PhD thesis summary Sydney, 30th June 2024

Processes and Dynamics of Global to Regional Ocean Heat Uptake and Variability

Maurice F. Huguenin[1,2,⋆]
[1]Centre for Marine Science and Innovation, University of New South Wales, Sydney, NSW, Australia
[2]ARC Australian Centre for Excellence in Antarctic Science, University of New South Wales, Sydney, NSW, Australia
⋆E-mail: m.huguenin-virchaux@unsw.edu.au

Abstract

Ocean warming limits the worst impacts of anthropogenic climate change because the ocean has absorbed over 90% of the additional heat trapped in the Earth system since the 1970s. However, sparse observations limit our understanding of the processes driving this ocean heat uptake. In my PhD thesis, I conducted three high-resolution ocean modelling projects to demonstrate how ocean warming has played out over the last 50 years, including how it is affected by El Niño-Southern Oscillation (ENSO), the Earth's dominant mode of interannual climate variability. In **Part 1**, published in *Nature Communications*, I highlight how Southern Ocean heat uptake accounts for almost all the planet's ocean warming, thereby controlling the rate of climate change. In **Part 2** (*Journal of Climate*), I analyse how changes in surface radiation and vertical mixing during ENSO events play a key role in modulating the volume of warm water in the equatorial Pacific, and how this knowledge can help us improve future ENSO predictions. For **Part 3** in *Geophysical Research Letters*, I investigated how surface wind changes over West Antarctica during ENSO influence ocean temperatures on the Antarctic continental shelf, with shelf warming having the potential to rapidly increase basal melting of floating ice shelves and increase global sea level. Alongside **Parts 1** and **3**, I published articles in *The Conversation* which reached over 63,000 readers worldwide. During my PhD candidature, I also finished a project highlighting how models from the fifth Coupled Model Intercomparison Project do not support a trend towards a more persistent future atmospheric circulation over Central Europe.

Part 1: The Southern Ocean drives global ocean heat uptake

The global ocean has absorbed almost all of the additional energy in the Earth system due to greenhouse warming over the last half century, accelerating sea level rise due to thermal expansion of seawater. However, our observations are still very sparse, and there are large uncertainties around where ocean heat uptake has occurred and where this heat is stored today. Here, I first equilibrated the 1° configuration of the global reanalysis-forced ocean-sea ice model ACCESS-OM2, using a spin-up that improves on earlier approaches, to better capture the recent increase in ocean warming. Then, I investigated recent ocean heat uptake trends basin-by-basin and associated separately with surface wind trends, thermodynamic properties (temperature, humidity and radiation) or both. Wind and thermodynamic changes each explain about 50% of global ocean heat uptake (Fig. 1). My work found this heat uptake to be enabled by cool Southern Ocean sea surface temperatures and the strong westerly winds that encircle the Antarctic continent. By forcing the model separately with only wind and thermodynamic-only trends, I showed that heat uptake is driven by sensible heat gain when thermal trends are held fixed in the model, while downward longwave radiation dominates when wind trends are fixed. These results address long-standing limitations in multidecadal ocean-sea ice model simulations to reconcile estimates of global ocean heat uptake, transport and storage.

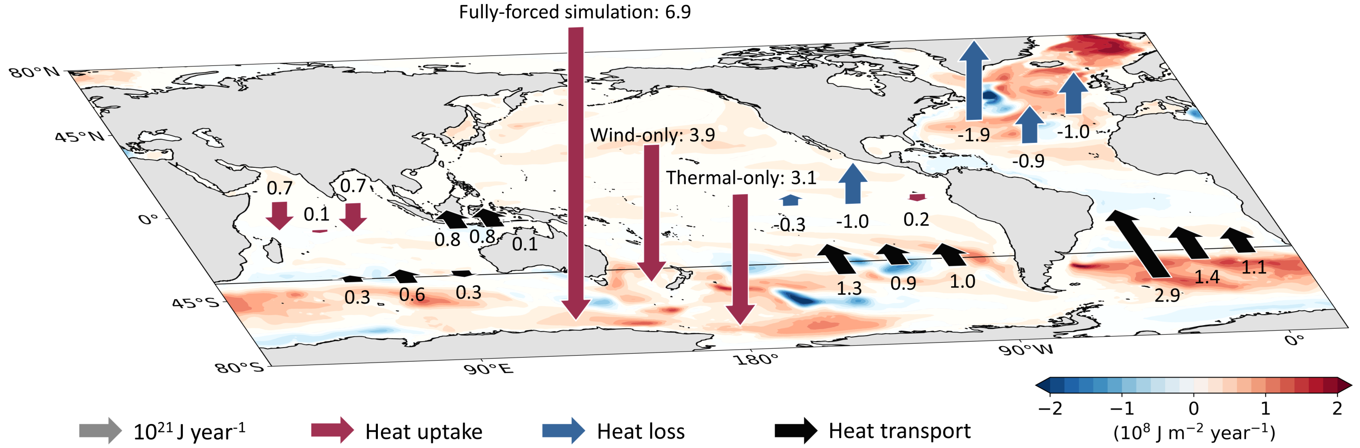

Figure 1: Schematic depicting anomalous global ocean heat uptake, heat loss and heat transport over the last half century in different historical ocean-sea ice model simulations. The spatial pattern shows ocean heat storage rates in the fully-forced simulation (10^8 J m^{-2} $year^{-1}$). The arrows are to scale and show basin-wide heat uptake, heat loss and heat transport rates (10^{21} J $year^{-1}$) in the full forcing (left arrow), wind-only (middle arrow) and thermal-only (right arrow) simulations. Values are rounded to one-decimal point accuracy. The transport rates across the Bering Strait are one magnitude smaller and not shown.

Part 2: Surface heat fluxes and vertical mixing play a key role in changing the volume of warm water during ENSO

The equatorial Pacific warm water volume, defined as the volume of water warmer than 20°C near the equator, is a key predictor for El Niño-Southern Oscillation (ENSO), and yet much about what controls this metric remains unknown. Traditional theories have linked warm water volume variations to horizontal advection but vertical mixing and air-sea heat fluxes may also have an impact. Here, I simulated ENSO events using the 1/4° version of ACCESS-OM2 by adding atmospheric anomalies associated with El Niño and La Niña to the baseline state. I used the water mass transformation framework to examine the individual contributors to changes in warm water volume. In both sets of simulations, El Niño's warm water volume discharge and La Niña's recharge are initiated by volume fluxes across the 20°C isotherm associated with changes in surface radiation and vertical mixing in the eastern equatorial Pacific. Changes in horizontal volume transport above 20°C between the equator and subtropical latitudes dominate later. During La Niña, surface radiation and vertical mixing are more important in changing warm water volume due to the shoaling of the 20°C isotherm in the eastern equatorial Pacific that enables strong volume fluxes across it. This describes a major source of asymmetry between the two ENSO phases.

Part 3: Subsurface warming of West Antarctica during El Niño

Recent satellite observations suggest that ENSO impacts, through its atmospheric teleconnection to the Amundsen Sea, the mass balance of the West Antarctic ice shelves by increasing basal melting. However, sparse ocean observations in this remote area limit our understanding of the associated processes. Here, I investigated how ENSO events modulate subsurface West Antarctic shelf temperatures using the 1/10° configuration of ACCESS-OM2. During El Niño, the subsurface shelf between 150 m and the shelf bottom can be up to 0.5°C warmer than usual in front of ice shelves, increasing ice shelf melt. This warming arises from a weaker Amundsen Sea Low and weaker coastal easterlies that reduce on-shelf Ekman transport of cold surface waters and decrease sea level on the shelf (Fig. 2). I identify several possible mechanisms which then lead to more on-shelf heat transport of warm Circumpolar Deep Water, with the most dominant being the bottom Ekman response (small white arrow in the upper panel of Fig. 2). During La Niña, a largely opposite response occurs; the Amundsen Sea Low and coastal easterlies strengthen, on-shelf surface Ekman transport increases and drives a wedge of cold water up towards the continent. This decreases cross-shelf transport of warm Circumpolar Deep Water via opposite mechanisms.

Final remark

Ongoing research into ocean temperature changes on different temporal and spatial scales is crucial to understanding current climate change and preparing for its future impacts. This thesis has added to our knowledge of ocean heat uptake and variability by highlighting the role of atmospheric changes over the Southern Ocean and during ENSO in the Pacific and in West Antarctica. These findings will contribute to (1) a better understanding of global sea level rise through ocean warming and its associated thermosteric contribution, (2) improved ENSO predictions through an increased knowledge of its key precursor, the warm water volume, and (3) an advanced awareness how ENSO events impact Antarctica, the rate of Antarctic ice shelf mass loss through basal melting and thus global sea level rise.

References and Acknowledgment

Huguenin, M. F., Holmes R. M., and England M. H. Drivers and distribution of global ocean heat uptake over the last half century. *Nature Communications*, 13(1):4921, 2022a. https://doi.org/10.1038/s41467-022-32540-5. **Part 1**.

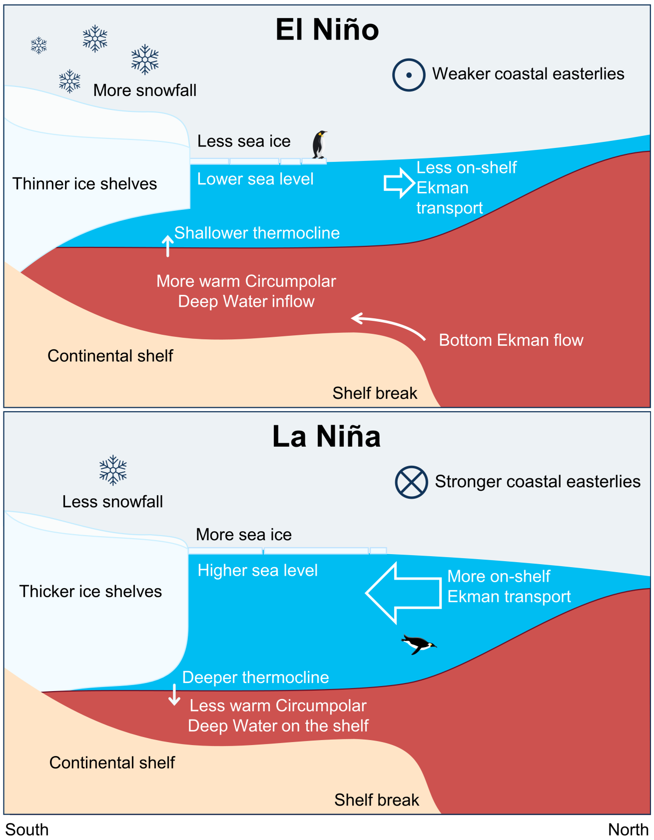

Figure 2. Schematic of physical changes on the West Antarctic continental shelf during El Niño and La Niña events. The symbols ⊙ and ⊗ show the anomalous anticyclonic (anticlockwise) and cyclonic (clockwise) Amundsen Sea Low circulation, and the outlined arrows show the on-shelf Ekman transport of cold (blue) Antarctic surface waters. The small white on-shelf arrow in the top panel shows the increased warm water transport during El Niño from the bottom Ekman flow. The emperor penguins have been added as artistic expression. Ecological impacts on sea life have not been investigated here.

Huguenin, M. F., Holmes R. M., and England M. H. Key role of diabatic processes in regulating warm water volume variability over ENSO events. *Journal of Climate*, 33(22):9945 – 9964, 2020a. https://doi.org/10.1175/JCLI-D-20-0198.1. **Part 2**.

Huguenin, M. F., Holmes R. M., Spence P., and England M. H. Subsurface warming of the West Antarctic continental shelf linked to El Niño-Southern Oscillation. *Geophysical Research Letters*, 51(7), 2024a. https://doi.org/10.1029/2023GL104518. **Part 3**.

Huguenin, M. F., Holmes R. M., and England M. H. The Southern Ocean absorbs more heat than any other ocean on Earth, and the impacts will be felt for generations. *The Conversation*, 2022b. URL https://theconversation.com/the-southern-ocean-absorbs-more-heat-than-any-other-ocean-on-earth-and-the-impacts-will-be-felt-for-generations-189561. **Part 1 outreach article**.

Huguenin, M. F., Holmes R. M., Spence P., and England M. H. Heat from El Niño can warm oceans off West Antarctica – and melt floating ice shelves from below. *The Conversation*, 2024b. URL https://theconversation.com/heat-from-el-nino-can-warm-oceans-off-west-antarctica-and-melt-floating-ice-shelves-from-below-226233. **Part 3 outreach article**.

Huguenin, M. F., Fischer E. M., Kotlarski S., Scherrer S. C., Schwierz C., and Knutti R. Lack of change in the projected frequency and persistence of atmospheric circulation types over Central Europe. *Geophysical Research Letters*, 2020b. https://doi.org/10.1029/2019GL086132. **This work was initiated during a research internship at ETH Zurich & MeteoSwiss, and completed in the first year of my PhD candidature**.

I thank A. Purich, R. M. Holmes and M. H. England for their input.