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**Key Points:**
- Southern Ocean eddies are key parts of the climate system
- Changes in the eddy field vary around the Southern Ocean basins
- Recent progress with high-resolution modeling highlights the relative importance of wind-driven versus stochastic variability

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# Understanding the structure of changes in the Southern Ocean eddy field

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**Abstract** The Southern Ocean is riddled with mesoscale eddies. Although just a few kilometers in size, these loops and vortices are key parts of the climate system and are important in controlling how ocean circulation responds to changes in forcing. Observations reveal that changes in the intensity of these eddies vary significantly around the Southern Ocean. This contrasts with the nature of the atmospheric forcing, which is more zonally symmetric. Recent progress using high-resolution modeling has pinpointed where intrinsic variability dominates over wind-driven variability; and hence, the areas where future responses to climatic changes in forcing are likely to be clearest.

## 1. Introduction

The global ocean is a fundamental component of the climate and ecological systems of our planet. It absorbs anthropogenic carbon and heat from the atmosphere, thus moderating the rate of climate change. In this role, the Southern Ocean—the vast sea that encircles Antarctica—is especially important, accounting for around half of the oceanic uptake of carbon and more than three quarters of its heat uptake [*Frölicher et al.*, 2014; *Mikaloff Fletcher et al.*, 2006]. This disproportionate influence is a consequence of the unique pattern of circulation of the Southern Ocean. Driven by the mighty westerly winds overlying it, and by strong exchanges of heat and freshwater at the sea surface, the Antarctic Circumpolar Current (ACC) flows continuously around the continent and is the largest current system on the planet (Figure 1). It redistributes heat, carbon, freshwater, and other important environmental properties between each of the world's major ocean basins, thus setting their large-scale distributions across the planet [*Rintoul et al.*, 2001].

The Southern Ocean is also significant as the key site globally where waters from 1 to 2 km depth rise up to the surface (Figure 1). This brings waters that are several hundred years old (and hence formed in a preindustrial era) into contact with the atmosphere, with which they can exchange heat and carbon [*Lumpkin and Speer*, 2007]. New water masses are formed that sink back into the interior of the ocean; these include the comparatively light mode and intermediate waters that sink to a few hundred meters depth and the dense bottom waters that flood the deepest layers of the global abyss [*Johnson*, 2008; *McCartney*, 1977].

Against this background of large-scale flows and planetary scale climate, it is increasingly being seen that small-scale processes are critical in structuring the ocean circulation and controlling its effects. Mesoscale eddies—the weather systems of the sea—are much smaller than their atmospheric counterparts, but their profound importance belies their size. In the Southern Ocean, a band of enhanced eddy variability lies along the path of the ACC (Figure 2); these eddies account for the majority of poleward oceanic heat transport across the current. Importantly, the small size of these eddies (a few kilometers to just a few tens of kilometers) means that most state-of-the-art climate models cannot resolve them explicitly and instead use parameterizations to attempt to capture their effects [*Gent and Danabasoglu*, 2011].

Dynamically, the role that these eddies play is of profound importance. While the ACC is at least partially wind forced, changes in its flow are known to be surprisingly small, despite much larger changes in the overlying wind field [*Böning et al.*, 2008]. One key factor in this is a cascade of energy from large scales (the hundreds or thousands of kilometers that typify basin-scale ocean circulation) to the much smaller scales that typify oceanic eddies. Consistent with this, observations from satellites indicate that the Southern Ocean eddy field varies more significantly in response to winds than does the ACC flow itself [*Hogg et al.*, 2015; *Meredith and Hogg*, 2006]. Further, it is known that changes in the wind-driven overturning circulation of the Southern Ocean (the collective upwelling of old waters and sinking of new waters; Figure 2) are dampened by eddy processes [*Marshall and Speer*, 2012].

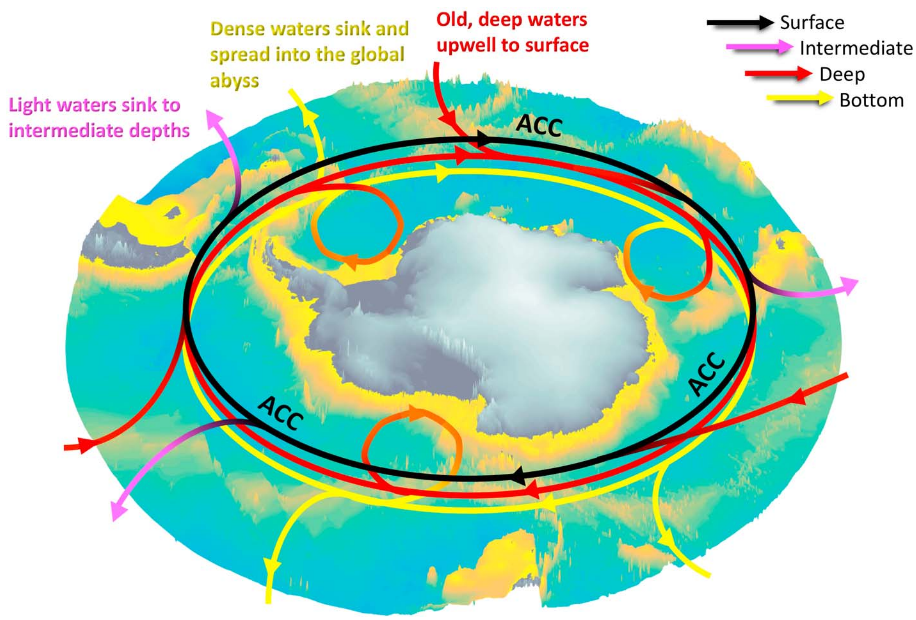


**Figure 1.** Schematic of the three-dimensional circulation of the Southern Ocean overlaid on the regional bathymetry. Mesoscale eddies play a key role in determining this circulation, being intimately involved in the upwelling of old, deep waters to the surface and in moderating the rate at which new water masses are formed and sink. Eddies also act to suppress changes in the horizontal flow of the Antarctic Circumpolar Current (ACC), the world's largest current system.

Despite a widespread acceptance of the importance of Southern Ocean eddies, some key aspects of their functioning have proved challenging to interpret, including the spatial structure of their temporal changes. Initial reports emphasized the circumpolarity of the wind-driven changes in the eddy field [*Meredith and Hogg*, 2006], though more recently it was noted that the Pacific, Indian, and Atlantic sectors of the Southern Ocean do not behave identically and the potential role of the El Niño–Southern Oscillation phenomenon has been suggested [*Morrow et al*., 2010]. Such issues are hard to assess using observational data alone: even with the availability of satellite-derived measures of surface eddy intensity (e.g., Figure 2), full understanding requires detailed dynamical investigations and additional insights below the sea surface.

## 2. Advances With Eddy-Resolving Simulations

Recent progress has been made using high-resolution ocean modeling, which has the potential for revealing the underlying dynamics of the changes observed, but which must be sufficiently realistic for the results to be reliably translatable to real-world scenarios. *Patara et al*. [2016] conducted simulations spanning several decades using a novel global ocean model configuration, with realistic seabed topography and eddy-resolving

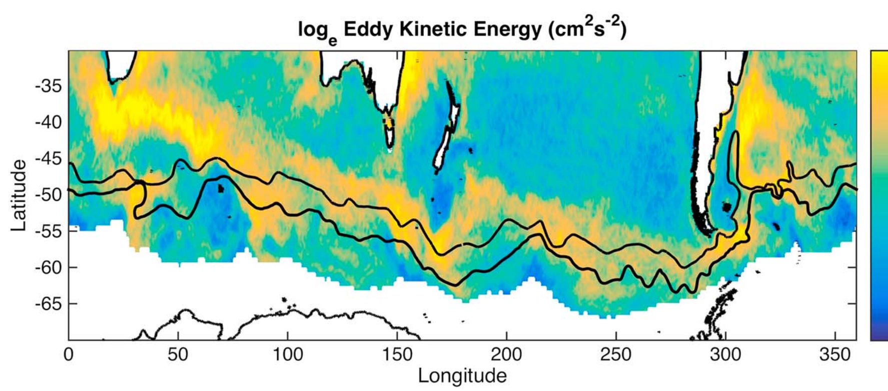


**Figure 2.** Distribution of the intensity of mesoscale eddies in the Southern Ocean, as depicted by the pattern of eddy kinetic energy measured by satellite radar instruments. The two main current cores of the ACC are marked (black lines), following *Orsi et al*. [1995].

(1/12°) resolution in the ACC region. Encouragingly, the model performed well in reproducing the observed spatial pattern in eddy intensity in the Southern Ocean and also its recently observed trends [*Hogg et al*., 2015]. The model was also able to reproduce a lagged response of eddy activity to changes in wind forcing, not dissimilar to that observed from satellite measurements [*Meredith and Hogg*, 2006].

This performance builds confidence that such models can capture many of the main elements of the Southern Ocean eddy field and their influence on globally-important flows. To investigate further the cause of the spatial pattern in the time-varying eddy distribution, *Patara et al*. [2016] derived a quantity that estimates how much of the eddy variability at a particular location is atmospherically forced, and how much is intrinsic. This is an important consideration: the Southern Ocean eddy field can generate its own variability via complex feedbacks that involve interaction with the seabed [*Hogg and Blundell*, 2006] and which could confound simple attempts to relate variability to surface forcings. *Patara et al*. [2016] found that the sensitivity of eddy intensity to changes in winds on interannual timescales is not uniformly distributed along the ACC. In the Pacific and Indian sectors of the Southern Ocean, the simulated eddy field was found to have a variability that matched that inferred from satellite observations and to be significantly dependent on changing winds. Conversely, in the Atlantic sector the eddy variability was seen not to match the satellite observations and was found to be mostly stochastic in nature.

The relative importance of stochastic and wind-driven contributions to interannual eddy variability was also reflected in different multidecadal trends, which were found to be stronger and predominantly wind-forced in the Pacific and Indian Oceans and weaker and more stochastic in the Atlantic. This represents progress in explaining the recently reported decadal trends in eddy intensity, which was found to be accelerating significantly around the Southern Ocean except in the Atlantic [*Hogg et al*., 2015]. *Patara et al*. [2016] speculate that the cause of the different behavior in the Atlantic could be due to the ACC being anomalously unstable upon leaving Drake Passage (the gap between South America and Antarctica, and the narrowest constriction of the ACC along its path) and potentially also due to the influence of highly variable systems on the northern flank of the ACC in the Atlantic, such as the Brazil-Malvinas Confluence zone and the Agulhas Retroflection.

Looking forward, the westerly winds that overlie the Southern Ocean are projected to continue strengthening under continued greenhouse gas forcing, and the work of *Patara et al*. [2016] reinforces assertions that the oceanic eddy field is likely to change in response, with potentially significant impacts. In particular, changes in mesoscale activity in a particular locality could impact upwelling, water mass formation, sea ice production and melt, marine biogeochemistry, and biological productivity. The findings of *Patara et al*. [2016] demonstrate that such future changes are likely to be markedly nonuniform in distribution, despite the much more zonally coherent changes in winds that may be driving them.

There are many unanswered questions, however, and many challenges remain in relation to our understanding and ability to predict the role of Southern Ocean eddies in the planetary system. The regionality of changes in eddy intensity is now well established, and its causes are becoming better known. Within these regions, areas of high eddy intensity associated with topographic obstacles and standing meanders of the ACC are increasingly being seen as important, both for determining the mean structure of the ACC and its overturning circulation [*Thompson and Naveira Garabato*, 2014]. It is important that we improve our understanding on this local scale and better determine the impacts of the difference in dynamics between these "hot spots" of variability and the rest of the ACC. Future effort should also investigate whether eddies will continue to moderate changes in overturning circulation to the same degree and whether any future reversals in the recent strengthening of winds over the Southern Ocean will return the circulation to the same state as it was previously or to a different one. There is also much to learn about the processes and rates by which Southern Ocean eddies act to mix deep and abyssal waters and how these rates will change as climatic forcing of the circulation evolves. Nonetheless, studies such as *Patara et al*. [2016] give cause for optimism that the spatially and temporally changing Southern Ocean eddy field could be represented well in future climate modeling efforts and that their depictions of the Southern Ocean's role in global climatic and ecological systems might be more reliably predicted.

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