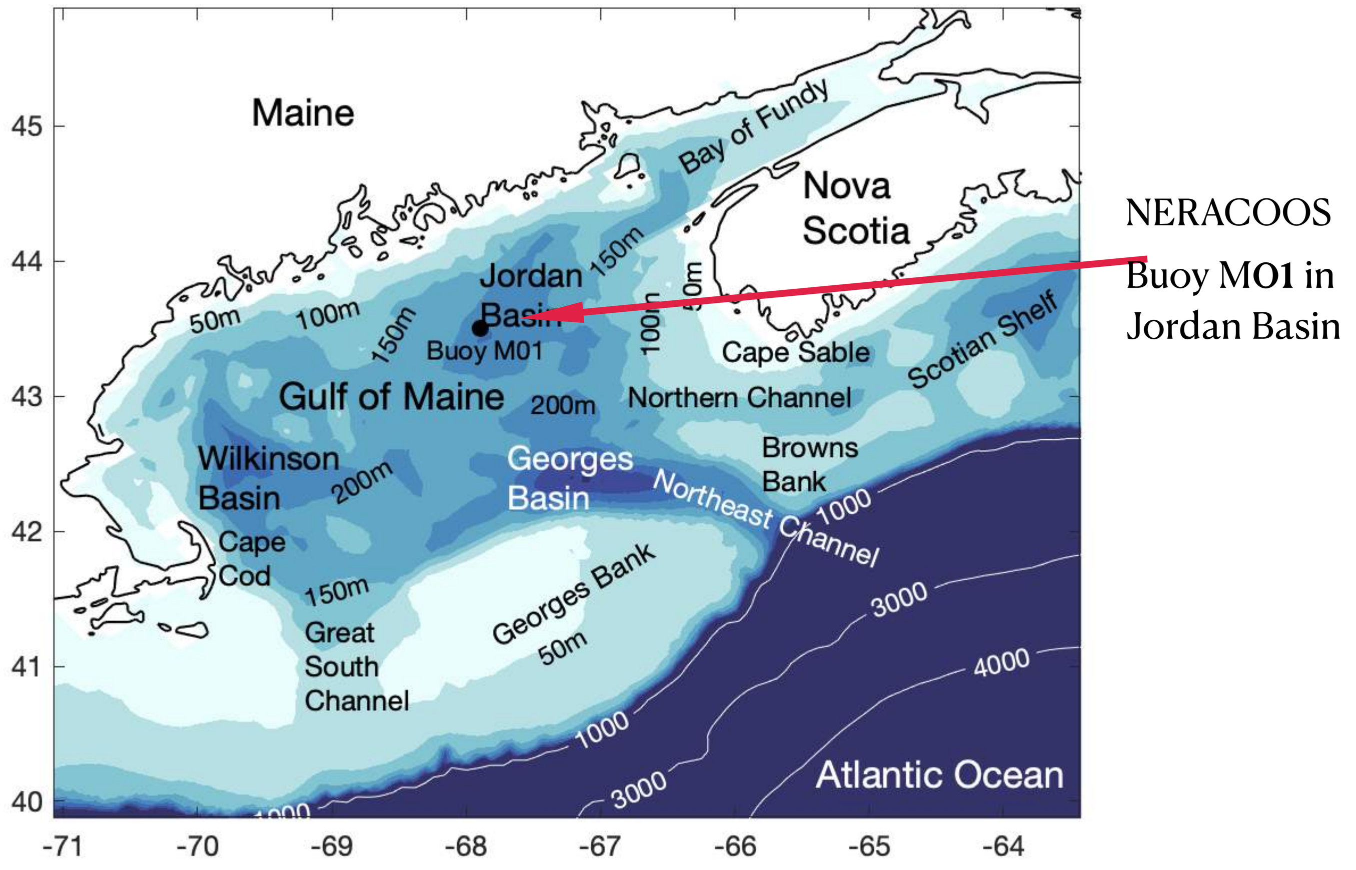
Haline Control of Unusually Deep Winter Mixing in the Gulf of Maine Investigated using a Regional Data-Assimilative Model

J. C. Levin (Rutgers University), S. A. Grodsky (University of Maryland), D. Vandemark (University of New Hampshire), and J. L. Wilkin (Rutgers University)

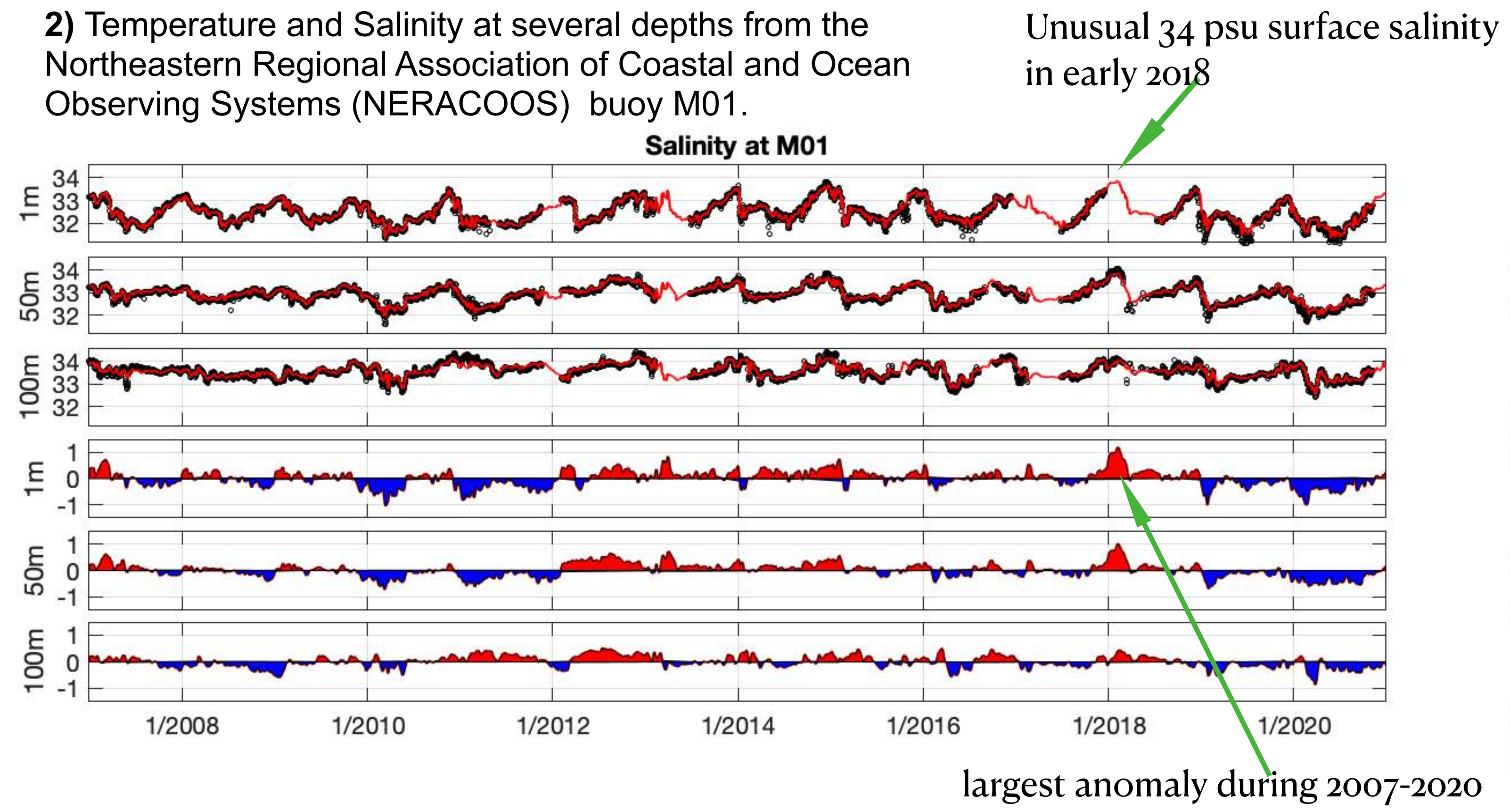


The Gulf of Maine is a shelf sea in the Northwest Atlantic. It is topographically confined and largely isolated from the Atlantic Ocean by the wide and shallow Georges and Browns Banks. There are three primary transport pathways in and out of the Gulf. These are the Northeast Channel that connects with the Northwest Atlantic Slope Sea, the shallower Northern Channel through which enters water from the upstream Nova Scotian Shelf to the east, and the shallow Great South Channel to the west of Georges Bank. The Gulf interior includes three relatively deep (250-300 m depth) basins - Jordan Basin, Wilkinson Basin, and Georges Basin.

Observations used in the study:

1) Surface Salinity from Soil Moisture Active Passive (SMAP) satellite mission

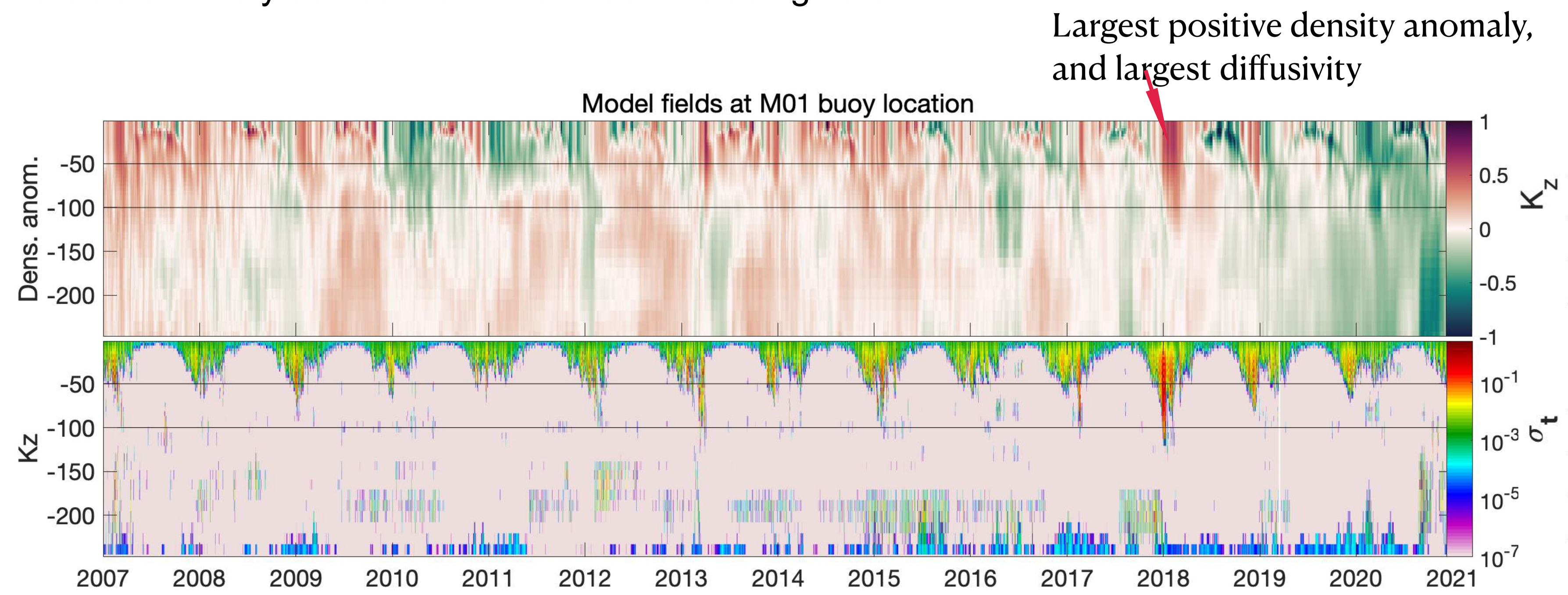
2) Temperature and Salinity at several depths from the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) buoy M01.



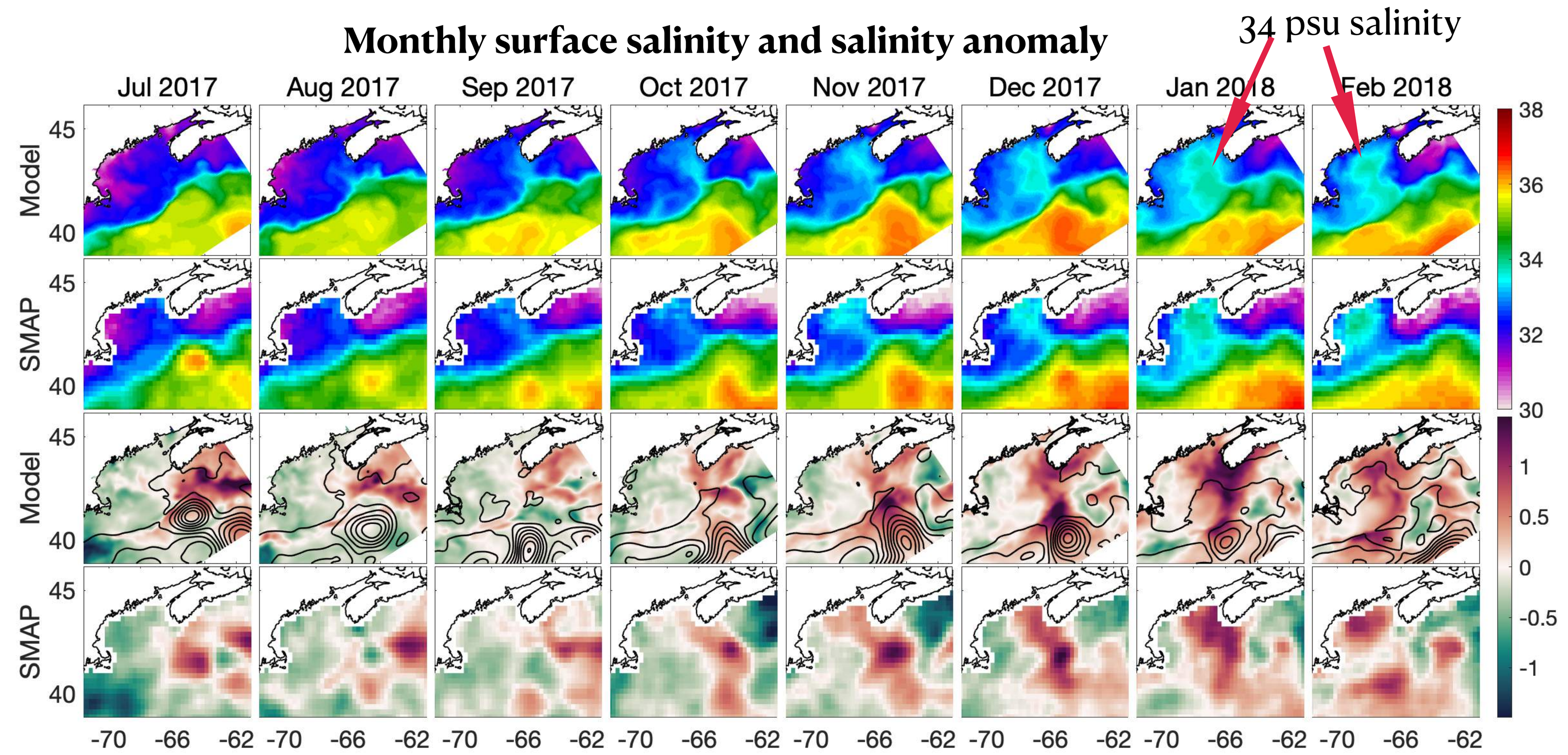
*Modeled (red line) and observed (black dots) time series of daily averaged salinity (**top three rows**) and salinity anomaly from the climatological monthly cycle (**bottom three rows**) at buoy M01 during 2007-2020. Anomalies are smoothed by applying two-week running mean to modeled salinity anomaly.*

The model follows observations well at each depth. It also reasonably fills numerous observational gaps such as occurred during winter 2017-2018 at z =1 m, a focus period in this study. One notable aspect of the Jan.-Feb 2018 time period is that the T and S observational changes at station M01 were so large and rapid that the data assimilation quality control rejected these observations. Therefore M01 data do not factor into model performance in this time window.

Summary. An unusually large positive salinity anomaly was observed across the eastern Gulf of Maine (GoM) in winter 2017-2018. Buoy measurements in Jordan Basin found this anomaly extended down to at least 100 m, the deepest mixing observed in the past 19 years. Similarly, this is the strongest positive regional salt anomaly in sea surface salinity (SSS) satellite observations. To determine the source waters driving this event and to diagnose the relative importance of forcing processes, passive tracer adjoint sensitivity experiments are performed using a data assimilating version of the Regional Ocean Modeling System. The model suggests that northeastward Scotian Shelf wind anomalies is one factor in the dramatic decrease in freshwater transport to Jordan Basin, which leads to an early winter upper water column salinity surplus. This salinity change weakens the normally haline-controlled vertical stratification across the eastern Gulf. Modeled upper ocean density and vertical diffusivity from 2007-2021 both show a maximum in January 2018. Winter 2017-2018 is the only period where the enhanced winter mixing extends below 100 m. Thus, anomalous vertical entrainment of saltier subsurface Gulf water is the major factor driving the extreme positive satellite-observed SSS anomaly across the eastern Gulf including Jordan Basin.

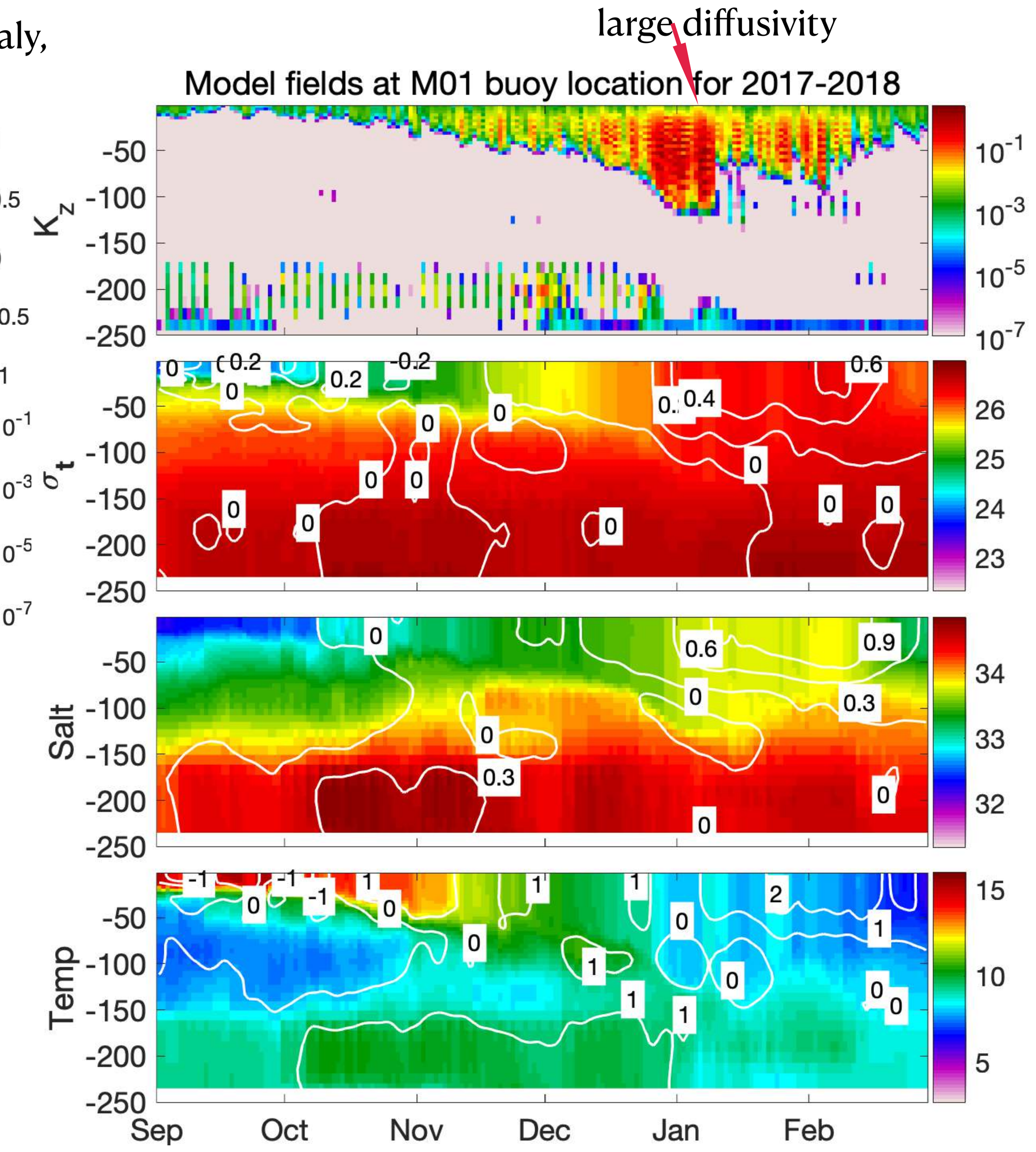


An annual cycle in the mixed layer is apparent in the diffusivity, K_z, results, shoaling to less than 10 m in summer and deepening to roughly 40-50 m in winter. Within the 14-year window, winter 2017-2018 levels of K_z are uniquely elevated. The extreme December 2017 K_z increase is closely followed by the largest positive density anomaly in the surface layer, a period that extends from 25 Dec. 2017 to 4 Mar. 2018. Vertical profiles of daily K_z in this period show the largest mixing anomalies in the record, exceeding the winter background by a couple of orders of magnitude and extended much deeper (below 100 m) than the usual 40-m depth.



*Regional maps of monthly-averaged model and SMAP surface salinity (**upper two rows**) and surface salinity anomaly (SSSA) (**lower two rows**) for Jul. 2017-Feb. 2018. Model SSH contours at 10 cm intervals are overlaid on top of model SSSA in the third row.*

There is a reasonable agreement between SMAP and model SSS at monthly scales. Absolute SSS and SSS anomalies (SSSA) for July 2017 to February 2018 are consistent in the eastern and central Gulf of Maine and out into the Slope Sea



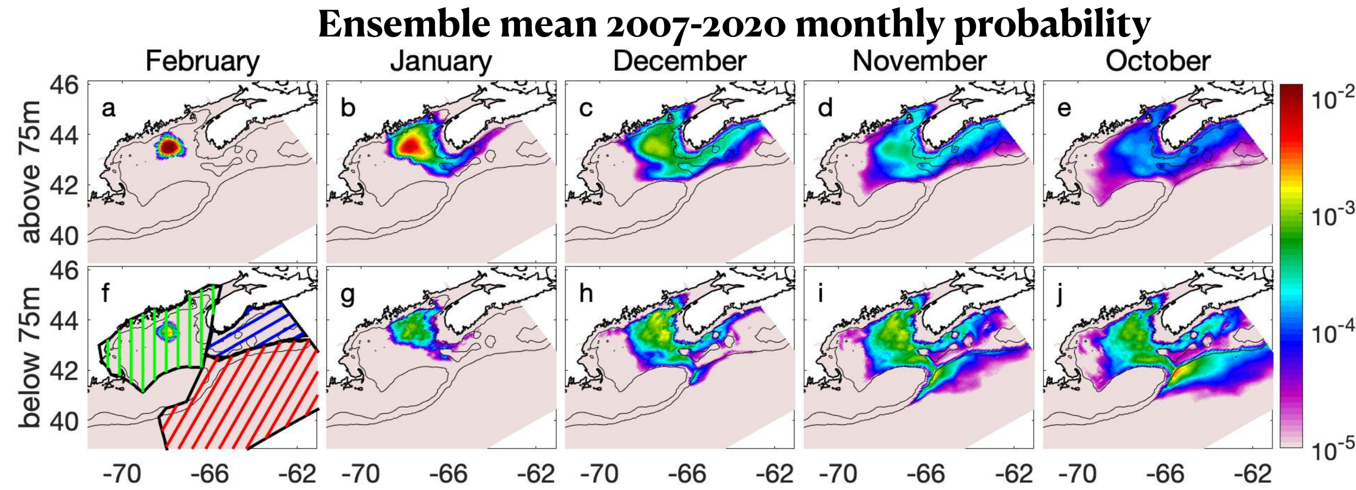
Model diffusivity K_z (m^2/s), σ_t (kg/m^3), S (psu) and T (°C) at M01 buoy location during 2017-2018 salinity event. Contours show anomalies from the climatological mean seasonal cycle.

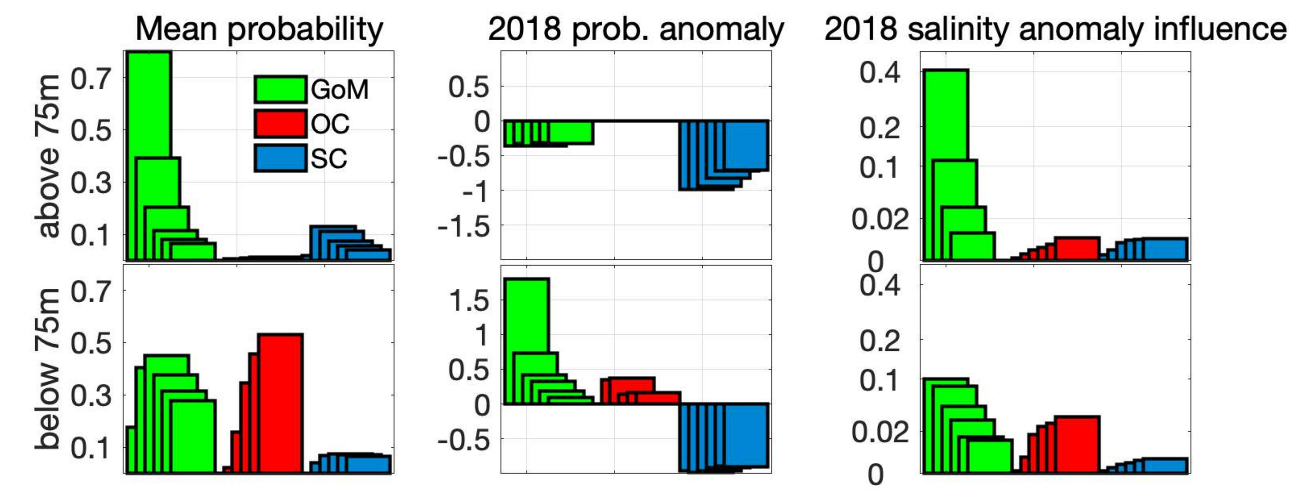
The 2018 density anomalies are increasing in early December in the upper 20-50 m. Below, at around 100 m, water warms significantly and shows a small but persistent decline in density. This is accompanied by excess K_z down to 50 m. The vertical evolution of temperature between the surface and 150 m from November to December also suggests that warm and salty water is building in the upper layer. By late December, density anomalies above 50 m show that the upper layer becomes denser then in typical years, approaching the average density only at 100 m leading to a loss of stratification. The strong positive mixed layer density anomaly decreases the upper ocean stability and preconditions the onset of the severe convective mixing prior to Jan. 2018. This is evident in the dramatic increase and deepening K_z to down below 120 m. The mixing anomaly extends into mid-January. A series of four storms crossed the region between 16 Dec. 2017 and 10 Jan. 2018, and while not atypical for the season, nor atypically strong, these storms provided the surface forcing

Model description. The analysis is based on a 4D-Var Regional Ocean Modeling System (ROMS)model configured for a large section of the NW Atlantic shelf, including the Scotian shelf, GoM, MAB, and adjoining Slope Sea and Gulf Stream. This model solves a set of hydrostatic, Boussinesq, primitive equations. The model domain has a uniform horizontal resolution of 7 km and 40 terrain-following vertical levels. Air-sea momentum, heat, and freshwater fluxes are computed using the bulk flux formulae from atmospheric fields provided by the North American Regional Reanalysis (NARR) for 2007-2013 and North American mesoscale available for 2014-2020. The vertical turbulent mixing scheme is based on the *k-kl* parameterization. The model is constrained at the open boundaries by daily output from 1/12° horizontal resolution Mercator-Ocean global data assimilation system after adjustment to remove seasonal biases. Oregon State Tidal Prediction Software (OTPS) harmonic tide is added to sea level and velocity boundary conditions. The model configuration includes freshwater discharge from 22 major local rivers.

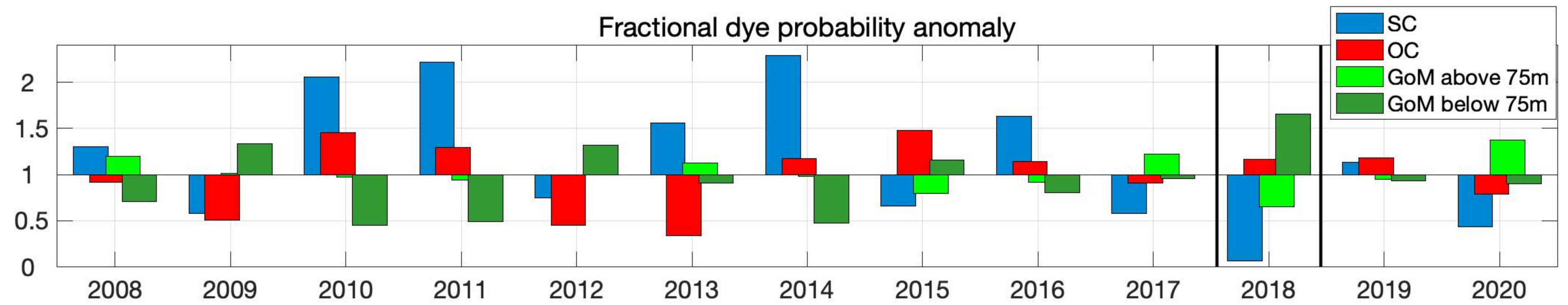
Assimilation scheme. The ROMS 4D-var data assimilation scheme is used in the analysis. Satellite altimeter along-track sea surface height anomaly (SSHA) data are combined with mean dynamic topography derived from a climatological reanalysis to create SSH observations that are assimilated into the model. The model also HF radar surface currents, sea surface temperature (SST) from microwave and infrared satellite sensors, and an extensive list of *in situ* observations. NERACOOS M01 data is assimilated but observations during Jan-Feb 2018 are not assimilated (discarded by model quality control as too unusual). SMAP observations are not assimilated.

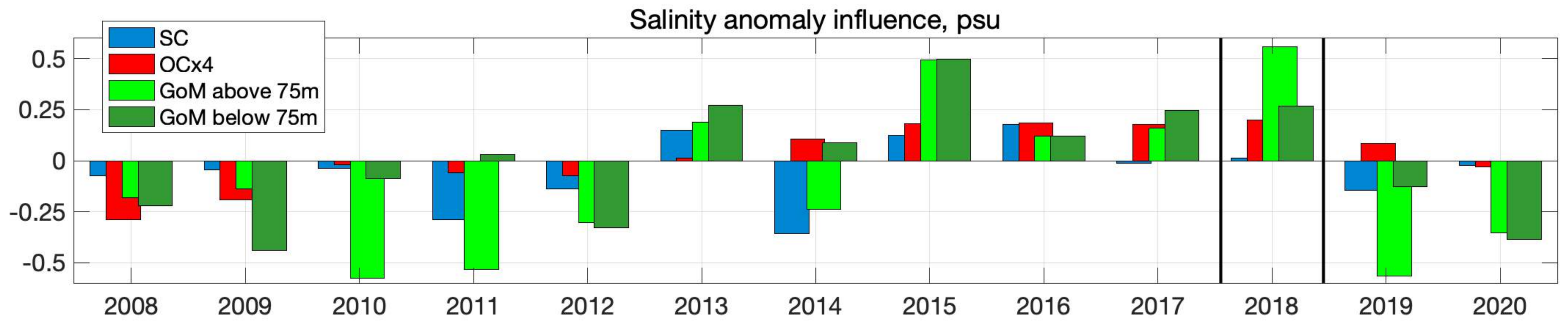
Analysis method. Model-based adjoint sensitivity analysis is used to trace the origins of salinity anomaly in GoM to source areas of the Scotian Shelf and open ocean. Adjoint sensitivity analysis is based on using the adjoint of an advection-diffusion equation to look at backward propagation of a passive tracer or dye. Looking at the backward-in-time evolution of the adjoint dye patch, we can quantify the fractional contribution of the areas that contribute to the phenomenon in question. The dye is released in upper 10m in first week of February each of 2007-2020 years at M01 location. We look at source contributions in an ensemble mean and 2018 anomaly.





***Left:** Spatial integrals of mean ensemble probabilities, computed separately for above and below 75 m for Gulf of Maine (GoM), open ocean (OC) and Scotian Shelf (SC). **Middle:** Spatial Integral of 2018 probability anomaly scaled by mean ensemble probability. **Right:** 2018 salinity anomaly influence (salt anomaly multiplied by probability). Integral probabilities are shown for each of the six preceding months, (Jan. to Aug.) by overlapping bars, with the leftmost bar corresponding to Jan., and rightmost – to Aug.*





*Spatial integrals of 2018 probability anomaly (**left**) and salinity anomaly influence (salt anomaly x probability) (**right**). Integral probabilities are shown separately for GoM above and below 75 m depths and SC and OC. 2018 shows the lowest Scotian Shelf input . The lower GoM layer also shows larger changes in 2018 than in other winters. Surface Jordan Basin water in February 2018 is composed of the largest amount of deep GoM water and the smallest amount of surface GoM water. 2018 also has the greatest positive GoM salinity contribution in the upper 75 m, suggesting elevated salinity in upper GoM through the fall. SC salinity anomaly contribution is negligible because there is little volume contribution.*