Simulated monthly ocean climatology of the northwestern Atlantic: 1980-2018

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by

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ABSTRACT

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A North Atlantic Ocean-ice Downscaling System has been developed, which consists of a high resolution model for the northwest Atlantic region nested to a low resolution model for the North Atlantic. The models are forced by the European Centre for Median Weather Forecasts Reanalysis Interim (ERI) product. The simulation was carried out for the period from 1980 to 2018. The northwest Atlantic model results are evaluated for ocean temperature and salinity, winter convection in the Labrador Sea and dominant shelf-scale currents, as well as winter sea ice extents. The model results are in good qualitative agreement with observations in terms of dominant features and in approximate quantitative agreement with observations at various locations. A monthly climatology of the model ocean temperature, salinity, currents, and sea ice extents over the northwestern Atlantic are established to help understand interannual and decadal oceanographic variability in this region. The dataset could also help address ecosystem science and fisheries management issues in the northwest Atlantic.

RÉSUMÉ

Han, G., Ma, Z., Wang, Z., Chasse, J., Lambert, N., Brickman, D., Long, Z., and Perrie, W. 2021. Simulated monthly ocean climatology of the northwestern Atlantic: 1980-2018. Can. Data. Rep. Hydrogr. Ocean Sci. 214: vi + 22 p.

Un système de réduction d'échelle pour la modélisation l'océan et la glace de l'atlantique-nord a été développé. Ce système est constitué d'un modèle à haute résolution couvrant le nord-ouest de l'atlantique imbriqué dans un second modèle à plus faible résolution couvrant l'ensemble de l'atlantique du nord. Ces modèles utilisent les forçages atmosphériques provenant des ré-analyses faites par le *Centre européen pour les prévisions météorologiques à moyen terme* (CEPMMT). Une simulation a été effectuée pour la période 1980-2018. Les résultats provenant du modèle couvrant le Nord-ouest de l'Atlantique sont évalués pour la température et la salinité de l'océan, la convection profonde hivernale dans la mer du Labrador, les transports le long du plateau continental, ainsi que la couverture de la glace hivernale. L'analyse des résultats montre qu'ils représentent bien les aspects dominants de la région et qu'ils concordent avec les mesures faites à différents endroits dans cette zone. Une climatologie mensuelle a été calculée pour la température, la salinité, les courants et la couverture de la glace afin de mieux comprendre les variations interannuelles et décennales dans la région Nord-ouest de l'Atlantique. Cette base de données peut aussi aider à mieux comprendre les écosystèmes de la région ainsi qu'à avoir une meilleure gestion des pêches.

1. Introduction

There are increasing demands for oceanographic climatology over the northwestern Atlantic with sufficient temporal and spatial resolution and with sufficient duration, in order to better understand climate variability and change as well as help assess their impacts on ecosystem and fisheries in this region. While global ocean model outputs such as from the Simple Data Assimilation Model (SODA, Carton and Giese, 2008) are useful to study climate variability and change on ocean basin scales, they may not have sufficient spatial resolution to well reproduce coastal or regional oceanographic processes, such as over the northwestern Atlantic shelf including the Labrador Shelf, the Newfoundland Shelf, the Scotian Shelf, the Gulf of Maine and the Gulf of St. Lawrence. Oceanographic processes at these coastal and regional scales typically respond to local and regional forcing (marine winds, heat fluxes, precipitation and runoff), which are not well represented in global models either. Thus, global model simulations may not be reliable for coastal and shelf waters. Improved simulations of ocean climate variability and change over the northwestern Atlantic shelf are required to study coastal and shelf oceanographic processes and to address ecosystem and fisheries issues.

There have been ocean climate modelling efforts for the northwestern Atlantic regions. Wu and Tang (2010) presented monthly ocean fields for selected years from 1999-2008 from a northwestern Atlantic shelf model, with empirically specified climatological open boundary conditions. There are also models focused on sub-domains of the northwestern Atlantic: one for the Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine (Long et al., 2015), and the other for the Labrador Shelf and Newfoundland Shelf (Ma et al., 2016; Han et al., 2019a; 2019b). Brickman and Wang (2016) produced monthly mean climatology for the northwestern Atlantic shelf region from a North Atlantic model for the period from 1990 to 2011.

In this study, we will establish a state-of-the-art North Atlantic Ocean-ice Downscaling System (NAODS), nesting an eddy-resolving model (a 1/12° grid resolution) for the northwest Atlantic region to an eddy-permitting model (a 1/4° grid resolution) for the North Atlantic with two-way dynamic exchanges across the nesting boundary. The ocean simulations will be carried out with the updated version of NEMO (version 3.6). The simulation period is from 1980 to 2018. The present model either has improved dynamics or covers longer period and bigger domain than the afore-mentioned models.

2. Model Configuration

The numerical ocean-ice model used in the present study is based on the NEMO, version 3.6 stable (Madec, 2016) modelling system and version 2 of the Louvain-la-Neuve Ice model (LIM2). NEMO 3.6 is a primitive equation, finite difference, ocean circulation model with a free sea surface and a partial z-coordinate system. The selection of the partial z-coordinate allows the bottom layer to vary as a function of geographical locations. In the vertical there are 50 layers, with the first grid at 1.54 m below surface and a maximum spacing of 215.75 m. Model bathymetry is from ETOPO1. Time splitting is included, with a barotropic time step chosen automatically to satisfy a maximum Courant number of 0.8. Model domain decomposition for parallel running is optimized by removing the non-ocean sub-domains during integration. The hydrostatic pressure gradient is calculated using leap-frog scheme on s-coordinate with pressure Jacobian formulation.

Tracer advection is total variation diminishing (TVD) scheme with sub-time stepping and the momentum advection is both energy and entropy conserving. For tracers, Laplacian viscosities are applied on iso-neutral levels. For momentum, Bilaplacian viscosities are applied on horizontal geopotential levels. A three-dimensional, time-varying Smargorinsky viscosity is activated to calculate the viscosity coefficient for tracer and momentum.

Vertical turbulence diffusivities are calculated using a turbulence closure model with a prognostic equation for the turbulent kinetic energy and a closure assumption for the turbulent length scales. The bottom friction uses a spatially varying log layer based drag coefficient with a minimum drag coefficient set at 0.002.

We applied the 6-hourly ECMWF Reanalysis Interim product (0.75^o) (Deea et al., 2011) as atmospheric forcing at the sea surface and the SODA 3.4.2 monthly mean product (0.5^o) (Carton and Giese, 2008) and major tides as lateral open boundary conditions. For the open boundary conditions, sea level and vertically averaged velocity were applied by using the Flather boundary condition, while three-dimensional temperature, salinity and velocity were specified with a 6-grid-point sponge layer relaxing from the open boundary towards the ocean interior. Relaxation was also applied for the sea ice boundary condition. Climatological monthly river runoffs were specified as surface precipitation (Bordeau et al., 2010).

The model was first run from 1 January 1980 until 31 December 1980 and repeated for another twenty-one years. Then the model was integrated forward from 1981 to 2018.

3. Model Results

3.1. TEMPERATURE, SALINITY AND MIXED-LAYER DEPTH

We compute climatologies of temperature and salinity for January and July, and compare them with the corresponding data from the EN4 dataset (Figures 2 and 3). Generally the model spatial patterns are consistent with the observational ones. However, the model overestimates the sea surface temperature and salinity over the continental slope.

Figure 4a shows the simulated winter (February, March and April) mixed-layer depth (MLD) in the Labrador Sea defined as the density difference of 0.01 kg m^{-3} to 10 m. The model results indicate deep mixing in the western Labrador Sea between the AR7W transect and 60^oN, consistent with observation-based climatology (de Boyer Montégut et al., 2004). Figure 4b shows the deepening of the mixed layer in 1982-1983, 1990-1994, and 2014-2017. The timing of extensive mixing in the early 1990s is consistent with observations (Lazier et al., 2002). The five years of re-stratification between 2000 and 2004 is also consistent with observations (Yashayaev, 2007).

3.2. CIRCULATION AND TRANSPORT

The model surface circulation is shown in Figure 5, with the mean climatology and annual means in 1980, 1993 and 2017. The climatological circulation clearly shows the pathway of the Labrador Current off Labrador, heading south to the Newfoundland Shelf, which are consistent with previous knowledge from numerical and observational studies. The Labrador Current exhibits inter-annual variabilities, weak in 1980 and 2017 and strong in 1993. The transports of the Labrador Current (Figure 6) integrated from the coast to the 3000 m isobath are calculated at the Flemish Cap transect (see Figure 5 for location). The mean transport at the Flemish Cap transect is about 22 Sv, consistent with observations and previous model results (Zantopp et al., 2017; Han et al., 2019). There is significant multi-decadal transport variability, with higher values over 1985-1998 and low values before and after. The multi-decadal range is around 10 Sv at the Flemish Cap transect.

3.3. VALIDATION WITH CURRENT METER AND ACOUSTIC DOPPLER CURRENT PROFILER (ADCP) CURRENTS

Moored current meter data are extracted from a database at the Bedford Institute of Oceanography (http://www.bio.gc.ca/science/data-donnees/base/run-courir-en.php). Observations were collected at several sites on the Flemish Pass area between 1980 and 1988 (Figure 7). About 90% of the data are from 1980, 1983, 1985 and 1986. Typically there are two to five monthly means at each mooring. The mooring depths range from 20 to 950 m, with a median value of 119 m. The analysis of observed data indicates dominant meridional flows of 0.16 $m\,s^{-1}$ southward and weak zonal flows of 0.03 $m\,s^{-1}$ without a dominant direction, on average. Model results are interpolated to the observational depth and time. Both model results and observations are averaged over the depth and over the 9-year period by month (Figure 8). The model meridional and zonal currents are consistent with observations. The meridional current has significant seasonal variation: strong in winter and fall but weak in summer. The observed root-mean-square (RMS) variability is 0.15 $m\,s^{-1}$. Statistical evaluations of the model results are summarized in Table 1. The RMS difference is 0.02 and 0.04 $m\,s^{-1}$ for the zonal and meridional components respectively, suggesting good agreement with observations. The overestimation in the southward meridional current could also be attributed to uncertainties of computing observational mean, in addition to the model uncertainty. The speed difference ratio (SDR) is defined as the ratio of the RMS value of the model-observation speed difference to the RMS value of the observed speed. The velocity difference ratio (VDR) is defined as the ratio of the RMS value of the model-observation velocity difference to the RMS value of the observed velocity.

Current meters were deployed at the edge of the Labrador Shelf, with observations from December 1991 to June 1992 at site A and from July to October 1991 at site B. A comparison of model monthly mean current profiles with moored measurements in the same month and year is shown in Figure 9. The model results show overall good agreement with observations for the Labrador Current along the shelf edge. The vertical gradient of the horizontal current is captured well in the simulated results at both sites. Nevertheless, the model overestimates the meridional current at site A. The comparisons indicate that the summer and fall vertical density structure is well represented. Quantitative statistics are also calculated (Table 2), showing fair agreement in the zonal and meridional velocity components. The RMS difference is 0.04 and 0.10 $m\,s^{-1}$ for the zonal and meridional components, respectively. The corresponding SDR and VDR are 0.23 and 0.20 respectively, indicating that the model captures the observed currents well.

A current meter at site C was deployed over the inner Scotian Shelf, with observations from September 2007 to April 2008. A comparison of model monthly mean current profiles with moored measurements in the same month and year is shown in Figure 10. The model results show overall good agreement with observations for the inner-shelf current in deep water from 80 m to bottom, with dominant westward velocity and relatively weak southward velocity. The vertical gradient of the horizontal current is captured well in the simulated results. Quantitative statistics are also calculated (Table 3), showing good agreement in the zonal and meridional velocity components. The RMS difference is 0.02 and 0.02 $m\,s^{-1}$ for the zonal and meridional components, respectively. The corresponding SDR and VDR are 0.10 and 0.11 respectively, indicating that the model captures the observed currents well.

ADCP current measurements at a site located in the inshore Labrador Current are available for 2014-2017. Measurements indicate the flow at this site is dominated by the zonal currents. The model monthly zonal currents show approximate agreement with observations (Figure 11).

3.4. SEA ICE

The model March sea ice concentration and extent are compared with observations derived from the digital archive regional dataset prepared by the Canadian Ice Service (Figure 12). The ice extent is defined as the total ice-covered area south of 55ºN with an ice concentration above 0.1 in each model and observation cell. There is approximate agreement between model and observational ice distribution over the Newfoundland and Labrador Shelf. The simulated sea ice extent (Figure 12e) over the Newfoundland and Labrador Shelf south of 55ºN shows generally good agreement with observations. Note that the northwest Atlantic model is not intended for the Gulf of St. Lawrence or the St. Lawrence Estuary. Instead, a 1/36º Gulf of St. Lawrence nested in the northwest Atlantic model, is being implemented for the Gulf and Estuary.

4. Summary

We have developed a coupled North Atlantic ocean-ice downscaling system: an eddy-resolving model for the northwest Atlantic region nested to an eddy-permitting model for the North Atlantic. The northwest Atlantic model results are evaluated against observations for sea level, temperature, salinity, currents, and ice. The evaluation shows that the model has reasonable skill in reproducing dominant temporal and spatial patterns and local variations over the northwestern Atlantic shelf and slope from monthly to decadal scales.

We have established a monthly, 1/12º climatology of the model ocean temperature, salinity, and currents for the northwestern Atlantic over the period from 1980 to 2018. The model climatology is available upon request.

Efforts are being made to improve boundary conditions for river runoff. The 1/36º sub-model for the Gulf of St. Lawrence is being implemented. The model results will be updated as they improve.

Acknowledgments

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TABLES

Table 1: Statistics comparing model currents and monthly mean observations in the Flemish Pass. U is the zonal velocity and V is the meridional velocity ($m\ s^{-1}$).

	RMS (Observed minus Model)	RMS (observed)	Correlation
U	0.02	0.01	0.84
V	0.04	0.15	0.83
SDR	0.08		
VDR	0.07		

Table 2: Statistics comparing vertical profiles of monthly mean simulated currents and the monthly mean observations at sites A and B. U is the zonal velocity and V is the meridional velocity ($\boldsymbol{m\ s^{-1}}$).

	RMS (Observed minus Model)	RMS (observed)	Correlation
U	0.04	0.13	0.82
V	0.10	0.19	0.90
SDR	0.23		
VDR	0.20		

Table 3: Statistics comparing vertical profiles of monthly mean simulated currents and the monthly mean observations at sites C. U is the zonal velocity and V is the meridional velocity ($m\ s^{-1}$).

	RMS (Observed minus Model)	RMS (observed)	Correlation
U	0.02	0.07	0.82
V	0.02	0.05	0.83
SDR	0.10		
VDR	0.11		

Figures

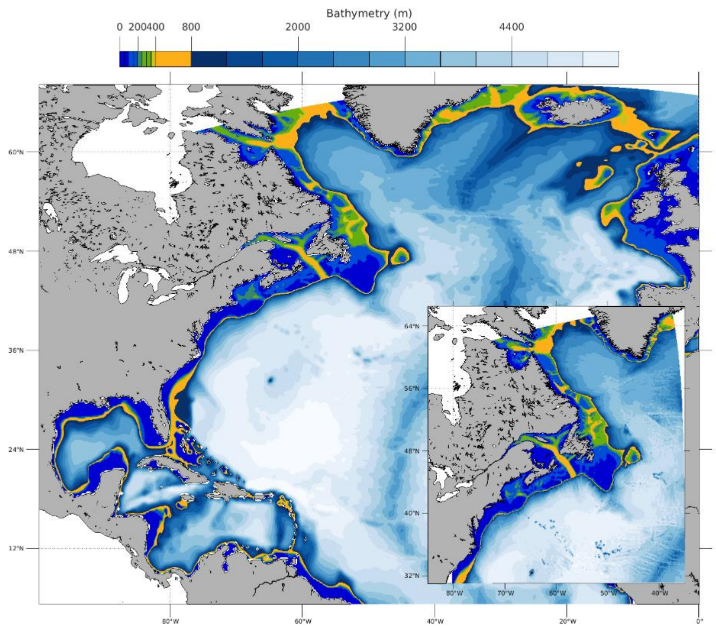

Figure 1: The North Atlantic model (parent) domain and the northwest Atlantic model (child) domain with bathymetry, respectively.

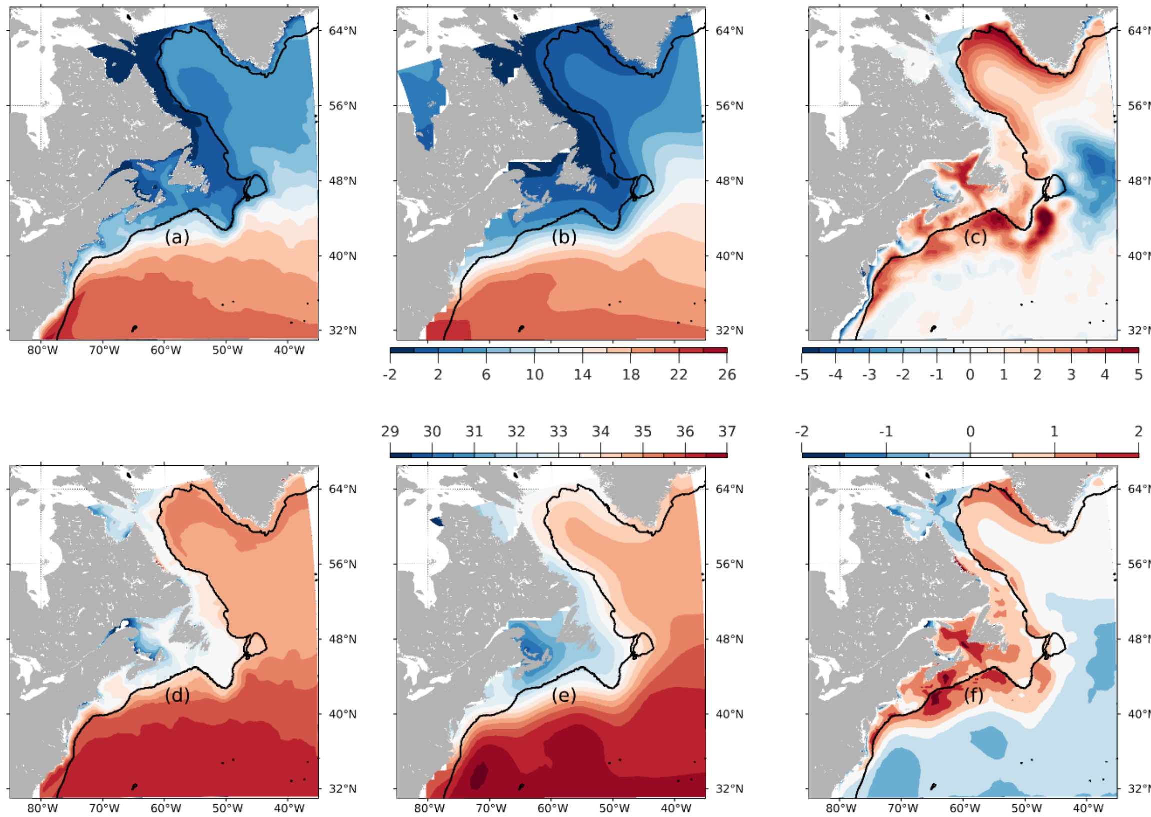

Figure 2: Panels on the top (a, b, c) are sea surface temperature and those on the bottom (d, e, f) represent sea surface salinity for the month of January, from a climatology of the 26 years run (1980-2005). Left panels are model output (a, d), middle panels are the EN4 observational dataset (b, e), and right panels are the difference between model and EN4 dataset.

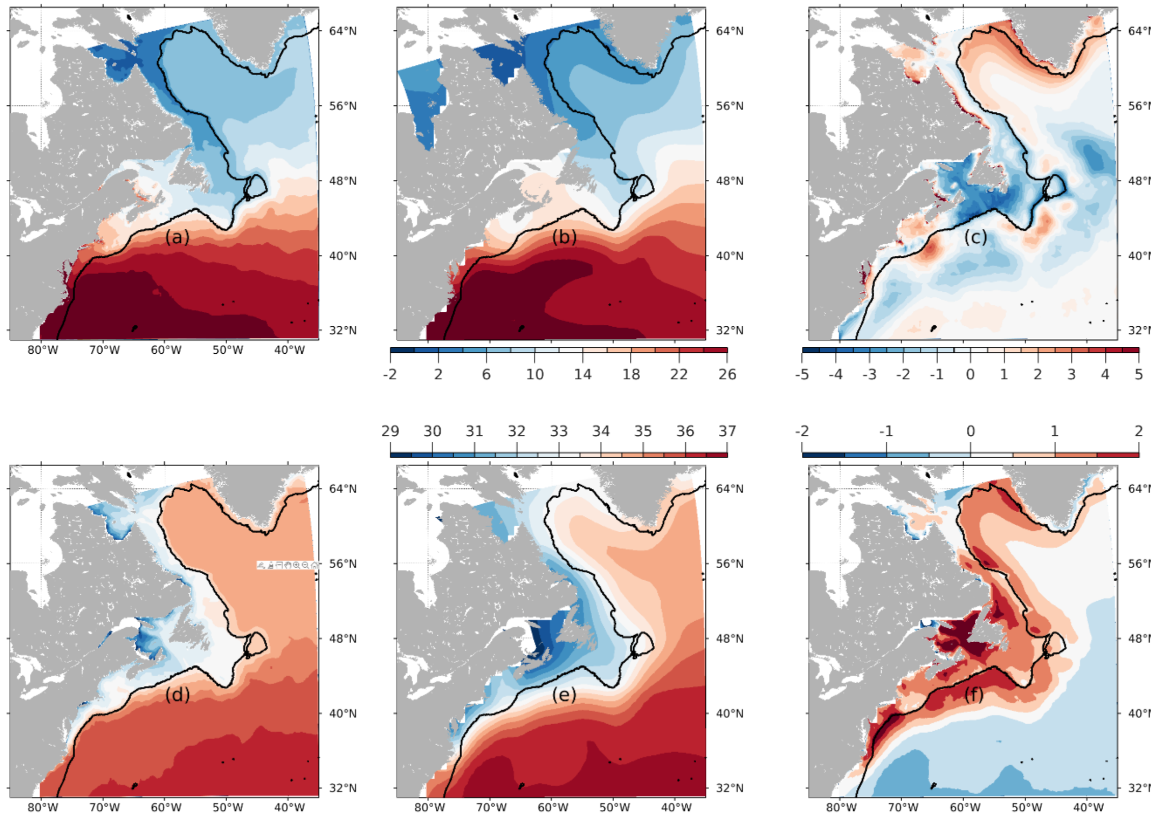

Figure 3: Panels on the top (a, b, c) are sea surface temperature and those on the bottom (d, e, f) sea surface salinity for the month of July, from a climatology of the 26 years run (1980-2005). Left panels are model outputs (a, d), middle panels are the EN4 observational dataset (b, e), and right panels are the difference between model and EN4 dataset.

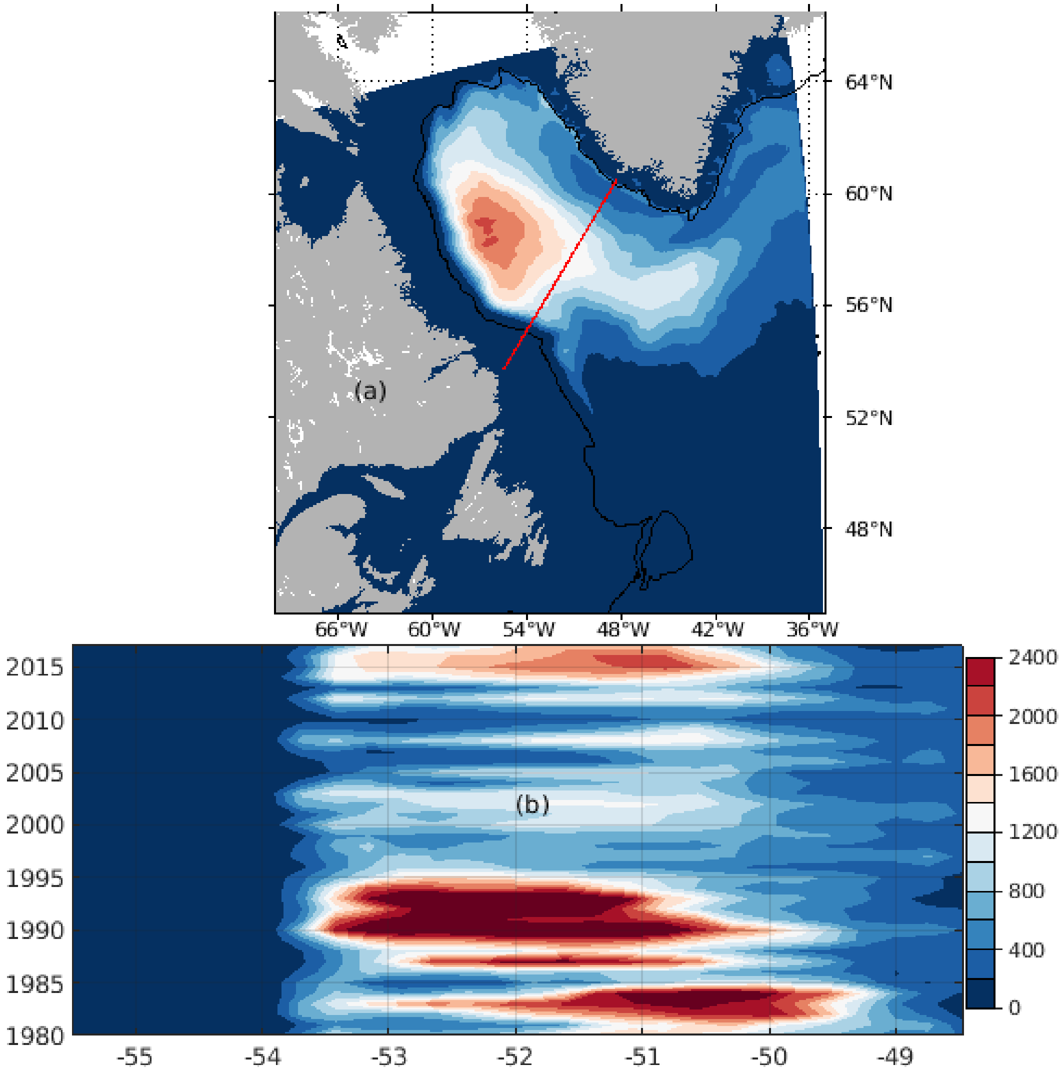

Figure 4: (a) Winter (February, March and April) mixed layer depth climatology in the Labrador Sea and part of Irminger Sea, averaged over 1980-2017. (b) Hovmöller diagram of the mixed layer depth evolution through the simulation, across the section indicated by the red line indicating AR7W transect.

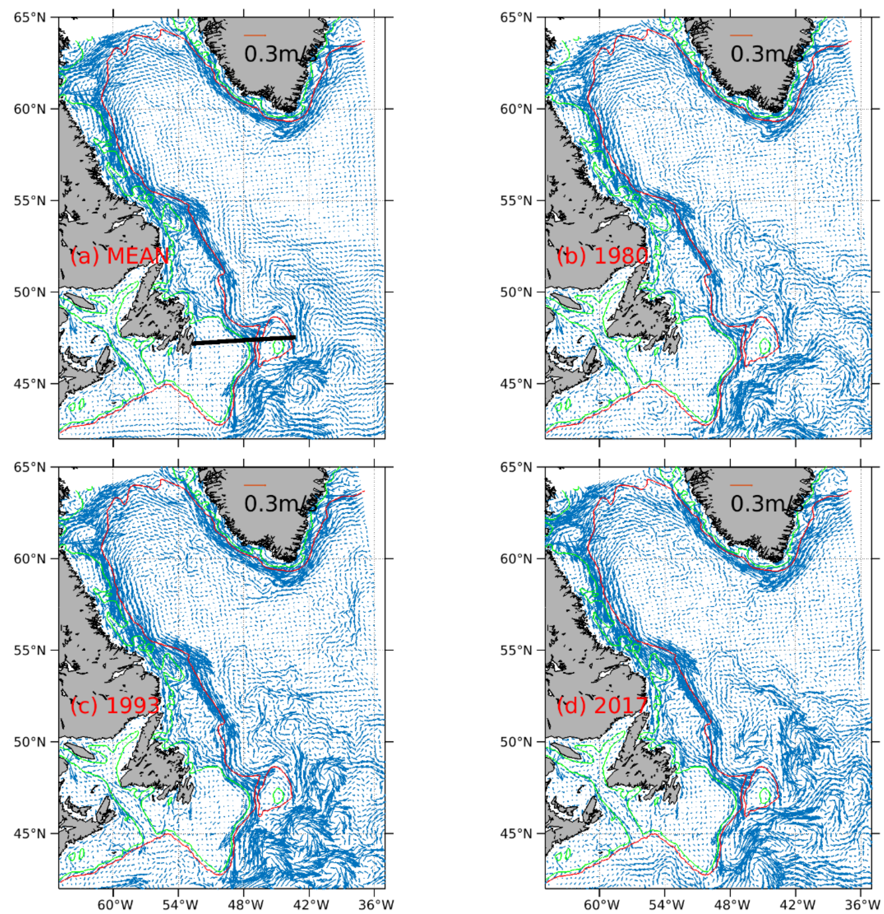

Figure 5: Map showing the Labrador Current and its adjacent circulation from model results. (a) the mean between 1980 and 2017, (b) 1980, (c) 1993 and (d) 2017. Black line indicates the transect for transport in Figure 6.

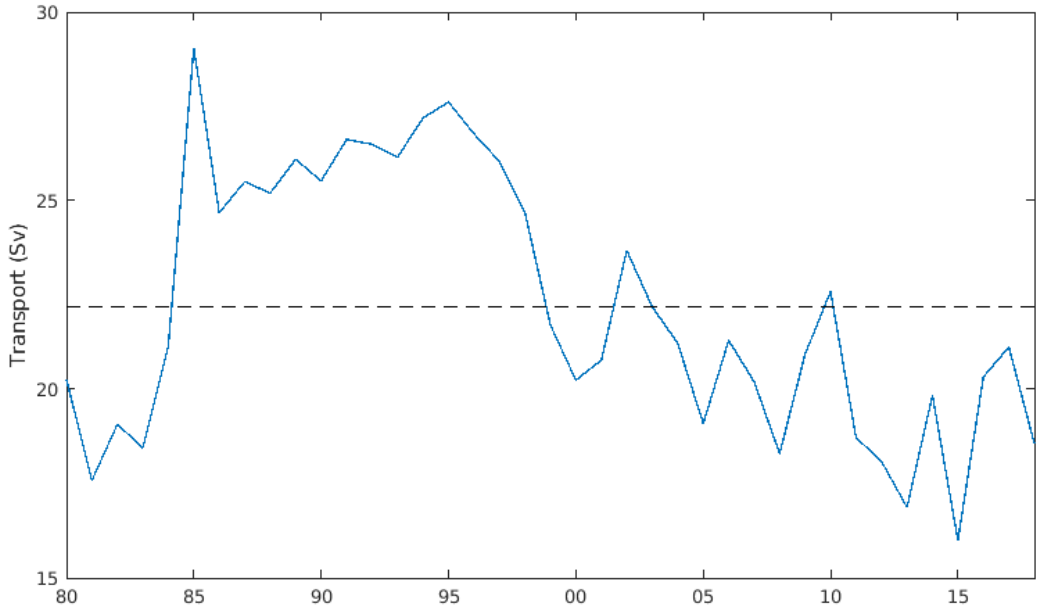

Figure 6: Time series of annual volume transport (positive southward) calculated through the water column across the Flemish Cap transect depicted in Figure 5. The dashed line depicts the mean transport over the study period.

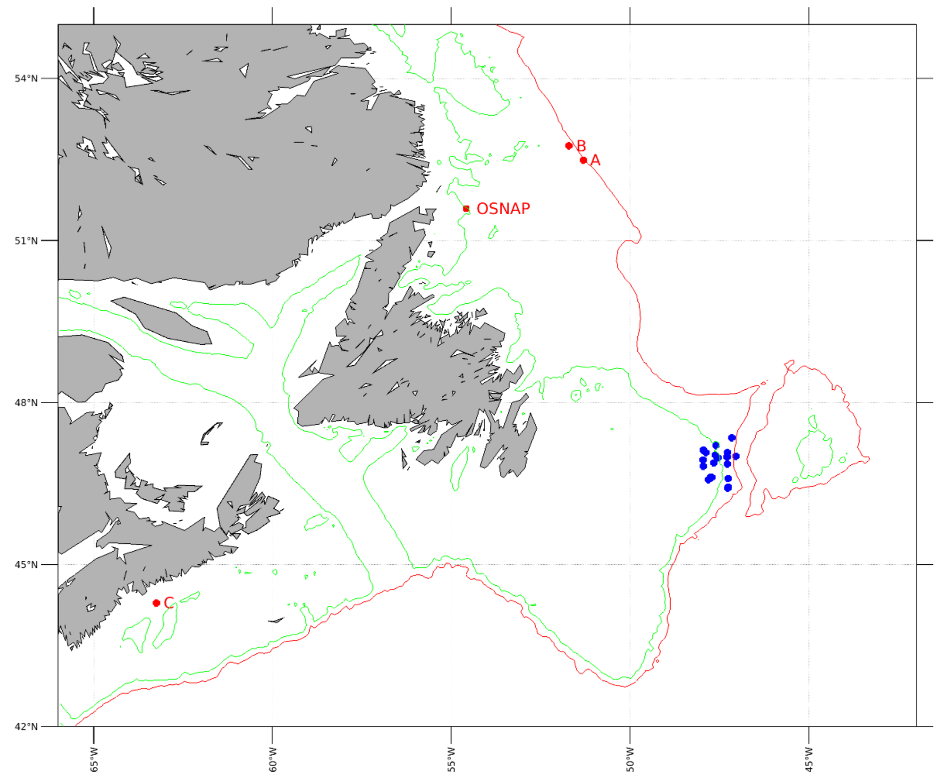

Figure 7: Mooring locations of current meters used in the model evaluation. The 200 and 1000 m isobaths are also shown.

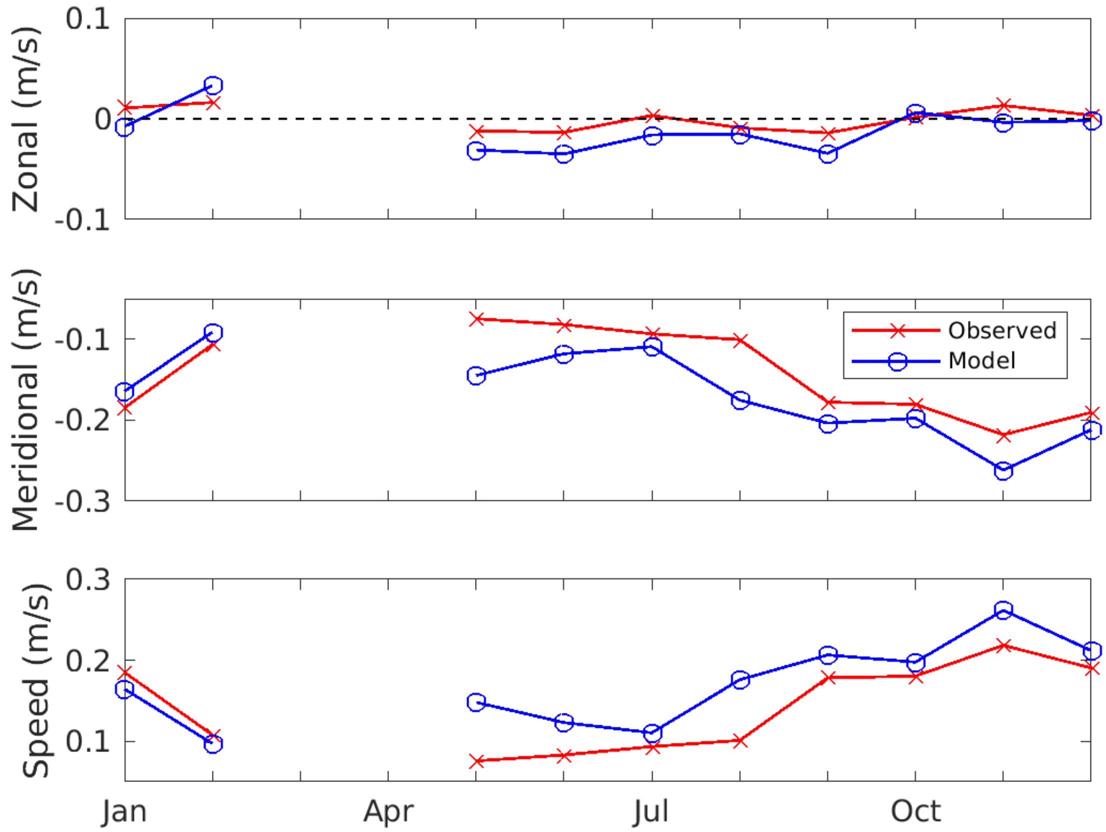

Figure 8: Monthly mean depth-averaged currents in the Flemish Pass. Locations are indicated by solid blue squares in Figure 7.

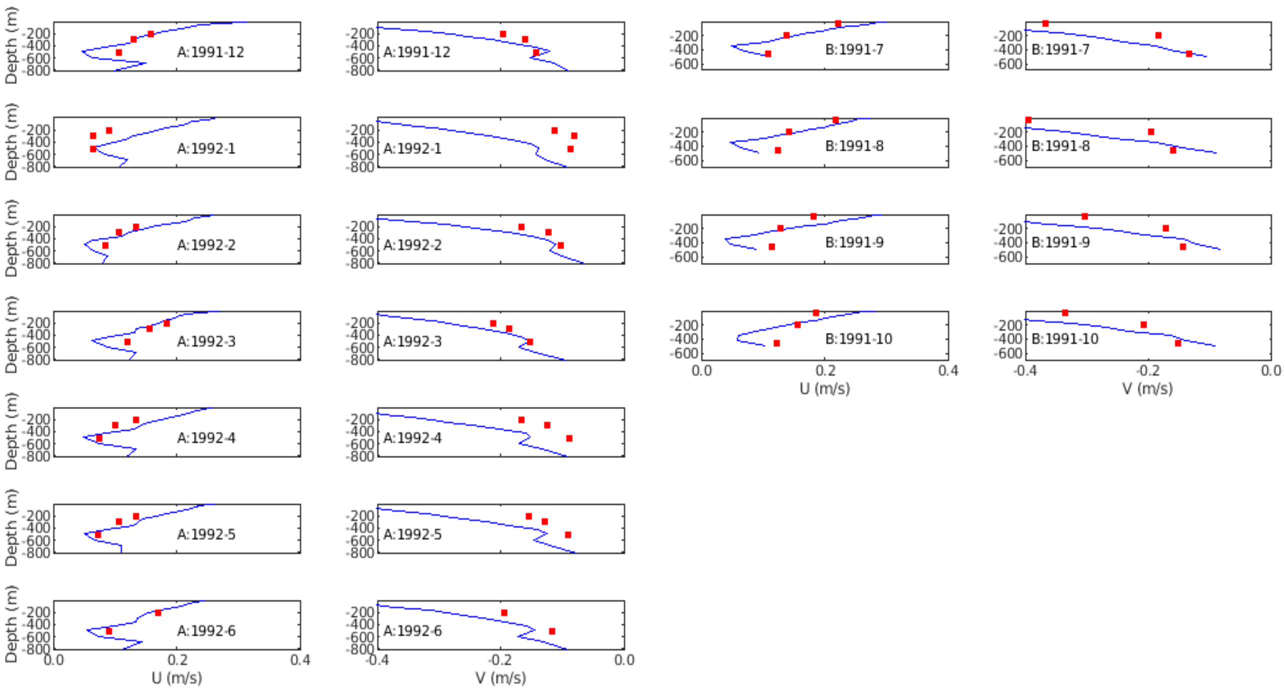

Figure 9: Comparisons between selected model monthly mean current profiles and moored measurements. U and V are the zonal and meridional components, respectively. Red squares are observations and the blue lines are the model results. See Figure 7 for the locations of sites A and B.

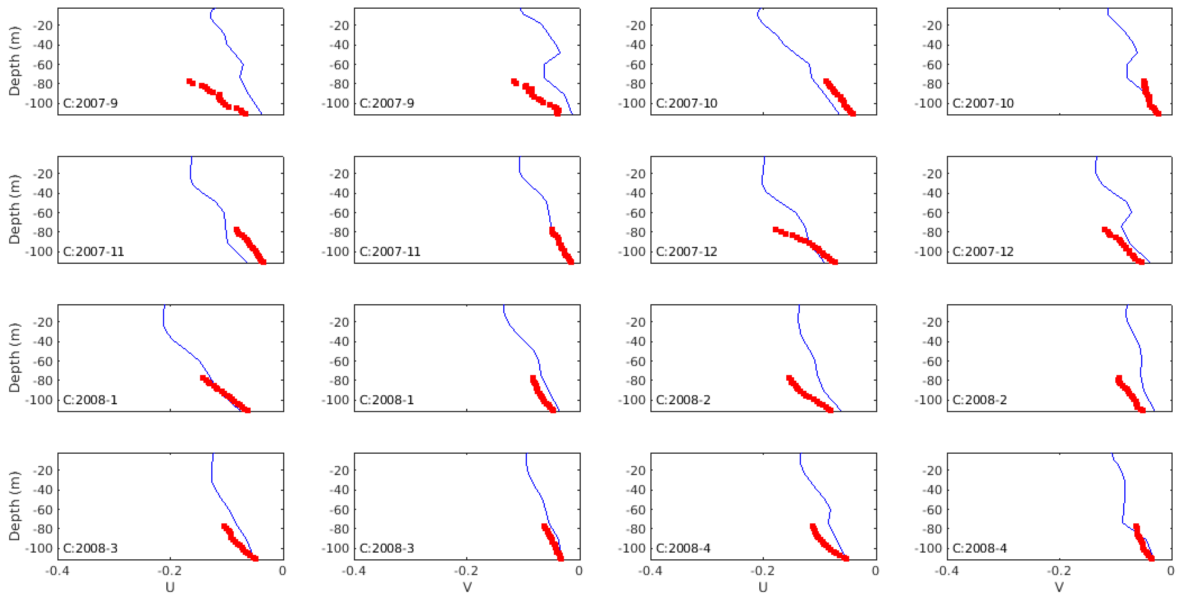

Figure 10: Comparisons between selected model monthly mean current profiles and moored measurements. U and V are the zonal and meridional components, respectively. Red squares are observations and the blue lines are the model results. See Figure 7 for the locations of site C.

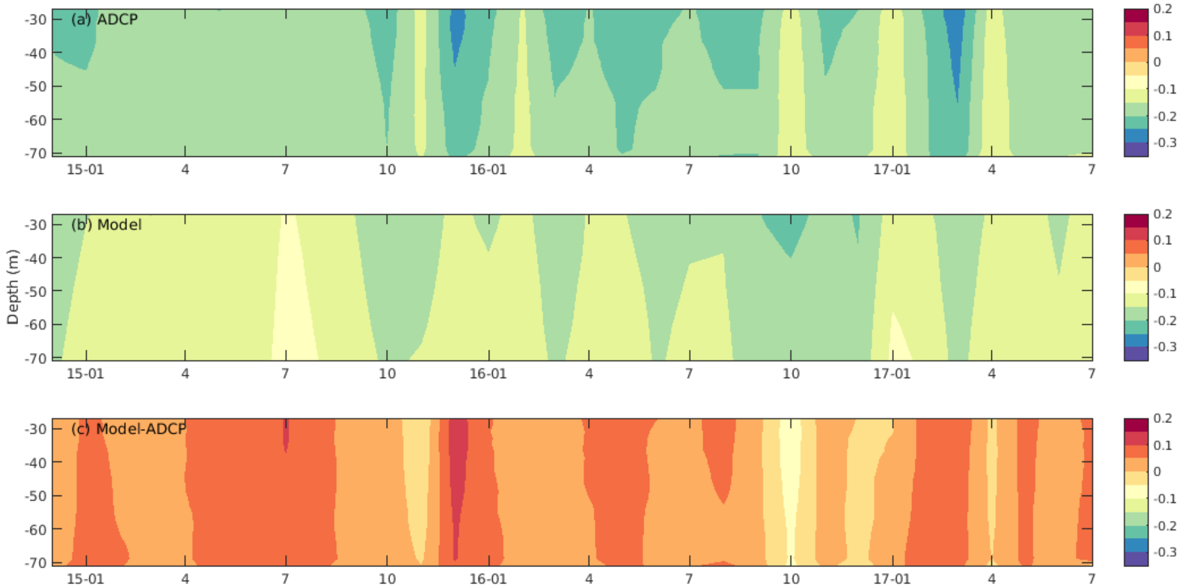

Figure 11: Monthly mean zonal currents at site OSNAP from December 2014 to July 2017. See Figure 7 for the locations of site OSNAP.

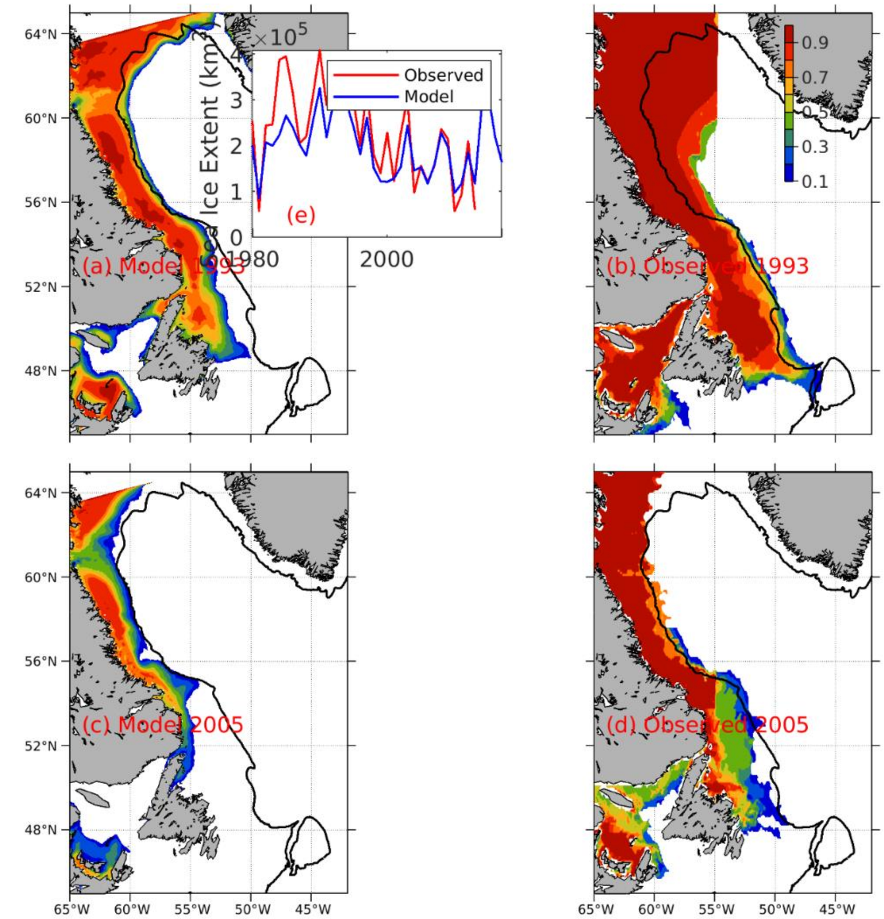

Figure 12: Sea ice concentration in March (a, b, c, d). The sea ice extent over the Newfoundland and Labrador Shelf south of $55^{o}N$ is shown in (e).