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ENERGETIC DYNAMICS OF OCEAN BASIN MODEL WITH ROTATION, SURFACE WIND, AND BUOYANCY FORCING

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EXECUTIVE SUMMARY

The sensitivity of the circulation in the Southern Ocean to changes in surface wind stresses is one of the pivotal questions in oceanography. We employed an idealized rectangular rotating model of this ocean basin and forced it at the surface with a buoyancy flux that varied with latitude and with wind stress profiles that differ in shape and magnitude between simulation runs. The resulting flow is primarily wind-driven mean flow and is compensated by small-scale transient eddies. The circulation within the domain is affected by both the magnitude of the wind stress and symmetry/asymmetry between the Easterlies and the Westerlies. As the wind stress increases, the circulation progresses from a buoyancy-driven regime dominated by dense water formation in the south to a wind-driven regime. We found that when the surface winds are too strong or the Westerlies and the Easterlies are of the same magnitude (unlike the modern-day ocean), the circulation differs significantly from the one observed in the ocean under modern-day wind stress and surface buoyancy conditions.

RESEARCH CHALLENGE

The Southern Ocean, the region of the ocean between the Antarctic continent and the continents to the north, plays an important role in the global meridional transport of heat and tracers, oxygenation of the bottom waters via the formation of dense Antarctic Bottom Water, and sequestration of atmospheric carbon. The energy in the Southern Ocean is drawn both from the strong and consistent zonal winds and differential surface buoyancy forcing. The circulation of the Southern Ocean can be divided into three distinct cells: the dense water formation cell originating near Antarctica (the lower cell), a cell of water originating in the North Atlantic that flows south at mid-depth and upwells in the Southern Ocean (the upper cell), and a surface water cell at mid-latitudes.

The response of the ocean circulation, in the Southern Ocean in particular, to changes in surface wind patterns due to changing climate has been one of the pivotal questions in oceanography. The changes in meridional, and particularly vertical transport, would affect the rates of carbon sequestration or its release back into the atmosphere and the supply of nutrients to support primary production in surface waters and the ocean food web.

METHODS & CODES

We ran five direct numerical simulations of an idealized rotating rectangular ocean basin, resolving the smallest dissipative scales, using the SOMAR code. All simulations were forced with a variable surface density field (dense near the southern end and lighter at the northern end of the domain). One simulation had only differential surface density profiles and no surface wind stress, and the remaining four simulations were forced with surface wind stress profiles of different magnitude and symmetry between the Easterlies and the Westerlies. These simulations were run from arbitrary initial conditions to a statistical steady state, such that both kinetic and available potential energies were not significantly variable in time. Each run was analyzed for the circulation stream functions and terms of the energy budget as well as the exchange rates between the kinetic and available potential energy reservoirs.

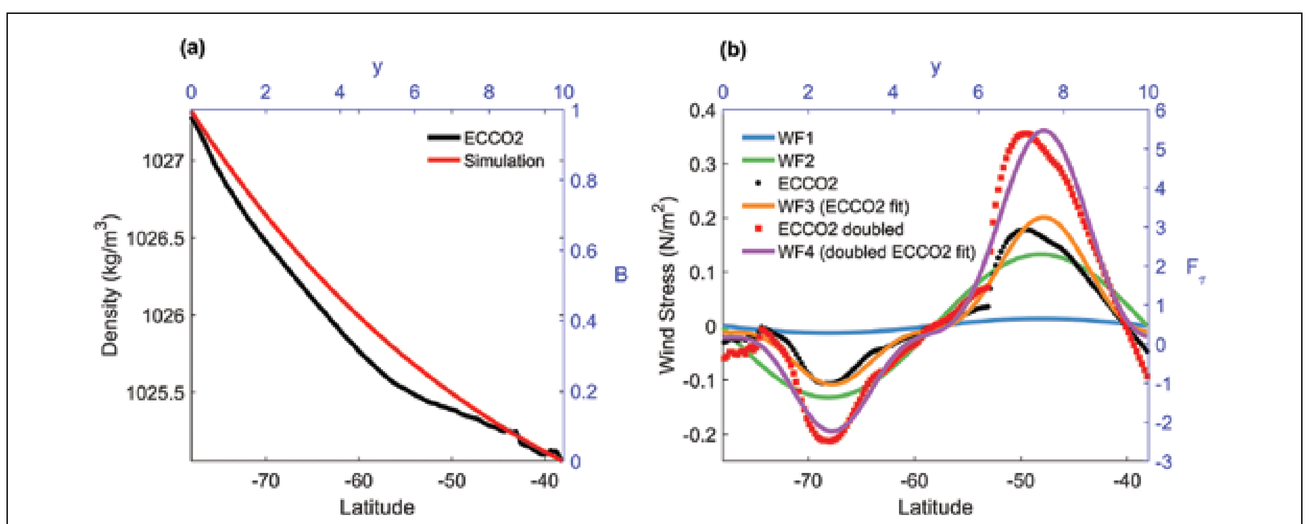

Figure 1: a) Surface density distribution over the Southern Ocean (ECCO2) and from the simulation boundary conditions. (b) Surface wind stress profiles: WF1 and WF2 are sinusoidal with symmetric Easterlies and Westerlies; WF3 is a polynomial fit of the wind stress over the Southern Ocean; WF4 is twice the magnitude of WF3. The black axes represent the parameters using the dimensional ocean values. The blue axes represent the nondimensionalized values used in the DNS.

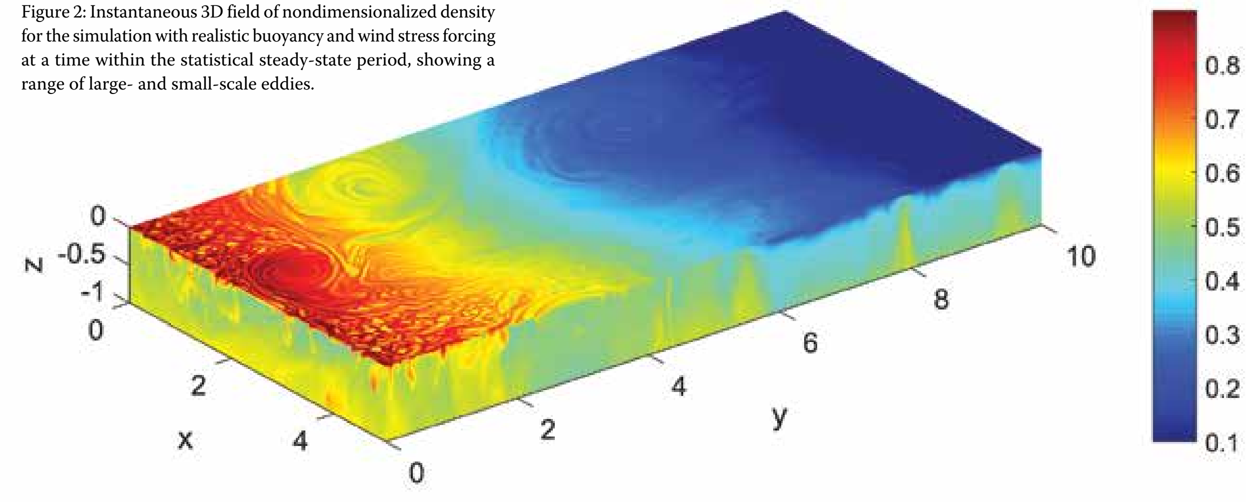

Figure 2: Instantaneous 3D field of nondimensionalized density for the simulation with realistic buoyancy and wind stress forcing at a time within the statistical steady-state period, showing a range of large- and small-scale eddies.

RESULTS & IMPACT

Many of the previous studies of the effects of increasing wind stress magnitudes with climate change have only focused on the changes in the Westerlies, disregarding how the interplay between the Easterlies and the Westerlies affects the circulation dynamics in the Southern Ocean. The Easterlies will become particularly important as ice melting progresses near Antarctica, exposing greater surface area affected by these winds.

This work is one of the first direct numerical simulation studies, resolving all energy scales of the system and dividing the flow into mean and turbulent components. Our study shows that as the wind stress, and subsequently the kinetic energy generation of the system, increases, the increase in the mean flow circulation that is wind-driven is compensated for by dissipation via smaller, transient turbulent eddies, and thus the dissipation of available potential energy (irreversible mixing) is unaffected by the wind stress magnitude.

However, the circulation in the basin is sensitive to both the profile shape and the magnitude of the surface wind stress. When there are no surface winds or the wind stress is small, the basin is dominated by the lower dense water formation cell. When the wind stress is double in magnitude of the modern-day wind stress levels, the basin is primarily wind-driven, dominated by the upper cell of waters traveling from the northern hemisphere at mid-depth and upwelling in the Southern Ocean, while the dense water formation cell disappears.

This lower cell also is not present when the maximum magnitudes of the Easterlies and the Westerlies are equal. The balance between the deep dense water formation cell at the southern end and the wind-driven upwelling cell in the middle, as observed in the Southern Ocean today, is only achieved when the wind stresses are of modern-day magnitude, and the Westerlies are approximately twice as strong as the Easterlies. The disappearance of the dense water formation cell under two other scenarios is particularly important to note because this cell plays a vital role in supplying oxygen to the bottom ocean waters and sequestering atmospheric carbon below the mixed layer.

WHY BLUE WATERS

The direct numerical simulations are highly computationally intensive because of the great spatial resolution required for the small dissipative scales. In addition, these simulations need to be run for 70,000 to 100,000 timesteps, which takes several months, in order to reach a statistical steady state. We are interested in both the temporal-average and the deviations from the mean field, meaning that output files (approximately 2.8 GB per file, one per timestep) have to be stored for further analysis.

Varvara Zemskova is a sixth-year PhD student studying physical oceanography at the University of North Carolina at Chapel Hill. She is working under the supervision of Brian White and planned to graduate in December 2018.