Does the Atlantic Meridional Overturning Circulation impact coastal sea level changes in the subtropical North Atlantic?

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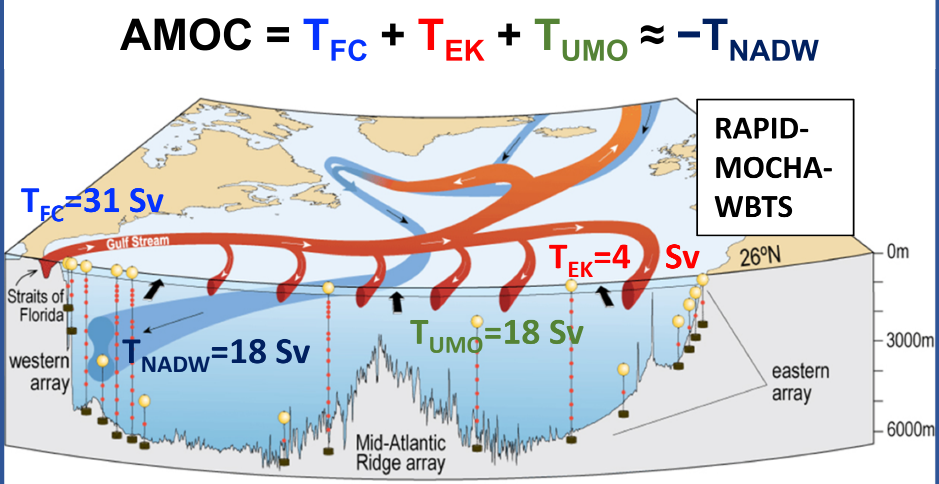
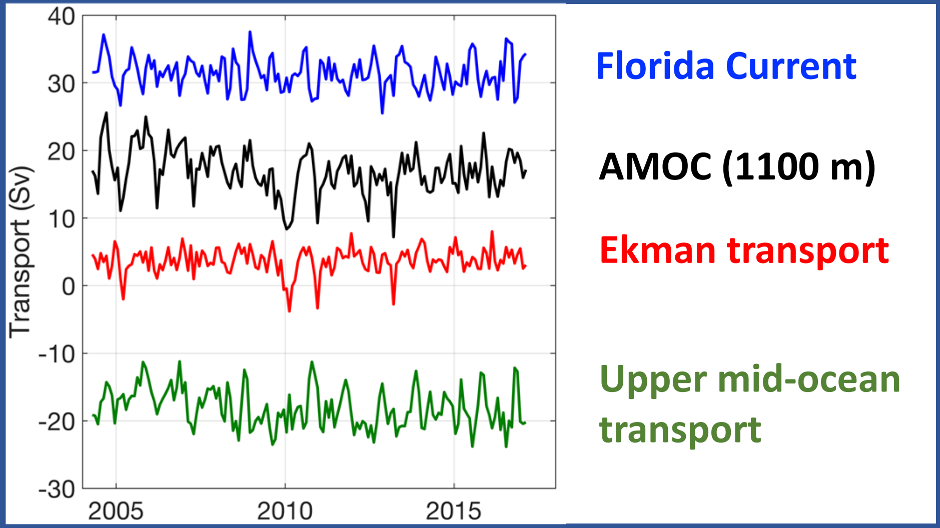
1. Introduction: Atlantic Meridional Overturning Circulation (AMOC) & Sea Level



From https://mocha.rsmas.miami.edu/methods/index.html



- The AMOC transports heat and freshwater meridionally, and thus contributes to the large-scale dynamic (not related to the global mean sea level rise) sea level variability.

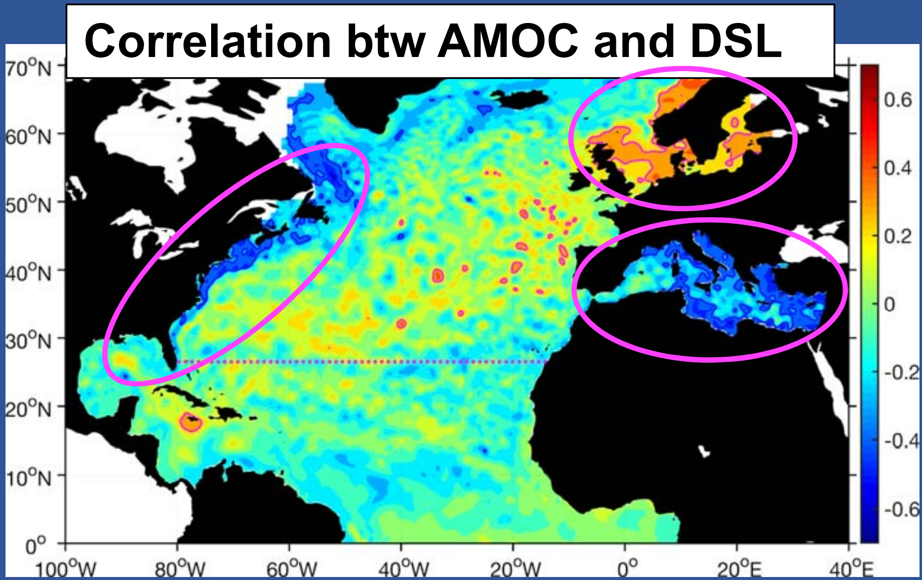
- The AMOC is projected to slowdown in the current century, which may lead to enhanced regional sea level rise, in particular along the North America east coast (Little et al., 2019; Chen et al., 2018; Hu et al., 2009).

- In theory, the AMOC is related to coastal sea level, because the northward mass transport (*T*) across a latitude (*y*) results from the difference between pressure at the eastern end (p_e) and the western end (p_w) of the section:

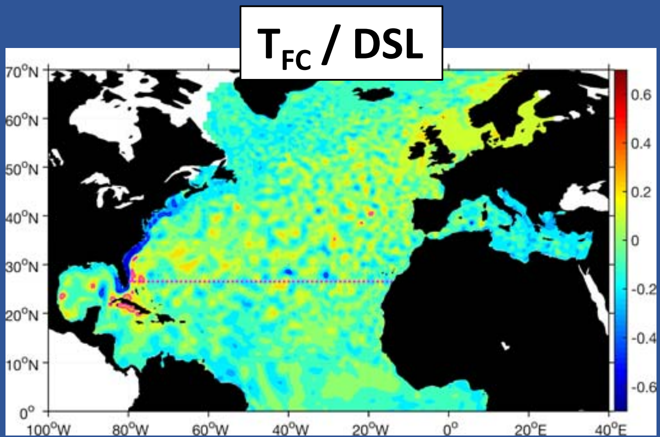
$$T(y) = \frac{1}{\rho_0 f} \int_{-H}^{0} [p_e(y,z) - p_w(y,z)]dz$$

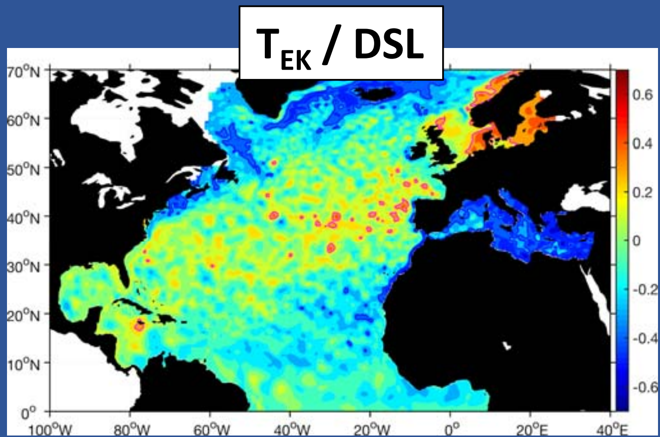
- In reality, this simple relationship between sea level and AMOC is complicated by local and remote forcing mechanisms.

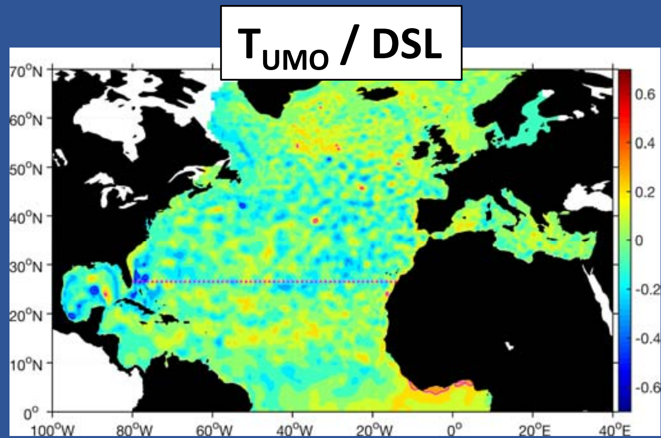
1. Introduction: Correlation between the AMOC at 26.5ºN and dynamic sea level



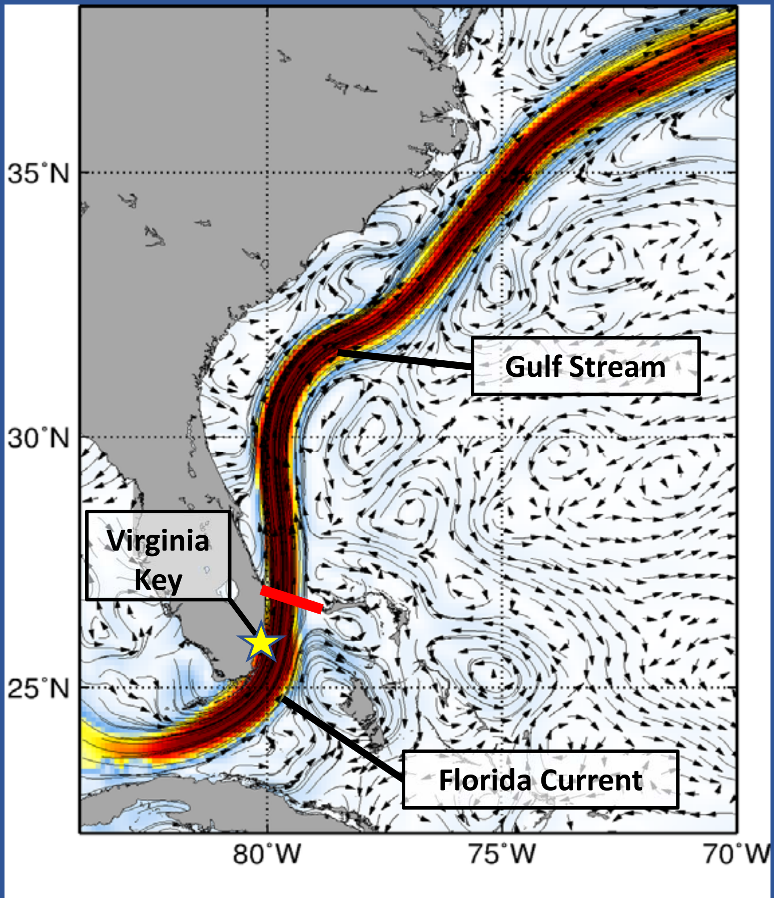
- ❑ AMOC is significantly correlated with sea level along the North America east coast, in the Mediterranean Sea, and over the northwest European shelf
- ❑ Correlation is mainly due to the Florida Current and Ekman transports, suggesting the roles of geostrophy and large-scale wind forcing, respectively
- ❑ Does the gyre-scale ocean circulation play a role in driving coastal sea level changes?

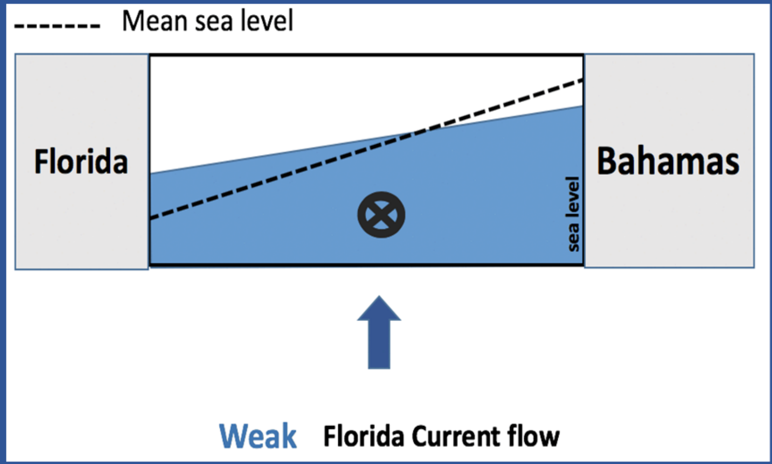


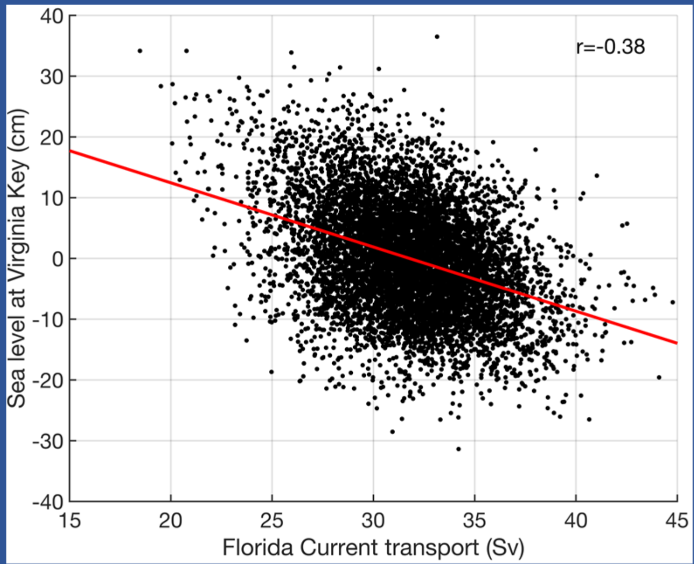




2. Florida Current transport and U.S. East Coast sea level





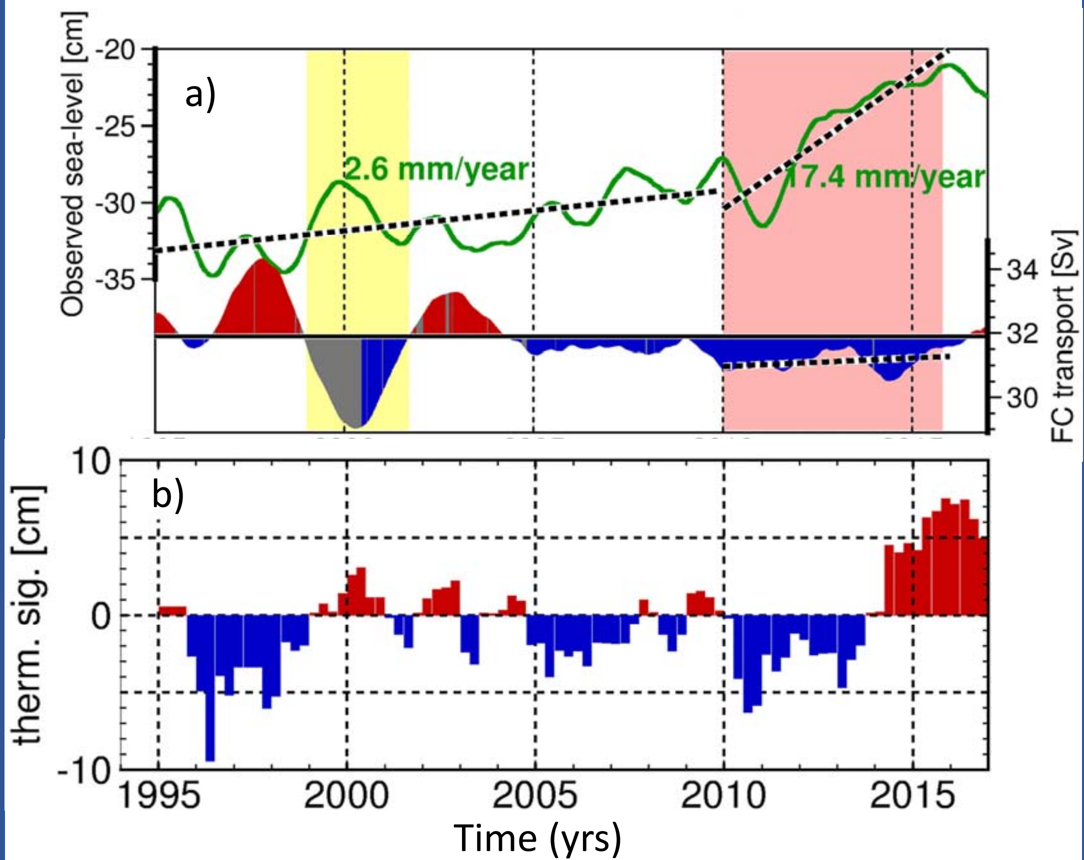


- Due to geostrophy, weak Florida Current can increase sea level in Miami by up to 20 cm, but the large scatter is due to local pressure and wind forcing and large-scale thermohaline changes.
- Similarly, it has been reported that changes in the Gulf Stream transport further north can affect sea level along the northeast U.S. coast, although the directly wind-induced variability is probably more important.

Andres et al. (2013),Ezer et al. (2013); Yin & Goddard (2013); Woodworth et al. (2014); Park and Sweet (2015); Goddard et al. (2015); Ezer (2016); Little et al., (2017); Piecuch et al. (2019)

2. Florida Current transport and U.S. East Coast sea level

Interannual changes of (a) the Florida Current volume transport and (b) thermosteric sea level anomaly in the Florida Straits

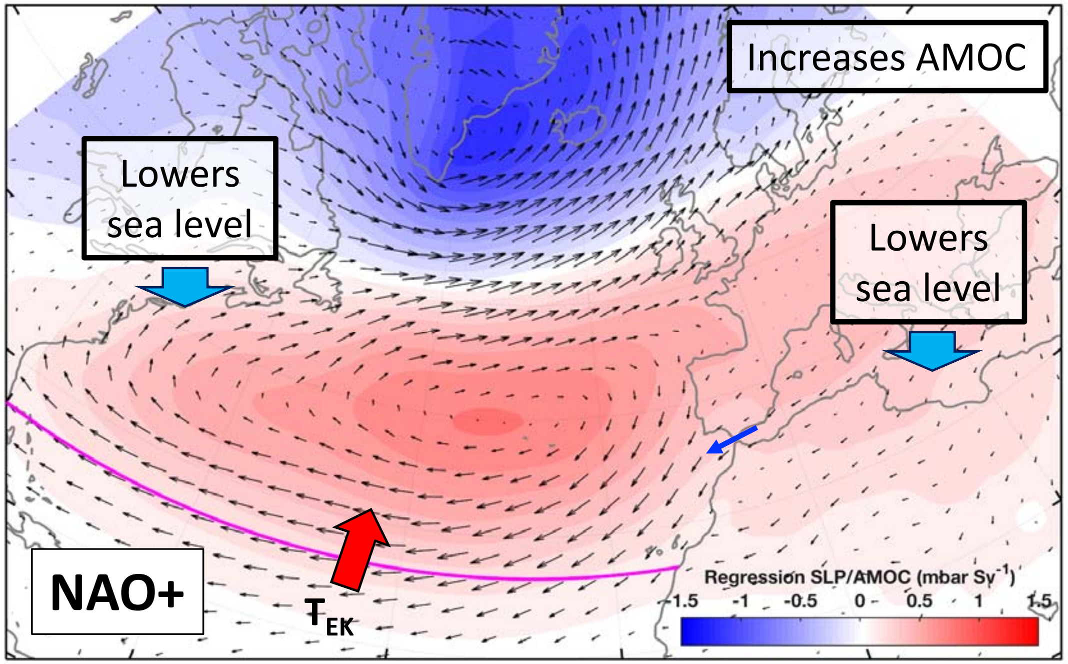


- **Strong oscillations in the Florida Current transport played an important role in sea level variations in Miami in 1997-2005.**
- **In other periods, the Florida Current volume transport is not the major contributor to the interannual changes of sea level along the east coast of Florida.**
- **The dynamic sea level rise south of Cape Hatteras in 2010-2015 (~10 cm) was mostly accounted for by an unprecedented warming of the Florida Current.**

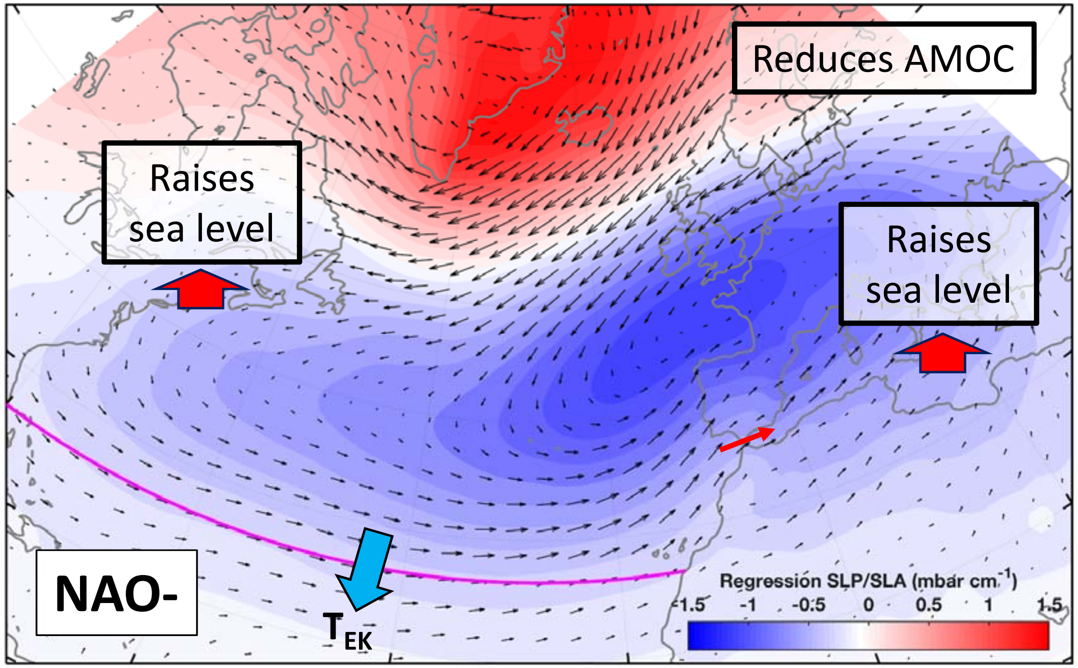
Domingues et al., (2018)

3. Large-scale wind forcing as a common driver

Regression of SLP and wind on AMOC at 26.5N



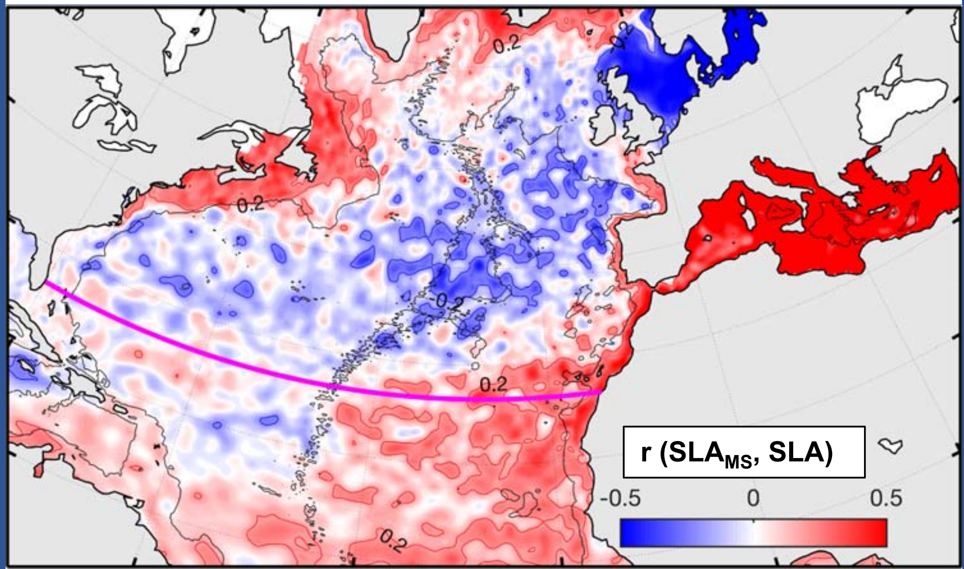
Regression of SLP and wind on sea level in the Med. Sea



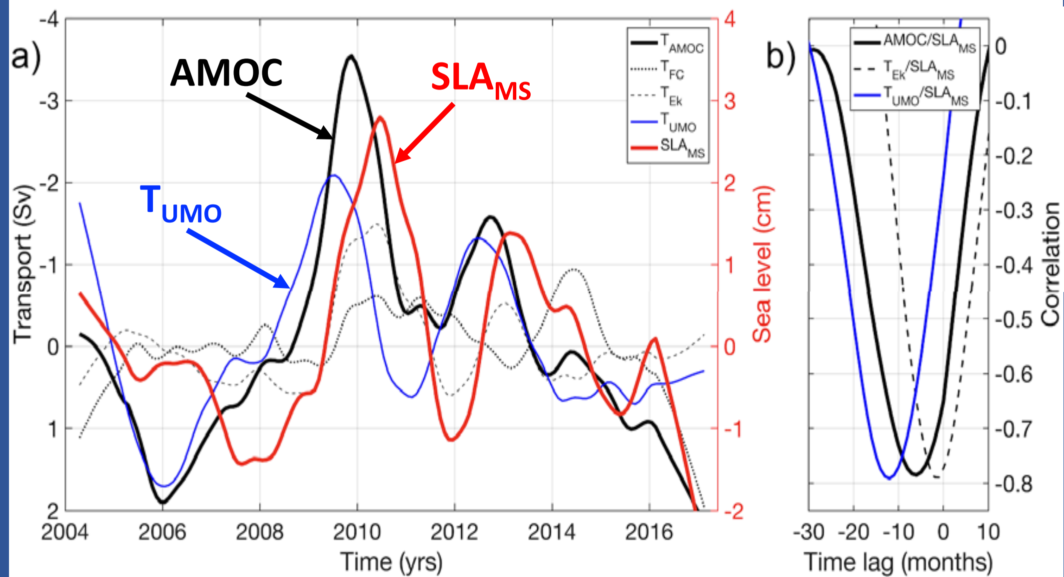
- Both the AMOC and the Mediterranean sea level are linked to large-scale wind forcing, modulated by North Atlantic Oscillation: the same atmospheric circulation pattern drives the Ekman transport at 26.5N and impacts the net mass flow into the Mediterranean Sea (Volkov et al., 2019; Volkov & Landerer, 2015; Landerer & Volkov, 2013).
- Anticorrelation between the AMOC and sea level along New England coast also arises from "ageostrophic processes forced by temporally coherent, spatially separated local atmospheric forcing mechanisms" (Piecuch et al., 2019).

4. Relation to gyre-scale thermodynamic processes

Correlation between the dynamic SLA_{MS} and SLA



Low-pass filtered AMOC components and Mediterranean sea level (SLA_{MS})

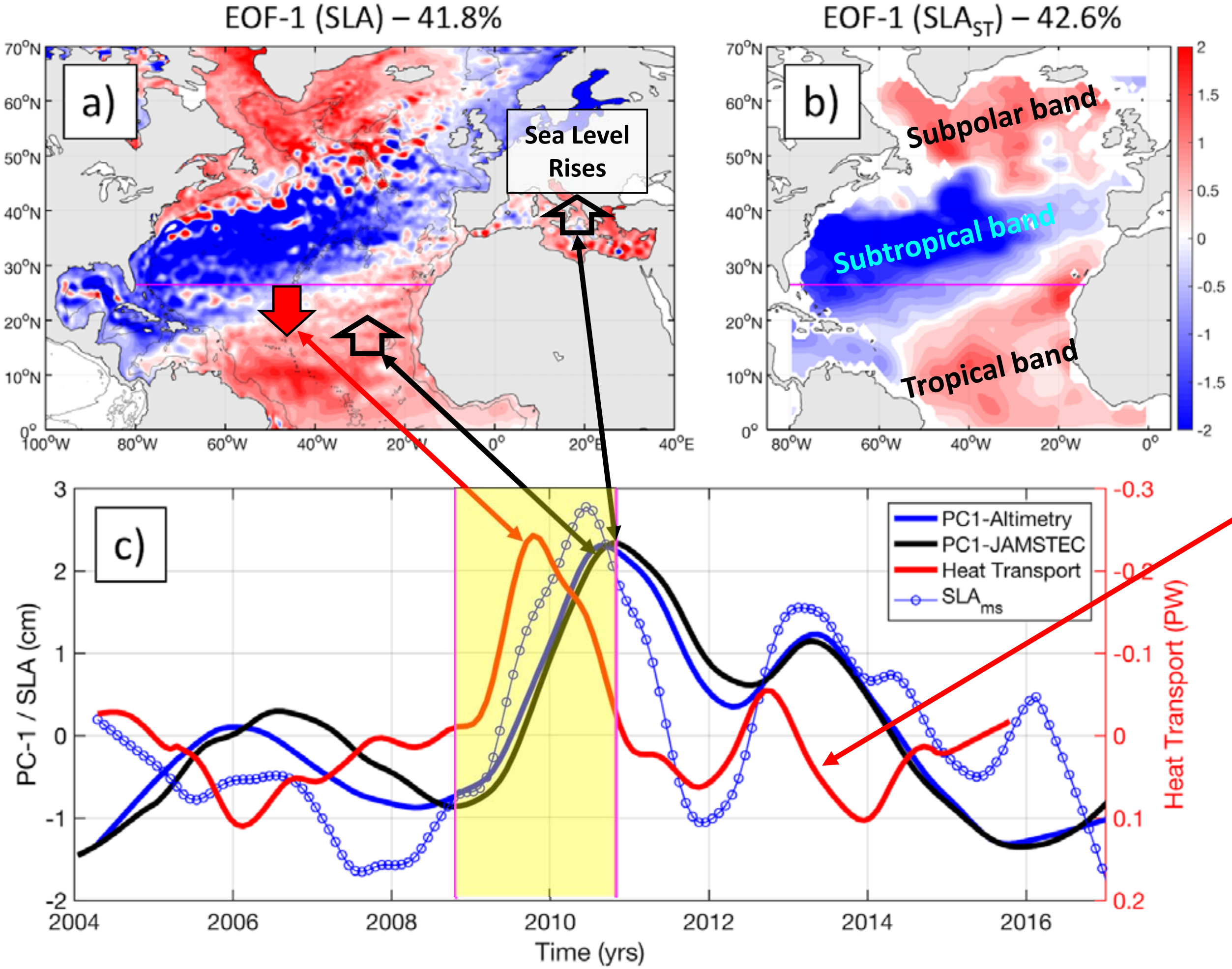


- ❑ Correlation map suggests that sea level averaged over the Mediterranean Sea (SLA_{MS}) is related to large-scale baroclinic processes in the North Atlantic
- ❑ A band of high correlation along the northwest African coast suggests the role of coastally trapped waves in propagating sea level signal northward (e.g. Calafat et al., 2012)
- ❑ On interannual time scales, AMOC & T_{UMO} are correlated with SLA_{MS} and lead it by 6 & 12 months, respectively → large-scale ocean circulation can potentially influence SLA_{MS}

Volkov et al., J. Clim. (2019)

5. The North Atlantic SSH Tripole

Leading mode of the interannual dynamic sea level variability in 2004-2016

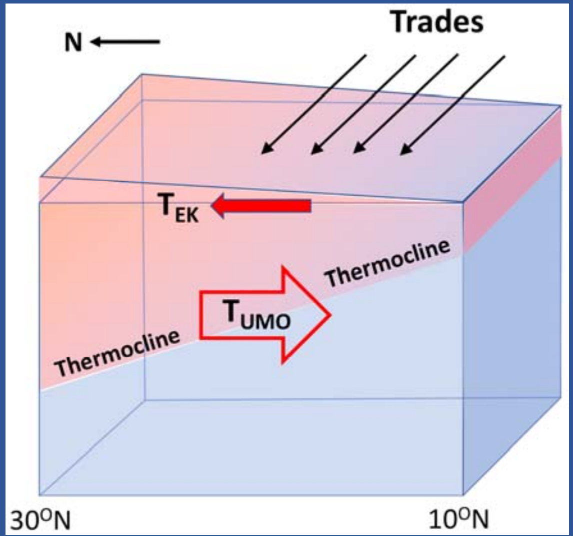


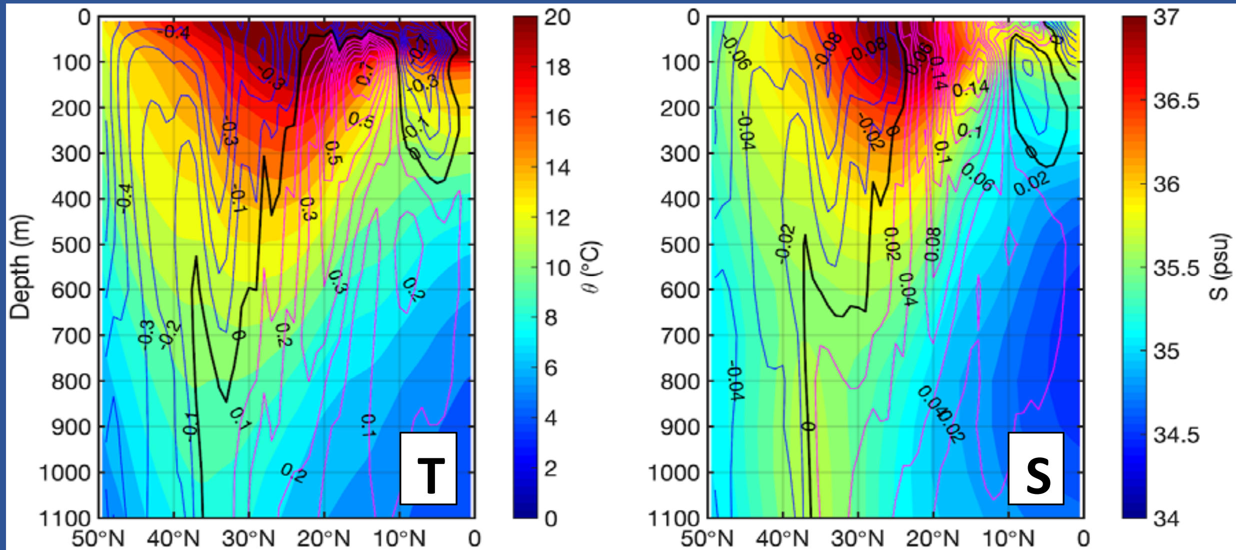
- Interannual dynamic sea level variability in the North Atlantic exhibits a TRIPOLE pattern.
- The RAPID-MOCHA-WBTS section lies approximately along the boundary between the subtropical and tropical bands of the TRIPOLE.
- The southward anomalies of Meridional Heat Transport (MHT) across 26.5N in 2009 and 2012 are followed by higher sea level in the tropical band of the TRIPOLE and in the Mediterranean ~1 year later.

Why are the southward MHT anomalies at 26.5N followed by positive SLA in the tropical band of the TRIPOLE?

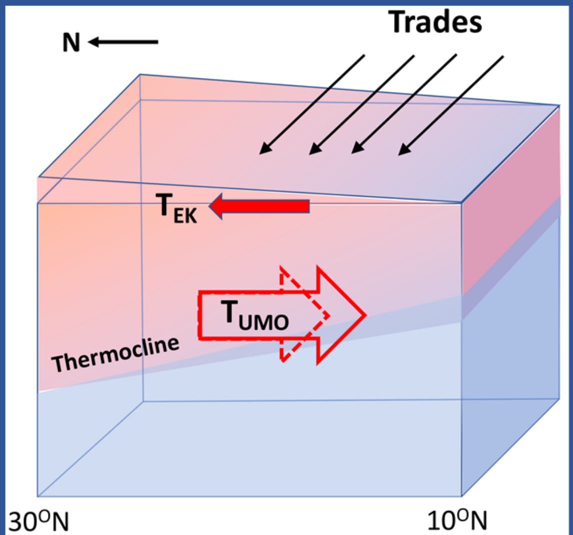
Volkov et al., J. Clim. (2019)

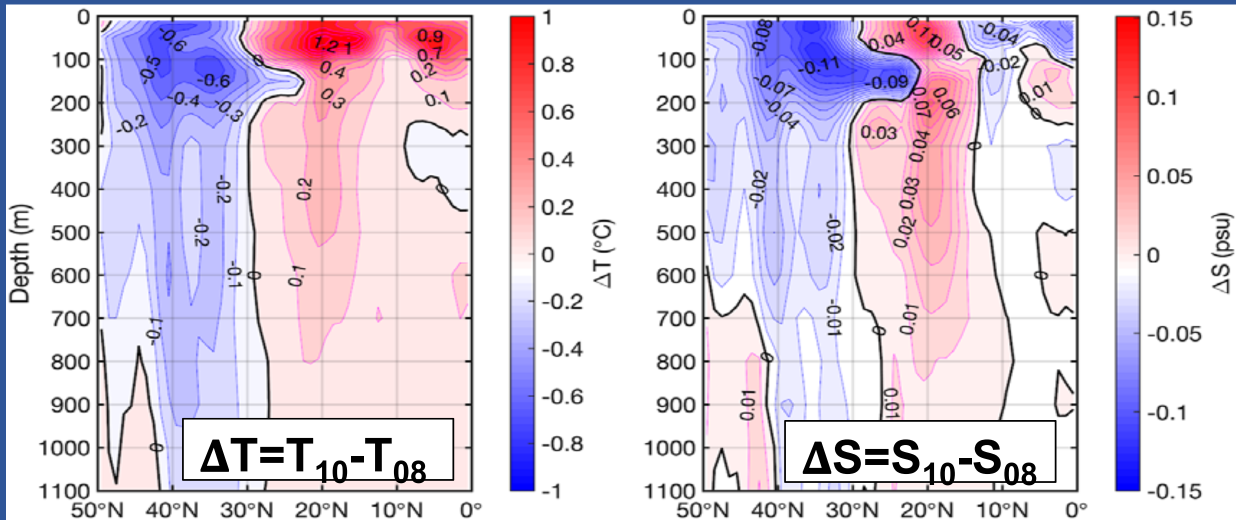
6. Relationship between the AMOC and the Tripole: 2008-2010 case





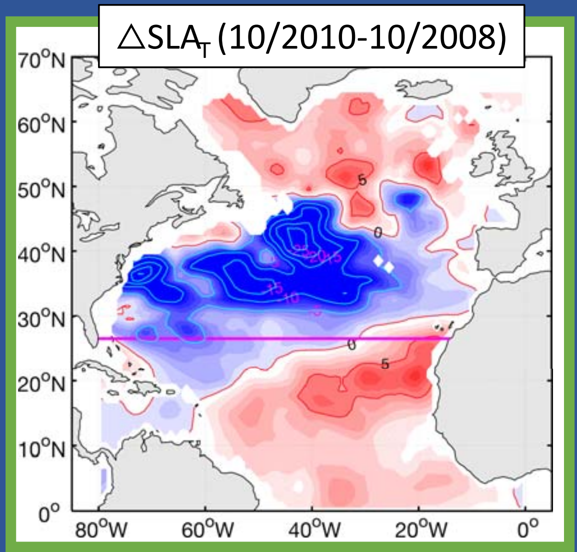
Mean State 2004-2018 From Argo

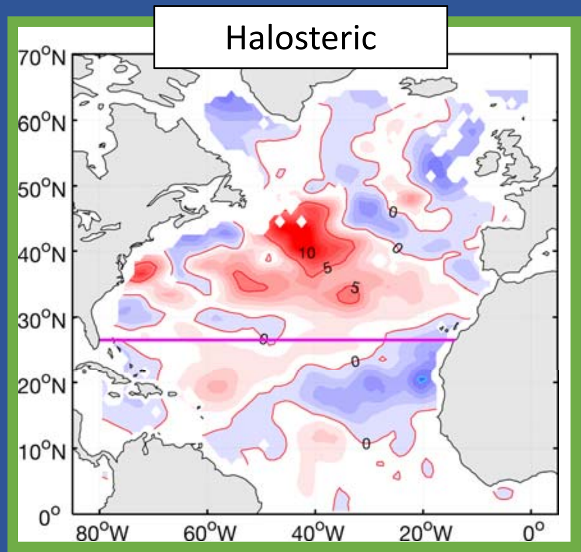


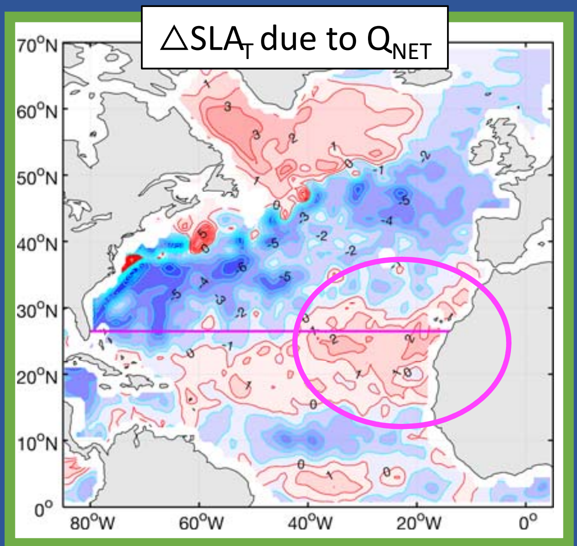


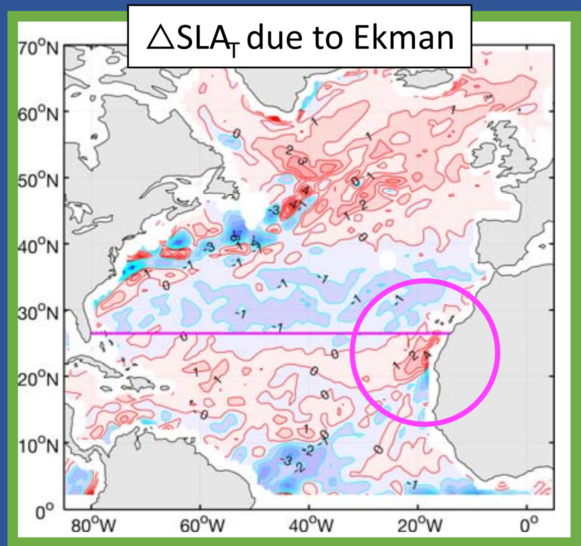
Southward T_{UMO} anomaly in 2009

7. Thermosteric sea level budget in 2008-2010

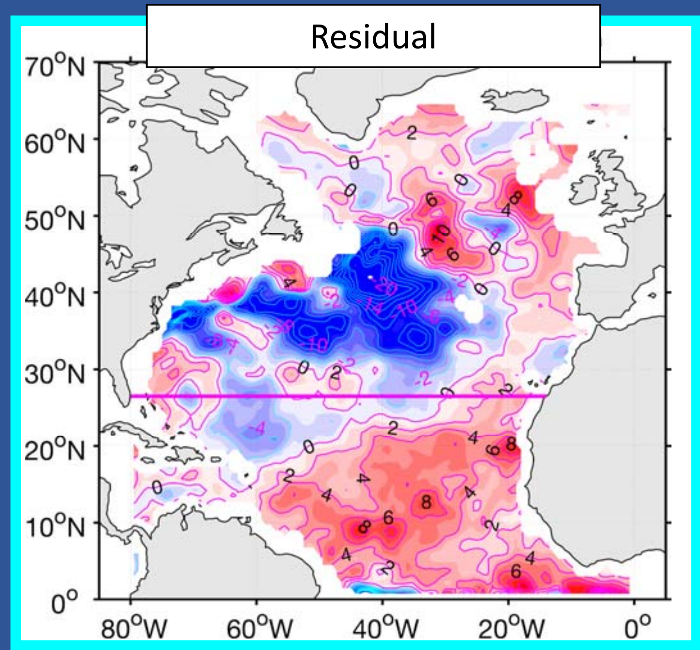








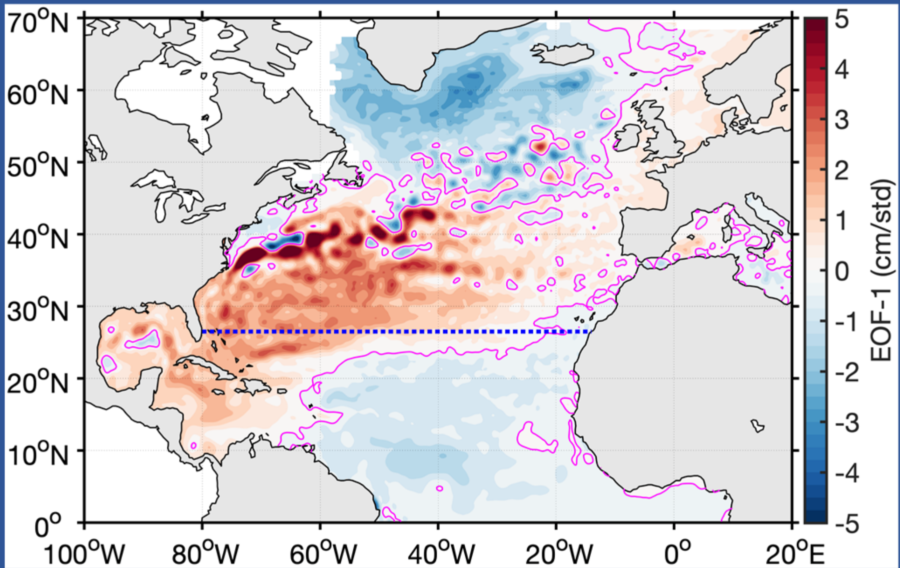
- **The NA SSH Tripole is mostly determined by the thermosteric component (changes in heat content), which is partially offset by the halosteric component**

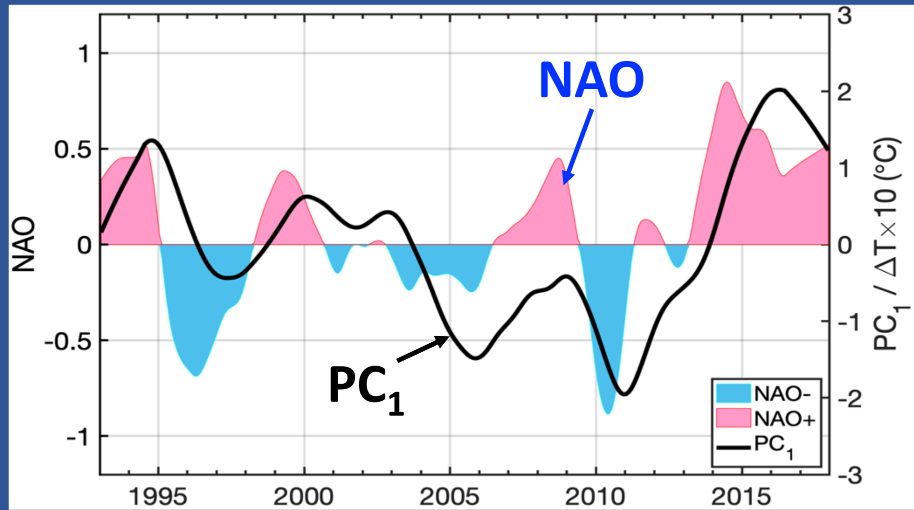


- **The sum of Q$_{NET}$ and Ekman advection does not fully explain the observed thermosteric sea level change in 2008-2010 → geostrophic advection is important**

Volkov et al., J. Clim. (2019)

8. North Atlantic SSH Tripole and North Atlantic Oscillation (NAO)

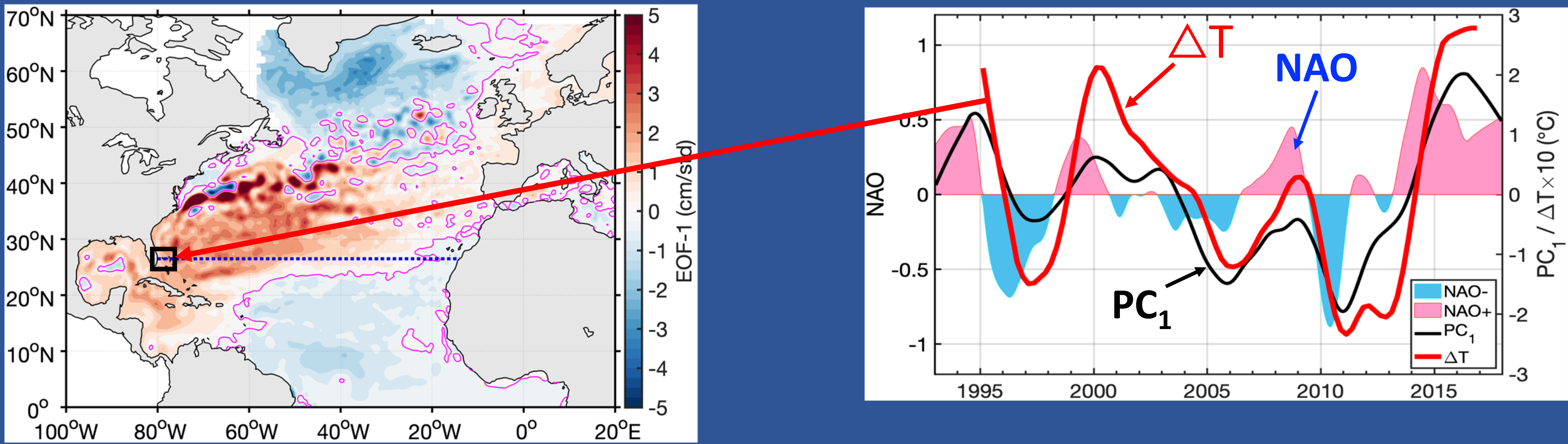




- NA SSH tripole holds for the entire satellite altimetry record

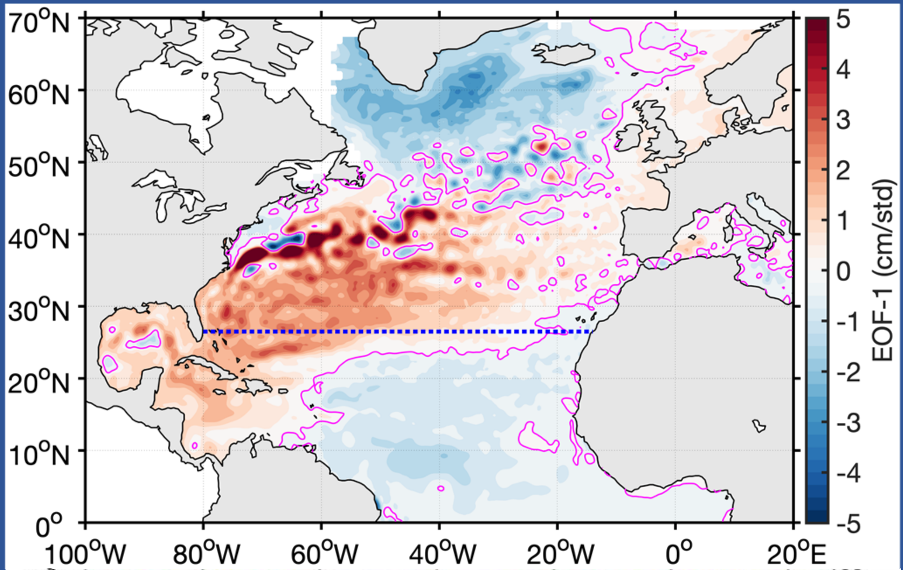
Volkov et al., Geophys. Res. Lett. (2019)

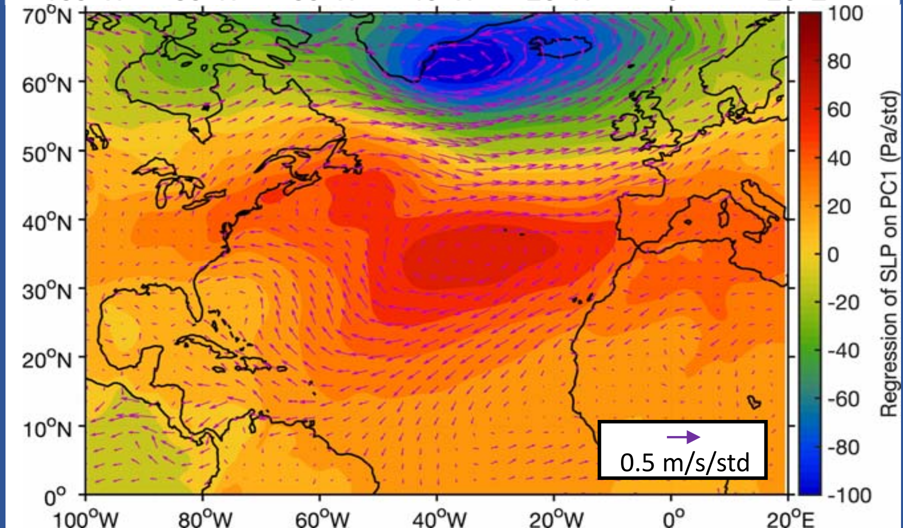
8. North Atlantic SSH Tripole and North Atlantic Oscillation (NAO)

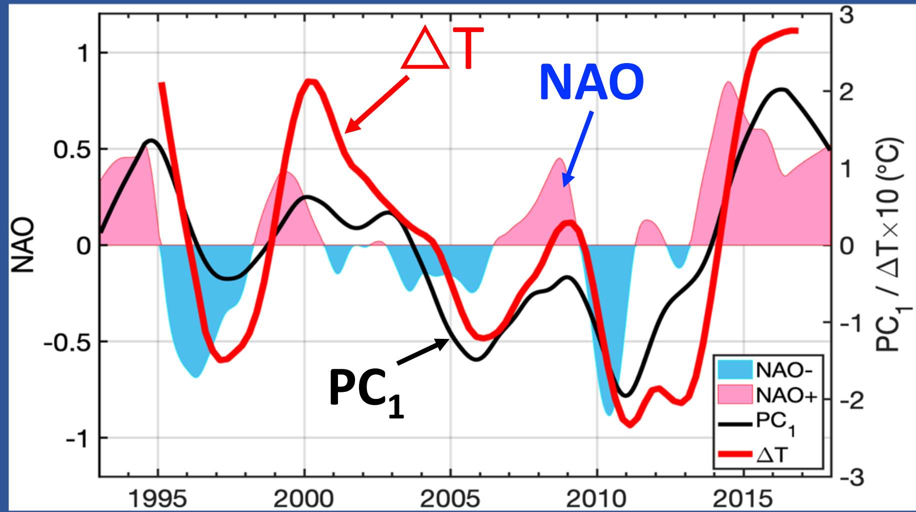


- NA SSH tripole holds for the entire satellite altimetry record
- Tripole is correlated with the upper 700-m temperature in the Straits of Florida (no Argo data there!)

8. North Atlantic SSH Tripole and North Atlantic Oscillation (NAO)



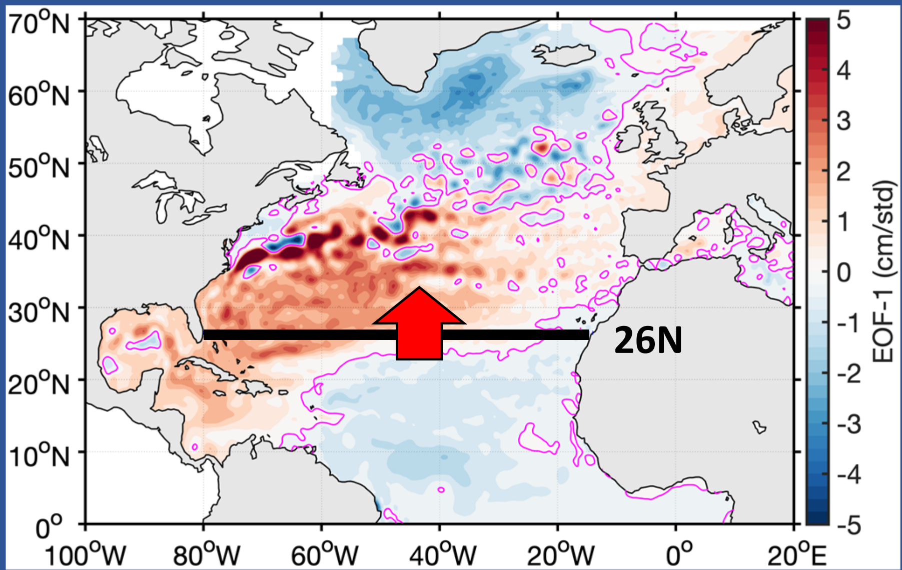


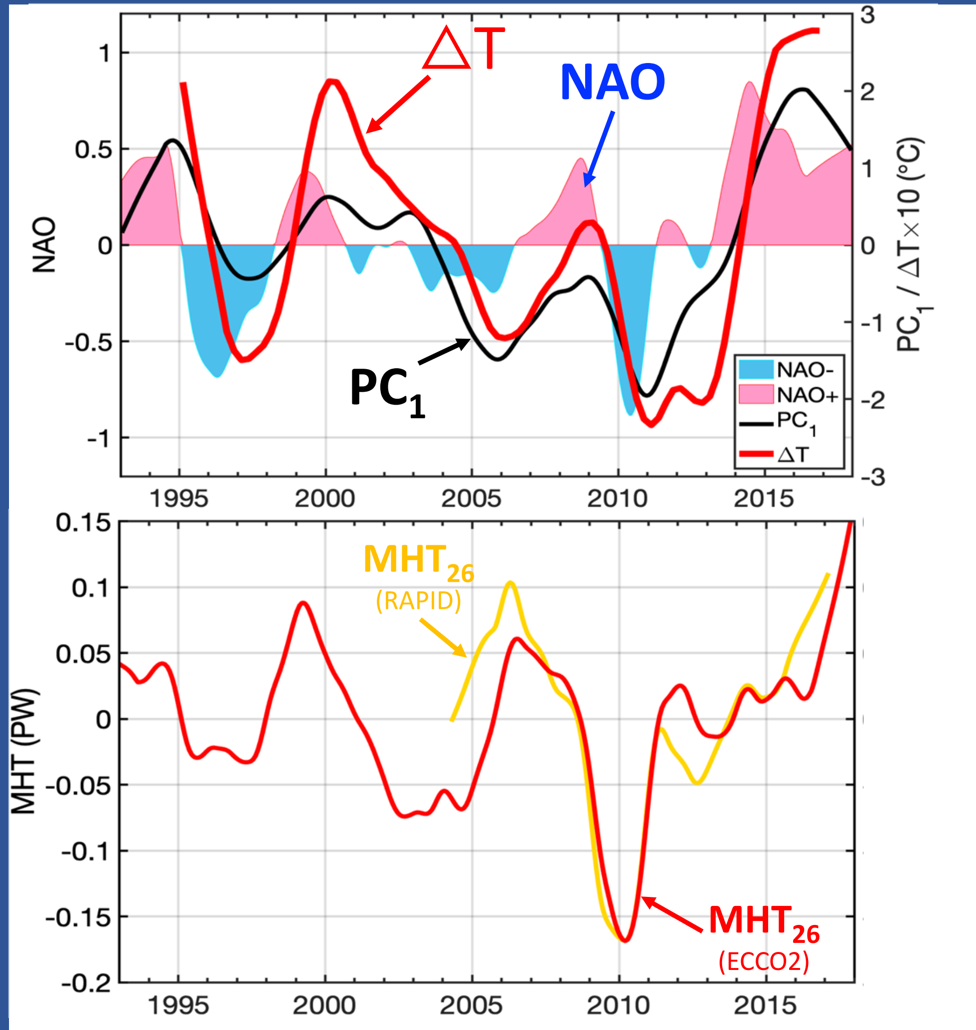


- NA SSH tripole holds for the entire satellite altimetry record
- Tripole is correlated with the upper 700-m temperature in the Straits of Florida (no Argo data there!)
- **The tripole is related to low-frequency NAO (r=0.7 at 9-mth time lag) → results from the adjustment of the large-scale horizontal and overturning ocean circulation to variable surface buoyancy and wind forcing**

Volkov et al., Geophys. Res. Lett. (2019)

9. North Atlantic SSH Tripole and gyre-scale oceanic heat divergence





- ECCO2 model realistically reproduces MHT anomalies at 26N → (assumption) can be used for other time periods and at other latitudes

Volkov et al., Geophys. Res. Lett. (2019)

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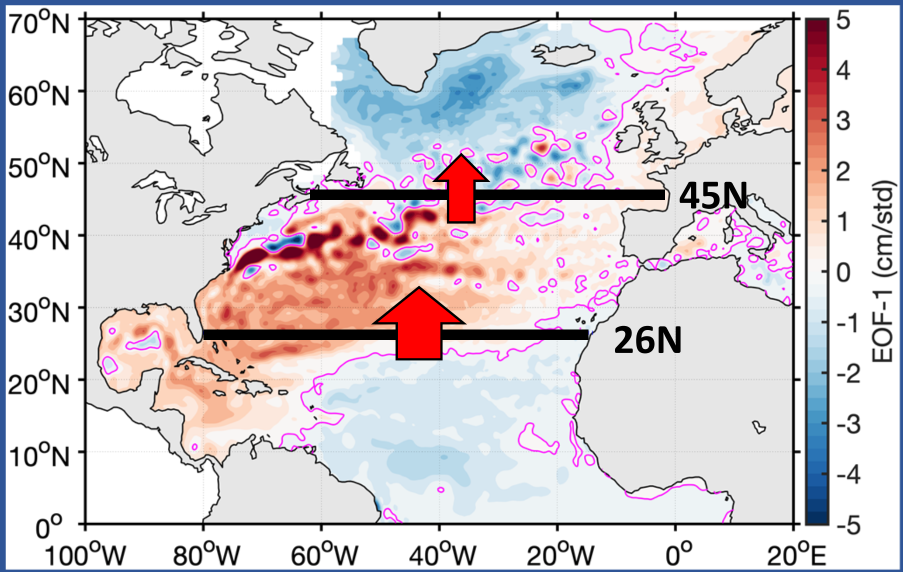
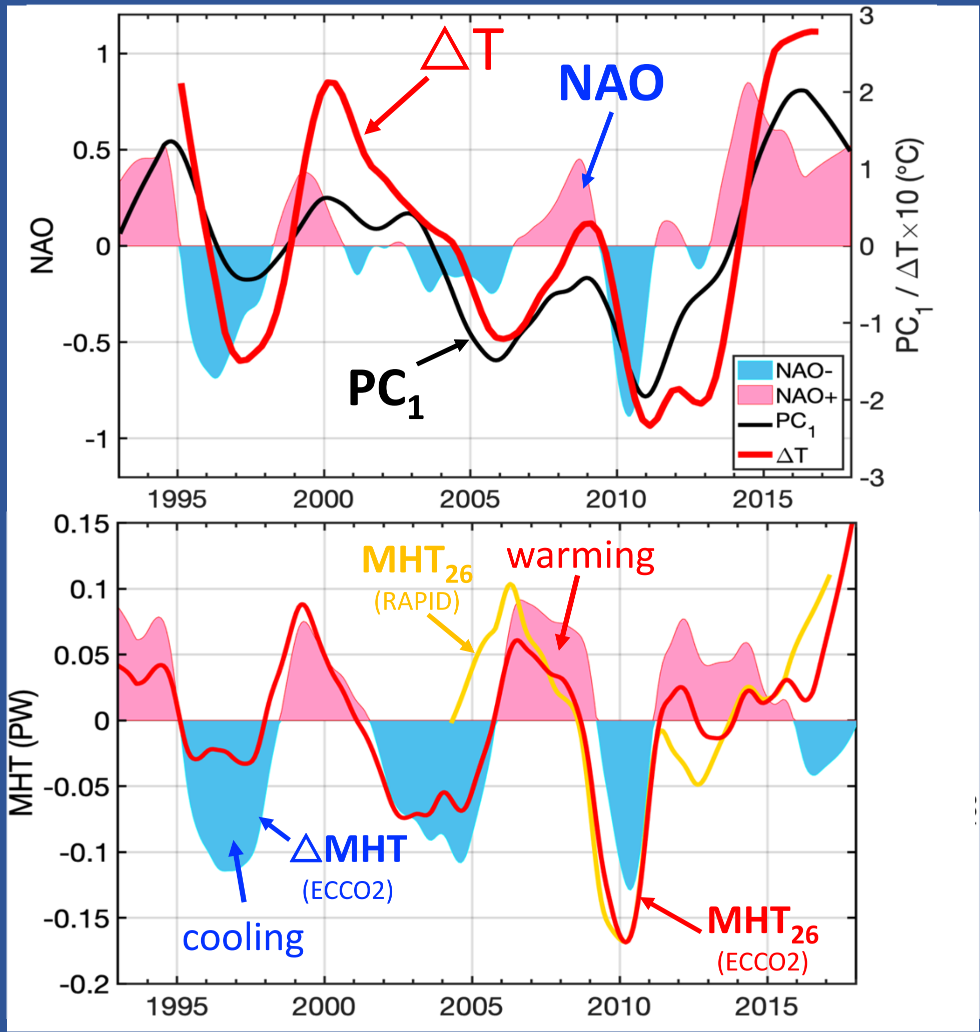


- ECCO2 model realistically reproduces MHT anomalies at 26N → (assumption) can be used for other time periods and at other latitudes
- MHT at 26ºN determines the sign of heat divergence between 26-45ºN



Volkov et al., Geophys. Res. Lett. (2019)

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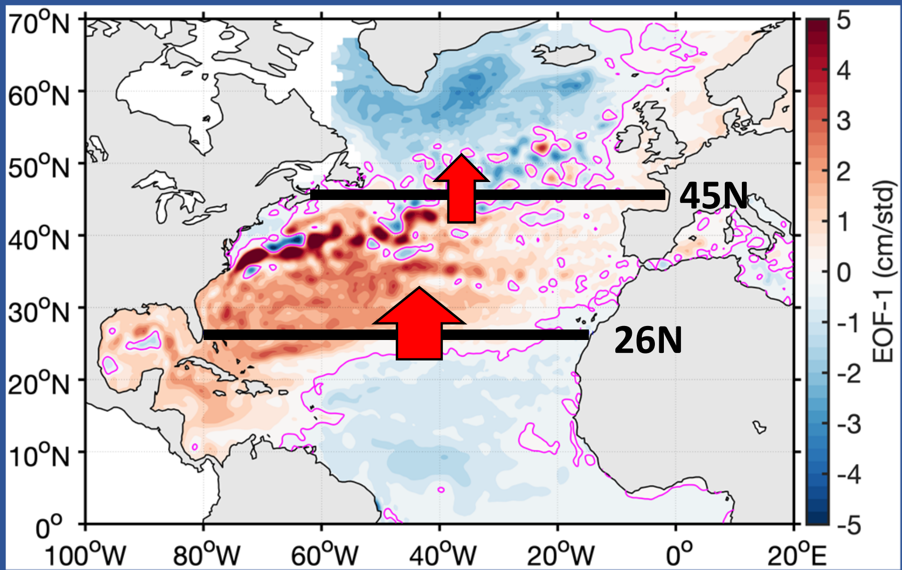
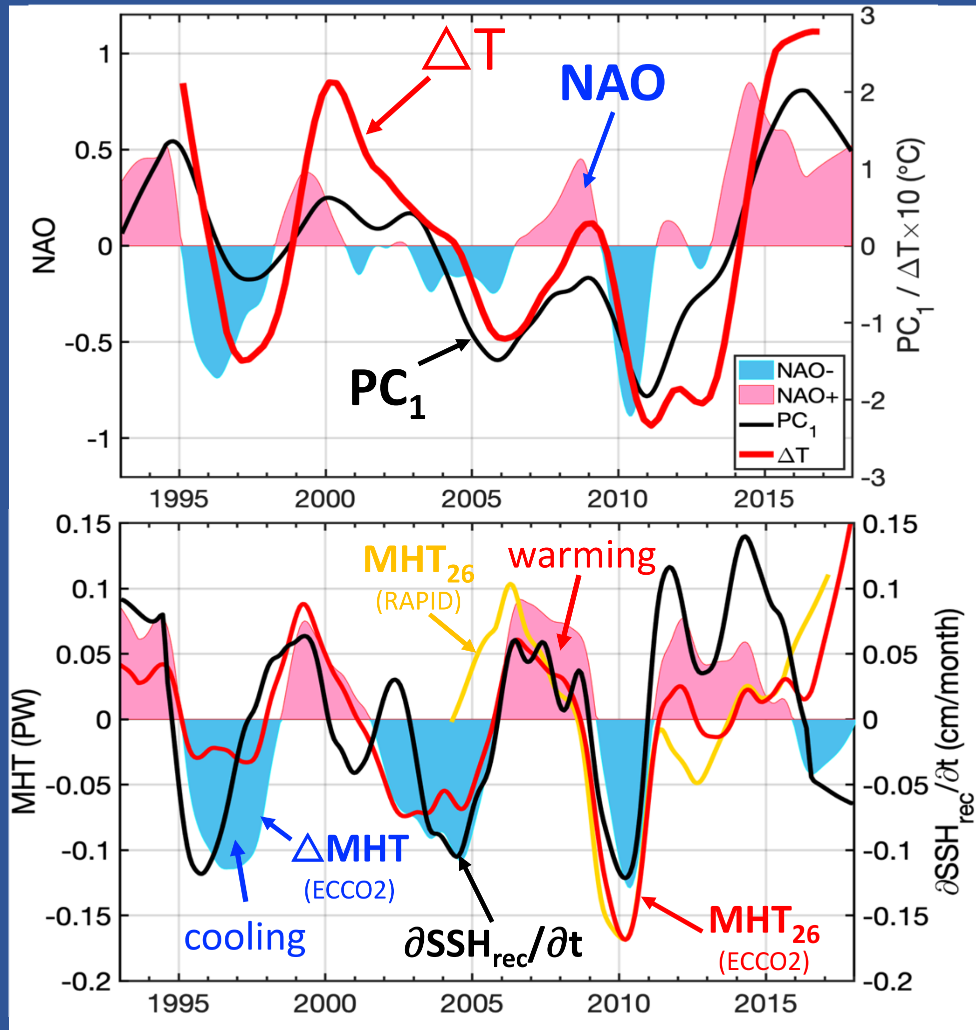
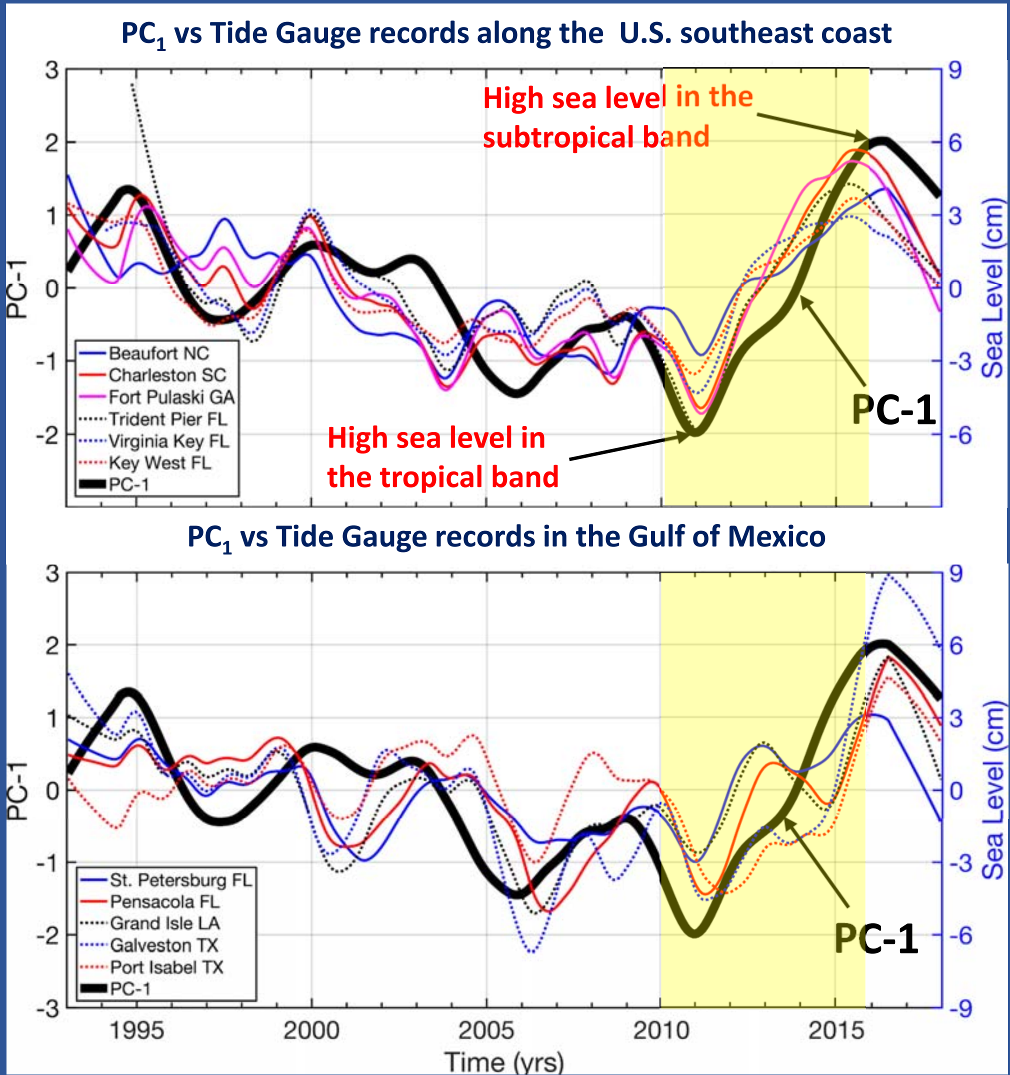


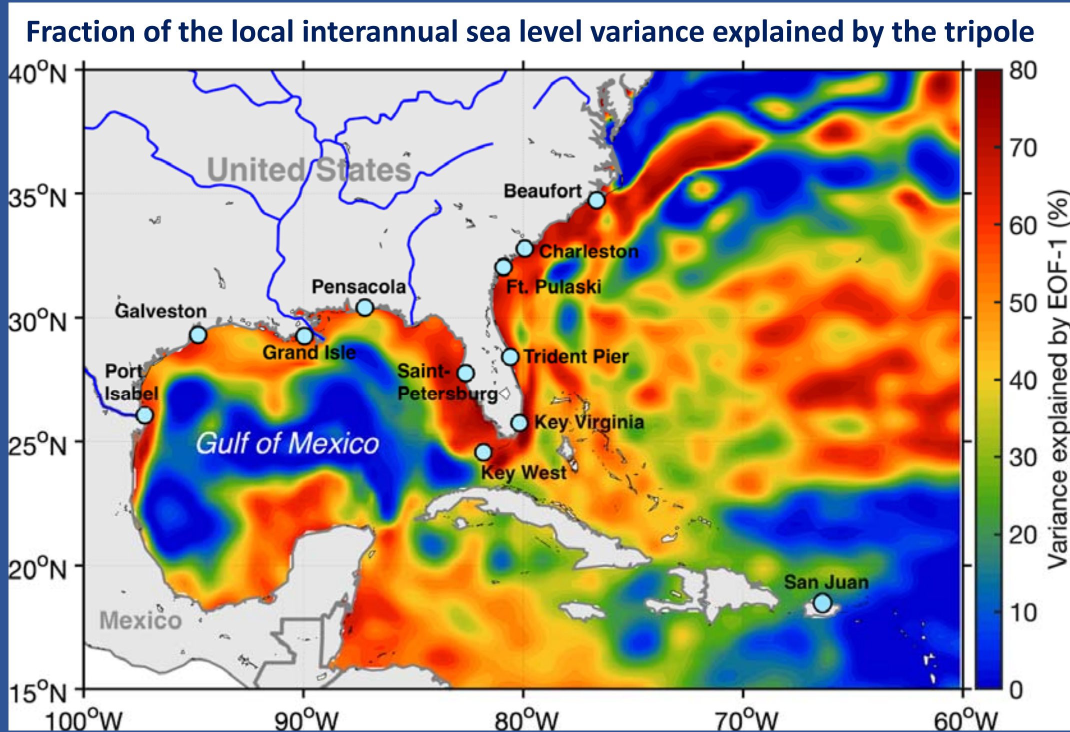
- ECCO2 model realistically reproduces MHT anomalies at 26N → (assumption) can be used for other time periods and at other latitudes
- MHT at 26ºN determines the sign of heat divergence between 26-45ºN
- The NA SSH Tripole is largely driven by oceanic heat divergence modulated by low-frequency NAO



Volkov et al., Geophys. Res. Lett. (2019)

10. North Atlantic SSH Tripole and sea level along the U.S. southeast coast





- The NA SSH Tripole explains 60-80% of the local interannual coastal sea level variance south of Cape Hatteras, in the Gulf of Mexico, and in the western Caribbean
- The tripole-related warming in the Straits of Florida accounted for the dynamic sea level rise in 2010-2015 along Florida east coast

Volkov et al., GRL (2019); Domingues et al., GRL (2018)

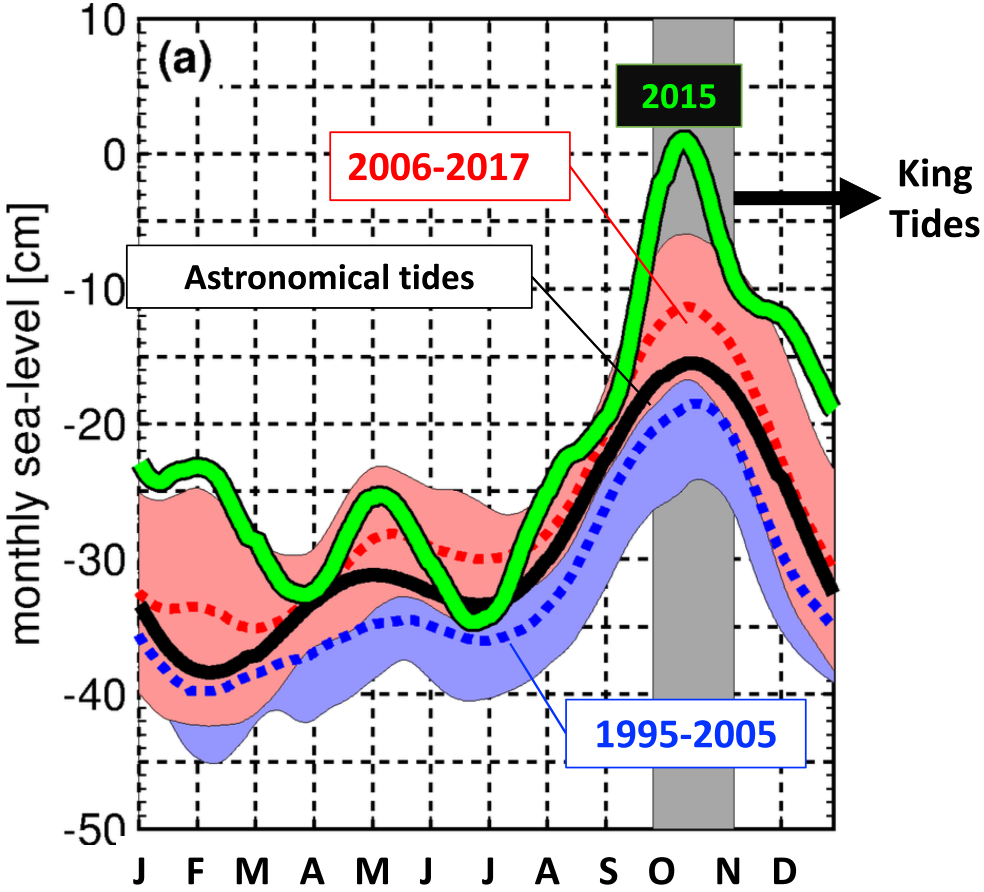
11. Implications: Why do we care about a few centimeters?

2017 King Tide in Miami Beach

Photo by Grant Rawson (UM/CIMAS)

2015 King Tide in Miami

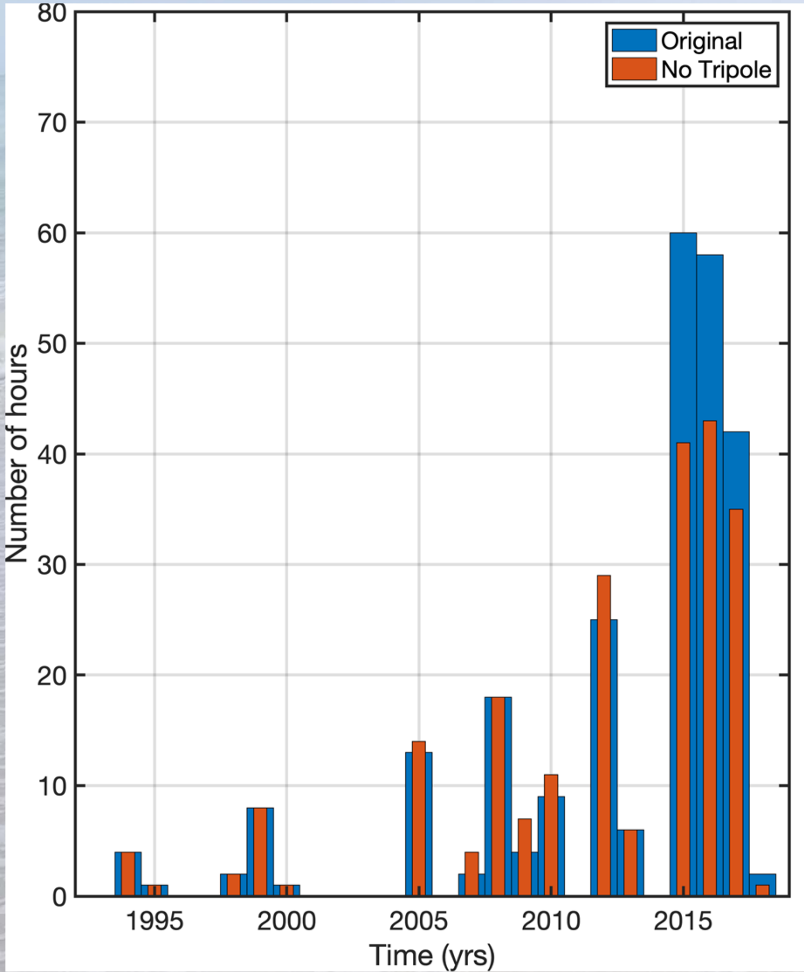
Monthly Sea-level in Miami



Extremely high 2015 King Tides in Miami were the result of the combined effect of the global mean sea level rise and the North Atlantic SSH Tripole.

Credits: R. Domingues (UM/CIMAS)

11. Implications: Tidal flooding in Miami with and without the NA SSH Tripole

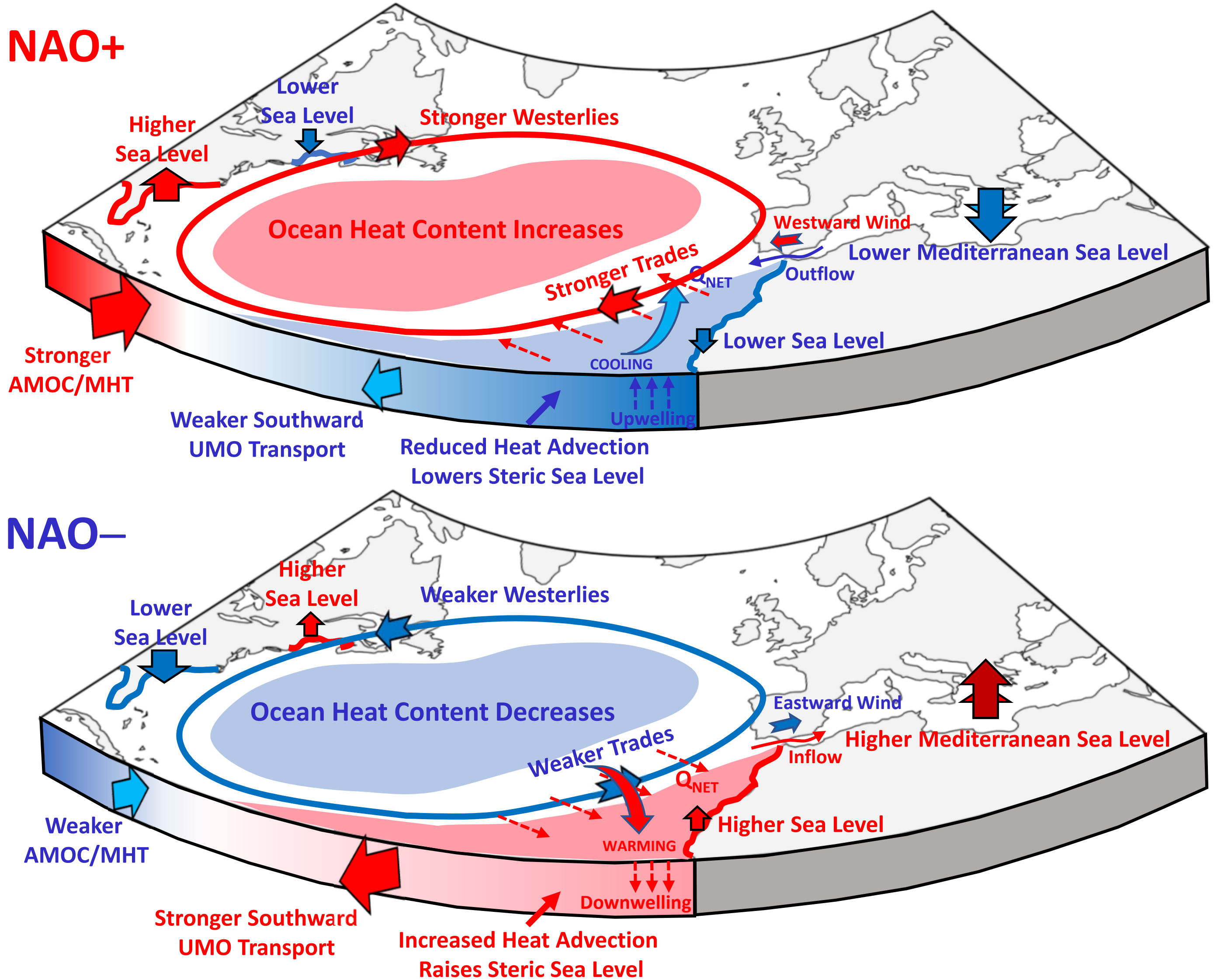


With the rising global mean sea level, the interannual oceanic heat convergence in the subtropical band of the North Atlantic SSH Tripole is already increasing the number of flooding hours in Miami

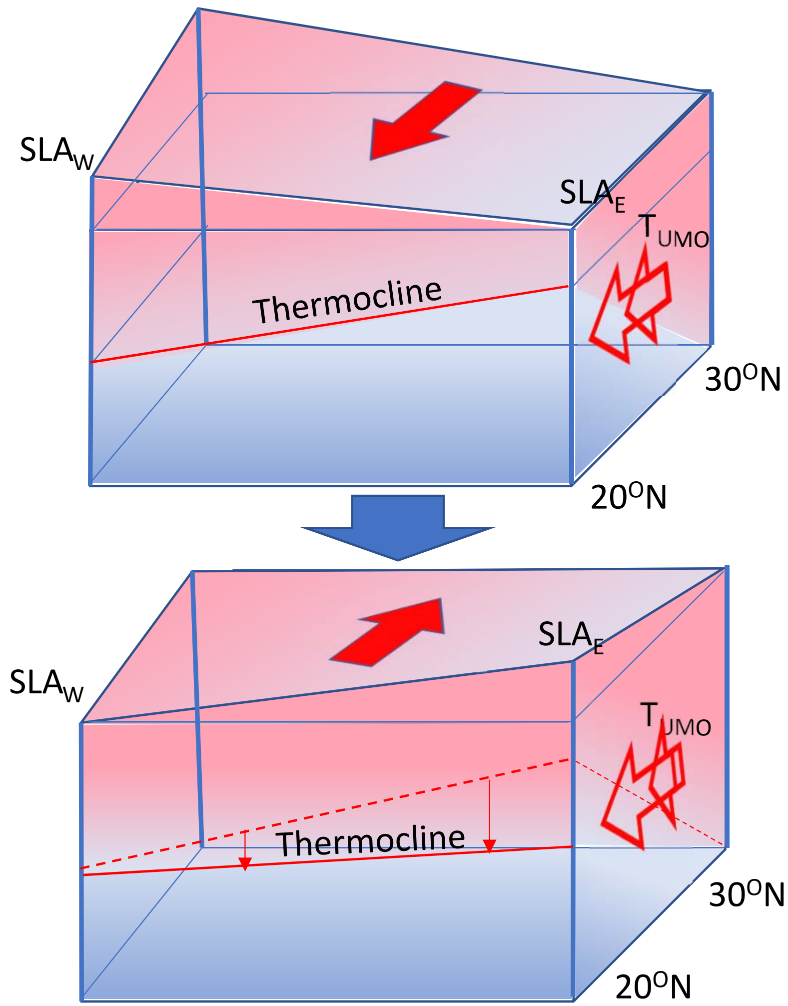
12. Conclusions

- The Atlantic Meridional Overturning Circulation is largely responsible for driving the interannual variability of gyre-scale sea level and heat content, characterized by the North Atlantic SSH Tripole.
- Heat exchange between the subtropical and tropical bands of the Tripole, well represented by heat transport across RAPID-MOCHA-WBTS section at 26.5N, drives thermosteric sea level change in both bands:
  - Thermosteric sea level anomalies in the tropical band can reach the Strait of Gibraltar and impact sea level in the Mediterranean
  - Thermosteric sea level in the subtropical band explains most of the interannual sea level variance along the U.S. southeastern seaboard, including the Gulf of Mexico
- Given that sea level is related to the time integral of oceanic heat advection, there is a potential for multi-year predictability using available observations of transports at the RAPID-MOCHA-WBTS section

Summary



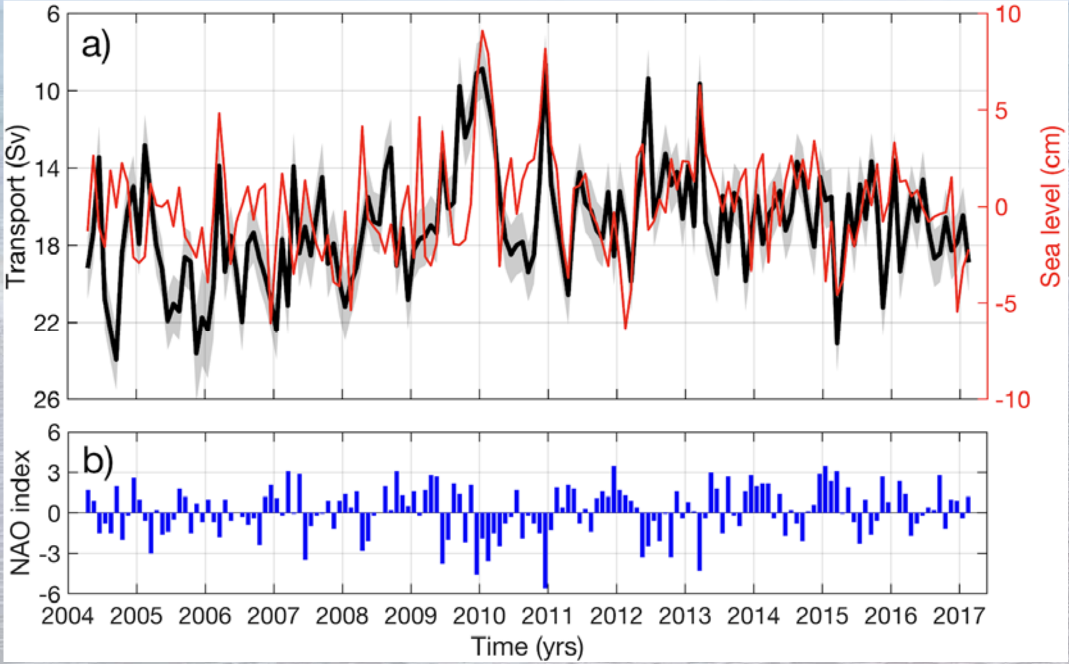
Sea Level Feedback on AMOC?



THANK YOU!

Questions?

Supporting Information: AMOC and Mediterranean sea level



Why are the AMOC at 26.5N and the Mediterranean sea level (SLA_{MS}) correlated?

Zero-lag correlations between the AMOC components, Mediterranean sea level, and NAO

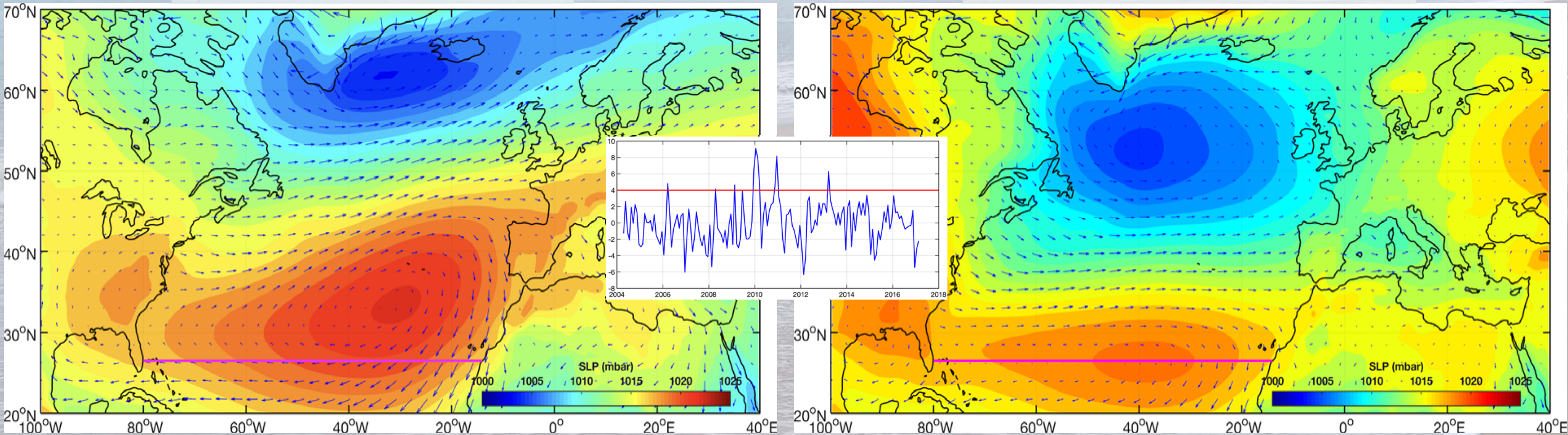
	SLA_{MS}	AMOC	T_{FC}	T_{EK}	T_{UMO}
SLA_{MS}		-0.40	-0.18	-0.52	0.04
AMOC			0.44	0.57	0.42
NAO	-0.48	0.43	0.13	0.77	-0.15

Correlation between the Mediterranean sea level (SLA_{MS}) and the AMOC arises mainly due to the Ekman transport (T_{EK}). The correlation of both the AMOC and SLA_{MS} with NAO suggests that *the large-scale wind forcing is a common driver.*

Volkov et al., J. Clim. (2019)

Supporting Information: AMOC and Mediterranean sea level

1979-2017 climatology | **Composite for SLA_{MS}>4 cm**

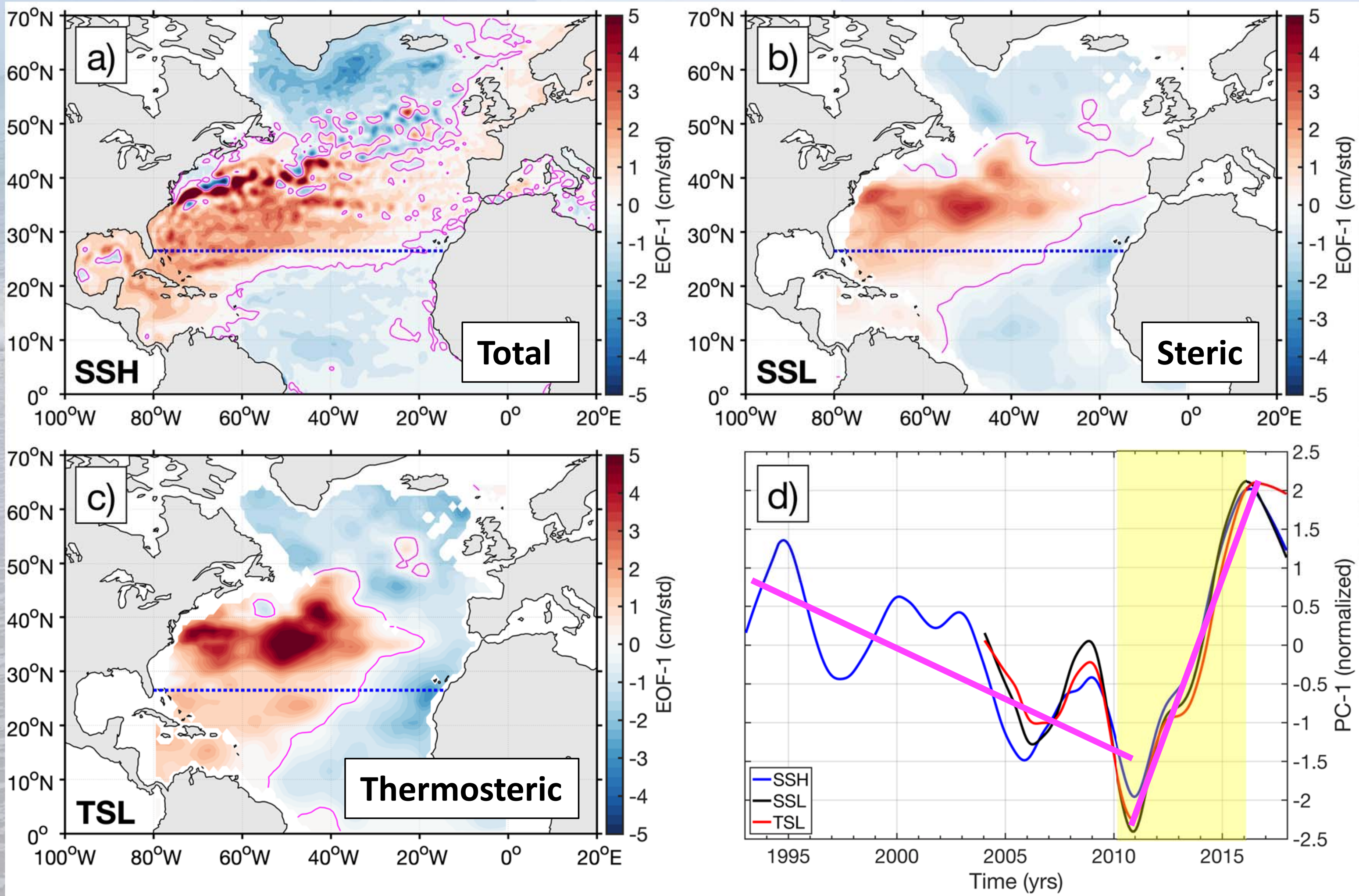


High Mediterranean sea level is observed when the subtropical High and subpolar Low centers become weaker and shit southward, so that the westerly winds are centered at about 35ºN and favor the flow into the Mediterranean Sea.

Volkov et al. (2019); Volkov & Landerer (2015); Landerer & Volkov (2013)

Supporting Information: North Atlantic SSH Tripole

EOF-1 (1993 – 2017)



The North Atlantic SSH TRIPOLE holds for the entire satellite altimetry record and it is mostly determined by the thermosteric sea level variability

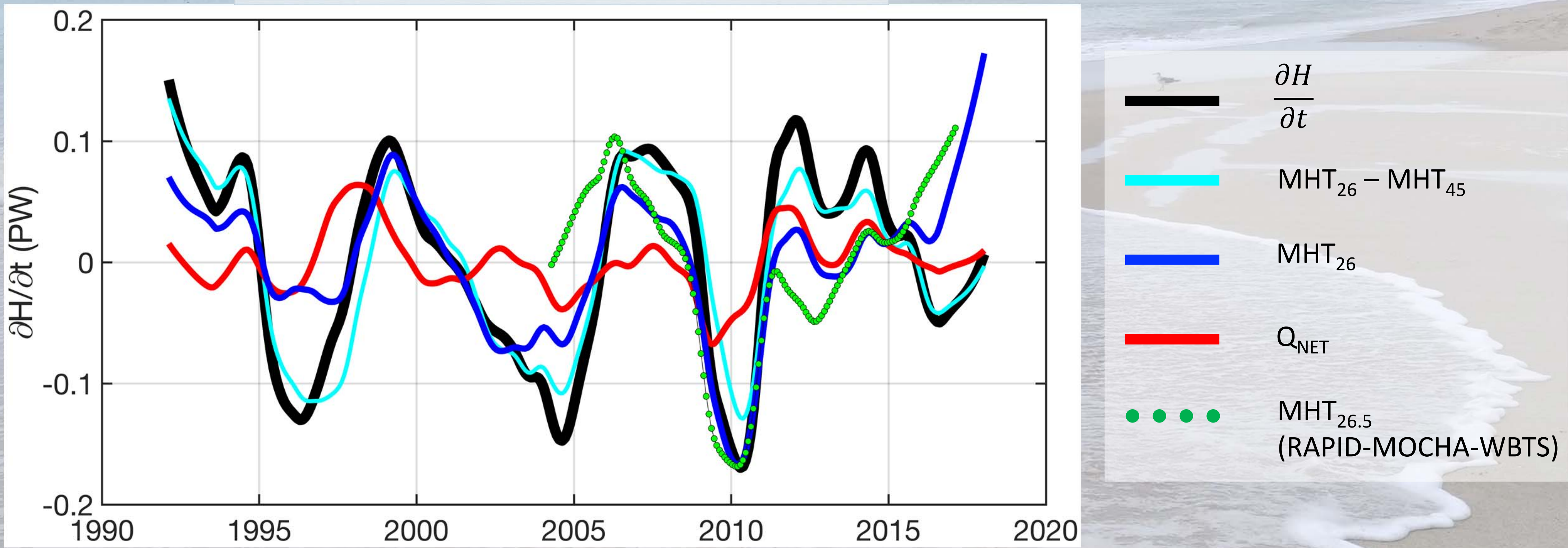
A decadal lowering of sea level occurred in 1993-2010 in the subtropical band of the TRIPOLE

A rapid increase of sea level and associated heat content occurred in 2010-2015, coincident with warming of the Florida Current and accelerated coastal sea level rise along Florida southeast coast

Volkov et al. (2019); Domingues et al. (2018)

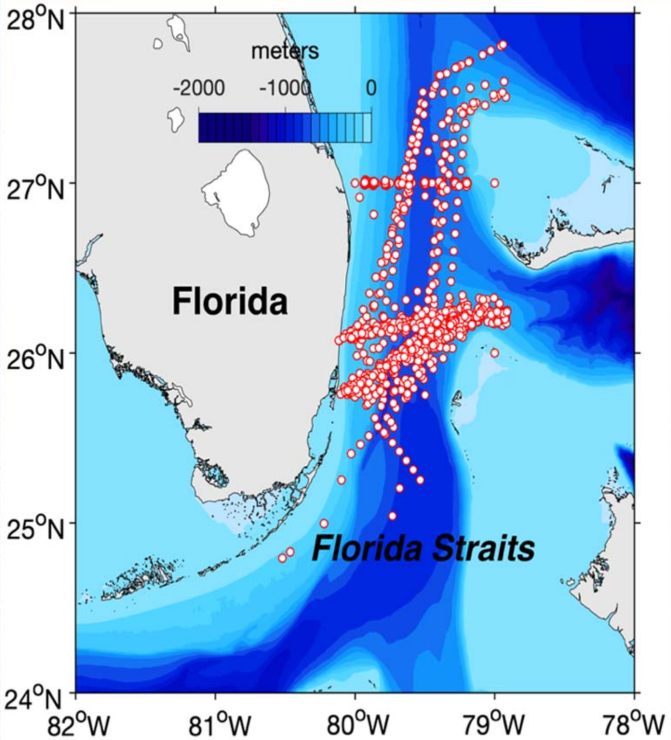
Supporting information: Heat budget between 26N and 45N

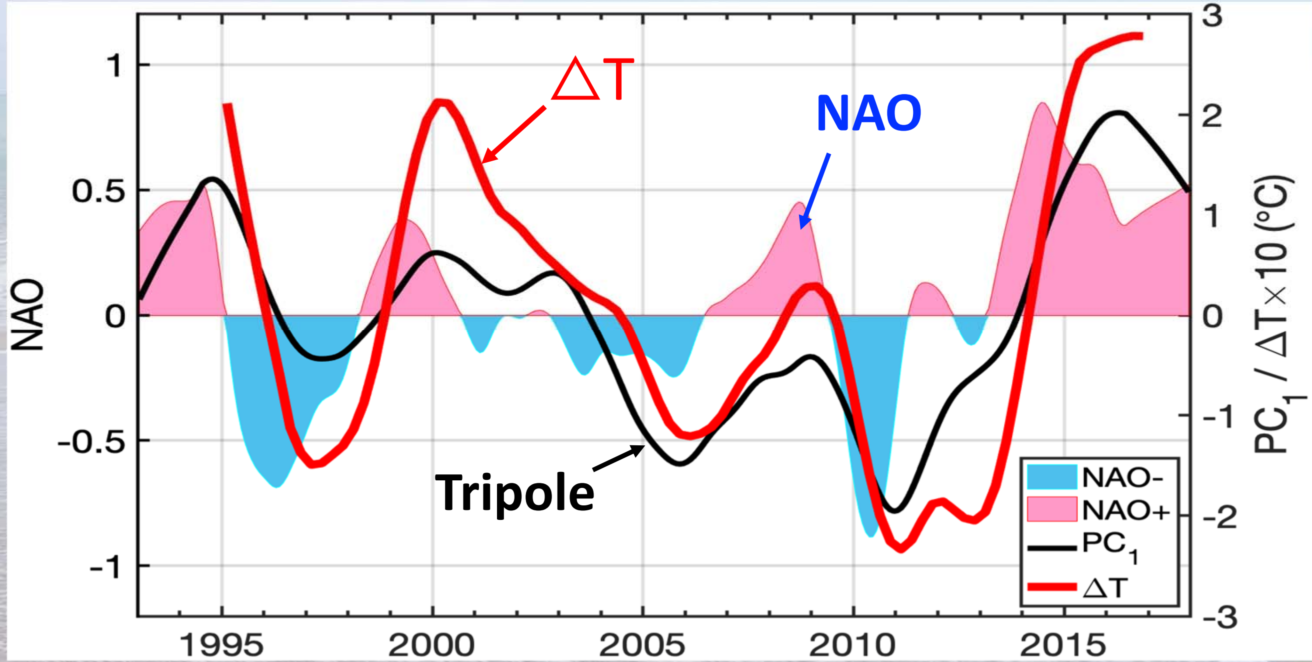
Heat budget between 26N and 45N in ECCO2



Supporting Information: NA SSH Tripole and Florida Current temperature

Locations of 541 CTD and 1925 XBT profiles in the Florida Straits used to calculate △T (no Argo floats here!)





Interannual sea level variability along Florida east coast is associated with thermosteric effects modulated by the North Atlantic SSH Tripole (e.g. warming of the Florida Current in 2010-2015)

Volkov et al., Geophys. Res. Lett. (2019)