# BNAM: An eddy-resolving North Atlantic Ocean model to support ocean monitoring

Z. Wang, Y. Lu, B. Greenan, D. Brickman, and B. DeTracey

Ocean and Ecosystem Sciences Division
Maritimes Region
Fisheries and Oceans Canada

Bedford Institute of Oceanography
PO Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

2018

**Canadian Technical Report of Hydrography and Ocean Sciences 327**

Fisheries and Oceans Canada
Pêches et Océans Canada

Canada

**Canadian Technical Report of Hydrography and Ocean Sciences**

Technical reports contain scientific and technical information of a type that represents a contribution to existing knowledge but which is not normally found in the primary literature. The subject matter is generally related to programs and interests of the Oceans and Science sectors of Fisheries and Oceans Canada.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts.*

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Regional and headquarters establishments of Ocean Science and Surveys ceased publication of their various report series as of December 1981. A complete listing of these publications and the last number issued under each title are published in the *Canadian Journal of Fisheries and Aquatic Sciences*, Volume 38: Index to Publications 1981. The current series began with Report Number 1 in January 1982.

**Rapport technique canadien sur l'hydrographie et les sciences océaniques**

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles mais que l'on ne trouve pas normalement dans les revues scientifiques. Le sujet est généralement rattaché aux programmes et intérêts des secteurs des Océans et des Sciences de Pêches et Océans Canada.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page de titre.

Les établissements de l’ancien secteur des Sciences et Levés océaniques dans les régions et à l'administration centrale ont cessé de publier leurs diverses séries de rapports en décembre 1981. Vous trouverez dans l'index des publications du volume 38 du *Journal canadien des sciences halieutiques et aquatiques*, la liste de ces publications ainsi que le dernier numéro paru dans chaque catégorie. La nouvelle série a commencé avec la publication du rapport numéro 1 en janvier 1982.

Canadian Technical Report of

Hydrography and Ocean Sciences 327

2018

# BNAM: An eddy-resolving North Atlantic Ocean model to support ocean monitoring

by

Z. Wang, Y. Lu, B. Greenan, D. Brickman, and B. DeTracey

Ocean and Ecosystem Sciences Division

Maritimes Region

Fisheries and Oceans Canada

Bedford Institute of Oceanography

P.O. Box 1006

Dartmouth, N.S.

Canada B2Y 4A2

Cat. No. Fs97-18/327E-PDF ISBN 978-0-660-28339-5 ISSN 1488-5417

Correct citation for this publication:

Wang, Z., Lu, Y., Greenan, B., Brickman, D., and DeTracey, B., 2018. BNAM: An eddy-resolving North Atlantic Ocean model to support ocean monitoring. Can. Tech. Rep. Hydrogr. Ocean. Sci. 327: vii + 18p.

**TABLE OF CONTENTS**

## ABSTRACT

Wang, Z., Lu, Y., Greenan, B., Brickman, D., and DeTracey, B., 2017. An eddy-resolving North Atlantic model (BNAM) to support ocean monitoring. Can. Tech. Rep. Hydrogr. Ocean. Sci. 327: vii + 18p.

This report describes the eddy-resolving Bedford Institute of Oceanography North Atlantic model (BNAM) whose primary use is to support DFO monitoring programs such as AZOMP (Atlantic Zone Off-Shelf Monitoring Program) and AZMP (Atlantic Zone Monitoring Program). The 1990-2017 model hindcast result is compared with observational data from surface drifter and satellite altimetry. The model demonstrates good skill in simulating surface currents, winter convection events in the Labrador Sea, and the Atlantic Meridional Overturning Circulation as observed at 26.5°N and 41°N. Model results have been used to interpret changes in the Labrador Current and observed warming events on the Scotian Shelf, and are reported through the annual AZMP Canadian Science Advisory Secretariat Process.

# RÉSUMÉ

Wang, Z., Lu, Y., Greenan, B., Brickman, D., et DeTracey, B., 2017. Modèle de résolution des tourbillons de l'Atlantique Nord pour appuyer la surveillance des océans. Can. Tech. Rep. Hydrogr. Ocean. Sci. 327: vii + 18p.

Le présent rapport décrit le modèle de résolution des tourbillons de l'Atlantique Nord de l'Institut océanographique de Bedford dont l'objectif principal est d'appuyer les programmes de surveillance de Pêches et Océans Canada tels que le Programme de monitorage de la zone Atlantique au large du plateau continental et le Programme de monitorage de la zone Atlantique (PMZA). Les résultats de la simulation rétrospective du modèle 1990-2017 sont comparés aux données d'observation des dériveurs de surface et à celles de l'altimétrie satellitaire. Le modèle simule bien les courants de surface, les phénomènes de convection hivernale dans la mer du Labrador et la circulation méridienne de retournement de l'Atlantique observée à 26,5 °N et à 41 °N. Les résultats tirés du modèle ont servi à interpréter les changements dans le courant du Labrador et à observer les phénomènes de réchauffement observés sur le plateau néo-écossais. Ils sont présentés dans le cadre du processus annuel du Secrétariat canadien de consultation scientifique du PMZA.

# 1 INTRODUCTION

This report describes the 1/12° North Atlantic model configuration (BNAM) developed at the Bedford Institute of Oceanography (BIO). The purpose of the development of this model was to support ongoing DFO monitoring programs such as AZOMP (Atlantic Zone Off-Shelf Monitoring Program) and AZMP (Atlantic Zone Monitoring Program). Results from this model are contributed annually to AZOMP and AZMP reports for NAFO (Northwest Atlantic Fisheries Organization) and CSAS (Canadian Science Advisory Secretariat).

The model is based on version 2.3 of NEMO (Nucleus for European Modelling of the Ocean), a state-of-the-art modeling framework of ocean modelling. The physical core consists of OPA (ocean) and LIM (sea-ice). Details about the NEMO modeling system can be found at https://www.nemo-ocean.eu/. The NEMO model was first introduced into DFO in 2005. Over the past decade, BIO scientists and collaborators have developed various configurations based on NEMO for different applications [e.g., Wang et al., 2010; Holloway and Wang, 2010; Zhang et al., 2010; Wang et al. 2011; Wang et al., 2013; Lu et al;, 2014; Wang et al., 2015; Wang et al., 2016; Brickman et al, 2018]. The development of BNAM has benefited from previous work of BIO researchers and collaborators working on the North Atlantic modelling based on different ocean models [e.g., Wright et al., 2006; Thompson et al., 2006; Lu et al., 2006; Lu et al., 2007].

The model is implemented on the HPC2 computing cluster maintained at BIO. The source code is compiled with an Intel Fortran compiler. The compiler settings can be found in the Appendix.

# 2 BASIC SETTINGS

A list of CPP (C Pre-Processor) keys used in this model can be found in Table 1. Bottom boundary layer parameterization (`key_bbl_adv` or `key_bbl_diff`) is not used. We use the time-splitting free surface scheme to calculate the sea surface height, instead of the filtered free surface scheme. Double diffusion parameterization is included, as it is generally recognized to be important during wintertime ice formation period when strong brine rejection occurs.

Table 1 CPP Keys used in the model

| Key | Description |
|---|---|
| `key_na6_bio` | Configuration name |
| `key_mpp_mpi` | Multi-processor computation |
| `key_dtatem` | Use temperature data for initial conditions |
| `key_datsal` | Use salinity data for initial conditions |
| `key_dtasss` | Use sea surface salinity for the SSS restoration |
| `key_flx_core`<br>`key_tau_daily`<br>`key_flx_bulk_daily` | Use CORE forcing and NCAR bulk formula (`key_flx_core`)<br>Use NCEP forcing (`key_tau_daily`; `key_flx_bulk_daily`) |
| `key_traldf_c2d` | 2D lateral diffusion for tracer (depends on horizontal resolution) |
| `key_dynldf_smag` | Smagorinsky horizontal mixing parameterization for dynamics |
| `key_ice_lim` | Ice model |

| | |
|---|---|
| `key_lim_fdd` | Ice model interaction with ocean |
| `key_dynspg_ts` | Time splitting free surface |
| `key_ldfslp` | Calculation of isopycnal slope |
| `key_obc` | Open boundaries |
| `key_zdftke` | TKE vertical mixing scheme |
| `key_ddm` | Double diffusion parameterization |

## 2.1 Horizontal grid

Figure 1 shows the model domain. The BNAM grid (1435×1122 (X×Y)) is extracted from the global 1/12 degree ORCA12 model grid (https://www.mercator-ocean.fr/en/science-publications/operational-systems/components-of-systems/), using x-indices from 2270 to 3704 and y-indices from 1590 to 2711. The southern and northern boundaries are located at 7°N and roughly 67°N, respectively. The BNAM domain includes a large portion of the Mediterranean Sea, a source of dense, warm and salty water that has significant influnces on watermass property of North Atlantic [Bozec et al., 2011]. Major portions of the Greenland, Iceland and Norwegian (GIN) Seas, and Hudson Bay occupy the northern part of the model domain, hence wintertime dense water formation process in the GIN seas and fresh water outflow from the Hudson Bay are incluced. The domain covers the entire subtropical gyre including the Gulf Stream. The inclusion of the Labrador Current and Gulf Stream enables the simulation of the interactions of the two currents that contribute to changes in watermass property on the Scotian Shelf [Brickman et al., 2018].

The minima of the grid sizes are 2.7 km (zonal direction) and 2.1 km (meridional direction) in the northern part of the domain. The maximum is 9.17 km, along the southern boundary.

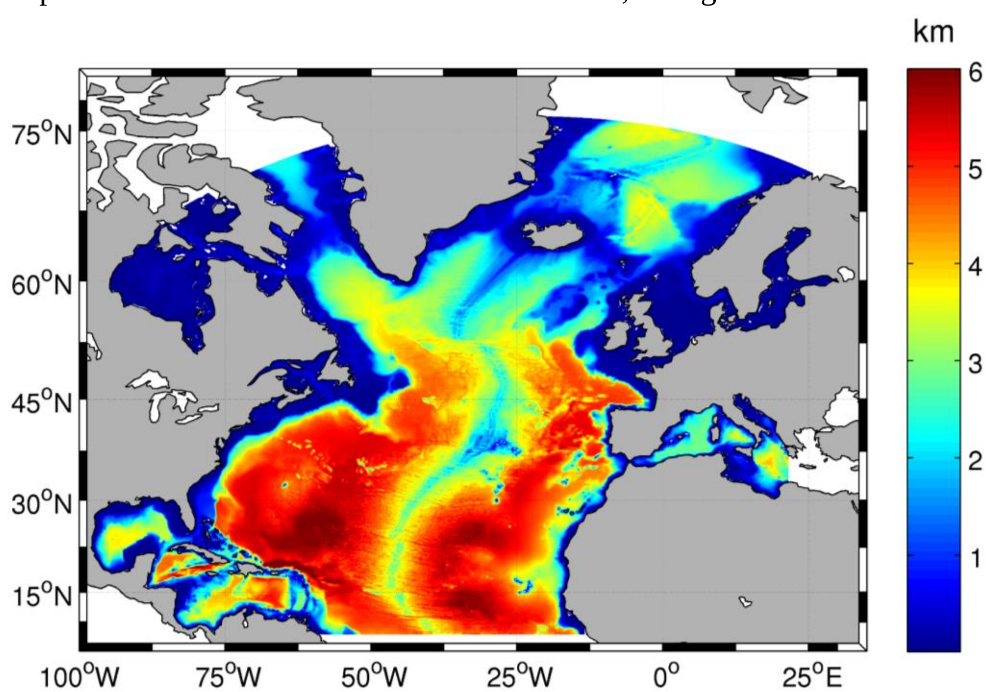


Figure 1. The BNAM model domain, with bathymetry (in km) denoted by color shading.

## 2.2 Vertical grid

There are 50 levels in the vertical, with varying thickness from 1 m at the top to 450 m at the bottom. The details of the vertical layers are given in the Appendix.

## 2.3 Bathymetry

The model bathymetry (shown in Figure 1) is taken from that used in the ORCA12 model of Mercator-Ocean, France. The partial cell scheme is applied to better represent the bathymetry (`ln_zps=.true.` in *namelist* `nam_zgr`). The following values are used to calculate the partial cell layer thicknesses (in *namelist* `namdom`): `e3zps_min=25` and `e3zps_rat=0.2`.

## 2.4 Initial conditions

The initial conditions for temperature and salinity (T/S), for mid and low latitudes, are derived from the WOA05 data set (https://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html). For high latitudes the PHC3.1 climatology (http://psc.apl.washington.edu/nonwp_projects/PHC/Climatology.html) is used. The T/S data are linearly interpolated onto the model grid in both the horizontal and vertical directions.

# 3 FORCING

## 3.1 Open boundary forcing

The BNAM model has two open boundaries, the northern and the southern ones. A monthly climatology compiled from the global ocean reanalysis product, GLORYS v2 (1993 to 2009; Ferry et al. 2010) is used at the northern and southern open boundaries. The open section in the Mediterranean Sea is treated as closed, and this treatment does not lead to unrealistic Mediterranean Sea outflow through the Gibraltar Strait. Sea level, temperature, salinity and velocity are linearly interpolated horizontally and vertically (3D variables) from the ¼º resolution GLORYS v2 grid onto the BNAM open boundary grids. The current version of BNAM does not include tidal forcing.

The relevant open boundary parameters in the *namelist* are as follows:

```
!  nobc_dta    = 0 the obc data are equal to the initial state
!              = 1 the obc data are read in 'obc   .dta' files
!  rdpeob  time relaxation (days) for the east open boundary
!  rdpwob  time relaxation (days) for the west open boundary
!  rdpnob  time relaxation (days) for the north open boundary
!  rdpsob  time relaxation (days) for the south open boundary
!  zbsic1  barotropic stream function on isolated coastline 1
!  zbsic2  barotropic stream function on isolated coastline 2
!  zbsic3  barotropic stream function on isolated coastline 3
!  ln_obc_clim  climatological obc data files (default T)
!  ln_vol_cst   total volume conserved

&namobc
```

```
nobc_dta   =   1
rdpnin     =   0.04
rdpsin     =   1.
rdpnob     =   0.04
rdpsob     =   150.
ln_obc_clim = .true.
ln_vol_cst  = .false.
```

Parameters relative to the western and eastern boundaries are not relevant to this configuration. The northern boundary is prescribed (non-radiative) by setting the two relaxation timescales to `rdpnin=dpnob=0.04 days`. A radiative boundary condition is used at the southern boundary to avoid over-determination, with time scales of 1 day for inflow and 150 days for outflow.

## 3.2 Continental runoffs

The monthly climatological runoff data is taken from the ORCA12 model input. We use the *namelist* variable `nrunoff=2`. In this case, a special treatment is applied in runoff regions i.e., where the array `upsrnfh` is nonzero. The array `socoefr`, read from the runoff file, has a value of zero where there is no runoff and 0.5 at runoff points. The vertical mixing is increased by the following line in module `step.F90`:

```
avt(:,:,2) = avt(:,:,2) + 2.e-3 * upsrnfh(:,:)
```

## 3.3 Atmospheric forcing files

Two surface forcing datasets are used in this hindcast run: CORE (Coordinated Ocean-ice Reference Experiments) and NCEP (National Centers for Environmental Prediction).

(1) CORE

The CORE forcing is downloaded from
http://data1.gfdl.noaa.gov/nomads/forms/core/COREv2.html [Large and Yeager, 2004]. BNAM was run for 10 years as spin-up using the climatological CORE Normal Year Forcing (NYF). After this spin-up period, the forcing was switched to the interannually varying CORE data starting from 1990.

The variables of input data are

- Air temperature and specific humidity: 6 hourly values
- Long wave and short wave radiation: daily values
- Precipitation (total precipitation and snow): monthly values

The surface turbulent heat fluxes, the outgoing radiation and albedo are calculated using the bulk formulae proposed with the CORE dataset [Large and Yeager, 2004].

(2) NCEP

The NCEP forcing is used after 2007 when no CORE forcing is available. The NCEP data are downloaded from ftp://ftp.cdc.noaa.gov. Daily forcing data is used. Variables in the input files include:

• Daily humidity and cloud
• Daily wind
• Daily air temperature
• Daily precipitation

A bulk formula available in the NEMO is used to calculate the air-sea fluxes.

We note that changing the surface forcing from CORE to NCEP in 2007 does not lead to notable changes in the model solution.

## 3.4 Forcing parameters

The forcing routine and the sea-ice model are called every baroclinic model time step (`nfice=1` and `nfbulk=1` in *namelist* `namdom`). We found that if the sea-ice model was called less frequently (e.g. at intervals of 6 time steps), the model became unable. Sea surface salinity is relaxed to the monthly WOA5 (Levitus et al., 1998) /PHC3.1 (Steel et al., 2001) climatology, but no relaxation is applied to sea surface temperature. No relaxation is applied to the ocean interior beneath surface.

# 4 SEA-ICE MODEL

BNAM uses the LIM2 ice model [Fichefet, T. and M.A. Morales Maqueda 1997] with two ice layers and one snow layer. Wang et al. [2010] found that LIM2 is very sensitive to a parameter related to ice formation in open water. This parameter is tuned following Wang et al. [2010] as `hiccrit=0.4, 0.4`. The full LIM2 *namelist* is:

```
!
!  ln_limdyn   : switch for ice dynamics (true) or not (false)
!  ln_limdmp : restoring Ice thickness and Fraction leads flag
!   acrit(1/2)   :  minimum  fraction  for  leads  in  the  Northern  (Southern)
Hemisphere
!  hnsdif      : computation of temperature in snow (=0.0) or not (=9999.0)
!  hicdif      : computation of temperature in ice  (=0.0) or not (=9999.0)
!
&namicerun
   ln_limdyn = .true.
   ln_limdmp = .FALSE.
   acrit     = 1.0e-06 , 1.0e-06
   hsndif    = 0.0
   hicdif    = 0.0
/
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!       namiceini   parameters for ice initialisation
!,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
!
!  ln_limini : Ice initialization state flag
!  ttest     : threshold water temperature for initial sea ice
!  hninn     : initial snow thickness in the north
!  hginn     : initial ice thickness in the north
!  alinn     : initial leads area in the north
!  hnins     : initial snow thickness in the south
!  hgins     : initial ice thickness in the south
```

```
!  alins     : initial leads area in the south
!
&namiceini
   ln_limini = .FALSE.
   ttest = 2.0
   hninn = 0.5
   hginn = 3.0
   alinn = 0.05
   hnins = 0.1
   hgins = 1.0
   alins = 0.1
/
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!       namicedia   parameters for ice diagnostics
!,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
!
!  fmtinf : format of the output values
!  nfrinf : number of variables written in one line
!  ntmoy  : instantaneous values of ice evolution or averaging
!  ninfo  : frequency of ouputs on file ice_evolu in case of averaging
!
&namicedia
   fmtinf = '1PE13.5 '
   nfrinf = 4
   ntmoy  = 1
   ninfo  = 1
/
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!       namicedyn   parameters for ice dynamic
!,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
!
!  epsd   : tolerance parameter
!  alpha  : coefficient for semi-implicit coriolis
!  bound  : boundary conditions (=0.0 no-slip, =1.0 free-slip)
!  dm     : diffusion constant for dynamics.
!  nbiter : number of sub-time steps for relaxation
!  nbitdr : maximum number of iterations for relaxation
!  om     : relaxation constant
!  resl   : maximum value for the residual of relaxation
!  cw     : drag coefficient for oceanic stress
!  angvg  : turning angle for oceanic stress
!  pstar  : first bulk-rheology parameter
!  c_rhg  : second bulk-rhelogy parameter
!  etamn  : minimun value for viscosity
!  creepl : creep limit
!  ecc    : eccentricity of the elliptical yield curve
!  ahi0   : horizontal eddy diffusivity coefficient for sea-ice (m2/s)
!
&namicedyn
   epsd   = 1.0e-20
   alpha  = 0.5
   dm     = 0.6e+03
   nbiter = 1
   nbitdr = 100
   om     = 0.5
   resl   = 5.0e-05
   cw     = 5.0e-03
```

```
   angvg  = 0.0
   pstar  = 1.0e+04
   c_rhg  = 20.0
   etamn  = 1.0e+07
   creepl = 2.0e-08
   ecc    = 2.0
   ahi0   = 200.e0
/
!
!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!       namicetrp   parameters for ice advection
!,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
!  bound  : boundary conditions (=0.0 no-slip, =1.0 free-slip)
&namicetrp
   bound  = 0.
/

!''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
!       namicethd   parameters for thermodynamic computation
!,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
!
!  hmelt        : maximum melting at the bottom
!    hiccrit(1/2):  ice  thickness  for  lateral  accretion  in  the  Northern
(Southern) Hemisphere
!                 caution 1.0, 1.0 best value to be used!!! (gilles G.)
!  hicmin       : ice thickness corr. to max. energy stored in brine pocket
!  hiclim       : minimum ice thickness
!  amax         : maximum lead fraction
!  swiqst       : energy stored in brine pocket (=1) or not (=0)
!  sbeta        : numerical caracteritic of the scheme for diffusion in ice
!                Cranck-Nicholson (=0.5), implicit (=1), explicit (=0)
!  parlat       : percentage of energy used for lateral ablation
!  hakspl       : slope of distr. for Hakkinen-Mellor's lateral melting
!  hibspl       : slope of distribution for Hibler's lateral melting
!  exld         : exponent for leads-closure rate
!  hakdif       : coefficient for diffusions of ice and snow
!  thth          : threshold thickness for comp. of eq. thermal conductivity
!  hnzst        : thickness of the surf. layer in temp. computation
!  parsub       : switch for snow sublimation or not
!  alphs        : coefficient for snow density when snow ice formation
!
&namicethd
   hmelt   = -0.15
   hiccrit = 0.4 , 0.4
   hicmin  = 0.2
   hiclim  = 0.05
   amax    = 0.999
   swiqst  = 1.
   sbeta   = 1.
   parlat  = 0.0
   hakspl  = 0.5
   hibspl  = 0.5
   exld    = 2.0
   hakdif  = 1.0
   thth    = 0.2
   hnzst   = 0.1
   parsub  = 1.0
```

```
alphs    = 1.0
```

# 5 OCEAN PARAMETERS

## 5.1 Free surface

The model run uses free surface (`key_dynspg_ts`) and also enforces constant volume over the model domain.

## 5.2 Advection schemes

The TVD (Total Variation Diminishing) scheme is used for tracers (`ln_traadv_tvd=.true.`). This scheme helps to maintain numerical stability in the presence of large gradient of the tracer distributions. A momentum advection scheme suitable for partial vertical steps (`ln_dynvor_een=.true.`) is used. This scheme conserves both energy and enstrophy.

## 5.3 Lateral mixing

- Tracers: a Laplacian isopycnal diffusion is used with `aht0=125` ($m^2s^{-1}$) at the equator.
- Dynamics: a modified Smagorinsky scheme is used to calculate the horizontal mixing viscosity. The scheme is:

$$(\alpha \times min(\Delta x \times \Delta y)/3.14.159265)^2 \times \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial y}{\partial y}\right)^2 + 0.5 \times \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2}$$

where $\Delta x$ *and* $\Delta y$ are the grid lengths in the x and y directions, and *u* and *v* are the velocities in the x and y directions, respectively. We set $\alpha = 1.4$.

## 5.4 Vertical mixing

The TKE (Turbulent Kinetic Energy) dependent diffusion scheme is used to compute the vertical mixing.

```
!-----------------------------------------------------------------------
!       namtke   turbulent eddy kinetic dependent vertical diffusion
!                ( #ifdef "key_zdftke" )
!-----------------------------------------------------------------------
!  ln_rstke flag to restart with tke from a run without tke (default F)
!  ediff    coef. to compute vertical eddy coef. (avt=ediff*mxl*sqrt(e) )
!  ediss    coef. of the Kolmogoroff dissipation
!  ebb      coef. of the surface input of tke
!  efave    coef. to applied to the tke diffusion ( avtke=efave*avm )
!  emin     minimum value of tke (m^2/s^2)
!  emin0    surface minimum value of tke (m^2/s^2)
!  nitke    number of restart iterative loops
```

```
!  ri_c     critic richardson number
!  nmxl     flag on mixing length used
!           = 0 bounded by the distance to surface and bottom
!           = 1 bounded by the local vertical scale factor
!           = 2 first vertical derivative of mixing length bounded by 1
!  npdl     flag on prandtl number
!           = 0 no vertical prandtl number (avt=avm)
!           = 1 prandtl number function of richarson number (avt=pdl*avm)
!           = 2 same as = 1 but a shapiro filter is applied on pdl
!  nave     =  horizontal averaged (=1) or not (=0) of avt  (default =1)
!  navb     = 0 cst background avt0, avm0 / =1 profile used on avtb
&namtke
   ln_rstke = .false.
   ediff = 0.1
   ediss = 0.7
   ebb   = 3.75
   efave = 1.
   emin  = 1.e-6
   emin0 = 1.e-4
   nitke = 50
   nmxl  = 2
   npdl  = 1
   navb  = 0
/
```

Enhanced vertical diffusion is used when convection is diagnosed. The corresponding *namelist* block is:

```
!-----------------------------------------------------------------------
!        namzdf     vertical physics
!-----------------------------------------------------------------------
! ln_zdfevd enhanced vertical diffusion              (default T)
! ln_zdfnpc Non-Penetrative Convection               (default T)
! avm0        vertical eddy viscosity for the dynamic (m2/s)
! avt0        vertical eddy diffusivity for tracers (m2/s)
! avevd       vertical coefficient for enhanced diffusion scheme (m2/s)
! nevdm       = 0 apply enhanced mixing on tracer only
!             = 1 apply enhanced mixing on both tracer and momentum
! ln_zdfexp  vertical physics: (=T) time splitting (T)     (Default=F)
!                              (=F) euler backward (F)
! n_zdfexp   number of sub-timestep for time splitting scheme
&namzdf
   ln_zdfevd = .true.
   ln_zdfnpc = .false.
   avm0      = 1.e-4
   avt0      = 1.e-5
   avevd     = 10.
   nevdm     = 1
   ln_zdfexp = .false.
   ln_zdfexp = 3
  /
```

## 5.5 Bottom friction and lateral boundary condition

A quadratic formation of bottom friction is used. The *namelist* is:

```
!-----------------------------------------------------------------------
!        nambfr    bottom friction
!-----------------------------------------------------------------------
! nbotfr type of bottom friction
!                     nbotfr = 0 , no slip
!                     nbotfr = 1 , linear friction
!                     nbotfr = 2 , nonlinear friction
!                     nbotfr = 3 , free slip
! bfri1     bottom drag coefficient (linear case)
! bfri2     bottom drag coefficient (non linear case)
! bfeb2     bottom turbulent kinetic energy (m^2/s^2)
&nambfr
   nbotfr = 2
   bfri1  =  4.e-4
   bfri2  =  2.5e-3
   bfeb2  =  2.5e-3
/
!-----------------------------------------------------------------------
!       namlbc   lateral momentum boundary condition
!-----------------------------------------------------------------------
!  shlat   lateral boundary condition on velocity
!                   shlat = 0 , free slip
!               0 < shlat < 2 , partial slip
!                   shlat = 2 , no slip
!               2 < shlat     , strong slip
&namlbc
   shlat  =     0.5
/
```

# 6 MODEL VALIDATION

The analyses of BNAM results have been reported in several publications that include the validation using a variety of observational data. Wang and Greenan [2014] used observed sea surface temperature and bottom temperature. Wang et al. [2016] used current meter mooring data at Hamilton Bank, and satellite altimeter data and winter convection depths in the Labrador Sea. Brickman et al. [2018] used observed bottom temperatures for the past several years. Below we present validations that are either for unreported variables, or the previously reported ones but with extensions either in terms of record length or spatial domains.

## 6.1 Comparison with surface drifter data

The observed surface drifter data are downloaded from the NOAA/AOML Global Lagrangian Drifting Buoy Database (http://www.aoml.noaa.gov/phod/dac/dacdata.php). The drifter data are binned into ¼ by ¼-degree boxes, and are then averaged for each bin. Figure 2 compares the surface currents from the surface drifters and BNAM, averaged over 1990-2015. The directions and magnitudes from the two sources are in good agreement. The model well captures the observed strong flow associated with the Gulf Stream, the Labrador Current, and the East and West Greenland Currents. The complicated flow structure near the Northwest Corner, i.e., a double-gyre feature found to the northeast of the Grand Banks, is well represented by the model.

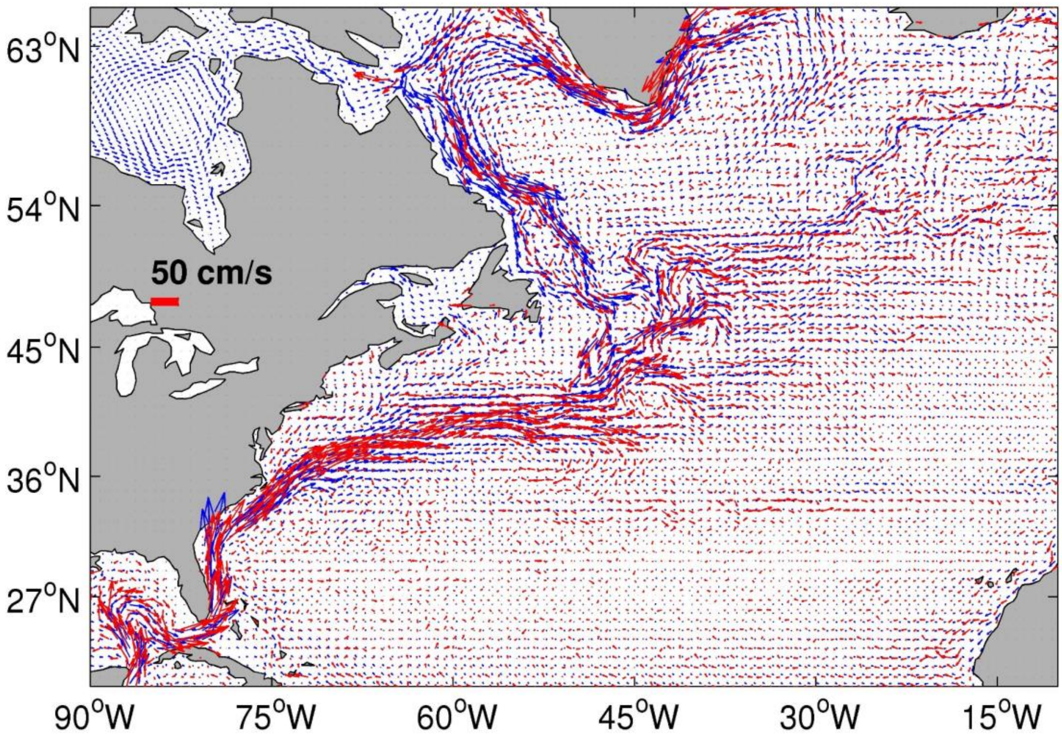


Figure 2. Surface currents averaged over 1990-2015 from BNAM (blue vectors) and surface drifter observations (red vectors). The model results are plotted every ninth of the model grids, and the observed data are plotted every third of the observed data grids.

## 6.2 Comparison with altimeter data

The altimeter data are obtained from AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data; http://www.aviso.altimetry.fr). This product is derived by objectively mapping the along-track altimeter data onto a ¼ degree Mercator grid. Figure 3 shows the root-mean-squared sea surface height (RMS SSH) variations from the altimeter data and the BNAM model.

The RMS SSH distribution from the altimeter observation and BNAM are generally consistent. Both show the largest RMS along the path of the eddy-rich and meandering Gulf Stream; and large values in a band along the Loop Current in the Gulf of Mexico and at the Northwest Corner. Notable differences are the model's underestimation along the Azores Current (in the area to the southeast of the Grand Banks); the overestimation in a region around 50ºN, 30ºW; and the too broad area of large RMS near Cape Hatteras, apparently associated with the Gulf

Stream overshooting. The overshooting feature is not persistent, but varies year by year (figures not shown).

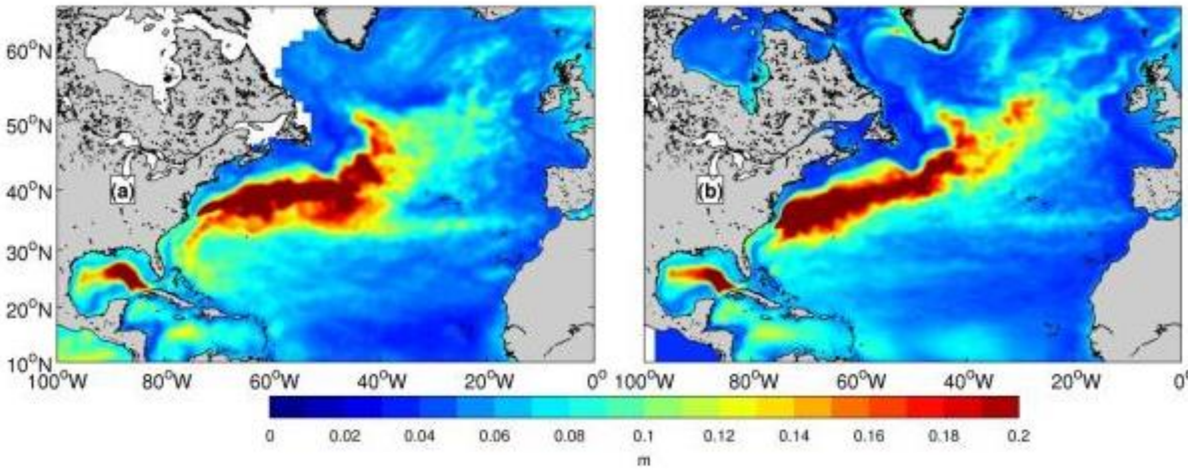


Figure 3. The root-mean-square of SSH (in meter) for the 1993 to 2015 period, from (a) the AVISO satellite altimeter data and (b) the BNAM model.

## 6.3 Comparison with observed convection depth

The annual spring survey of the Labrador Sea has been conducted by DFO during the past two decades (http://www.bio.gc.ca/science/monitoring-monitorage/azomp-pmzao/azomp-pmzao-en.php ) [Yashayaev and Loder, 2009]. Observations were made along the AR7W line extending from the Labrador Shelf to the Greenland Shelf. Figure 4 shows a comparison of the convection depths from observations and BNAM during 1990-2015. Observational estimates prior to 2002 are based on temperature and salinity data from the spring cruises along the AR7W line. From 2002 onwards, the observed convection depths are based on Argo float data aggregated to the central Labrador Sea. Modeled convection depths are defined as the largest wintertime (January, February, and March) mixed layer depth in the Labrador Sea.

The observed convection depths are larger than 2000 m during 1990-1995, changed to be smaller values (1000-1500 m) from 1996 to 2007, and returned to large values in 2008, 2014 and 2015. The modeled convection depths generally follow the observed variability although differences exist, especially for 1996 and 1997. The correlation coefficient between the observed and modelled convection depths is 0.85, significant at the 95% confidence level.

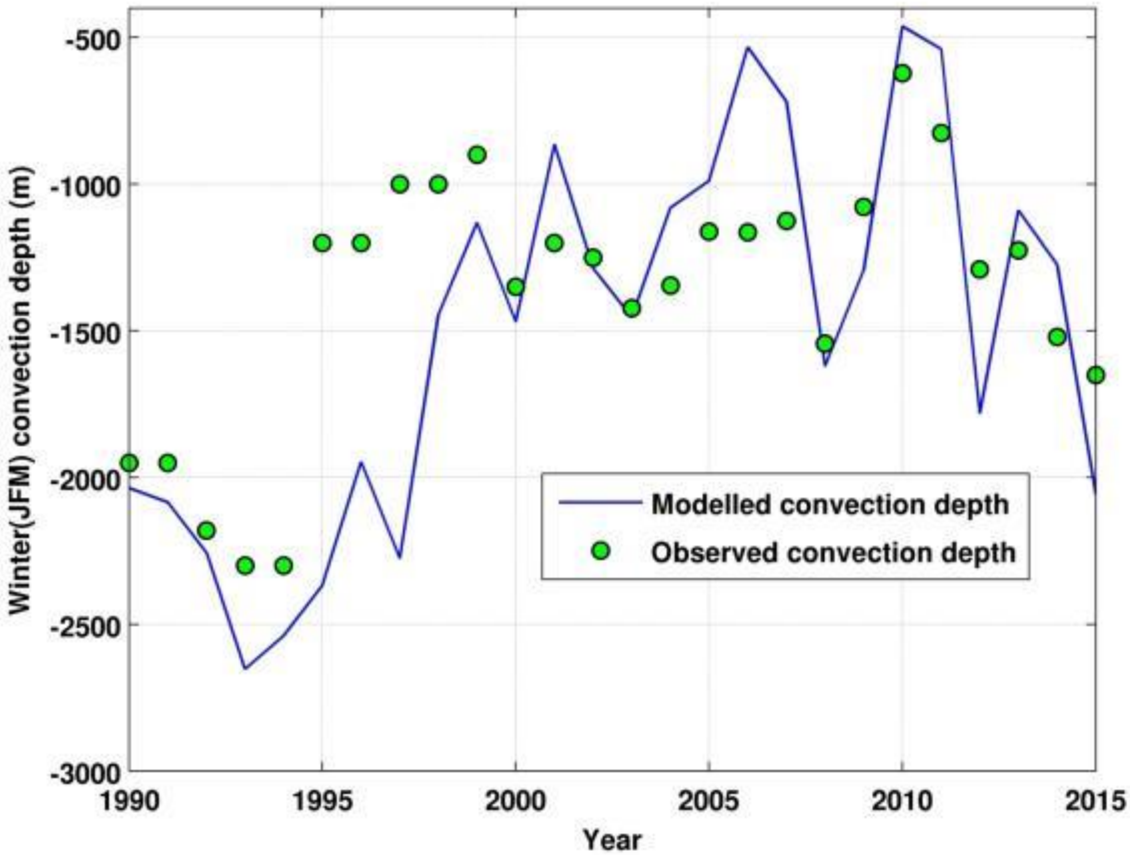


Figure 4. The observed convection depths (green dots) and the modelled maximum wintertime (JFM) mixed layer depths (blue curve) in Labrador Sea.

## 6.4 Comparison with observed AMOC at 26.5ºN and 41ºN

The observed AMOC transport at 26.5ºN is estimated from the RAPID/MOCHA array [Cunningham et al., 2007] available at a daily resolution from April 2004 to March 2014. It is calculated as the sum of the Florida Strait transport, Ekman transport and upper mid-ocean transport from moorings placed across 26.5ºN. The observed AMOC estimates at 41ºN are taken from Willis [2010], computed using Argo floats and altimeter data, available as monthly means from January 2002 to October 2013. At 26.5ºN, the mean AMOC transport is 15 Sv from BNAM and 17 Sv from the RAPID/MOCHA array. At 41ºN, the mean AMOC transport is 12 Sv from BNAM and 13 Sv from observations. The standard deviations of the AMOC transport from observations (BNAM) are 3.5 (3.0) Sv at 26.5ºN, and 2.9 (3.0) Sv at 41ºN line. Figure 5 shows the time series of the observed and modeled AMOC transport anomalies. Their correlations are 0.68 at 26.5ºN and 0.47 at 41ºN.

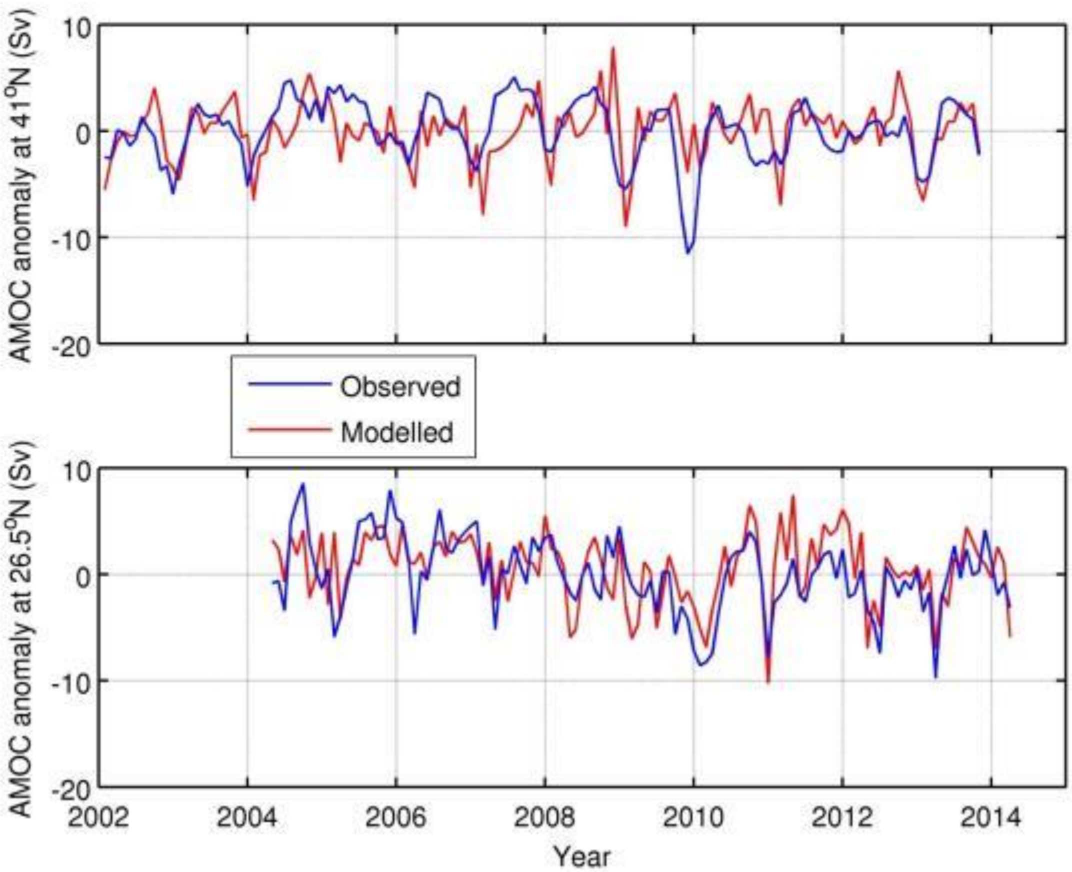


Figure 5. Time series of AMOC transport anomalies at 41°N (upper panel) and 26.5°N (lower panel) from observations (blue) and model (red).

# 7 MISCELLANEOUS

The baroclinic time step is set to 360 s, and the barotropic one is 6 s. The model output frequency is monthly. The model restarts at January 1st for each model year.

Using 96 cores on the HPC2 cluster machine, one model year is completed in 2.62 days.

# 8 ACKNOWLEDGEMENTS

The late Dr. Daniel Wright played a major role in introducing the NEMO model to DFO, and led a team of ocean modellers at BIO (including Youyu Lu, Zeliang Wang, Frederic Dupont, and Michael Dunphy) on initial applications of NEMO for modelling the global and North Atlantic Oceans. Dave Brickman, Joel Chassé and Adam Drozdowski used the NEMO model for regional studies when the model was introduced to BIO. Fraser Davidson from the Northwest Atlantic Fisheries Center (NAFC) started to use the NEMO model in 2004. We thank Li Zhai and Adam Drozdowski for the internal reviews of this report.

# 9 REFERENCES


Bozec, A., M.S. Lozier, E.P. Chassignet, and G.R. Halliwell (2011), On the variability of the Mediterranean Outflow Water in the North Atlantic from 1948 to 2006. J. Geophys. Res., 116, C09033, doi: 10.1029/2011JC007191.

Brickman, D., D. Hebert, and Z. Wang (2018), Mechanism for the recent ocean warming events on the Scotian Shelf of eastern Canada. Cont. Shelf Res, doi:10.1016/j.csr.2018.01.001.

Cunningham, S.A., T.O. Kanzow, D. Rayner, M.O. Baringer, W. E. Johns, J. Marotzke, H.R. Longworth, E.M. Grant, JJ-M Hirschi, L.M. Beal, C.S. Meinen, and H.L. Bryden (2007), Temporal variability of the Atlantic Meridional Overturning Circulation at 26.5°N. Science 317:935–938. doi:10.1126/science.1141, 304.

Ferry, N., L. Parent, G. Garric, B. Barnier, N.C. Jourdain, and the Mercator Ocean team (2010), Mercator global eddy permitting ocean reanalysis GLORYS1V1: Description and results, Mercator Quarterly Newsletter 36, available at: http://www.mercator-ocean.fr/fre/actualites-agenda/newsletter/newsletter-Newsletter-36-Data-assimilation-and-its-application-to-Ocean-Reanalyses, January 2010.

Fichefet, T., and M.A. Morales Maqueda (1997), Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics. J. Geophys. Res., 102, 12609- 12646.

Holloway, G., and Z. Wang (2009), Representing eddy stress in an Arctic Ocean model, J. Geophys. Res., 114, C06020, doi:10.1029/2008JC005169.

Large, W., and S. Yeager (2004), Diurnal to decadal global forcing for ocean and sea- ice models: the datasets and flux climatologies. NCAR technical note: NCAR/TN-460+STR, CGD division of the National Center for Atmospheric Research. Available on the GFDL CORE web site.

Levitus S, Boyer, T. P., Conkright, M. E., O'Brian, T., Antonov, J., Stephens, C., Stathopolos, L., Johnson, D., Gelfeld, R., 1998. World Ocean Database 1998, NOAA Atlas NESDID, 18.

Lu, Y., D.G. Wright, and R.A. Clarke (2006), Modelling deep seasonal temperature changes in the Labrador Sea. Geophysical Research Letters, 33, L23601, doi:10.1029/2006GL027692.

Lu, Y., D.G. Wright, and I. Yashayaev (2007), Modelling hydrographic changes in the Labrador Sea over the past five decades. Prog. Oceanogr., 73, 406-426, doi:10.1016/j.pocean.2007.02.007.

Lu, Y., S. Higginson, S. Nudds, S. Prinsenberg, and G. Garric (2014), Volume fluxes though the Canadian Arctic Archipelago and Davis Strait: Linking monthly variations to forcing in different seasons. Journal of Geophysical Research, 119(3), 1927–1942, doi:10.1002/2013JC009408.

Steel, M., Morley, R., Ermold, W., 2001. PHC: A global ocean hydrography with a high quality Arctic Ocean, J. Clim., 14, 2079-2087.

Thompson, K.R., D.G. Wright, Y. Lu, and E. Demirov (2006), A simple method for reducing seasonal bias and drift in eddy resolving ocean models. Ocean Modelling 13, 109-125.

Wang, Z., D. Brickman, B. Greenan, and I. Yashayaev (2016), An abrupt shift in the Labrador Current System in relation to winter NAO events. J. Geophys. Res. Oceans, 121, 5338–5349, doi:10.1002/2016JC011721.

Wang, Z., and B. Greenan (2014), Physical oceanographic conditions on Newfoundland Shelf/Flemish Cap from a model perspective (1990-2012), NAFO SCR Doc. 14/008, Serial No. N6298, Northwest Atlantic Fisheries Organization.

Wang, Z., G. Han, and F. Dupont (2015), Effects of Spectral Nudging on Oceanic States in a Coarse-Resolution Model. Atmosphere-Ocean, vol. 53, Iss. 3.

Wang, Z., G. Holloway, and C. Hannah (2011), Effects of parameterized eddy stress on volume, heat, and freshwater transports through Fram Strait. J. Geophys. Res., 116, C00D09, doi:10.1029/2010JC006871.

Wang, Z., Y. Lu, D.G. Wright, and F. Dupont (2010), Sea ice sensitivity to the parameterisation of open water area. J. of Operational Oceanography, 2.

Willis, J.K. (2010), Can in situ floats and satellite altimeters detect long-term changes in Atlantic Ocean overturning? Geophys. Res. Lett., 37, L06602, doi:10.1029/2010GL042372.

Wright, D.G., K.R. Thompson, and Y. Lu (2006), Assimilating long-term hydrographic observations in an eddy-permitting model of the North Atlantic. J. Geophys. Res., 111, C09022, doi:10.1029/2005JC003200.

Yashayaev, I., and J.W. Loder (2009), Enhanced production of Labrador Sea Water in 2008. Geophys. Res. Lett., 36, L01606, doi:10.1029/2008GL036162.

Zhang, X., Y. Lu, K.R. Thompson, J. Jiang, and H. Ritchie (2010), The tropical Pacific Ocean and the Madden-Julian Oscillation: Role of wind and buoyancy forcing. Journal of Geophysical Research, 115(5), 1-11, C05022, doi:10.1029/2009JC005734.

# Appendix

## Compiling options for BNAM on BIO HPC2 cluster

```
#-Q- HPC    #- Global definitions for Linux Compiler Intel v8
#-Q- HPC    M_K = gmake
#-Q- HPC    P_C = cpp
#-Q- HPC    P_O = -P -C -traditional $(P_P) -
I/export/opt/netcdf/3.6.3/intel/medium/include -I/opt/hpmpi/include
#-Q- HPC    #-D- MD    F_D = -g
#-Q- HPC    #-D- MN    F_D =
#-Q- HPC    #-P- I4R4  F_P = -i4
#-Q- HPC    #-P- I4R8  F_P = -i4 -r8
#-Q- HPC    #-P- I8R8  F_P = -i8 -r8
#-Q- HPC    #-P- ??    F_P =
#-Q- HPC    F_C = mpif90 -O3 -xSSE4.2 -c -cpp -assume byterecl
#-Q- HPC    F_O = $(P_P) $(F_D) $(F_P) -I$(MODDIR) -module $(MODDIR) -
I/opt/hpmpi/include -I/export/opt/netcdf/3.6.3/intel/medium/include
#-Q- HPC    F_L = mpif90 -O3 -xSSE4.2
#-Q- HPC    L_O =
#-Q- HPC    A_C = ar -r
#-Q- HPC    A_G = ar -x
#-Q- HPC    C_C = gcc -c
#-Q- HPC    C_O =
#-Q- HPC    C_L = gcc
#-Q- HPC    #-
#-Q- HPC    NCDF_INC = /export/opt/netcdf/3.6.3/intel/medium/include
#-Q- HPC    NCDF_LIB = -L/export/opt/netcdf/3.6.3/intel/medium/lib -lnetcdf
#-Q- HPC    #-
```

## Vertical levels

Value of coefficients for vertical mesh:

```
zsur =   -8494.48000000000
za0  =    257.609000000000
za1  =    256.819000000000
zkth =    40.0000000000000
zacr =    10.0000000000000
```

Reference z-coordinate depths and scale factors:

| level | gdept | gdepw | e3t | e3w |
|---|---|---|---|---|
| 1 | 0.49 | 0.00 | 1.02 | 1.00 |
| 2 | 1.54 | 1.01 | 1.07 | 1.05 |
| 3 | 2.65 | 2.09 | 1.14 | 1.10 |
| 4 | 3.82 | 3.22 | 1.21 | 1.17 |
| 5 | 5.08 | 4.44 | 1.31 | 1.26 |
| 6 | 6.44 | 5.75 | 1.42 | 1.36 |
| 7 | 7.93 | 7.17 | 1.56 | 1.49 |
| 8 | 9.57 | 8.73 | 1.73 | 1.64 |
| 9 | 11.41 | 10.46 | 1.94 | 1.83 |
| 10 | 13.47 | 12.40 | 2.19 | 2.06 |
| 11 | 15.81 | 14.60 | 2.50 | 2.34 |
| 12 | 18.50 | 17.11 | 2.88 | 2.68 |

| | | | | |
|---|---|---|---|---|
| 13 | 21.60 | 19.99 | 3.34 | 3.10 |
| 14 | 25.21 | 23.33 | 3.90 | 3.61 |
| 15 | 29.44 | 27.24 | 4.59 | 4.23 |
| 16 | 34.43 | 31.84 | 5.42 | 4.98 |
| 17 | 40.34 | 37.26 | 6.43 | 5.90 |
| 18 | 47.37 | 43.70 | 7.67 | 7.02 |
| 19 | 55.76 | 51.38 | 9.16 | 8.38 |
| 20 | 65.81 | 60.56 | 10.98 | 10.03 |
| 21 | 77.85 | 71.56 | 13.18 | 12.03 |
| 22 | 92.33 | 84.76 | 15.85 | 14.45 |
| 23 | 109.73 | 100.63 | 19.06 | 17.38 |
| 24 | 130.67 | 119.71 | 22.93 | 20.91 |
| 25 | 155.85 | 142.68 | 27.58 | 25.15 |
| 26 | 186.13 | 170.29 | 33.14 | 30.23 |
| 27 | 222.48 | 203.47 | 39.75 | 36.30 |
| 28 | 266.04 | 243.28 | 47.59 | 43.51 |
| 29 | 318.13 | 290.93 | 56.83 | 52.03 |
| 30 | 380.21 | 347.82 | 67.62 | 62.02 |
| 31 | 453.94 | 415.51 | 80.13 | 73.65 |
| 32 | 541.09 | 495.72 | 94.49 | 87.07 |
| 33 | 643.57 | 590.29 | 110.79 | 102.40 |
| 34 | 763.33 | 701.17 | 129.07 | 119.68 |
| 35 | 902.34 | 830.31 | 149.26 | 138.93 |
| 36 | 1062.44 | 979.64 | 171.22 | 160.03 |
| 37 | 1245.29 | 1150.93 | 194.71 | 182.79 |
| 38 | 1452.25 | 1345.69 | 219.37 | 206.92 |
| 39 | 1684.28 | 1565.09 | 244.78 | 232.01 |
| 40 | 1941.89 | 1809.88 | 270.44 | 257.61 |
| 41 | 2225.08 | 2080.31 | 295.85 | 283.21 |
| 42 | 2533.34 | 2376.12 | 320.51 | 308.30 |
| 43 | 2865.70 | 2696.58 | 344.00 | 332.42 |
| 44 | 3220.82 | 3040.52 | 365.96 | 355.19 |
| 45 | 3597.03 | 3406.40 | 386.15 | 376.29 |
| 46 | 3992.48 | 3792.47 | 404.42 | 395.53 |
| 47 | 4405.22 | 4196.82 | 420.73 | 412.82 |
| 48 | 4833.29 | 4617.46 | 435.09 | 428.15 |
| 49 | 5274.78 | 5052.47 | 447.60 | 441.57 |
| 50 | 5727.92 | 5500.00 | 458.39 | 453.20 |