Westerly winds overturning oceans

Exploring the fundamental dynamics of atmosphere-ocean interactions in the Southern Ocean and their implications for past and future climate change

Supervisory team

Primary: Michael Byrne, Graeme MacGilchrist, Simon Lee
Supporting: Andrea Burke, James Rae

Outline project description

The westerly winds that blow over the Southern Ocean are some of the most energetic on Earth. Colloquially known as "the roaring forties" (warning seafarers of their fierce nature and the latitude band in which to expect them), the winds are strong enough to drive the global ocean circulation – bringing cold, dense, carbon-rich water from the ocean's dark abyss all the way to its surface – with far-reaching implications for global climate. Changes in the strength and location of these winds, and associated impacts on the ocean circulation and carbon cycle, have together been hypothesized as a major driver of past climate transitions, such as the ice ages, as well as a crucial uncertainty in projections of future climate change. Nevertheless, the fundamental dynamics of these westerly winds, and their relationship to past and future climate changes, remain highly uncertain.

This ambitious PhD will focus on understanding the underlying dynamics of atmosphere-ocean interactions in the Southern Ocean. Specifically, the project will address three crucial unanswered questions:

1. What governs the strength of the westerly winds, and the empirical relationship between wind strength and latitude? How does this relationship vary across ocean conditions, and in response to global warming?
2. What determines the position of the major ocean currents in the Southern Ocean, and how does this change in response to changes in westerly wind strength and location?
3. How does the coupled atmosphere-ocean system in southern mid-latitudes change in response to global warming, and how do these changes accelerate or decelerate climate change via their impact on the carbon cycle?

Success in addressing these questions will advance fundamental understanding of the coupled atmosphere-ocean system and will provide new insights into the pace of global warming, the extent of sea level rise, and changes in marine ecosystems. Specifically, the models used in climate change projections that inform the Intergovernmental Panel on Climate Change (IPCC) will be validated against this newly developed dynamical understanding, allowing their veracity to be scrutinized.

The student will address these questions using a host of tools, including theoretical frameworks and conceptual models, gridded observational datasets, idealized numerical simulations, and complex climate models. They will have freedom to explore the above questions in an order guided by their curiosity, but the following timeline is suggested:

Year 1. Develop a conceptual model of the relationship between westerly wind strength and ocean surface temperatures, based on the atmospheric momentum budget. Simultaneously, using an idealized numerical model configuration of the atmosphere overlying a prescribed ocean state, vary the ocean conditions and examine the induced changes in the atmosphere to test and refine the conceptual model.

Year 2. Explore and progress existing conceptual models of the ocean currents' position and strength, and their sensitivity to the overlying winds, the ocean temperature profile, and the ocean bathymetry. Test this conceptual model using an idealized, regional ocean model configuration with prescribed overlying atmospheric conditions. Vary the atmospheric conditions to explore the ocean response in a vorticity framework.

Year 3. Run global warming scenarios with a complex climate model, resolving the interacting dynamics between changing ocean and atmosphere conditions. Use this model to interrogate the previously derived conceptual models and develop further theory on how a dynamic relationship between the atmosphere and ocean alters the expected behaviour. Assess Southern Ocean atmosphere-ocean interactions in IPCC-grade climate model simulations.

Year 4. Write up and submit thesis.

Throughout the PhD, the student will write up and publish their results in academic journals as well as attend conferences to present their work, integrating them within the research community and alerting the community to their work. Additionally, they will attend summer schools on two or three occasions to continually enhance and broaden their learning and to develop relationships with their peers.

Strategic relevance

This project brings together several early and mid-career faculty members in the School who have not previously worked together, but whose expertise aligns around this topic. It thus represents an important evolution of the COASt (Climate Oceans and Atmosphere @ St Andrews) research consortium beyond informal interaction and into active research. It is anticipated that this research project will be the starting point for several future projects and grant proposals.

The proposed research tackles a problem at the interface of climate dynamics and global biogeochemical cycles. Although the student will focus on understanding the dynamics, their results will have broad implications for our understanding of biogeochemical processes and their evolution in both the past and future. It is thus of broad interest to an Earth Sciences school whose members work on a wide variety of periods of environmental change, and who seek to understand the evolving Earth system and its physical and geochemical drivers.

The student will develop model configurations and analysis tools that can be re-used by other members of their research groups, as well as the groups of other faculty members. This will include idealized configurations of both the ocean and atmosphere, relevant to addressing a wide range of fundamental questions in climate science, as well as tools for analyzing global climate and Earth system models. The latter is particularly relevant to the School more broadly, where many faculty are seeking to develop capabilities in this direction for their own research questions, as well as in undergraduate teaching modules.

Finally, being directly relevant to global environmental change, and aiming to reduce uncertainty in future climate projections, this research is closely aligned with several priority areas highlighted in the University Strategy, including *Evolution, Behaviour and Environment*, and *Sustainability*.

Supervision arrangements

The supervisory team is perfectly suited to supporting this research project focused on atmosphere-ocean interactions. Expertise in atmospheric dynamics, including conceptual and idealized model frameworks, is offered by Dr Byrne and Dr Lee. Likewise, on the ocean side, this is provided by Dr MacGilchrist. This constitutes the primary supervisory team, while further support and guidance on the links to biogeochemical cycles and the dynamics of past climates will be provided by Dr Burke and Dr Rae. As well as dedicated supervisory meetings, the student will benefit from attending the established bi-weekly COASt meetings – an informal environment where they will enjoy frequent interactions with all supervisors, as well as numerous students and postdoctoral researchers working on related problems.

The supervisory team, who are at a variety of career stages, has an excellent breadth of experience in successful PhD student supervision. Dr Byrne has successfully graduated one PhD student and has a further student making good progress through their research. Dr MacGilchrist was co-advisor for a recently submitted PhD thesis and has further experience co-advising students at previous institutions. Dr Burke and Dr Rae have graduated numerous students over their time at the university. This provides a supportive and well-informed environment for Dr Lee, who is a new lecturer in the School, to develop experience as a PhD supervisor.

Further reading

Gray, William R., Casimir de Lavergne, Robert C. Jnglin Wills, Laurie Menviel, Paul Spence, Mark Holzer, Masa Kageyama, and Elisabeth Michel. 2023. ‘Poleward Shift in the Southern Hemisphere Westerly Winds Synchronous With the Deglacial Rise in CO2’. *Paleoceanography and Paleoclimatology* 38 (7): e2023PA004666. https://doi.org/10.1029/2023PA004666.

Rintoul, Stephen R. 2018. ‘The Global Influence of Localized Dynamics in the Southern Ocean.’ *Nature* 558 (7709): 209–18. https://doi.org/10.1038/s41586-018-0182-3.

Deng, Kaiqiang, Cesar Azorin-Molina, Song Yang, Chundi Hu, Gangfeng Zhang, Lorenzo Minola, and Deliang Chen. 2022. ‘Changes of Southern Hemisphere Westerlies in the Future Warming Climate’. *Atmospheric Research* 270 (June):106040. https://doi.org/10.1016/j.atmosres.2022.106040.