Enhancing Models to their Fullest Potential: Constraining Error in a Regional Ocean Model of Halifax Harbour

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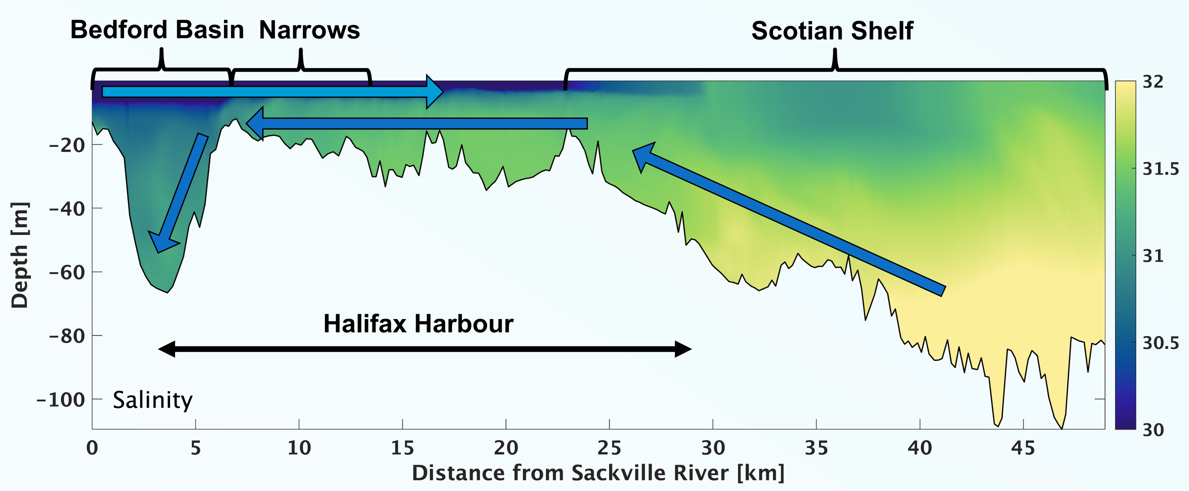


Introduction

Halifax Harbour, a small, mid-latitude fjord in Atlantic Canada is dominated by two-layer estuarine flow **(left).**

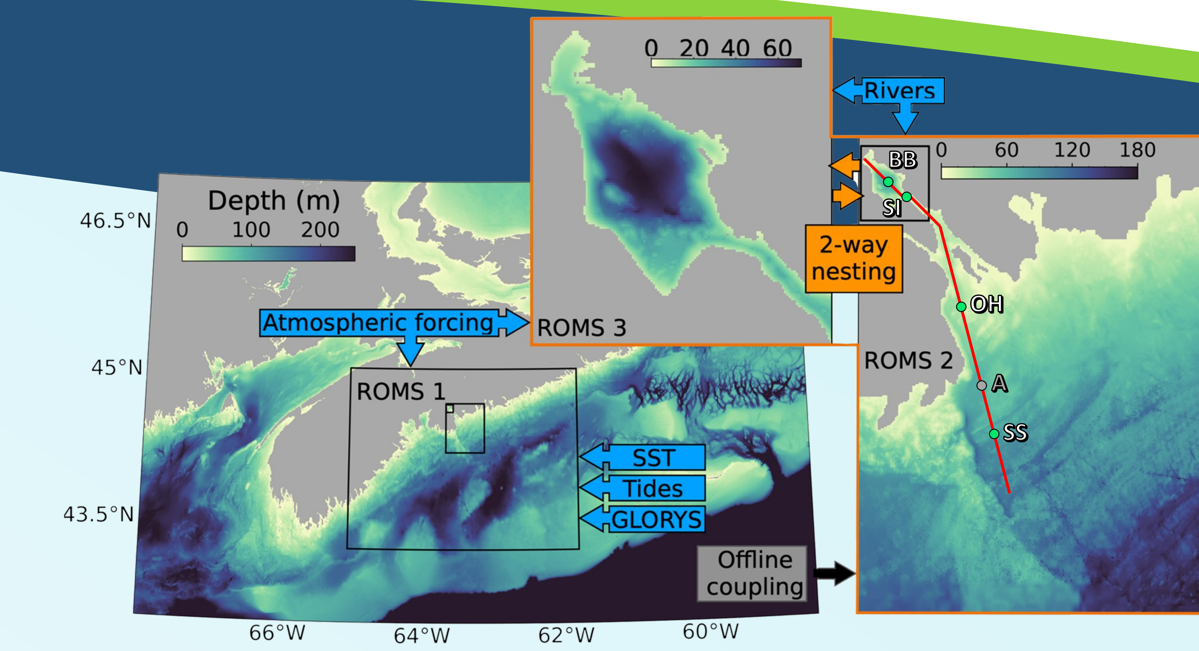
Sporadic intrusion events replace the bottom water of Bedford Basin, the 70-m deep basin at the head of the Harbour, with waters from the adjacent Scotian Shelf.

Physical and biogeochemical properties are strongly influenced by these intrusion events, estuarine circulation, mixing/stratification, tides, and winds.

The Model

Right The three nested domains of the Scotian Shelf and Halifax Harbour model set up with the Regional Ocean Modelling System (ROMS).

Model output along the transect (**in red**) and ERA 5 atmospheric forcing (**station A**) were extracted from a 20-year hindcast (2002-2022) to investigate intrusion events.



Intrusion Events

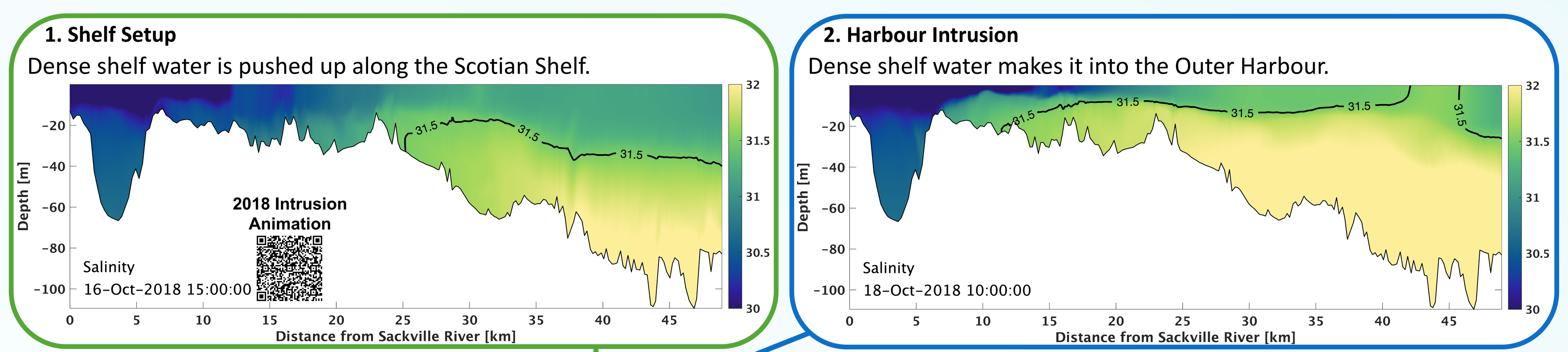
Mechanism

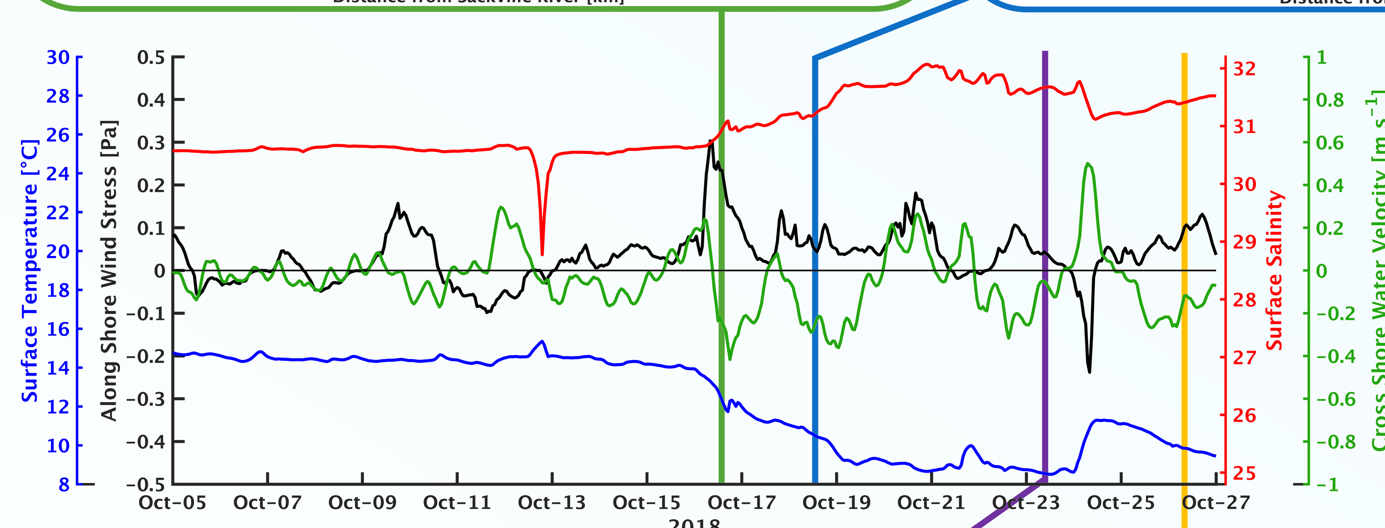
Right Depicts the story of a simulated intrusion in 2018.

Below Surface temperature during the 2018 intrusion showing coastal upwelling (**QR code animation**).

SW (along-shore) winds are known to cause upwelling along the Scotian Shelf which drives cold, salty bottom water towards shore (**Stages 1-2**).

We suggest SW winds to be the driving mechanism of these two stages.



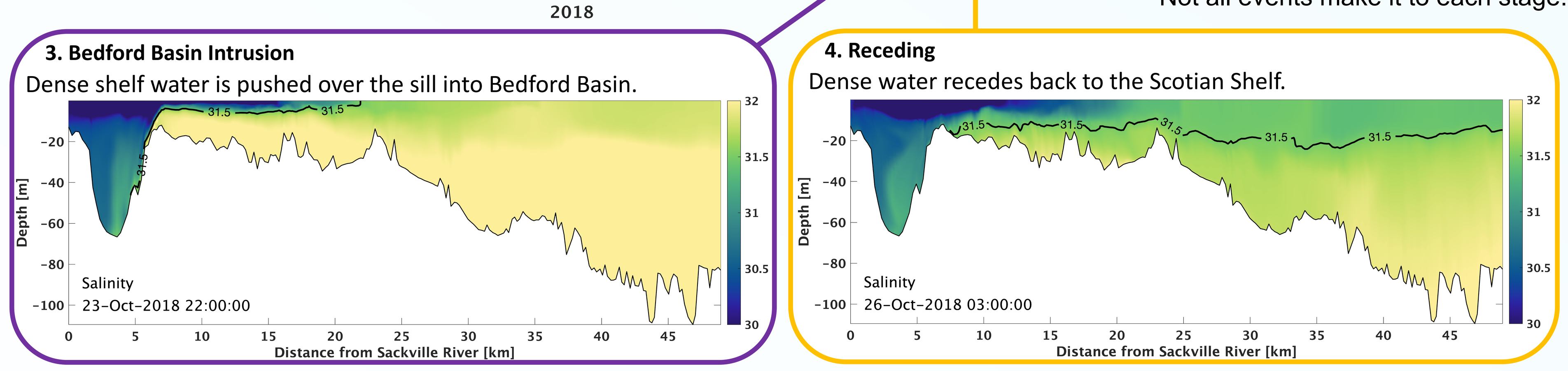


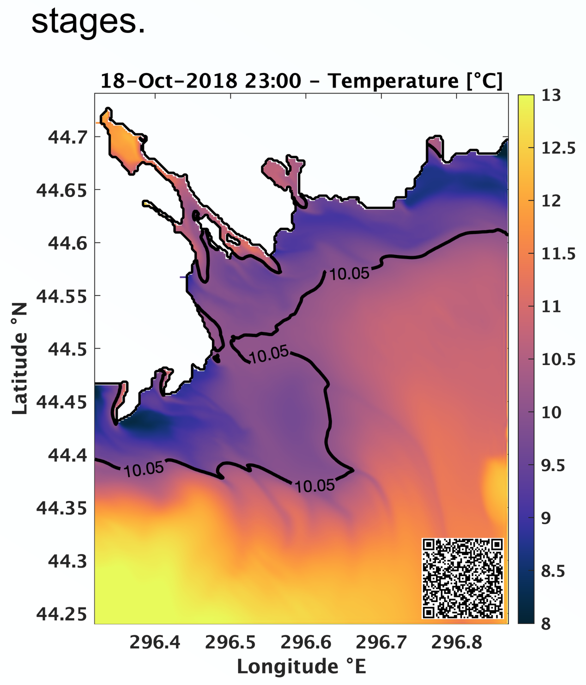
Four distinct stages of an intrusion event, illustrated by hourly salinity transect snapshots (**QR code for animation**), can be identified.

Left Timeseries of surface temperature, salinity, cross-shore velocity and along-shore wind stress at station A.

Positive along-shore wind stress: SW
Positive cross-shore velocity: towards shore

Not all events make it to each stage.



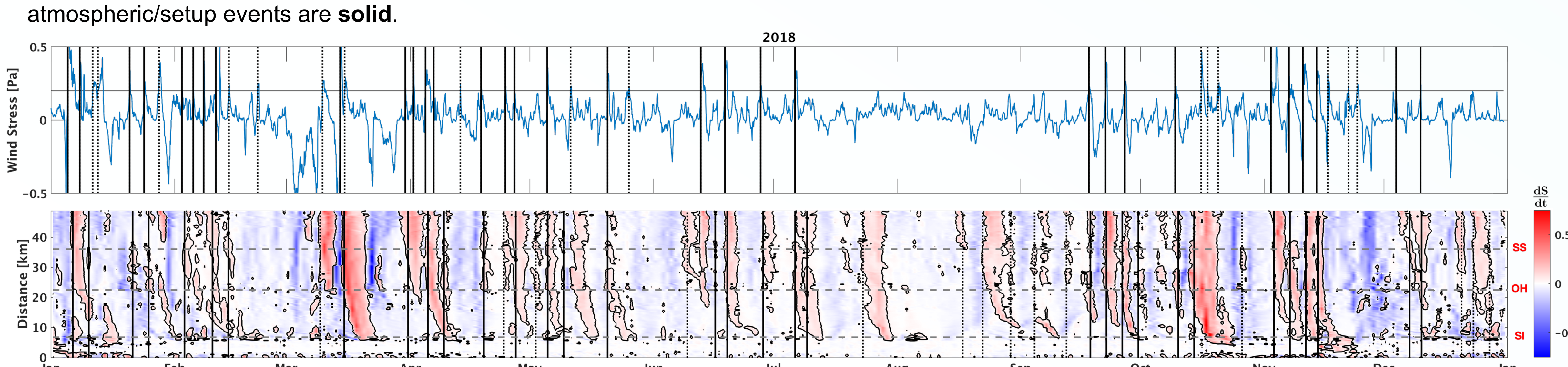


Detection

Below are time series of SW (along-shore) wind stress from model forcing (**top**) and bottom $\frac{dS}{dt}$ along the transect (**bottom**), from daily output of the 20-year hindcast (intrusions are best identified by a rapid salinity increase).

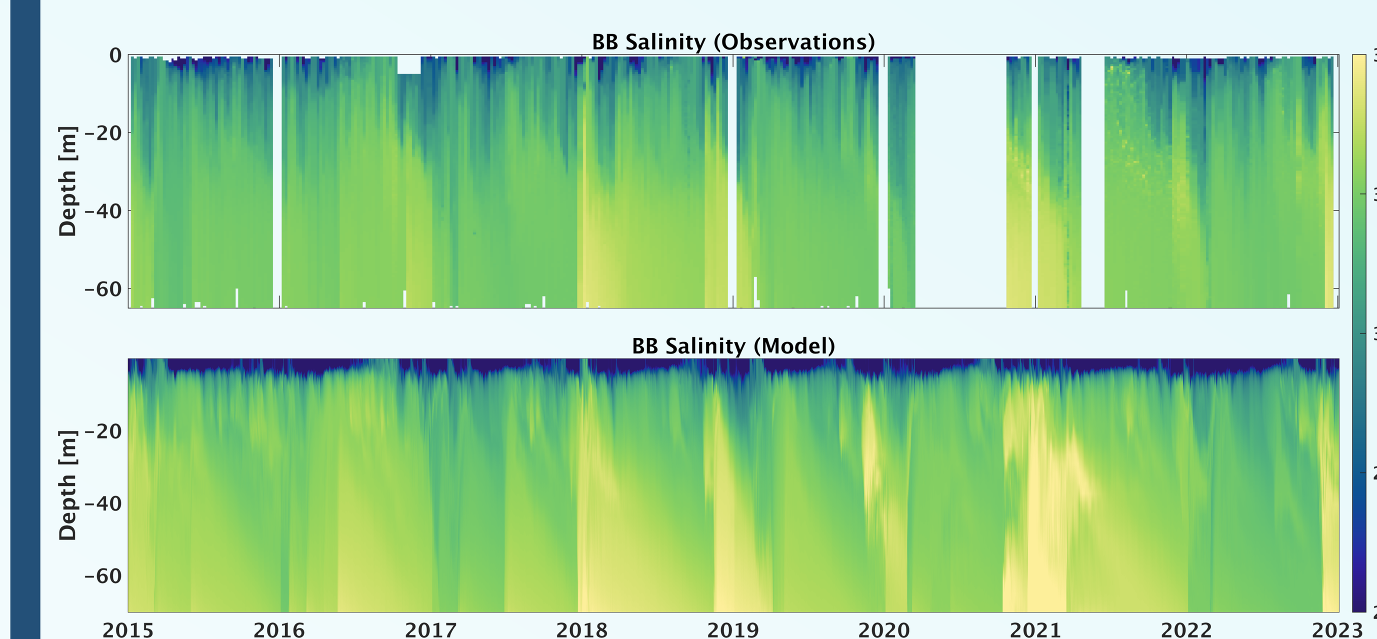
Stage 1 intrusions can be identified by $\frac{dS}{dt}$ above 0.035 [S d⁻¹] (**black contour; bottom**) reaching station SS (**upper grey dashed line; bottom**).

Atmospheric mechanisms (along-shore wind stress) and "Shelf Setup" events are flagged automatically by a script (**dotted vertical lines**). Overlapping atmospheric/setup events are **solid**.



Improving Model Accuracy

Errors



Left Comparison of salinity profile time series from the center of Bedford basin (**station BB**) between observations (**top**) and model (**bottom**).

Comparison shows good agreement, with some discrepancies arising from estuarine circulation, stratification and intrusions.

Model transect EOFs (**below**) demonstrate that processes related to the river (**top**) and intrusions (**bottom**) dominate model variability (61% and 15% respectively) and hence are important to simulate correctly.

Amplitudes (**below**) for EOF #1 (**top**) are highly correlated (0.71) with river discharge and for EOF #2 (**bottom**) show positive peaks during example times of simulated intrusions (**dashed vertical lines**).

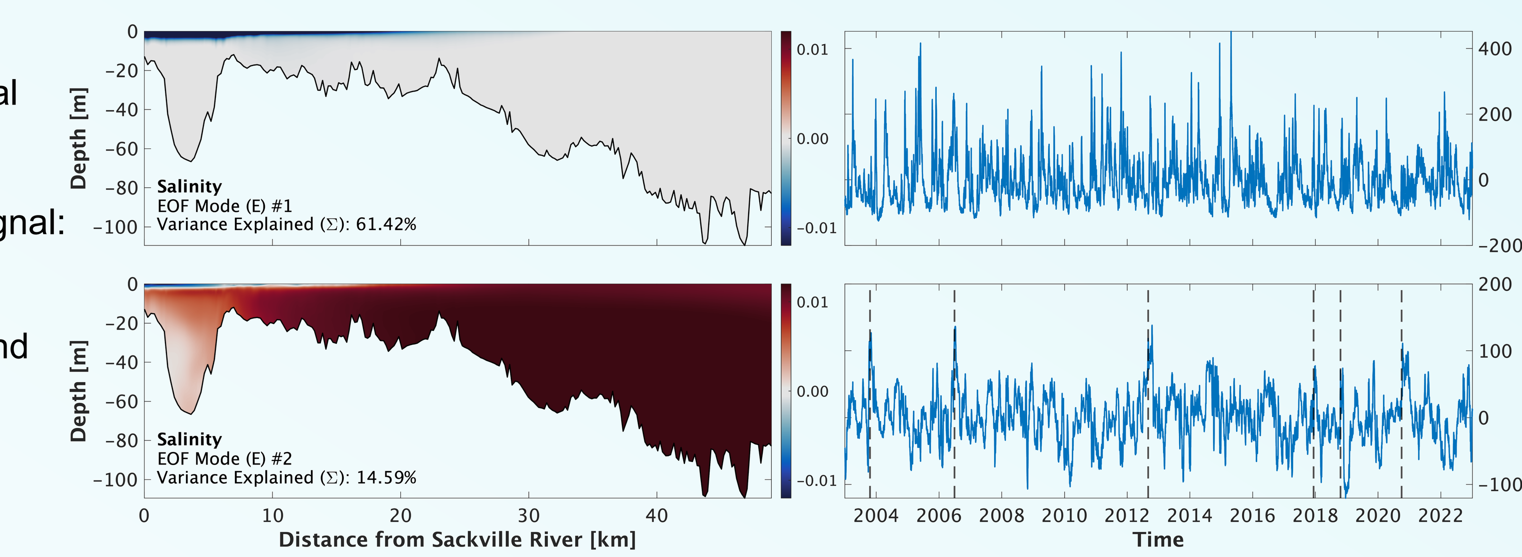
Model EOFs

Model output (X) can be decomposed via Empirical Orthogonal Functions (EOFs) into a collection of spatial modes (E) and corresponding amplitude time series (A^T). Singular values (Σ) provide the relative importance of each mode to the overall signal:

$$X = E\Sigma A^T$$

Right are the two most dominant EOF modes (E; **left side**) and their amplitude time series (A^T; **right side**).

Model representation error can be obtained by using cross validation techniques to truncate noisy EOF modes.



EOF Reconstruction

The cost function (**below**) can be solved for a_t (amplitudes at time, t) that minimize the least-squares difference between observations (y_t) and model equivalents ($H_t E\Sigma a_t$):

$$J(a_t) = (H_t E\Sigma a_t - y_t)^T R^{-1} (H_t E\Sigma a_t - y_t) + (\Sigma a_t)^T \Lambda^{-1} \Sigma a_t$$

The cost function is weighted by the sum of model representational and observational error (R).

The additional term penalizes solutions using EOF modes that explain little variability (Λ).

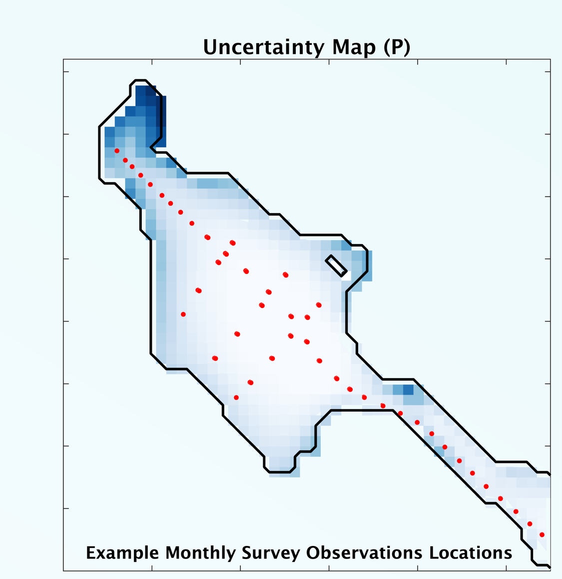
Optimized a_t can be used to reconstruct model output; which should have improved accuracy due to being constrained by observations.

The uncertainty mapping (P) of the model reconstruction can be derived from the solution:

$$\mathbf{D}\Sigma a_t = h$$
$$D = E^T H_t^T R^{-1} H_t E + \Lambda^{-1}$$
$$h = E^T H_t^T R^{-1} y_t$$
$$P = ED^{-1}E^T$$

Uncertainty maps only require locations and uncertainty of observations and EOF modes.

Above right Example uncertainty map for current sampling scheme of Bedford Basin.



Acknowledgements

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