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.

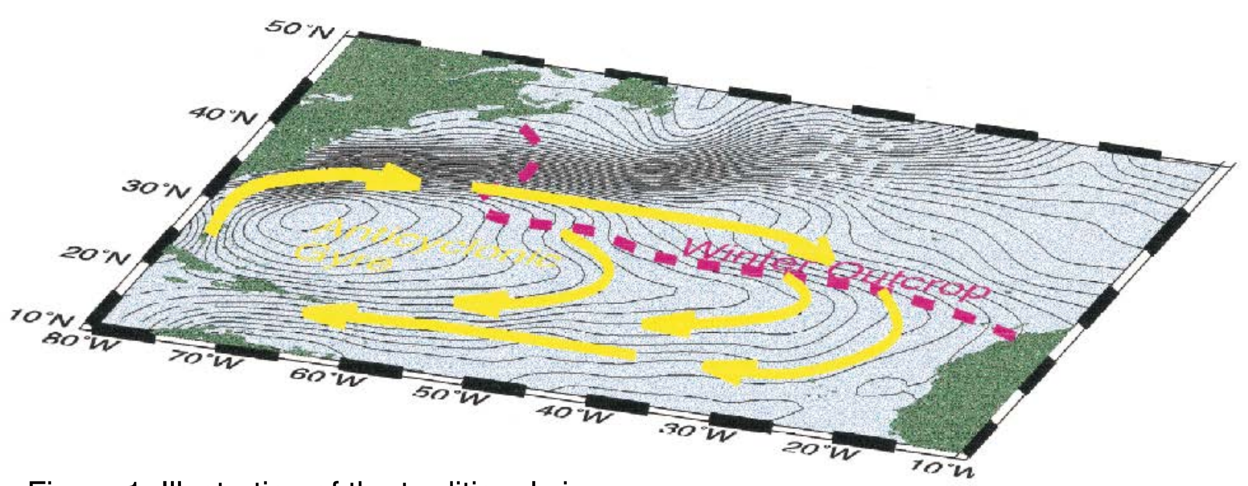

Figure 1: Illustration of the traditional view of subtropical ventilation, portraying the dominant role of the large-scale gyre circulation. From Robbins et al (2000).

Box A1: Strain

The impact of nonlinear flow on a patch of fluid is quantified by the strain. At a stagnation point in a two-dimensional, non-divergent flow, a rectangular fluid parcel will be exponentially filamented in time along the axis of principal strain (Figure 2).

Defining the side lengths as dx(t) and dy(t) parallel and perpendicular to the axis of principal strain, the fluid patch will evolve according to $dx(t)=dx(0)\exp(t/t_{strain})$, $dy(t)=dy(0)\exp(-t/t_{strain})$, where t_{strain} is the inverse of the strain rate (calculated from the horizontal velocity gradients).

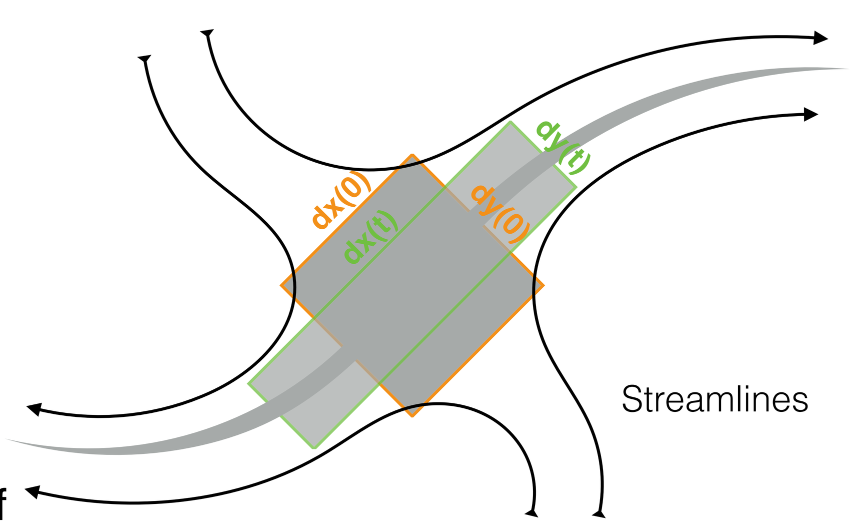

Figure 2: Schematic illustration of the deformation of a rectangular fluid parcel at a stagnation point in a flow. The fluid parcel is highlighted in orange in its initial location and in green after some time t.

Filamentation number

Mesoscale eddies rapidly reduce the filament width of ventilated fluid parcels (see Box A1). The extent of this filamentation can be approximated from the ratio of the timescales over which a given region is ventilated (t_{vent}) and strained (t_{strain}), defined as a 'filamentation number', F.

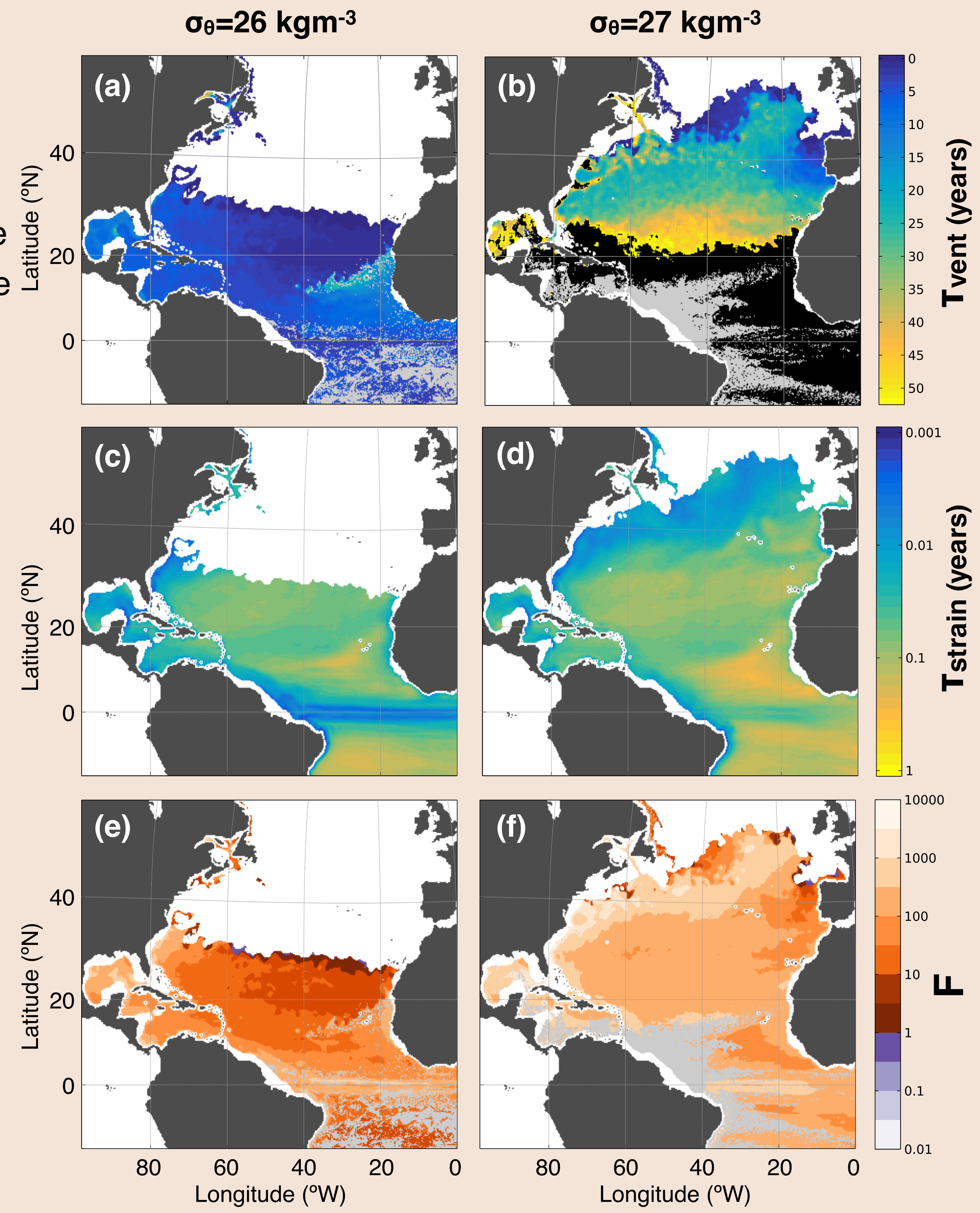

Figure 3: (a,b) Ventilation timescale (spatial median of Lagrangian age for 15,625 adjacent particles), (c,d) strain timescale (temporal median for last 30 years of model run) and (e,f) filamentation number on potential density surfaces 26 and 27 kg m^{-3} in a 1/4 degree ocean circulation model. Black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

Evaluated in a 1/4° 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.

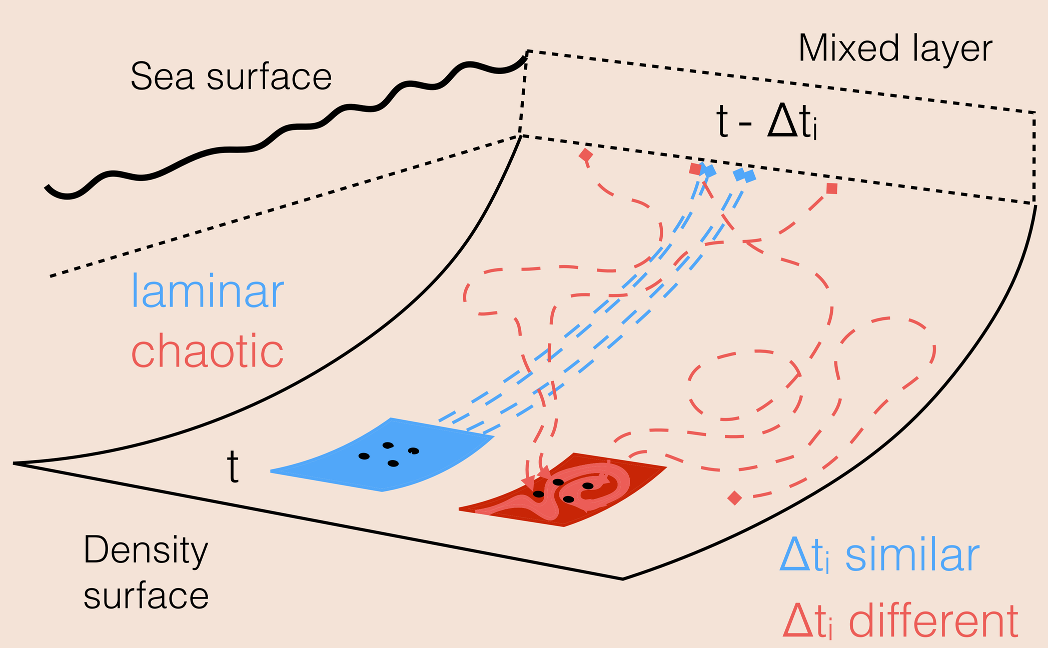

Figure 4: Schematic illustration of laminar (blue) and chaotic (red) ventilation pathways for adjacent particles on a density surface. The particles are adjacent at time t and the ith particle left the mixed layer at time ti.

Blue ~ small F (short ventilation time or laminar flow) ~ large filament width ~ adjacent particles ventilated at similar location and time ~ 'regular' mapping.

Red ~ large F (long ventilation time or turbulent flow) ~ small filament width ~ adjacent particles ventilated at different locations and times ~ 'chaotic' mapping.

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.

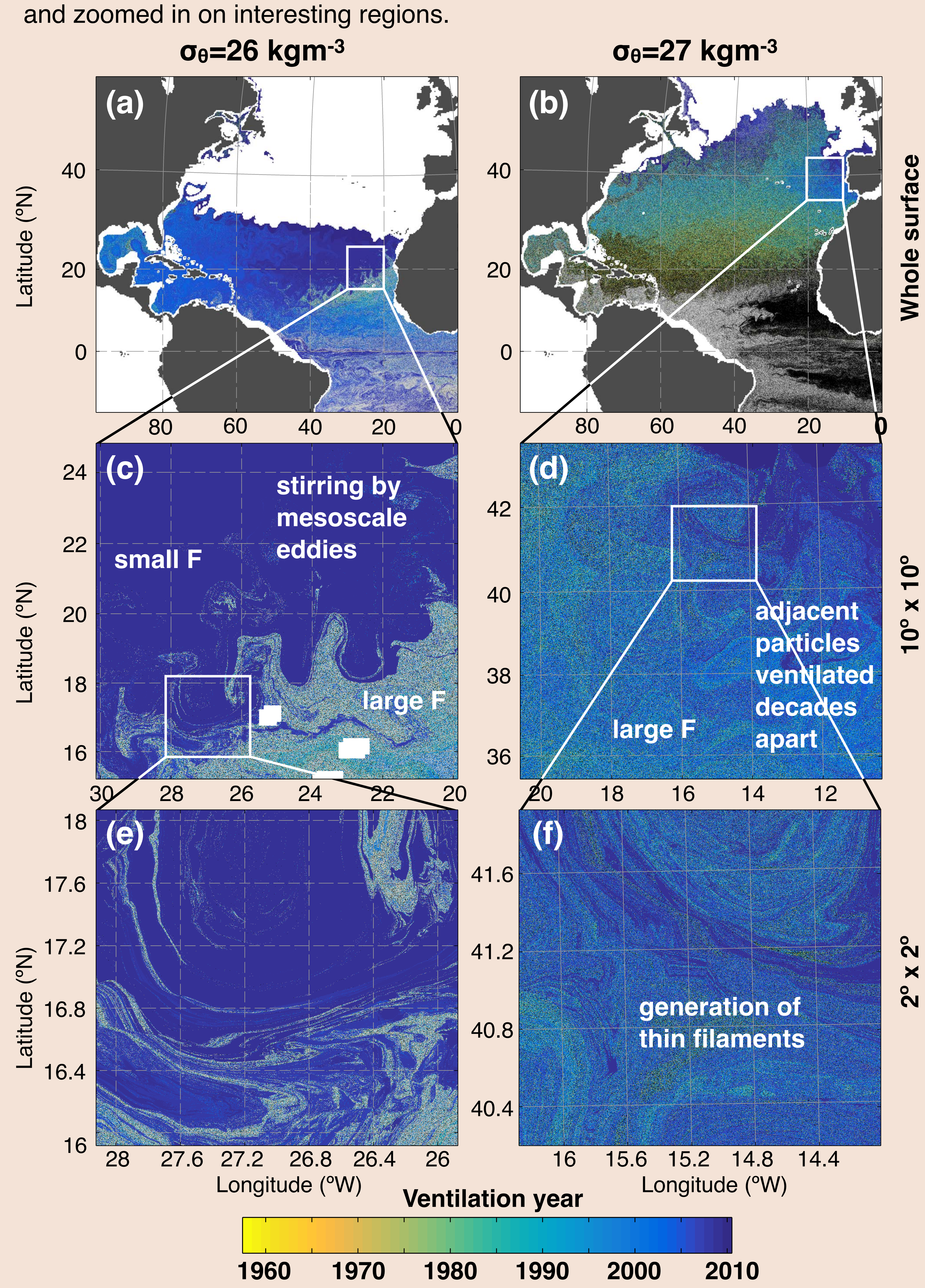

Figure 5: Mapping of ventilation year on 26 and 27 at the end of March 2010, evaluated by Lagrangian tracking. (a,b) whole density surface, (c,d) 10x10 box at 1 km resolution, (e,f) 2x2 box at 200 m resolution. Black: particle unventilated in model run. Grey: particle ventilated outside experimental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

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.

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References
Robbins, P. E. et al (2000) The importance of lateral diffusion for the ventilation of the lower thermocline in the subtropical North Atlantic. Journal of Physical Oceanography, 30:67-89.