Specification for Test Models of Ice Shelf Cavities

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1 Introduction

This document describes ice shelf cavities, designed as test-beds for existing hydrodynamic models (e.g. ones described by Grosfeld et al. (1997); Jenkins and Holland (2002); Pereira et al. (2002); and one based on the Princeton Ocean Model of Blumberg and Mellor (1987)). It is proposed that several model cavities will ultimately be defined, with nomenclatures like '*G.NN*', where '*G*' defines a specific geometry, and '*NN*' defines specific realisations of the model of each cavity.

Two geometries are currently defined: Geometry 1, based closely on 'Experiment 1' of Grosfeld et al. (1997) and Geometry 2, which is similar to Geometry 1 but with the region of flat ice shelf changed to open ocean. Geometry has one realisation (Model 1.01) and Geometry 2 has two (Models 2.01 and 2.02). Physical constants prescribed below have generally been selected (somewhat arbitrarily) from Grosfeld et al. (1997) and Holland and Jenkins (1999).

It should be noted that it may not be possible for all models to adhere exactly to the following specifications. In such cases, modellers are asked to provide details of such differences.

2 Specification of Model 1.*NN*

2.1 Geometry

The geometry of models 1.*NN* is identical to that of 'Experiment 1' of Grosfeld et al. (1997). It is a closed rectangular basin of **uniform depth 900 m**, spanning **15° of longitude**, and **latitudes 80° South** to **70° South**. The whole basin is covered with an ice shelf, with the ice draft rising linearly from **700 m at 80° South to 200 m at 76° South**, and remaining constant at **200 m from 76° South to 70° South**. The geometry is uniform in the east-west direction and is shown in Figures 1 and 2. This geometry, which involves no open-sea region, obviates any numerical problems associated with a steep ice front (although future cavities will probably include an ice front as a more stringent test of the models).

Additional constants, related to the geometry, are defined in Table 1.

Description	Value
Radius of the Earth (assumed spherical)	6371020 m
Sidereal day (used in calculation of Coriolis parameter)	86164.1 s

Table 1: Constants associated with the geometry.

The model should be run in **spherical coordinates**, with **the Coriolis parameter varying as the sine of the latitude**.

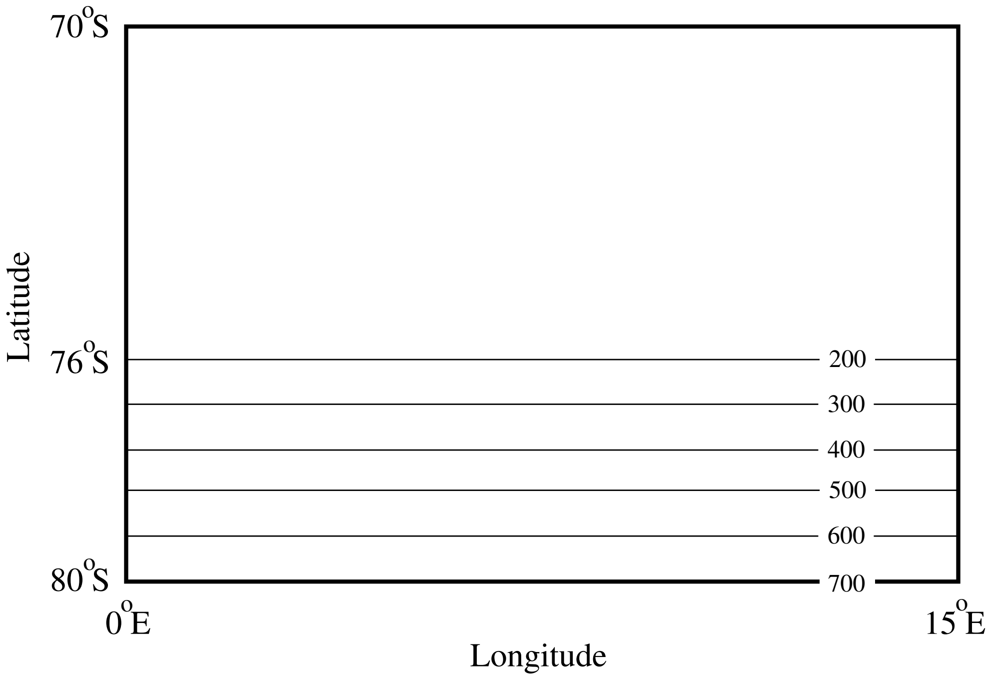

Figure 1: Plan of model basin for Geometry 1, showing ice draft contours (m). The span of longitude is 15°; the absolute values of longitude are arbitrary.

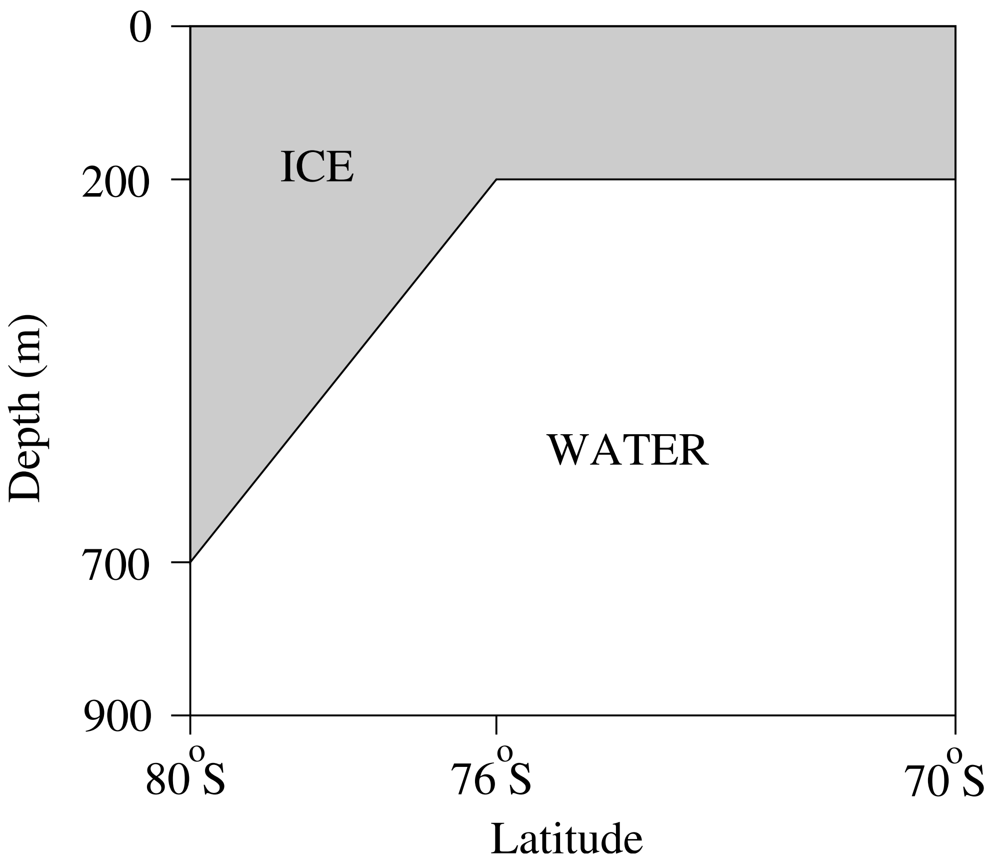

Figure 2: Elevation view of model basin for Geometry 1.

2.2 Model 1.01

2.2.1 Introduction

This model closely resembles that of Grosfeld et al. (1997). It is forced only by melting and refreezing underneath the ice shelf.

2.2.2 Initial Conditions

The water is initially at rest and with **potential temperature -1.9° C** and **salinity 34.4 PSU**.

2.2.3 Mixing Coefficients

Under stably stratified conditions, constant horizontal mixing coefficients are employed as shown in Table 2. If the water column becomes unstable a convective adjustment scheme is required, in which case it is recommended that the enhanced coefficients shown in Table 2 are used. Otherwise, the modeller should indicate the method of convective adjustment used.

Description	Value (m^2s^{-1})	
	Stable	Unstable
Horizontal eddy viscosity	600	600
Horizontal eddy diffusivity	100	100
Vertical eddy viscosity	0.001	0.1
Vertical eddy diffusivity	0.00005	0.005

Table 2: Mixing coefficients.

2.2.4 Recommended Spatial and Temporal Resolution, and Run Time

The dependence of accuracy on grid sizes and time steps will vary from model to model. However, recommended values are shown in Table 3.

Description	Value
Grid increment in longitude	0.3°
Grid increment in latitude	0.1°
Number of vertical layers	≥ 10
Distribution of vertical layers	preferably more concentrated in upper and lower boundary layers
Time step	as appropriate to the model
Run time	30 years, but preferably to approximately steady state

Table 3: Recommended spatial and temporal resolutions, and run time.

2.2.5 Boundary Conditions at Sea Bed

At the sea bed, the bottom stress is described by the quadratic bottom friction law:

$$\mathbf{B} = -\rho C_D \mathbf{u}_B |\mathbf{u}| \tag{1}$$

where

B is the bottom stress,

ρ is the water density,

C_D is a drag coefficient (prescribed as **0.0025**), and

$\mathbf{u}_B$ is the water velocity in the model cell adjacent to the sea bed.

2.2.6 Boundary Conditions at Ice/Water Interface

At the ice/water interface, the interfacial stress is described by the quadratic law:

$$\mathbf{S} = -\rho C_I \mathbf{u}_I |\mathbf{u}| \tag{2}$$

where

S is the interfacial stress,

C_I is a drag coefficient (prescribed as **0.0025**), and

$\mathbf{u}_I$ is the water velocity in the model cell adjacent to the ice/water interface.

The heat flux at the interface is described by:

$$Q = \rho C_p \gamma (T_I - T_f) \tag{3}$$

where

Q is the upward heat flux,

C_p is the specific heat of water (prescribed as $\mathbf{3974\ J\ kg^{-1}\ K^{-1}}$),

γ is an exchange velocity (prescribed as $\mathbf{0.0001\ m\ s^{-1}}$),

T_I is the thermodynamic temperature of the model cell adjacent to the ice/water interface, and

T_f is the in-situ freezing point of seawater at that pressure (in units of thermodynamic temperature).

It is assumed that no heat is diffused into the ice shelf, so that the rate of production of fresh water is given by:

$$q = \frac{Q}{\rho L} \tag{4}$$

where

q is the rate of production of fresh water, and

L is the latent heat of fusion (prescribed as **334000 J kg^{-1}**).

The model is assumed to conserve volume, so that the effect of producing fresh water at a rate q is simulated by an upward flux of salt given by:

$$s = \frac{\rho q S_0}{1000} \tag{5}$$

where

s is the rate of addition of salt (kg m^{-2} s^{-}1), and

S_0 is a constant reference salinity (prescribed as **34.4 PSU**).

Equations (3), (4) and (5) give:

$$s = \frac{Q S_0}{1000L} = \frac{\rho C_p \gamma (T_I - T_f) S_0}{1000L} \tag{6}$$

The use of a constant reference salinity (S_0), rather than the local salinity, ensures that the salt and heat fluxes are exactly proportional (by the constant factor $S_0/(1000L)$), so that the solution for a closed basin may tend to a steady state in both salinity and temperature.

2.2.7 The Reference Level and the Reference Density

The **potential temperature** and **potential density** should be defined **relative to 0 m** (see Figure 2).

Boussinesq models require the specification of a reference density. Where this is required, it should be prescribed as **1030 kg m^{-3}** (i.e. approximately the in-situ density of water at -1.9° C, 34.4 PSU and depth 550 m).

3 Specification of Model 2.*NN*

3.1 Geometry

The geometry of models 2.*NN* is similar to that of models 1.*NN* (i.e. 'Experiment 1' of Grosfeld et al. (1997)) but with the 200-metre deep section of ice shelf replaced by open water. It is a closed rectangular basin of **uniform depth 900 m**, spanning **15° of longitude**, and **latitudes 80° South** to **70° South**. The ice draft rising linearly from **700 m at 80° South to 200 m at 76° South**, with open water **from 76° South to 70° South**. The geometry is uniform in the east-west direction and is shown in Figures 3 and 4. This geometry includes a steep ice front which provides a test of the pressure-gradient problems often associated with sigma-coordinate models.

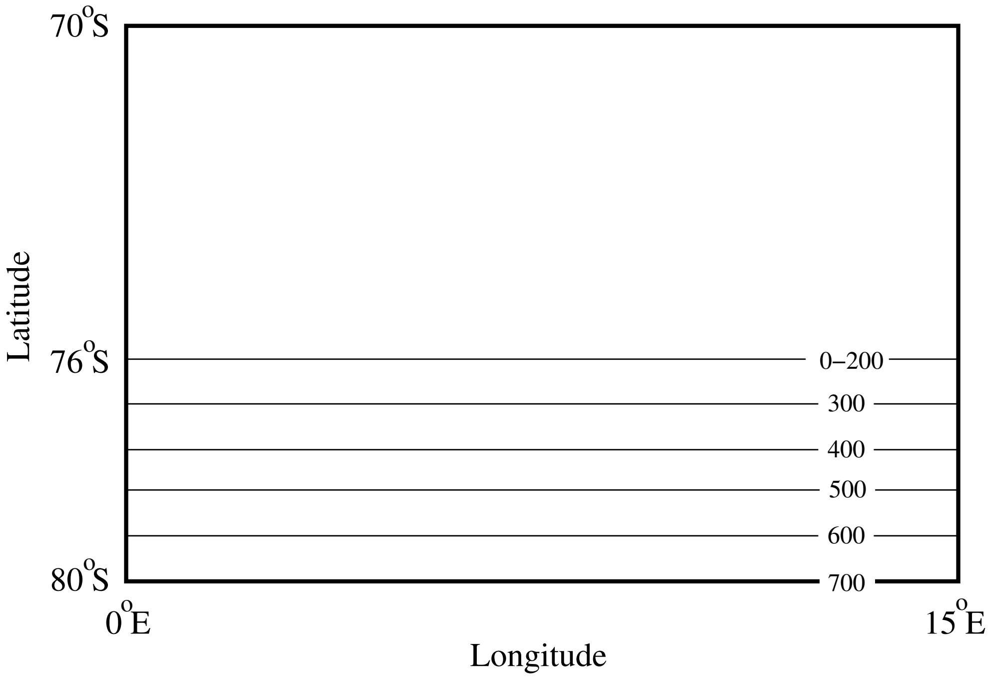

Figure 3: Plan of model basin for Geometry 2, showing ice draft contours (m). The span of longitude is 15°; the absolute values of longitude are arbitrary.

Additional constants, related to the geometry, are defined in Table 4.

Description	Value
Radius of the Earth (assumed spherical)	6371020 m
Sidereal day (used in calculation of Coriolis parameter)	86164.1 s

Table 4: Constants associated with the geometry.

The model should be run in **spherical coordinates**, with **the Coriolis parameter varying as the sine of the latitude**.

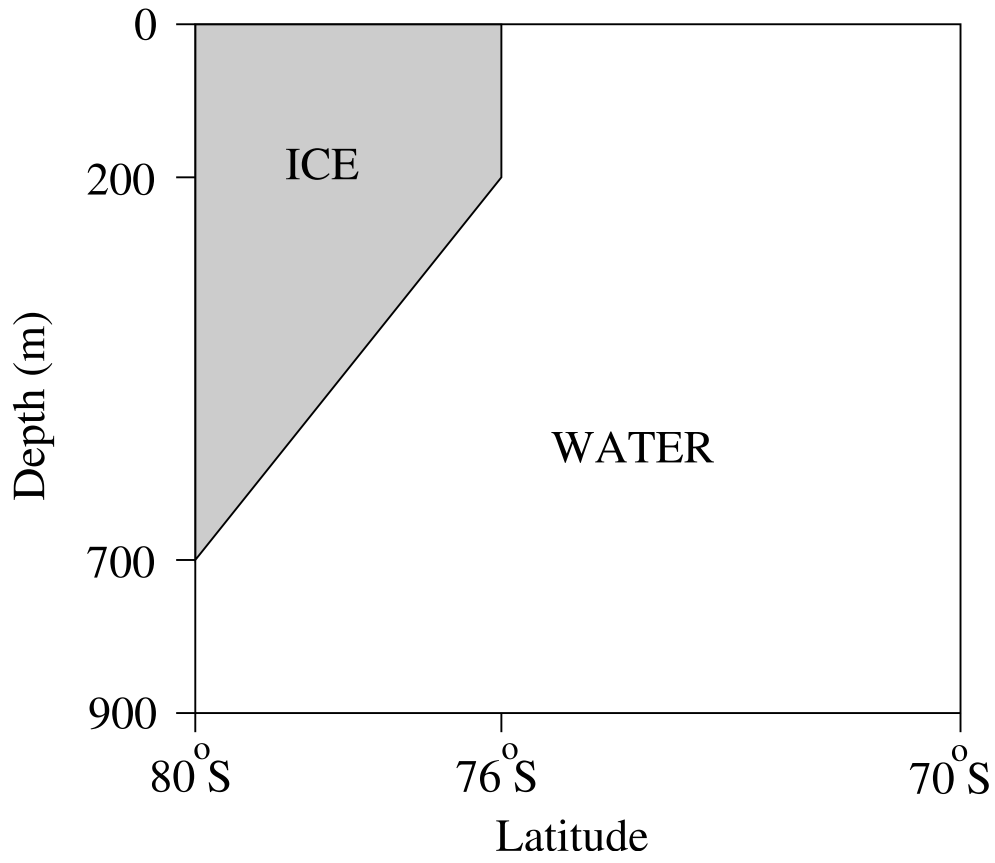

Figure 4: Elevation view of model basin for Geometry 2.

3.2 Model 2.01

3.2.1 Introduction

This model, which has a region of open ocean, is forced by melting and refreezing underneath the ice shelf, and relaxation to steady prescribed values of temperature and salinity over the open ocean.

3.2.2 Initial Conditions

The water is initially at rest and with **potential temperature -1.9° C** and **salinity 34.4 PSU**.

3.2.3 Mixing Coefficients

Under stably stratified conditions, constant horizontal mixing coefficients are employed as shown in Table 5. If the water column becomes unstable a convective adjustment scheme is required, in which case it is recommended that the enhanced coefficients shown in Table 5 are used. Otherwise, the modeller should indicate the method of convective adjustment used.

Description	Value (m^2s^{-1})	
	Stable	Unstable
Horizontal eddy viscosity	600	600
Horizontal eddy diffusivity	100	100
Vertical eddy viscosity	0.001	0.1
Vertical eddy diffusivity	0.00005	0.005

Table 5: Mixing coefficients.

3.2.4 Recommended Spatial and Temporal Resolution, and Run Time

The dependence of accuracy on grid sizes and time steps will vary from model to model. However, recommended values are shown in Table 6.

Description	Value
Grid increment in longitude	0.3°
Grid increment in latitude	0.1°
Number of vertical layers	≥ 10
Distribution of vertical layers	preferably more concentrated in upper and lower boundary layers
Time step	as appropriate to the model
Run time	30 years, but preferably to approximately steady state

Table 6: Recommended spatial and temporal resolutions, and run time.

3.2.5 Boundary Conditions at Sea Bed

At the sea bed, the bottom stress is described by the quadratic bottom friction law:

$$\mathbf{B} = -\rho C_D \mathbf{u}_B |\mathbf{u}| \qquad (7)$$

where

$\mathbf{B}$ is the bottom stress,

ρ is the water density,

C_D is a drag coefficient (prescribed as **0.0025**), and

$\mathbf{u}_B$ is the water velocity in the model cell adjacent to the sea bed.

3.2.6 Boundary Conditions at Ice/Water Interface

At the ice/water interface, the interfacial stress is described by the quadratic law:

$$\mathbf{S} = -\rho C_I \mathbf{u}_I |\mathbf{u}| \tag{8}$$

where

$\mathbf{S}$ is the interfacial stress,

C_I is a drag coefficient (prescribed as **0.0025**), and

$\mathbf{u}_I$ is the water velocity in the model cell adjacent to the ice/water interface.

The heat flux at the interface is described by:

$$Q = \rho C_p \gamma (T_I - T_f) \tag{9}$$

where

Q is the upward heat flux,

C_p is the specific heat of water (prescribed as $\mathbf{3974\ J\ kg^{-1}\ K^{-1}}$),

γ is an exchange velocity (prescribed as $\mathbf{0.0001\ m\ s^{-1}}$),

T_I is the thermodynamic temperature of the model cell adjacent to the ice/water interface, and

T_f is the in-situ freezing point of seawater at that pressure (in units of thermodynamic temperature).

It is assumed that no heat is diffused into the ice shelf, so that the rate of production of fresh water is given by:

$$q = \frac{Q}{\rho L} \tag{10}$$

where

q is the rate of production of fresh water, and

L is the latent heat of fusion (prescribed as $\mathbf{334000\ J\ kg^{-1}}$).

The model is assumed to conserve volume, so that the effect of producing fresh water at a rate q is simulated by an upward flux of salt given by:

$$s = \frac{\rho q S_0}{1000} \tag{11}$$

where

s is the rate of addition of salt (kg m^{-2} s^{-}1), and

S_0 is a constant reference salinity (prescribed as **34.4 PSU**).

Equations (9), (10) and (11) give:

$$s = \frac{QS_0}{1000L} = \frac{\rho C_p \gamma (T_I - T_f) S_0}{1000L} \tag{12}$$

The use of a constant reference salinity (S_0), rather than the local salinity, ensures that the salt and heat fluxes are exactly proportional (by the constant factor $S_0/(1000L)$), so that the solution for a closed basin may tend to a steady state in both salinity and temperature.

3.2.7 Boundary Conditions at Air/Water Interface

At the air/water interface, the interfacial stress is zero and the thermodynamic temperature and salinity are relaxed to prescribed values, T_p and S_p, using a relaxation time, τ. Therefore, the following is performed each time step, δt:

$$T_s = T_s + (1 - \exp(-\delta t/\tau))(T_p - T_s) \tag{13}$$

and

$$S_s = S_s + (1 - \exp(-\delta t/\tau))(S_p - S_s) \tag{14}$$

where

T_s is the surface thermodynamic temperature, and

S_s is the surface salinity.

The **prescribed surface thermodynamic temperature** and **salinity**, T_p and S_p are **-1.9° C** and **34.4 PSU**, respectively. The **relaxation time**, τ, is **30 days**.

It is generally better to specify the surface boundary conditions for temperature and salinity by prescribing **surface fluxes**, rather than the actual temperature or salinity values. This may be done by firstly defining an effective vertical transport velocity as the ratio of the thickness of the top model cell to the relaxation time. The surface flux of temperature (say) is then derived from the product of this transport velocity and the difference between the temperature of the top cell and the prescribed relaxation temperature. The advantage of this method is that the vertical flux of heat or salt is immediately available for budgeting purposes.

3.2.8 The Reference Level and the Reference Density

The **potential temperature** and **potential density** should be defined **relative to 0 m** (see Figure 4).

Boussinesq models require the specification of a reference density. Where this is required, it should be prescribed as **1030 kg m^{-3}** (i.e. approximately the in-situ density of water at -1.9° C, 34.4 PSU and depth 550 m).

3.3 Model 2.02

3.3.1 Introduction

This model, which has a region of open ocean, is forced by melting and refreezing underneath the ice shelf, and relaxation to seasonally-varying values of temperature and salinity over the open ocean.

3.3.2 Initial Conditions

The water is initially at rest and with **potential temperature -1.9° C** and **salinity 34.4 PSU**.

3.3.3 Mixing Coefficients

Under stably stratified conditions, constant horizontal mixing coefficients are employed as shown in Table 7. If the water column becomes unstable a convective adjustment scheme is required, in which case it is recommended that the enhanced coefficients shown in Table 7 are used. Otherwise, the modeller should indicate the method of convective adjustment used.

Description	Value (m^2s^{-1})	
	Stable	Unstable
Horizontal eddy viscosity	600	600
Horizontal eddy diffusivity	100	100
Vertical eddy viscosity	0.001	0.1
Vertical eddy diffusivity	0.00005	0.005

Table 7: Mixing coefficients.

3.3.4 Recommended Spatial and Temporal Resolution, and Run Time

The dependence of accuracy on grid sizes and time steps will vary from model to model. However, recommended values are shown in Table 8.

Description	Value
Grid increment in longitude	0.3°
Grid increment in latitude	0.1°
Number of vertical layers	≥ 10
Distribution of vertical layers	preferably more concentrated in upper and lower boundary layers
Time step	as appropriate to the model
Run time	30 years, but preferably to approximately (periodic) steady state

Table 8: Recommended spatial and temporal resolutions, and run time.

3.3.5 Boundary Conditions at Sea Bed

At the sea bed, the bottom stress is described by the quadratic bottom friction law:

$$\mathbf{B} = -\rho C_D \mathbf{u}_B |\mathbf{u}| \tag{15}$$

where

B is the bottom stress,

ρ is the water density,

C_D is a drag coefficient (prescribed as **0.0025**), and

$\mathbf{u}_B$ is the water velocity in the model cell adjacent to the sea bed.

3.3.6 Boundary Conditions at Ice/Water Interface

At the ice/water interface, the interfacial stress is described by the quadratic law:

$$\mathbf{S} = -\rho C_I \mathbf{u}_I |\mathbf{u}| \tag{16}$$

where

S is the interfacial stress,

C_I is a drag coefficient (prescribed as **0.0025**), and

$\mathbf{u}_I$ is the water velocity in the model cell adjacent to the ice/water interface.

The heat flux at the interface is described by:

$$Q = \rho C_p \gamma (T_I - T_f) \tag{17}$$

where

Q is the upward heat flux,

C_p is the specific heat of water (prescribed as $\mathbf{3974\ J\ kg^{-1}\ K^{-1}}$),

γ is an exchange velocity (prescribed as $\mathbf{0.0001\ m\ s^{-1}}$),

T_I is the thermodynamic temperature of the model cell adjacent to the ice/water interface, and

T_f is the in-situ freezing point of seawater at that pressure (in units of thermodynamic temperature).

It is assumed that no heat is diffused into the ice shelf, so that the rate of production of fresh water is given by:

$$q = \frac{Q}{\rho L} \tag{18}$$

where

q is the rate of production of fresh water, and

L is the latent heat of fusion (prescribed as $\mathbf{334000\ J\ kg^{-1}}$).

The model is assumed to conserve volume, so that the effect of producing fresh water at a rate q is simulated by an upward flux of salt given by:

$$s = \frac{\rho q S_0}{1000} \tag{19}$$

where

s is the rate of addition of salt (kg m^{-2} s^{-}1), and

S_0 is a constant reference salinity (prescribed as **34.4 PSU**).

Equations (17), (18) and (19) give:

$$s = \frac{Q S_0}{1000L} = \frac{\rho C_p \gamma (T_I - T_f) S_0}{1000L} \tag{20}$$

The use of a constant reference salinity (S_0), rather than the local salinity, ensures that the salt and heat fluxes are exactly proportional (by the constant factor $S_0/(1000L)$), so that the solution for a closed basin may tend to a steady state in both salinity and temperature.

3.3.7 Boundary Conditions at Air/Water Interface

At the air/water interface, the interfacial stress is zero and the thermodynamic temperature and salinity are relaxed to prescribed values, $T_p(t)$ and $S_p(t)$ (which are functions of time, t), using a relaxation time, τ. Therefore, the following is performed each time step, δt:

$$T_s = T_s + (1 - \exp(-\delta t/\tau))(T_p - T_s) \tag{21}$$

and

$$S_s = S_s + (1 - \exp(-\delta t/\tau))(S_p - S_s) \tag{22}$$

where

T_s is the surface thermodynamic temperature, and

S_s is the surface salinity.

The **relaxation time**, τ, is 30 days, and the **prescribed surface thermodynamic temperature** and **salinity**, $T_p(t)$ and $S_p(t)$ are shown in Figure 5.

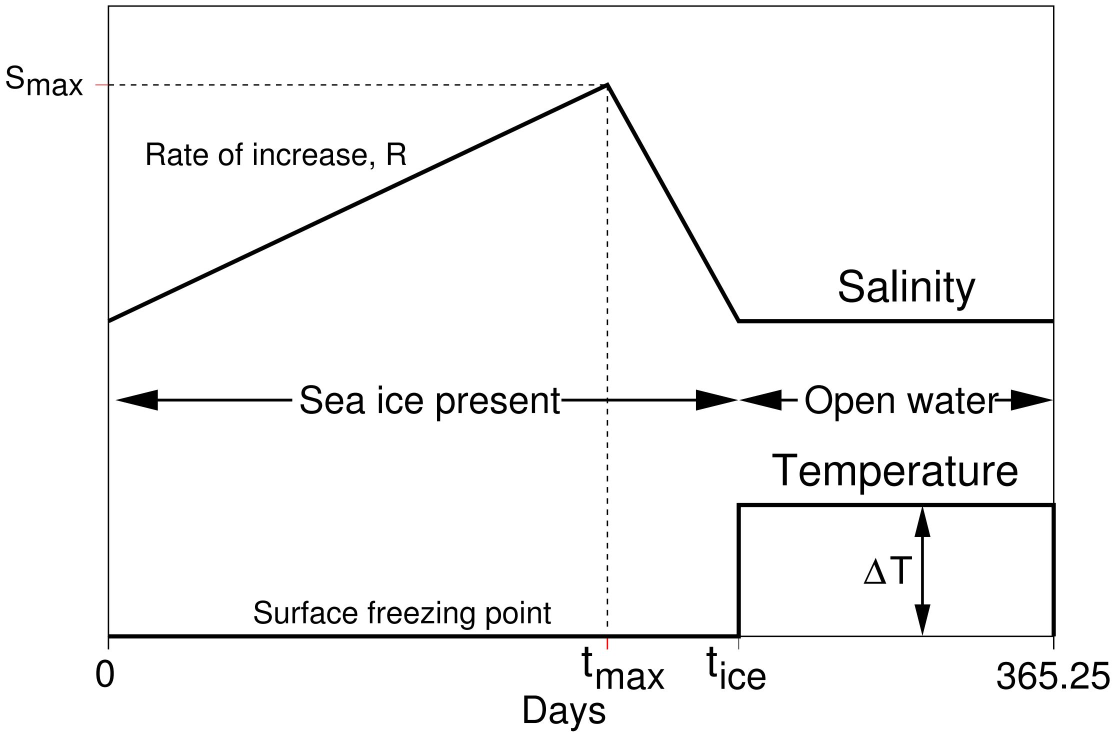

Figure 5: Seasonal variation of surface salinity and temperature.

The variables in Figure 5, which are typical of those for the seasonal variation of temperature and salinity in Prydz Bay, Eastern Antarctica, are shown in Table 9.

It is generally better to specify the surface boundary conditions for temperature and salinity by prescribing **surface fluxes**, rather than the actual temperature or salinity values. This

Variable	Value
S_{max}	35.0 (Practical Salinity Scale)
R	0.01 /day (Practical Salinity Scale)
ΔT	1° C
t_{max}	167.2 days
t_{ice}	220 days

Table 9: Relaxation variables.

may be done by firstly defining an effective vertical transport velocity as the ratio of the thickness of the top model cell to the relaxation time. The surface flux of temperature (say) is then derived from the product of this transport velocity and the difference between the temperature of the top cell and the prescribed relaxation temperature. The advantage of this method is that the vertical flux of heat or salt is immediately available for budgeting purposes.

3.3.8 The Reference Level and the Reference Density

The **potential temperature** and **potential density** should be defined **relative to 0 m** (see Figure 4).

Boussinesq models require the specification of a reference density. Where this is required, it should be prescribed as **1030 kg m^{-3}** (i.e. approximately the in-situ density of water at -1.9° C, 34.4 PSU and depth 550 m).

4 Required Outputs

4.1 Fields

This is at present very much open to discussion. As a minimum, I would suggest that the following are provided at different times as the steady state is approached:

- Plotted 3-D vector fields of horizontal velocity.
- Plotted 3-D scalar fields of potential temperature, salinity, potential density and vertical velocity.
- Plotted 2-D fields of horizontal barotropic streamfunction.
- Plotted 2-D fields of overturning streamfunction, integrated in the east/west direction.
- Plotted 2-D fields of the melt rate.

4.2 Integral Properties

In addition, plots of the following integral properties should be provided as a function of time:

- Total heat (J; relative to 0 °C)
- Total salt (kg)
- Total kinetic energy (J)
- Total potential energy (J; relative to 0 m (see Figures 2 and 4))
- Spatially integrated positive melt rate and spatially integrated negative melt rate (ms^{-1})

Results should be provided in netCDF format (preferably adhering to the NetCDF Climate and Forecast (CF) Metadata Conventions).

(See: `http://my.unidata.ucar.edu/content/software/netcdf/index.html`

and: `http://www.cgd.ucar.edu/cms/eaton/cf-metadata/index.html`)

The output data should be made available at a suitable web site.

4.3 Additional Information

In addition, details of model algorithms (not specified above) should be provided, such as:

- The equation of state.
- The freezing point algorithm.
- The way in which pressure is specified at the ice/water interface. (*Note* that this may be an important difference between the rigid-lid and free-surface models.)

If modellers feel that some of the above specifications are over-prescriptive, they should provide both results from models defined as above, and also from models which use their normal parameterisations.

5 Acknowledgements

The author thanks David Holland and Adrian Jenkins for help in designing this specification.

6 References

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