nature geoscience

ARTICLES

PUBLISHED ONLINE: 14 MARCH 2010 | DOI: 10.1038/NGEO812

Zonally asymmetric response of the Southern Ocean mixed-layer depth to the Southern Annular Mode

J. B. Sallée[1]*, K. G. Speer[2] and S. R. Rintoul[1]

Interactions between the atmosphere and ocean are mediated by the mixed layer at the ocean surface. The depth of this layer is determined by wind forcing and heating from the atmosphere. Variations in mixed-layer depth affect the rate of exchange between the atmosphere and deeper ocean, the capacity of the ocean to store heat and carbon and the availability of light and nutrients to support the growth of phytoplankton. However, the response of the Southern Ocean mixed layer to changes in the atmosphere is not well known. Here we analyse temperature and salinity data from Argo profiling floats to show that the Southern Annular Mode (SAM), the dominant mode of atmospheric variability in the Southern Hemisphere, leads to large-scale anomalies in mixed-layer depth that are zonally asymmetric. From a simple heat budget of the mixed layer we conclude that meridional winds associated with departures of the SAM from zonal symmetry cause anomalies in heat flux that can, in turn, explain the observed changes of mixed-layer depth and sea surface temperature. Our results suggest that changes in the SAM, including recent and projected trends attributed to human activity, drive variations in Southern Ocean mixed-layer depth, with consequences for air–sea exchange, ocean sequestration of heat and carbon, and biological productivity.

The Southern Annular Mode (SAM) refers to an oscillation of atmospheric mass that results in changes in the westerly winds over the Southern Ocean. The positive phase of the SAM is associated with a poleward shift and strengthening of the westerlies[1]. On timescales from a few weeks to years, the SAM is the dominant mode of variability of the Southern-Hemisphere atmosphere. A tendency towards an increasingly positive SAM in recent decades is one of the strongest climate trends observed in the Southern Hemisphere. The trend has been attributed to loss of ozone in the polar stratosphere resulting from human activities[2]. Climate models predict that increases in greenhouse-gas forcing will cause a similar strengthening of the westerlies[3,4].

The influence of the SAM is manifest in many variables, including sea-level pressure, surface air temperature and geopotential height[1]. In the ocean, the SAM has been related to variability in sea ice, eddy kinetic energy, sea surface temperature (SST) and circulation[5–12]. Changes in the upper ocean associated with SAM forcing have an impact on carbon uptake and storage in the Southern Ocean, both directly, through upwelling and outgassing[13], and indirectly, by influencing nutrient cycles and phytoplankton activity[14,15].

Changes in the mixed-layer depth (MLD) have significant implications for both physical and biogeochemical processes. Correlations between horizontal velocity and variations in the MLD result in an exchange of fluid between the mixed layer and the ocean interior (that is, subduction)[16]. Intermediate waters subducted in the Southern Ocean ventilate the thermocline of the Southern-Hemisphere subtropical gyres and contribute to global budgets of heat, fresh water and nutrients[17–20]. Most of the anthropogenic carbon stored by the Southern-Hemisphere oceans has accumulated in the intermediate waters whose properties are set in the mixed layer of the Southern Ocean[21]. Anomalies in MLD modulate the exchange of oxygen and carbon dioxide between the ocean and the atmosphere[14,15]. The depth and the properties of the mixed layer also influence the availability of light and nutrients to support phytoplankton growth and therefore the overall level of biological productivity in the sea[22].

The depth and properties of the mixed layer are influenced by mechanical stirring by the wind stress and by buoyancy forcing: buoyancy loss drives convection and entrainment of underlying fluid; buoyancy gain restratifies the water column and inhibits entrainment. The mixed layer would therefore be expected to respond to changes in the atmosphere associated with climate variability and change, including the SAM and greenhouse warming. However, the response of the ocean mixed layer to changes in atmospheric forcing has not been measured owing to a lack of long-term observations in the remote Southern Ocean. The Argo programme now provides more than seven years of temperature and salinity profiles, allowing a better understanding of the dynamics and variability of the mixed layer[16,23]. Here we use the Argo profiles to relate variability in the MLD to the SAM, providing the first strong evidence of the influence of climate variability on the stratification of the upper layer of the Southern Ocean.

Variability of the Southern Ocean mixed layer

Argo floats drift with the ocean currents and measure a vertical profile of temperature and salinity in the upper 2,000 m every ten days. The floats have already provided more profiles than the historical ship-based data set. We can now resolve the large-scale structure and seasonal cycle of the MLD in the Southern Ocean (Fig. 1). Summer MLDs reach about 100 m in the vicinity of the Antarctic Circumpolar Current (ACC). Winter cooling destabilizes the water column and increases the MLD. The deepest winter mixed layers (and largest seasonal cycles) are found north of the ACC, particularly in the eastern Indian and Pacific oceans. Removal of buoyancy during autumn and winter gradually deepens the mixed

[1]CSIRO-CMAR/CAWCR, Castray Esplanade, Hobart 7000, Tasmania, Australia, [2]Oceanography, Florida State University, 900 Call St, Tallahassee, Florida 32306, USA. *e-mail: jbsallee@gmail.com.

26. Kraus, E. B. & Turner, J. S. A one-dimensional model of the seasonal thermocline. *Tellus* **19,** 88–97 (1966).
27. Rintoul, S. & England, M. Ekman transport dominates air–sea fluxes in driving variability of Subantarctic Mode Water. *J. Phys. Oceanogr.* **32,** 1308–1321 (2002).
28. Dong, S., Sprintall, J. & Gille, S. An assessment of the Southern Ocean mixed layer heat budget. *J. Clim.* **20,** 4425–4442 (2007).
29. Boyd, P. P. W. *et al.* Climate-mediated changes to mixed-layer properties in the Southern Ocean: Assessing the phytoplankton response. *Biogeosciences* **5,** 847–864 (2008).
30. Boyd, P. *et al.* A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature* **407,** 695–702 (2000).
31. Huang, R. X. The three-dimensional structure of wind-driven gyres: Ventilation and subduction. *Rev. Geophys.* **29** (suppl.), 590–609 (1991).
32. Marshall, G. Trends in the Southern Annular Mode from observations and reanalyses. *J. Clim.* **16,** 4134–4143 (2003).
33. Downes, S., Bindoff, N. & Rintoul, S. Impact of climate change on the subduction of mode and intermediate water masses in the Southern Ocean. *J. Clim.* **22,** 3289–3302 (2009).
34. Ridgway, K., Dunn, J. & Wilkin, J. Ocean interpolation by four-dimensional weighted least squares: application to the waters around Australasia. *J. Atmos. Ocean. Technol.* **19,** 1357–1375 (2002).
35. Sallée, J. B., Wienders, N., Morrow, R. & Speer, K. Formation of Subantarctic Mode Water in the southeastern Indian Ocean. *Ocean Dyn.* **56,** 525–542 (2006).
36. Onogi, K. *et al.* The JRA-25 reanalysis. *J. Meteorol. Soc. Jpn* **85,** 369–432 (2007).
37. Dong, S., Sprintall, J. & Gille, S. Location of the Polar Front from AMSR-E satellite sea-surface temperature measurements. *J. Phys. Oceanogr.* **36,** 2075–2089 (2006).

Acknowledgements

We acknowledge the role of Jeff Dunn in developing and making available the loess fitting method. K.G.S. received support from NSF OCE-0822075, OCE-0612167 and OCE-0622670. J.B.S. was supported by a CSIRO Office of the Chief Executive (OCE) postdoctoral fellowship. S.R.R. was supported by the Australian Government's Cooperative Research Centres Programme through the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE-CRC). J.B.S. and S.R.R. were also supported by the CSIRO Wealth from Oceans National Research Flagship. This study has benefited from discussions with R. Matear, A. Lenton, N. Cassar and P. Boyd.

Author contributions

J.B.S. directed the analysis of the several datasets used in this study and shared responsibility for writing the manuscript. K.G.S. and S.R.R. participated in the data analysis and shared responsibility for writing the manuscript. All authors contributed to the final version of the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to J.B.S.