A New Dynamical Feature of Wind-driven Ocean Circulation

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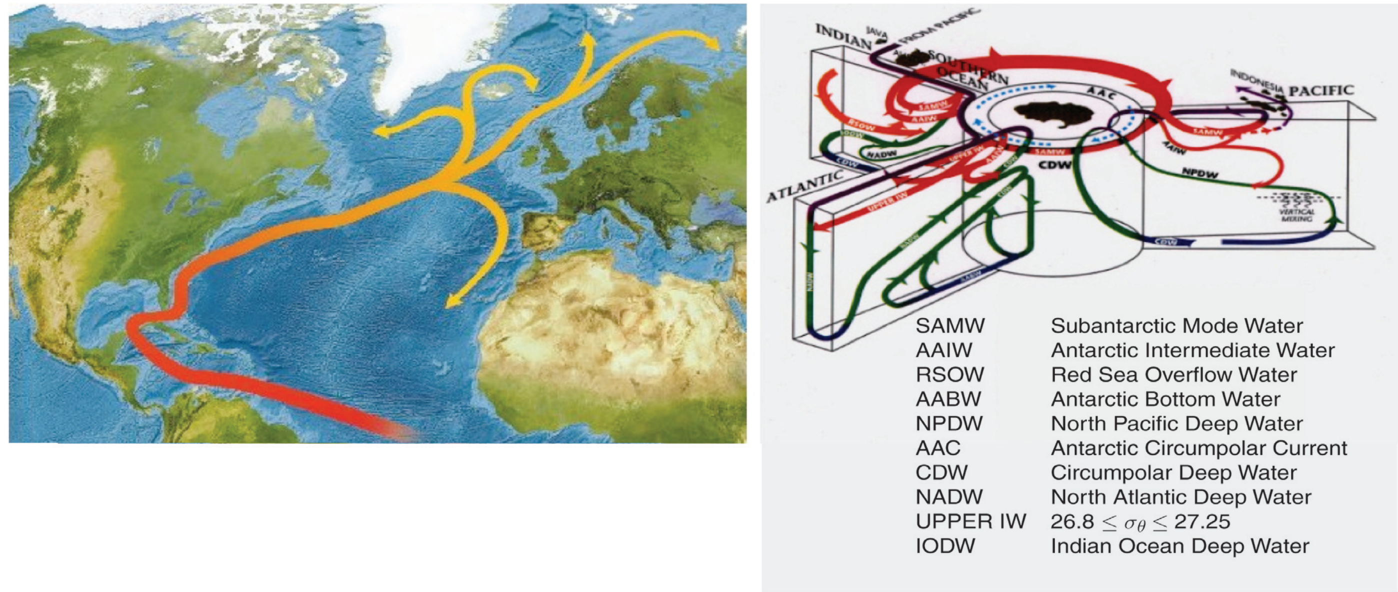
The Climate, Ocean, and Sea Ice Modeling (COSIM) project at LANL aims to develop, test, and apply ocean and ice models in support of DOE Climate Change Research and to deliver improved climate data and models needed to determine acceptable levels of greenhouse gas emissions (http://climate.lanl.gov).

Roughly half of the heat from the tropical regions that receive an excess of insolation is transported poleward by the world's oceans to the higher latitudes as part of the global climate system. While this is achieved through a combination of complicated and interlinked circulation patterns, it is useful to separately consider the swifter and mainly horizontal wind-driven circulation of the upper ocean (e.g., Fig. 1) and the large-scale overturning, but more sluggish buoyancy-driven "conveyor belt" circulation of the full ocean (Fig. 1), since the dynamics of these two circulation patterns are distinct.

The classical picture of wind-driven gyre circulation is one of broad, sweeping flows associated with the interiors of the large-scale wind-driven subtropical gyres of the upper ocean (see Fig. 2). The subsequent discovery of mesoscale eddies seemingly rounded off our understanding of such wind-driven gyre circulation. However, in a fundamental departure from this understanding, we find that multiple, alternating zonal-jet structures can develop in the ocean (in addition to the usual gyre circulation and mesoscale eddies) in response to purely large-scale and steady-wind forcing (see Fig. 2 [1,2]).

To place these results in context, we note that recent observational [3] and computational (e.g., [4,5]) evidence point to the occurrence of alternating zonal jets in the world oceans (see Fig. 3). These jets bear a similarity to the more exotic alternating zonal jets in Jovian atmospheres (e.g. [6])—a crucial difference, however, is their weaker amplitude with respect to other dynamical features in Earth's oceans. Studies of zonal jets in the presence of the important oceanic effects of continental boundaries and nonuniform stratification are at present lacking, and this study aims to fill an important gap in the understanding of the dynamics of these jets.

As to the practical relevance of the study, consider: the way in which the rapidly rising levels of CO_2 in the atmosphere plays out in terms of climate change is crucially controlled by the dynamics of ocean circulation. However, ocean circulation itself is a strongly coupled multiscale phenomenon with important dynamics spanning vast ranges of spatial and temporal scales. Also note that a striking aspect of ocean circulation is that the dynamics over this vast range of scales is associated with a multitude of coherent features at different scales (somewhat in contrast to idealized studies of classical 3D turbulence, which is homogeneous and soup-like). Alternating zonal jets in the world oceans is one such new feature at scales intermediate between the gyre scale circulation and mesoscale eddies. Thus, from the point of view of modeling ocean circulation, a removal of the scale-gap that was assumed to exist between mesoscale eddies and gyre-scale circulation makes the parameterization problem more difficult for coarse-scale studies, but opens up the possibilities for more sophisticated and anisotropic parameterization schemes. Furthermore, the likely ubiquitous presence of multiple zonal jets and their effect on the transport of important scalars could lead to fundamental improvements in our understanding of global ocean circulation. For example, the enhancement of potential vorticity gradients at the boundaries of these jets acts as a barrier to mixing.



SAMW	Subantarctic Mode Water
AAIW	Antarctic Intermediate Water
RSOW	Red Sea Overflow Water
AABW	Antarctic Bottom Water
NPDW	North Pacific Deep Water
AAC	Antarctic Circumpolar Current
CDW	Circumpolar Deep Water
NADW	North Atlantic Deep Water
UPPER IW	$26.8 \leq \sigma_\theta \leq 27.25$
IODW	Indian Ocean Deep Water

Fig. 1. Global ocean circulation that accounts for roughly half of the poleward heat transfer (that drives the climate system) is a combination of a) surface-intensified wind-driven circulation, as exemplified by the Gulf Stream and the subtropical gyre of the North Atlantic (shown on the left), and b) large-scale overturning circulation that is buoyancy-driven and popularly called the ``conveyor-belt'' circulation (schematic on right from [7]).

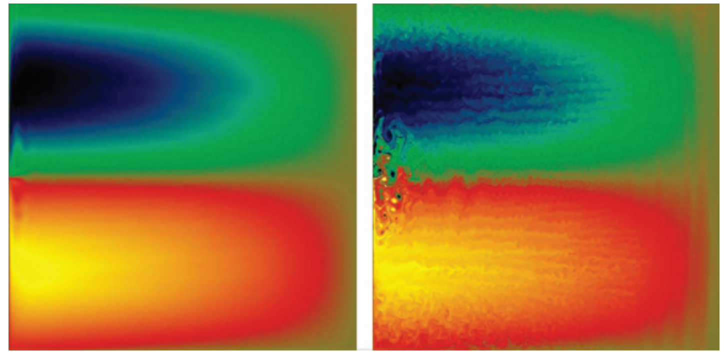


Fig. 2. In an idealized setting of the wind-driven circulation, broad, sweeping flow in the interiors accompanied by swift return western boundary currents are expected (as on the left). Instability of such a circulation gives rise to mesoscale eddies (as seen in the western central region in the picture on the right). But we find for the first time that even with steady and large-scale winds alone, distinct multiple zonal jets—jets that are narrow in the latitudinal direction and elongated in the zonal direction—can appear (as in the picture on the right). In these pictures, the baroclinic stream function is colorcoded—the domain is a mid-latitude ocean basin forced by steady double-gyre wind forcing. The x-axis points eastward and the y-axis points northward.

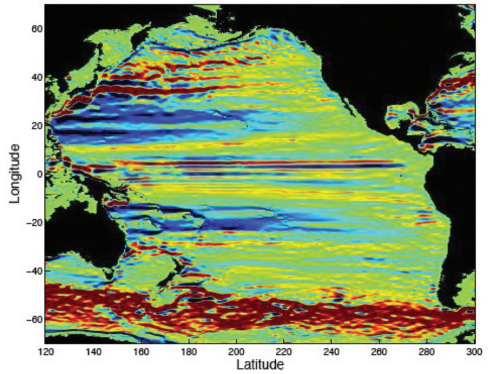


Fig. 3. Computational and observational evidence for alternating zonal jets in the world oceans have emerged in the past few years. For example, in this figure from [5], showing zonal velocity at 400 m, alternating zonal jets are evident in the Pacific. This study used POP, developed at LANL (http://climate.lanl.gov), and is forced by unsteady winds and buoyancy. Simplified process studies as in Fig. 2 help us better understand the dynamics and importance of such jets.

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