Sensitivity of northwestern North Atlantic shelf circulation to surface and boundary forcing: A regional model assessment

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ABSTRACT The northwestern North Atlantic shelf circulation, influenced by both North Atlantic subpolar and subtropical gyres, is one of the hydrographically most variable regions in the North Atlantic Ocean and hosts biologically rich and productive fishing grounds. With the goal of simulating conditions in this productive and complex region, we implemented a nested regional ocean model for the northwest North Atlantic shelves including the Gulf of Maine, the Scotian Shelf, the Gulf of St. Lawrence, the Grand Banks, and the adjacent deep ocean. Configuring such a model requires choosing external data to supply surface forcing and initial and boundary conditions, as well as the consideration of nesting options. Although these selections can greatly affect model performance and results, often they are not systematically investigated. Here we assessed the sensitivity of our regional model to a suite of atmospheric forcing datasets, to sets of initial and boundary conditions constructed from multiple global ocean models and a larger scale regional ocean model, and to two variants of the model grid – one extending further off-shelf and resolving Flemish Cap topography. We conducted model simulations for a 6-year period and assessed model performance relative to a regional climatological dataset of temperature and salinity, observations collected from multiple monitoring stations and cruise transect lines, satellite sea surface temperature (SST) data, and descriptions of regional currents from literature. Based on this model assessment, we determined the model configuration that best reproduces observations. We find that while all surface forcing datasets are capable of producing model SST close to observed, the different datasets result in significant differences in model sea surface salinity (SSS). We find that initial and boundary conditions based on global ocean models do not necessary produce realistic circulation, and climatological initial and boundary conditions can improve model performance over those from global ocean models. Beyond optimizing model performance, we gained mechanistic understanding of model responses to variable nesting, surface forcing and domain choices.

i. Background

The northwestern North Atlantic is:

- Host to ***biologically rich and productive*** fishing grounds.
- Characterized by ***coastal marine shelves (< 200 m depth).***
- Characterized by ***large dynamic complexity: influence of both North Atlantic subpolar and subtropical gyres via the Labrador Current and Gulf Stream*** (Loder et al., 1998), contains a semi-enclosed sea (e.g. Gulf of St. Lawrence), and exhibits the largest observed sea surface temperature variability in the North Atlantic (Thompson et al., 1988).

Model motivation:

- Given the dynamical complexity, this region is unlikely to be well represented by a global ocean model.
- We implemented a nested regional ocean model for the northwest North Atlantic shelves, including the Gulf of Maine, the Scotian Shelf, the Gulf of St. Lawrence, the Grand Banks, and the adjacent deep ocean.

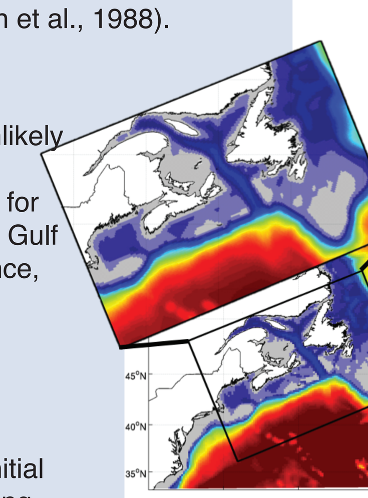


Fig 1. Location of regional biophysical model domain and bathymetry (see inset) in the northwest North Atlantic .

Assessment of North Atlantic shelf circulation:

- Depends on external data: surface forcing and initial and boundary conditions derived from model nesting selection.
- Model configuration choices can greatly affect results and performance, but often they are not systematically investigated when applying downscaling.
- Wilkin and Hunter (2013) found that model simulations with boundary information from a regional climatology outperformed those created from most ocean models, for a regional model of the Mid-Atlantic Bight shelf.
- We assessed the sensitivity of our regional model to a suite of atmospheric forcing datasets, to sets of initial and boundary conditions constructed from different global ocean models and a larger scale regional ocean model, and to two variants of the model grid – one extending further off-shelf and resolving Flemish Cap topography.

Fig 2. Atlantic Zone Monitoring Program (AZMP) repeat cruise sections over the northwest North Atlantic shelves.

Model assessment goal:

- Determine the model configuration that best reproduces observations.
- Gain insight into which factors are key to improving model performance.

Table 1. Regional circulation features.

	MEAN STATE	ANNUAL VARIABILITY
Labrador Current (LC)	Coastal & shelf-edge components; trifurcation: Avalon Channel, Flemish Pass, north of Flemish Cap (Loder et al. 1998)	Annual var ~≈ 4 Sv (Lazier & Wright 1993); More intense in Nov than July (Han et al 2008)
Grand Bank (GB)	Weak flow, overall southerly	-
Gulf of St. Lawrence (GSL)	Large scale cyclonic circulation (Loder et al. 1998); Gaspé Current in northwestern GSL transports low-salinity estuarine water to central GSL(Benoit et al 1985)	-
Cabot Strait (CS)	GSL outflow on western side	Annual var ~≈ 0.5 Sv (El Sabh, 1977); Maximum outflow in fall (1.3 Sv) vs minimum in spring (0.5 Sv) (model results of Han & Loder 2003)
Shelf break current (SBC)	Strong, persistant, surface-intensified southwest transport 1-3 Sv (Han and Loder 2003), larger upstream (i.e. Banquereau > Halifax section)	Largest values fall, winter, spring
Scotian Shelf (SS)	Clockwise flow around Sable Island Bank (SIB) (Hannah et al 2001); Anticyclonic gyres & partial gyres over outer banks (Han & Loder 2003)	SIB gyre weakest in spring (Hannah et al 2001)
Nova Scotian Current (NSC)	Eastern SS: flows southwestward continuously near the surface; Central/Western SS: addition from SBC meander across SS	Annual var ~≈ 0.6 Sv (Anderson & Smith 1989); Strongest in winter (1.0 Sv), weakest in summer (0.25 Sv) (Halifax section; Hannah et al 2001)
Gulf of Maine (GOM)	Cyclonic flow around inner basins; Anticyclonic flow around GOM outer banks (Loder et al. 1998)	Variable inflow to GOM from SS ~≈0.4 Sv (Smith 1988)
Gulf Stream	Off shelf northeastward transport	-

Table 2. Description of external datasets.

DATA ID	Details	Description
CORE	CORE Version 1 (Large and Yeager, 2004)	Informed by both reanalysis and satellite data with interannually varying forcing and 2° x 2° horizontal resolution. Created by the Clivar Working Group for Ocean Model Development (WGOMD) for use in the Common Ocean-Ice Reference Experiments (CORE) for the period 1999-2004.
NARR	National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) (Mesinger et al., 2006)	Assimilates observed precipitation for improved hydrological cycling. Temporal resolution is 3 hours, except (daily) net surface solar radiation, and temporal coverage extends from 1979 to 2012. Provided on a Lambert Conformal Conic grid (grid size ~32 km). We interpolated the data onto a ~0.25° regular grid.
ECMWF	European Centre for Medium-Range Weather Forecasts (ECMWF) global atmospheric reanalysis (ERA-Interim) (Dee et al., 2011)	Temporal resolution is 3 hours, except (daily) mean net surface solar radiation. Data are instantaneous values or time averages, with temporal coverage from 1979 through 2012. Data provided on T255 res. spectral grid (~0.7°), and we interpolated the data to a ~0.125° regular grid.
ECMWF-EVAP	Same as above	Same as above, but with evaporation additionally specified from the data (as opposed to being calculated internally within the model).
UBS	Urrego-Blanco and Sheng (2012) regional physical ocean model	Based on NEMO-OPA9 physical model of the northwest North Atlantic. Extends from 33 to 55°N in latitude and 80°W to 33°W in longitude, and has ~1/4° horizontal resolution, 46 vertical levels, and a coupled sea ice model. Using Geshelin et al. (1999) climatology for initial conditions and CORE surface forcing, the model was integrated from 1987 (from an initial state of rest) to 2004. From this simulation, we employ 5-day average model data from the last 6 years (1999 -2004).
UBSclim	Same as above	Long-term (1999-2004) monthly mean output from UBS.
HYCOM	HYCOM+NCODA global 1/12° analysis, experiments 60.5 - 90.6	HYCOM 2.2 ocean model assimilates satellite observations of *SSH* and *SST*, and in-situ XBT, ARGO float, and moored buoy *T* and *S* data via Navy Coupled Ocean Data Assimilation (NCODA) (Cummings, 2005). Has 32 vertical levels, and uses the Navy Operational Global Atmospheric Prediction System (NOGAPS) surface forcing. Data assimilation is only performed south of 47°N before 9/2008. Daily average output.
HYCOM debias	Same as above	Replaced monthly mean *T* and *S* in each grid cell with that from Geshelin et al. (1999) climatology. Note documentation warning that prior to September 2008 (when global data assimilation begins), experiments contain sub-surface *T* bias in many locations.
MERCATOR	MERCATOR GLORYS2V1	Employs ORCA025 NEMO ocean model with 1/4° grid and 75 vertical levels (Barnier et al., 2006). Incorporates observations of satellite-derived *SST* and *SSH*, and in-situ *T* and *S*, using reduced order Kalman filter via the SEEK algorithm (Pham et al., 1998; Tranchant et al., 2008). Surface forcing from ECMWF ERA-Interim. Daily average output.
MERCATOR debias	Same as above	Replaced monthly mean *T* and *S* in each grid cell with that from the Geshelin et al. (1999) climatology. Documentation states that biases in *T* and *S* below 300m may be an issue in the Gulf Stream region (Barnier and Ferry, 2011).

ii. Model Description & Methods

Atlantic Canada Model (ACM) description:

- ***Physical-biological model setup (ROMS):***
  - ~10 km horizontal resolution, 30 vertical levels
  - Atmospheric surface forcing provided to model from external dataset (Air *T*, air *P*, humidity, rain, winds, net shortwave & longwave radiation)
  - Biogeochemical module of Fennel et al. (2006, 2009)
  - Capable of assimilating observations (Hu et al., 2012)
  - Includes river runoff
- ***Nesting the AC Model:***
  - Physical initial & boundary conditions (*T, S, U, V, sea surface height*) provided by larger scale model
  - T and S nudged in the outermost 10 grid points to the larger scale model (nudging strength decays away from the boundary)

Vary model configuration:

- ***3.5 Surface forcing datasets***: CORE, NARR, ECMWF, ECMWF+EVAP (Table 2)
- ***6 Ocean model nesting datasets***: UBS, UBSclim, HYCOM, HYCOMdebias, MERCATOR, MERCATORdebias (Table 2)
- ***2 Model grid variants:*** Original, Large (see section v)

Perform model experiments:

Run ID	Surface-forcing	Nesting	Grid
Vary Surface Forcing			
ACM-CORE	*CORE*	*UBSclim*	*Original*
ACM-NARR	*NARR*	*UBSclim*	*Original*
*ACM-ECMWF**	*ECMWF*	*UBSclim*	*Original*
ACM-ECMWF-EVAP	*ECMWF+EVAP*	*UBSclim*	*Original*
Vary Nesting Data			
ACM-UBS	*ECMWF*	*UBS*	*Original*
*ACM-UBSclim**	*ECMWF*	*UBSclim*	*Original*
ACM-HYCOM	*ECMWF*	*HYCOM*	*Original*
ACM-MERCATOR	*ECMWF*	*MERCATOR*	*Original*
ACM-HYCOMdebias	*ECMWF*	*HYCOM debiased*	*Original*
ACM-MERCATORdebias	*ECMWF*	*MERCATOR debiased*	*Original*
Vary Model Grid			
*ACM-Orig**	*ECMWF*	*UBSclim*	*Original*
ACM-Large	*ECMWF*	*UBSclim*	*Large*

* *Note: ACM-ECMWF, ACM-UBSclim, and ACM-Orig are identical simulations.*

Evaluate model performance by comparison to:

- AVHRR Pathfinder satellite sea surface temperatures
- Geshelin et al. (1999) regional 3-D monthly mean climatology for *T* & *S*
- Atlantic Zone Monitoring Program (AZMP) transects & station data for *T* & *S*
- Off shelf CTD vertical profiles of *T* & *S* from Bedford Institute Oceanography
- Circulation features described in literature

iii. Results: Vary Surface Forcing

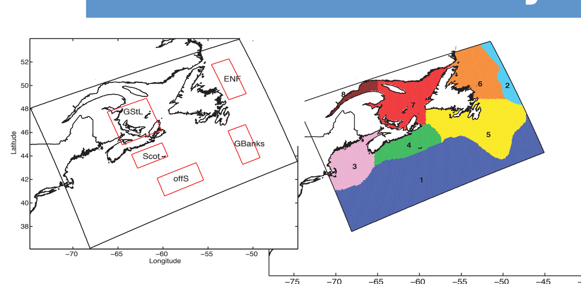


Fig 3. Model domain analysis locations. Sub-regions (left) include Gulf of St. Lawrence, Scotian Shelf, offshore, Grand Banks, & East of Newfoundland. Areas 1-8 (right).

Providing evaporation degrades model SSS:

- Model shelf sea surface is too saline when evaporation is externally provided (i.e. not calculated internally within ROMS), although small improvement in SSS for region of Gulf Stream.

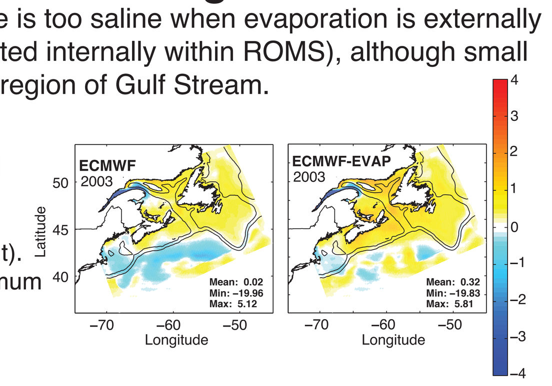


Fig 4. Model-climatology difference in mean annual sea surface salinity for ACM-ECMWF (left) and ACM-ECMWF-EVAP (right). Domain-wide mean, minimum and maximum difference values are reported.

CORE surface forcing produces poor model shelf circulation:

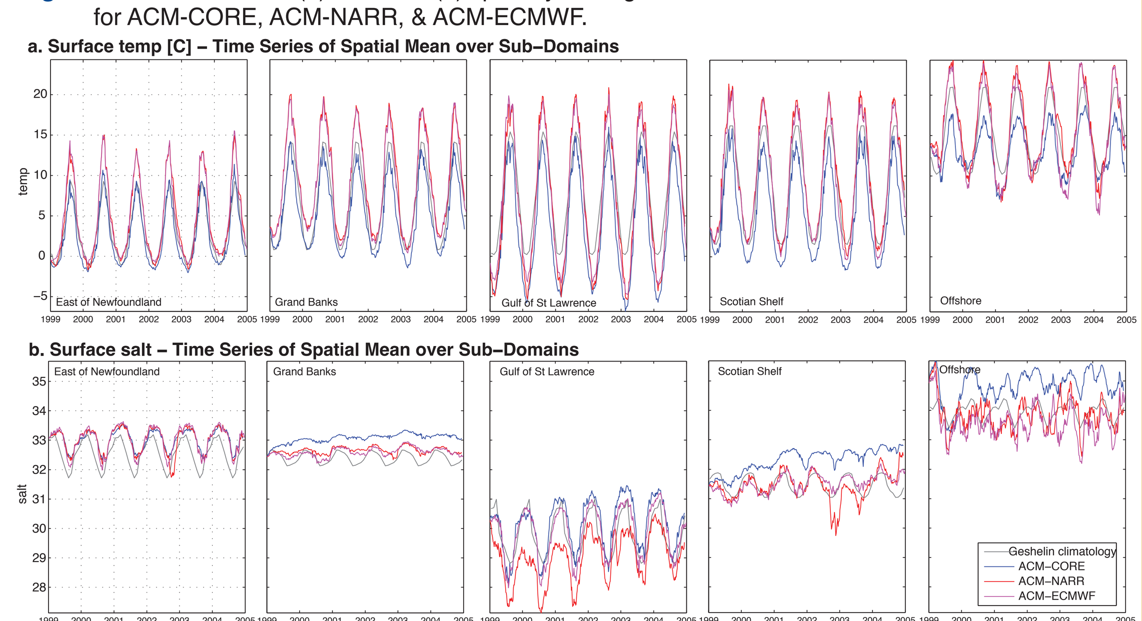
w.r.t.= "with respect to"

Lowest R2 for SSS, SST (w.r.t. Geshelin), bottom T and bottom S.
Largest time mean bias in SSS (Areas 1, 4, 5, and entire domain).
Largest time mean bias in SST (w.r.t. Geshelin) in all shelf areas (Areas 3-8).

ECMWF and NARR surface forcing both result in good model shelf circulation:

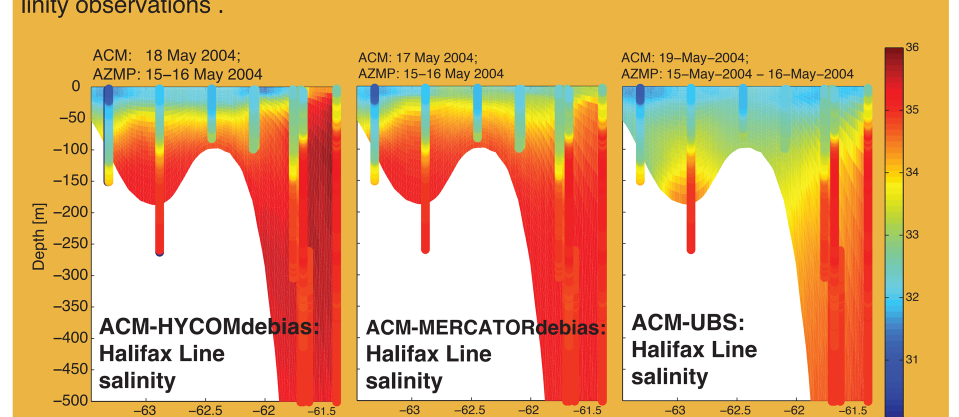
- ***ACM-ECMWF:***
  - Best domain-averaged time series of SSS (highest R2 & lowest mean bias, 0.85 and +0.01, respectively);
  - Highest SST R2 value in ALL Areas & entire domain (w.r.t. satellite SST);
  - Highest SST R2 value in Areas 1-4 & 6-7 (w.r.t. climatology).
- ***ACM-NARR:***
  - Best domain-averaged SST (w.r.t. climatology) with highest R2 & lowest mean bias values (0.97 and -0.43°C, respectively);
  - Best domain-averaged R2 and mean bias values for bottom *T* (w.r.t climatology) (R2 = 0.86, mean bias = -0.08°C);
  - Lowest SSS bias in Areas 1, 4, 6, 7.

Fig 5. Time series of SST (a) and SSS (b) spatially averaged over each sub-domain, for ACM-CORE, ACM-NARR, & ACM-ECMWF.



iv. Results: Vary Model Nesting

Fig 6. Model salinity at the AZMP Halifax Line from ACM-HYCOMdebias (left), ACM-MERCATORdebias (center), & ACM-UBS (right) in May 2004, overlain with AZMP salinity observations .



Nesting with HYCOM or MERCATOR degrades model shelf circulation:

- Model shelf sea surface is too saline when HYCOM, HYCOMdebias, MERCATOR, or MERCATORdebias are used as initial & boundary conditions.
- Surface velocity fields indicate that the Gulf Stream may be too closely situated to the shelf slope, and shows the Shelf Break Current (SBC) transports water in the opposite direction from observed (i.e. northeast as opposed to southwest).
- Both ACM-UBS and ACM-UBSclim adequately simulate shelf circulation.
- ACM-UBSclim has the best RMSE in domain-average bottom *T* & *S*, and appears to outperform ACM-UBS in capturing regional circulation features.

v. Results: Vary Model Grid

Fig 7. Original (top) and large (bottom) model domain grids (color corresponds to bathymetry).

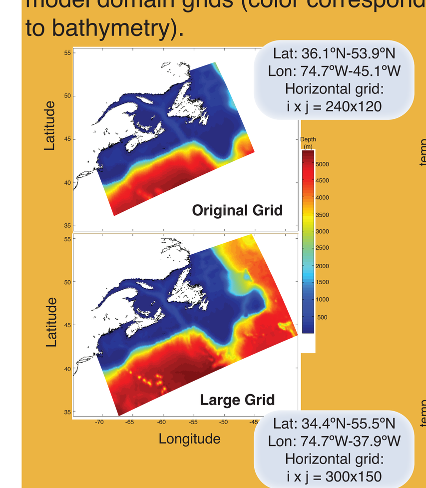
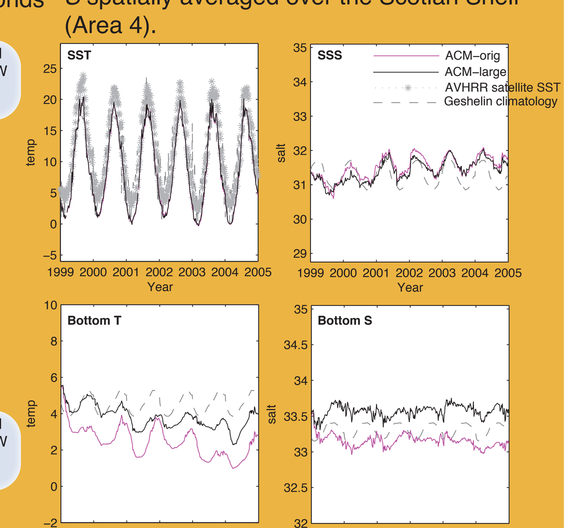


Fig 8. Time series of surface and bottom *T* and *S* spatially averaged over the Scotian Shelf (Area 4).



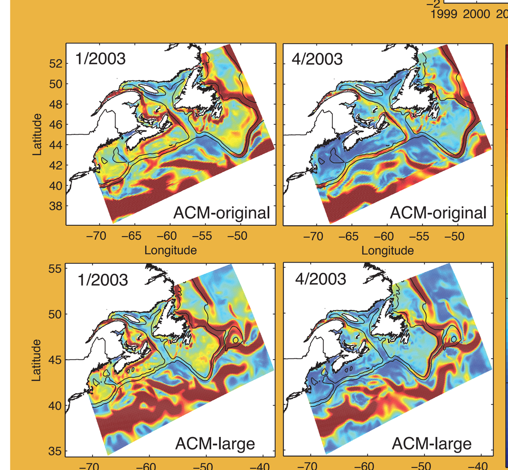


Fig 9. Monthly mean surface velocity (m/s) in January (left) and April (right) 2003 from ACM-orig (top) and ACM-large (bottom).

Expanding the model grid results in:

- Similar time evolution of *SST* and *SSS*
- Increased Scotian Shelf and Gulf of Maine bottom *S* and bottom *T* (and increased Grand Banks bottom *T*)
- Similar surface velocities for Nova Scotian Current (NSC)
- Surface velocities indicate circulation differences, as follows:
  - *Coastal Labrador Current strengthened;*
  - *Tail of Grand Banks flow weakened slightly;*
  - *Cabot Strait outflow weakened;*
  - *Shelf Break Current weaker and less well defined.*

One explanation is that the small increase in horizontal resolution in the large domain increases eddy activity, which increases mixing over the slope and results in greater transport of heat and salt onto the shelf.

vi. Conclusions

Surface Forcing:

- **ECMWF and NARR surface forcing both result in good model shelf circulation, while ECMWF-EVAP results in degraded results, and CORE produces poor shelf circulation.**

Model Nesting:

- **UBS and UBSclim perform well, while global ocean models - in their raw or debiased form - do not.**
- **Climatological boundary conditions (using UBSclim) are associated with a small performance increase.**

Model Grid:

- **Expanding the model grid results in less desireable expressions of surface velocity, and increases in bottom T & S on the Scotian Shelf and Gulf of Maine.**

Common biases across datasets:

Relative to the climatology, the shelf regions exhibit these commonalities:

SSS is too high east of Newfoundland and in the eastern GSL (small bias);
& is too fresh in Lower St. Lawrence Estuary & Scotian Shelf regions;
Bottom salinity is too high in Gulf of Maine and western Scotian Shelf;
& is too fresh on the Eastern Scotian Shelf
--> East-west Scotian Shelf bottom *S* gradient is weaker than climatology.
Bottom temperature is too warm in the Grand Banks region;
& is too cool in the eastern Scotian Shelf & Bay of Fundy.

vi. References

Anderson and Smith (1989) Oceanographic observations on the Scotian Shelf during CASP. Atmos.-Ocean, 27(1), 130-156..
Barnier et al. (2006) Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy permitting resolution. Ocean Dynamics. doi:10.1007/s10236-006-0082-1.
Barnier and Ferry (2011) GLobal Ocean ReanalYses and Simulations: GLORYS2V1 product scientific and technical notice for users. Technical notice version 1. Mercator-Ocean, France.
Cummings (2005) Navy Coupled Ocean Data Assimilation (NCODA).
Dee et al. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137: 553–597. doi: 10.1002/qj.828.
El Sabh (1977) Oceanographic features, currents, and transport in Cabot Strait. Journal of the Fisheries Board of Canada, 34(4), 516-528..
Geshelin et al. (1999) Monthly mean climatologies of temperature and salinity in the western North Atlantic. Can. Data Rep. Hydrogr. Ocean Sci., 153, 62 pp. Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada.
Fennel et al. (2006) Nitrogen cycling in the Middle Atlantic Bight: Results from a three-dimensional model and implications for the North Atlantic nitrogen budget. Global Biogeochemical Cycles, 20, GB3007, 1-14. doi: 10.1029/2005GB002456.
Fennel et al. (2009) Modeling denitrification in aquatic sediments. Biogeochemistry, 93, 159-178.
Han and Loder (2003) Three-dimensional seasonal-mean circulation and hydrography on the eastern Scotian Shelf. Journal of Geophysical Research, 108, 1-21. doi: 10.1029/2002JC001463.
Han et al. (2008) Seasonal variability of the Labrador Current and shelf circulation off Newfoundland. Journal of Geophysical Research, 113, C10013. doi:10.1029/2007JC004376.
Hannah et al. (2001) Seasonal circulation on the Western and Central Scotian Shelf. Am. Met. Soc. 31,591-615.
Hu et al. (2012) Data assimilation with a local Ensemble Kalman Filter applied to a three-dimensional biological model of the Middle Atlantic Bight. Journal of Marine Systems, 94, 145-156.
Large and Yeager (2004) Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies. CGD Division of the National Center for Atmospheric Research, NCAR Technical Note: NCAR/TN-460+STR. 105 pp.
Lazier and Wright (1993) Annual velocity variations in the Labrador Current. Journal of Physical Oceanography, 23(4), 659-678.
Loder et al. (1998) The coastal ocean off northeastern North America: A large-scale view. In A. R. Robinson & K. H. Brink (Eds), The Sea. Vol 11, The Global Coastal Studies. Regional Studies and Syntheses (pp. 105-133). USA: John Wiley & Sons, Inc.
Mesinger et al. (2006). North American Regional Reanalysis. Bulletin of the American Meteorological Society, 87, 343–360. doi: 10/1175/BAMS-87-3-343.
Pham et al. (1998) A singular evolutive extended Kalman filter for data assimilation in oceanography. Journal of Marine systems, 16(3), 323-340.
Smith (1988) Abundance indices from research survey data. In D. Rivard (Ed.) Collected papers on stock assessment methods. CAFSAC Res. Doc. 88/61: 16-43.
Thompson et al. (1988) Sea surface temperature variability in the shelf-slope region of the northwest Atlantic. Atmosphere-Ocean, 26, 292-299.
Tranchant et al. (2008) Expected impact of the future SMOS and Aquarius Ocean surface salinity missions in the Mercator Ocean operational systems: New perspectives to monitor the ocean circulation. Remote Sensing of Environment, 112, 1476-1487.
Urrego-Blanco and Sheng (2012) Interannual variability of the circulation over the Eastern Canadian Shelf. Atmosphere-Ocean, 50, 277-300. doi: 10.1080/07055900.2012.680430.
Wilkin and Hunter (2013) An assessment of the skill of real-time models of Mid-Atlantic Bight continental shelf circulation. Journal of Geophysical Research: Oceans, 118, 2919-2933. doi: 10.1002/jgrc.20223.