



Pathways of upwelling deep waters to the surface of the Southern Ocean

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Upwelling of Atlantic, Indian and Pacific deep waters to the sea surface in the Southern Ocean closes the global overturning circulation and is fundamentally important for oceanic uptake of anthropogenic carbon and heat, nutrient resupply for sustaining oceanic biological production, and the melt rate of ice shelves. Here we go beyond the two-dimensional view of Southern Ocean upwelling, to show detailed Southern Ocean upwelling pathways in three dimensions, using hydrographic observations and particle tracking in high-resolution ocean and climate models. The northern deep waters enter the Antarctic Circumpolar Current (ACC) via narrow southward currents along the boundaries of the three ocean basins, before spiraling southeastward and upward through the ACC. Upwelling is greatly enhanced at five major topographic features, associated with vigorous mesoscale eddy activity. Deep water reaches the upper ocean predominantly south of the southern ACC boundary, with a spatially nonuniform distribution, regionalizing warm water supply to Antarctic ice shelves and the delivery of nutrient and carbon-rich water to the sea surface. The timescale for half of the deep water to upwell from 30°S to the mixed layer is on the order of 60-90 years, which has important implications for the timescale for signals to propagate through the deep ocean. In addition, we quantify the diabatic transformation along particle trajectories, to identify where diabatic processes are important along the upwelling pathways.