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Boundary Conditions in the Navy Coastal Ocean Model

Peter A. Rochford
Paul J. Martin

Oceanography Division

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14. ABSTRACT

The explicit treatment of boundary conditions (BCs) implemented in the Navy Coastal Ocean Model (NCOM) is described for the cases of lateral cyclic boundaries, the air-sea interface, and open lateral boundaries. Cyclic BCs can be specified to configure the NCOM for one-dimensional simulations within a vertical plane. The air-sea BCs permit surface focusing using atmospheric pressure, wind stress, surface fluxes for scalar fields (temperature, salinity), and penetrating solar irradiance. A relaxation of sea surface temperature (SST) and sea surface salinity (SSS) to observed or climate fields can also be applied. For the vertical mixing submodels, the surface roughness can be specified and the BC for the turbulent kinetic energy (TKE) can be either the value or flux of the TKE at the surface.

A variety of horizontal BCs at the open boundaries are available for the elevation, velocities, and scalar field at the open boundaries. A clamped on a Flather radiation condition can be applied to the elevation and normal depth-averaged velocity. Boundary conditions that can be used for the tangential depth-averaged velocity and baroclinic velocities include a zero gradient, Orlanski radiation, and advective BC. For scalar fields, BC options include prescribed values, Orlanski radiation, and an advective BC. Zero gradient BCs in the horizontal are implemented for the vertical velocity and vertical mixing variables.

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BOUNDARY CONDITIONS IN THE NAVY COASTAL OCEAN MODEL

1. INTRODUCTION

The Navy Coastal Ocean Model (NCOM) (Martin 2000) is an ocean general circulation model (OGCM) being developed as the ocean component of the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS). COAMPS is being developed for operational use by the Navy (Hodur 1997). In addition to being used as an ocean component of COAMPS, the NCOM can be used as a stand-alone OGCM for studies of ocean dynamics ranging from the littoral scale of coastal regions up to basin and global scales.

NCOM has a free surface and is based on the primitive equations and the hydrostatic, Boussinesq, and incompressible approximations. The model uses an Arakawa C grid and is leapfrog in time with an Asselin filter to suppress timesplitting. The propagation of surface waves and vertical diffusion are treated implicitly. A choice of the Mellor-Yamada Level 2 or Level 2.5 turbulence models is provided for the parameterization of vertical mixing. The horizontal grid is curvilinear. The vertical grid uses sigma coordinates for the upper layers and z-level (constant depth) coordinates for the lower layers, and the depth at which the model changes from sigma to z-level coordinates can be specified by the user. A source term in the model equations can be used to specify input of river and runoff inflows.

Boundary conditions (BCs) have been implemented in the NCOM to provide forcing at the surface and at lateral open boundaries. At the surface, the BCs that can be applied include surface atmospheric pressure and wind stress, penetrating solar radiation, and fluxes of scalar fields including heat and moisture fluxes for the temperature and salinity. Surface values of scalar fields can also be relaxed towards prescribed values. Local tidal forcing can be applied by specifying the horizontal gradient of the surface elevation due to the local tidal potential.

At lateral open boundaries, a variety of BCs can be used to specify the flow into and out of the model domain, to specify the values of scalar fields, to provide tidal forcing, and to allow for gravity wave transients and disturbances to propagate out of the region. Most of these BCs have been implemented as "tendencies" towards desired boundary values with time scales appropriate to the particular phenomena.

The NCOM also provides for the use of cyclic lateral BCs in either or both horizontal directions. Besides allowing for periodic domains, these BCs also allow the NCOM to be run as a two-dimensional (2-D) vertical section or as a one-dimensional (1-D) profile with variability only in the vertical, i.e., like a local mixed-layer model. The 2-D and 1-D capabilities are very useful for running test problems.

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In this report we document the BCs that have been implemented in NCOM version 1.5. Section 2 introduces some notation that will be used throughout the remainder of the report. Section 3 describes the cyclic BCs available and how to configure the NCOM for 1-D or 2-D simulations. Section 4 presents the surface forcing that can be applied at the air-sea interface with particular attention to the required physical units. Section 5 discusses the surface BC for the turbulence submodels. Section 6 explains the various possible BCs that can be applied along the NCOM open boundaries for the elevation, barotropic and baroclinic velocities, vertical velocities, scalar fields, and the vertical mixing variables. Section 7 discusses some pros and cons of the various BCs. Section 8 provides a short summary of the BCs.

Four appendices are included in this report to provide more detailed information on specific aspects of BCs in the NCOM. Appendix A provides a useful list of the many Fortran variable names used throughout the report. Appendix B presents details on the NCOM grid indexing scheme for open boundaries. Appendix C gives the advective BCs in finite difference form for each of the external boundaries (west, east, south, and north) for ease of comparison with the Fortran coding within the NCOM. Finally, Appendix D provides a glossary of acronyms used in this report.

2. NOTATION

The lateral grid dimensions in the NCOM are denoted by (n, m) where the first index refers to the x-direction and the second index to the y-direction. Domain decomposition has been implemented in the NCOM to make it computationally scalable on parallel computer architectures. This means the NCOM grid can be decomposed into subsections (tiles) so that computations on each subsection can be performed on a separate processor. Since each tile requires information from its adjacent neighbors to perform the finite difference computations, the implementation of domain decomposition requires that the tiles overlap each other by one or more grid points, i.e., have a boundary zone or halo one or more grid points wide around each tile. The method of domain decomposition is further described in Wallcraft and Moore (1997).

Throughout the remainder of this report we use Δt_i to represent the time step for the model (note that the NCOM currently uses the same timestep for the internal and external modes). The horizontal grid spacing at the mass points of the C-grid is denoted by Δx and Δy, and superscripts (e.g., $\Delta x^u, \Delta x^v$) are used to denote the corresponding grid spacing at the velocity points (c.f. Appendix B). D is the total ocean depth ($D = \zeta - H$), where ζ is the free surface deviation and $z = H$ is the depth of the ocean bottom. Superscripts (D^u, D^v) denote the corresponding values at the velocity points. Finite differences in variables X are denoted by $\delta_{2t}X$, $\delta_x X$, and $\delta_y X$ for the $2\Delta t$ time steps, Δx and Δy spacing, respectively.

To help the reader determine how to specify the various BCs, we frequently specify the corresponding Fortran variable name used in the NCOM. This is given in capital letters, usually within parentheses or brackets following the description of the associated quantity.

3. CYCLIC BC

Cyclic boundaries in the horizontal x and y directions are very useful for running test problems and performing process studies to investigate the response of simple ocean domains to idealized forcing. A common test problem is a periodic alongshore channel, which can be used to investigate processes occuring along an idealized section of coast.

The cyclic boundaries in the NCOM can also be used to perform 1-D simulations in the vertical or 2-D simulations within a vertical plane since the cyclic boundaries can maintain horizontal homogeneity in the direction of periodicity. Of course, in this mode of operation the NCOM will not be as efficient as a true 1-D or 2-D model; however, efficiency is usually not an important factor in 1-D and 2-D studies. One-dimensional simulations can be used to investigate surface or bottom mixed layer dynamics and the response of coupled bio-physical systems to vertical mixing and various surface forcings. Two-dimensional simulations can be used to look at, for example, the dynamics along a single section normal to a coast.

Cyclic boundaries in the lateral directions are specified via the INDCYC parameter (c.f. Appendix A). The allowed possible values are

INDCYC = 0 (default) which specifies no cyclic boundaries,

INDCYC = 4 for cyclic boundaries in the x-direction,

INDCYC = 5 for cyclic boundaries in the y-direction,

INDCYC = 6 for cyclic boundaries in both the x and y directions.

When performing 1-D or 2-D simulations, the grid dimension in the cyclic direction is set to one if the model is being run with low (i.e., 2nd-order) differencing, but must be set to two if any higher-order differencing is being used. The grid overlap required for performing model calculations in the cyclic direction is handled by the halos.

Note that previously a provision existed within the NCOM for applying cyclic boundaries without using halos. In this implementation of cyclic boundaries, three points at the beginning of the grid in the cyclic direction (points 1 to 3) were overlapped with three points at the end of the grid (e.g., points n-2 to n in the x-direction), and the minimum required number of grid points in the cyclic direction was four (to allow a 3-point overlap). The use of these cyclic boundaries was specified with INDCYC values from 1 to 3. However, the recent implementation of options for higher-order differences within the NCOM requires a larger overlap in the cyclic grid direction (5 points rather than 3). Hence, cyclic boundaries are currently only implemented via halos.

When cyclic boundaries are used, no open BCs need to be specified in the cyclic direction. Note that the halos are always updated as if cyclic boundaries are being used, even if they are not. In the case where closed or open lateral boundaries are being used, the boundary calculations are not affected by the halo values since the latter are not used in the calculations.

4. AIR-SEA BC

A variety of air-sea BC options are available in the NCOM to provide the user with some flexibility in specifying surface atmospheric forcing. Surface atmospheric forcing fields that can be specified include surface air pressure, surface wind stress, penetrating solar radiation, and surface fluxes of scalar variables such as heat and salt fluxes.

OGCMs frequently have difficulty providing accurate simulations of sea surface temperature (SST) and sea surface salinity (SSS) when driven only by externally prescribed fluxes since systematic errors in the fluxes or the OGCM will tend to cause the model SST and SSS to drift away from observed values. For this reason, the NCOM can also be forced by heat and freshwater fluxes calculated from a relaxation of the model SST and SSS to externally prescribed SST and SSS fields.

It is generally preferable to relax the model SST and SSS values to prescribed values by calculating a flux rather than by direct relaxation to the prescribed values since the relaxation rate in the latter case depends on the upper-layer thickness, which can vary significantly (e.g., over several orders of magnitude if sigma coordinates are being used). If the relaxation is done via a corrective flux, the rate of relaxation will be independent of the upper-layer thickness. Note that the two methods are formally equivalent.

The flux that results from relaxation to prescribed values can be used as the sole flux or can be added to the externally prescribed flux. The latter procedure is preferable since with this procedure the SST and SSS relaxation carries less of the burden of determining the entire surface flux. For the same reason, it is important that the externally prescribed fluxes be accurate, e.g., if the model and the prescribed fluxes were perfect, no correction of the model SST and SSS would be needed. It is especially important to provide fairly accurate estimates of the solar flux since a significant part of the solar flux penetrates below the ocean surface (which is why it is treated separately from the surface heat flux). The penetration of solar radiation can have a significant effect on the SST (Rochford et al. 2001), upper-ocean mixing, and the formation of the seasonal thermocline (Martin 1985).

The surface forcing desired is activated by setting the appropriate surface forcing options and parameters (c.f. Appendix A) and providing the appropriate surface fields. When the input flag INDSBC = 0, there is no surface atmospheric forcing and no surface atmospheric forcing fields need be supplied. This flag overrides the other surface atmospheric forcing flags. When INDSBC = 1, surface atmospheric forcing is applied and the various surface atmospheric fields can be individually selected via input flags.

Most of the flags for the individual surface forcing fields have three possible values: 0 if the forcing field is not applied to the ocean, 1 if the field is read from an input file, and 2 if the field is to be obtained from a coupled atmospheric model (this last option is not yet implemented). The input flags for the individual atmospheric forcing fields are atmospheric pressure P (INDATP), wind stress $\tau = (\tau_x, \tau_y)$ (INDTAU), surface fluxes for temperature T (INDSFT) and salinity S (INDSFS), and surface solar irradiance IR (INDSOL). Note that each of these surface forcing fields must be provided to the NCOM on an A-grid configuration.

There is an additional input flag for the solar radiation field (INDCLD) to denote whether the input field is actually solar radiation or some representation of the amount of cloud cover. The option for cloud cover input is not currently implemented.

The NCOM currently assumes that the surface albedo is accounted for in the input solar radiation, i.e., the input solar radiation is the net solar radiation absorbed by the ocean and does not include the part of the solar radation that is reflected back into the atmosphere.

The depth of penetration of solar radiation into the ocean is governed by two input flags: INDEXT provides for penetration of solar radiation if set to 1 and does not if set to 0, and INDTYPE is used to select a solar extinction profile. Values of INDTYPE from 1 to 5 correspond to Jerlov seawater optical types I, IA, IB, II, and III (Jerlov 1968, Mobley 1994). These optical types range from fairly clear water found in the the central ocean gyres (type I) to fairly turbid water (type III). Note that these input parameters allow only a single seawater turbidity type within the domain. However, solar extinction within the NCOM is stored at the upper interface of each grid cell in a 3-D array (EXT), which is defined in subroutine SOLEXT. Hence, spatially and time varying solar extinction could easily be implemented (Rochford et al. 2001).

The surface wind stress, solar radiation, and scalar (heat and salt) surface fluxes are defined as positive downward. That is, a positive value of τ indicates a surface stress acting to drive the surface current in the positive x or y direction, and a positive value of the solar or surface heat flux will act to warm the surface layer of the ocean. Note that this is the reverse of the convention used by the Princeton Ocean Model (POM), where the surface heat fluxes are defined to be positive upward.

All surface forcing fields must be supplied in dynamical units, i.e., the units of the associated physical quantity being forced. The surface atmospheric pressure is expressed in terms of meters of water. Note that only the horizontal gradient of P drives the ocean, i.e., the mean value of P has no effect. For a surface pressure given in mb, it is suggested that the pressure in dynamical units P' be calculated as

$$P' = (P - 1000) \times 100/(g\rho_0), \tag{1}$$

where g is the gravitational acceleration and ρ_0 the density of seawater. Note that an atmospheric pressure of $1\,\mathrm{mb} = 100\,\mathrm{N m^{-2}} = 100\,\mathrm{kg\,m^{-1}\,s^{-2}}$ corresponds to a surface elevation of about 1 cm.

For wind stress, the units are $\mathrm{m^2 s^{-2}}$. This is obtained from the standard definition of wind stress via

$$u_*^2 = \tau/\rho_0, \tag{2}$$

where the quantity u_* is referred to as the surface friction velocity.

The dynamical units of the surface fluxes for scalar fields ($R_* u_*$) are (scalar units) $\mathrm{m\,s^{-1}}$. For the particular case of surface heat and salt fluxes, they are $^\circ\mathrm{C\,m\,s^{-1}}$ and $\mathrm{psu\,m\,s^{-1}}$, respectively. The temperature flux ($T_* u_*$) is obtained from

$$T_* u_* = Q/(\rho_0 C_p), \tag{3}$$

where Q is the net surface heat flux (the sum of the shortwave and longwave radiation and latent and sensible heat fluxes) and C_p is the specific heat capacity of seawater. The salinity flux ($S_* u_*$) is obtained from the excess moisture flux of evaporation over precipitation ($E - P$) multiplied by the surface salinity S_0

$$S_* u_* = S_0(E - P)/\rho_0. \tag{4}$$

The temporal variability of the externally provided surface forcing fields must be the same for P', u_*^2, $T_* u_*$, and $S_* u_*$. This requires time interpolation or frequency subsampling when using fields of different temporal variability within this group. Prescribed SST and SSS values can be input with different temporal variability. For real-time forcing, the elapsed time of the model run is used internally within the NCOM for the time interpolation of the surface field to the model time step. For climate forcing, the time is computed relative to the climate period (CLIMATP = 365 days).

The option to relax the model SST and SSS to specified values (T_s and S_s, respectively) is selected by setting the corresponding input flag (INDSST or INDSSS) equal to 1 if the SST and SSS are input with the same temporal variability. If SSS is input with a temporal variability different from that used for SST, INDSSS is set equal to 2. The corrective surface fluxes for the relaxation are calculated as

$$T_* u_* = \lambda_T (T_0 - T_s), \tag{5}$$

$$S_* u_* = \lambda_S (S_0 - S_s), \tag{6}$$

where λ_T (RLAXSST) and λ_S (RLAXSSS) are the rate of relaxation of the model SST and SSS in meters per day ($\mathrm{m\,d^{-1}}$), respectively. If prescribed fluxes and relaxation are both being used, the two sets of fluxes are added together.

The surface atmospheric forcing fields are defined within subroutine OSURFBC and are linearly interpolated in time from the prescribed values.

5. SURFACE ROUGHNESS AND TKE

The surface roughness and the surface value or flux of turbulent kinetic energy (TKE) can be specified for the turbulence submodels. The surface roughness in the NCOM is the effective vertical mixing length at the surface of the ocean due to wave action. The surface roughness is currently used in the turbulence models to provide a surface BC for the vertical turbulent mixing length.

The surface roughness is stored in a 2-D array and can be specified at each horizontal model grid point. Integer flag INDSURF is used to specify the method to be used to determine the surface roughess. For INDSURF = 0 the surface roughness is set to zero and for INDSURF = 2 the surface roughness z_0 is estimated from the surface wind stress (friction velocity) using the Charnock relation

$$z_0 = c_h u_*^2 / g, \tag{7}$$

where c_h is the Charnock constant (CHARNOK). The value INDSURF = 1 is to provide for 2-D fields of surface roughness to be read from an input file, the idea being to use data from a wave model or a wave height analysis. This option is not currently provided, but could be implemented by a user.

The Mellor-Yamada Level 2.5 turbulence model (Mellor and Yamada 1974, 1982) also requires a surface value of TKE or a value of the surface TKE flux as discussed by Craig and Banner (1994). Integer flag INDTKES is used to select which BC is used. For INDTKES = 1, the surface value of TKE is calculated from the surface friction velocity as $b_1^{2/3} u_*^2$, where b_1 is a constant used to scale the dissipation of TKE. For INDTKES = 2, the surface flux of TKE is estimated from the friction velocity as $100\, u_*^3$.

6. OPEN BC

Most applications of an OGCM to an ocean basin or a coastal region require that the OGCM use information along the open boundaries of the model domain to achieve a realistic simulation of the local ocean dynamics. This information may be provided by larger-scale OGCMs, climatologies, and larger grids within the OGCM if it is nested.

The NCOM in its current configuration can be run using open boundary condition data from the following sources: no open boundaries (INDOBC = 0), i.e., a rigid wall along the exterior boundary of the grid; initial values used at boundary points for all time (INDOBC = 1), i.e., static open BCs; boundary data from an input file (INDOBC = 2) with data either temporally varying or static; and boundary data from the coarser grid in which it is nested in the case of a nested grid (INDOBC = 3). Note that cyclic boundaries are not included in the grid points considered to define the open boundaries.

It is important for an OGCM to be able to accommodate external information at its open boundaries such as surface elevation, velocities and transports, values of scalar fields, and tides. The velocities and transports at the boundaries must be consistent with the density field. The OGCM must also be able to radiate interior waves out of the model domain with minimal consequences on the OGCM simulation. A variety of open BCs have been implemented in the NCOM based on findings from other modelers that have demonstrated good performance in fulfilling these criteria.

Open BCs are specified via the OPENBC subroutine of the NCOM. Boundary conditions have been implemented for the elevation, barotropic normal and tangential velocity, baroclinic normal and tangential velocity, vertical velocity, scalar fields (e.g., temperature and salinity), and vertical mixing variables. These are each described in turn below. Note that some of the BCs work better than others. Some pros and cons of the BC are discussed in this section and in Section 7. The Fortran variable names for the various fields can be found in Appendix A.

6.1 Elevation and Normal Barotropic Velocity

Two BCs are provided for dealing with the surface elevation and normal barotropic velocity at the open boundaries: clamped (INDOBE = 1) and Flather (INDOBE = 2). These BCs involve both the surface elevation and the normal barotropic velocity at the boundary; hence, the BC for these two fields are discussed together.

6.1.1 Calculation of the Free-Surface Mode

To understand how the elevation and barotropic BCs influence the model solution, a brief explanation of the free-surface mode calculation is warranted. In the NCOM, the free surface is calculated implicitly where the surface pressure gradients in the momentum equations and the divergence terms in the surface elevation equation have a component at the new time level $(n+1)$ being calculated. The finite difference equations for the free-surface mode are (Martin 2000)

$$\frac{\Delta x^u \Delta y^u}{2\Delta t}\delta_{2t}(D^u\overline{u}) = -\Delta y^u D^u g \delta_x(\alpha_1\zeta^{n+1} + \alpha_2\zeta^n + \alpha_3\zeta^{n-1}) + D^u\overline{G_u}, \tag{8}$$

$$\frac{\Delta x^v \Delta y^v}{2\Delta t}\delta_{2t}(D^v\overline{v}) = -\Delta x^v D^v g \delta_y(\alpha_1\zeta^{n+1} + \alpha_2\zeta^n + \alpha_3\zeta^{n-1}) + D^v\overline{G_v}, \tag{9}$$

$$\begin{aligned}\frac{\Delta x \Delta y}{2\Delta t}\delta_{2t}\zeta = &-\delta_x(\Delta y^u(\beta_1(D^u\overline{u})^{n+1} + \beta_2(D^u\overline{u})^n + \beta_3(D^u\overline{u})^{n-1})) \\ &- \delta_y(\Delta x^v(\beta_1(D^v\overline{v})^{n+1} + \beta_2(D^v\overline{v})^n + \beta_3(D^v\overline{v})^{n-1})) + \Delta x \Delta y D\overline{Q},\end{aligned} \tag{10}$$

where $(\overline{u}, \overline{v})$ are the depth averaged velocities. The $D^u\overline{G_u}$ and $D^v\overline{G_v}$ are the vertical integrals of all the forcing terms of the equations for the baroclinic velocity u and v, respectively, except for the surface elevation gradient terms, and $D^u = \overline{D}^x$ and $D^v = \overline{D}^y$. $\overline{Q}$ is the depth-averaged mass flux source term. The α_i (β_i) specify the fractional weighting of the surface elevation gradient in the momentum equations (divergence terms in the depth-averaged continuity equation) at the new ($i = 1$), current ($i = 2$), and previous ($i = 3$) time levels. See Section 3.6 of Martin (2000) for further details.

The equations for the free-surface mode are solved by substituting the expressions for $(D^u\overline{u})^{n+1}$ and $(D^v\overline{v})^{n+1}$ from Eqs. (8) and (9) into Eq. (10) and solving for the new surface elevation ζ^{n+1}. The resulting equation is an elliptic equation for ζ^{n+1}, which can be solved with an iterative or a direct method (NCOM currently uses an iterative solver).

The free surface mode is solved such that the baroclinic velocities, barotropic transports, and elevation are self-consistent with respect to each other. This is accomplished via the following calculation sequence:

1. Advection velocities and horizontal eddy coefficients needed for momentum, new densities, and new baroclinic pressure gradients are calculated.
2. New 3-D horizontal velocities are calculated and the forcing terms from the 3-D momentum equations are vertically integrated to provide the forcing terms needed for the depth-averaged momentum equations that are used to calculate the free-surface mode.
3. The depth-averaged momentum and continuity equations are solved for the new surface elevation and depth-averaged velocities.
4. The new 3-D velocity fields calculated in Step 2 are corrected by adding a depth-independent adjustment, so that their vertical mean agrees with the new depth-averaged velocities calculated in Step 3. This effectively corrects the 3-D velocities for the new surface elevation gradient.
5. The velocity field that will be used to advect the scalar fields is calculated by adding a depth-independent adjustment to the 3-D velocity fields at time level n, so that the depth-averaged advection velocities are consistent with the depth-averaged continuity equation.
6. An Asselin filter is applied to the velocity and surface elevation fields. The filtered 3-D velocities are then corrected to be consistent with the filtered depth-averaged velocities using the same procedure as in Step 4.

The adjustment of the advection velocities in Step 5 ensures that the velocity field used to advect the scalar fields is numerically nondivergent. This is necessary to avoid spurious sources and sinks when using the flux form of numerical advection.

6.1.2 Clamped BC

With a clamped BC (INDOBE = 1) the boundary condition used for the free surface mode of the model is the specified surface elevation at the boundary. This BC is generally used only when tidal forcing is the sole forcing both at the boundary and within the model domain. The reason for this restriction is that surface waves generated by other forcing within the model domain will reflect from the boundary back into the interior when a clamped BC is used. These reflections can severely or catastrophically degrade the model solution in the interior of the domain.

Transient surface waves generated as the tidal cycle spins up will also reflect at the boundary. These transient waves will eventually dissipate due to internal damping, mainly from bottom friction. The time required for the transient waves to die away and for the model solution to settle down to a repeating tidal cycle will depend on the bottom depth and the magnitude of the bottom friction, and can range from a day or two for a shallow coastal region to a couple of months for a large basin.

With a clamped BC the normal baroclinic velocity at the boundary is calculated by the model; hence, data for this field at the boundary are not needed. Note that tidal simulations with a clamped BC can provide a means for calculating the tidal velocities at the boundary that are needed for using the Flather radiation BC.

6.1.3 Flather BC

With the Flather BC (INDOBE = 2), the BC is on the normal barotropic transport ($V_n = \overline{v}_n D$, where $\overline{v}_n$ is the depth-averaged normal velocity) rather than the elevation (Flather and Proctor 1983). The advantage of the Flather BC over the clamped BC is that the Flather BC allows barotropic disturbances within the model domain to propagate out through the boundaries (i.e., radiate) rather than reflect back into the interior. The disadvantage is that values of both the surface elevation and the normal barotropic transport are needed for implementation. The normal barotropic transport for the Flather BC is calculated within the NCOM as

$$V_n = V_n^{circ} + V_n^{tide} + C_{bt}(\eta - \eta^{circ} - \eta^{tide}), \tag{11}$$

where V_n^{circ} and η^{circ} are the prescribed normal barotropic transport and elevation at the boundary for the ocean circulation, V_n^{tide} and η^{tide} are the normal barotropic transport and elevation for the prescribed tidal forcing, C_{bt} is the surface wave speed

$$C_{bt} = \sqrt{gD}, \tag{12}$$

and η is the NCOM elevation at the first interior point next to the boundary.

The Flather BC is quite flexible because it allows both tidal and circulation transports to be specified at the boundary, while at the same time allowing barotropic disturbances to propagate out. It can sometimes be used to relax V_n^{circ} and η^{circ} to interior values in the case where values of V_n^{circ} and η^{circ} are unavailable. We note that the Flather radiation condition has also been applied in other OGCMs (Oey and Chen 1992a-b; Rochford and Shulman 2000).

6.2 Tangential Barotropic Velocity

The BCs for the tangential barotropic velocity are formulated in terms of the tangential barotropic transport ($V_t = \overline{v}_t D$ where $\overline{v}_t$ is the depth-averaged tangential velocity). There are three BCs provided for the tangential barotropic velocity: a zero gradient (INDOBVB = 1), an Orlanski radiation condition (INDOBVB = 2), and an advective BC (INDOBVB = 3).

6.2.1 Zero Gradient BC

When a zero gradient condition is applied (INDOBVB = 1) the tangential barotropic transport at the open boundary is set equal to the value at the first interior point next to the boundary, i.e., the field is set to have a zero gradient in the direction normal to the boundary. This is a simple BC, but it frequently works fairly well.

6.2.2 Orlanski Radiation BC

For the Orlanski radiation BC option (INDOBVB = 2), the NCOM uses an Orlanski radiation BC for outward propagating barotropic disturbances and relaxation to an externally prescribed value for inflowing disturbances. The radiation condition introduced by Orlanski (1976) (see also Miller and Thorpe (1981)) is a variation of the Sommerfeld radiation condition. For the tangential barotropic transport the equation for the Orlanski radiation condition is

$$\frac{\partial V_t}{\partial t} + c\frac{\partial V_t}{\partial x_n} = 0, \tag{13}$$

where the phase speed c is calculated for the variable V_t at each boundary point and x_n is the coordinate normal to the boundary with increasing value in the inflow direction. Note that the phase speed is defined to be negative for inflow ($c < 0$) and positive for outflow ($c \geq 0$).

The Orlanski radiation condition is implemented in the NCOM using a leapfrog temporal formulation as

$$V_t(B, N+1) = \frac{1}{(1+a)}\left[(1-a)\,V_t(B, N-1) + 2a\,V_t(B-1, N)\right], \tag{14}$$

where B denotes the grid point location of the boundary, $B-1$ denotes the first interior grid point location from the boundary, N denotes the time level, and a is given by

$$a = \max[0, \min[1, c\Delta t/\Delta x]], \tag{15}$$

where

$$\frac{c\Delta t}{\Delta x} = \frac{V_t(B-1, N-1) - V_t(B-1, N+1)}{V_t(B-1, N+1) + V_t(B-1, N-1) - 2V_t(B-2, N)}, \tag{16}$$

and requires values of V_t at the three time levels $N-1$, N, and $N+1$.

The Orlanski radiation BC is only used for an outward propagating signal ($c \geq 0$). The relaxation in the case of an inward propagating signal ($c < 0$) is governed by

$$\frac{\partial V_t}{\partial t} = \lambda_V \left(V_t^{circ} + V_t^{tide} - V_t\right), \tag{17}$$

where V_t^{circ} is the prescribed tangential barotropic velocity for the ocean circulation, V_t^{tide} is the prescribed tidal contribution, and λ_V^{-1} is the time scale of relaxation for V_t [RLXOBVB = $(\lambda_V \Delta t_i)^{-1}$].

6.2.3 Advective BC

An alternative approach to the Orlanski radiation BC is to apply one-way external forcing using an advective BC (INDOBVB = 3) for the tangential barotropic transports (Rochford and Shulman 2000). This is a forward, upwind, two-time-level scheme where the advection term is lagged (i.e., is at the central time level). Here the externally specified tangential barotropic transport is advected into the model domain in the case of inflow, and the internal tangential barotropic transport is advected to the open boundary in the case of outflow. Note that we define $\overline{v}_n \geq 0$ for inflow and $\overline{v}_n < 0$ for outflow where $\overline{v}_n$ is the depth-averaged normal velocity. This leads to a BC of the form

$$\frac{\partial V_t}{\partial t} + \overline{v}_n \frac{\partial V_t}{\partial x_n} = 0, \tag{18}$$

where

$$\frac{\partial V_t}{\partial x_n} = \begin{cases} (V_t - V_{ob})/\Delta x_n & \overline{v}_n \geq 0 \text{ (inflow)} \\ (V_i - V_t)/\Delta x_n & \overline{v}_n < 0 \text{ (outflow)}, \end{cases} \tag{19}$$

with V_i the tangential barotropic transport at the first grid point inside the open boundary $[V_t(B-1,N)]$, V_{ob} the tangential barotropic transport provided at the open boundary, and Δx_n the grid spacing in the direction normal to the boundary.

The advective BC is implemented in the NCOM using a leapfrog temporal formulation

$$V_t(B,N+1) = V_t(B,N) - \frac{\Delta t_i}{2\Delta x_n}\{(c+|c|)[V_t(B,N) - V_{ob}(B,N)] + (c-|c|)[V_i(B,N) - V_t(B,N)]\}, \tag{20}$$

$$c = \frac{V_n(B,N)}{\max(\epsilon, D(B,N))}, \tag{21}$$

where Δt_i is the model time step and $\epsilon = 10^{-8}$ is included to avoid division by zero. Further details on Eq. (19) can be found in Appendix C.

6.3 Normal Baroclinic Velocity

Four BCs are provided for the normal baroclinic velocities: use the value calculated internally by the model (INDOBU = 1), use an Orlanski radiation condition (INDOBU = 2), combine an upwind horizontal advection to the value calculated by the model (INDOBU = 3), and use an advective-radiative BC (INDOBU = 4).

Note that all baroclinic model velocities, including the values at the boundaries, are adusted at each timestep at each horizontal point by a constant value such that the depth-averaged value agrees with the depth-averaged velocity computed for the barotropic mode (c.f. Section 6.1.1). This means barotropic signals (e.g., tidal signals) will be incorporated into the baroclinic velocities at the open boundary points even though they are not explicitly accounted for when setting the baroclinic velocities at the boundary points.

6.3.1 Internal Model Calculated Value for BC

The NCOM always calculates a value for the normal baroclinic velocity at the open boundary points using the same calculation as for the interior velocity points, except that the advection and horizontal mixing terms are omitted (because all the quantities needed to calculate these terms in the manner of the other interior points are not available at the open boundary points).

When INDOBU = 1, this internally calculated value of the normal baroclinic velocity is taken as the boundary value. Note that this BC works fairly well, but is usually improved if horizontal advection is included (i.e., for INDOBU = 3).

6.3.2 Orlanski Radiation BC

For INDOBU = 2, an Orlanski radiation condition is used to set the normal baroclinic velocity at the open boundary points for outward propagating disturbances, and a relaxation to an externally prescribed value is used for inward propagating disturbances. These BCs are calculated in similar fashion to those for the tangential barotropic velocity. The time scale for relaxation to the externally prescribed normal baroclinic velocity is specified by the input parameter RLXOBV.

6.3.3 Internal Model Calculated Velocity plus Advection BC

For INDOBU = 3, the normal baroclinic velocity calculated internally by the model at the open boundary points is modified by adding to it a change due to advection. An upwind advection term normal to the boundary is applied that uses the interior model normal velocity when advection is outward and the prescribed normal velocity when the advection is inward. The equation describing the advection is

$$\frac{\partial v_n}{\partial t} + v_n \frac{\partial v_n}{\partial x_n} = 0, \tag{22}$$

where the normal gradient of the velocity is calculated as

$$\frac{\partial v_n}{\partial x_n} = \begin{cases} (v_n - v_{ob})/\Delta x_n & v_n \geq 0 \text{ (inflow)} \\ (v_i - v_n)/\Delta x_n & v_n < 0 \text{ (outflow)}, \end{cases} \tag{23}$$

where v_i is the baroclinic velocity at one grid point inside the open boundary $[v_t(B-1,N)]$, and v_{ob} is the specified (external or coarse grid) value at the open boundary.

This advective BC is implemented using a leapfrog scheme that is identical in form to that used for the tangential barotropic transports

$$\begin{aligned} v_t(B,N+1) = v_t(B,N) - \frac{\Delta t_i}{2\Delta x_n}\{&(c+|c|)[v_t(B,N) - v_{ob}(B,N)] + \\ &(c-|c|)[v_i(B,N) - v_t(B,N)]\}, \end{aligned} \tag{24}$$

where in this case $c = v_n(B,N)$, and Δt_i is the internal time step. Further details on Eq. (23) are found in Appendix C.

6.3.4 Advective-Radiative BC

A radiative variation of the advective BC has been found to work quite well in the POM when applied to the normal baroclinic velocity (Rochford and Shulman 2000). To compare NCOM simulations with those from the POM, this same BC has been included as an option in the NCOM (INDOBU = 4). The radiational BC is applied to the normal baroclinic velocity v_n as

$$\frac{\partial v_n}{\partial t} - C_{bc} \frac{\partial v_n}{\partial x_n} = 0, \tag{25}$$

where C_{bc} is the phase speed for outward radiation of the normal velocity, and the normal coordinate is positive in the direction of inflow. While it is possible to implement an implicit algorithm to evaluate the phase speed, a value for C_{bc} is explicitly prescribed for computational efficiency. This requires that the user specify C_{bc} in units of $\mathrm{m\,s^{-1}}$ via the cgwb(ib,2) variable in subroutine OPENBC. We note that the PWC POM of CoBALT uses $C_{bc} = 0.005\,(gD)^{1/2}$ (Rochford and Shulman 2000). The optimal choice for C_{bc} must be determined through numerical tests. To reduce the development of noise, a Hanning filter is applied afterwards to v_n parallel to the boundary

$$v_n(B, N+1) = (1-\lambda_1)\left[v_n(B,N) + C_{bc}\frac{\partial v_n(B,N)}{\partial x_n}\right] + \lambda_1 v_{ob} \tag{26}$$

$$v_n(B-1, N+1) = (1-\lambda_2)\,v_n(B-1,N) + \lambda_2 v_{ob}, \tag{27}$$

with $\lambda_1 = 0.1$ and $\lambda_2 = 0.05$. The normal derivative is given by Eq. (23) and acquires the same finite difference form as given in Eq. (24).

6.4 Tangential Baroclinic Velocity

The open BCs available for the tangential baroclinic velocities are zero gradient (INDOBV = 1), Orlanski radiation (INDOBV = 2), and advective (INDOBV = 3).

6.4.1 Zero Gradient BC

The zero gradient BC for the tangential baroclinic velocity (INDOBV = 1) is applied in similar fashion to the zero gradient BC for the tangential barotropic velocity. The values at the boundary are set equal to the values of the tangential baroclinic velocity just inside the boundary. This simple BC frequently works fairly well.

6.4.2 Orlanski Radiation BC

The Orlanski radiation BC for the tangential baroclinic velocity (INDOBV = 2) is applied in the same way as the Orlanski radiation condition for the tangential barotropic velocity. A discussion of this BC will therefore not be repeated here.

6.4.3 Advective BC

The advective BC for the tangential baroclinic velocity v_t (INDOBV = 3) uses a forward, upwind, two-time-level finite differencing scheme. The equation is

$$\frac{\partial v_t}{\partial t} + v_n \frac{\partial v_t}{\partial x_n} = 0. \tag{28}$$

The normal gradient of the tangential baroclinic velocity is given here by

$$\frac{\partial v_t}{\partial x_n} = \begin{cases} (v_t - v_{ob})/\Delta x_n & v_n \geq 0 \text{ (inflow)} \\ (v_i - v_t)/\Delta x_n & v_n < 0 \text{ (outflow)}, \end{cases} \tag{29}$$

where v_i is the baroclinic velocity at one grid point inside the open boundary $[v_{t,n}(B-1,N)]$, and v_{ob} is the specified (external or coarse grid) value at the open boundary. This BC is implemented in the same manner as for the tangential barotropic transport and normal baroclinic velocity

$$v_t(B,N+1) = v_t(B,N) - \frac{\Delta t_i}{2\Delta x_n}\{(c+|c|)[v_t(B,N) - v_{ob}(B,N)] + (c-|c|)[v_i(B,N) - v_t(B,N)]\}, \quad (30)$$

with the difference that here $c = v_n(B,N)$ and Δt_i is the internal time step.

6.5 Vertical Velocity

A zero gradient BC in the horizontal is applied to the vertical velocity w along all open boundaries, i.e.,

$$\frac{\partial w}{\partial x_n} = 0, \quad (31)$$

where x_n is in the direction normal to the open boundary. With this BC, the vertical velocity at a boundary point is set equal to the value at the adjacent interior grid point.

6.6 Scalar Fields

Four BCs are provided for the scalar (e.g., temperature and salinity) fields: the externally prescribed values are put directly on the boundary (INDOBR = 1), Orlanski radiation (INDOBR = 2), horizontal advection (INDOBR = 3), and full advection (INDOBR = 4).

6.6.1 Prescribed Values

With this BC (INDOBR = 1), the externally prescribed values of the scalar fields are placed directly on the boundary. This direct specification of the boundary values tends, in general, to be reflective, i.e., not radiative. This BC is used when performing two-way nesting when values of the scalar fields are fed back from the nested grid to the main grid. In this case, the solutions on the nested grid and on the main grid are closely coupled and the direct placement of the values of the scalar fields from the main grid onto the boundary of the nest helps to maintain the close coupling. Hence, a radiative BC is not required.

6.6.2 Orlanski Radiation BC

With this open BC (INDOBR = 2), scalars r are relaxed to an externally prescribed value for inflow and an Orlanski radiation condition is applied for outflow. The relevant equation in the case of inflow is

$$\frac{\partial r}{\partial t} = \lambda_r \left(r_{ob} - r\right),$$

where r_{ob} is the prescribed scalar field at the open boundary, and λ_r^{-1} is the corresponding time scale of relaxation [RLXOBR = $(\lambda_r \Delta t_i)^{-1}$]. For outflow, the radiation condition applied is

$$\frac{\partial r}{\partial t} + c\frac{\partial r}{\partial x_n} = 0,$$

where the phase speed c is calculated for each scalar field r, and x_n is the coordinate normal to the boundary with increasing value in the inflow direction.

The relaxation condition in the case of inflow is implemented using a leapfrog temporal formulation as

$$r(B,N+1) = r(B,N) + 2\lambda_r \left[r_{ob} - r(B,N)\right]. \tag{32}$$

For outflow, the Orlanski radiation condition for scalars is implemented as given by Eqs. (14) to (16) with V_t replaced by r. An Asselin temporal filter is applied after the boundary value is updated to prevent time splitting with the leapfrog temporal integration scheme.

6.6.3 Advective BC

A horizontal advective BC is applied to the scalars at the open boundaries that is forward in time (2 time level) and upwind as implemented for the barotropic and baroclinic transports (INDOBR = 3)

$$\frac{\partial r}{\partial t} + v_n \frac{\partial r}{\partial x_n} = 0. \tag{33}$$

The normal gradients of the scalars are given here by

$$\frac{\partial r}{\partial x_n} = \begin{cases} (r - r_{ob})/\Delta x_n & v_n \geq 0 \text{ (inflow)} \\ (r_i - r)/\Delta x_n & v_n < 0 \text{ (outflow)}, \end{cases} \tag{34}$$

where r_i is the scalar at one grid point inside the open boundary $[r(B-1,N)]$, and r_{ob} is the prescribed (external or coarse grid) value at the open boundary. For scalars, this BC is implemented in the NCOM as

$$r(B,N+1) = \begin{cases} r(B,N) - (c\Delta t_i/\Delta x_n)\left[r(B,N) - r_{ob}(B,N)\right] & c \geq 0 \text{ (inflow)} \\ r(B,N) - (c\Delta t_i/\Delta x_n)\left[r_i(B,N) - r(B,N)\right] & c < 0 \text{ (outflow)}, \end{cases} \tag{35}$$

with $c = v_n(B,N)$. To prevent time splitting with the leapfrog temporal integration scheme, an Asselin temporal filter is applied after the boundary value is updated.

6.6.4 Advective BC with Vertical Advection

In some situations, such as with internal wave propagation, or strong upwelling or downwelling along the open boundaries, it may be desirable to include the effect of vertical advection as well as horizontal advection on the boundary values of the scalar fields. The equation for vertical advection of a scalar field at the boundary is

$$\frac{\partial r}{\partial t} + w \frac{\partial r}{\partial z} = 0, \tag{36}$$

where w is the vertical velocity (positive value upwards). Such an option is available in the NCOM (INDOBR = 4) as a forward in time (2 time level), centered scheme that is applied after the scalars have been updated for the horizontal BC (r')

$$r(B,N+1,k) = r'(B,N,k) + c\left[r(B,N,k+1) - r(B,N,k-1)\right] \tag{37}$$

$$c = -\frac{\Delta t_i}{2}\left[\frac{w(B,N,k) + w(B,N,k+1)}{\Delta z_k + \Delta z_{k+1}}\right]. \tag{38}$$

Here k denotes the vertical level and $\Delta z_k = zw_k - zw_{k+1}$ is the distance between the top of levels k and $k+1$. As in the case with no vertical advection, an Asselin temporal filter is applied after the boundary value is updated (c.f. Section 6.6.3).

6.7 Vertical Mixing Variables

A zero gradient BC is applied to the turbulent length scale (l) and the vertical eddy coefficients for momentum (k_m) and scalars (k_h) as in Section 6.5. When the Mellor-Yamada level 2.5 scheme is used (INDZK = 3), this BC is also applied to twice the turbulent kinetic energy (q^2) and its product with the turbulence length scale l.

6.8 Tidal Forcing

The NCOM provides the option of superimposing tidal forcing along the open boundaries on any boundary data that are used (INDTIDE ≥ 1). This option is typically used for cases where tidal forcing is important but is not included in the boundary data, or where some particular tidal constituents are desired but are not included in the boundary data. The default option is no tidal forcing beyond that implicitly included in the boundary fields (INDTIDE $= 0$).

Tidal forcing is prescribed at the boundary via an input file that specifies the particular tidal constituents ($n = 1, \ldots, n_{tc}$) for which data are being provided and the amplitude and phase of the fields for each of the tidal constituents. The fields presently included are the elevation and the normal and tangential barotropic transport (velocity times depth).

The total elevation and barotropic transports due to the tides are calculated as the sum of the values of the individual constituents, i.e.,

$$\eta^{tide} = \sum_{n=1}^{n_{tc}} \eta_n^{tc} \cos(\omega_n^{tc} t - \theta_n^{tc}), \tag{39}$$

$$V_n^{tide} = \sum_{n=1}^{n_{tc}} U_n^{tc} \cos(\omega_n^{tc} t - \phi_n^{tcn}), \tag{40}$$

$$V_t^{tide} = \sum_{n=1}^{n_{tc}} V_t^{tc} \cos(\omega_n^{tc} t - \phi_t^{tct}), \tag{41}$$

where ω_n^{tc} is the frequency of a tidal constituent in units of Hz and t is the elapsed model time in seconds. The tidal velocity transport variables $(U_n^{tc}, V_n^{tc}, \phi_n^{tcn}, \phi_n^{tct})$ are only used if the Flather radiation BC is applied for the elevation. They are not used when the elevation is clamped along the open boundary. These latter two BCs are described next.

The input tidal data should consist of the equilibrium tidal amplitudes and phases. The amplitude and phase correction for the individual tidal constituents, which depends on the location and time of year, will be calculated by the NCOM (in subroutine TIDE_FAC) based on the longitude and latitude of the domain and the initial date (IDATE) and time (ITIME) of the simulation.

Note that rotation of the tidal velocity data to adjust them to the local orientation of the model grid is not just a simple rotation since both the amplitudes and phases of the velocities have to be taken into account.

The tides in the ocean are forced by the local tidal potential, which is due to astronomical forces. For small coastal domains of less than 100 to 200 km in horizontal extent, the effect of the local tidal potential on a simulation of the tides is generally very small and is usually neglected, i.e., the forcing of the tide at the lateral boundary of the domain is sufficient. However, the tidal potential forcing becomes increasingly important as the size and depth of the domain is increased, and may need to be accounted for in larger domains.

The tidal potential forcing enters the model in the momentum equations as the horizontal derivative of the equilibrium surface elevation corresponding to the tidal potential for a particular tidal constituent (this is the same way that the surface atmospheric pressure is implemented). NCOM provides a variable (EP) for the total tidal potential, a subroutine (TIDEPOT) to calculate EP, and a logical flag (TIDPOT) to turn the tidal potential forcing on or off. However, subroutine TIDEPOT is currently only acting as a placeholder for the tidal potential calculation, i.e., it currently just returns a value of zero for EP. In order to implement the tidal potential within the NCOM, subroutine TIDEPOT must be modified to calculate the tidal potential corresponding to the tidal constituents being used. Note that the tidal potential for a given tidal constituent is a function of the location and time.

7. DISCUSSION

As noted previously, some BCs work better than others. Some of the BCs in the NCOM have been implemented for certain specific applications, or for testing and comparison purposes, and may not be good BCs for general use. Here we provide some discussion of the pros and cons of the various BCs and some recommendations.

7.1 Air-Sea BC

The NCOM provides for forcing by the surface atmospheric pressure gradient. This forcing tends to be less important than the wind stress and fluxes of temperature and salinity for driving the ocean. For this reason it is frequently not accounted for in ocean modeling. However, the effect of atmospheric pressure is not negligible and can be important in certain situations, e.g., surface pressure differences across straits can force significant flows through the straits.

The surface wind stress is of prime importance in driving the ocean and accurate wind stresses are needed to get accurate predictions of ocean currents and mixing. Obtaining accurate wind stresses can be a problem and this is especially true in coastal areas where available wind stress data may not be adequate to describe the true temporal and spatial variability.

For scalar fields, both surface fluxes and surface values can be prescribed. Using prescribed fluxes alone tends to cause drift of the model near-surface values over time due to errors in the fluxes and in the model itself. The drift can occur quite rapidly, especially for the temperature in shallow coastal areas, which can heat or cool quickly. Without feedback of the local SST to the surface heat flux, a prescribed heat flux cannot respond to the changing SST the way that it should and unrealistic SST values can develop within days or even hours.

Using relaxation of scalar fields to prescribed surface values alone may also be undesirable since this forces the relaxation to carry the full burden of computing the surface flux. Under such circumstances a short relaxation time scale will be needed to keep the model values close to the prescribed values. A better approach is to provide the best estimates of the surface fluxes that are available while simultaneously relaxing to prescribed values. With this combination of forcing, if the fluxes are reasonably accurate, only a moderate rate of relaxation to the prescribed values should be needed to keep the model surface values on track. It is especially important to prescribe accurate solar radiation since solar heat penetrates into the sea and this penetration significantly affects upper ocean heating and mixing and the development of the seasonal thermocline.

An alternative for calculating surface fluxes is to use the model SST and SSS along with prescribed surface marine parameters such as wind speed, cloud cover, humidity, and air temperature and pressure to calculate the fluxes via bulk aerodynamic formulas (Rochford et al. 2000, Kara et al. 2000). The surface marine parameters can be obtained from atmospheric model forecasts in the same way as the air-sea fluxes themselves. The advantage of this approach is it allows a feedback from the ocean SST in the heat flux calculation while at the same time allowing for a reasonably accurate air-sea temperature difference to occur. This method will tend to force the model SST to within 1 to 3 °C of the prescribed air temperature (Rochford et al. 2000), which in turn, will reflect the SST that was used for the atmospheric model prediction.

Another alternative is to use two-way coupling between the ocean model and an atmospheric model so that proper air-sea feedbacks between the two models will occur automatically. This, of course, is an objective of the current work with NCOM. Such two-way coupling between atmospheric and ocean models, however, has a number of issues of its own (Codron et al. 2000).

7.2 Open BC

For the surface elevation and normal barotropic transport, the Flather radiation condition is the most flexible BC to use. This BC allows specification of the general circulation and tidal forcing at the open boundary and allows disturbances within the domain to radiate out. The clamped BC for surface elevation is generally only useful for tidal forcing because it reflects outward propagating disturbances back into the interior, which can disrupt the solution. Even for tidal forcing, use of a clamped BC requires a longer time for the tidal solution to settle down to a steady tidal cycle than when using the Flather BC. This is because of the time required to dissipate transient tidal signals generated during the spinup and reflected at the boundary by the clamped BC.

The advantage of the clamped BC for forcing tides is that the normal velocity at the boundary is not needed, i.e., the BC is on the elevation and the normal velocity is calculated by the model. Because of this, the clamped BC can be used to calculate tidal velocities at the boundary, which can then be used in a more general simulation with the Flather BC. This procedure is useful since tidal velocity data from an external source tends to be less reliable than tidal elevation data.

For the tangential barotropic velocity, the simple zero gradient BC usually works fairly well. The Orlanski radiation BC would be a second choice. The advective BC tends to respond too slowly to changes at the boundary since the advective time scale is much slower than the speed of barotropic signals.

For the normal baroclinic velocity, the model calculated value works well, and is generally improved by the addition of the upwind advection calculation.

For the tangential baroclinic velocity, as for the tangential barotropic velocity, the zero gradient BC seems to work well and the Orlanski radiation BC would be a second choice.

For scalar fields, the Orlanski radiation condition seems to work best.

8. SUMMARY

We have described here how BCs have been implemented in the NCOM for cyclic boundaries, the air-sea interface, and along open boundaries. We have included some explanation of the surface BCs for the turbulence submodels, and have discussed the pros and cons of the various BCs available for the air-sea and open boundaries. The variety of formulations that can be applied for the latter gives NCOM users a great deal of flexibility in tailoring this OGCM to their available forcing functions and particular ocean applications. These can range from one-dimensional modeling studies with cyclic BCs and surface forcing of high temporal resolution through to basin-scale and regional coastal models forced by operational meteorology products from weather forecast centers and open BCs from global ocean models. We hope that this report will be valuable to meteorologists and oceanographers when configuring the NCOM for their particular ocean applications.

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Appendix A

FORTRAN SYMBOLS

The Fortran variable names used in the NCOM that are cited within this report are listed below for ease of reference.

A1. Physical Options

The mixing scheme used in the NCOM simulation determines whether open BCs will also be applied to the turbulent kinetic energy (TKE) and its product with the turbulence length scale.

INDZK	type of vertical mixing to be used: =1 constant values (zkmmin, zkhmin), =2 Mellor-Yamada level 2 scheme, =3 Mellor-Yamada level 2.5 scheme, =4 Mellor-Yamada level 2.5 scheme with option for Craig and Banner (1994) treatment of surface TKE flux and length scale.

A2. Numerical Options and Parameters

The method that is applied to solve for the free surface mode affects how the BCs are applied for the elevation and barotropic transport.

INDBARO	method of solution used for free surface mode: =1 full explicit, the model is run with a single (very small) explicit timestep, =2 semi-implicit, =3 split-explicit (not currently implemented).
ASF	Asselin filter coefficient for temporal filtering
EG1, EG2	temporal weights for surface elevation gradient in the barotropic momentum equations at the new and central time levels.

A3. Surface Forcing Options and Parameters

Surface forcing is applied according to the options set below. When INDSBC = 0, all the surface flux arrays are set to zero and there is no surface forcing. It overides all other surface forcing flags. When INDSBC = 1, surface forcing is provided as specified by the other surface forcing flags.

INDSBC	flag to turn on or off all surface forcing: =0 no surface forcing, =1 surface forcing.
INDATP	surface atmospheric pressure forcing: =0 no forcing is applied, =1 provided from input data file, =2 provided from coupled atmospheric model.
INDTAU	surface wind stress forcing: =0 no forcing is applied, =1 provided from input data file, =2 provided from coupled atmospheric model.
INDSFT	temperature surface flux: =0 no forcing is applied, =1 provided from input data file, =2 provided from coupled atmospheric model.
INDSFS	salinity surface flux: =0 no forcing is applied, =1 provided from input data file, =2 provided from coupled atmospheric model.
INDSOL	solar radiation flux: =0 no forcing is applied, =1 provided from input data file, =2 provided from coupled atmospheric model.
INDSST	sea surface temperature (SST) relaxed to specified value via a correction to surface flux with rate defined by RLAXSST (defined below): =0 SST relaxation is not used, =1 SST relaxation is used.
INDSSS	sea surface salinity (SSS) relaxed to specified value via correction to surface flux with rate defined by RLAXSSS (defined below): =0 SSS relaxation is not used, =1 SSS relaxation is used, =2 SSS relaxation is used with input file separate from SST input file.
RLAXSST	rate of relaxation of SST to specified value in meters/day.
RLAXSSS	rate of relaxation of SSS to specified value in meters/day.

A4. Lateral Boundary Options

Listed below are the various options for applying conditions for fields along lateral cyclic and open boundaries.

INDCYC	flag to denote periodic (cyclic) boundaries: =0 no cyclic boundaries, =4 cyclic in x, =5 cyclic y, =6 cyclic in x and y.
INDOBC	flag to denote source of open boundary condition data:

	=0 no open boundaries, all open boundary points are set to land, =1 use initial values at boundary points for all time, =2 use boundary data from input file, =3 use boundary data from grid in which nested.
INDOBE	open boundary conditions for surface elevation: =1 clamped (elevation specified), =2 Flather radiation condition.
INDOBR	open boundary condition for scalar fields (T and S): =1 specified (not implemented), =2 Orlanski radiation for outgoing and relaxation to specified value for incoming, =3 horizontal advective boundary condition, =4 full 3D advective boundary condition.
INDOBU	open boundary condition for normal baroclinic velocity: =1 calculated by the model ignoring advection and horizontal mixing, =2 Orlanski radiation for outgoing and relaxation to specified value for incoming, =3 model calculated as in (1) plus upwind horizontal advection, =4 advective boundary condition.
INDOBV	open boundary condition for tangential baroclinic velocity: =1 zero gradient, i.e., set the same as the interior value, =2 Orlanski radiation for outgoing and relaxation to specified value for incoming, =3 advective boundary condition.
INDOBVB	open boundary condition for depth-averaged tangential velocity: =1 zero gradient, i.e., set the same as the interior value, =2 Orlanski radiation condition for outgoing and relaxation to specified value for incoming, =3 advective boundary condition.
INDTIDE	include specified tidal forcing at open boundaries: =0 no tides, > 0 tides.

A5. Lateral Boundary Parameters

These are the time scales used to relax to specified values when the signal is incoming for the Orlanski radiation boundary condition. They are specified as an e-folding time in model timesteps. Note that this has the disadvantage that the results will be dependent upon the time step if the values are not changed when the timestep is changed.

RLXOBVB	relaxation time scale/Δt_i for depth-averaged velocity.
RLXOBV	relaxation time scale/Δt_i for baroclinic velocity.
RLXOBR	relaxation time scale/Δt_i for scalar fields.

A6. Lateral Boundary Fields

These are the variable names used to contain the various fields along the lateral boundaries. Note that the velocities are defined in terms of whether they are normal or tangential to the boundary. For example, the zonal baroclinic component u is normal at the W and E edges (v_n) and tangential at the N and S edges (v_t).

EOB	elevation at lateral boundaries.
ROB	scalars at lateral boundaries.
UBOB	barotropic transport normal to lateral boundaries. For the E–W boundaries it is U and for the N–S boundaries it is V.
VBOB	barotropic transport tangential to lateral boundaries. For the E–W boundaries it is V and for the N–S boundaries it is U.
UOB	baroclinic velocity normal to lateral boundaries. For the E–W boundaries it is u and for the N–S boundaries it is v.
VOB	baroclinic velocity tangential to lateral boundaries. For the E–W boundaries it is v and for the N–S boundaries it is u.
EOB	elevation values at lateral boundaries.

A7. References

Craig, P.D. and M.L. Banner, 1994: Modeling wave-enhanced turbulence in the ocean surface layer. *J. Phys. Oceanogr.* **24**, 2546–59.

Appendix B

GRID INDEXING FOR OPEN BCS

The indexing to identify the locations of boundary grid points in the NCOM must be robust enough to handle open boundaries, nesting of grids, domain decomposition of the grid into tiles for parallel computations, and model domains with changing land points. To accommodate these possibilities, the open boundary points are identified according to a depth (or land-sea) mask (H) and an array (IEC) denoting whether the edge of a particular tile is an exterior edge of the model domain (IEC = 1) or an interior edge that abuts a neighboring tile (IEC = 0). Cyclic boundaries (identified by INDCYC) are not included in the setting of open boundary points as a matter of course.

The open boundary points are indexed in a sequential manner (NOBPT $= 1, 2, \ldots,$ NOB) for the west (W), east (E), south (S), and north (N) boundaries as indicated in Fig. B1. Indexing starts in the lower left (SW) corner and proceeds up the left (W) edge to the (NW) corner. Indexing then continues from the lower right (SE) corner and proceeds up the right (E) edge to the (NE) corner. Next it is along the bottom (S) edge from the lower left (SW) corner to the lower right (SE) corner, and finally along the top (N) edge from the upper left (NW) corner to the upper right (NE) corner. The index limits for the open boundary points at each of the WESN edges are stored in separate 2×4 arrays for the elevation (NEOB), the normal velocity (NUOB), and the tangent velocity (NVOB). Using elevation as an example, the index limits for each of the edges are stored as indicated in Table B1.

Table B1 — Index Limits for Elevation Points

Edge	Index Start	Index End
W	NEOB(1,1)	NEOB(2,1)
E	NEOB(1,2)	NEOB(2,2)
S	NEOB(1,3)	NEOB(2,3)
N	NEOB(1,4)	NEOB(2,4)

To illustrate the indexing scheme we present in Table B2 the index limits for the scalars and velocities for the domain used in the California Current System (CCS) model of the Coupled Biophysical-Dynamics Across the Littoral Transition (CoBALT) project. The latter domain has a completely open western boundary, a completely closed eastern boundary, and partially open southern and northern boundaries. On the 163×229 domain grid, the number of open scalar grid points is n = 229, 0, 162, and 79, for the WESN edges, respectively. For u and v along the W boundary, the numbers of points are 227 and 228, respectively, because the u(1,1), u(1,m), and v(1,1) corner points are not used (c.f. Table B3). The length of the edge is defined as $L = \text{NEOB}(2,*) - \text{NEOB}(1,*) + 1$. Note that the model program assigns the E boundary an end index value that is less than the starting index to suppress loop iteration, thereby simplifying coding. For the scalar boundary points, the corner points are always included with the W and E boundary segments and not with the N and S boundary segments.

Table B2 — Index Limits for CCS Lateral Boundaries

	NEOB			NUOB			NVOB		
Edge	Start	End	L	Start	End	L	Start	End	L
W	1	229	229	2	228	227	1	228	228
E	0	-1	0	0	-1	0	0	-1	0
S	230	390	161	230	390	161	229	389	161
N	391	468	78	391	468	78	390	467	78

The index value NOBPT contained within the ranges $\text{NEOB}(1,*) \leq \text{NOBPT} \leq \text{NEOB}(2,*)$ provides the pointer to the grid location (I, J) of the elevation boundary point via I = IOB(NOBPT) and J = JOB(NOBPT), with the same being true for the normal velocity points using NUOB. The indexing logic is the same for NVOB except the grid locations are given via I = IVOB(NOBPT) and J = JVOB(NOBPT). For each elevation boundary point, the associated adjacent interior grid point (IOBI, JOBI) is identified as well as its direction relative to the boundary point. The grid locations for the boundary points of the tangent velocity are stored in separate arrays (IVOB, JVOB) because of the separate indexing used for the tangent velocities. As an example, we provide in Table B3 the (I, J) grid locations for the CCS lateral boundary limits given in Table B2.

Table B3 — Grid Locations (I, J) of CCS Lateral Boundary Limits

	NEOB		NUOB		NVOB	
Edge	Start	End	Start	End	Start	End
W	(1,1)	(1,229)	(1,2)	(1,228)	(1,2)	(1,229)
E	...	...	...	...	...	...
S	(2,1)	(162,1)	(2,1)	(162,1)	(2,1)	(162,1)
N	(2,229)	(79,229)	(2,229)	(79,229)	(2,229)	(79,229)

The indexing scheme used for the open boundary data in the NCOM may or may not seem particularly intuitive. It was chosen to save time and storage for cases where open boundary points occur on only a small part of the external model boundary. Subroutine OBCPTS in the NCOM sets up the locations and indexes of the boundary points when a simulation is started (based on the model bathymetry) and can also be used to define the boundary points when setting up the input boundary data for a simulation. Using OBCPTS to define the open boundary points and performing interpolations in terms of the location (latitude, longitude, and depth) of the boundary points can reduce the work involved in setting up the open boundary data.

For parallel processing, the NCOM requires that the overall horizontal grid dimensions be an integral multiple of the number of tiles used in the respective coordinate direction. Hence, in order to increase the flexibility in setting the model domain size, the open boundaries can be inset from the edge of the grid. Input parameter IBO specifies the number of grid points that the boundary is inset from the edge of the grid along each side (i.e., the W, E, S, and N sides) of the domain. If the boundary is on the edge of the grid, IBO is set equal to zero. For the grid illustrated in Fig. B1, the open boundaries are at the edge of the grid, i.e., at n1 = 1 and n2 = n, m1 = 1, and m2 = m.

```
                                   (4)
                                  ---->
                                  NORTH
                  1     2     3                n-2   n-1    n
        NW     1     2     3                 n-2   n-1   n         NE
          +-------------------------------------------------------+
          |   NU  B  B                                   B  B     |
          |    v  v  v                                   v  v     |
       m  | B> u* e  u  e  u  e  .  .  .  .  u  e  u  e  u  e  <B |  m
          |    |     |     |                 |     |     |        |
  m       | B> +--v--+--v--+--v--   .     .  +--v--+--v--+--v- <B |      m
          |    |     | ....|.................|.....|....  |        |
      m-1 |    u* e  u :e  u  e  .  .  .  .  u  e  u  e: u  e     | m-1
          |    |     | :   |                 |     |   : |        |
 m-1      |    +--v--+--v--+--v--   .     .  +--v--+--v--+--v-    |     m-1
          |    |     | :   |                 |     |   : |        |
      m-2 |    u* e  u :e  u  e  .  .  .  .  u  e  u  e: u  e     | m-2
          |    |     | :   |                 |     |   : |        |
 m-2      |    +--v--+--v--+--v--   .     .  +--v--+--v--+--v-    |     m-2
     _    |            :                               :          |    _
    / \ W |       .  . :.  .  .  .  .  .  .  .  .  .  .:  .  .     | E / \
     |  E |            :         Interior              :          | A  |
 (1) |  S |       .    :.    .     .     .     .    .:    .     | S  | (2)
     |  T |            :                               :          | T  |
          |    |     | :   |                 |     |   : |        |
        3 |    u* e  u :e  u  e  .  .  .  .  u  e  u  e: u  e     | 3
          |    |     | :   |                 |     |   : |        |
    3     |    +--v--+--v--+--v--   .     .  +--v--+--v--+--v-    |      3
          |    |     | :   |                 |     |   : |        |
        2 |    u* e  u :e  u  e  .  .  .  .  u  e  u  e: u  e     | 2
          |    |     | ....|.................|.....|....  |        |
    2     | B> +--v--+--v--+--v--   .     .  +--v--+--v--+--v- <B |      2
          |    |     |     |                 |     |     |        |
        1 | B> u* e  u  e  u  e  .  .  .  .  u  e  u  e  u  e  <B | 1
          |    |     |     |                 |     |     |        |
    1     |NU> +--v*-+--v*-+--v*-   .     .  +--v*-+--v*-+--v* <NU|      1
          |    ^  ^  ^                                   ^  ^     |
          |   NU  B  B                                   B  B     |
          +-------------------------------------------------------+
        SW     1     2     3                 n-2   n-1   n         SE
                  1     2     3                n-2   n-1    n
                                  SOUTH
                                  ---->
                                   (3)
```

Fig. B1 — Indexing used for the NCOM open boundaries. Here e denotes the elevation, u and v the velocity components, B the open boundary, and NU the grid points not used in the NCOM.

Appendix C

FINITE DIFFERENCE ADVECTIVE BC EQUATIONS

To make it easier for the user to understand the coding of the advective BCs, we present here the advective BC equations for each of the WESN boundaries in finite difference form for the specific case of the tangential barotropic transport. All equations originate from

$$\frac{\partial V_t}{\partial t} = -v_n \frac{\partial V_t}{\partial x_n}, \tag{C1}$$

where x_n is the coordinate normal to the boundary having increasing value in the inflow direction, and inflow (outflow) is the direction into (out of) the model domain. The normal derivative of the tangential component is given by

$$\frac{\partial V_t}{\partial x_n} = \begin{cases} (V_t - V_{ob})/\Delta x_n & V_n \geq 0 \text{ (inflow)} \\ (V_i - V_t)/\Delta x_n & V_n < 0 \text{ (outflow).} \end{cases} \tag{C2}$$

This differential equation has the finite difference form

$$\begin{aligned} V_t(B, N+1) = V_t(B, N) - \frac{\Delta t_i}{2\Delta x_n}[(c + |c|)[V_t(B,N) - V_{ob}(B,N)] + \\ (c - |c|)[V_i(B,N) - V_t(B,N)]\}, \end{aligned} \tag{C3}$$

$$c = \frac{v_n(B,N)}{\max(\epsilon, D(B,N))}, \tag{C4}$$

where Δt_i is the model time step, Δx_n is the grid spacing in the normal direction, and ϵ is a small constant to avoid division by zero. The definition of V_n in Eq. (C2) and V_i in Eqs. (C2) and (C3) differs for each of the WESN boundaries.

C1. Western Boundary

Figure C1 shows the relevant variables for the western boundary. For this boundary, the variables are

$$V_n = \frac{1}{2}\left[\mathrm{U(ivob+1, jvob-1) + U(ivob+1, jvob)}\right] \tag{C5}$$

$$V_t = \mathrm{V(ivob, jvob)} \tag{C6}$$

$$V_i = \mathrm{V(ivob+1, jvob)} \tag{C7}$$

$$\Delta x_n = \Delta x. \tag{C8}$$

For this case the normal coordinate is $x_n = x$ and yields for the normal derivative

$$\frac{\partial V_t}{\partial x_n} = \begin{cases} (V_t - V_{ob})/\Delta x & V_n \geq 0 \text{ (inflow)} \\ (V_i - V_t)/\Delta x & V_n < 0 \text{ (outflow).} \end{cases} \tag{C9}$$

Note the open boundary lies along the normal velocity points, and that the tangential velocities in Fig. C1 therefore actually lie between the boundary value (B) and the interior value (In).

Out	B	In	
	|		$\rightarrow$ inflow
$\times$	$\times$	$\times$	
	|		$\leftarrow$ outflow
V_{ob}	V_t	V_i	

Fig. C1 — Tangential barotropic transports at the western boundary of the NCOM domain. The boundary is denoted by B. The region to the left (Out) is outside the NCOM domain while the region to the right (In) is inside. The direction of inflow/outflow is indicated by the arrows.

C2. Eastern Boundary

Figure C2 shows the relevant variables for the eastern boundary. For this boundary, the variables are

$$V_n = -\frac{1}{2}\left[\text{U(ivob, jvob} - 1) + \text{U(ivob, jvob)}\right] \tag{C10}$$

$$V_t = \text{V(ivob, jvob)} \tag{C11}$$

$$V_i = \text{V(ivob} - 1\text{, jvob)} \tag{C12}$$

$$\Delta x_n = \Delta x. \tag{C13}$$

Here the normal coordinate is $x_n = -x$ and yields the same expression for $\partial V_t/\partial x_n$ as in the case of the western boundary.

In	B	Out	
	|		$\leftarrow$ inflow
$\times$	$\times$	$\times$	
	|		$\rightarrow$ outflow
V_i	V_t	V_{ob}	

Fig. C2 — Same as in Fig. C1, but for the eastern boundary

C3. Southern Boundary

Figure C3 shows the relevant variables for the southern boundary. For this boundary, the variables are

$$V_n = \frac{1}{2}\left[\text{V(ivob} - 1\text{, jvob} + 1) + \text{V(ivob, jvob} + 1)\right] \tag{C14}$$

$$V_t = \text{U(ivob, jvob)} \tag{C15}$$

$$V_i = \text{U(ivob, jvob} + 1) \tag{C16}$$

$$\Delta x_n = \Delta y. \tag{C17}$$

In		$\times$		V_i	$\uparrow$ inflow
	—	$\times$	—	V_t	
Out		$\times$		V_{ob}	$\downarrow$ outflow

Fig. C3 — Same as in Fig. C1, but for the southern boundary

C4. Northern Boundary

Figure C4 shows the relevant variables for the northern boundary. For this boundary, the variables are

$$V_n = -\frac{1}{2}\left[\mathrm{V(ivob-1,jvob)} + \mathrm{V(ivob,jvob)}\right] \tag{C18}$$

$$V_t = \mathrm{U(ivob,jvob)} \tag{C19}$$

$$V_i = \mathrm{U(ivob,jvob-1)} \tag{C20}$$

$$\Delta x_n = \Delta y. \tag{C21}$$

Out		$\times$		V_{ob}	$\downarrow$ inflow
	—	$\times$	—	V_t	
In		$\times$		V_i	$\uparrow$ outflow

Fig. C4 — Same as in Fig. C1, but for the northern boundary

Appendix D

GLOSSARY

The acronyms appearing throughout this report are listed below for ease of reference.

pseudo 1D	one-dimensional in the vertical
pseudo 2D	two-dimensional vertical plane
BC	boundary condition
CCS	California Current System
COAMPS	Coupled Ocean-Atmosphere Mesoscale Prediction System
CoBALT	Coupled Biophysical-Dynamics Across the Littoral Transition
Fortran	Formula translator
IR	surface solar IRradiance
NCOM	Navy Coastal Ocean Model
OGCM	Ocean General Circulation Model
PWC	Pacific West Coast
POM	Princeton Ocean Model
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TKE	Turbulent Kinetic Energy