Skillful multiyear to decadal predictions of sea level in the North Atlantic Ocean and U.S. East Coast

Liping Zhang, Thomas L. Delworth, Xiaosong Yang and Fanrong Zeng,
NOAA/GFDL, UCAR and Princeton University

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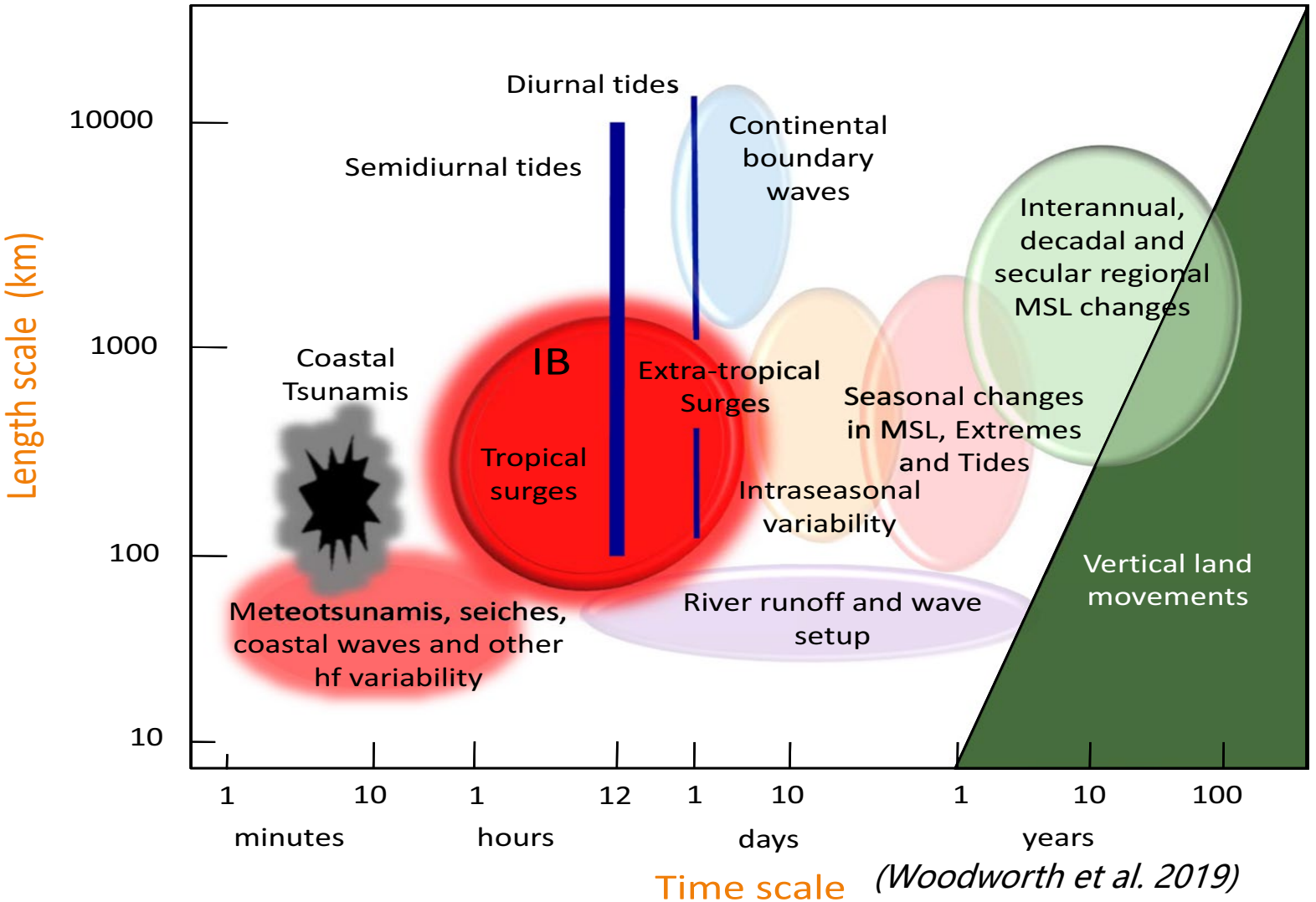
North Atlantic and U.S. East Coast sea level variability

Hourly to daily timescales: Tide, waves, storms, hurricanes
Seasonal to multidecadal: ocean and climate variabilities
Centennial: global warming, vertical land movement



(Woodworth et al. 2019)

Motivation and Scientific question:

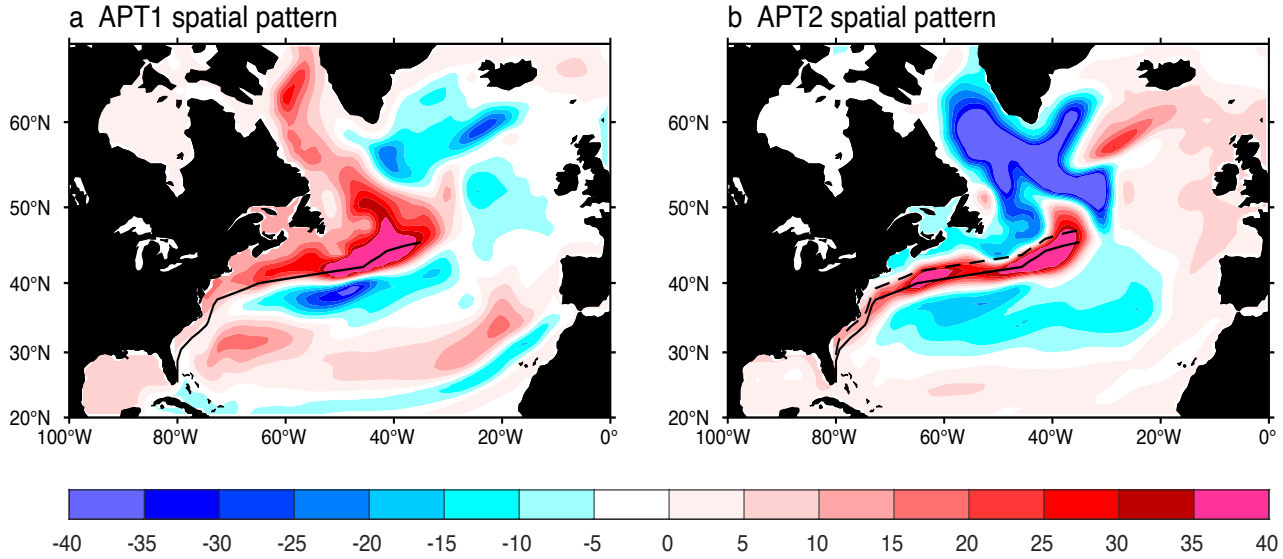
- Prediction of sea level beyond seasonal time scales has received much less attention
- Skillful decadal predictions for the AMOC and heat content that are relevant for sea level
- It is desirable to investigate the multiyear to decadal prediction of sea level

Outline

1. **North Atlantic Sea level predictability in SPEAR control run** ("perfect model" skill)
2. **North Atlantic Sea level prediction skill in SPEAR initialized decadal hindcasts** (verified with Satellite Observation)
3. **Sea level prediction skill along the U.S. East Coast** (verified with Tide Gauge (TG) Observations)
4. **Summary and Caveat**

North Atlantic Sea level predictability in SPEAR control run

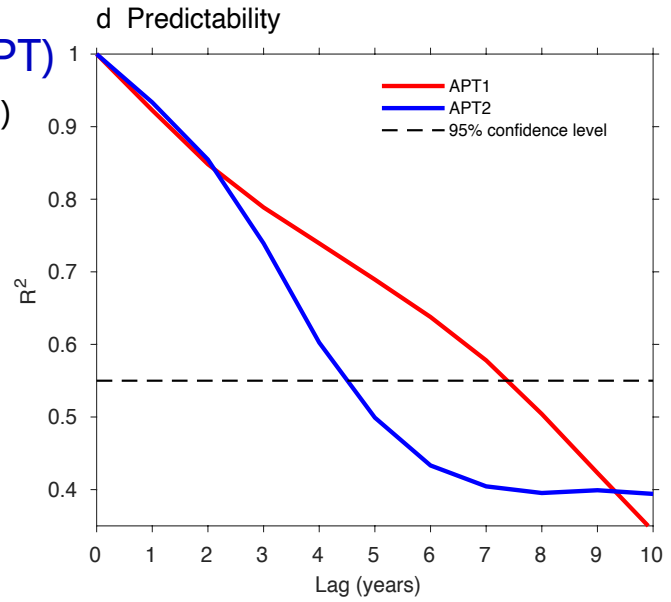
The most predictable North Atlantic sea level patterns



Average predictability time (APT) Method (DelSole and Tippett 2009a,b)

$$\mathrm{APT} = 2\sum_{\tau=1}^{\infty}\left(1-\frac{\delta_\tau^2}{\delta_\infty^2}\right)$$

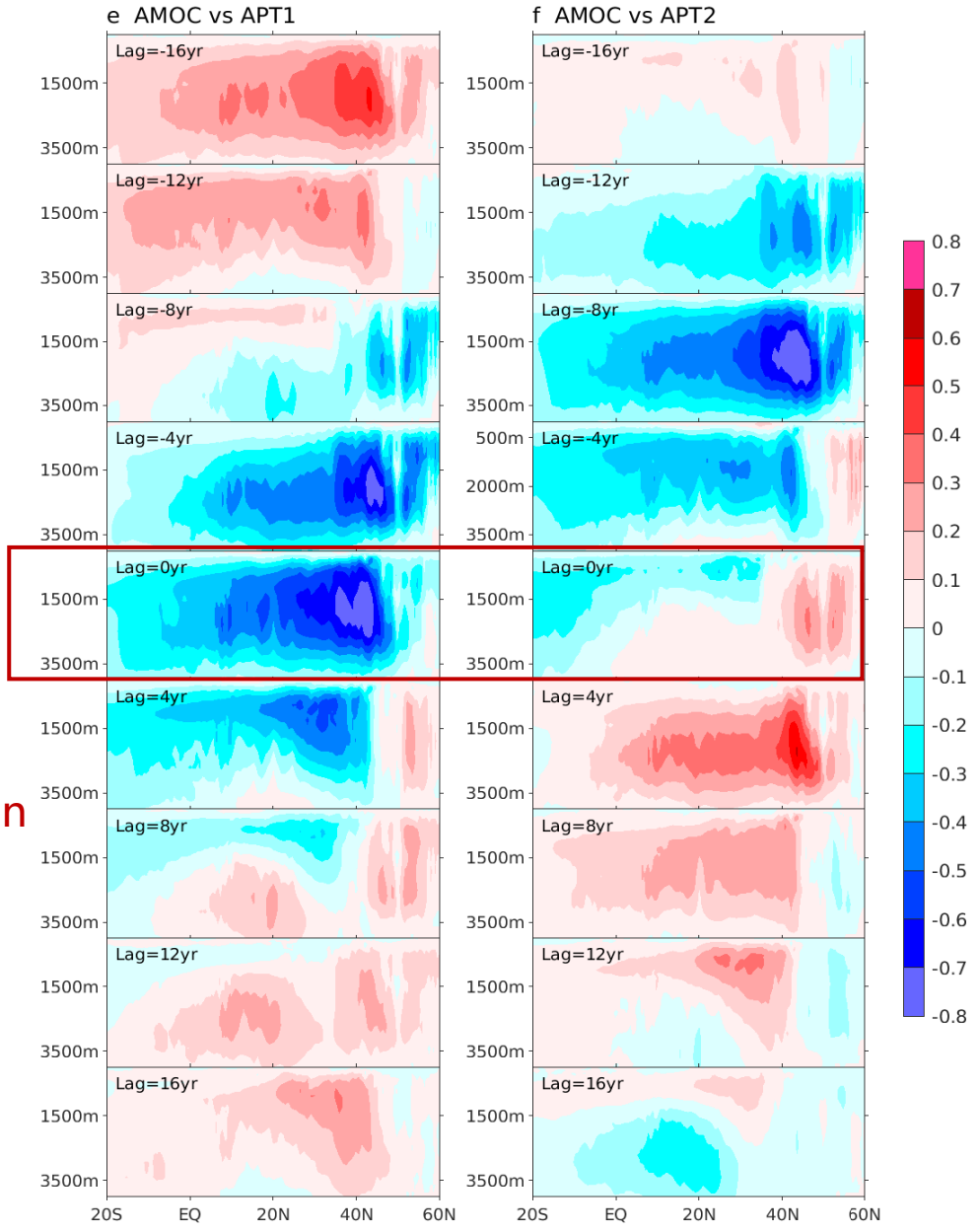
where δ_τ^2 is ensemble forecast variance at lead time τ and δ_∞^2 is climatological variance.



Lagged regression of AMOC on the APT timeseries

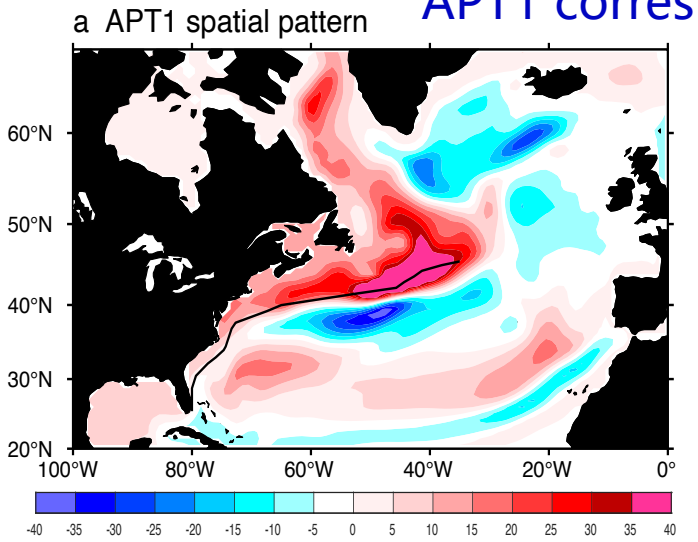
APT1: AMOC mature phase

APT2: AMOC transition phase



North Atlantic Sea level predictability in SPEAR control run (mechanisms)

APT1 corresponds to the mature negative phase of AMOC:

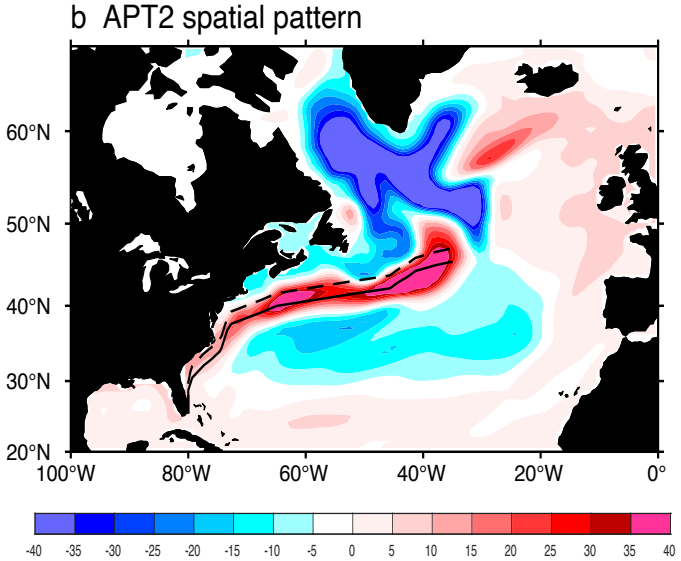


Contributions from both dynamic and steric sea level components

Black solid line:
mean Gulf Stream (GS) path

- The negative density anomalies lead to expanded water column and positive sea level anomalies
- The weak GS corresponds to high sea levels along the U.S. East Coast due to geostrophic balance

APT2 corresponds to AMOC transition phase (negative to positive):

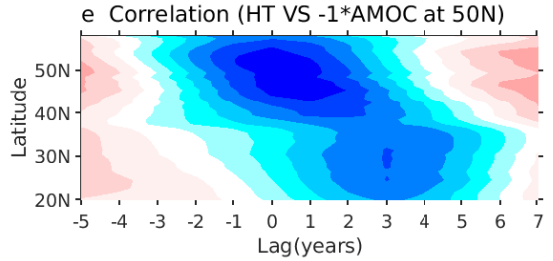


Contribution from thermosteric sea level component

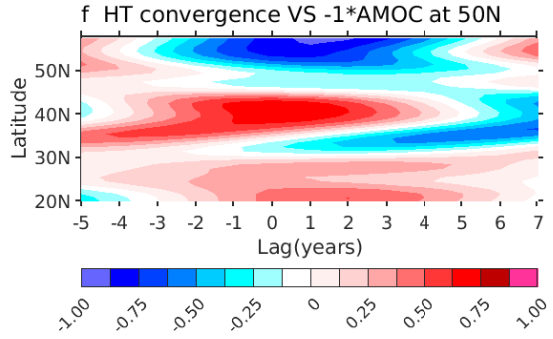
Black dash line:
GS path in the AMOC transition phase

- The weak AMOC propagate southward, with a northward shift of Gulf Stream path
- The northward heat transport anomalies lead to a heat convergence nearby the Gulf Stream path

Heat transport (HT) VS -1*AMOC index



HT convergence VS -1*AMOC index

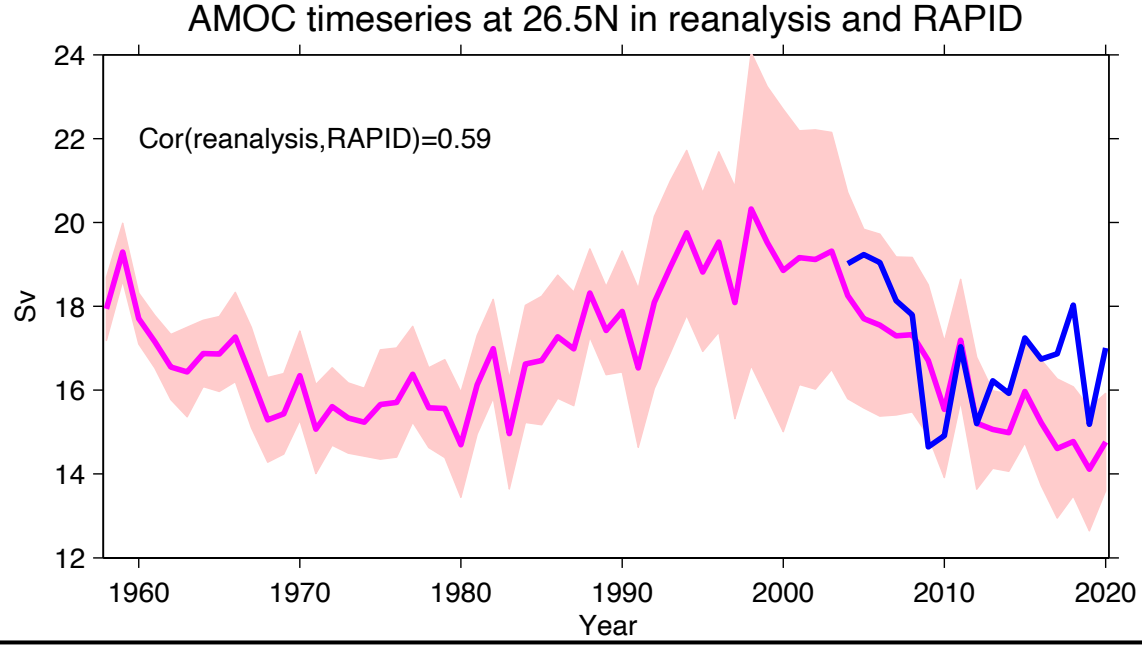


North Atlantic sea level prediction skill in SPEAR initialized decadal hindcasts

SPEAR decadal hindcasts:
Initialized from SPEAR reanalysis

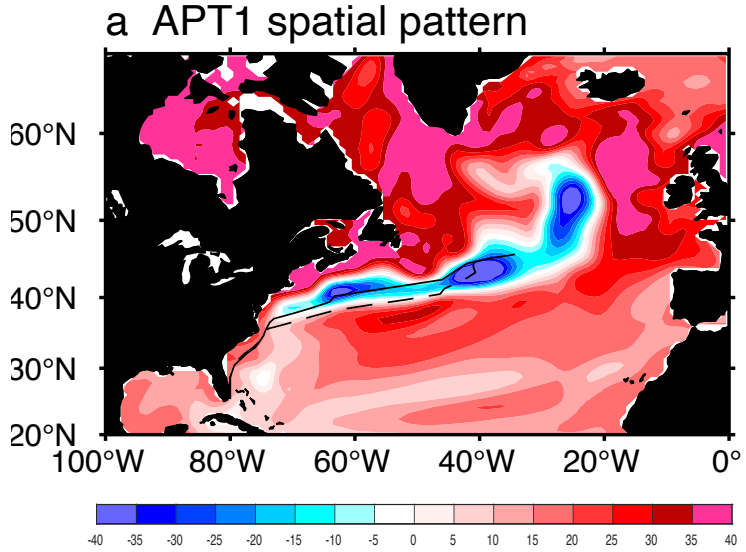
SPEAR reanalysis:
The atmosphere component was restored toward JRA-55; SST was restored to ERSST

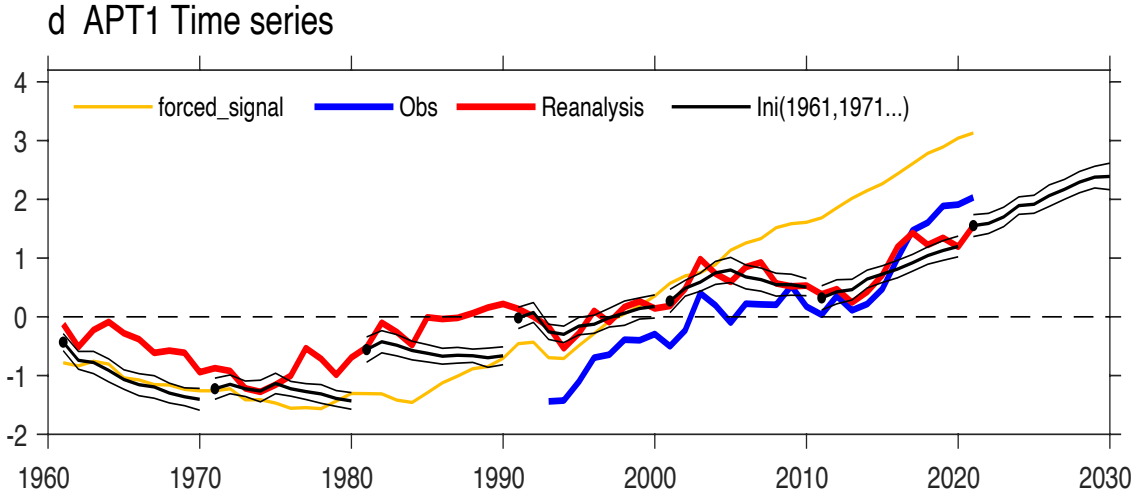
The multidecadal AMOC evolutions are reasonable in SPEAR reanalysis

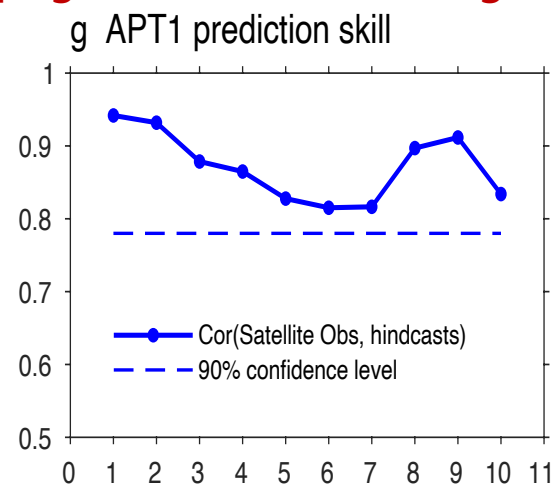


North Atlantic Sea level prediction skill (APT method applied to hindcasts, verified by satellite)

APT1: upward trend, arise from anthropogenic radiative forcing

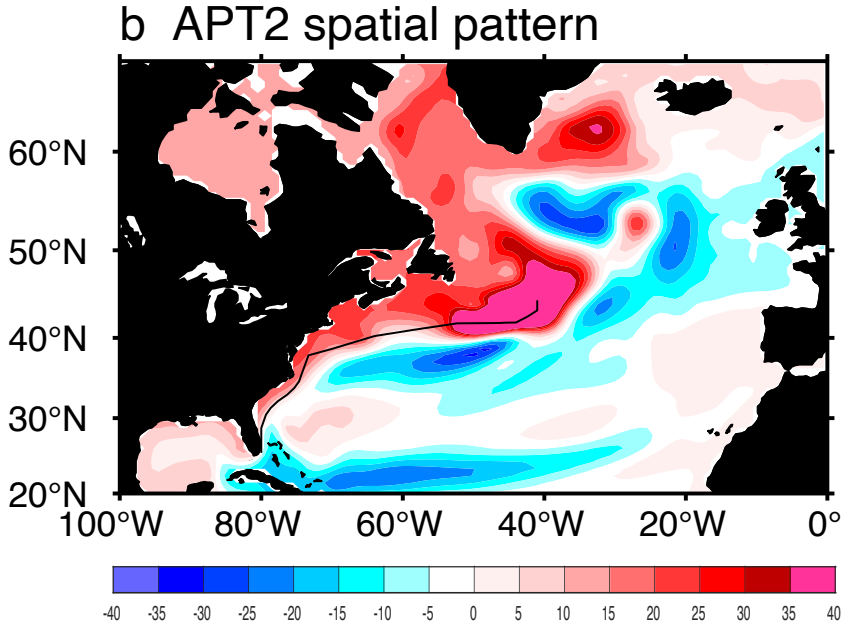




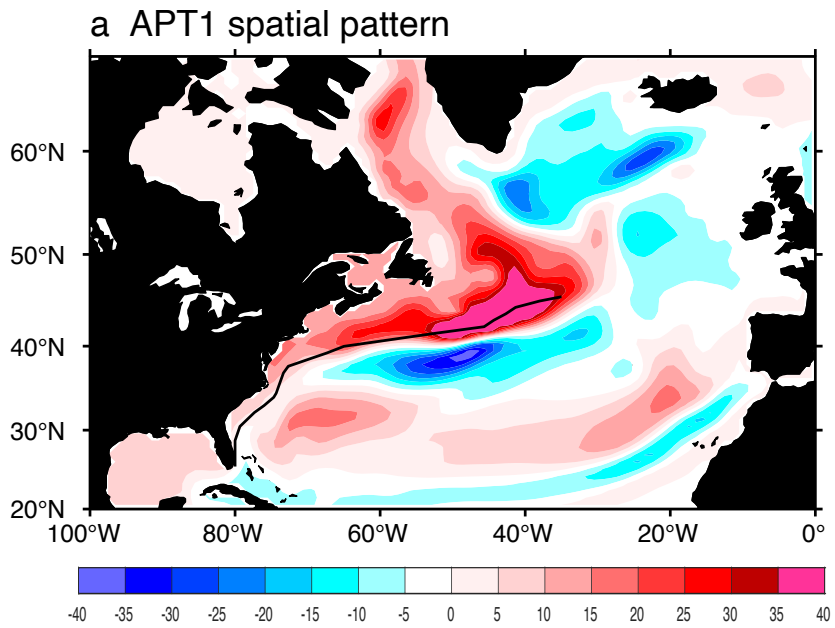


North Atlantic Sea level prediction skill in SPEAR initialized decadal hindcasts

SPEAR decadal hindcasts



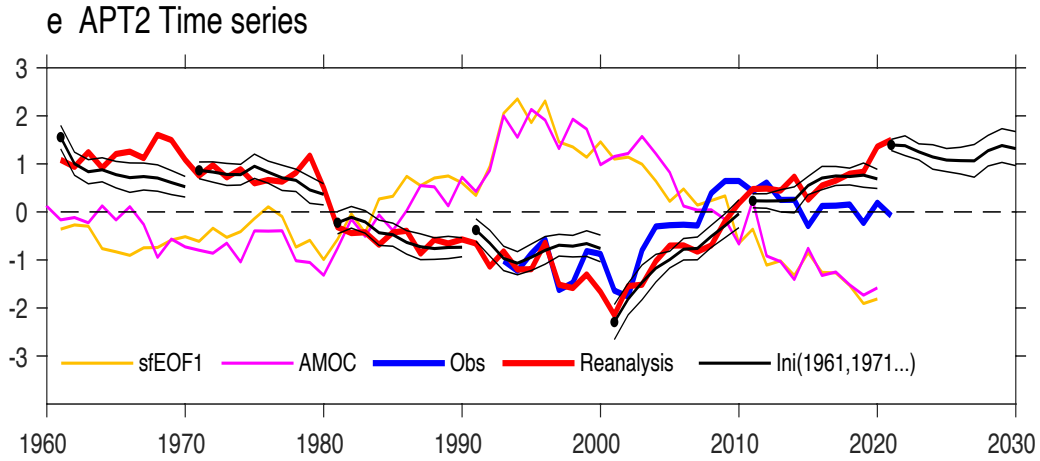
SPEAR control run

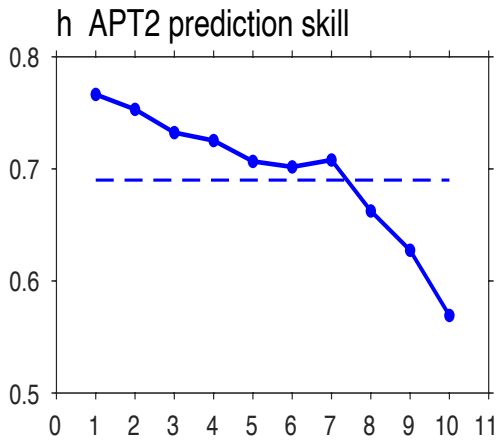


- The APT2 in hindcasts highly resembles the APT1 in control run
- A key role of AMOC mature phase

APT2 timeseries and prediction skill:

Pink line: AMOC index in SPEAR reanalysis; Black line: Hindcasts; Red line: reanalysis; Blue line: Observation or prediction skill

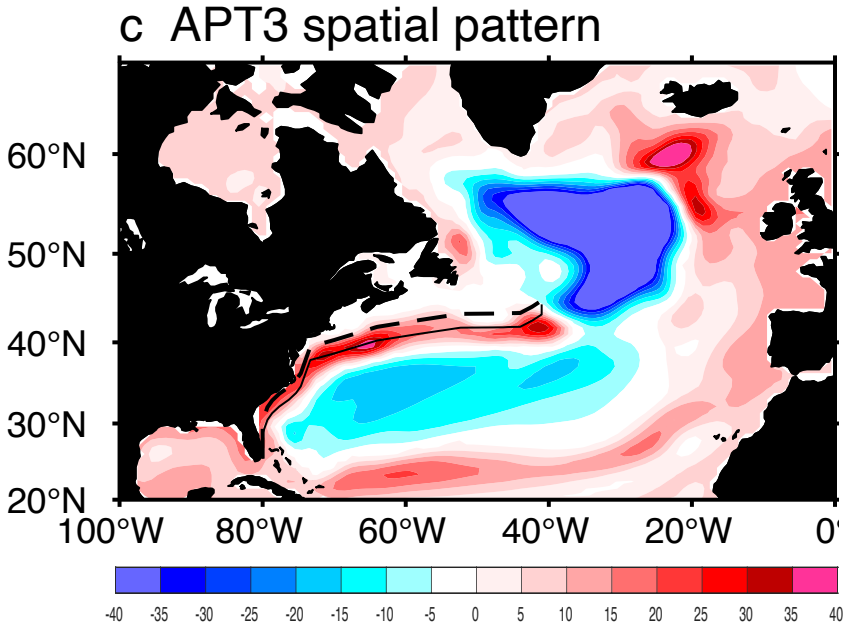




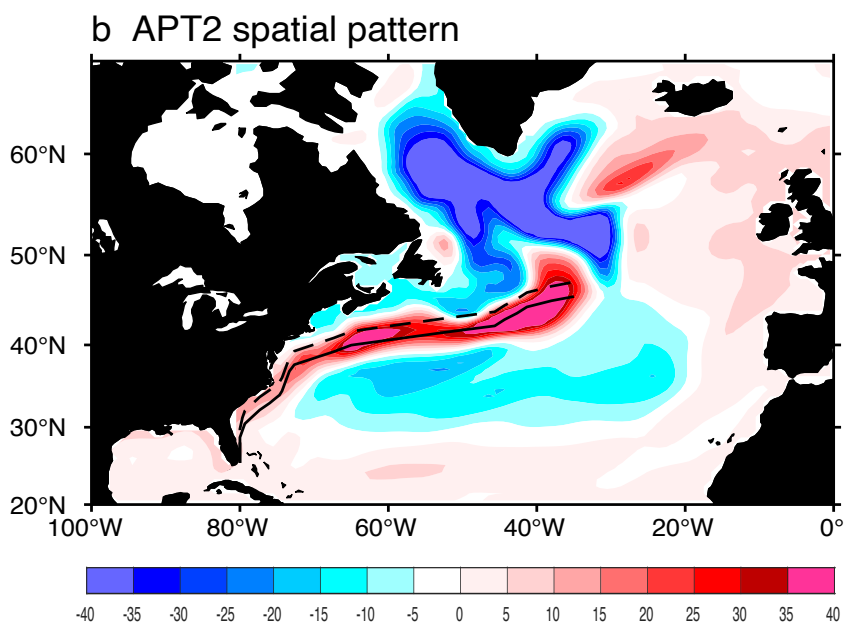
- Prediction skill: ~5years
- Predictability source: AMOC mature phase
- imprints on the U.S. Northeast Coast

North Atlantic Sea level prediction skill in SPEAR initialized decadal hindcasts

SPEAR decadal hindcasts



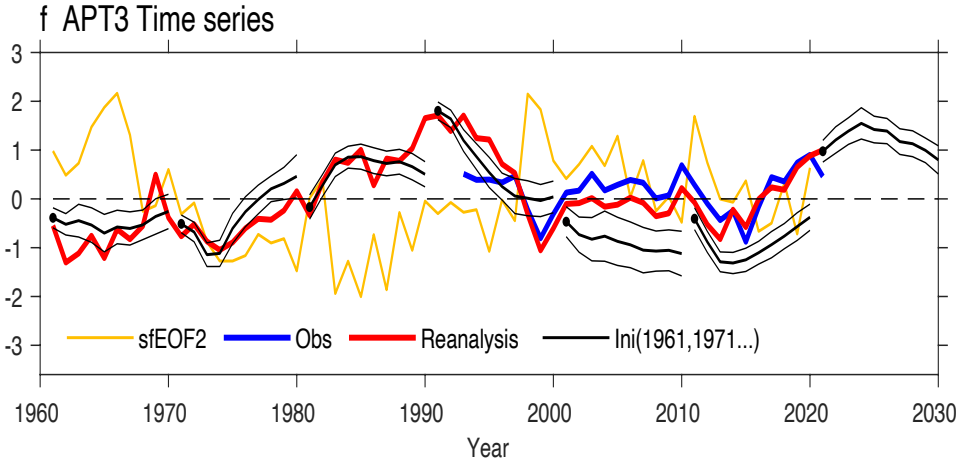
SPEAR control run

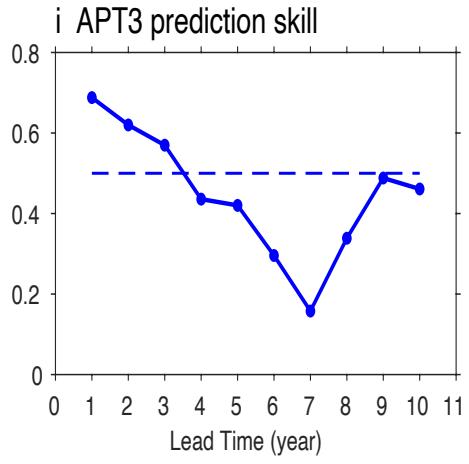


- The APT3 in hindcasts highly resembles the APT2 in control run
- A key role of AMOC transition phase

APT3 timeseries and prediction skill:

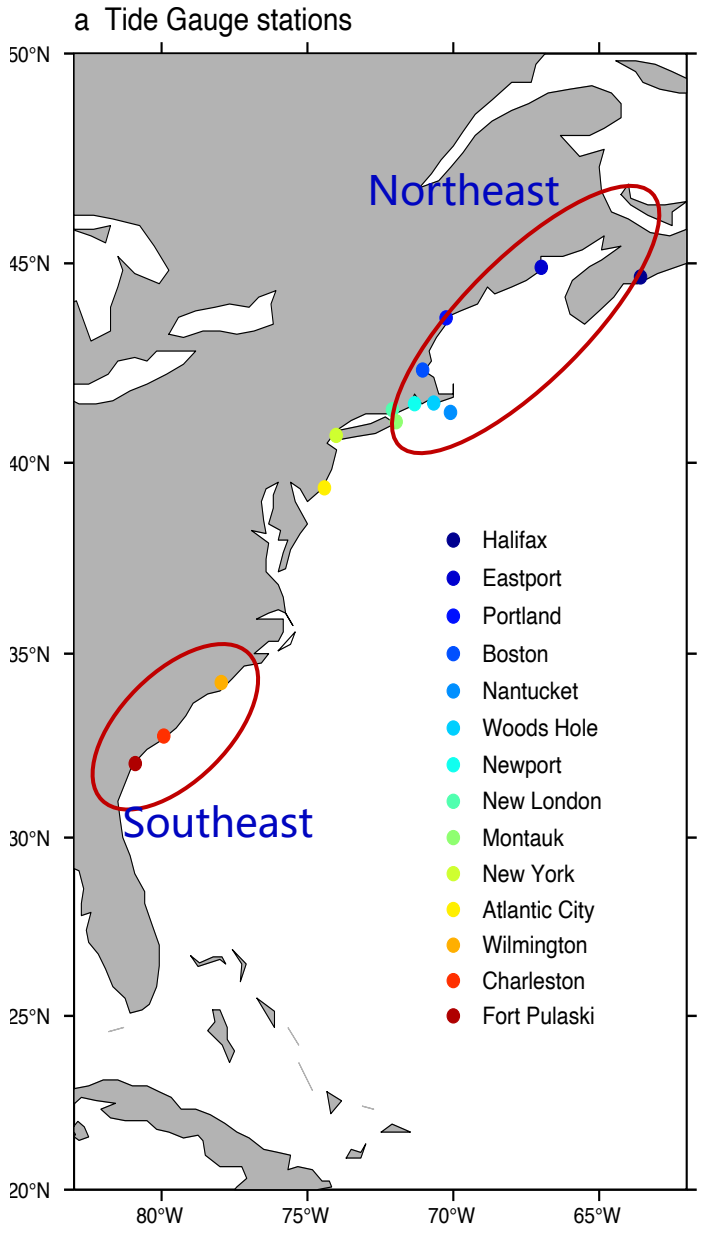
yellow line: AMOC transition phase in SPEAR reanalysis; Black line: Hindcasts; Red line: reanalysis; Blue line: Observation or prediction skill





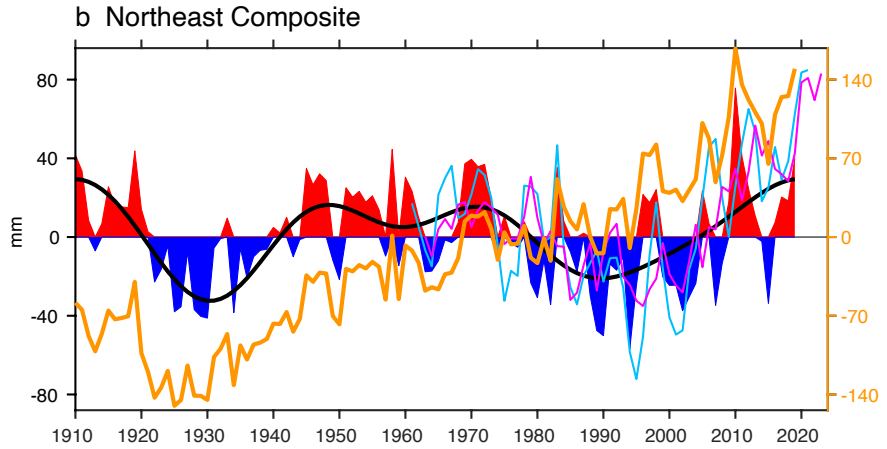
- Prediction skill: ~3years
- Predictability source: AMOC transition phase
- imprints on the U.S. Southeast Coast

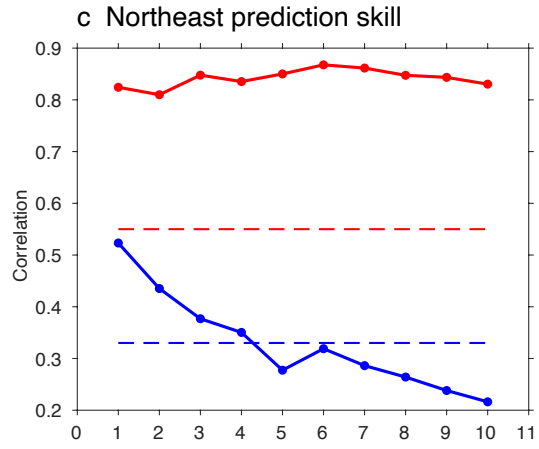
Sea level prediction skill along the U.S. East Coast



U.S. Northeast Coast

Yellow line (red/blue shading): total (detrended) sea level in TG observations
Black line: low pass filtered TG observation; blue/pink lines: hindcasts

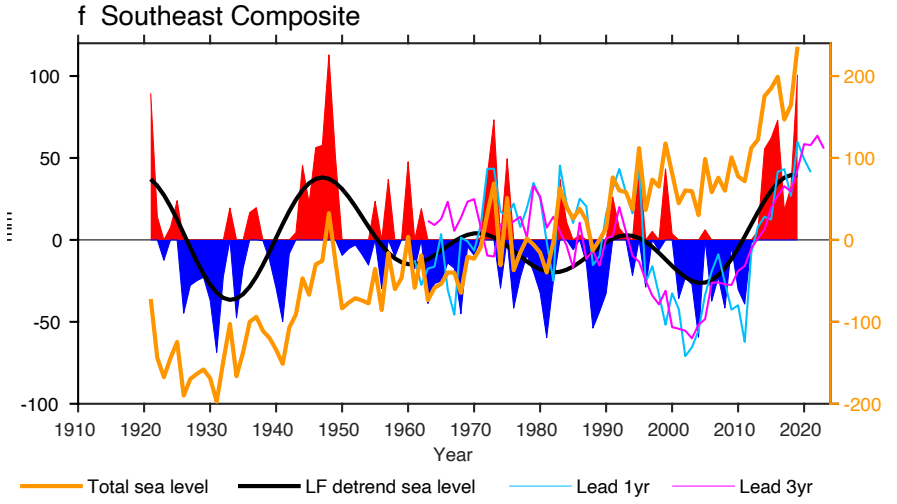


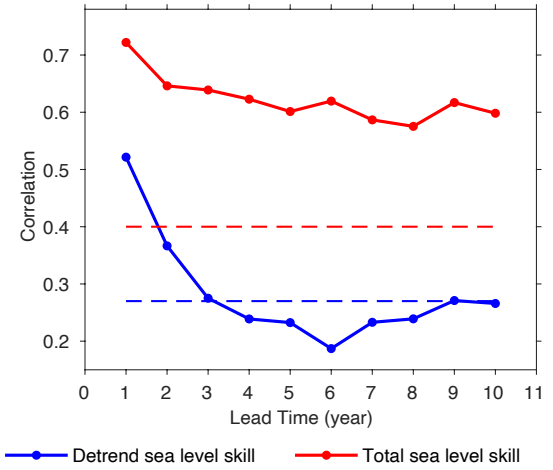


Trend skill:
~10 years

Detrended skill:
~4 years

U.S. Southeast Coast



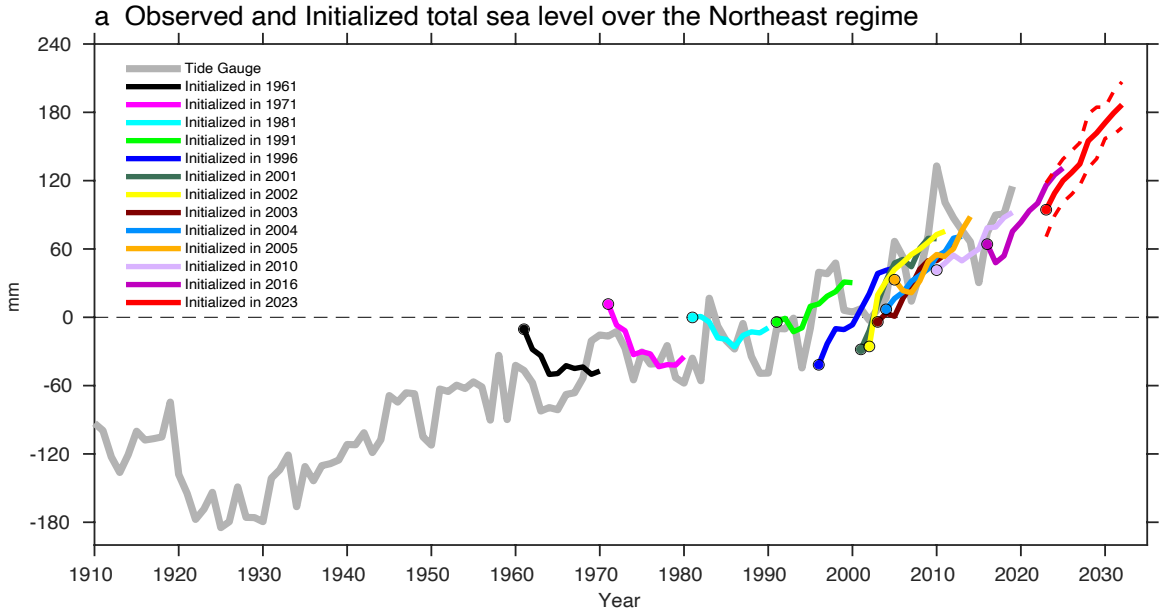


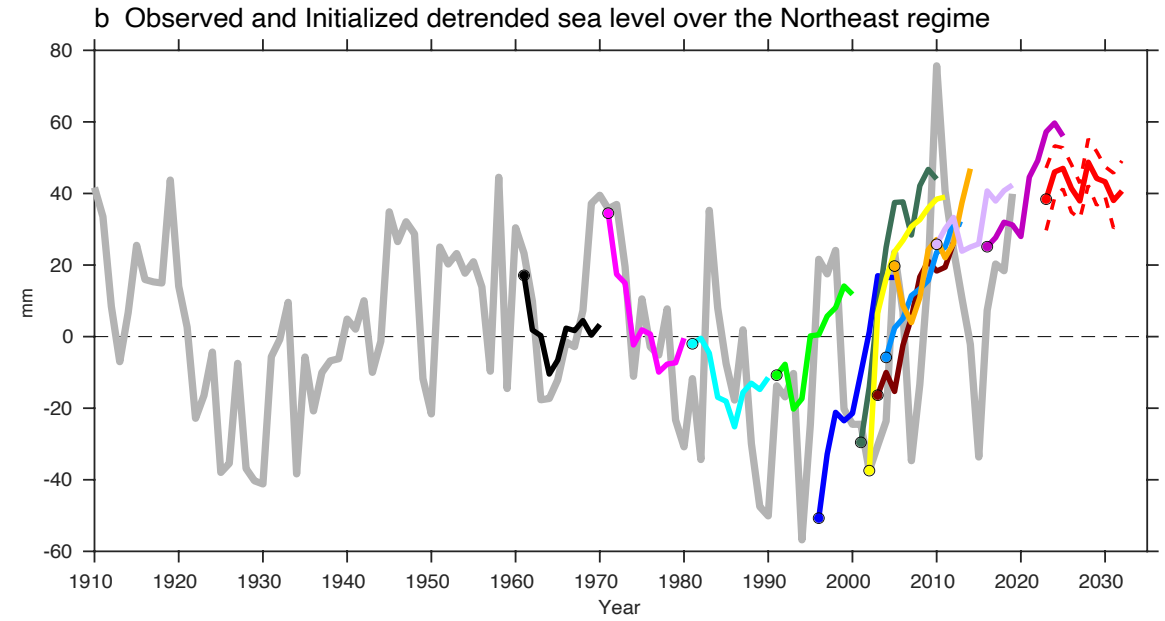
Trend skill:
~10 years

Detrended skill:
~3 years

Future prediction of sea level along the U.S. Northeast Coast

10-year predictions of sea level at different initialization years





Our initialized forecasts indicate that:

- The total sea level will continue to rise in the next decade (external forcing and AMOC states)
- The internal sea level component will continually have above normal anomalies for the next decade (keep flat)
- The prediction initialized between 1995-2003 well captures the transition to high sea level events after 2005
- All hindcasts underestimate the extreme sea level high event during 2009-2010

Conclusion and Summary

- **The most predictable component of North Atlantic sea level is a basin scale upward trend (~10 years prediction skill), arising from external radiative forcing.**
- **Additional predictability comes from the multidecadal variations of the AMOC (3-5 years prediction skill).**
- **The detrended sea level skills along the U.S. East Coast are more related to the AMOC mature (transition) state in the Northeast (Southeast) regime.**

❖ **Caveats:**

SPEAR doesn't have land ice and tide components, land subsidence/lift
Low ocean resolution (**Mom6 dynamic downscaling decadal prediction system (1/12°), include tide**)

❖ **Undergoing work:**

Machine learning method to estimate predictability (Gu et al. 2024)
Attribution study: the rapid acceleration of sea level rise along the U.S. Southeast Coast after 2010 (Zhang et al. 2024a, in revision)
U.S. coastal flooding (extreme sea levels) and predictability, linkages with the AMOC (Zhang et al. 2024b,c)

Thank you