Can the AMOC impact sea level in the Mediterranean Sea?

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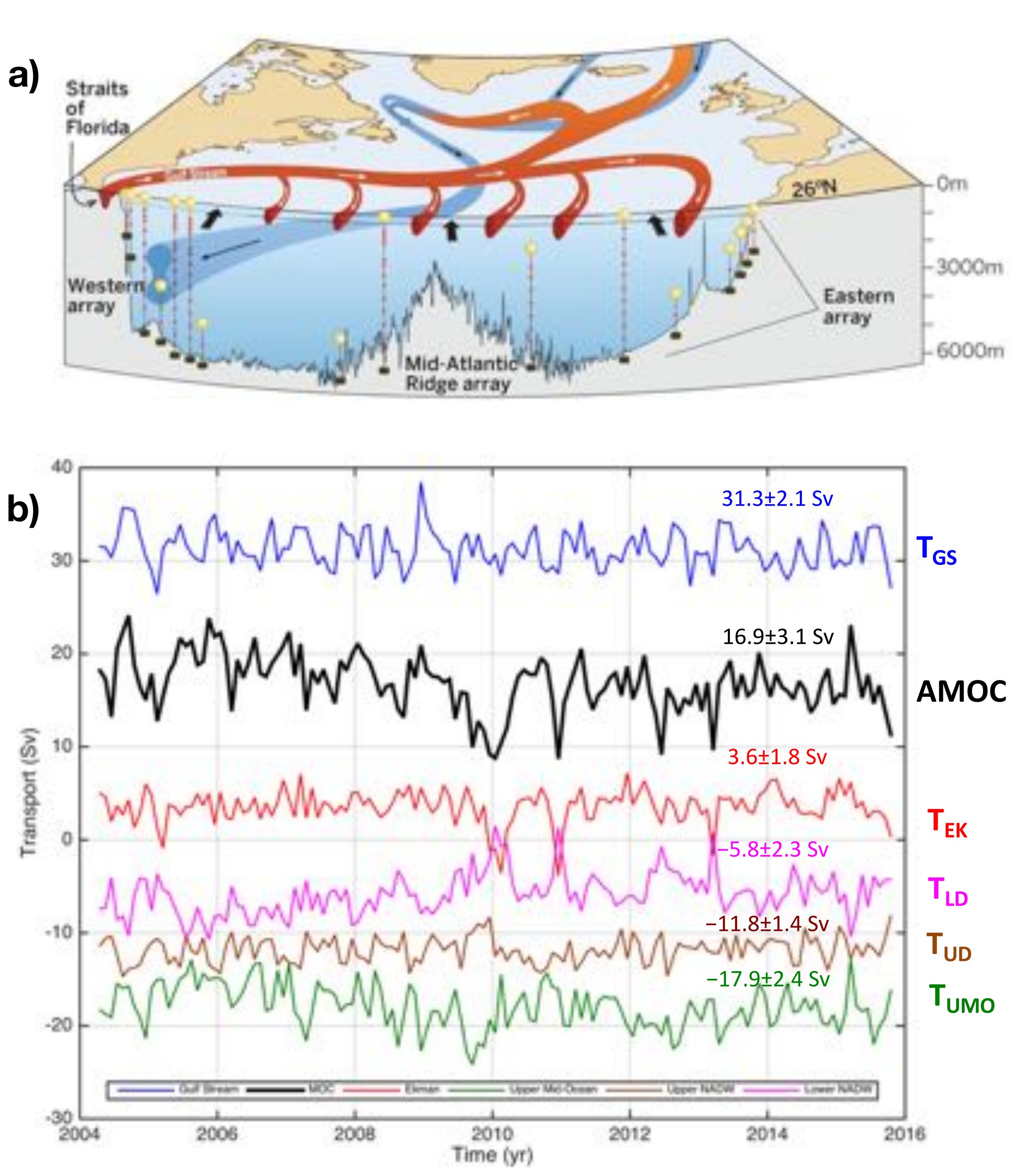

Figure 1. (a) Schematic of the Atlantic Meridional Overturning Circulation with the RAPID/MOCHA/WBTS array (credit National Oceanographic Centre), and (b) meridional transports at 26.5°N: (blue) the Gulf Stream (T_{GS}); (red) Ekman transport (T_{EK}); (green) upper mid-ocean transport (0-1100 m, T_{UMO}); (brown) the upper North Atlantic Deep Water transport (1100-3000 m, T_{UD}); (magenta) the lower NADW transport (3000-5500, T_{LD}). The AMOC transport (black) = T_{GS} + T_{EK} + T_{UMO}. and it is balanced by the NADW transport (T_{UD} + T_{LD}).

1. Overview

The Mediterranean Sea can be viewed as a "barometer" of the North Atlantic Ocean, because its sea level responds to oceanic-gyre-scale changes in atmospheric pressure and wind forcing, related to the North Atlantic Oscillation (NAO). The climate of the North Atlantic is influenced by the Atlantic Meridional Overturning Circulation (AMOC) as it transports heat from the South Atlantic towards the Subpolar North Atlantic. This study reports on a relationship between the AMOC transport measured at 26°N (Fig. 1) and the Mediterranean Sea level anomaly (SLA_{MS}) during 2004-2017: a reduced/increased AMOC transport is associated with a higher/lower sea level in the Mediterranean (Fig. 2,3; Table 1). It is shown that on monthly to interannual time scales the AMOC and sea level are both driven by similar NAO-like atmospheric circulation patterns (Fig. 4). Stronger/weaker trade winds present during a positive/negative NAO state: (i) drive northward/southward anomalies of Ekman transport across 26°N that directly affect the AMOC; and (ii) are associated with westward/eastward winds over the Strait of Gibraltar that force water to flow out/in the Mediterranean Sea and thus change its average sea level. In addition, **the interannual changes in the AMOC transport can lead to changes in steric sea level near the North Atlantic eastern boundary (Fig. 5-7). The latter sea level signals (i) propagate towards the Strait of Gibraltar in the form of coastally trapped waves and cause sea level changes in the Mediterranean Sea, and (ii) represent a mechanism for negative feedback on the AMOC.**

2. Data Used

- Satellite altimetry maps of sea level anomaly (SLA) from CMEMS (http://marine.copernicus.eu/)
- Transports of AMOC components from RAPID/MOCHA/WBTS (Fig. 1)
- Gridded temperature and salinity profiles (mostly Argo-based) from JAMSTEC used to compute steric (SLA_{ST}), thermometric (SLA_T), and halosteric (SLA_S) sea level anomaly.
- Sea level pressure (SLP), wind velocity and stress, net surface heat flux, and sea surface temperature (SST) from ERA-Interim re-analysis

3. The basin-wide Mediterranean Sea level is correlated with the AMOC and NAO

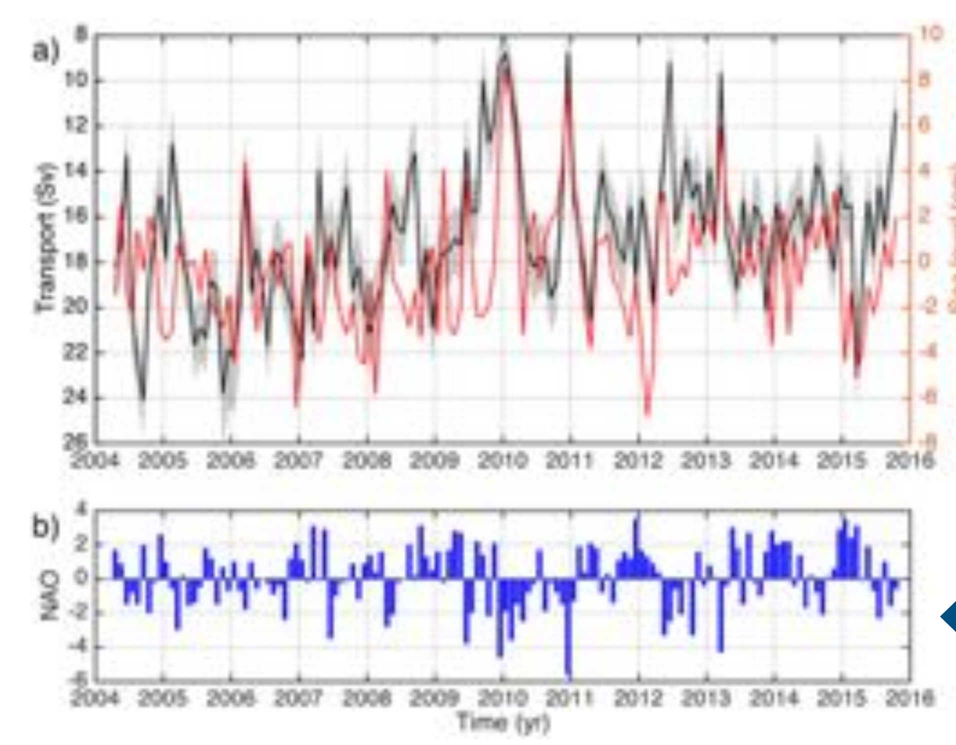

Table 1. Correlation coefficients between the non-seasonal sea level averaged over the Mediterranean (SLA), monthly station-based NAO indices, and meridional transports across 26°N. The 95% significance level for correlation is about 0.25.

	SLA	T_{AMOC}	T_{GS}	T_{EK}	T_{UMO}	T_{UD}	T_{LD}
SLA		-0.40	-0.18	-0.52	0.04	-0.01	0.46
NAO	-0.48	0.43	0.13	0.77	-0.15	-0.12	-0.42

Figure 2. (a) AMOC northward transport 26.5°N (black curve) with measurement uncertainty (shaded band) and sea level anomaly (with the global mean and seasonal cycle subtracted) averaged over the Mediterranean Sea (red curve). (b) Monthly station-based NAO index from Hurrell (2016).

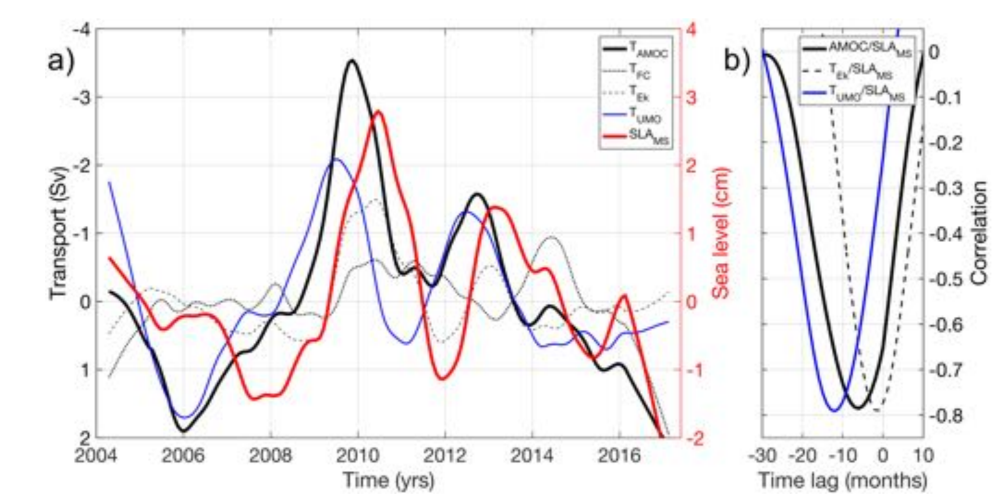

Figure 3. (a) The smoothed time series of SLA_{MS} (red) and the AMOC northward transport components: (black) T_{AMOC}, (dotted black) T_{GS}, (dashed black) T_{EK}, (blue) T_{UMO}. (b) Lagged correlations of (black) SLA_{MS} and T_{AMOC}, (dotted black) SLA_{MS} and T_{EK}, (blue) SLA_{MS} and T_{UMO}. All time series were detrended.

4. Mechanisms responsible for correlation between the AMOC and Mediterranean Sea level

- **Monthly time scales: both the AMOC and SLA_{MS} are driven by similar NAO-modulated wind patterns**

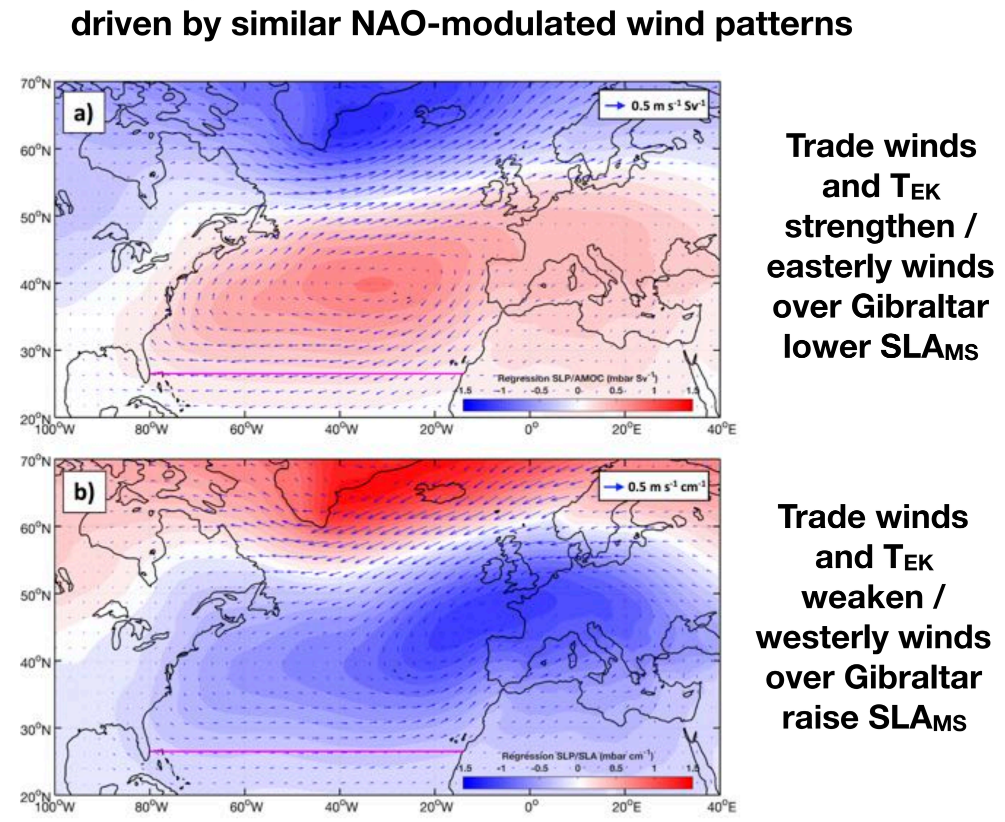

Figure 4. The regression maps of monthly sea level pressure and 10-m wind velocity from ERA-Interim projected on (a) the AMOC transport across 26.5°N and (b) sea level in the Mediterranean Sea. Seasonal cycle is removed.

- **Interannual time scales: (i) sea level exhibits tri-pole pattern of variability (Fig. 5a,b); the RAPID/MOCHA/WBTS array nearly follows the boundary between the subtropical and equatorial-tropical bands, characterized by downward and upward doming isotherms, respectively (Fig. 6a); meridional heat transport anomalies at 26.5°N lead to heat convergence/divergence in the equatorial-tropical band, which in turn impacts sea level in the Mediterranean (Fig. 5,6).**

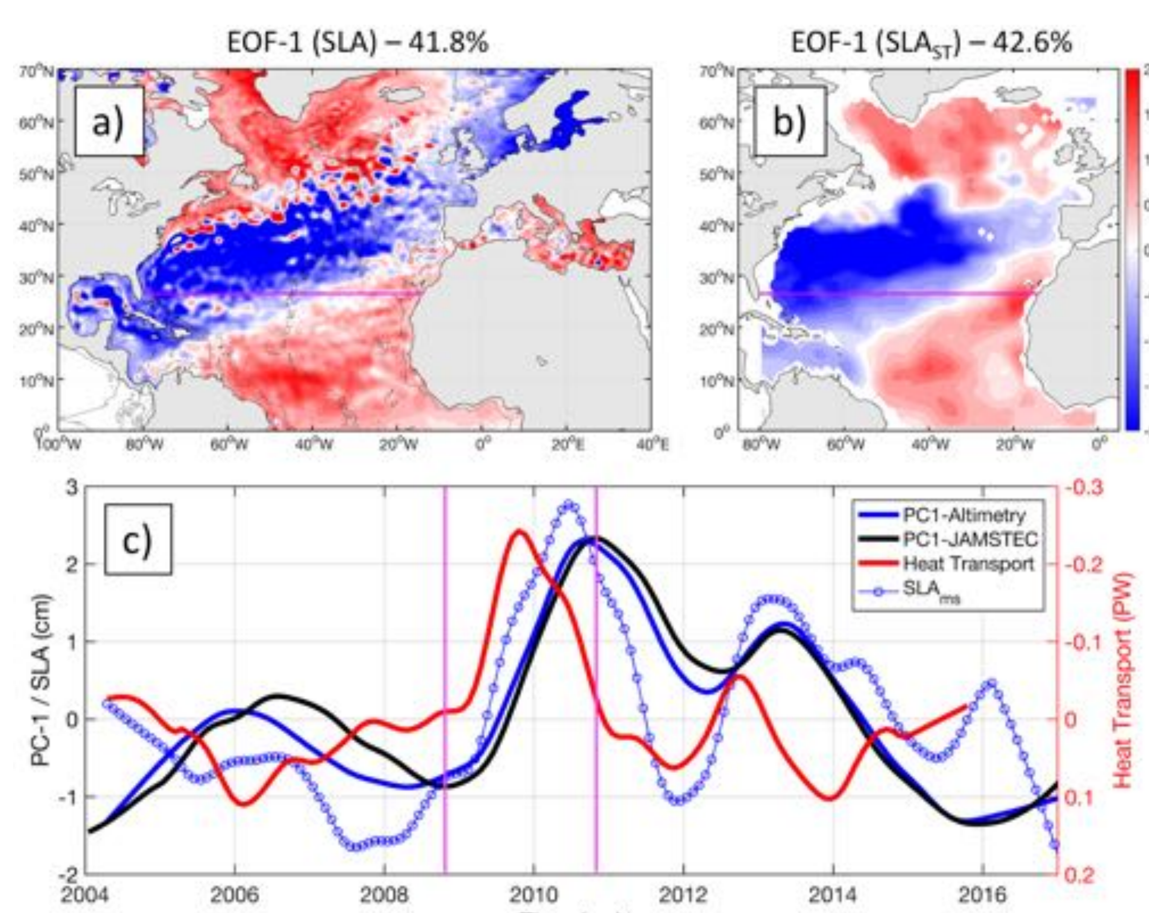

Figure 5. The first empirical mode of sea level variability: the spatial patterns of EOF-1 of (a) SLA from satellite altimetry and (b) SLA_{ST} from JAMSTEC data, and (c) the time evolution (principal component) of EOF-1 for SLA (blue) and SLA_{ST} (red). In (c), blue curve with circles shows SLA_{MS} and red curve shows the meridional heat transport across 26.5°N (note that y-axis for heat transport is reversed).

Note that the steric sea level (SLA_{ST}) is mostly determined by the thermometric component (SLA_T), which is further analyzed in Fig. 7.

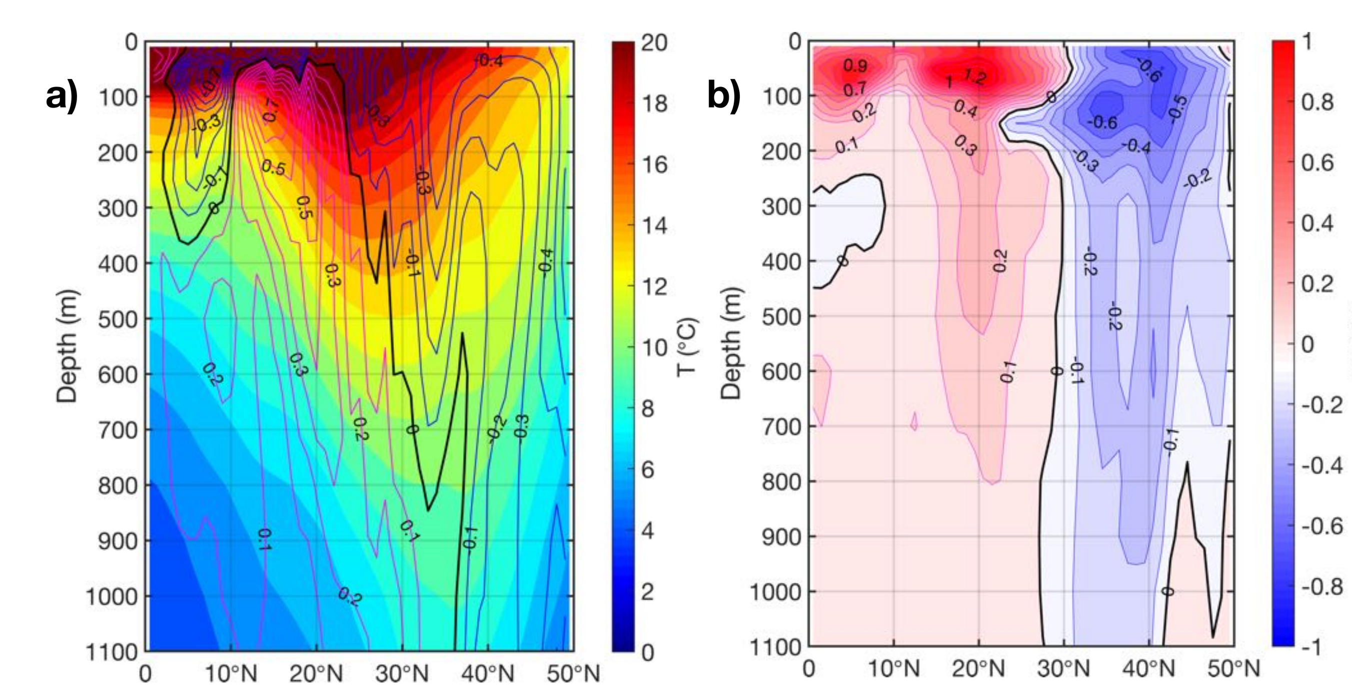

Figure 6. (a) The JAMSTEC time-mean profile of temperature averaged between 10°W-40°W, with the meridional gradients (contours) of temperature (°C per 100 km) gradients. (b) The differences of the low-pass filtered temperature between Oct 2010 (high sea level near the eastern boundary) and Oct 2008 (low sea level near the eastern boundary), indicated by magenta lines in Fig. 5c.

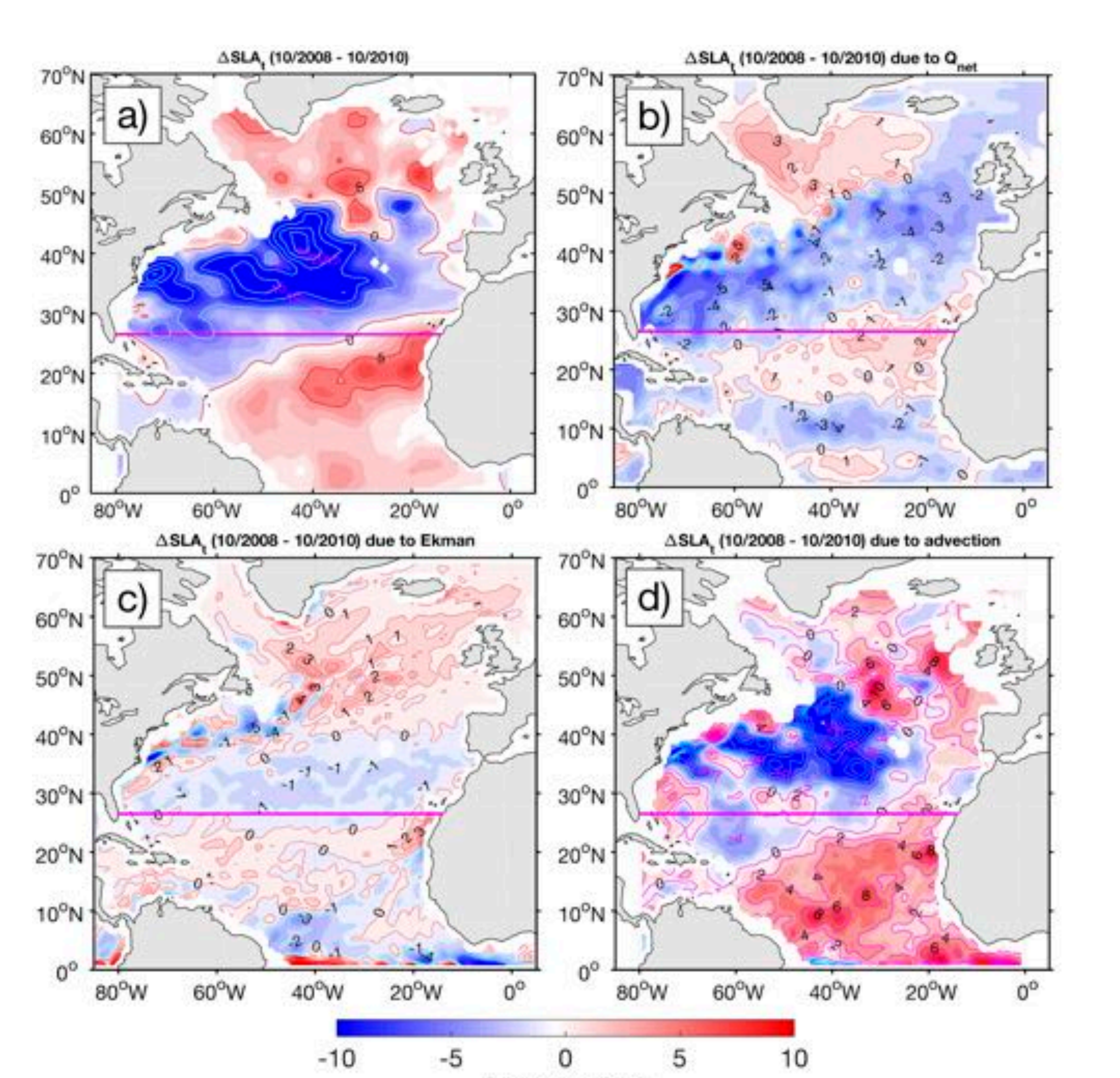

Figure 7. (a) Thermosteric sea level change from Oct. 2008 to Oct. 2010 and processes responsible for this change: (b) the sea level change driven by the net surface heat flux (Q_{NET}); (c) the sea level change due to the Ekman temperature advection; and (d) the residual (d=a-b-c) illustrating the contribution of advection by geostrophic currents.

5. Summary

- The AMOC and the Mediterranean Sea level are linked, because they are both forced by the same NAO-induced atmospheric circulation pattern. Anticyclonic/cyclonic anomalies of the subtropical atmospheric circulation drive the northward/southward Ekman transport anomalies at 26°N, and they are associated with westward/eastward wind anomalies across the Strait of Gibraltar that pump water out/in the Mediterranean Sea and, thus, lower/raise its sea level (Fig. 8).
- On interannual time scales, a negative/positive anomaly of the meridional heat transport leads to heat convergence/divergence in the equatorial-tropical band, which is associated with sea level rise that affects the northwest coast of Africa and ultimately the Mediterranean (Fig. 8). An increase/decrease of sea level near the eastern boundary changes the zonal sea level gradient across the subtropical North Atlantic and, therefore, provides a negative feedback mechanism on the AMOC.

Key Points:

- **Sea level in Mediterranean is correlated with Atlantic Meridional Overturning Circulation (AMOC)**
- **Sea level in Mediterranean and AMOC are driven by similar atmospheric circulation patterns related to North Atlantic Oscillation**
- **Reduced AMOC leads to heat convergence near the eastern boundary and associated coastal sea level signal that propagates towards Mediterranean Sea**

Acknowledgements. This work was funded by the NASA Ocean Surface Topography Science Team program (via Grant Number NNX13AO73G), with additional support from the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory.

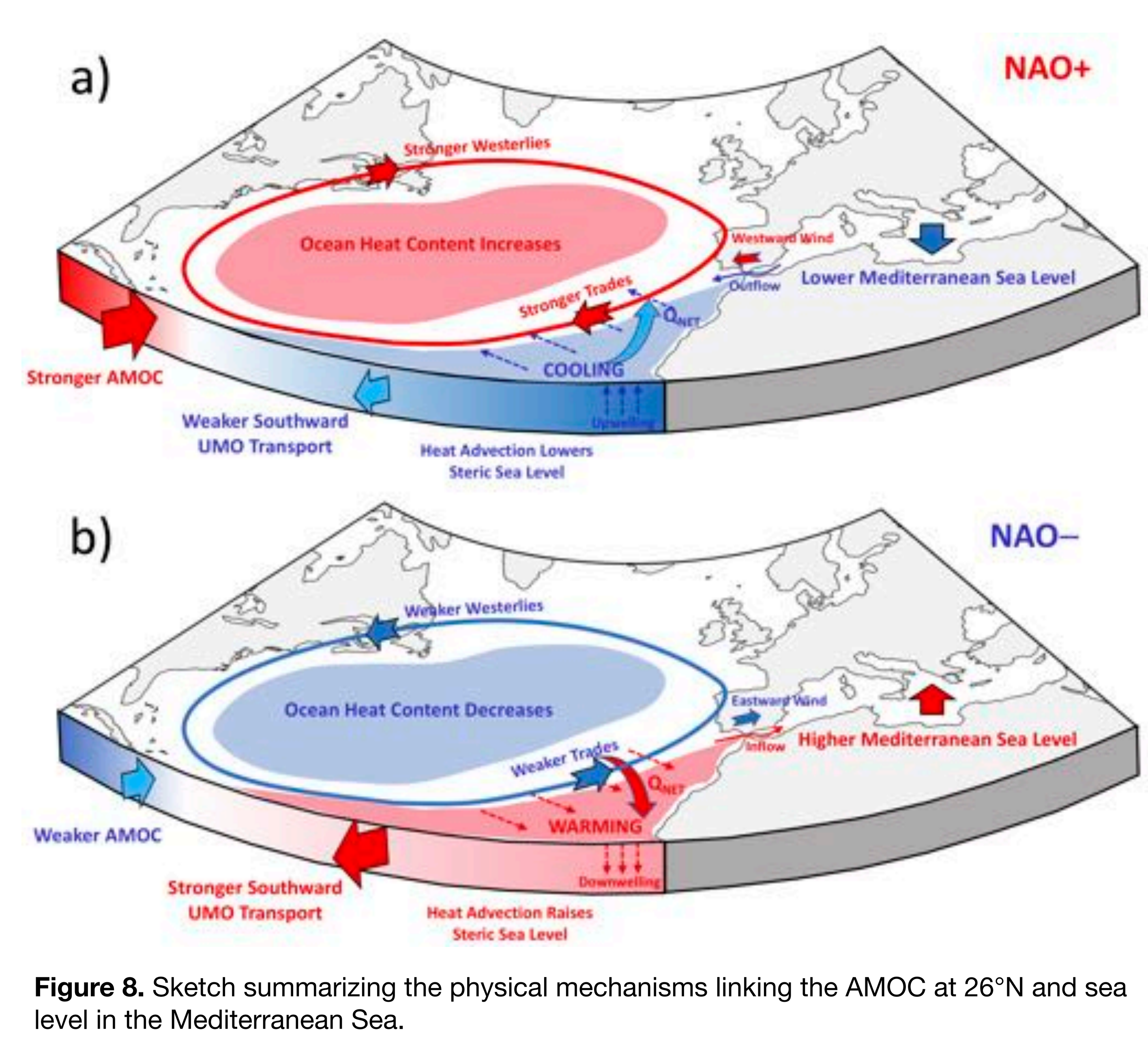

Figure 8. Sketch summarizing the physical mechanisms linking the AMOC at 26°N and sea level in the Mediterranean Sea.