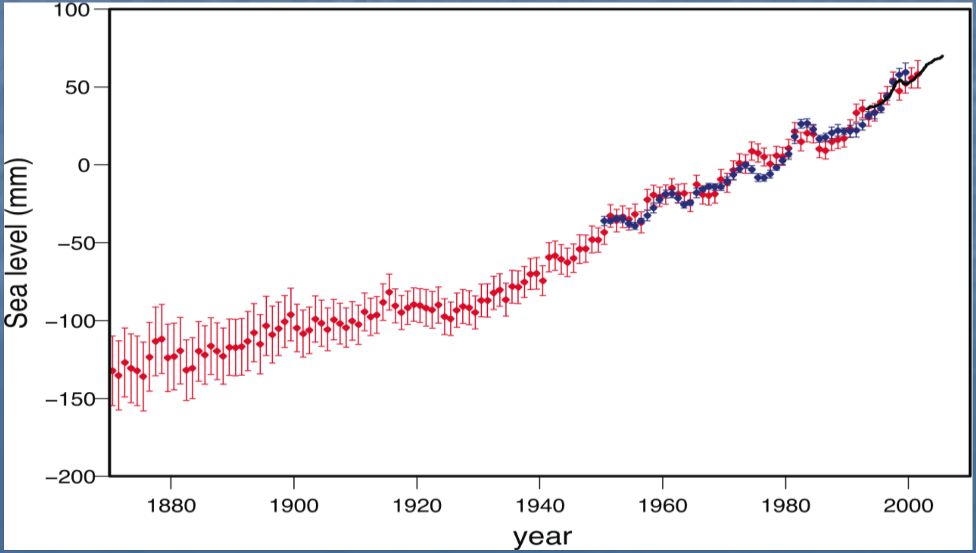
-around 280 good quality presently working (GLOSS)

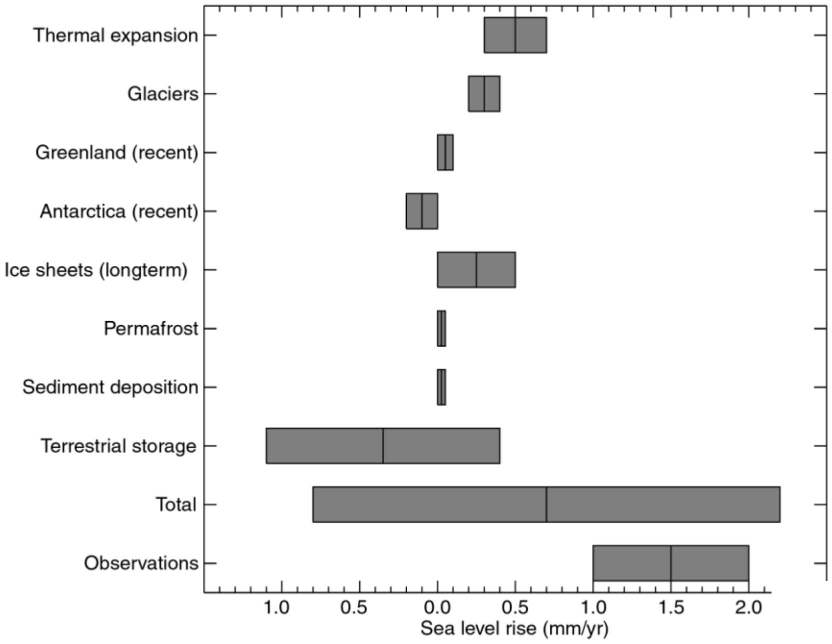
-around 1600 short records worldwide

# Is sea level accelerating?

- 6 of the longest sea level records from Northern Europe showing a small acceleration of sea level change into the 20th century
- 0.3 mm/yr/century






## Third Assessment : 1-2 mm/yr

## Fourth Assessment-

## Global value 1.8 ± 0.5 mm/yr

## 1990s 3.1 ± 0.8 mm/yr

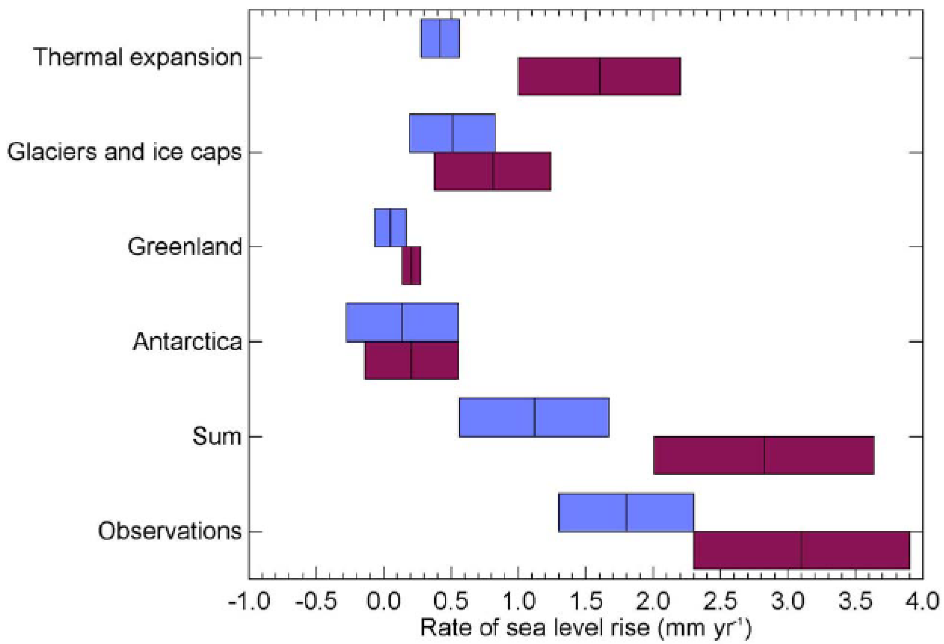
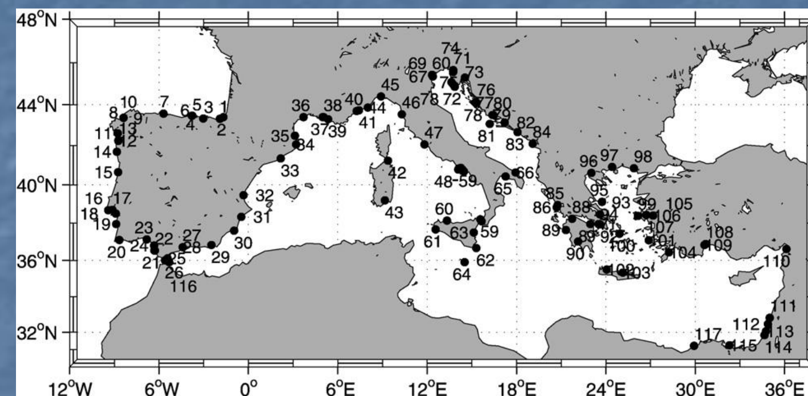



**Figure 5.5.9.** Estimates of the various contributions to the budget of the global mean sea level change compared with the observed rate of rise for 1961–2003 (blue) and 1993–2003 (red). The bars represent 95% errors. The errors of the separate terms have been combined in quadrature to obtain the error on their sum.

# Observational network

Fig. 1. Tide gauge records longer than 7 years available.



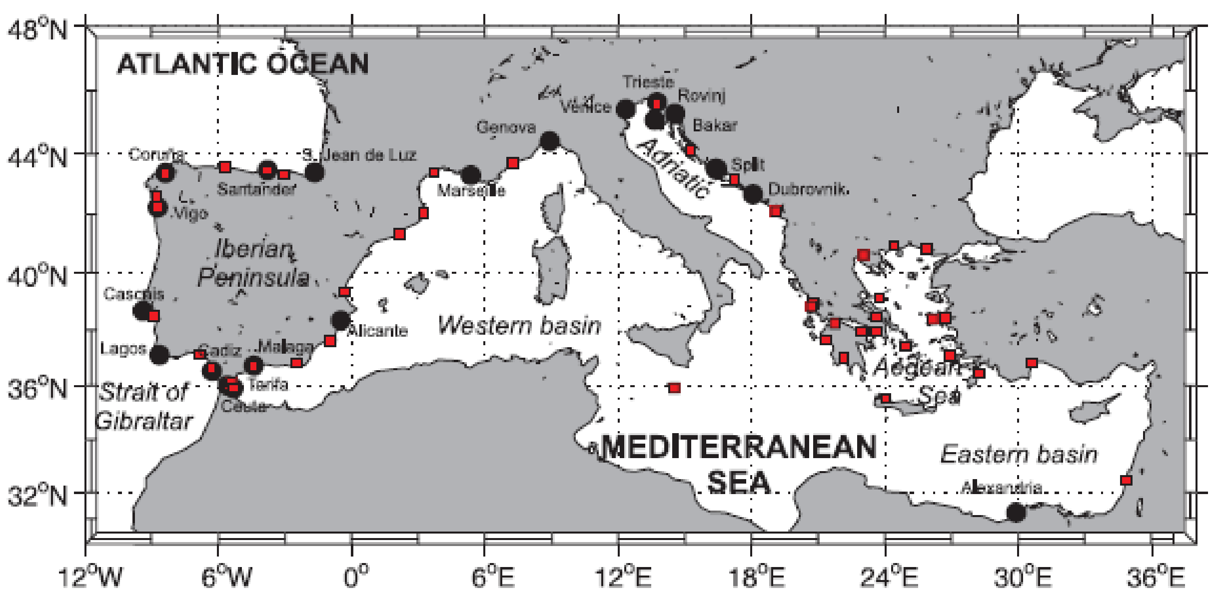




**Figure 1.** Location of the tide gauges. Black dots correspond to the longest time-series (>35 yr) which are labelled, while red squares are the shorter records

river runoff) affecting our estimation of steric signal.

It was hoped at the beginning of the study that the removal of the direct atmospheric forcing and the steric contribution from

operation and percentage of data gaps. Yearly time-series for these records are plotted in Figs 2(a)–(c), where nearby stations have been grouped into three different areas: Atlantic, Western Mediterranean

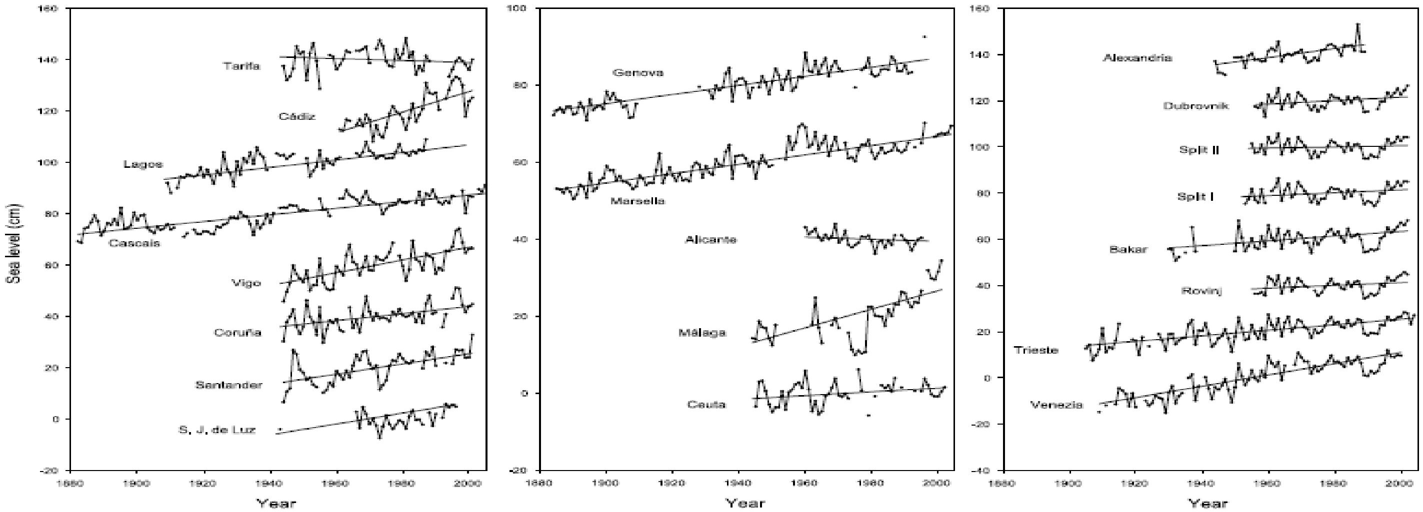
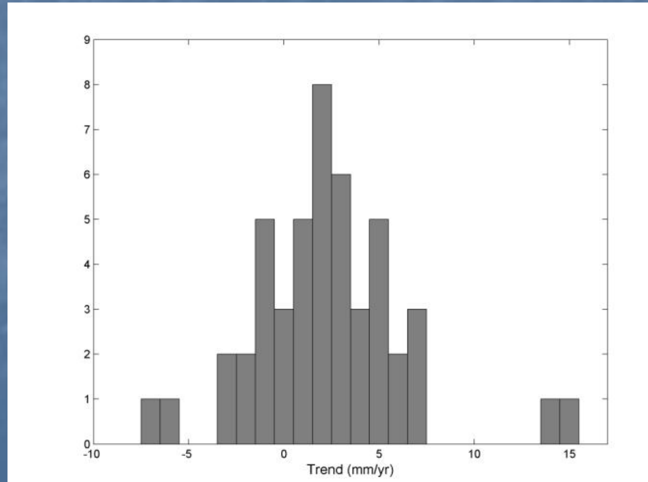



**Figure 2.** Yearly observations and linear sea level trends for the longest sea level records in Southern Europe. (a) Atlantic area and Gibraltar, (b) remaining stations in Gibraltar and Western Mediterranean and (c) Adriatic and Eastern Mediterranean.



# Trends for records shorter than 30 years



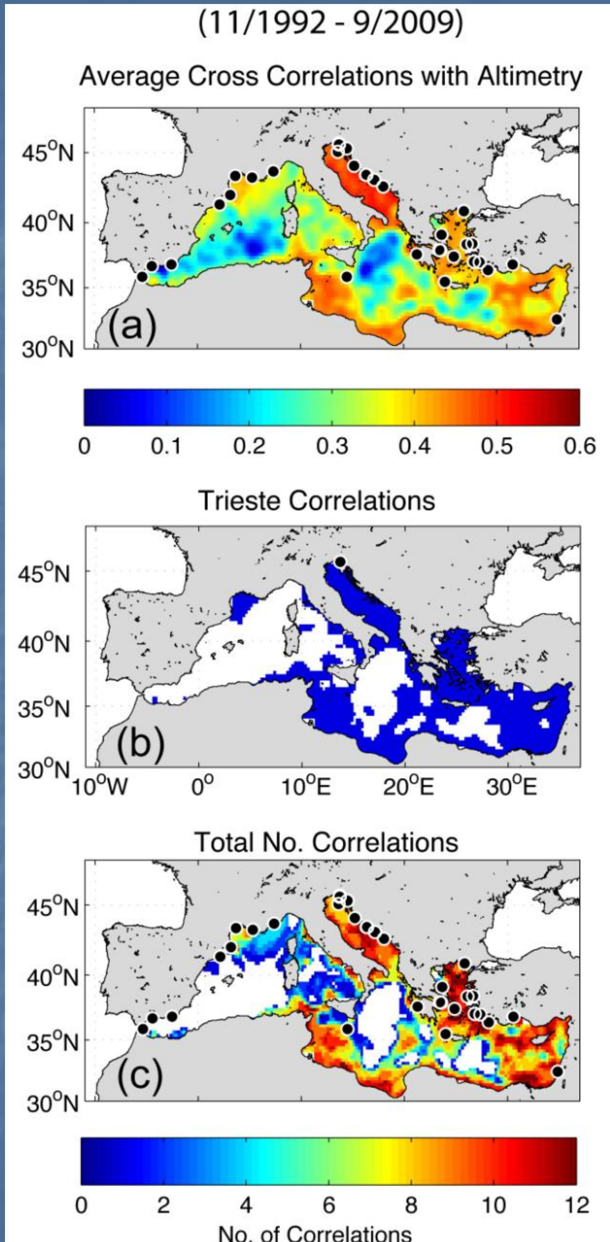
# Trends

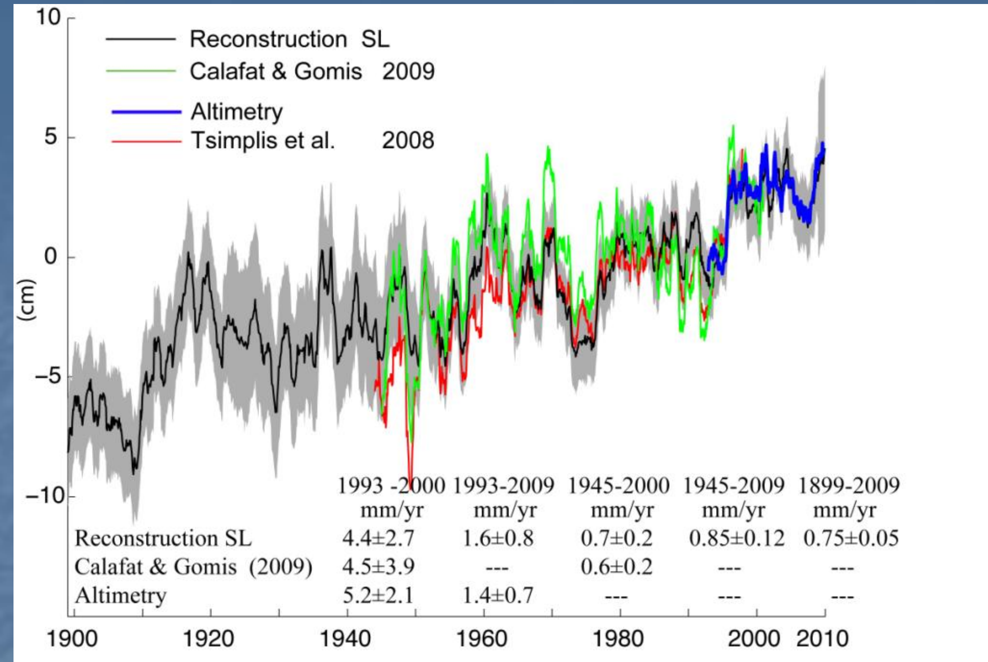
- 5 longest tide gauges(~100 yr)
  (+1.2) to (+1.5 mm/yr) (±0.1 mm/yr)
- 35 tide gauges longer than 35 yr
  (+0.3) to (-0.7) mm/yr (±0.4 mm/yr)
- altimetry
  1/1993-12/2011 3.0 ±0.5 mm/yr (0.1)

# Reconstruction

- EOFs of altimetry
- Rates of change from tide-gauges

- Important assumptions
  - EOFs are stable in time
  - Areas uncorrelated with tide-gauges have rates of changes (at least) comparable to tide-gauges




| | 1993 -2000 mm/yr | 1993-2009 mm/yr | 1945-2000 mm/yr | 1945-2009 mm/yr | 1899-2009 mm/yr |
|---|---|---|---|---|---|
| Reconstruction SL | 4.4±2.7 | 1.6±0.8 | 0.7±0.2 | 0.85±0.12 | 0.75±0.05 |
| Calafat & Gomis (2009) | 4.5±3.9 | --- | 0.6±0.2 | --- | --- |
| Altimetry | 5.2±2.1 | 1.4±0.7 | --- | --- | --- |

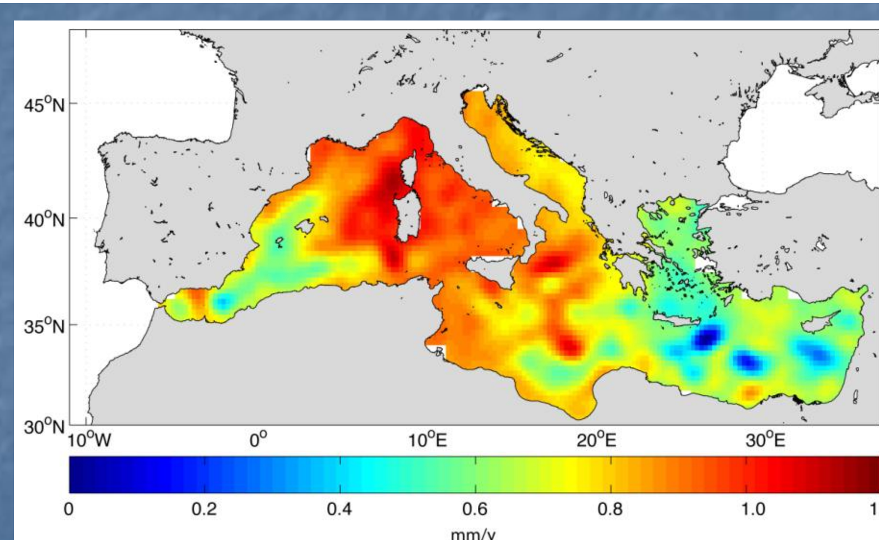



**Figure 8** Reconstructed Sea Level Trends using the first seven leading EOFs (1899 - 2009)

How can we have uncertainty of 0.1 mm/yr in a trend calculated on patters that have 3 mm/yr uncertainty?

# There is decadal variability in the trends

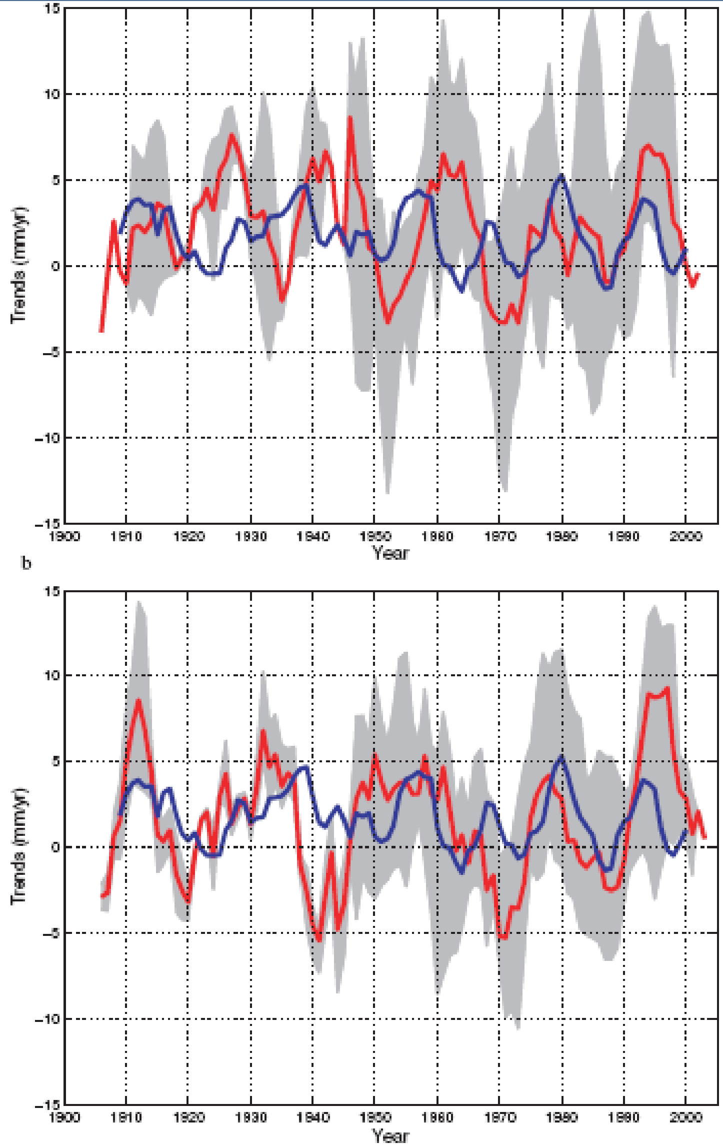



Figure 5. Decadal rates of observed sea level change, overlapped year to year, for the longest tide gauges separated in the Atlantic sites (a) and Mediterranean stations (b) (grey shadowed area). Red solid line represents the mean values and the global average derived by Holgate (2007) is also plotted as the blue line.

Marcos and Tsimplis (2008)

# Can we explain the observed trends?

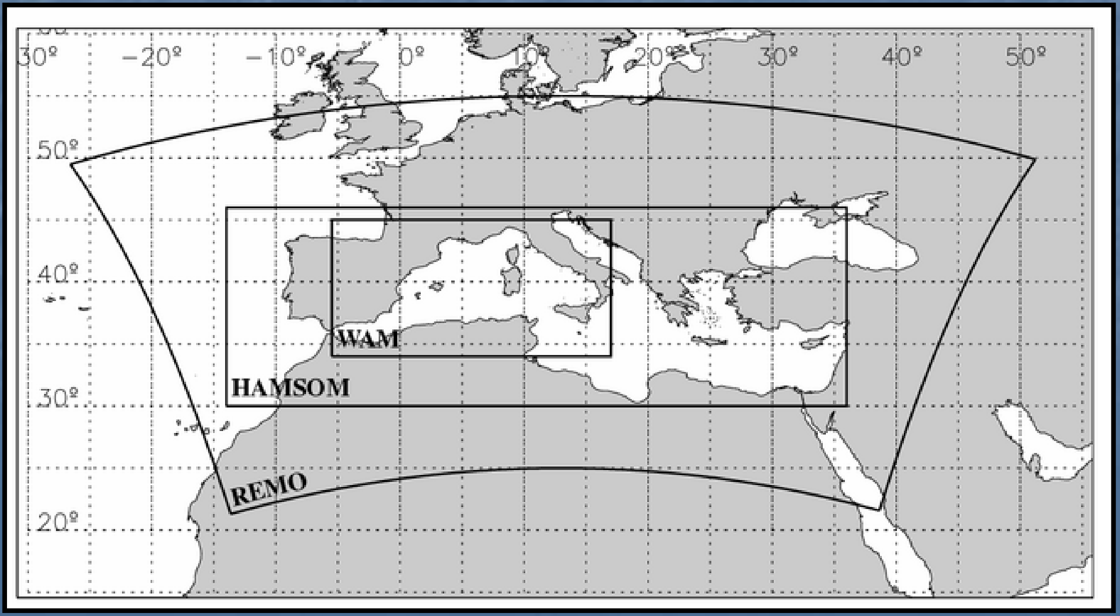
- Regional sea level = steric + atmospherically forced change + mass addition through Gibraltar + land movements (basin changes)
  - Steric – from T and S observations
  - Atmospherically forced – 2d models
  - Land movements
    - GIA
    - Subsidence
    - Water extraction
    - Tectonics
    - Dams?
- Importance of separating forcing

# Atmospheric pressure and wind

The barotropic model HAMSOM is the sea-level forecasting operational model of the Spanish harbour authority (*Puertos del Estado*).

The model was forced by a downscaling of atmospheric pressure and wind fields generated by the model REMO (from a NCEP re-analysis) in the framework of the HIPOCAS project.

The resulting 44 years (1958-1991) of atmospheric and sea level data constitute a homogeneous, high resolution data set.




Domain of models REMO, HAMSOM and WAM (the latter is a wave model not referred in this work).

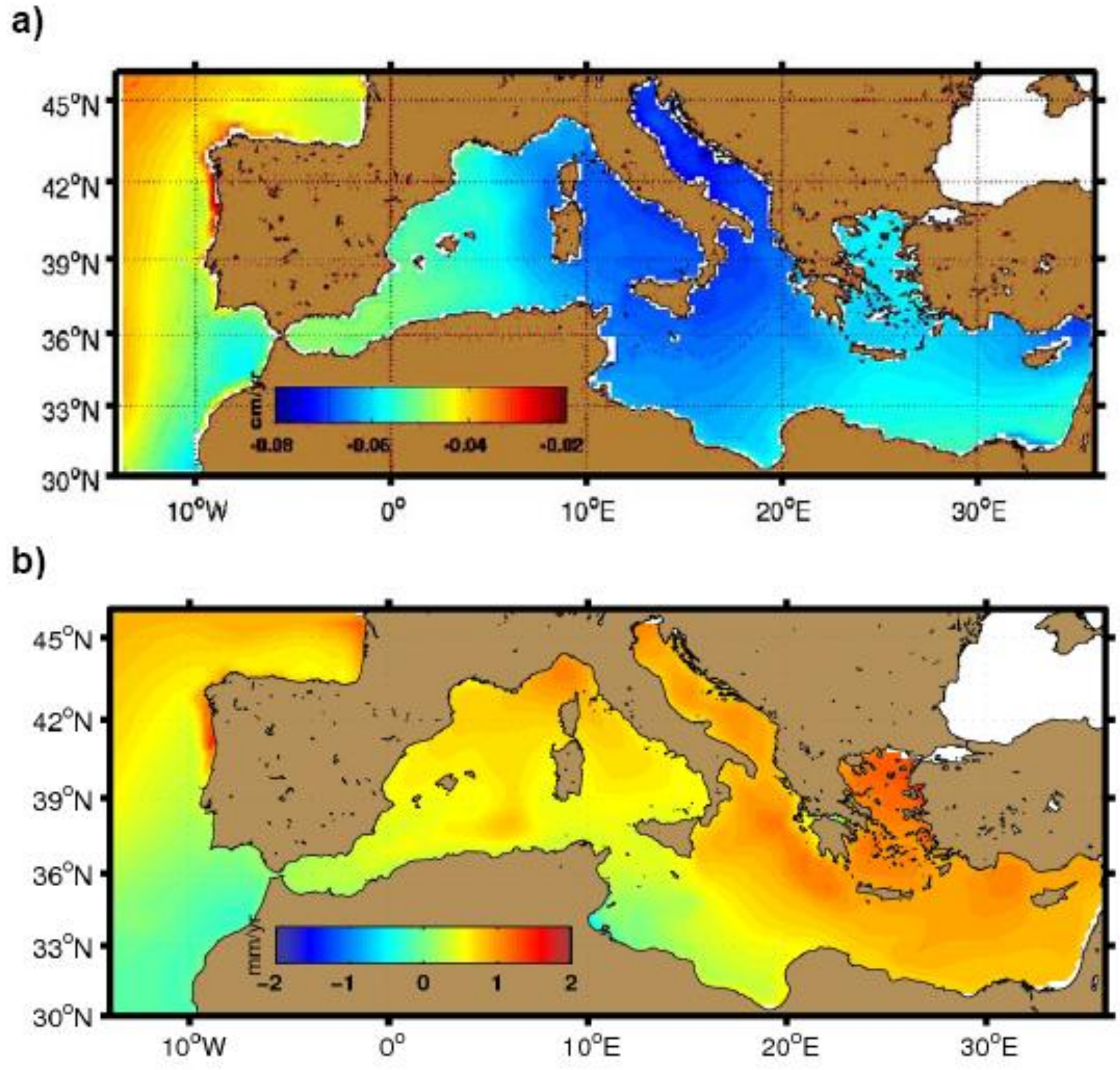



**Figure 7.1.** Spatial distribution of trends of the atmospheric contribution to sea level as obtained from HAMSOM outputs: (a) for the whole modeled period (1958-2001); (b) for the period (1993-2001). Note the different units: (a) cm/yr; (b) mm/yr. (from Gomis et al., 2008).

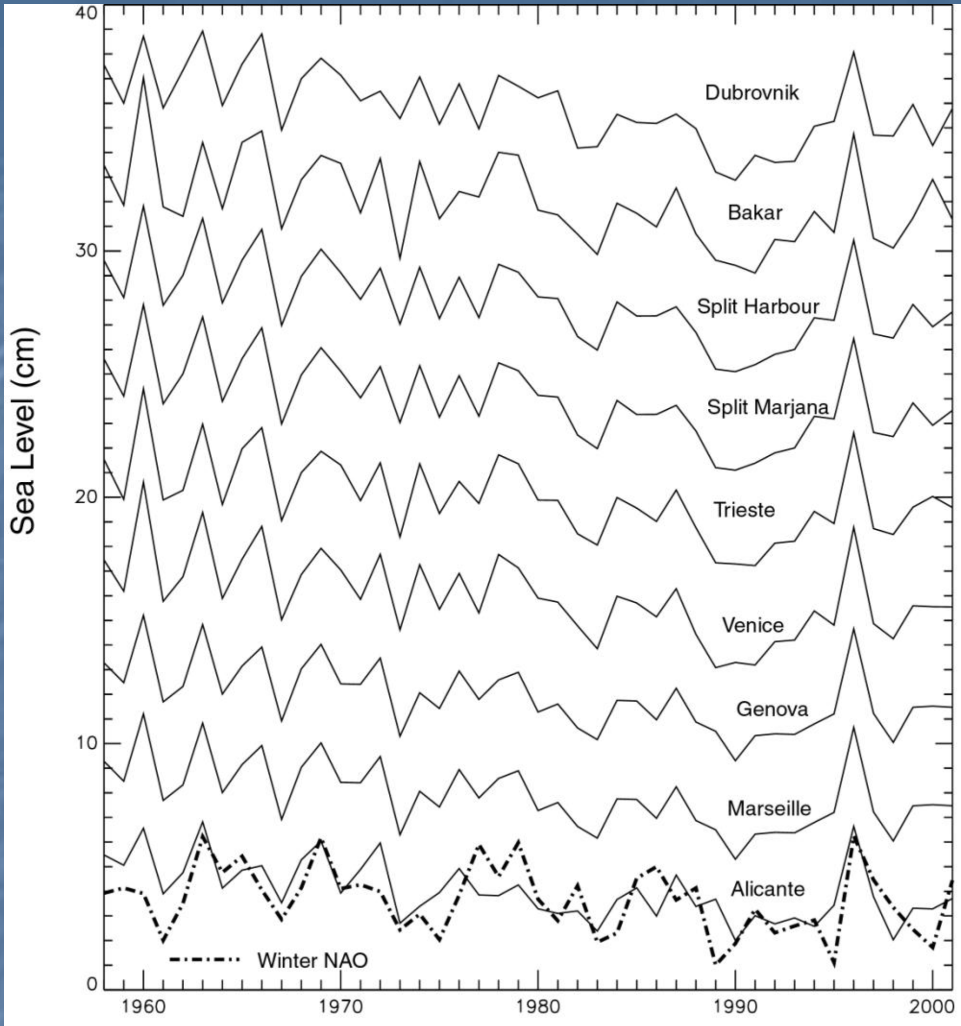



**Figure 3.** The mean annual sea level time series from the model at the points near the selected tide gauges. The winter (December-March) NAO is also shown as a dash-dotted line.

Modelled sea level at tide gauges from wind and pressure only

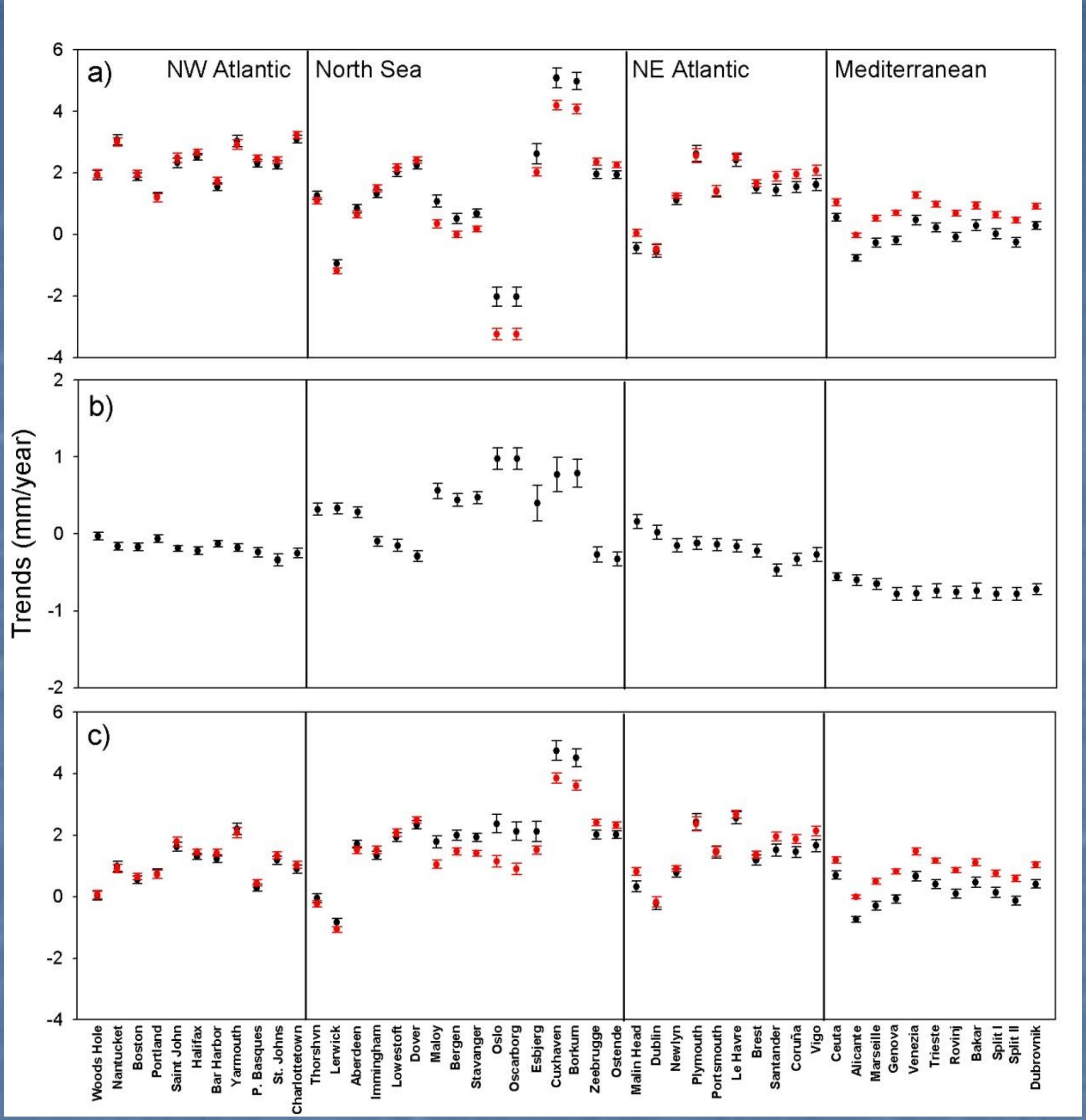
The WINTER NAO is also shown

Tsimplis et al., GRL,2005

Observations and corrected for P and wind values (red)

P and wind corrections

GIA corrected- ICE 4G




Marcos and Tsimplis,2007 (GRL)

# Best (?) guess

- Basin estimate 0.7 ± 0.3 mm/yr)
- Meteorological forcing  -0.7 ± 0.1 mm/yr
- Steric forcing 0.5 ± 0.4 mm/yr)
- Mass increase 1 mm/yr
  - Calafat and Gomis (2010)
  - In agreement with Marcos and Tsimplis (2007) and Tsimplis et al. (2009)

**Table 4**
Errors associated with the various parameters used. Steric and atmospheric errors are stated for records longer than 20 years.

| | Associated errors |
|---|---|
| GIA | ±0.5 mm/yr |
| Steric | ±1.0 mm/yr |
| Atmospheric | ±1.0 mm/yr |
| Sea level (proxies) | ±0.6 mm/yr |
| Sea level (TG) standard error | ±0.3 mm/yr |
| Sea level (TG) error related to the length of the record | ±0.7 mm/yr |

Tsimplis et al. (2011)

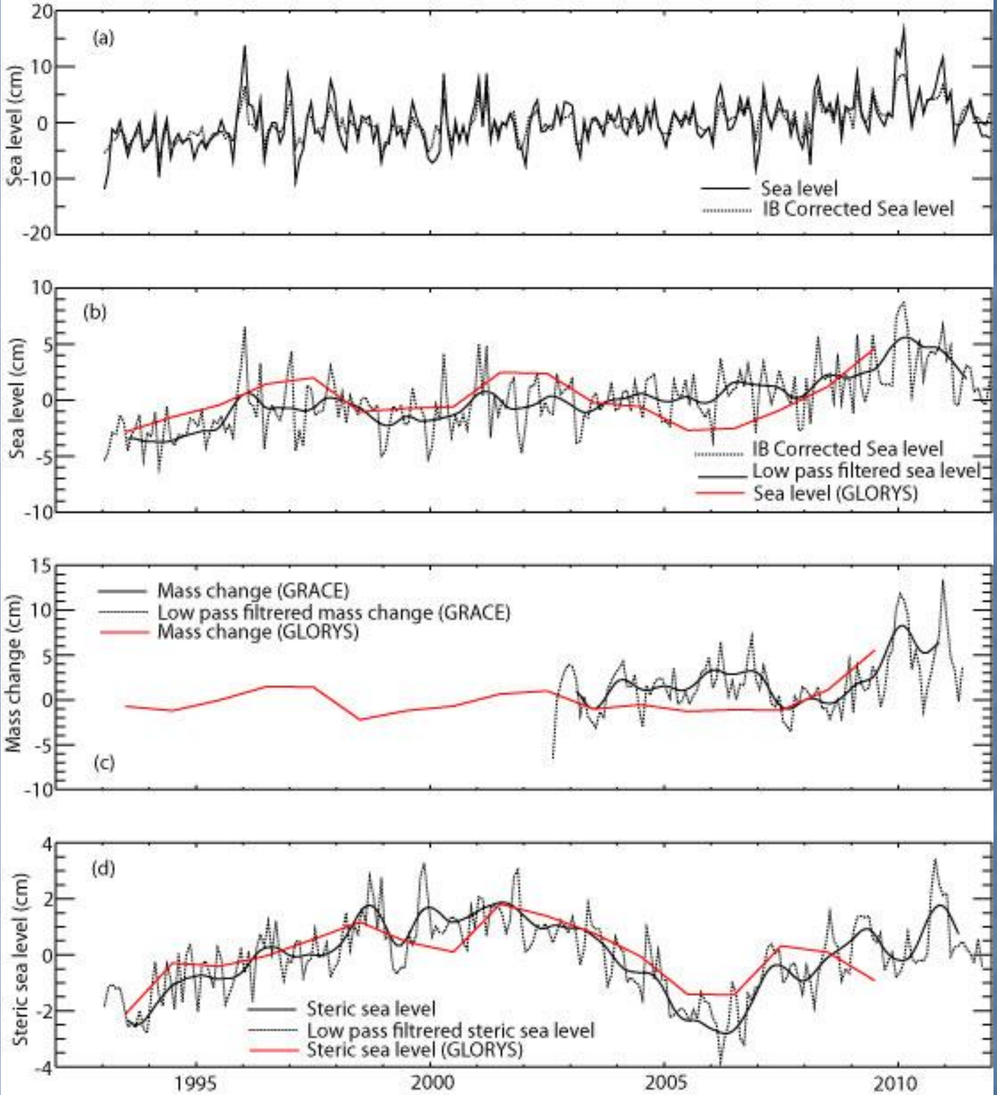
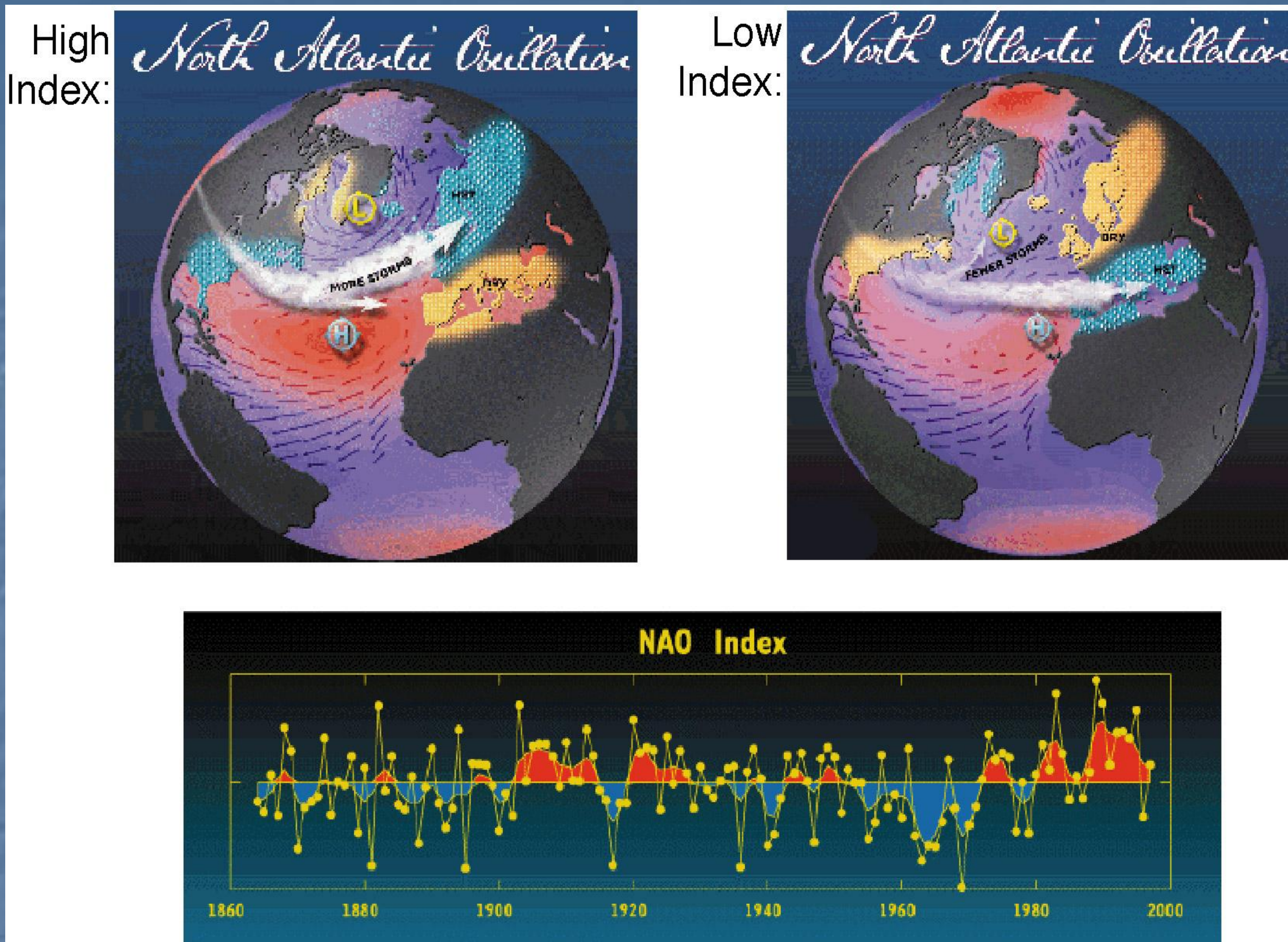



**Figure 1.** (a) Mean monthly anomalies of sea level from altimetry and corrected altimetry with the inverse barometer applied (dotted lined); (b) invrese barometer corrected altimetry, low pass filtered values (dotted line) and sea level from the oceanic model used in GLORYS (red line) (c) mass change from GRACE (dotted line), filtered values and mass estimate from the oceanic model used in GLORYS estimated from sea level minus steric effcet (red line); (c) steric sea level, filtered values (dotted line) and steric sea level from the model used in GLORYS (red line). The steric component of GLORYS has been detrended.




Major Influence: The North Atlantic oscillation
Is it linked with Global Warming?
What is the role of the ocean? Predictability?

The NAO influence on Mediterranean Sea level (winter)

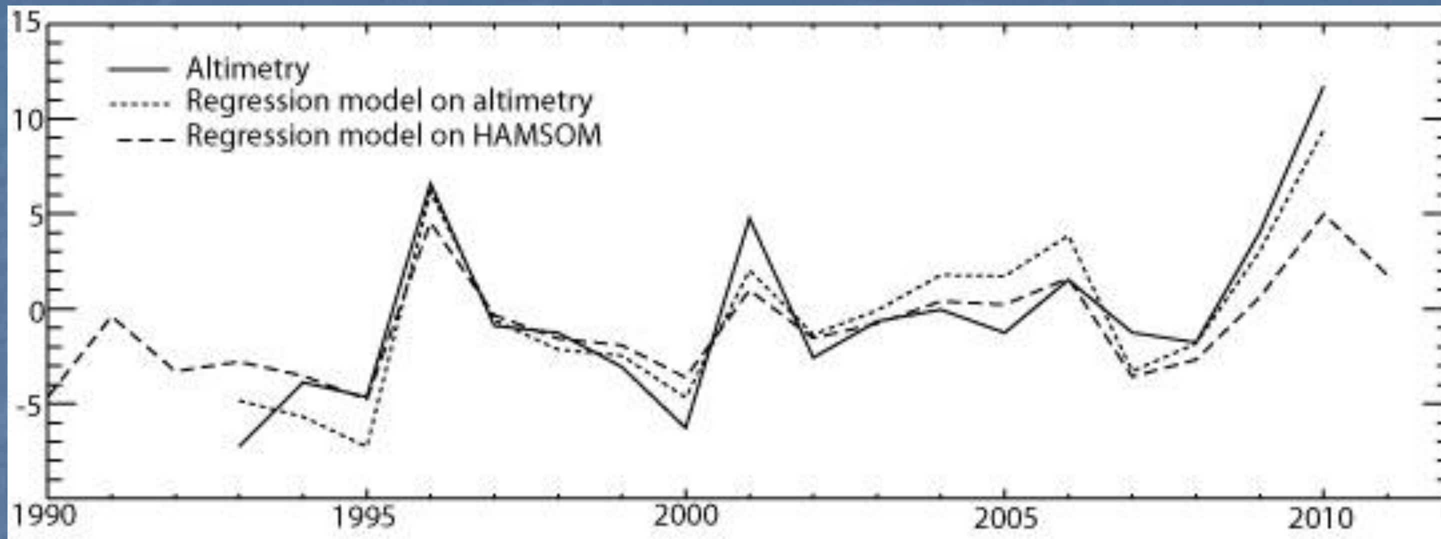



**Figure 4.** Winter values for altimetry not corrected for IB (continuous line); the regression model based on the NAO with regression coefficient -2.8 cm/unit NAO and a trend of 1.9 mm/yr (dotted line); the regression model on the basis of the relationship of the total atmospheric forcing (pressure and wind) with regression coefficient of 2 cm/unit NAO.

The NAO do
Sea

The model discrepancy suggests that in addition to the wind and pressure forcing there is a component which must be from the large scale oceanic circulation.

The two steps in sea level are linked with NAO changes. Is there any significance in this?

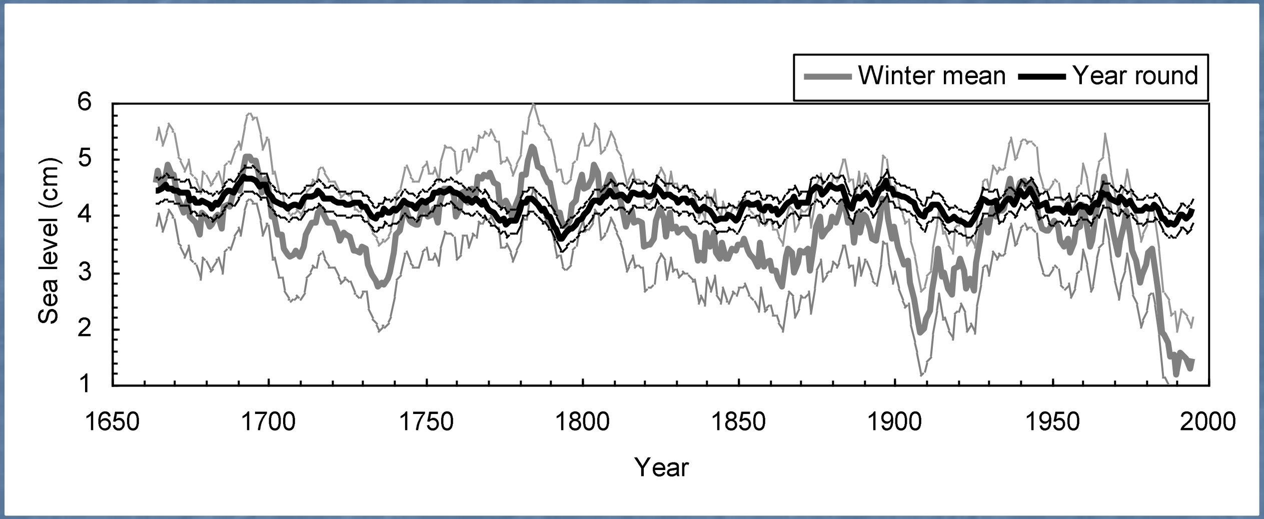
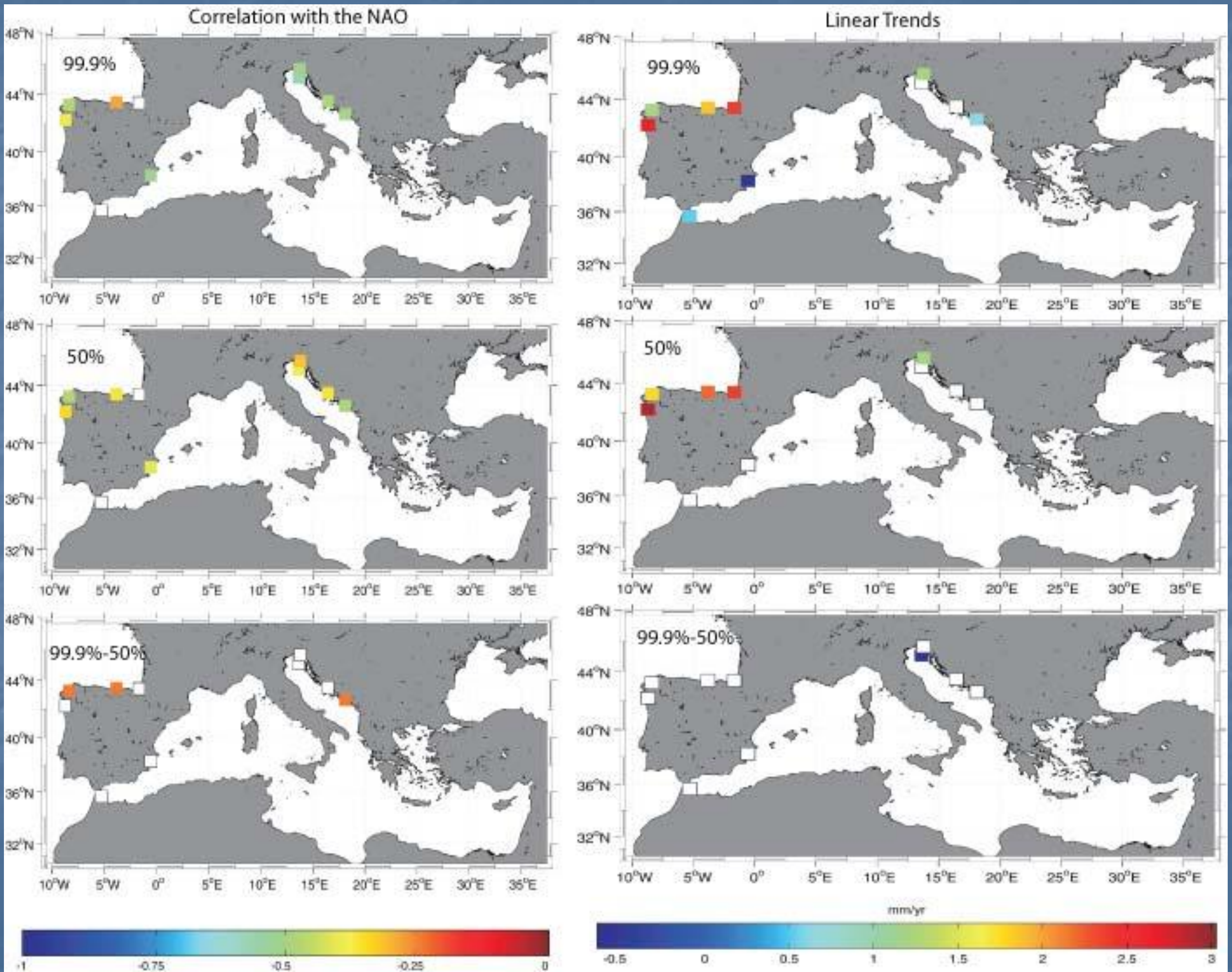


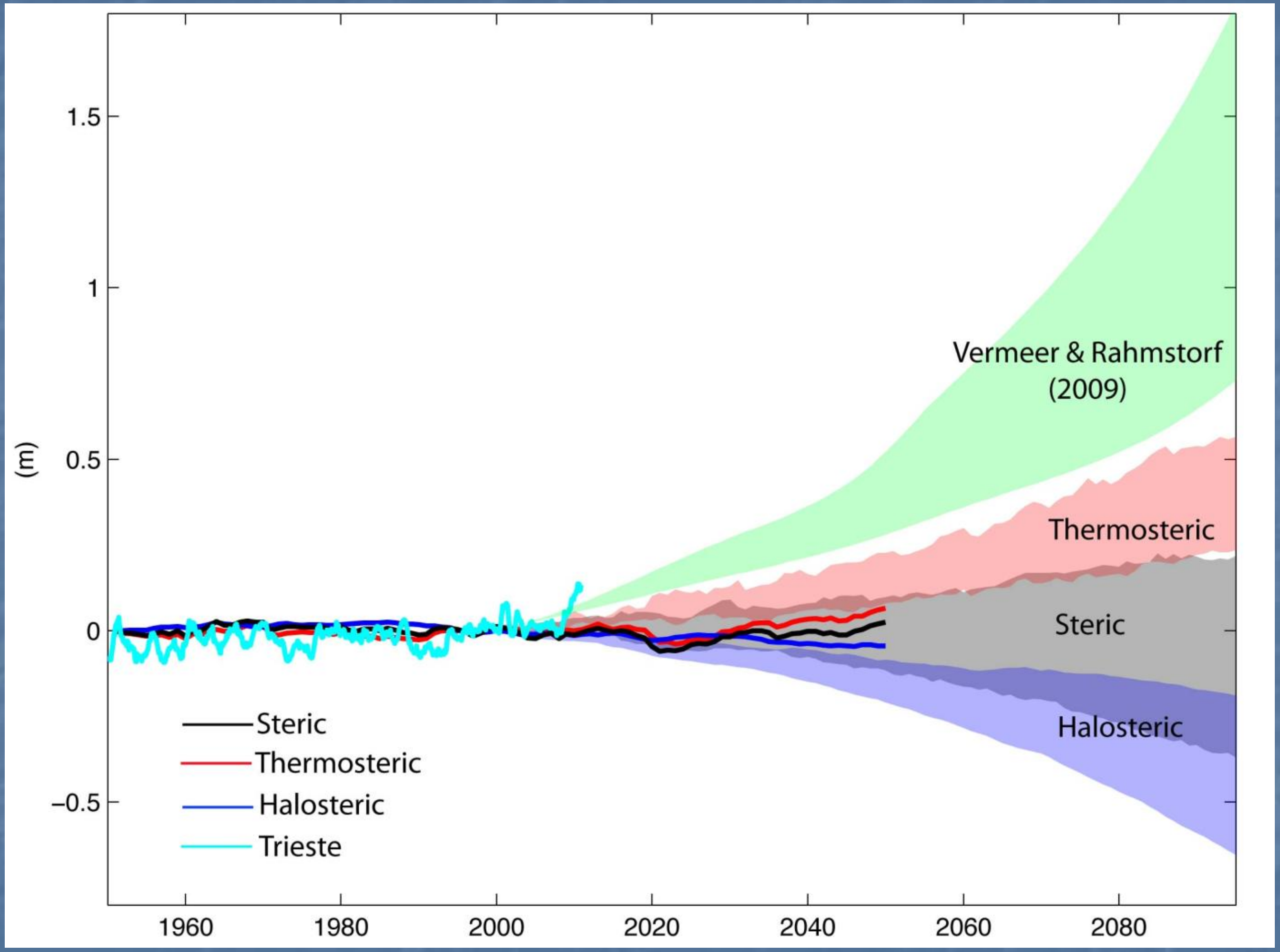

Figure 9. 10-year moving average of the monthly sea level series reconstructed from the NAO index and of winter (Dec-Mar) mean sea level reconstructed from the winter NAO index. The uncertainty associated with the reconstruction of both series has been plotted.

Gomis et al., 2006

# Extremes of residual sea level for records longer than 25 years



Projecting the future….



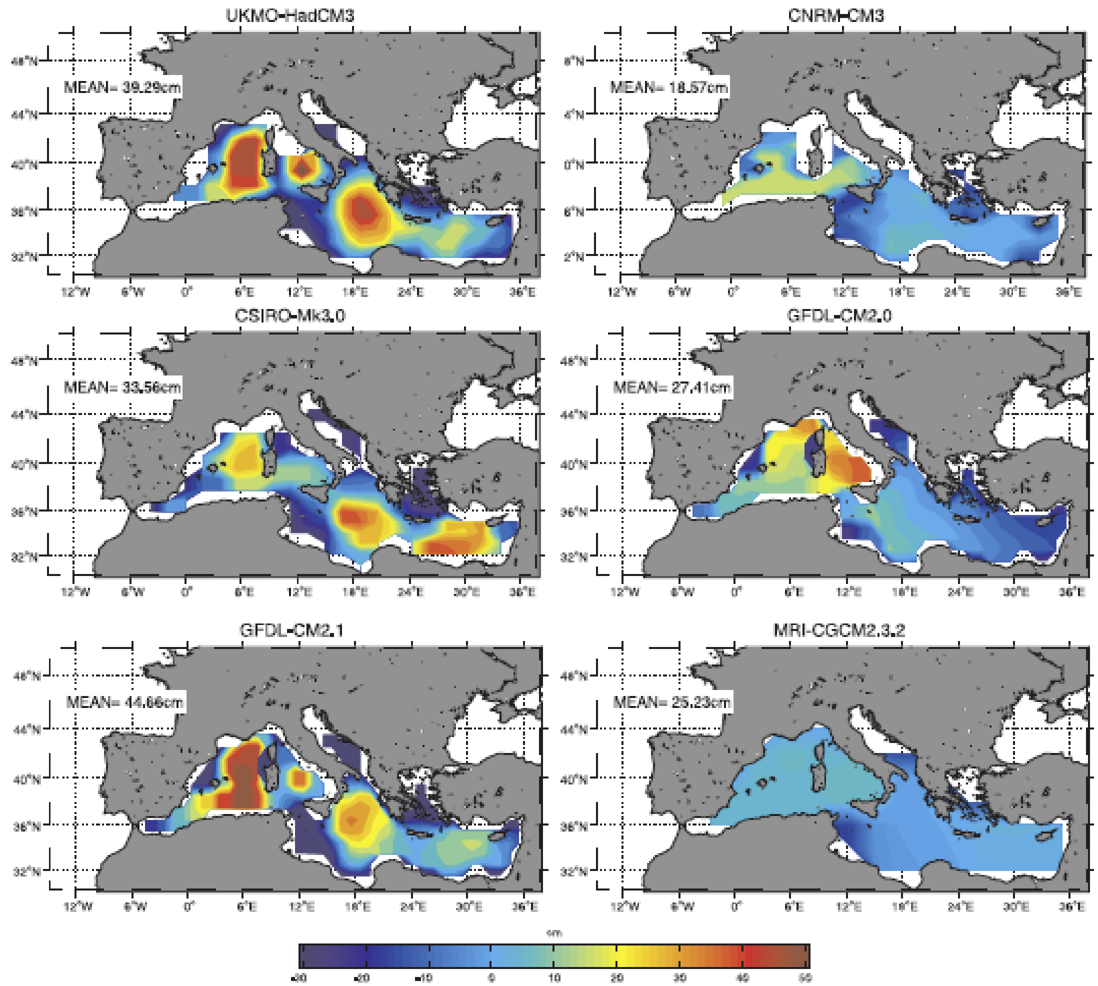
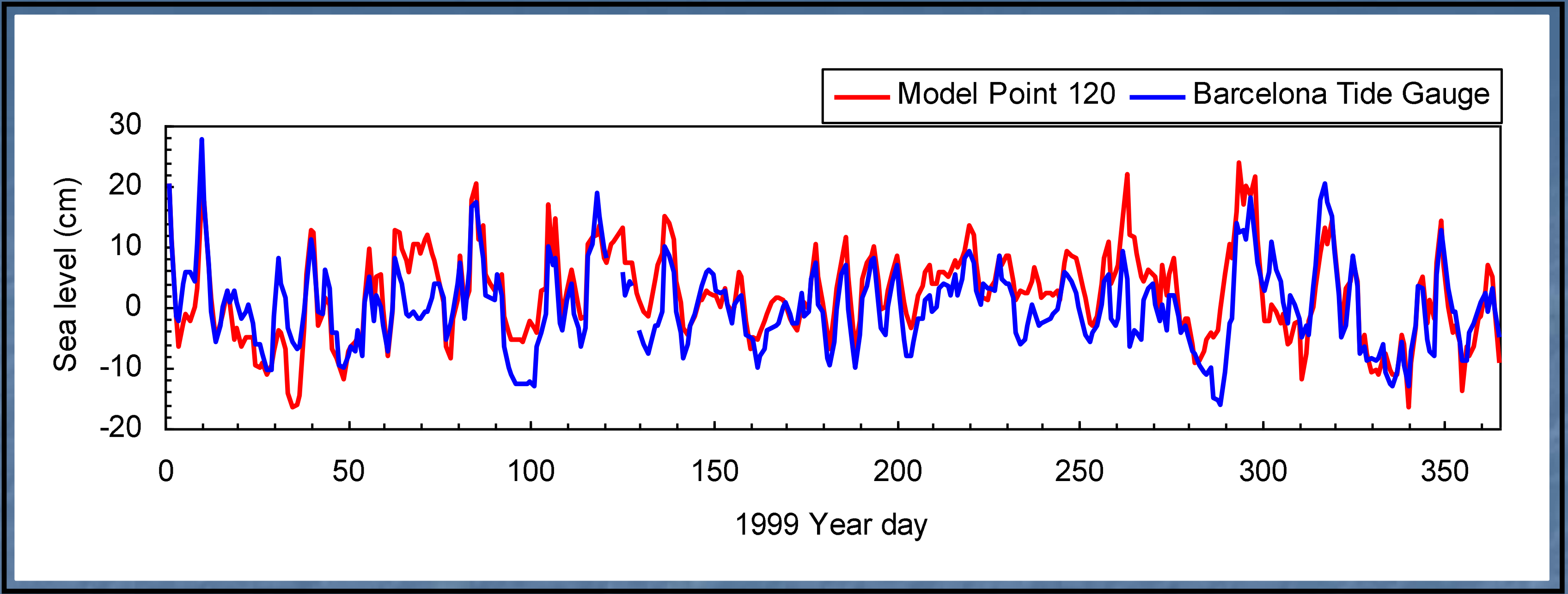



Figure 10. As in Figure 9 but for thermosteric sea level.

# Conclusions

- We have "consensus" on how fast sea level is rising and has been rising in the Mediterranean.
- We understand why sea level in the Mediterranean goes up less than Atlantic sea level
- Extremes have been rising in line with the mean sea level
- Uncertainty in each of the forcing parameters is (I think) is 1 mm/yr for most forcing.
- The NAO is dominant for sea level interannual variability and changes in trends over several decades. Can be used for empirical modelling
- Changes in the NAO can be shown to produce accelerations of the order shown in N. European records (BUT NAO influence not constant).
- Sea level does not go up linearly. We need to understand why and how it is rising in this way. It suggest respond to oceanic circulation changes rather than linear mass addition.
- Modelling, reconstruction and empirical estimates of sea level components ALL have significant uncertainty and these are underestimated.
- Model predictions are presently deficient- the density structure, the thermohaline cell and probably the communication with the Atlantic are not described accurately enough. Does this matter for sea level?




Correlation between observed sea level residuals and model outputs is around 0.8 or higher, with RMS errors of order 5 cm.

| | ATLANTIC SECTOR | WESTERN BASIN | EASTERN BASIN | Uncertainty |
|---|---|---|---|---|
| Overall trend | –0.44 mm/yr | –0.60 mm/yr | –0.62 mm/yr | ± 0.04 mm/yr |
| Season | (mm/yr) | (mm/yr) | (mm/yr) | (mm/yr) |
| Winter | –0.67 | –0.73 | –0.56 | ± 0.42 |
| Spring | 0.26 | 0.20 | 0.07 | ± 0.16 |
| Summer | 0.30 | 0.45 | 0.30 | ± 0.11 |
| Autumn | 0.08 | 0.10 | 0.21 | ± 0.24 |

Marked negative trend in winter [-1.3, -1.2] mm/yr and smoother negative trend in summer [-0.3,-0.2] mm/yr.

**Table 3.** From left- to right-hand columns: Name of the stations, values of variance of yearly observations, percentage of variance explained by the atmospheric contribution, observed trends, atmospherically induced trends, trends of atmospherically corrected series (observation minus atmospheric contribution) and steric sea level trends for the period 1960–2000; residual (observations minus atmospheric and steric contributions) trends.

| Station name | Variance ($cm^2$) | Per cent variance atm. | Observed trend | Atm. trend | Atm. residual | Steric trend | Residual | Residual + PGR |
|---|---|---|---|---|---|---|---|---|
| S.J. de Luz | 8.84 | 19.73 | 1.7 ± 0.7 | −0.7 ± 0.2 | 2.1 ± 0.6 | −0.1 ± 0.3 | 2.7 ± 0.6 | 2.6 ± 0.6 |
| Santander | 13.45 | 20.92 | 1.6 ± 0.5 | −0.4 ± 0.1 | 2.1 ± 0.5 | −0.3 ± 0.3 | 2.4 ± 0.6 | 2.4 ± 0.6 |
| Coruña | 12.42 | 31.18 | 1.9 ± 0.5 | −0.3 ± 0.2 | 2.2 ± 0.4 | −0.4 ± 0.3 | 2.5 ± 0.5 | 2.6 ± 0.5 |
| Vigo | 19.00 | 25.41 | 1.7 ± 0.6 | −0.2 ± 0.2 | 2.0 ± 0.5 | −0.4 ± 0.3 | 2.5 ± 0.5 | 2.6 ± 0.5 |
| Cascais | 7.64 | 30.66 | 0.0 ± 0.4 | −0.5 ± 0.1 | 0.6 ± 0.3 | −0.7 ± 0.5 | 1.2 ± 0.7 | 1.2 ± 0.7 |
| Cadiz | 19.78 | 14.82 | 4.5 ± 0.7 | −0.6 ± 0.1 | 5.0 ± 0.6 | −1.3 ± 0.6 | 7.1 ± 0.8 | 7.0 ± 0.8 |
| Tarifa | 13.45 | −11.73 | −1.3 ± 0.5 | −0.6 ± 0.1 | −0.8 ± 0.5 | −2.0 ± 0.6 | **0.9 ± 0.7** | **1.0 ± 0.7** |
| Ceuta | 8.09 | 9.81 | 0.6 ± 0.4 | −0.6 ± 0.1 | 1.0 ± 0.4 | −2.1 ± 0.6 | 3.0 ± 0.8 | 3.2 ± 0.8 |
| Malaga | 21.28 | 14.17 | 4.1 ± 0.7 | −0.6 ± 0.1 | 4.5 ± 0.6 | −1.8 ± 0.6 | 6.9 ± 0.8 | 7.1 ± 0.8 |
| Alicante | 2.14 | 36.53 | −0.7 ± 0.3 | −0.7 ± 0.1 | 0.0 ± 0.2 | −0.7 ± 0.3 | 1.0 ± 0.4 | 1.0 ± 0.4 |
| Marseille | 6.94 | 40.51 | −0.0 ± 0.4 | −0.7 ± 0.2 | 0.7 ± 0.2 | −0.1 ± 0.4 | **1.1 ± 0.4** | **1.1 ± 0.4** |
| Genova | 6.81 | 46.76 | −0.3 ± 0.4 | −0.9 ± 0.2 | 0.6 ± 0.2 | −1.3 ± 0.3 | 2.0 ± 0.5 | 2.1 ± 0.5 |
| Venice | 14.92 | 29.34 | 0.3 ± 0.4 | −0.9 ± 0.2 | 1.2 ± 0.3 | −1.6 ± 0.3 | 2.6 ± 0.4 | 2.8 ± 0.4 |
| Trieste | 9.00 | 48.56 | 0.3 ± 0.4 | −0.8 ± 0.2 | 0.9 ± 0.3 | −1.6 ± 0.3 | **2.4 ± 0.3** | **2.6 ± 0.3** |
| Rovinj | 8.64 | 44.89 | −0.2 ± 0.4 | −0.8 ± 0.2 | 0.7 ± 0.3 | −1.6 ± 0.3 | **2.2 ± 0.3** | **2.3 ± 0.3** |
| Bakar | 13.17 | 44.57 | 0.2 ± 0.5 | −0.8 ± 0.2 | 0.9 ± 0.4 | −1.6 ± 0.3 | **2.4 ± 0.4** | **2.6 ± 0.4** |
| Split I | 10.31 | 42.69 | −0.2 ± 0.5 | −0.9 ± 0.2 | 0.6 ± 0.3 | −1.6 ± 0.3 | 2.0 ± 0.4 | 2.1 ± 0.4 |
| Split II | 9.33 | 45.72 | −0.4 ± 0.4 | −0.9 ± 0.2 | 0.4 ± 0.3 | −1.6 ± 0.3 | 2.0 ± 0.4 | 2.2 ± 0.4 |
| Dubrovnik | 8.50 | 42.82 | 0.2 ± 0.4 | −0.9 ± 0.2 | 0.9 ± 0.3 | −1.7 ± 0.3 | 2.5 ± 0.4 | 2.6 ± 0.4 |

*Notes:* Those stations where the steric and the atmospherically corrected series are significantly correlated at 99 per cent confidence level are highlighted in boldface; residual-PGR trends are the previous value corrected for PGR. Steric trends are calculated using MEDAR database for the Mediterranean stations and Ishii for the Atlantic ones. Trends are in mm $yr^{-1}$ and uncertainties correspond to standard errors.

Note: Steric trends at the closest grid points down to 300m.

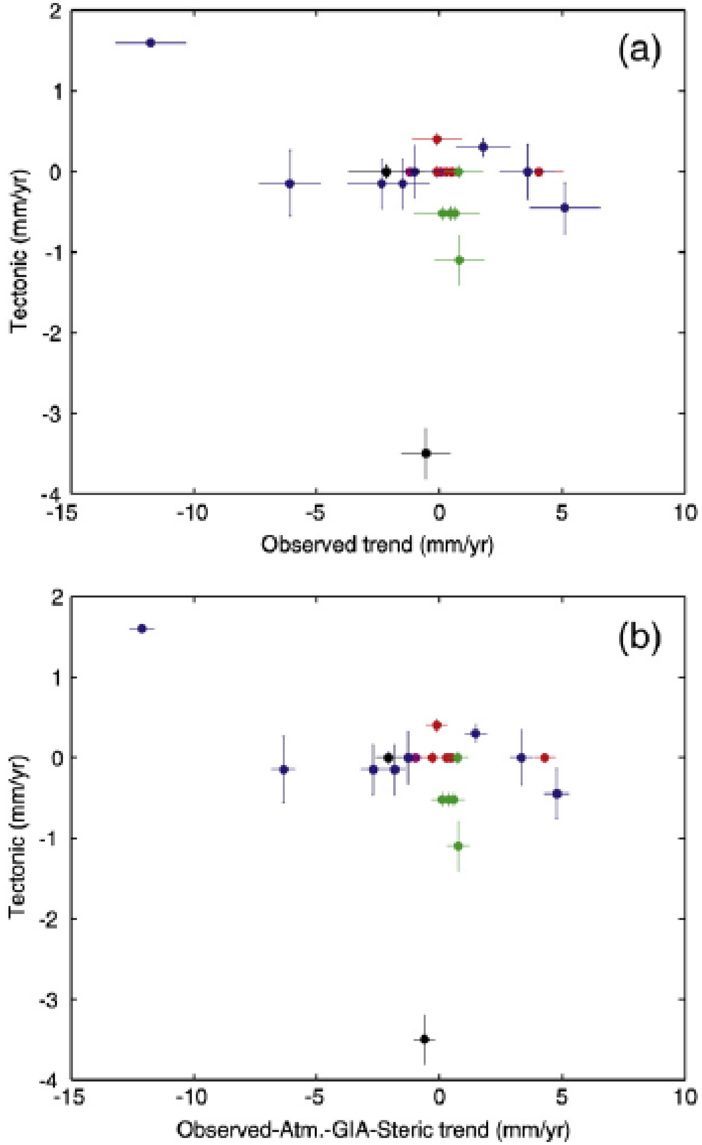



Fig. 4. a) Observed from tide gauges versus land movements linear trends for selected stations. b) As in a) but observed trends are corrected for atmospheric, steric and GIA effects. Colours identify different regions: red is western Mediterranean, pink is Gibraltar, green is Adriatic, blue is Aegean and black is eastern Mediterranean.