Chaos in Ocean Ventilation
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Introduction
Ventilation of the subtropical North Atlantic ocean plays a critical role in climate by setting the properties of the ocean interior, including the rate of uptake of heat and carbon. Traditionally, the time-mean gyre circulation has been considered to dominate the ventilation process, such that water flows along time-mean, laminar streamlines into the ocean interior (Figure 1). However, the turbulent nature of the time-varying ocean circulation, manifest in a vigorous mesoscale eddy field, is likely to complicate the pathways along which water is transported. The purpose of this work is to quantify the chaotic nature of ventilation pathways in the subtropical ocean, challenging the existing paradigm of laminar ventilation.

Box A1: Strain
The impact of nonlinear flow on a patch of fluid is quantified by the strain.

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \text{strain} \]

where \( \frac{\partial u}{\partial x} \) and \( \frac{\partial v}{\partial y} \) are the gradients of the horizontal velocity components.

The filamentation number is large (>1) across two density surfaces in the subtropical North Atlantic thermocline (Figure 3). The filamentation number, calculated as a filamentation number, indicates the chaotic nature of ventilation pathways by which a region is ventilated. This is illustrated schematically in Figure 4, where we consider the ventilation pathways that were followed by adjacent particles on a density surface.

Evaluated in a 1/4º numerical ocean circulation model (NEMO), the filamentation number is large (>1) across two density surfaces in the subtropical North Atlantic thermocline (Figure 3). The extent of filamentation, approximated by the filamentation number, indicates the chaotic nature of pathways by which a region is ventilated. This is illustrated schematically in Figure 4, where we consider the ventilation pathways that were followed by adjacent particles on a density surface.

Figure 1: Illustration of the traditional view of subtropical ventilation, portraying the dominant role of the large-scale gyre circulation. From Rottino et al (2000).

Figure 2: Schematic illustration of the deformation of a rectangular fluid parcel at a stagnation point in a flow. The fluid parcel is highlighted in orange in its initial location and in green after some time t.

Figure 3: (a,b) Ventilation timespace (spatial median of Lagrangian age for 15,625 adjacent particles), (c,d) strain timescale (temporal median for last 30 years of model run) and (e,f) filamentation number on potential density surfaces 26 and 27 kg m⁻³ in a 1/4 degree ocean circulation model. Black regions were unventilated during the model run, grey regions were ventilated from regions outside the experimental domain.

Figure 4: Schematic illustration of laminar (blue) and chaotic (red) ventilation pathways for adjacent particles on a density surface. The particles are adjacent at time 1 and the 9th particle left the mixed layer at time t.

Figure 5: Mapping of ventilation year on 26 and 27 at the end of March 2010, evaluated by Lagrangian tracking. (a,b) Whole density surface, (c,d) 10x10 box at 1 km resolution, (e,f) 2x2 box at 200 m resolution. Black: particle unventilated in model run. Grey: particle ventilated outside experimental domain.

Mapping chaotic ventilation pathways
We perform the mapping illustrated schematically in Figure 4 to determine the ventilation year of patches of adjacent particles across two density surfaces and zoomed in on interesting regions.

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<th>( \sigma_0 = 26 \text{ kg m}^{-3} )</th>
<th>( \sigma_0 = 27 \text{ kg m}^{-3} )</th>
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<td>Small F</td>
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Summary
➤ A filamentation number (the ratio of ventilation and strain timescales) indicates the chaotic nature of ventilation pathways, and is found to be large across two density surfaces in the subtropical North Atlantic thermocline, particularly at depth.
➤ Mapping confirms the chaotic nature of ventilation pathways, with adjacent particles ventilated decades apart. The mapping also shows the stirring of fluid by mesoscale eddies.

References

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