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Spurious sea ice formation caused by oscillatory ocean tracer advection schemes

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ABSTRACT

Tracer advection schemes used by ocean models are susceptible to artificial oscillations: a form of numerical error whereby the advected field alternates between overshooting and undershooting the exact solution, producing false extrema. Here we show that these oscillations have undesirable interactions with a coupled sea ice model. When oscillations cause the near-surface ocean temperature to fall below the freezing point, sea ice forms for no reason other than numerical error. This spurious sea ice formation has significant and wide-ranging impacts on Southern Ocean simulations, including the disappearance of coastal polynyas, stratification of the water column, erosion of Winter Water, and upwelling of warm Circumpolar Deep Water. This significantly limits the model's suitability for coupled ocean-ice and climate studies. Using the terrain-following-coordinate ocean model ROMS (Regional Ocean Modelling System) coupled to the sea ice model CICE (Community Ice CodE) on a circumpolar Antarctic domain, we compare the performance of three different tracer advection schemes, as well as two levels of parameterised diffusion and the addition of flux limiters to prevent numerical oscillations. The upwind third-order advection scheme performs better than the centered fourth-order and Akima fourth-order advection schemes, with far fewer incidents of spurious sea ice formation. The latter two schemes are less problematic with higher parameterised diffusion, although some supercooling artifacts persist. Spurious supercooling was eliminated by adding flux limiters to the upwind third-order scheme. We present this comparison as evidence of the problematic nature of oscillatory advection schemes in sea ice formation regions, and urge other ocean/sea-ice modellers to exercise caution when using such schemes.

1. Introduction

A central element of ocean models is the advection of temperature and salinity, simulated using a number of different numerical methods (Griffies et al., 2000). These advection schemes are susceptible to various types of numerical error (Hecht et al., 2000; Shchepetkin and McWilliams, 1998; Lilly, 1965), including issues with stability, artifical dissipation (by which water masses overmix), and artifical oscillations. It is the last such issue that we focus on here. Oscillations, also known as overshoots or dispersion, are characterised by tracer fields that appear jagged and erratic after advection, with false extrema (Shchepetkin and McWilliams, 1998). These oscillations most likely occur near steep gradients in the given tracer field, which can be poorly resolved at low resolution.

Oscillatory behaviour in various tracer advection schemes has been well-studied (Hecht et al., 2000; Shchepetkin and

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McWilliams, 1998; Pietrzak, 1998), and its potential for undesirable feedbacks with ocean processes has been demonstrated (Hecht, 2010; Farrow and Stevens, 1995; Gerdes et al., 1991). However, there are no published investigations of how oscillatory behaviour interacts with coupled ocean/sea-ice models. When simulating regions of sea ice formation, there is a major threshold associated with the freezing point. Oscillations which cause the ocean temperature to fall below the freezing point therefore have physical significance beyond simple numerical error, as acknowledged by Hecht et al. (2000). In some ways this situation is similar to the simulation of regions with strong freshwater inflow, where oscillations could cause negative salinity.

In this study, we use a terrain-following-coordinate ocean model (Shchepetkin and McWilliams, 2005; Galton-Fenzi et al., 2012) with a coupled sea ice model (Hunke et al., 2015) to show that oscillatory tracer advection schemes have a significant impact on sea ice formation. When oscillations cause the ocean temperature to fall below the freezing point, this spurious supercooling is then removed from the near-surface layers as frazil ice. This frazil forms even if the ocean is already shielded from atmospheric heat fluxes by a layer of solid sea ice. As a result, unphysically thick patches of sea ice occur. These thick patches of sea ice have a significant influence on other physical processes, including coastal polynyas, stratification of the water column, dense water formation, and the properties of deep water masses. Note that despite the similar terminology, this phenomenon is distinct from the temporal oscillations in ice-ocean Ekman transport discussed by Roberts et al. (2015).

Steep horizontal gradients in tracer fields are more common in the local coordinate space of sigma- or terrain-following-coordinate ocean models (Griffies et al., 2000), which discretise the vertical dimension using fractional depth of the water column rather than absolute depth. Here we use “horizontal” to describe a line or surface of constant vertical level on the terrain-following grid, rather than of constant depth. If the underlying bathymetry is steep, horizontally adjacent grid cells can lie at quite different depths. A sharp gradient in depth often translates to a sharp gradient in tracers such as temperature or salinity. By contrast, the same region modelled with z-coordinates would have weaker temperature and salinity gradients between horizontally adjacent grid cells, which would by definition lie at exactly the same depth. Since the ocean is, for the most part, well mixed in the horizontal but stratified in the vertical, there are more opportunities for sharp horizontal gradients in sigma-space than in z-space. As a consequence, sigma-coordinate and terrain-following coordinate ocean models may be particularly susceptible to artificial oscillations over areas of steep bathymetry.

Advection schemes are typically tested on idealised domains, often at very high resolution and sometimes with reduced dimensionality. In practice, however, advection schemes are ultimately incorporated into “realistic configurations”, which we define here as three-dimensional forward models on observed domains, generally with rougher bathymetry and lower resolution than idealised setups. We believe it is valuable to communicate the effects of numerical error on realistic configurations, since they are the ones most often used to understand observations, make future projections, and ultimately inform policy. By understanding how errors present themselves in realistic domains, with realistic forcing and commonly used resolution, we hope to forewarn other members of the ocean modelling community who might otherwise experience similar problems, and to provide an acceptable solution.

2. Advection schemes

In a finite-volume discretisation of the primitive equations for ocean circulation, the concentration of a tracer at a given grid box represents the volume average over that grid box. The advection of the tracer depends on the advective fluxes through each face of the grid box. However, the calculation of these fluxes depends on the area-averaged concentration of the tracer over each face, and there is no exact solution for the interpolation of these values from the adjacent volume-averages. Several different numerical methods have been developed to address this interpolation, giving rise to different advection schemes. In our simulations we compare three different advection schemes from the standard distribution of ROMS (the Regional Ocean Modelling System (Shchepetkin and McWilliams, 2005)), as well as a limiter scheme designed to remove oscillations from one of the advection schemes.

2.1. Centered fourth-order

The centered fourth-order advection scheme (Shchepetkin and McWilliams, 2005) interpolates tracers to grid box faces using a midpoint-average modified by a gradient or curvative term. This interpolation is centered, and fourth-order accurate, in space. While this scheme is less prone to oscillations than its second-order counterpart (Shchepetkin and McWilliams, 1998), oscillations still occur (Leonard and Mokhtari, 1990).

2.2. Akima fourth-order

The Akima fourth-order advection scheme (Shchepetkin and McWilliams, 2005) differs from the centered fourth-order scheme only in its calculation of the gradient or curvature term, which utilises harmonic averaging rather than a simple midpoint average. Shchepetkin and McWilliams (2005) found that this scheme reduces oscillations compared to the centered fourth-order scheme.

2.3. Upwind third-order

There are several different schemes in the upwind third-order family; here we use the scheme known as UTOPIA (Shchepetkin and McWilliams, 2005; Rasch, 1994; Leonard, 1993). The interpolation of tracers to grid box faces is not centered in space, but rather is biased toward the upwind or upstream direction, which depends on the sign of the given velocity component. Upwind schemes in general suppress oscillations (Griffies et al., 2000), as the truncation errors associated with upwind interpolation are dominated by dissipation rather than dispersion. In first-order upwind schemes, this can lead to unphysical diapycnal mixing which breaks down fronts between water masses. In comparison, third-order schemes exhibit significantly reduced artificial dissipation (Leonard, 1993). The residual is considered “implicit diffusion” which can often be compensated for by reducing or even eliminating explicitly parameterised diffusion (Farrow and Stevens, 1995; Dinniman et al., 2015). Note that we use this scheme only for horizontal tracer advection; it is paired with the centered fourth-order advection scheme in the vertical.

2.4. Upwind limiters

While the upwind third-order scheme is known to significantly reduce oscillations compared to centered advection schemes, oscillations can still occur near sharp gradients (Leonard, 1993). These oscillations can be targeted and removed using a flux limiter scheme. Here we implement the “universal limiter” developed by Leonard and Mokhtari (1990) as part of the ULTRA-SHARP scheme; see also Norris (2000). This scheme calculates limits for the interpolated tracer values at each grid box face, and by enforcing these limits it clips false extrema, as follows:

Let C^* be the concentration of a tracer interpolated by the upwind third-order advection scheme to a given grid box face in the