# Regional Sea Level Rise in the North Sea and Mediterranean basins

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## Introduction

The coastline of the North Sea and of the Mediterranean Sea are among the most densely populated coasts in the world. The low-lying coasts, e.g. German Bight, Dutch and Adria coasts, are particularly vulnerable to storm surges and long-term sea level change. An accurate estimate of the long-term trends in relative sea level and of its causes is thus of primary importance.

The relative sea level (RSL) fluctuations as measured by tide gauges include both absolute sea level changes and vertical land motions (VLM) due to glacial isostatic adjustment (GIA), tectonic processes, coastal subsidence or uplift. The poster discusses the various contribution in the two regions. In the last two decades satellite observation of the geocentric sea level change and mass transport are available, since 1993 with satellite altimetry and since 2003 with satellite gravimetry. Atmospheric and steric data are from model and observations.

## North Sea - Long-term Sea Level variability

- Sea level: The estimated absolute mean sea level (MSL) trend in the North Sea is $1.5 \pm 0.1$ mm/yr for 1900-2011, which is consistent with the global means during the same period [1]. Fig 1 (left) shows the trends of sea level observed at 22 tide gauges over the 1950-2011. The monthly tide gauge time series have been corrected by the effect of atmosphere using the 20CRV2 monthly pressure field (NOAA), the annual and semi-annual signals have been then eliminated. No correction for the Global Isostatic Adjustment (GIA) is applied. The decadal scale variability is similar amongst sites with differences at higher frequeny between the stations. The global sea level reconstruction by [6] reproduces the sea level trend within 0.5 mm/yr, while the differences at high frequency between the stations are less well reproduced (Fig. 2). We distinguish 4 sub-regions: the SW North Sea (R1: stations 1 to 6); SE North Sea (R2: 7 to 14); NE North Sea (R3: 15 to 17); NW North Sea (R4: 18 to 22).

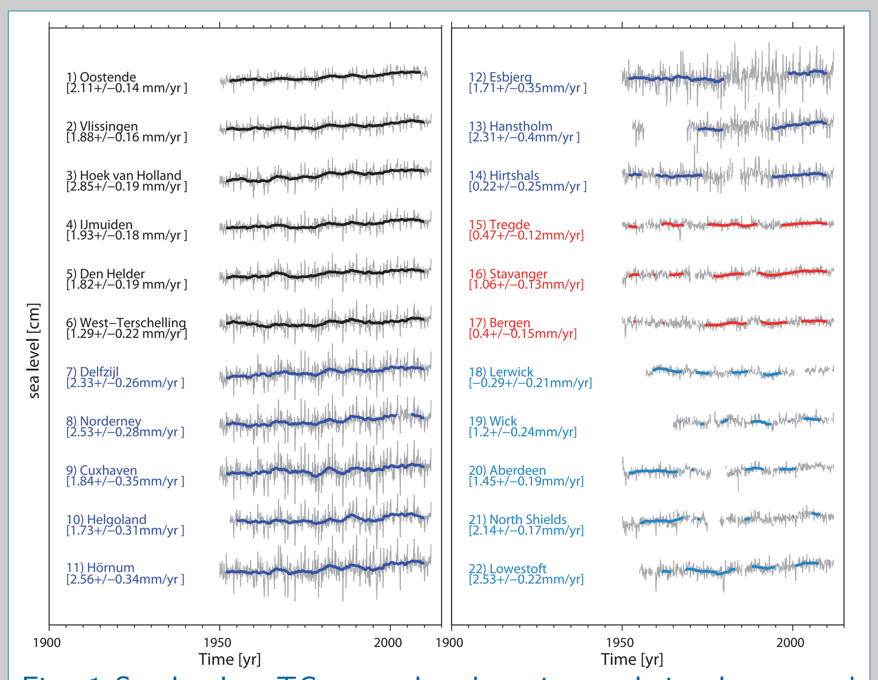

Fig. 1 Sea level at TG, annual and semi-annual signals removed (gray), and 48 months running average

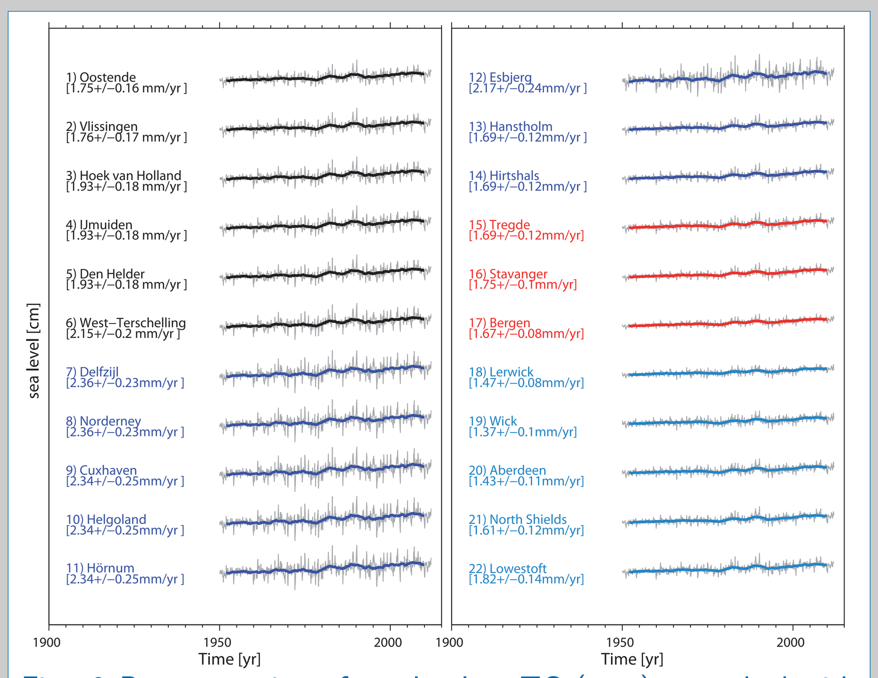

Fig. 2 Reconstruction of sea level at TG (gray) smoothed with 48 months running average

- Atmospheric forcing: Local atmospheric forcing mainly initiates MSL variability on timescales up to a few years, with the inverted barometric effect (IB) dominating the variability along the UK and Norwegian coastlines and wind controlling the MSL variability in the south from Belgium up to Denmark [1]. The highest MSL variability is found in the German Bight (Region 2). Fig. 4 shows the explained variability by different contributors and the de-seasonalized standard deviations of observed local MSL and atmospherically corrected MSL.

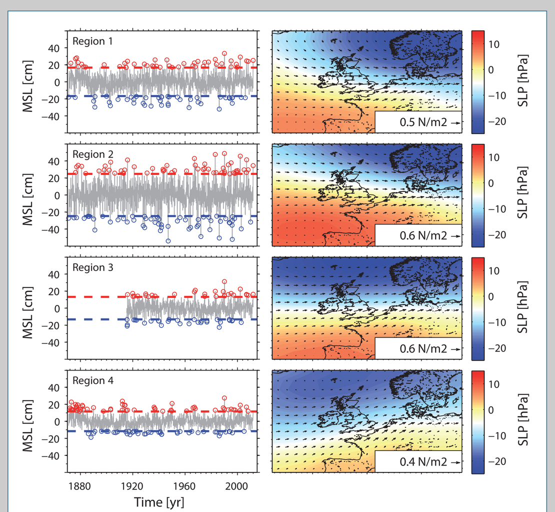

Fig. 3 Atmospheric composites for phases of extremely high minus extremely low MSL in the four sub-regions.

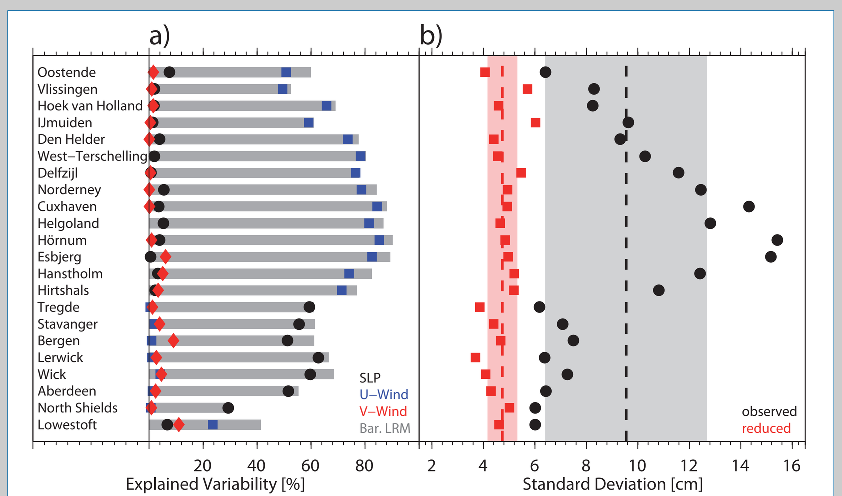

Fig. 4 Explained variability of local de-trended MSL by local atmospheric forcing (a) and standard deviations of observed and atmospherically corrected MSL (b).

- Steric contribution: At intra- and inter-annual time scales the large influence of atmospheric forcing decouples the North Sea from the surrounding areas. On decadal timescales the coherence between the different stations in the basin is much higher and the barotropic response of the ocean to local SLP and wind stress forcing becomes negligible. Since the North Sea is mostly shallow the steric height calculated locally does not account for the remaining fluctuations, however the steric component in the Norwegian Trench gives a significant steric signal (Fig.5). On decadal timescales, sea level variability mainly reflects steric changes, which are largely forced remotely. A spatial correlation analysis of altimetry observations and gridded steric heights suggests evidence for a coherent signal extending from the Norwegian shelf down to the Canary Islands (Fig.6, [1]).

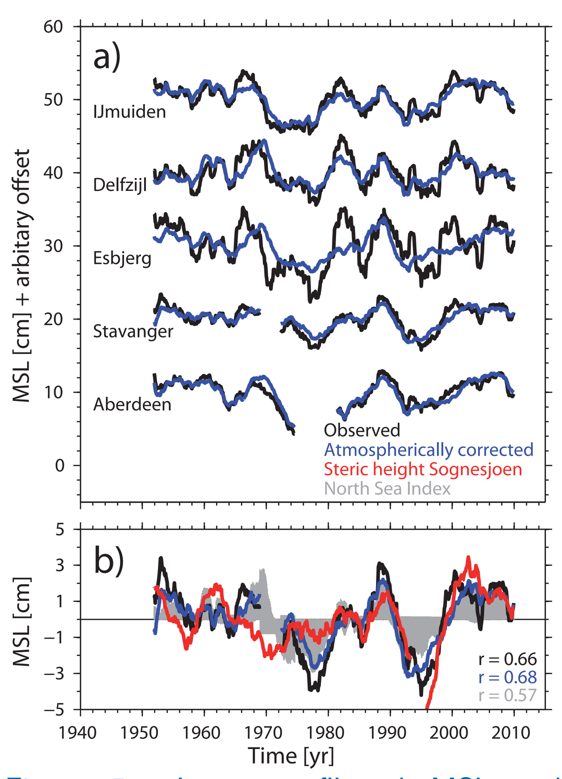

Fig. 5 Low-pass filtered MSL and atmospherically-corrected component compared to the steric component in Sognesjoen (red).

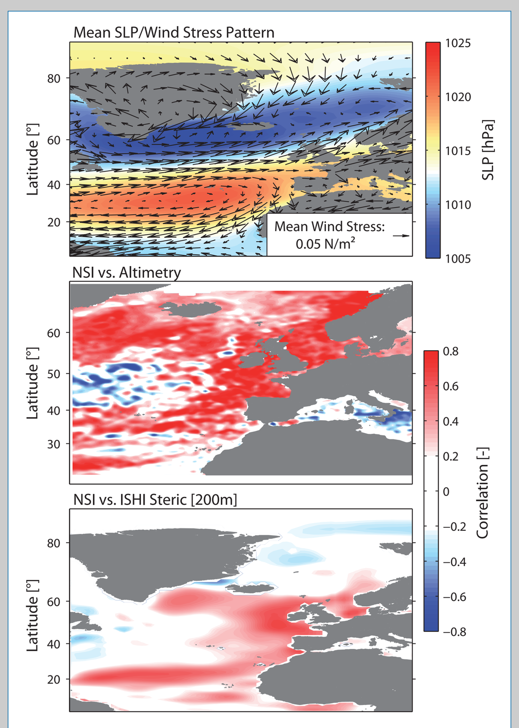

Fig. 6 Average SLP and wind stress pattern (top). Linear correlation between North Sea MSL index (NSI) and altimetry (middle) and between NSI and steric heights (bottom).

## Mediterranean - Long-term Sea Level variability

- Sea level: The annual sea level variability over 1970-2010 is from satellite altimetry and from a regional reconstruction in 1970-2005 based on EOFs patterns derived from a 33-year run of the ARPERA-forced NEMOMED8 ocean model [7], [9]. Reconstruction and altimetry agree over the overlapping period (Fig. 7). Here altimetry is from the Sea Level Essential Climate Variable (ECV) of the ESA Climate Change Initiative (CCI) (see also [2]).
- Mass change: The mass change evaluated from steric-corrected altimetry in 1993-2010 agrees with the GRACE-derived mass change (2002-2010) [3] and with the steric-corrected reconstruction (Fig. 8). The trend of the steric-corrected reconstruction is $1.17 \pm 0.15$ mm/yr in 1970-2006. Detrended low pass filtered mass change and global climatic index NAO have a high correlation (0.8).

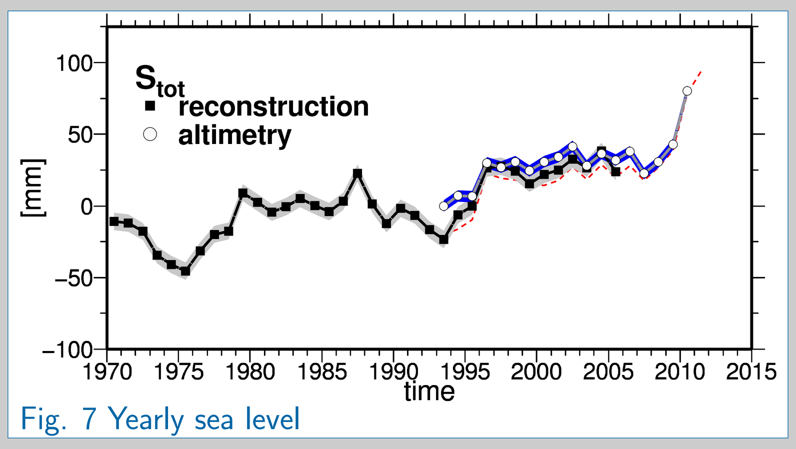

Fig. 7 Yearly sea level

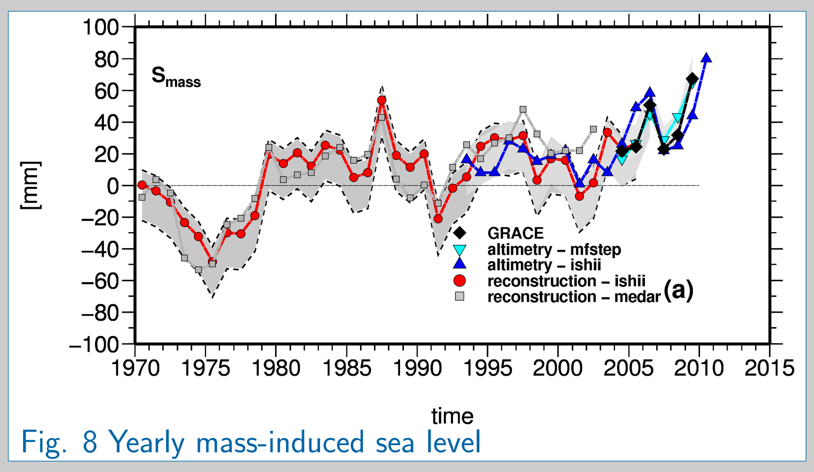

Fig. 8 Yearly mass-induced sea level

- Steric sea level: the steric component of sea level is evaluated from the global Ishii and from the regional Medar/Medatlas climatologies [8] [4] and show a similar interannual variability (Fig. 9).

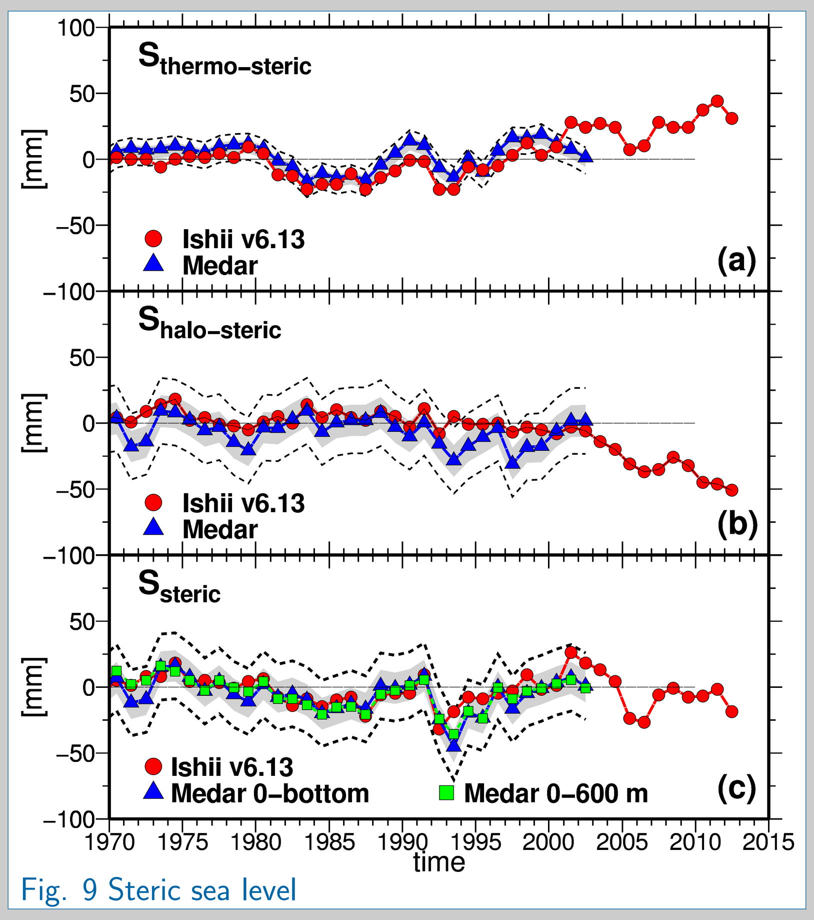

Fig. 9 Steric sea level

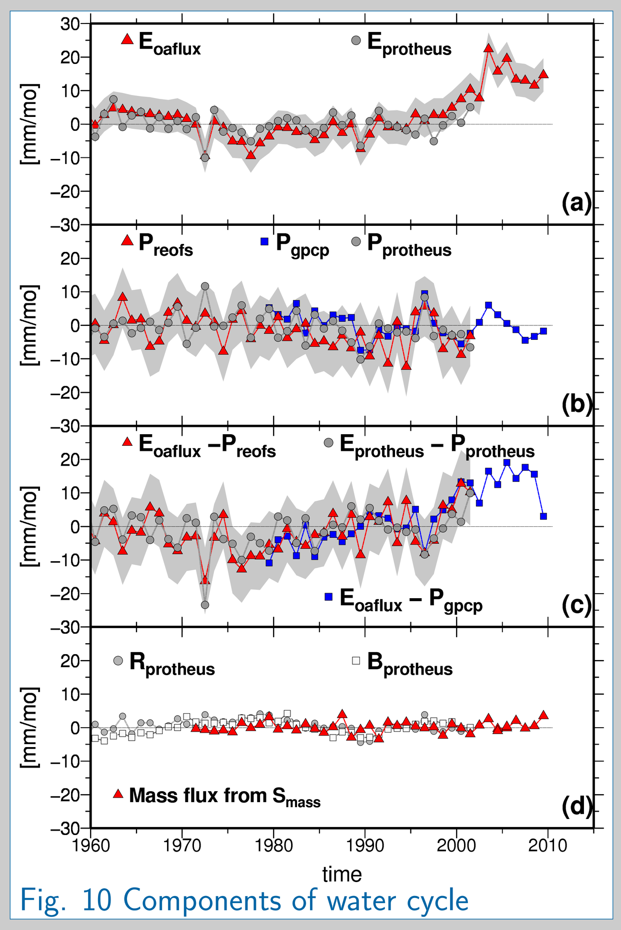

Fig. 10 Components of water cycle

- Water budget: Fig.10 shows the basin average of Evaporation (E), Precipitation (P), E-P, E is from OAFlux and P from REOFS datasets. We observe that at low frequency, E-P has larger amplitude than the mass change.

The basin averaged water mass change per month dm/dt (difference for successive months) has no long-term trend (Fig. 11).

Runoff (R) and Black Sea inflow (B) from the PROTHEUS model are negligible with respect to other surface fluxes. PROTHEUS is a regional ocean-atmosphere coupled model over 1970-2001 forced laterally by ERA40, its ocean component is forced by the MedAltas monthly climatological data.

The Gibraltar Flow computed as G = E - P - R - B + dm/dt is compared to a simulation using the PROTHEUS model (Fig. 13). Both results point to an increase in net water flux at Gibraltar over 1970-2009 ($0.8 \pm 0.2$ mm/month per year from the observational approach). Simulated Gibraltar net water flux shows decadal variability during 1960-2009 with a net Gibraltar water flux decrease during 1960-1970 before the 1970-2009 increase. Such variability follows closely the E-P one.

The analysis shows that the mass change of the sea water is small compared to water mass fluxes at the sea surface and does not show a long-term trend over 1970-2009. The decadal variations in net evaporation at the sea-surface, such as the increase during 1970-2009, drive the changes in net inflow at Gibraltar. River runoff and net inflow at the Bosphorus Strait have only a modulating effect.

The Atlantic Multi-decadal Oscillation (AMO) and the North Atlantic Oscillation (NAO) have relevant indirect influences on net water flux at Gibraltar via their influence on regional E, P and R (Figs. 12, 14). See [5], who found that wind stress anomalies near Gibraltar and SL change are related to large-scale Atlantic variability.

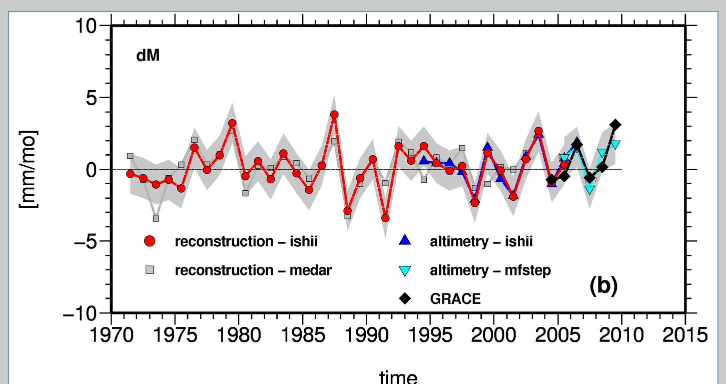

Fig. 11 Yearly mass-induced variation of sea level anomaly

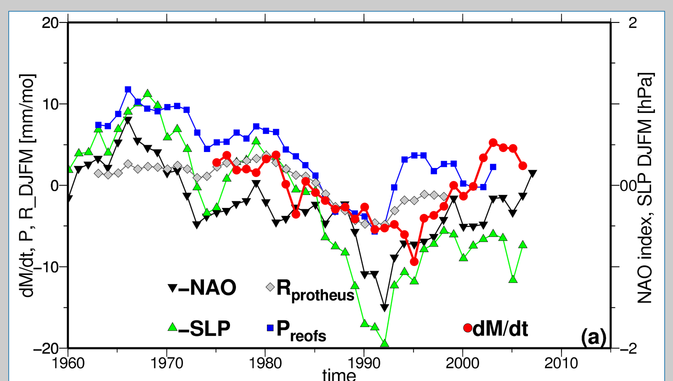

Fig. 12 Large-climate NAO and water mass budget components

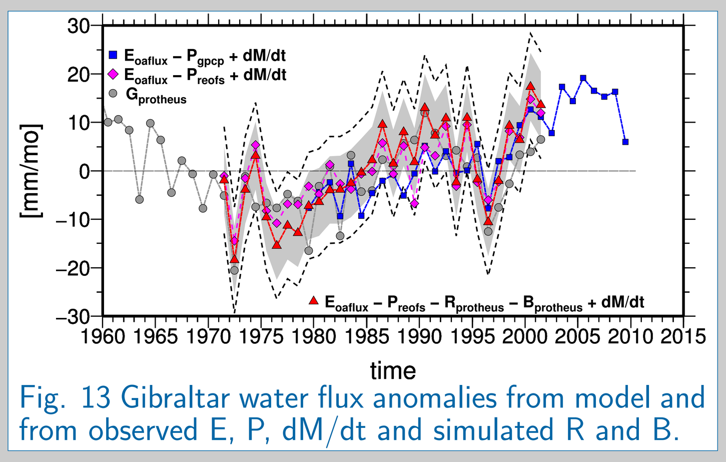

Fig. 13 Gibraltar water flux anomalies from model and from observed E, P, dM/dt and simulated R and B.

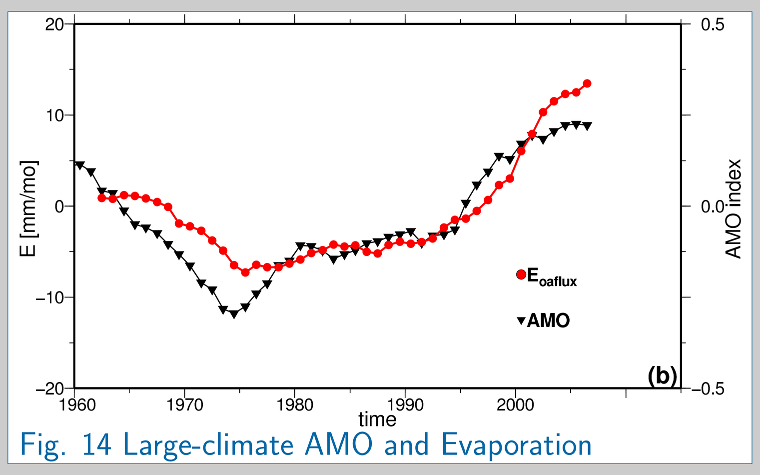

Fig. 14 Large-climate AMO and Evaporation

## Conclusions

- North Sea : local atmospheric forcing affects sea level (SL) variability at intra- and interannual-time scales
- North Sea : the steric component in the Atlantic Ocean affects the mass component on decadal time scales
- Mediterranean Sea : the mass components affects the SL on decadal time scales
- Mediterranean : the change in mass component of SL is small compared to water fluxes at sea surface
- Mediterranean : the water cycle evolves towards a drier regime and an increase in loss of freshwater. Changes in the net flow at Gibraltar are related to Evaporation (E) and Precipitation (P).
- Mediterranean : The AMO and NAO influence the net water flux at Gibraltar via E, P, R.

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**Acknowledgements**

We acknowledge ESA and JPL/CNES, AVISO for the altimeter data. Support from the STREMP Project within the DFG priority program "Mass Transport in the Earth System, SSP1257" and from the ESA Climate Change Initiative (CCI) are acknowledged.

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