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Effect of Grids on North Atlantic Overflow Simulations

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Abstract We are exploring the effect of using various grid structures on resolving the physical process called overflow. This is when dense cold water overflows from a basin. This process is responsible for the majority of dense water in oceans and creates many of the currents in oceans. In particular, if affects a large part of the North Atlantic, as overflow occurs in the Denmark Strait and in the Faroe Bank Sea Channel. Since there are many ocean models, we are trying to determine the optimal grid structure for resolving the overflow process. If the model cannot accurately resolve the overflow process, then the simulation will be incorrect as currents in oceans will be incorrect. Among the many ocean and ice models in use today is HyPOP (Hybrid-Coordinate Parallel Ocean Program). Using this model, we are testing three grid types, fixed Z Grids, arbitrary Lagrangian-Eulerian grids, and sigma-coordinate grids. We examine how each of these grids affects the outcome of our overflow simulations, and which grid gives the optimal results.

Introduction to Climate Modeling

Climate Modeling is a global problem. Scientists want to resolve physical processes across the globe during the course of their simulation. There are many climate models in use today, but one of the most widely used is the Community Climate System Model (CCSM). This model has different modules that are put together to form a global climate model. Each module models a different portion of the climate, be it ocean, land, ice, atmosphere, etc. Typically an independent group works on a specific module individually. The scientists at Los Alamos National Laboratory currently work on the ocean modules for this model, which is called the Parallel Ocean Program (POP). They are also working on a new iteration of this called the Hybrid-Coordinate Parallel Ocean Program (HyPOP). This research will use these two models to study a physical process known as overflow.

Mathematical Model

POP and HyPOP use the Primitive equations, with hydrostatic and Boussinesq approximations, to describe their dynamics. These equations are given in spherical polar coordinates with a vertical z-coordinate below.

Momentum Equations:

$$\frac{\delta}{\delta t}u + \mathcal{L}(u) - \frac{(uv\tan\phi)}{a} - fv = -\frac{1}{\rho_0 a\cos\phi}\frac{\delta p}{\delta\lambda} + \mathcal{F}_{Hx}(u,v) + \mathcal{F}_V(u)$$

$$\frac{\delta}{\delta t}v + \mathcal{L}(v) + \frac{(u^2\tan\phi)}{a} + fu = -\frac{1}{\rho_0 a}\frac{\delta p}{\delta\lambda} + \mathcal{F}_{Hy}(u,v) + \mathcal{F}_V(v)$$

$$\mathcal{L}(\alpha) = \frac{1}{a\cos\phi}\left[\frac{\delta}{\delta\lambda}(u\alpha) + \frac{\delta}{\delta\phi}(\cos\phi v\alpha)\right] + \frac{\delta}{\delta z}(w\alpha)$$

$$\mathcal{F}_{Hx}(u,v) = A_M\left\{\nabla^2 u + u\frac{(1-\tan^2\phi)}{a^2} - \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\delta v}{\delta\lambda}\right\}$$

$$\mathcal{F}_{Hy}(u,v) = A_M\left\{\nabla^2 v + v\frac{(1-\tan^2\phi)}{a^2} - \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\delta u}{\delta\lambda}\right\}$$

$$\nabla^2\alpha = \frac{1}{a^2\cos^2\phi}\frac{\delta^2\alpha}{\delta\lambda^2} + \frac{1}{a^2\cos\phi}\frac{\delta}{\delta\phi}\left(\cos\phi\frac{\delta\alpha}{\delta\phi}\right)$$

$$\mathcal{F}_V(\alpha) = \frac{\delta}{\delta z}\mu\frac{\delta}{\delta z}\alpha$$

Continuity Equation:

$$\mathcal{L}(1) = 0$$

Hydrostatic Equation:

$$\frac{\delta p}{\delta z} = -\rho g$$

Equation of State:

$$\rho = \rho(\Theta, S, p) \rightarrow \rho(\Theta, S, z)$$

Tracer Transport:

$$\frac{\delta}{\delta t}\varphi + \mathcal{L}(\varphi) = \mathcal{D}_H(\varphi) + \mathcal{D}_V(\varphi)$$

$$\mathcal{D}_H(\varphi) = A_H\nabla^2\varphi$$

$$\mathcal{D}_V(\varphi) = \frac{\delta}{\delta z}\kappa\frac{\delta}{\delta z}\varphi$$

Both models use a Finite Volume scheme to discretize these equations. The two models differ in the grids used in this discretization.

Grids for Discretization

- Z Grids:
  These grids are fixed in space. They are typically set up as a standard Cartesian grid, with rectangular volumes. One benefit of this is you don't have to worry about elements having a zero thickness, which would not be physical. Another benefit of this grid type is it is easy to conceptualize and implement, however one down side is it poorly reflects the floor of the ocean.
- Sigma Coordinate Grids:
  These grids are a simple mapping, from a domain with a curved topography to a domain that is a straight edged rectangle, where the verticle dimension would extend from zero to one. Using this, zero would indicate the surface of the ocean, and one would indicate the floor of the ocean. The benefit of these grids is that the volumes follow the topography of the ocean better than a Z grid would. However, they are fixed in time again, and using these grids doesn't tell you anything extra for visualization purposes.
- Arbitrary Lagrangian-Eulerian Grids:
  These (ALE) grids are variable in time, and have horizontal grid lines that follow contours of constant density in the ocean. Layers can grow and shrink as time goes on which can cause a zero thickness, so this must be appropriately handled, since a zero thickness could cause a significant amount of numerical problems. These volumes are typically thought of as rectangular bricks, however the top and bottom might not be even, or straight for that matter. The benefit of this grid type, is the grid elements are lined up in a way where all of their transport moves out the sides, so the grids follow the actual flow of the ocean. Also, these grids typically follow the topography very well, since the flow is along the topography.

Goal of Research

The focus of this research is going to be on the different grid types. The hope is to determine which grid optimally resolves the overflow process given a resolution. Since each of the different grid types has its own benefits and drawbacks, the choice of grid could change based on Topography, or Grid size.

What is Overflow?

Overflow is a physical process that happens in a few different areas around the globe. Two of these areas are the Denmark Strait (Between Greenland and Iceland), and the Faroe Bank Sea Channel (between Iceland and Europe). North of Europe there is a basin in the ocean, the water in the basin is cooled by the atmosphere above it. As this water cools, it become more and more dense. As it becomes more dense, it falls to the bottom of the ocean. After some time, the basin is filled with this cold dense water to the point that any more cold dense water doesn't fall all the way down, and instead overflows out of the basin and through either of these two channels, into the North Atlantic. Overflow in the North Atlantic is responsible for the majority of the oceans cold and/or dense water, and this creates a large current along the ocean's topography.

Region of Interest

Although overflow occurs in many places around the globe, this research is going to focus on overflow in the North Atlantic. Two places where Overflow occurs naturally in the North Atlantic are the Denmark Strait and the Faroe Bank Sea Channel which are depicted in Figure 1.

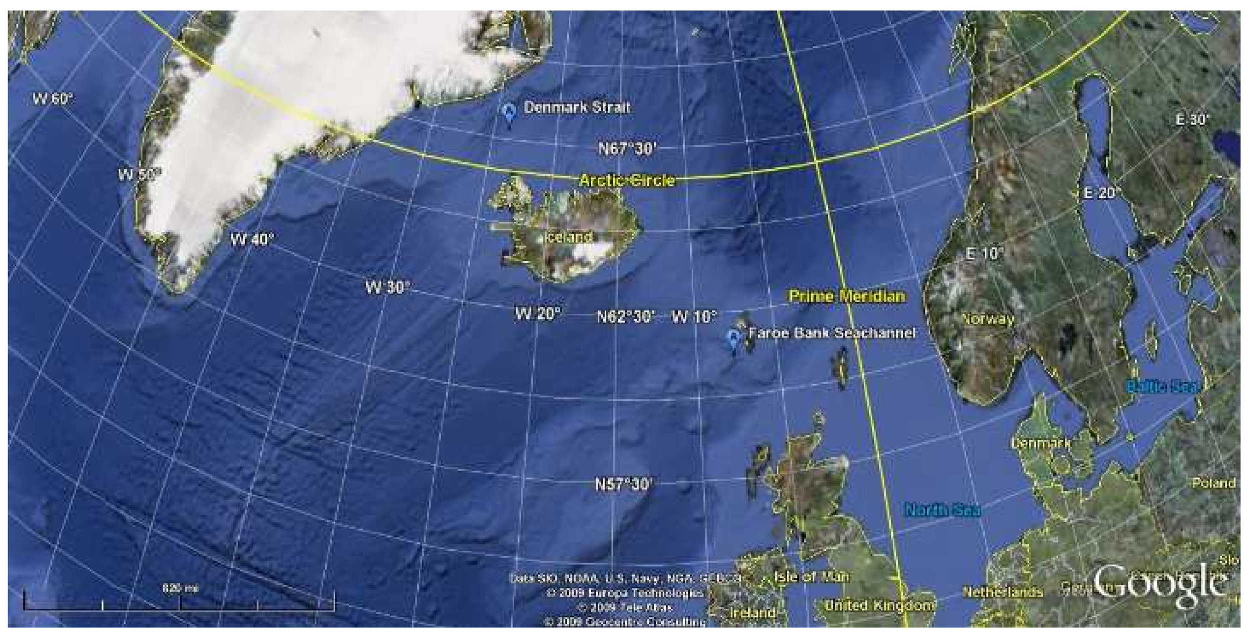

Figure 1: Aerial View of Denmark Strait and Faroe Bank Sea Channel

This research will be performed on an idealized domain, however it should resemble these physical regions. The actual topography that will be used can be seen in Figure 2.

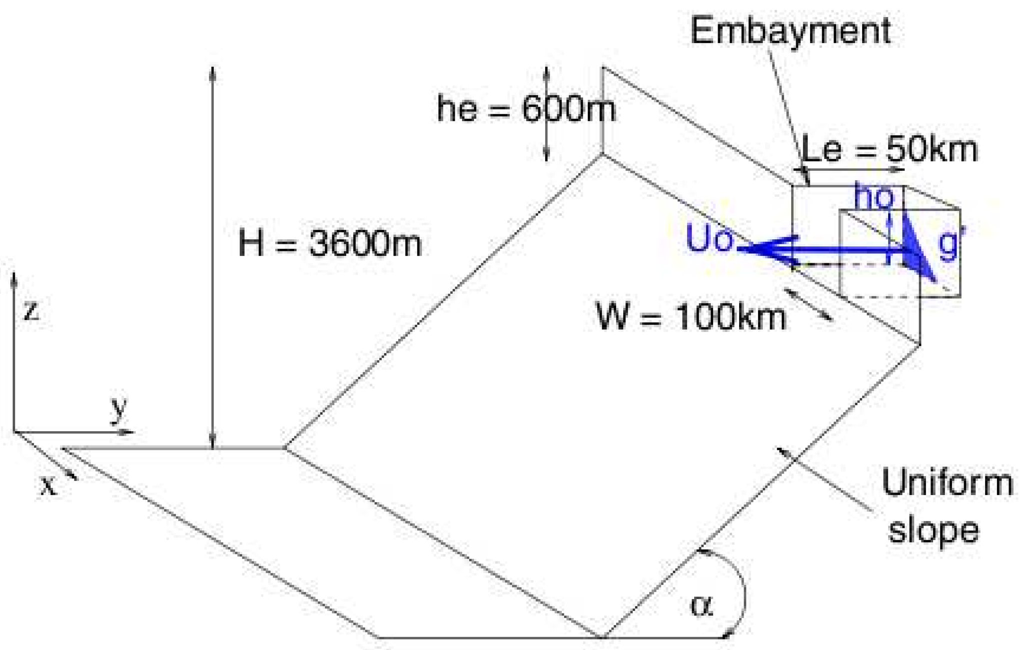

Figure 2: Schematic showing the model domain, with the overflow water entering through a flat bottomed embayment, which descends down a uniform slope from the northern side[1]

Similar research has been conducted using Z and Isopycnal (ALE) grids, which will be a good comparison for this work. We are interested in testing two grid sizes, the first being $\Delta x = \Delta y = 50$km, $\Delta z = 144$m, and the second being $\Delta x = \Delta y = 10$km, $\Delta z = 144$m.

Current Results

Some preliminary flow results can be seen below.

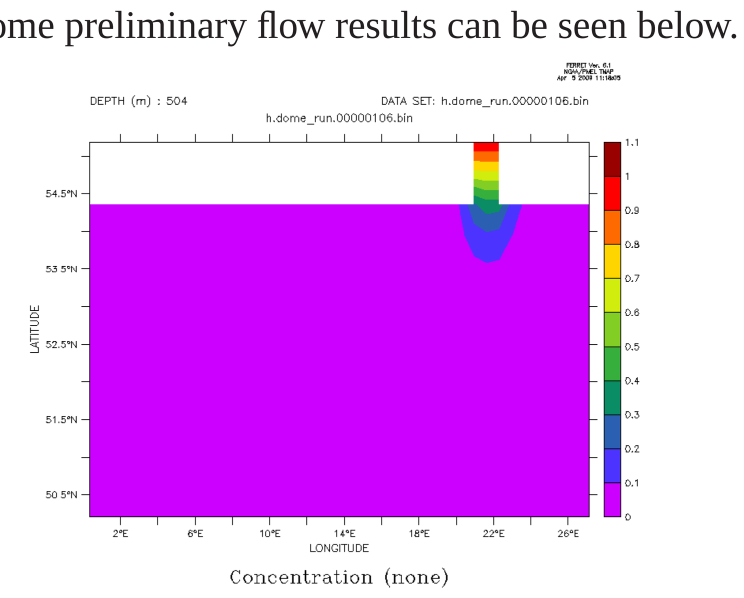

Figure 3: Concentration after 6 days

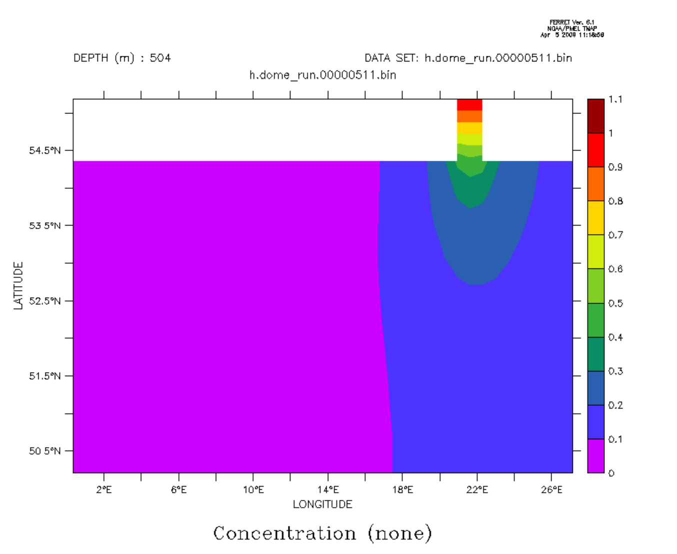

Figure 4: Concentration after 4 months and 11 days

These results were created on a $50km * 50km * 144m$ grid. The embayment was filled with cold dense water with an arbitrary concentration of 1, and the ambient water was linearly stratified with an arbitrary concentration of 0. There is also a very slow inflow of cold dense water with a concentration of 1 through the embayment.

Future Work

- Perform basic inflow runs on 10km*10km*144m Z grid
- Implement statistics for observations
- Migrate Grids and Statistics to HyPOP
- Test grids using ALE and Sigma Coordinate Grids

References

[1] S. Legg, R. W. Hallberg, J. B. Girton, Ocean Modeling **69**, 11, (2006).