# Signature of the Atlantic Meridional Overturning Circulation in the North Atlantic Dynamic Sea Level


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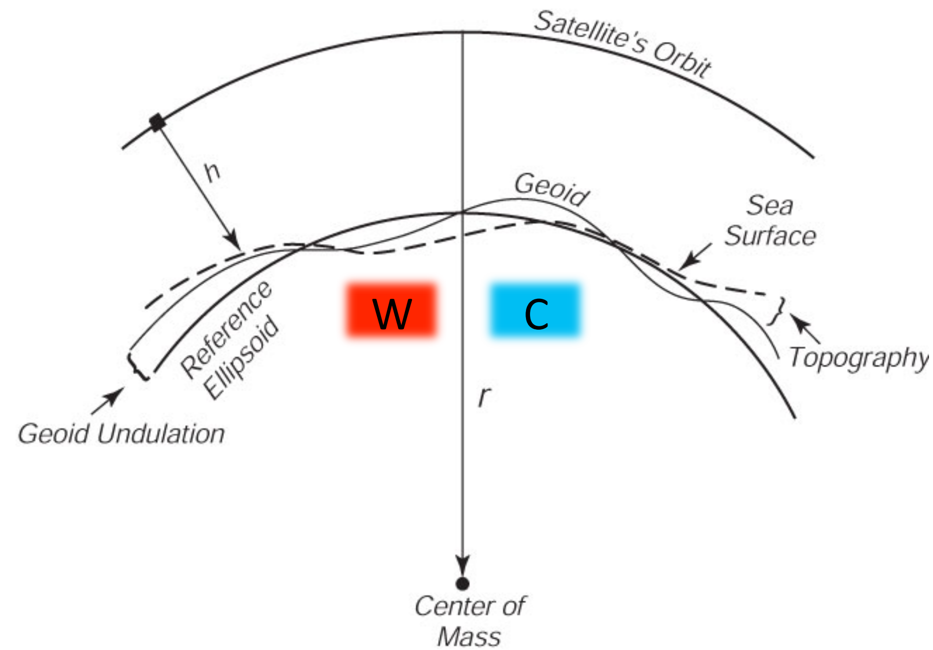
# Outline

- Mean dynamic sea level (DSL) in the North Atlantic and along the U.S. East Coast
- Sea level rise (SLR) observations
  - Satellite altimetry
  - Tide gauges
- GFDL ESM2M simulations and projections
  - Two modes of the DSL variability and change
  - AMOC-DSL relationship
  - 21st century projections of the DSL along the U.S. East Coast
- Conclusions

# Terminology

- Dynamic sea level ($\eta$): the sea surface deviation from the geoid (z=0 in climate models).

$$g\nabla\eta = \underbrace{-\frac{g}{H\rho_0}\int_{-H}^{0}\int_{z}^{0}\nabla\rho\, dz'\, dz}_{baroclinic}\underbrace{-f\mathbf{k}\times\mathbf{V}}_{barotropic}$$

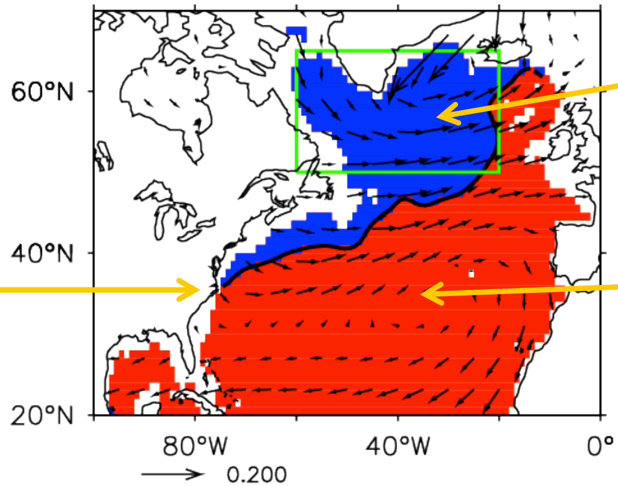


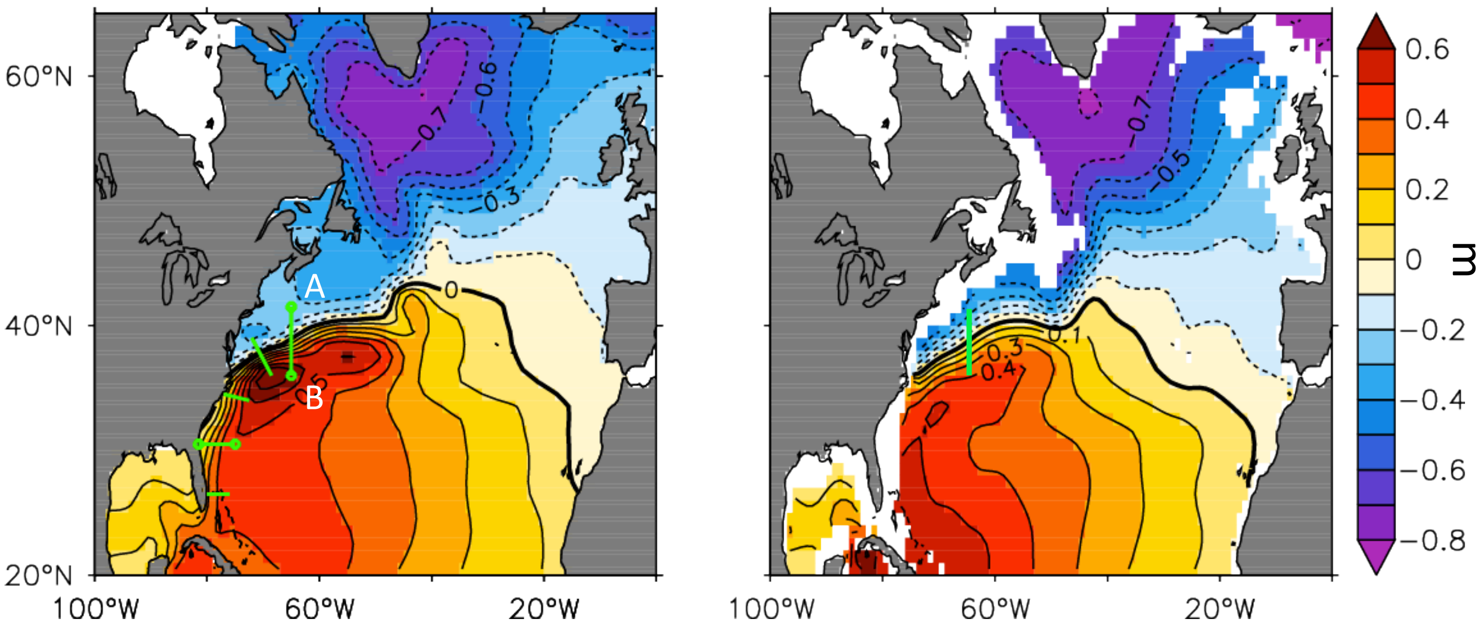

- Steric sea level ($h$): sea level gradient induced by of ocean density variation

$$h(x,y,t) = -\frac{1}{\rho_0}\int_{-Z}^{0}[\rho(T,S,P)-\rho_0]dz$$

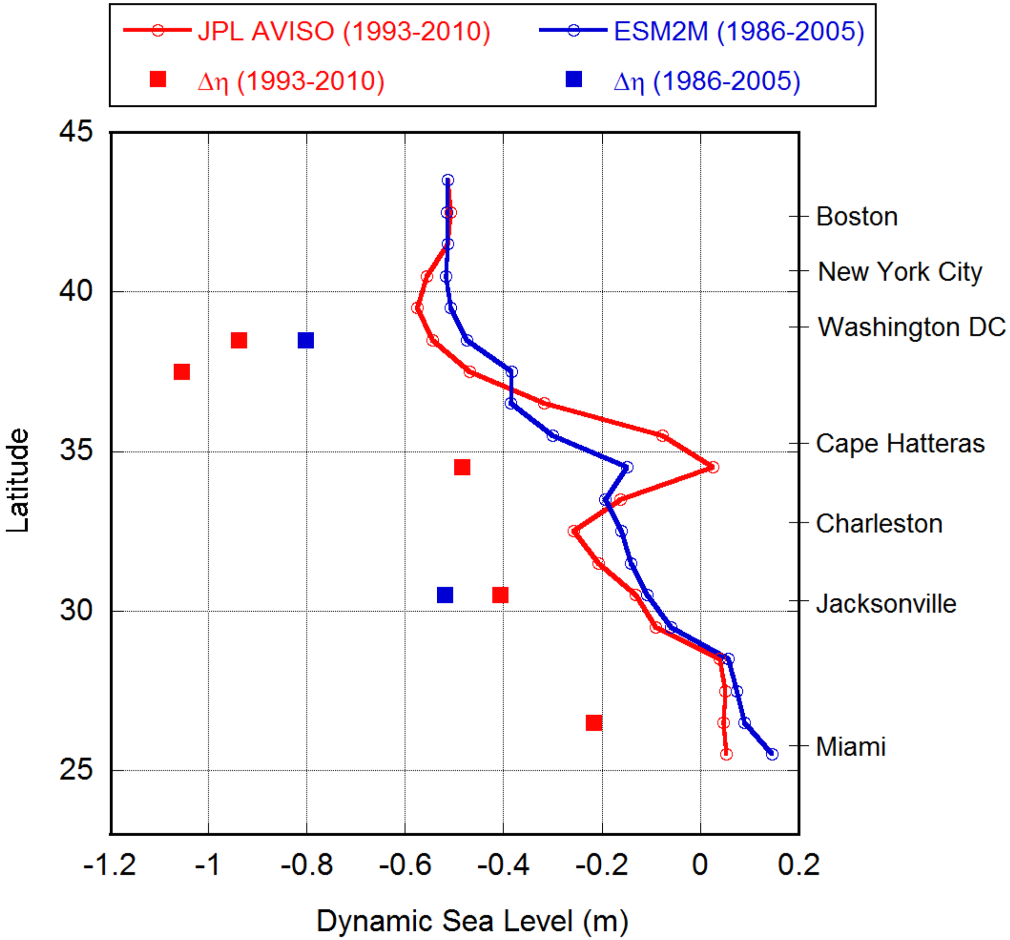
- Thermosteric sea level: temperature effect $h_{thermo}(x,y,t) = -\frac{1}{\rho_0}\int_{-Z}^{0}[\rho(T,S_0,P)-\rho_0]dz$
- Halosteric sea level: salinity effect $h_{halo}(x,y,t) = -\frac{1}{\rho_0}\int_{-Z}^{0}[\rho(T_0,S,P)-\rho_0]dz$

# Mean DSL in the North Atlantic



# Offshore and Alongshore Gradient




- Cross-current DSL difference:
  Cape Hatteras
  Upstream: 0.2-0.5 m
  Downstream: 0.9-1.1 m

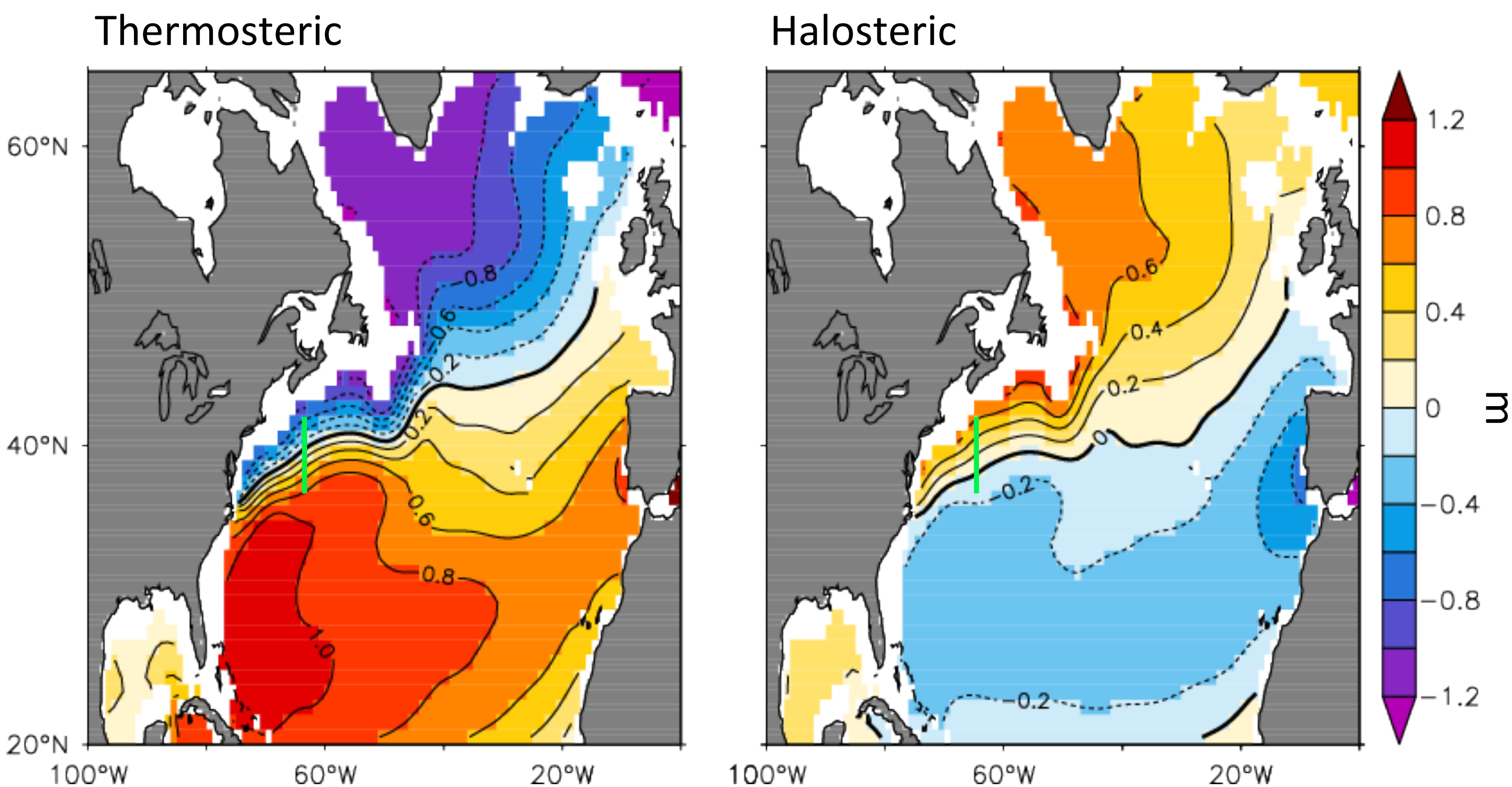
- Alongshore gradient
  - 0.6 m drop from Florida to Maine
  - Strong gradient north of Cape Hatteras

- Steric effect associated with distribution of different water masses

Lines: Mean DSL along the East Coast of U.S.

Rectangles: Mean DSL difference across the Gulf Stream (Δη)

# Temperature and Salinity Effect




- PHC, upper 1500 m
- The DSL gradient is mainly set up by the temperature variation
- Salinity effect partially compensates

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# Decadal Trend of the North Atlantic DSL

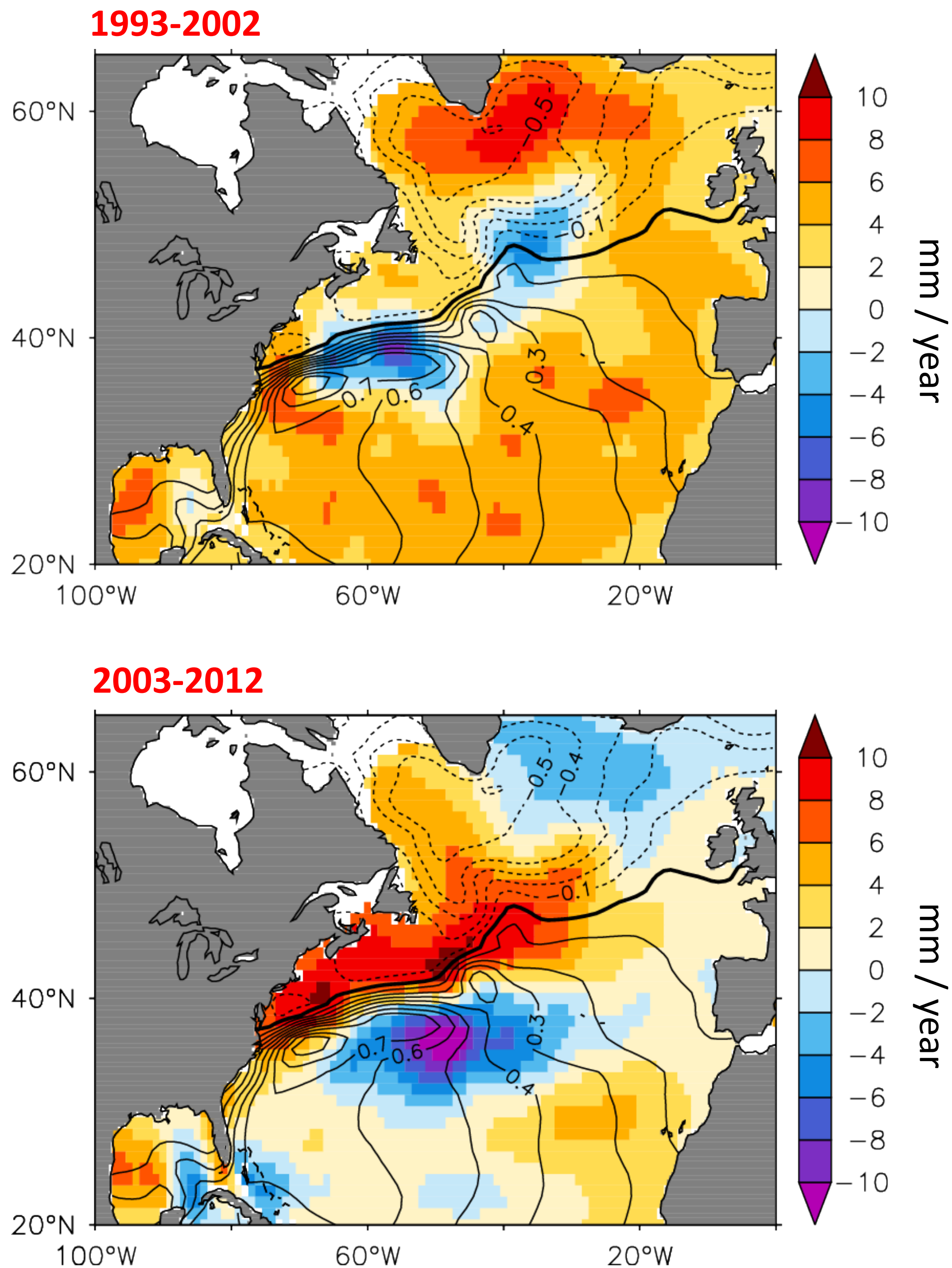
Covarying dipole between the Gulf Stream and subpolar gyre

*(Hakkinen and Rhines, 2004; Zhang, 2008; Lorbacher et al., 2010)*

Contrast across the Gulf Stream and Cape Hatteras

North – high
South – low

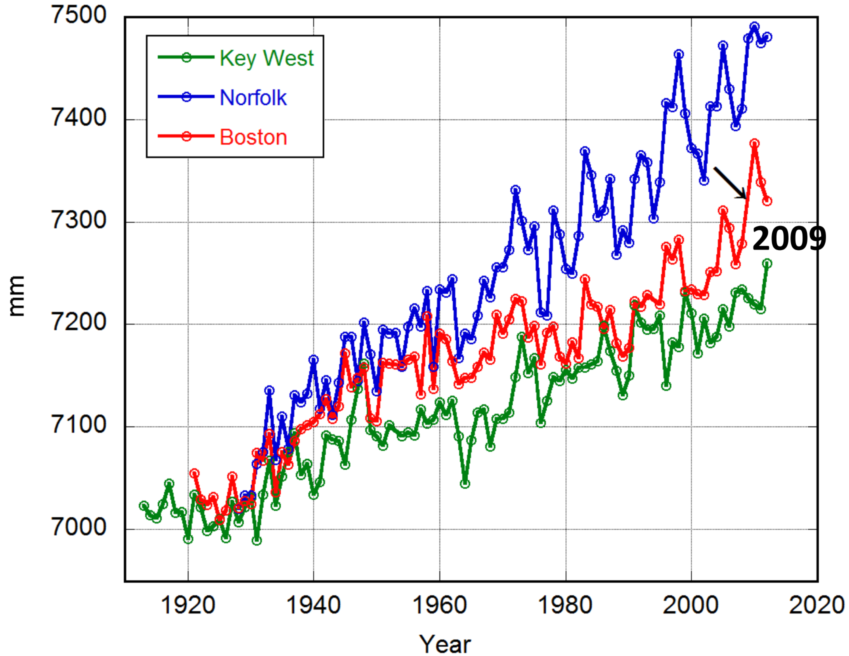
*(Yin et al., 2009; Sallenger et al., 2012; Ezer et al., 2013)*

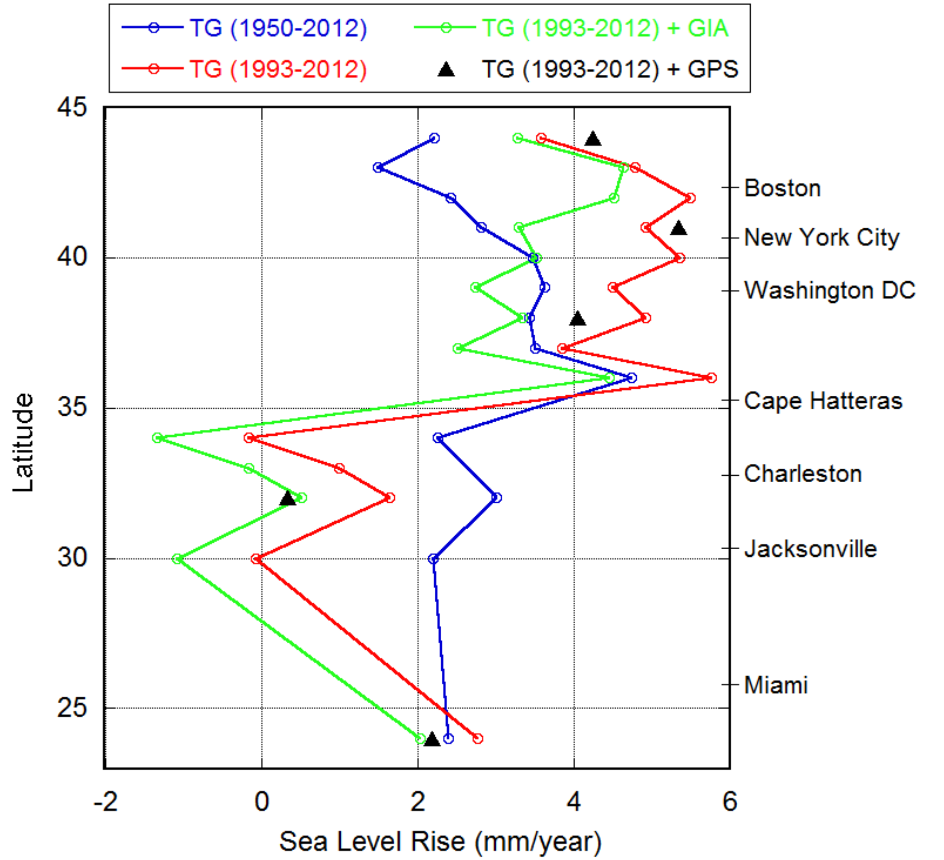



(CSIRO altimetry data)

# U.S. East Coast SLR Regimes


# Coastal SLR Patterns




Long-term annual tide gauge data *(PSMSL)*

Key West – Southeast
Norfolk – Mid-Atlantic
Boston – New England

**U.S. East Coast SLR Patterns**

**1950-2012** Middle-High

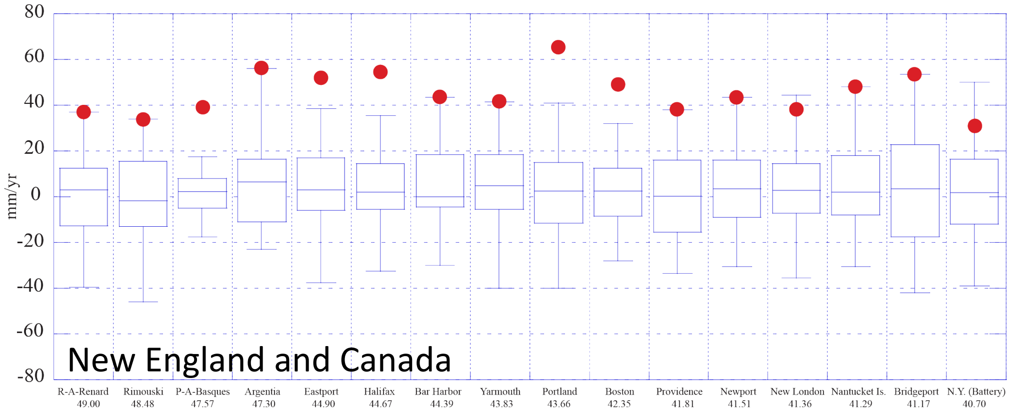
SLR faster in Mid-Atlantic
SLR rate decreased to the north and south

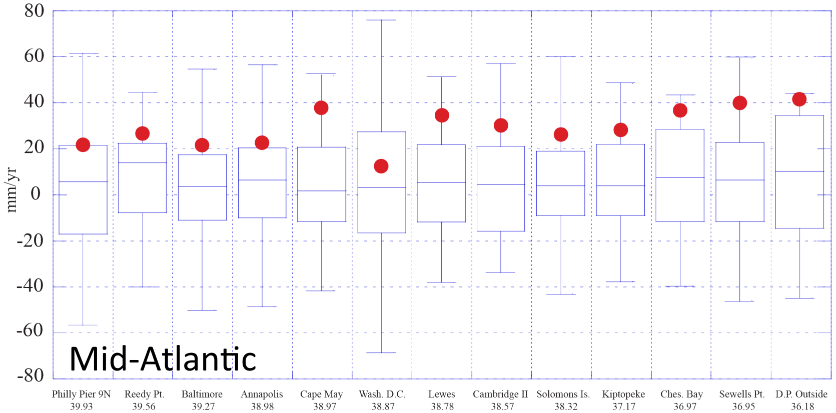
**1993-2012** North-High South-Low

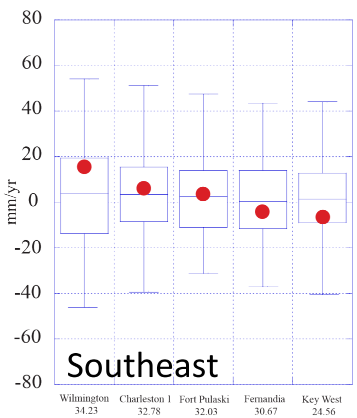
SLR faster north of Cape Hatteras
SLR slower south of Cape Hatteras

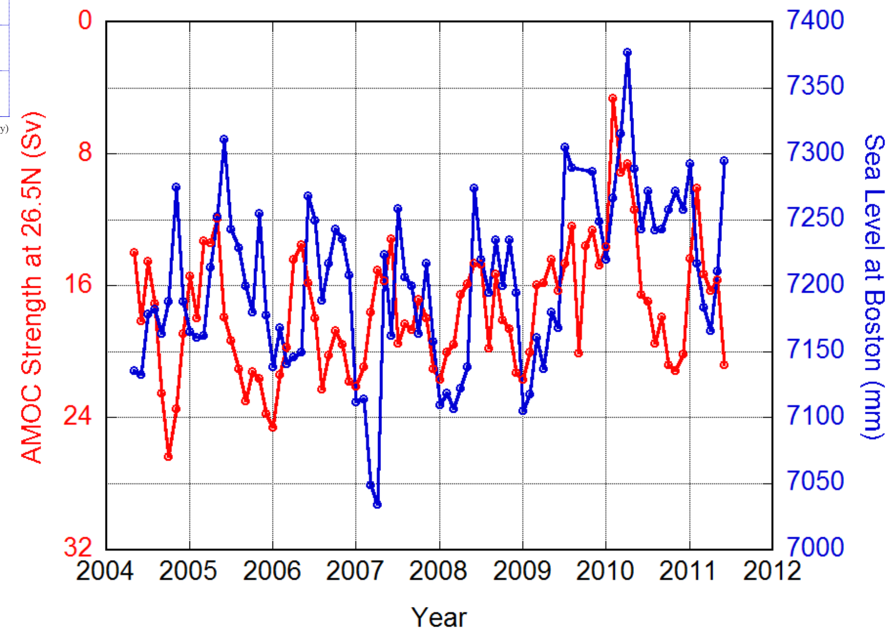
*GPS correction: Woppelmann et al. 2009*
*GIA correction: Peltier 2004*

# AMOC vs SLR




**Anomalous 2009**

Long-term annual tide gauge data

SLR in a particular year:

$$SLR(t) = \frac{SL(t+1) - SL(t-1)}{2}$$

**Correlation**

Annual mean: -0.8

Monthly data: -0.5 for 2 month lag

*AMOC time series from McCarthy et al., 2012*

*PSMSL tide gauge data at Boston*

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# GFDL ESM2M

- Delworth et al., 2006; Dunne et al., 2012
- Atmosphere: 2.5$^{o}$x2$^{o}$, 24 levels;  Ocean: 1$^{o}$x(1$^{o}$-1/3$^{o}$), 50 levels
- Free ocean surface and real freshwater flux
- Explicit simulation of global carbon cycle
- CMIP5 runs: historical (1861-2005);  RCP projection runs (2005-2100)
- Dynamic sea level rise analysis

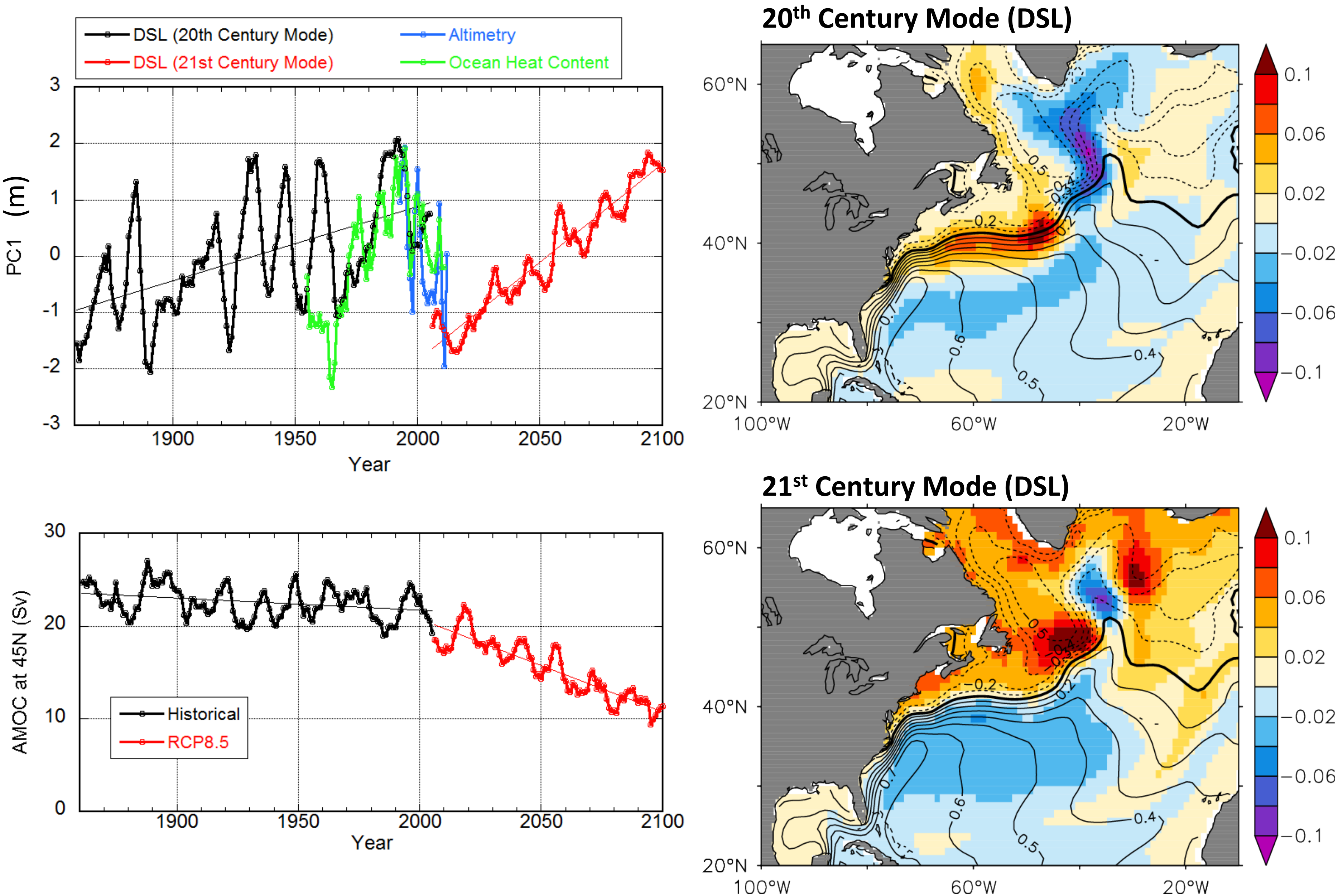
$$\Delta\eta(x,y,t) = \frac{\Delta p_b(x,y,t)}{g\rho_0} + \Delta h'(x,y,t)$$

Mass redistribution    Local steric

$$\Delta h(x,y,t) = -\frac{1}{\rho_0}\int_{-H}^{\eta} \Delta\rho \, dz$$

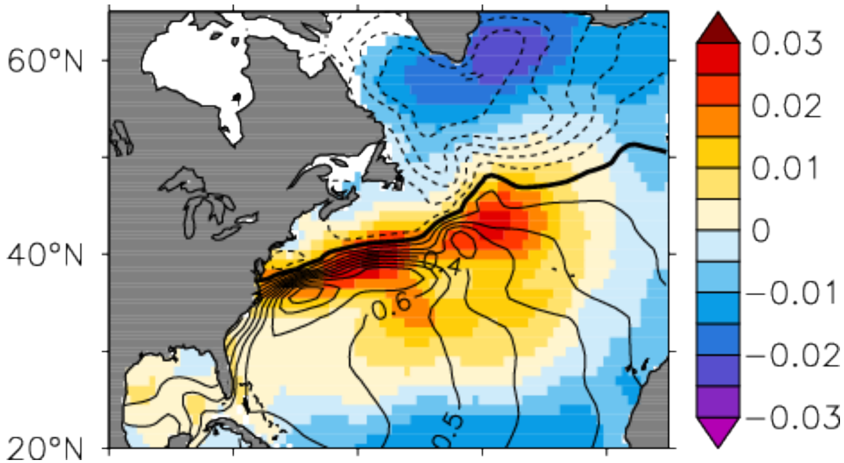
$$\overline{\Delta h}(t) = \frac{1}{A}\int_{global} \Delta h \, dA$$ (Global steric)

$$\Delta h'(x,y,t) = \Delta h - \overline{\Delta h}$$ (Local steric)


DSL (20th Century Mode)
DSL (21st Century Mode)
Altimetry
Ocean Heat Content
PC1 (m)
Year
AMOC at 45N (Sv)
Historical
RCP8.5
Year
20th Century Mode (DSL)
21st Century Mode (DSL)
60°N
40°N
20°N
100°W
60°W
20°W
0.1
0.06
0.02
−0.02
−0.06
−0.1

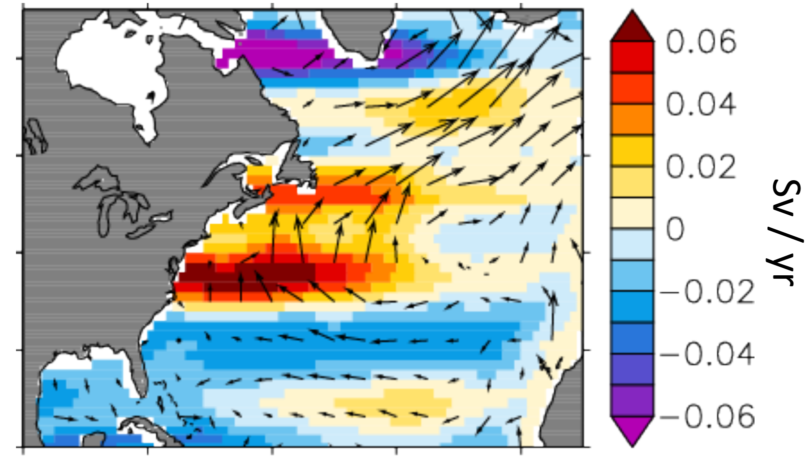
# 20th Century Mode (obs)

EOF1 altimetry (1993-2012)



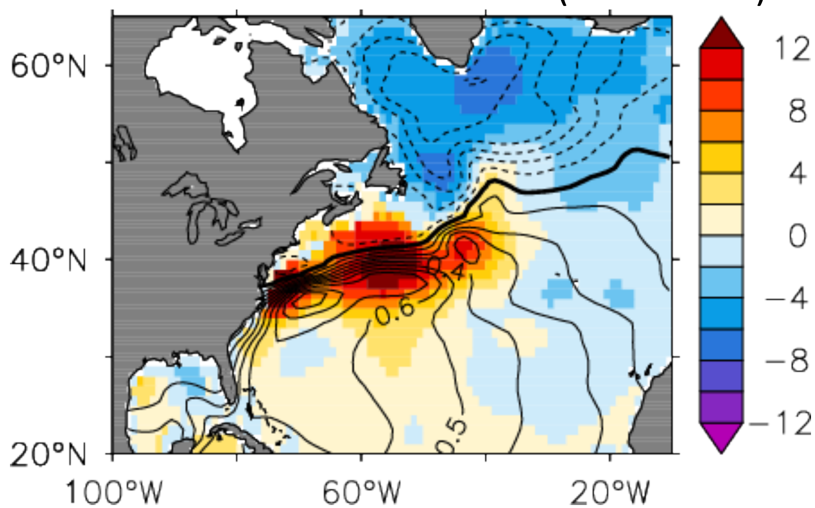

*CSIRO data*

Trend of wind stress and
Sverdrup streamfunction (1948-2007)



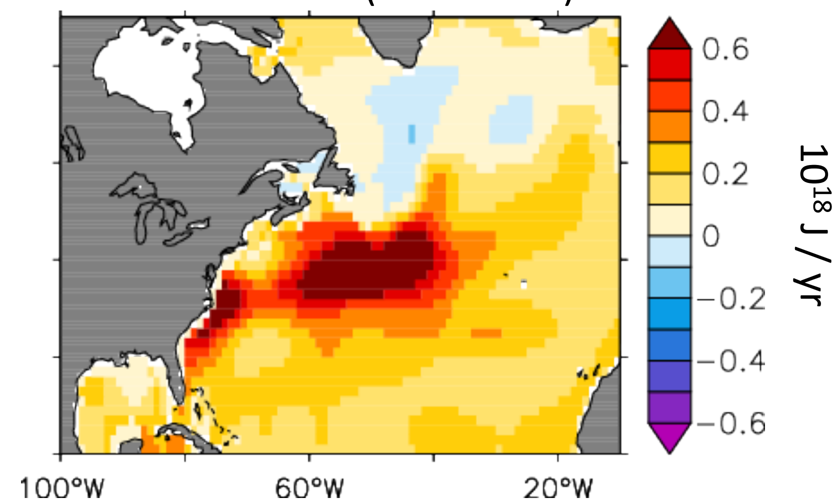

*CORE forcing data* 5.000E−04 (Pa/yr)

EOF1 Ocean Heat Content (1955-2012)



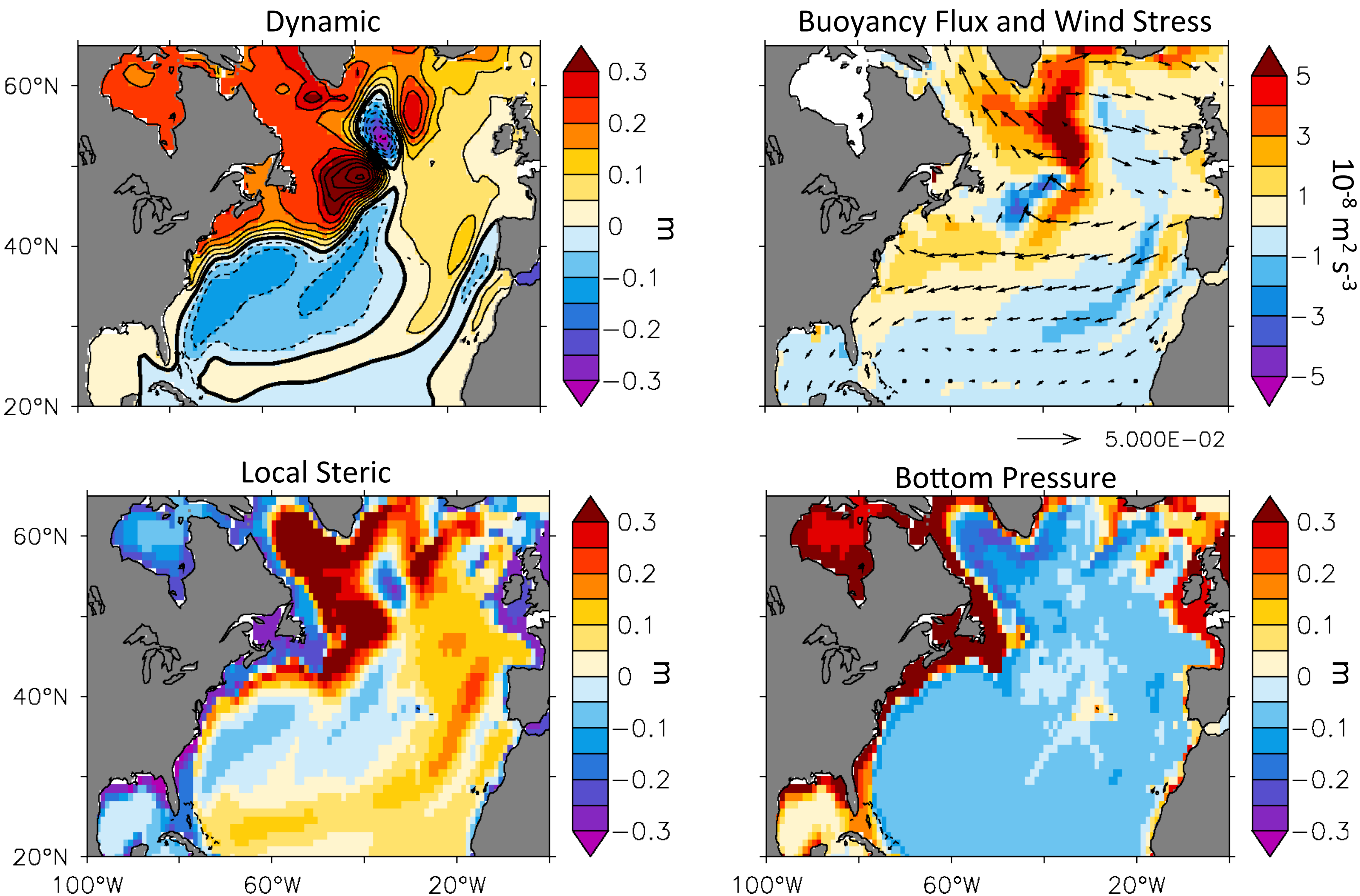

*NOAA NCDC upper 700 m data*

Trend of OHC (1955-2012)



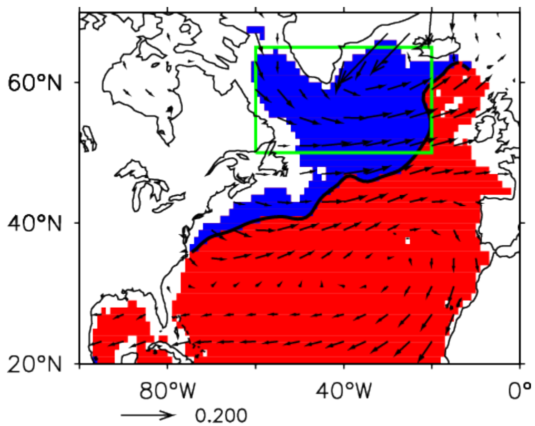

*NOAA NCDC data*

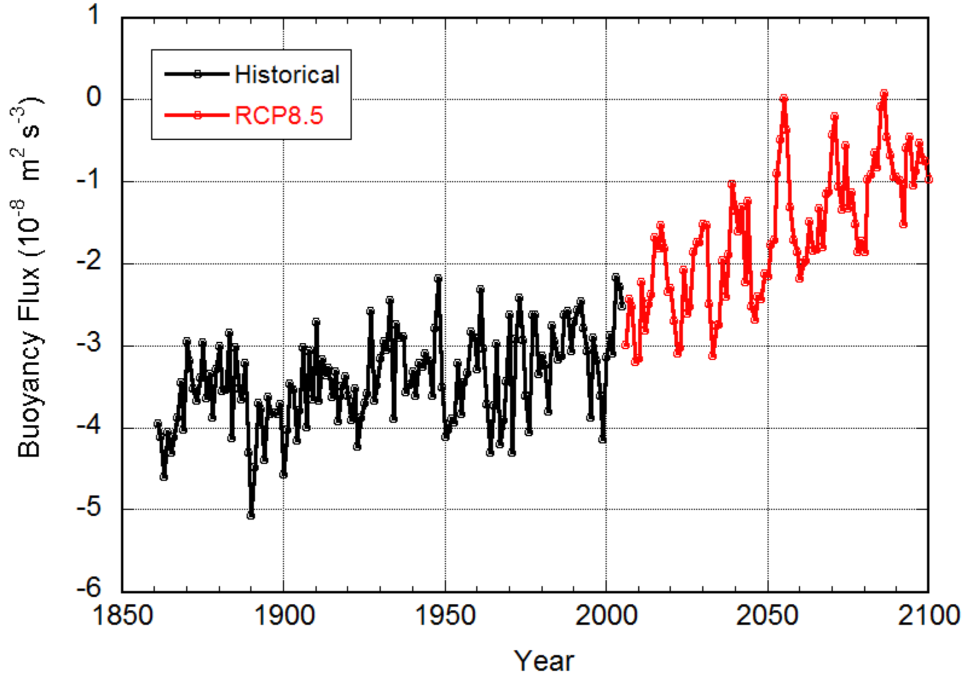
# 21st Century Mode




- GFDL ESM2M - RCP8.5 - 2091-2100 minus 1986-2005

# Mechanism

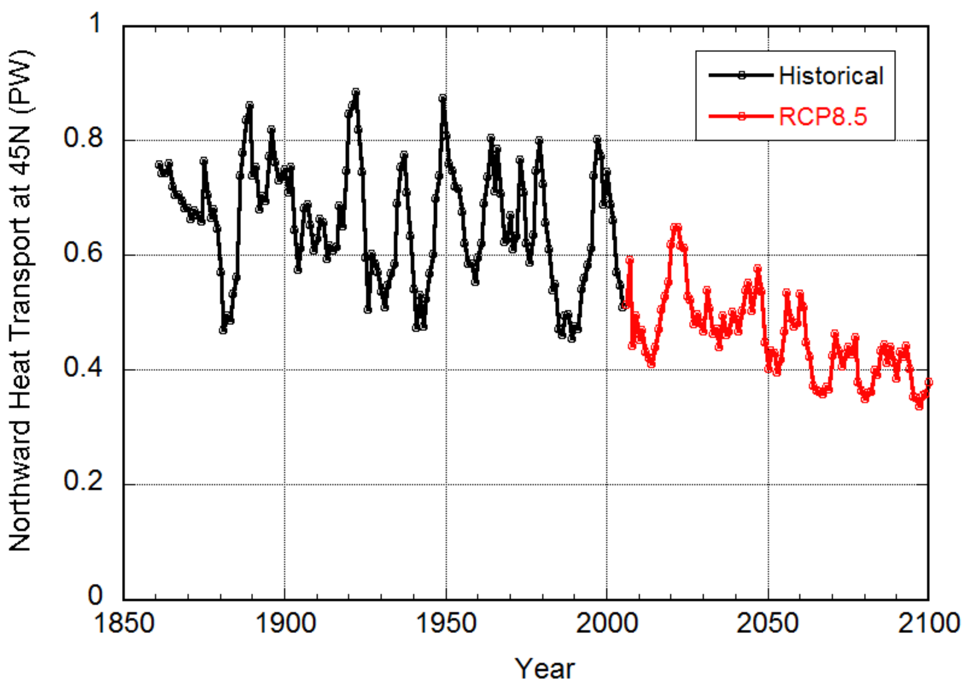


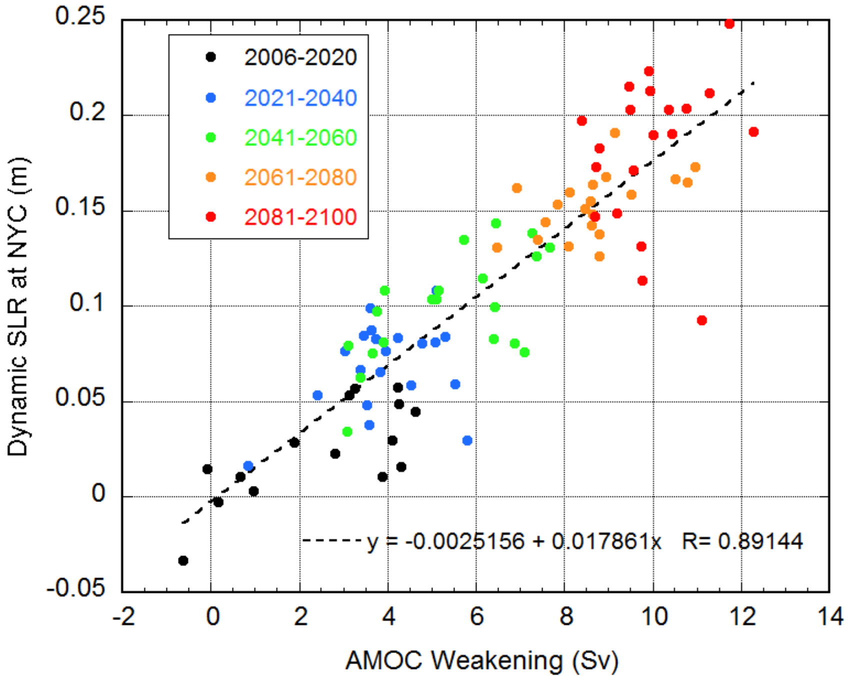

Buoyancy flux:

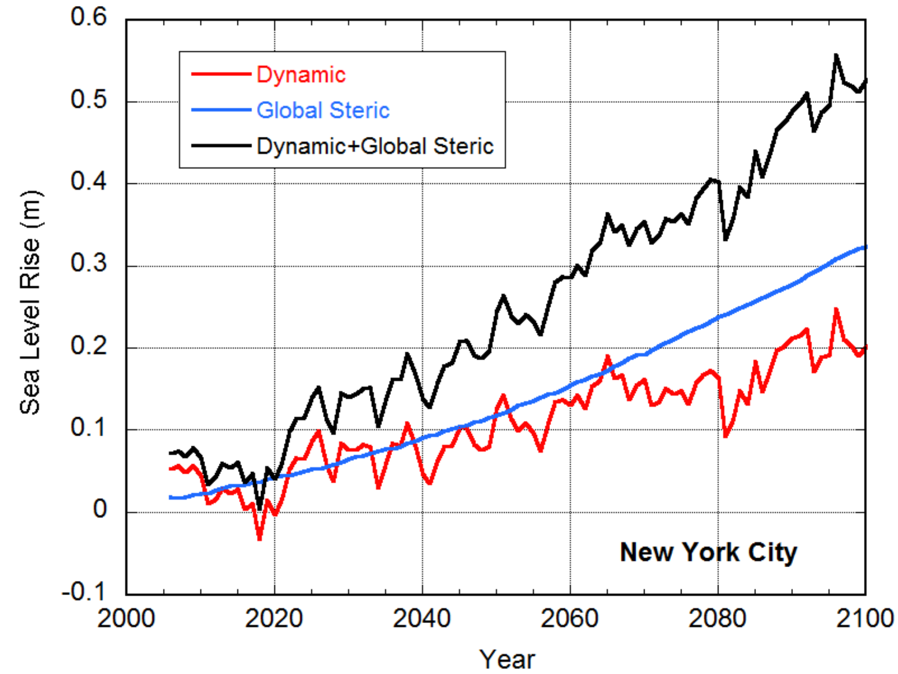
$$B = (g/\rho_0)[\alpha Q_{HF}/c_p - \rho_0 \beta S(E-P-R)]$$

α: thermal expansion coefficient
β: saline contraction coefficient
$Q_{HF}$: net air-sea heat flux
$c_p$: specific heat for seawater
E: evaporation
P: precipitation
R: runoff



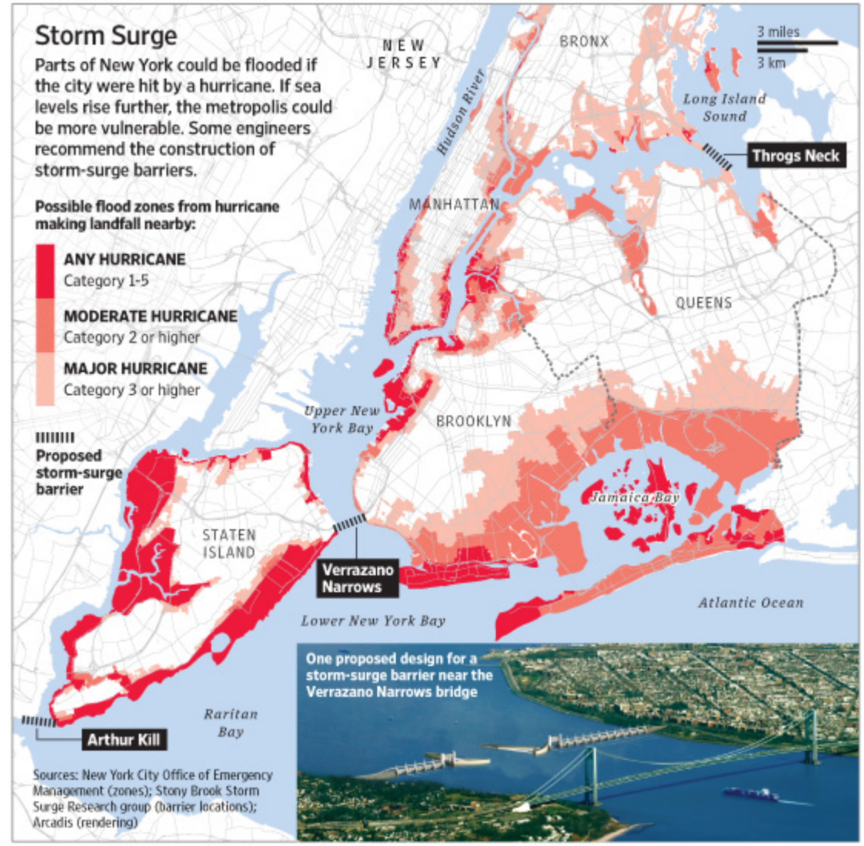
# AMOC vs DSL




- High correlation between the AMOC weakening and dynamic SLR on the U.S. East Coast
- Dynamic SLR superimposed on global mean SLR, leading to high vulnerability of the U.S. East Coast to future SLR

# Impact




- ➢ Elevated storm surges, beach erosion, inundation of low-lying area, damages to coastal infrastructure and ecosystems

# Conclusions

- The SLR along the U.S. East Coast switched from a middle-high pattern (faster in Mid-Atlantic) during the 20$^{th}$ century to a north-high south-low pattern (separating at Cape Hatteras) during the past decades.
- GFDL ESM2M suggests two distinct modes of the DSL variability and change in the 20$^{th}$ and 21$^{st}$ century in the North Atlantic.
- The middle-high pattern of coastal sea level rise during the 20$^{th}$ century was induced by northward shift of the Gulf Stream.
- The north-high south-low pattern during the 21$^{st}$ century is mainly caused by the significant decline of the cross-Gulf-Stream density contrast, i.e., the baroclinic process associated with the AMOC weakening.
- The northeast coast of the U.S. is particularly vulnerable to future sea level rise and storm surge.