Lagrangian blobs of buoyancy embedded in Eulerian models

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1. Introduction

Open ocean convection and downslope flows are important processes in setting deep and bottom water properties. To overcome many of the traditional challenges of representing these processes in quasi-Eulerian vertical coordinate ocean models, a framework for the Lagrangian discretisation of SGS convection and downslope flows is being formulated and implemented.

The Lagrangian framework arbitrarily re-labels parcels of fluid in a grid cell that can then be treated pseudo-independently from the gridded model. The parcels ("blobs") can then be moved around in three dimensions and interact with the Eulerian model in an arbitrary manner. In doing so, blobs can effect transport of properties vertically through the water column and laterally.

The combined properties of the Eulerian and Lagrangian models are:

1. The Eulerian model and the Lagrangian model operate within the same coordinate system (for example latitude, longitude and depth).
2. The mass of the system (in non-Boussinesq models) or volume of the system (in Boussinesq models) must evolve in a conservative manner.
3. Tracer fields must evolve in a conservative manner.
4. Momentum can evolve in a conservative manner, depending on the implementation of the Lagrangian scheme – but is not necessary to the framework.

2. "Static" blob parameterisations

The first step in implementing the Lagrangian framework is to implement parameterisations that are analogous to existing Eulerian parameterisations and then to extend those parameterisations to provide insight into possible benefits, pitfalls and challenges of implementing "dynamic" blob schemes.

2.1 The NCON scheme

One of the original convective parameterisations is that of Cox (1984), in which vertically adjacent grid cells are tested for instability. If an instability is found, then their tracer is homogenised in order to make the water column conditionally stable. Rather than an explicit homogenisation of adjacent grid cells, two blobs are instantaneously exchanged, with the net result being the homogenisation of properties (depicted diagrammatically in figure 1).

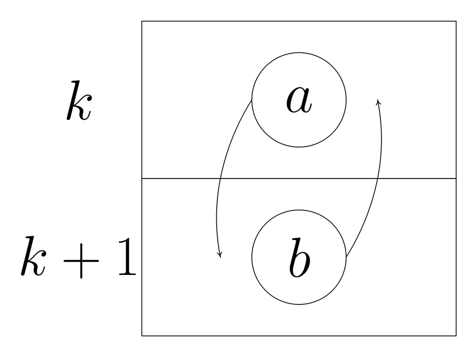


Figure 1: *Illustration of the transfer of material in the Lagrangian NCon-like scheme.*

Figure 2 shows a comparison between the traditional Eulerian NCon and the new Lagrangian NCon averaged for the last 50 years of a 1000 year run of the box test case (see chapter 25 of Griffies, 2007). As can be seen, there is close agreement, indicating that in this instance, the Lagrangian framework has successfully replicated the NCon scheme (only tracer and not mass is included in the original scheme).

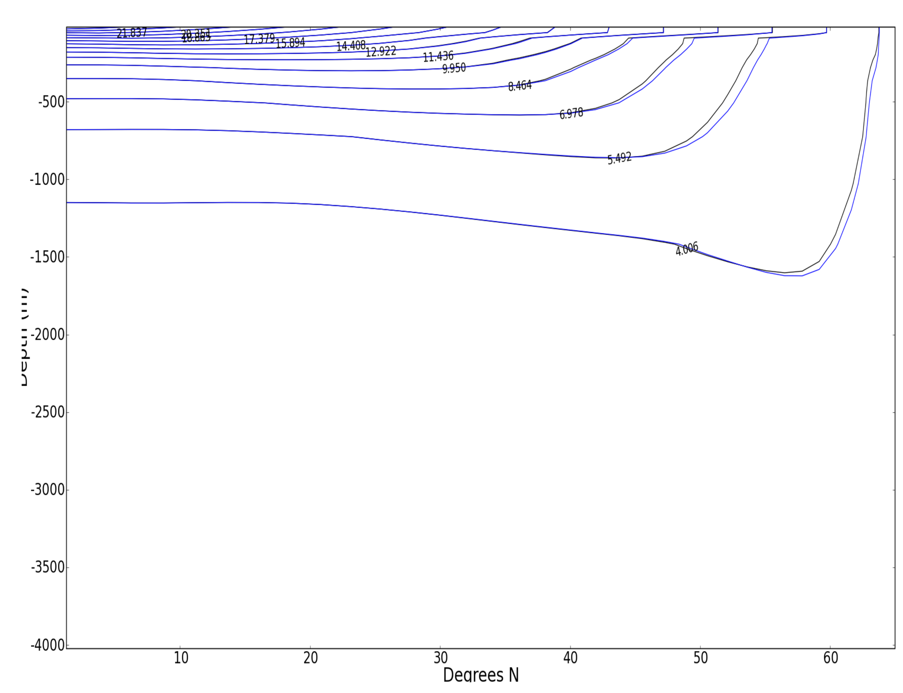


Figure 2: *Zonally averaged temperature (°C). Blue lines indicate the standard NCon scheme, and black lines indicate the Lagrangian NCon-like scheme.*

2.2 Overflow schemes

The Campin and Goosse (1999) overflow scheme transports dense shelf water to its neutral level or bottom grid cell (whichever is most shallow) in an adjacent deep ocean water column. It then also prescribes a "return" flow. A parameterisation directly analogous to this scheme has been implemented and tested (dubbed the "full return overflow scheme" and depicted in figure 3). The scheme has also been modified so as not to provide the return flow, but to instead transport mass and tracer from the shelf to the deep ocean as depicted in figure 3.

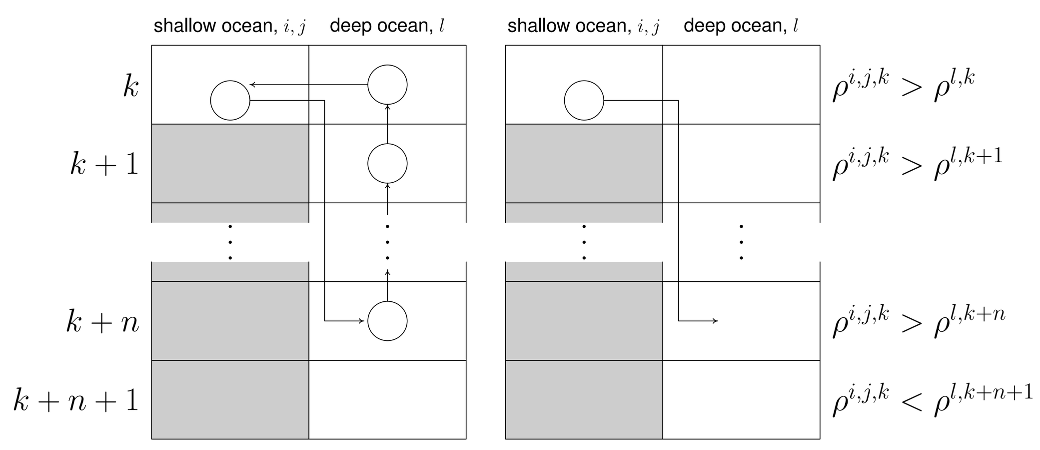
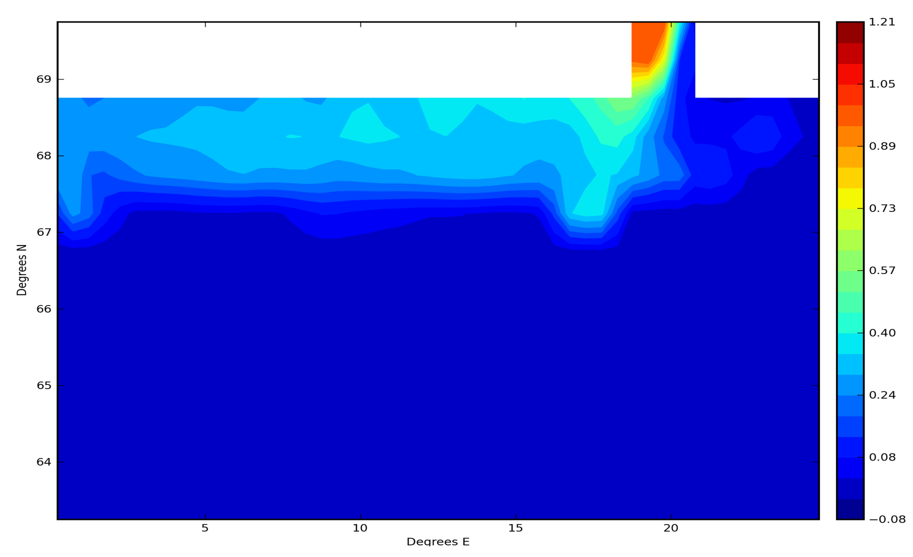
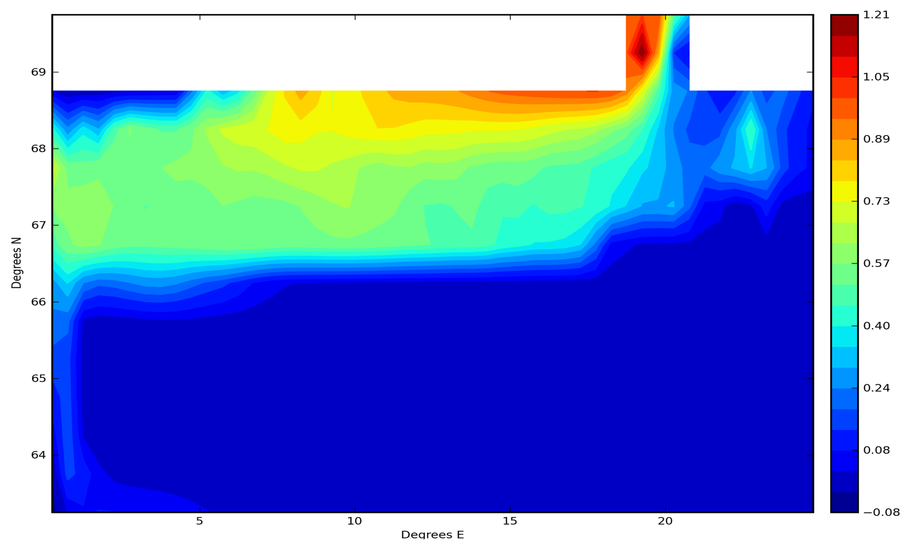


Figure 3: *Schematic illustration of the full return blob overflow scheme (left) and no return blob overflow scheme (right).* $l = (i+1,j), (i,j+1), (i-1,j) or (i,j-1)$.

This modification (dubbed the "no return overflow scheme") provides insight into the properties of a scheme that transports mass and tracer without explicitly specifying a return flow, thereby allowing the bulk prognostic equations of the model to respond to the SGS lateral transport of mass. The difference in results between a prescribed return flow and no prescribed return flow is illustrated in figure 4.



(a) The full return overflow scheme.



(b) The no return overflow scheme.

Figure 4: *Bottom cell salinity in the DOME test case (see chapter 28 of Griffies, 2007, for details) averaged over the last 10 days of a one year run. Density is a linear function of temperature only, and so salinity acts as a passive tracer.*

In order to maintain numerical stability, the mass transport effected by the no return scheme is much less than the full overflow scheme. Despite the difference in explicit SGS overflow mass transport, figure 4 indicates that the downslope transport of the no return scheme is much greater than the full return scheme.

3. Future work – "dynamic blobs"

One of the most exciting aspects of this Lagrangian framework is that there exists the possibility to admit realistic dynamics for open ocean convection and downslope flows. It is anticipated that the explicit representation of such SGS processes will improve model realism, and further constrain models.

3.1 Governing Equations

We specify the momentum equations for the blobs as

$$\rho_{\mathsf{L}}\frac{\mathsf{d}u_{\mathsf{L}}}{\mathsf{d}t} = -\rho_{\mathsf{L}}v_{\mathsf{L}}f + \rho_{\mathsf{L}}w_{\mathsf{L}}f^* - \frac{\partial p}{\partial x} + \rho_{\mathsf{L}}F^{(x)} + \rho_{\mathsf{L}}\mathcal{S}^u \quad (1)$$

$$\rho_{\mathsf{L}}\frac{\mathsf{d}v_{\mathsf{L}}}{\mathsf{d}t} = \rho_{\mathsf{L}}u_{\mathsf{L}}f - \frac{\partial p}{\partial y} + \rho_{\mathsf{L}}F^{(y)} + \rho_{\mathsf{L}}\mathcal{S}^v \quad (2)$$

$$\rho_{\mathsf{L}}\frac{\mathsf{d}w_{\mathsf{L}}}{\mathsf{d}t} = -\rho_{\mathsf{L}}u_{\mathsf{L}}f^* - g(\rho_{\mathsf{L}} - \rho_{\mathsf{E}}) + \rho_{\mathsf{L}}F^{(z)} + \rho_{\mathsf{L}}\mathcal{S}^w, \quad (3)$$

where subscript L and E are Lagrangian and Eulerian model values respectively, $(F^{(x)}, F^{(y)}, F^{(z)})$ is the interfacial contact force vector, f^* is the horizontal component of the Earth's rotation vector and all other symbols have their standard meaning. These equations can be modified and simplified according to the requirements of a particular parameterisation. For instance, formulating a scheme which is analogous to a dynamic Lagrangian discretisation of the Price and O'Neil Baringer (1994) streamtube model results in the following momentum equations

$$\frac{\mathsf{d}u_{\mathsf{L}}}{\mathsf{d}t} = -v_{\mathsf{L}}f - g\frac{\rho_{\mathsf{L}} - \rho_{\mathsf{E}}}{\rho_{\mathsf{L}}}\frac{\partial H}{\partial x} - \frac{1}{\rho_{\mathsf{L}}}\frac{\partial p}{\partial x} - \frac{\tau^x_{\text{bot}}}{\rho_{\mathsf{L}}h_{\mathsf{L}}} - \frac{\mathscr{E}u_{\mathsf{L}}}{h_{\mathsf{L}}} \quad (4)$$

$$\frac{\mathsf{d}v_{\mathsf{L}}}{\mathsf{d}t} = u_{\mathsf{L}}f - g\frac{\rho_{\mathsf{L}} - \rho_{\mathsf{E}}}{\rho_{\mathsf{L}}}\frac{\partial H}{\partial y} - \frac{1}{\rho_{\mathsf{L}}}\frac{\partial p}{\partial y} - \frac{\tau^y_{\text{bot}}}{\rho_{\mathsf{L}}h_{\mathsf{L}}} - \frac{\mathscr{E}v_{\mathsf{L}}}{h_{\mathsf{L}}} \quad (5)$$

$$\frac{\mathsf{d}w_{\mathsf{L}}}{\mathsf{d}t} = -g\frac{\rho_{\mathsf{L}} - \rho_{\mathsf{E}}}{\rho_{\mathsf{L}}} - \frac{\tau^z_{\text{bot}}}{\rho_{\mathsf{L}}h_{\mathsf{L}}} - \frac{\mathscr{E}w_{\mathsf{L}}}{h_{\mathsf{L}}}, \quad (6)$$

where $\mathscr{E}$ is an entrainment rate.

One of the advantages of this flexible framework is that it is possible to have two dynamic regimes, one in which blobs are in contact with topography ("bottom" blobs) and another which are not in contact with topography ("free" blobs). Blobs may also switch between these two regimes, a concept which is illustrated in figures 5 and 6. The ability to have multiple dynamic regimes allows for a more complete treatment of convection.

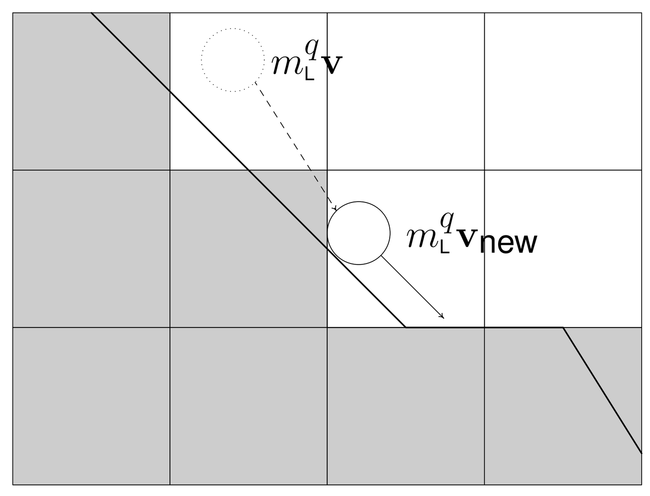


Figure 5: *The process by which an open ocean blob, becomes a bottom blob by interacting with topography.*

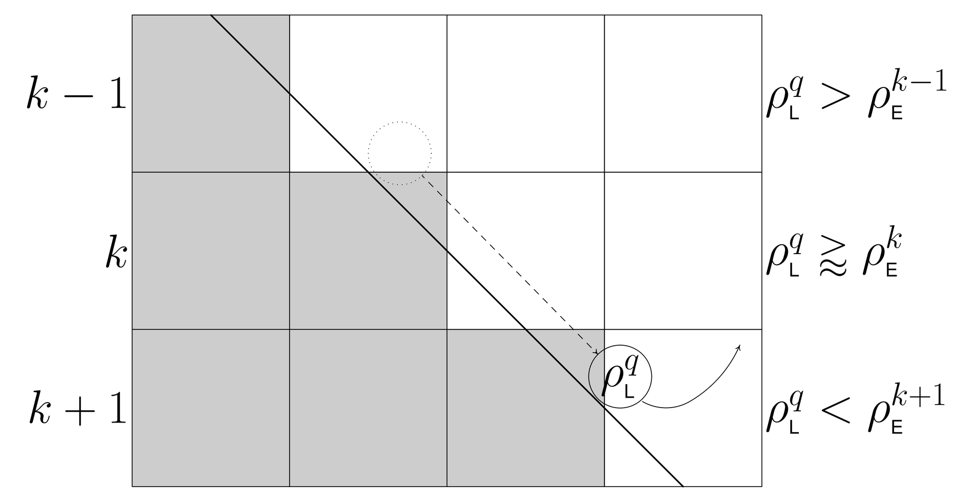


Figure 6: *The process of boundary layer separation.*

4. Discussion and Conclusion

The Lagrangian framework offers a potential avenue for an improved representation of open ocean convection and downslope flows in quasi-Eulerian vertical coordinate models. Some static regimes have been implemented to test the framework and investigate properties of the parameterisations. The next phase of this project is to implement simple dynamical formulations in order to test the framework, and provide a platform with which more complete schemes can be developed.

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