Modelling Radiocarbon Uptake by the Southern Ocean

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INTRODUCTION

The circulation of the Fine Antarctic Resolution Model (FRAM) is being applied in the development of an off-line and radiocarbon validated tracer model for the Southern Ocean. The tracer model represents a solution to the three dimensional advection and diffusion equation. Its spatial resolution is that of the FRAM with 0.5^{o} in longitudinal and 0.25^{o} in latitudinal direction as well as 32 levels in the vertical. The model will be applied to interpret the observed three dimensional distribution of radiocarbon within the Australian sector of the Southern Ocean. Here, a radiocarbon sampling program is being carried out along the WOCE Section SR4 between Tasmania and Antarctica. Additional samples were obtained in water of the South Australian Basin allowing to establish a three dimensional picture of the carbon-14 distribution for the sector.

In this note, a brief report is given on the outcome of a numerical experiment which was carried out for an ideal tracer. The modelled distribution of the tracer is explained and agrees well with the known physical mechanism observed in some regions of the Southern Ocean. A notable outcome of this application is the modelled renewal of South Indian Ocean thermocline water. Surface water originating in the south eastern part of the Indian Ocean ventilates the Indian Ocean thermocline and moves northward.

METHOD

The equation describing the transport and mixing of a scalar ocean water property is the general equation of conservation. For a substance C, it is given (e.g. Semtner, 1986: here modified by including 'S') in the form:

$$\boxed{\frac{\partial C}{\partial t} + L \cdot C = k \cdot \frac{\partial^2 C}{\partial z^2} + A_h \cdot \nabla^2 C + S}$$

In this equation, L was defined as an advection operator taking the form:

$$\boxed{LC = \frac{1}{a \cdot \cos\phi} \cdot \frac{\partial}{\partial \lambda}(u \cdot C) + \frac{1}{a \cdot \cos\phi} \cdot \frac{\partial}{\partial \phi}(v \cdot C \cdot \cos\phi) + \frac{\partial}{\partial z}(w \cdot C)}$$

The horizontal Laplacian operator is taking the form of:

$$\boxed{\nabla^2 C = \frac{1}{a^2 \cdot \cos^2\phi} \cdot \frac{\partial^2 C}{\partial^2 \lambda} + \frac{1}{a^2 \cdot \cos\phi} \cdot \frac{\partial C}{\partial \phi}\left(\frac{\partial C}{\partial \phi} \cos\phi\right)}$$

In the above, ϕ and λ are the longitude and the latitude; z the vertical co-ordinate; a is the earth radius; k and A_h are representing vertical and horizontal eddy diffusivity; t is time; u, v, and w are the components of the three dimensional velocity vector; S is a source term including negative sources (sinks) and positive sources for C. In the case of a coarse resolution OGCMs, temperature and salinity sources are usually simulated by relaxation to observed climatology. For radiocarbon, S can take a more complex form. In its simplest expression, it represents radioactive decay as a sink term. In the experiment represented here, only a source term was specified.

A copy of the highly vectorised form of the FRAM tracer code and other data input fields were obtained from Dr. D. Stevens (1994, per. comm). The vectorised code was partially converted into CM-5 FORTRAN for parallel processing purposes. The code was implemented on a CM-5 with 32 processors and 128 vector units at the South Australian Centre for Parallel Processing in Adelaide. It is possible to increase the present computing speed further, however, the initial experiments of which an example is represented below, are being carried out with the existing version of the code.

The radiocarbon validated tracer model is being developed in a off-line version. No explicit solution is obtained for the velocity field. To solve for the unknown velocities required in the tracer equation, the results of the FRAM (eg. FRAM Group, 1991) are applied. A mean circulation was obtained by deriving an average from the accumulated monthly data sets of year 10 to 16 (de Cuevas, 1994; pers. com.) of the FRAM integration. It was expected that the average velocity field would be in a steady state in a statistical sense with only a minor time dependent fraction. Convective overturn is simulated in the tracer model by applying a convective mask derived from monthly dumps of overturning events during the FRAM integration (Stevens, 1994; pers. com.).

MODEL EXPERIMENTS

The application of an ideal tracer allows to study in some detail the physical mechanisms represented by the tracer model. In this initial experiment, a tracer is introduced at the surface at each time step with the unit and magnitude '1'. The initial concentration is set to '0' everywhere. The time step was chosen with 14.400 s and the model was run for a total of 10950 timesteps. In the following, the concentration in layer 1, layer 8 (290 m), and along three transects across the Southern Ocean obtained at the end of the simulation were discussed. The tracer data were represented as overlays on black and white raster images of the cross sectional velocity which was given in units of [cm/s]. Velocities toward the east are positive and in the 'white' range, those toward the west are negative and toward the 'black' range. In this manner, frontal zones associated with strong flow toward the east appear in white, frontal zones with strong flow toward the west appear in black.

Notice should be taken that the vertical tracer distribution occurs in layers rather than depths and therefore, a distortion of the vertical axis is shown. The thickness of the layers ranges from 20.3 m in the surface layer to 233 m in the bottom layer. The depths of layers 4, 6, 8, 10, 15, 22, 26, and 32 correspond to 86 m, 169 m, 290 m, 532 m, 1508 m, 3071 m, 3989 m and 5382 m respectively. It follows a discussion of the tracer distribution below.

Tracer Distribution in the Surface Layer (Figure 1)

The concentration of the tracer in the surface layer of the Southern Ocean is represented in Figure 1. Isolines are shown ranging from 250, 500, 1000, 2000, 4000, 8000 to 10000. The purpose of the representation is to highlight the large scale distribution of the tracer which divides approximately into three main regions. The highest concentration is found in the subtropical oceans. Generally lower is the concentration within the path of the Antarctic Circumpolar Current (ACC) where the lowest concentration is observed in regions of deep convective overturn. Minima in the tracer concentration with values below 500 are also found in the Weddell Sea and Ross Sea. The control of advection on the distribution is indicated in the tracer distribution. Minimal advection toward the centres of the subtropical gyres results in an accumulation and retention of the tracer while within the main path of the ACC, the tracer is advected rapidly or convected into deeper layers. Northward advection in the Tasman Sea is shown by the excursion of the 1000 and 2000 isolines. The front between the Malvinas and Brasil currents features prominently at approximately 39° S and 55° W.

Tracer Distribution in the Layer 8 (Figure 2)

For the representation of the tracer distribution in layer 8, the contours in this figure are chosen with 25, 50, 100, 200, 300, 400, and 500. The modelled distribution represents a reversed image of the surface distribution. The subtropical gyres are characterised by the lower concentration while the areas of convective overturn show an increased concentration of the tracer. It is obvious, that the convection is deepest in the latitudinal band between approximately 44° S and 54° S, while close to the Antarctic continent it reaches only down to depths of 200 to 300 m. The excursion of the isolines southwest of Australia show some northwest transport of the tracer. It is a strong indication for the ventilation of the Indian Ocean permanent thermocline by water subducted south of or near 39° S and 120° E. Prominent topographic features are reflected in the tracer distribution. The Kerguelen Plateau is indicated by the southward excursion of the isolines at approximately 80° E while in the proximity of the Campbell Plateau the isolines diverge.

Tracer Distribution at the Greenwhich Meridian (Figure 3)

The distribution of the tracer is determined through the interaction of advection, convection, horizontal and vertical eddy diffusivities. South of 59° S, the vertical displacement is controlled primarily by vertical diffusion. Close to the Antarctic continent and between approximately 67° S and 70° S, a convergence is indicated by the vertical excursion of the isolines in the top 100 m of the water column. This convergence is most likely associated with the east wind drift resulting in a southerly transport and subsequent vertical motion. The main path of the ACC is associated with a depletion of the tracer in the surface layer and an outcropping of the isoline.

The Polar Front, the Subantarctic Front and the Subtropical Front are indicated at approximately 56° S, 50° S and 41° S respectively. The tracer is convected, or advected out of this region into the subtropical gyre. The convective displacement is indicated by the vertical excursion of the isolines between approximately 35° S and 54° S. Further to the north of the main path of the ACC, there seems to be some indication of Ekman pumping at approximately 30° S down to layer 6 at 169 m.

Tracer Concentration at 180° in the Pacific Ocean (Figure 4)

The southern part of this transect is located in the Ross Sea. Convective mixing displaced the tracer down to 290 m indicated by the vertical excursion of the isolines. The northern and southern boundaries of the ACC are located at approximately 64° S and 49° S. The region in between is depleted in the top few hundred meters shown by the outcropping of the '750' isoline. Distinct influence of the topography on the flow and also the distribution of the tracer is observed above the Chatman Rise at approximately 49° S. The isolines sharply descend toward the north. The highest concentration along this transect is found again in the area of the subtropical gyre were the accumulation of the tracer due to input at the surface is not opposed by strong advective or convective processes.

Tracer Concentration at 50 W in the Atlantic Ocean (Figure 5)

The other area of the Southern Ocean where known convective overturn occurs close to the Antarctic continent is the Weddell Sea. The vertical distribution of the tracer is clearly influenced by the process of convective overturn down to a depth of 290 m (layer 8). The main path of the ACC is observed between approximately 63° S and 41° S with the most distinct front, ie. the highest horizontal velocities located at 53° S. North of 54° S convective mixing results also in a vertical excursion of the isolines while between 44° S and 39° S some influence of Malvinas-Brasil confluence is observed in the vertical tracer distribution.

CONCLUSION

The observed distribution of the ideal tracer seems to confirm well with the known knowledge of physical processes operating within the upper 1000 m the Southern Ocean. To investigate the models performance in the deep layers a longer integration of the model is required. For the proposed application to study the distribution of radiocarbon in the Southern Ocean, however, the model's application is appropriate.

REFERENCES

FRAM Group (1991). An Eddy-Resolving Model of the Southern Ocean. Eos. Transaction. AGU. 72(15). 174-175.

Semtner, A. J. (1986). Finite Difference Formulation of a World Ocean Model. In: Advanced Physical Oceanographic Modelling. J. J. O'Brien (ed.). 187-202.

FIGURE CAPTIONS

Figure 1: Distribution of the tracer in the surface layer. Contours are given in intervals of 250, 500, 1000, 2000, 4000, 6000, 8000, and 10000.

Figure 2: Distribution of the tracer in layer 8 (290 m). Contours are given in intervals of 25, 50, 100, 200, 300, 400, and 500.

Figure 3: Distribution of the tracer along the Greenwhich Meridian. Contours are given in intervals of 1, 10, 50, 100, 250, 500, 750, 1000, 1250, 1500, 1750 and 2000. The contours are overlaid on an image of the westeast component of the velocity vector. Positive velocities appear within the 'whiter' range of the image.

Figure 4: Distribution of the tracer along 180° in the Pacific Ocean. Contours are given in intervals of 1, 10, 50, 100, 250, 500, 750, 1000, 1250, 1500, 1750 and 2000. The contours are overlaid on an image of the westeast component of the velocity vector. Positive velocities appear within the 'whiter' range of the image.

Figure 5: Distribution of the tracer along 50° W in the Atlantic Ocean. Contours are given in intervals of 1, 10, 50, 100, 250, 500, 750, 1000, 1250, 1500, 1750 and 2000. The contours are overlaid on an image of the westeast component of the velocity vector. Positive velocities appear within the 'whiter' range of the image.