Downscaling the Ocean Response to the Madden-Julian Oscillation in the Northwest Atlantic

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1. Introduction and Motivation

Subseasonal-to-seasonal (S2S) prediction is a global effort to forecast the state of the atmosphere and ocean with lead times between two weeks and a season. On S2S timescales, variability in the tropics is dominated by the Madden-Julian Oscillation (MJO, Madden and Julian, 1971, 1972) which can influence the atmospheric circulation around the globe (e.g., Zhang, 2013; Woolnough, 2019). In the extratropics, the coherent circulation anomalies related to the MJO interact with modes of climate variability and have direct influence on weather (e.g., Cassou 2008; Lin et al., 2009; Riddle et al., 2013; Stan et al., 2018; Merrifield et al., 2020).

The influence of the MJO on the extratropical ocean has received releatively little attention. The ocean and atmosphere exchange heat and momentum through fluxes across the air-sea interface. It is therefore likely that the atmospheric anomalies in response to the MJO also affect the surface ocean.

Research Questions:

- Does the MJO influence the surface ocean in the North Atlantic on S2S timescales?
- What are the underlying physical mechanisms causing the ocean response?
- Can a regional high-resolution ocean model reproduce the ocean response?
- How is the effect of atmospheric forcing in response to the MJO vertically projected into the subsurface ocean?

2. Data

Real-Time Multivariate MJO (RMM) Index (Wheeler and Hendon, 2004)

- Based on 850 hPa and 200 hPa wind and outgoing longwave radiation
- Principle components associated with first two combined empirical orthogonal functions (EOFs)
- 8 Phases describing geographic position of convective anomaly dipole
- Daily values available from 1979 to present. Focus on winter months (DJF) from 1981 to 2019

NOAA Optimal Interpolation Sea Surface Temperature (OISSTv2; Reynolds et al., 2007)

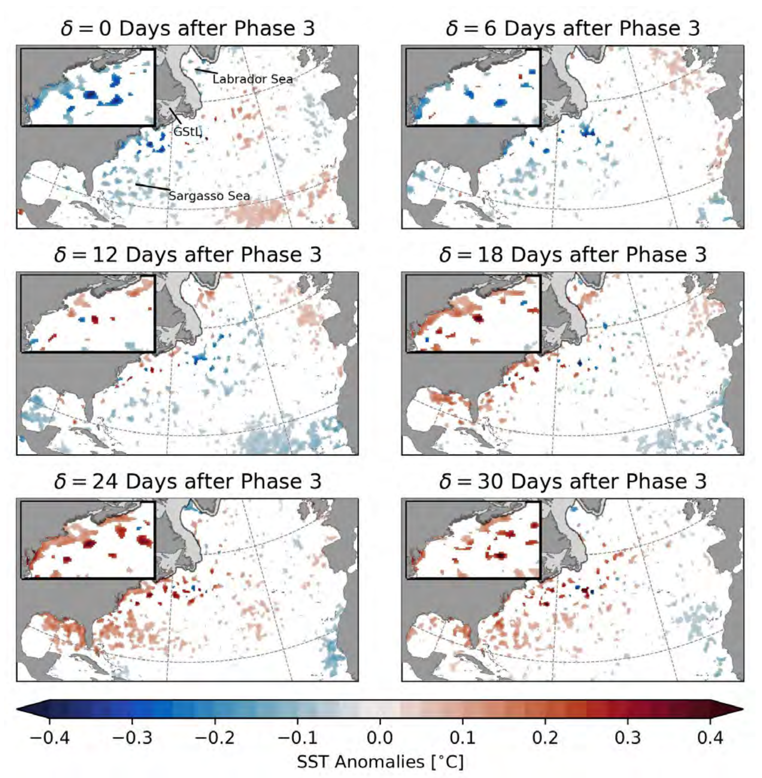
- Statistically interpolated satelite and in-situ observations
- Daily mean SST fields on global 1/4°-grid. Focus on North Atlantic during DJF from 1981 to 2019
- Bandpass-filtered (15-100 day passband) anomalies from smoothed daily climatology

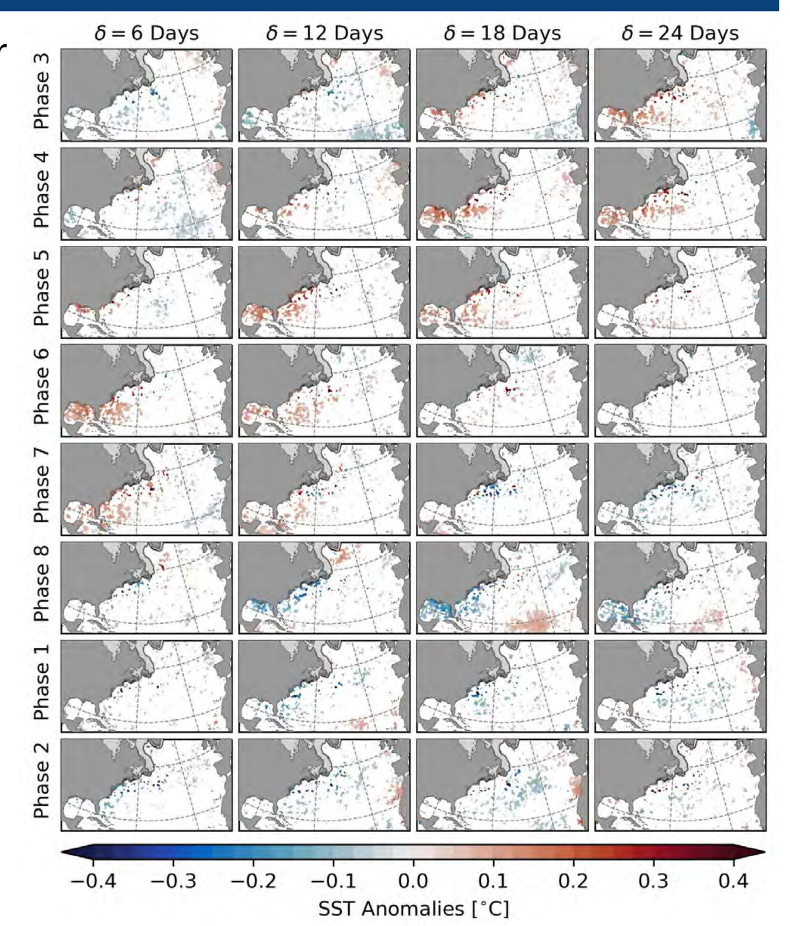
Objectively Analyzed Air-Sea Fluxes (OAFlux; Yu and Weller, 2007)

- Synthesis of satellite observations and reanalysis products
- Air-sea heat fluxes based on COARE bulk formulae
- Surface radiation data from International Satellite Cloud Climatology Project (ISCCP)
- Daily mean fields on global 1°-grid. Focus on North Atlantic during DJF from 1985-2009

3. Composite Analysis of SST Observations

- MJO epsisodes when RMM Aplitude > 1 during winter
- Mean SST anomaly given an MJO phase and lag δ





The shown anomalies are significantly different from zero at the 10% significance level assessed using a bootstrapping method.

- Significant relationship between MJO and large-scale SST changes in the North Atlantic
- Maximum anomalies along North American east coast at lags δ = 3-4 weeks after phases 3 and 7

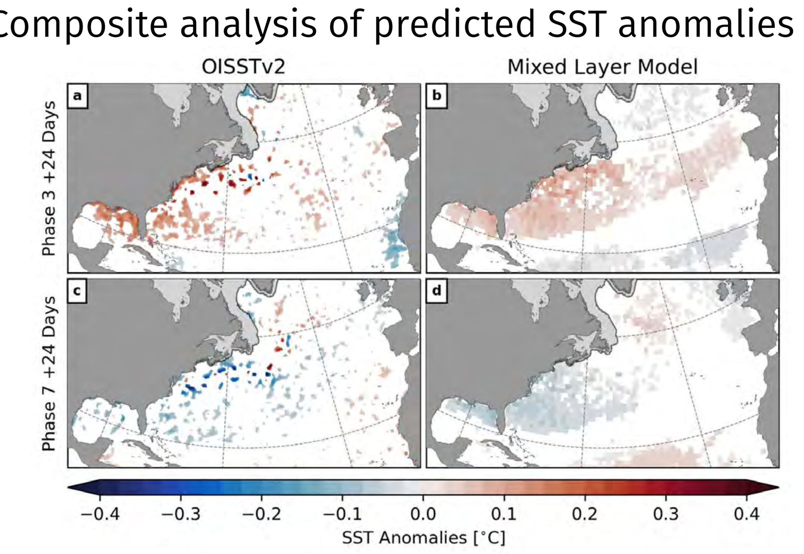
4. Physical Mechanisms and Teleconnections

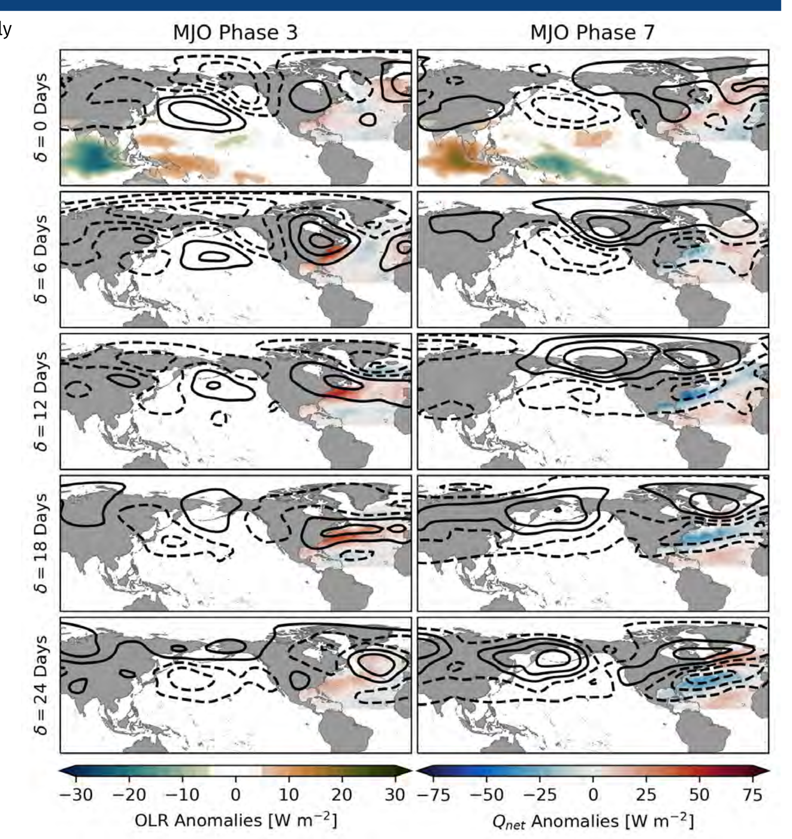
Surface Mixed Layer Model

$$\frac{\partial T_a}{\partial t} = \frac{Q_{net}}{\rho_0 c_{p,w} H_m} - \lambda T_a$$

T_a: Temperature Anomaly
Q_{net}: Net Heat Flux
H_m: Mixed Layer Depth
λ: Damping Rate
ρ_0: Density
$c_{p,w}$: heat capacity

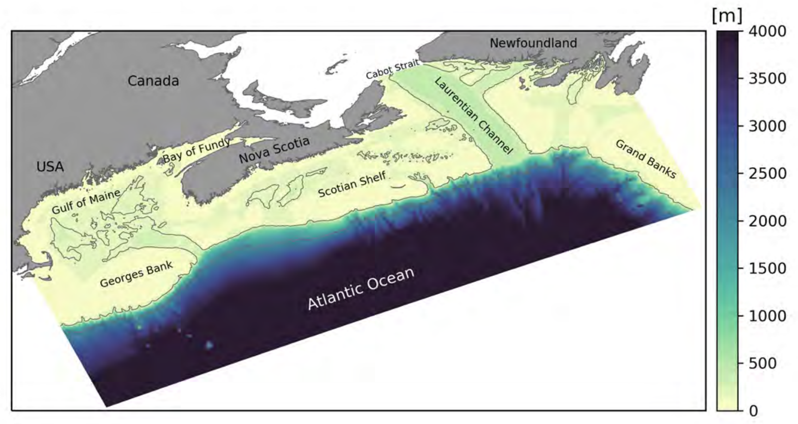
- Forcing: bandpass-filtered OAFlux Q_{net} anomalies
- Estimation of constant parameters H_m and λ
- Composite analysis of predicted SST anomalies





- MJO induces Rossby wave train (e.g., Sardeshmukh and Hoskins, 1988)
- Atmospheric response (e.g., Cassou 2008; Riddle et al., 2013) leads to advection of air masses
- Associated changes in sensible and latent heat fluxes create SST anomalies

5. Gulf of Maine and Scotian Shelf (GoMSS) Model



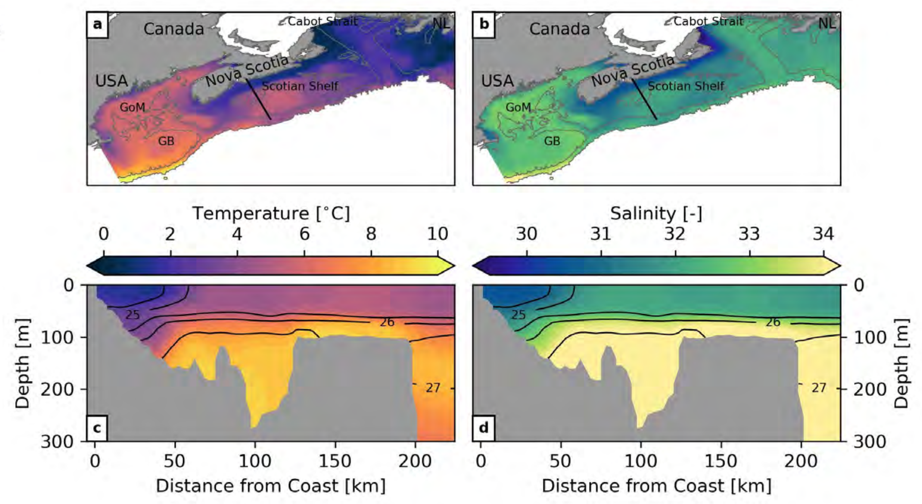
- NEMO v3.6
- 1/36° grid spacing
- 52 z*-layers
- GLORYS12v1 open boundary forcing
- CFSR and CFSv2 surface forcing
- Tidal forcing (5 constituents)

See Katavouta and Thompson (2016) for more details and model validation.

Decomposition of Model Forcing

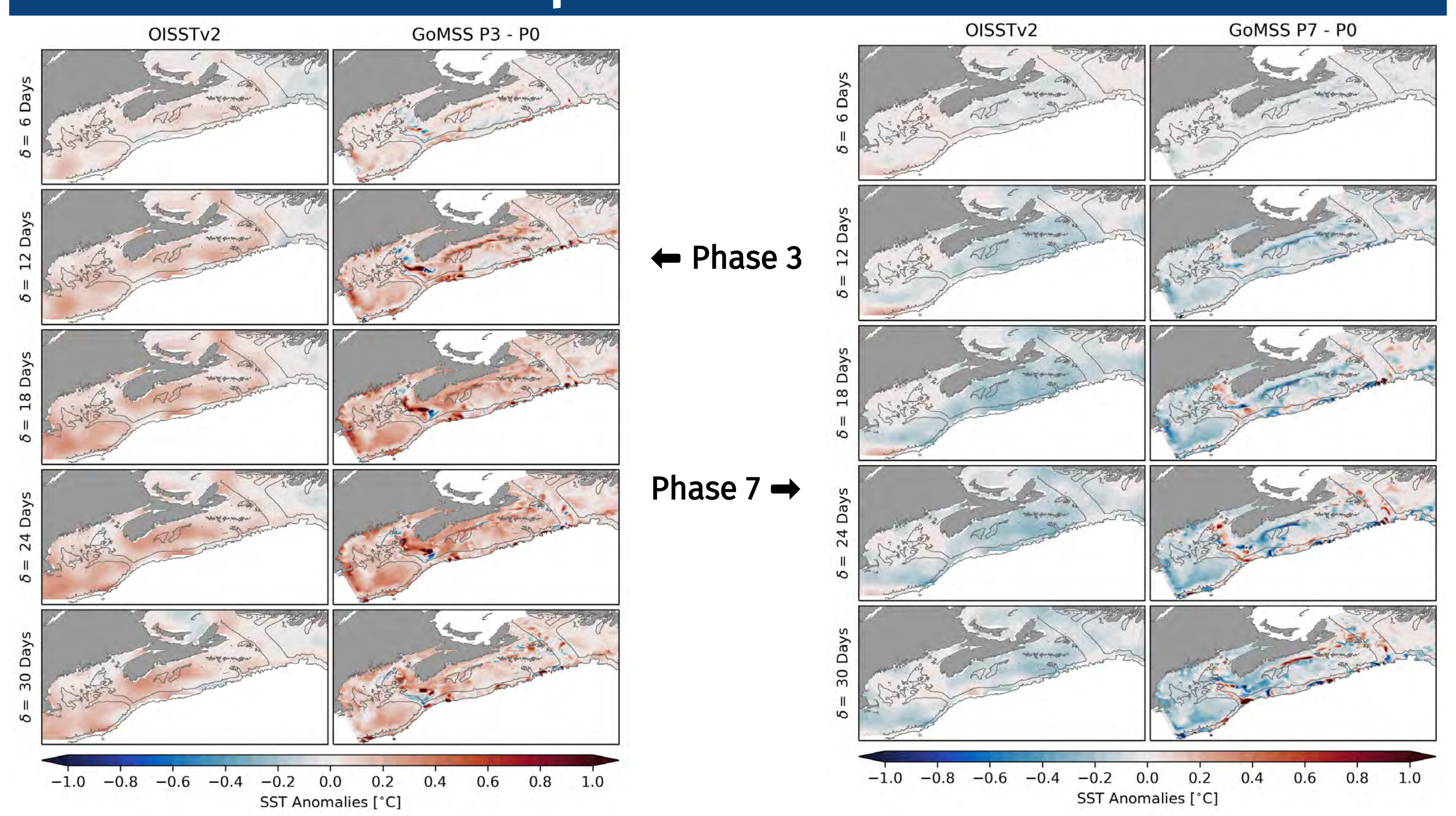
$$F = \overline{F} + F'_a + \tilde{F}_o + \hat{F}(j, \delta)$$

$\overline{F}$: Climatology
F'_a: High-Frequency Atmospheric Forcing
$\tilde{F}_o$: Tidal Forcing
$\hat{F}(j, \delta)$: Forcing on S2S timescales (MJO composites)
j=1, 2,..., 8: MJO phase
δ: Lag after MJO phase

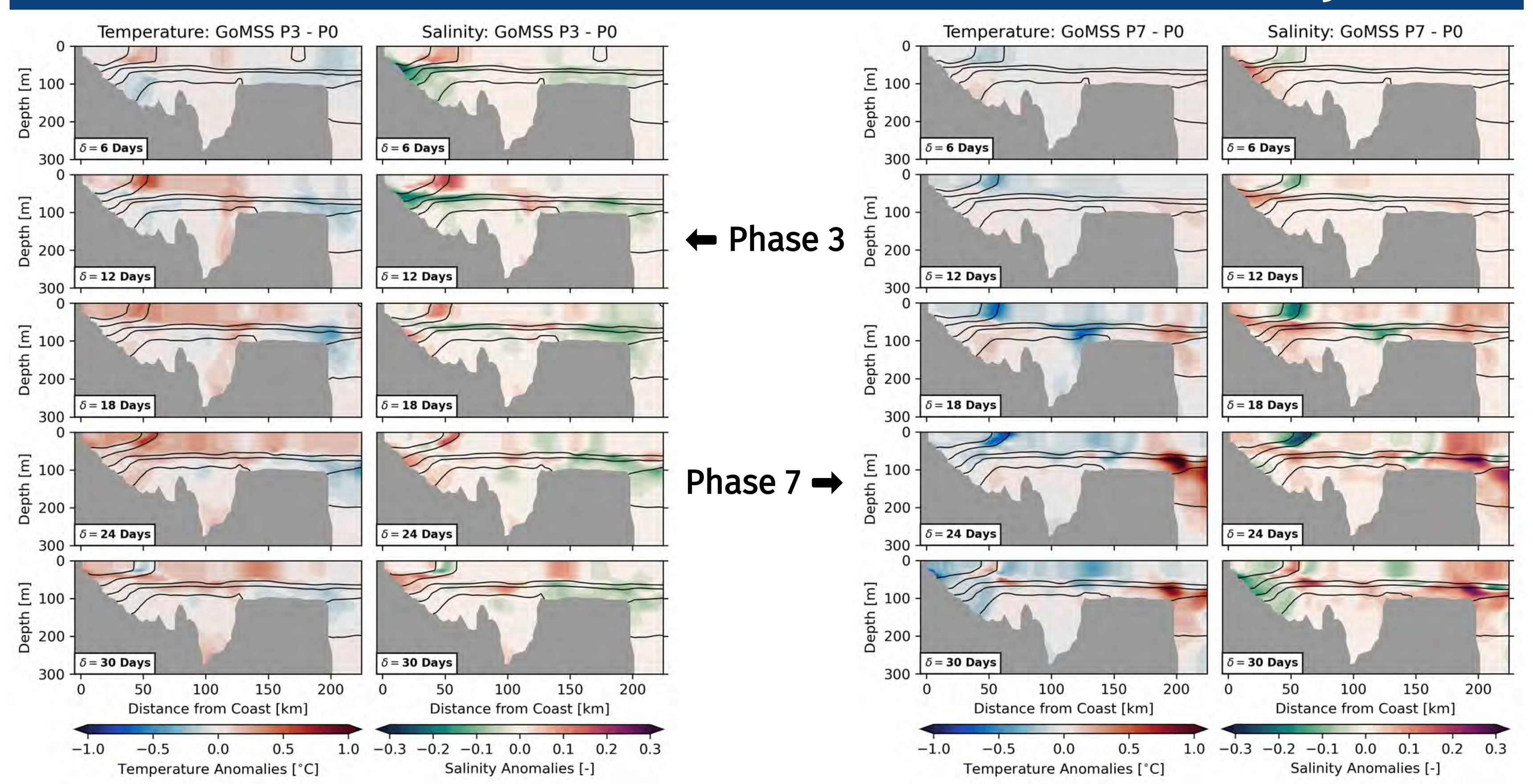


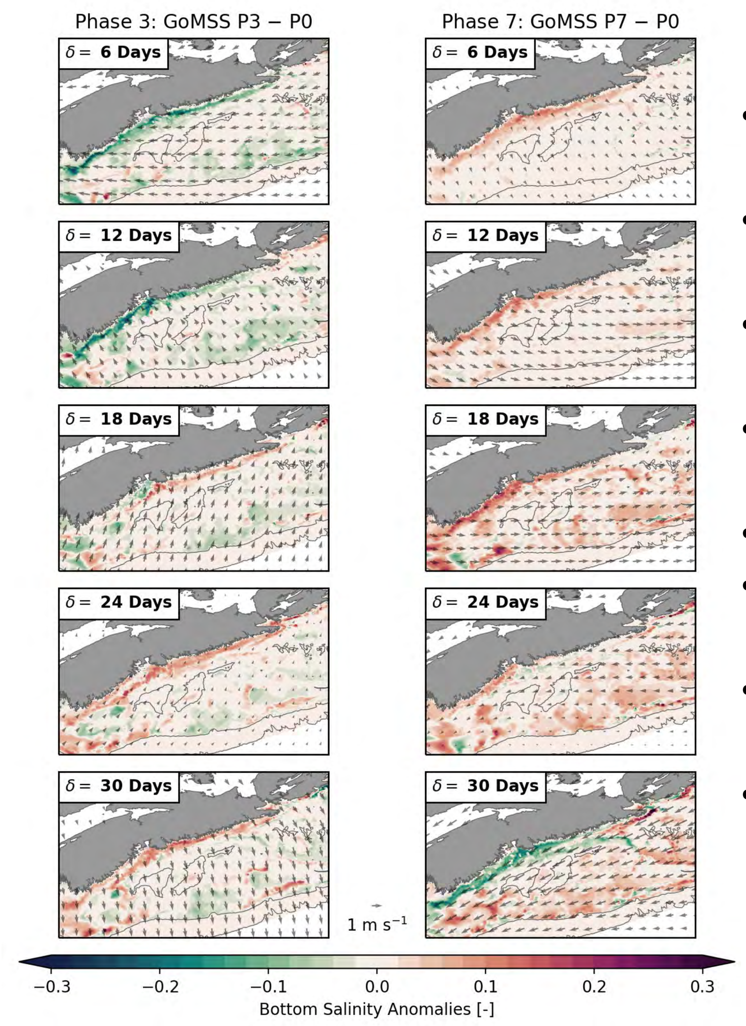
- 3 months model spin-up
- 49-day simulations with and without $\hat{F}(j, \delta)$

6. Predicted Surface Response



7. Predicted Subsurface and Small-Scale Ocean Variability





- The surface ocean response to the MJO extends throughout mixed layer
- In regions with enhanced tidal mixing, anomalies can penetrate through the whole water column
- Strong, localized temperature and salinity anomalies along the outer edge of the Nova Scotia Current
- Narrowing and widening of current 18-24 days after MJO phases 3 and 7, respectively
- Displacement of front due to horizontal advection
- Wind forcing also leads to anomalous downwellling and upwelling along the coast
- Downwelling and upwelling signatures are less apparent in temperature due mitgation by heat fluxes
- Anomalous upwelling along shelf break after phase 7 leads to intrusions of warm and salty waters

8. Summary and Conclusion

Does the MJO influence the surface ocean in the North Atlantic on S2S timescales?

- Significant SST changes in the North Atlantic with a lag δ = 3-4 weeks after MJO phases 7 and 3
- Strongest anomalies occur in northern Gulf of Mexico and along the east coast of North America
- MJO is a source of S2S predictability for the extratropical ocean
- Temporal "windows of opportunity" will enable more accurate S2S predictions of the ocean

What are the underlying physical mechanisms causing the ocean response?

- North Atlantic S2S variability is primarily driven by atmospheric teleconnections with the MJO
- Air-sea heat fluxes linked to atmospheric MJO response lead to large-scale SST anomalies

Can a regional high-resolution ocean model reproduce the ocean response?

- Regional high-resolution ocean models are able to capture the large-scale response to the MJO
- Added value: information about changes on meso- and frontal scales and at depth

How is the effect of atmospheric forcing in response to the MJO vertically projected into the subsurface ocean?

- Large-scale temperature anomalies are confined to surface mixed layer
- In regions with strong tidal mixing, the signal can penetrate to the seafloor
- Wind forcing in response to the MJO also leads to anomalous downwelling and upwelling along the coast of Nova Scotia and the shelf break