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# Impacts of Antarctic Ice Mass Loss on New Zealand Climate

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**Key Points:**

- Meltwater due to Antarctic ice-mass loss results in sea-surface cooling to the southeast of New Zealand in historical and future scenarios
- Including additional Antarctic meltwater in climate model simulations increases wintertime surface westerly winds south of New Zealand
- The magnitude of the response is uncertain due to the wide spread in estimates of observed and projected Antarctic mass imbalance

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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**Abstract** We investigate the impacts of meltwater from Antarctic Ice Sheet (AIS) mass loss on New Zealand climate in a state-of-the-art global climate model. We conduct simulations with additional meltwater from AIS mass loss for both the historical period and a high-emissions future scenario. The ocean surface to the southeast of New Zealand cools, with the largest change in winter and spring. The additional meltwater results in a northward shift of the oceanic sub-tropical front near New Zealand, which partially offsets the projected southward shift of this front in a warming climate. Wintertime surface westerly winds to the south of New Zealand also increase with the addition of the meltwater. The magnitude of the impact of Antarctic meltwater is uncertain due to the wide spread in estimates of Antarctic mass imbalance, but has important implications for future projections for New Zealand climate.

**Plain Language Summary** Meltwater entering the Southern Ocean due to the Antarctic ice sheet losing mass is not typically included in climate model simulations. We investigate the effect of this missing meltwater on New Zealand climate with a state-of-the-art climate model. We ran simulations with additional meltwater for both the recent past and a projection of the future assuming high greenhouse gas emissions. While the impacts over the land of New Zealand are small, the meltwater causes cooling to the southeast of New Zealand, which offsets the projected warming in this region and has important implications for the local ocean. Wintertime westerly winds to the south of New Zealand also increase. While the exact amount of meltwater entering the Southern Ocean from Antarctica in the recent past and into the future is uncertain, we have shown it may have important impacts on New Zealand climate.

## 1. Introduction

Mass loss from the Antarctic continent has increased over the last few decades (Slater et al., 2021), and is expected to increase further in the future (Seroussi et al., 2020). This mass loss represents a large source of fresh meltwater to the Southern Ocean, and has been shown to drive surface cooling in the Southern Ocean and Antarctic sea ice expansion in climate model experiments that include it (e.g., Bintanja et al., 2013, 2015; Bronselaer et al., 2018; Mackie, Smith, Ridley, et al., 2020; Mackie, Smith, Stevens, et al., 2020; Pauling et al., 2016, 2017; Swart & Fyfe, 2013; Thomas et al., 2023). There has been disagreement between different modeling studies about the magnitude of the effect of this meltwater on Antarctic sea ice and the Southern Ocean, and determining the reasons for these discrepancies has been hindered by different studies using different amounts, spatial distributions and temporal distributions of freshwater input. This has led to recent efforts to conduct a model intercomparison study with various standardized freshwater input scenarios, the Southern Ocean Freshwater Input from Antarctic Initiative (SOFIA, Swart et al., 2023).

Schmidt et al. (2023) conducted simulations in the GISS-E2.1-G coupled climate model with added meltwater around Antarctica and Greenland as estimated from observational data by Mankoff et al. (2021) and Slater et al. (2021). They found that including the meltwater brought the modeled Antarctic sea ice and Southern Ocean sea surface temperature (SST) trends closer to observed trends than in the simulations without the meltwater. They argue that this should motivate the inclusion of meltwater from ice sheet mass imbalance as a standard historical forcing for all models in the next phase of the Coupled Model Intercomparison Project (CMIP).

The Southern Ocean cooling induced by Antarctic ice sheet mass loss has been shown to have far-reaching impacts, for example, through teleconnections to the tropical eastern Pacific (Dong et al., 2022). New Zealand and its exclusive economic zone (EEZ) sit at the interface between subtropical and subantarctic waters (delineated by the sub-tropical front), which are projected to undergo different changes in a warmer future (Bopp et al., 2013;

Law et al., 2018; Rickard et al., 2016). In the subtropical waters to the north primary productivity is projected to decrease, while productivity may increase in the subantarctic waters to the south. Global warming (without enhanced melting) is projected to shift the sub-tropical front poleward (e.g., Yang et al., 2020), while the Southern Ocean cooling and freshening due to enhanced freshwater input from Antarctica is expected to shift this ocean front equatorward. Due to its proximity to the Southern Ocean and Antarctica, the climate of New Zealand is likely to be strongly influenced by changes in these regions, and so we ask: how does Antarctic ice sheet mass loss impact the climate of New Zealand?

Projections with climate models that participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012) show that New Zealand can expect sea surface temperatures to increase by up to 1.1°C by 2100 under a medium-emissions scenario, and up to 2.5°C under a high-emissions scenario (Law et al., 2018). Near-surface air temperatures are projected to increase by 1.4°C(3.0°C) under a medium(high)-emissions scenario (Ministry for the Environment, 2018). The frequency of "hot days" (maximum temperature above 25°C) is projected to increase by up to a factor of 4 under a high-emissions scenario, and droughts and extreme wind events are projected to increase over much of the country. Gibson et al. (2024) found that models participating in CMIP6 (Eyring et al., 2016) project an increase in wintertime precipitation for the west coast of the South Island of New Zealand, with inconsistent changes in the North Island and in summer. Neither CMIP5 nor CMIP6 simulations included meltwater input and the associated Southern Ocean cooling due to projected Antarctic ice-sheet mass loss. In this study we aim to quantify the effect of this missing meltwater on the historical and future climate of New Zealand.

## 2. Data and Methods

The model experiments used in this study follow the forcing protocol defined in the *hist-antwater-92-11* and *ssp585-ismip6-water* "Tier 2" experiments defined as part of the Southern Ocean Freshwater Input from Antarctica Initiative (SOFIA, Swart et al., 2023). In *hist-antwater-92-11* the additional freshwater input ramps linearly from 0 Sv in 1992 at a rate of $1.1 \times 10^{-3}$ Sv $yr^{-1}$ until 2020, at which point the input rate is 0.022 Sv. In the *ssp585-ismip6-water* experiment the freshwater input is prescribed over the period 2015–2100 according to Antarctic mass loss rates from the Ice Sheet Model Intercomparison Project Phase 6 (ISMIP6, Seroussi et al., 2020), reaching approximately 0.2 Sv by the end of the 21st century. These experiments were chosen due to them having the largest meltwater forcing, thus giving an upper bound (based on the SOFIA protocol) on the effect of meltwater on New Zealand climate, and maximizing the signal-to-noise-ratio in the response.

The model used in this study is the CMIP6 model HadGEM3-GC3.1-LL (Kuhlbrodt et al., 2018), which forms the physical core of the New Zealand Earth System Model (Behrens et al., 2020). The NEMO ocean (Gurvan et al., 2019) and GSI8.1 sea ice model (Ridley et al., 2018) components were run at ORCA1 (nominally 1°) horizontal resolution, with 75 vertical layers in the ocean. The Unified Model (UM) atmosphere model component (Walters et al., 2019) was run at $1.875° \times 1.25°$ horizontal resolution, with 85 vertical layers. This model version reproduces the observed global climate similarly well to the medium-resolution version of HadGEM3-GC3.1 (Williams et al., 2018), while having an order of magnitude lower computational cost. It has also been shown to reproduce Southern Ocean properties well relative to the medium-resolution version of the same model (Kuhlbrodt et al., 2018) and relative to other models with a 1° ocean resolution (Thomas et al., 2023). Importantly for New Zealand climate, the Southern Ocean warm bias, a common problem among coupled climate models, is reduced in the low-resolution version of the model (Kuhlbrodt et al., 2018).

We compare our simulations to the historical and SSP5-8.5 experiments from the Coupled Model Intercomparison Project Phase 6 (CMIP6, Eyring et al., 2016; O'Neill et al., 2016). We also make use of the SSP2-4.5 experiment to extend the historical simulations from the end of 2014 to the end of 2020, as specified in the SOFIA protocol. We compare the model output to the ERA5 reanalysis (Hersbach et al., 2020).

The simulations for this work were run using the identical forcing and model setup as in the CMIP6 historical, ssp245 and ssp585 simulations for HadGEM3-GC3.1-LL, except for the addition of the meltwater from Antarctica as described in the SOFIA protocol. The ssp245 simulations were used to extend the historical simulations from their CMIP6 end date in 2014 until the end of 2020. We ran 10 ensemble members for the *hist-antwater-92-11* experiment, corresponding to members r1i1p1f3–r5i1p1f3 and r11i1p1f3–r15i1p1f3 from the HadGEM3-GC31-LL CMIP6 historical and ssp2-4.5 simulations. We ran 4 ensemble members for the *ssp585-*

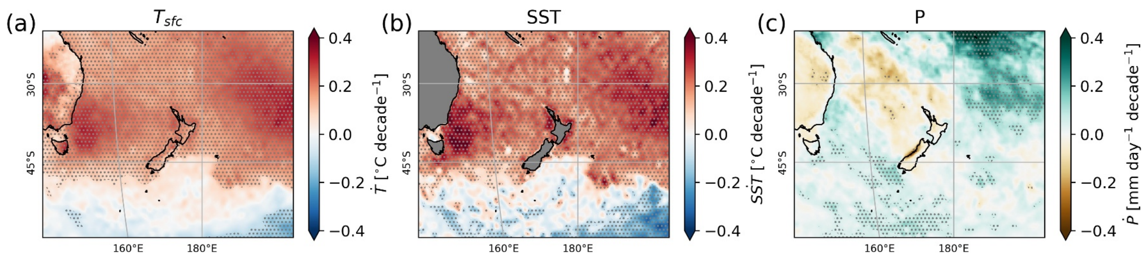


**Figure 1.** Trend in (a) 2 m air temperature, (b) sea surface temperature, and (c) and precipitation over the period 1979–2020 in the ERA5 reanalysis. Stippling denotes where the trend is statistically significant at the 95% confidence level.

*ismip6-water* experiment, corresponding to ensemble members r1i1p1f3–r4i1p1f3 from the HadGEM-GC31-LL CMIP6 ssp585 simulations. For *hist-antwater-92-11* and *ssp585-ismip6-water* results are presented as the difference between the experiment and its corresponding CMIP6 run with no additional meltwater averaged over the all ensemble members for the last 10 years (2011–2020) or 30 years (2071–2100) of the simulations respectively.

The region of interest for New Zealand climate used in this study is 145°E to 160°W, 60°S to 20°S, which encompasses the New Zealand Exclusive Economic Zone (EEZ), as defined in Law et al. (2018). Statistical significance of the anomalies shown in this paper was computed using a 2-tailed Student's *t*-test.

## 3. Results

We first examine how climate has changed in New Zealand over the satellite era. The ERA5 reanalysis shows that 2 m air temperatures and SSTs have warmed around, over, and to the north of New Zealand, with no statistically significant trends to the south (Figures 1a and 1b). Trends in precipitation are not statistically significant over or near New Zealand, with some areas of significant increase well to the north (Figure 1c).

We next analyze how well HadGEM3-GC3.1-LL reproduces the observed 2 m air temperature, sea surface temperature (SST), precipitation, and surface wind speed evolution over the satellite era. While the ensemble-mean trends in the model may not necessarily resemble the observed trends (Figure 2), the ensemble members with the highest correlation to the observed patterns do capture the observed trends (Figures 2b, 2e, 2h, and 2k). This is not surprising since observations represent a single realization of internal variability, and so we do not necessarily expect the average over many realizations to exhibit a similar spatial pattern. The magnitude of the warming is slightly larger in the model than in observations, likely due to HadGEM3-GC31-LL having a high effective climate sensitivity (Andrews et al., 2019).

The addition of meltwater due to Antarctic ice-mass loss results in cooling of both 2 m air temperatures and SSTs to the southeast of New Zealand in both the *hist-antwater-92-11* and *ssp585-ismip6-water experiments* (Figures 3a–3d). This cooling is strongest in winter and spring in both the historical and future scenarios, with little significant response in the summer (see Figures S1 and S2 in Supporting Information S1). In the *hist-antwater-92-11* experiment the sea surface around Tasmania and extending into the Tasman Sea warms, possibly indicating a change in the East Australian Current. Analysis of the trend in sea surface temperature shows that the addition of meltwater changes the trend such that the model trend become more consistent with the trend in the ERA5 reanalysis (see Figures S5 and S6 in Supporting Information S1). The cooling to the southeast of New Zealand in the *ssp585-ismip6-water* experiment is consistent with a northward shift of the current in that region, induced by the cooling of the Southern Ocean farther south in response to the meltwater.

To investigate the cause of the temperature changes around New Zealand in both the *hist-antwater-92-11* and *ssp585-ismip6-water* experiments, we examine the sea surface height (SSH) and ocean surface velocity responses (Figures 3e, 3f, 3g, and 3h). SSH is an integral quantity linking surface temperature to changes in ocean heat content and currents (divergence of vertically integrated velocity). We see an increase in SSH near Tasmania that extends to the east, mirroring the temperature response in that region in the *hist-antwater-92-11* experiment. There is also an increase in the strength of the East Australian Current that is advecting warm waters to the south. The strengthening of this current is also consistent with an increase in the wind stress curl in the Tasman Sea (not shown). This indicates that the warming in the Tasman Sea is circulation-driven, and is due to changes in the East Australian Current (Figure 3b). This change in circulation and warming is not present in the *ssp585-ismip6-water*

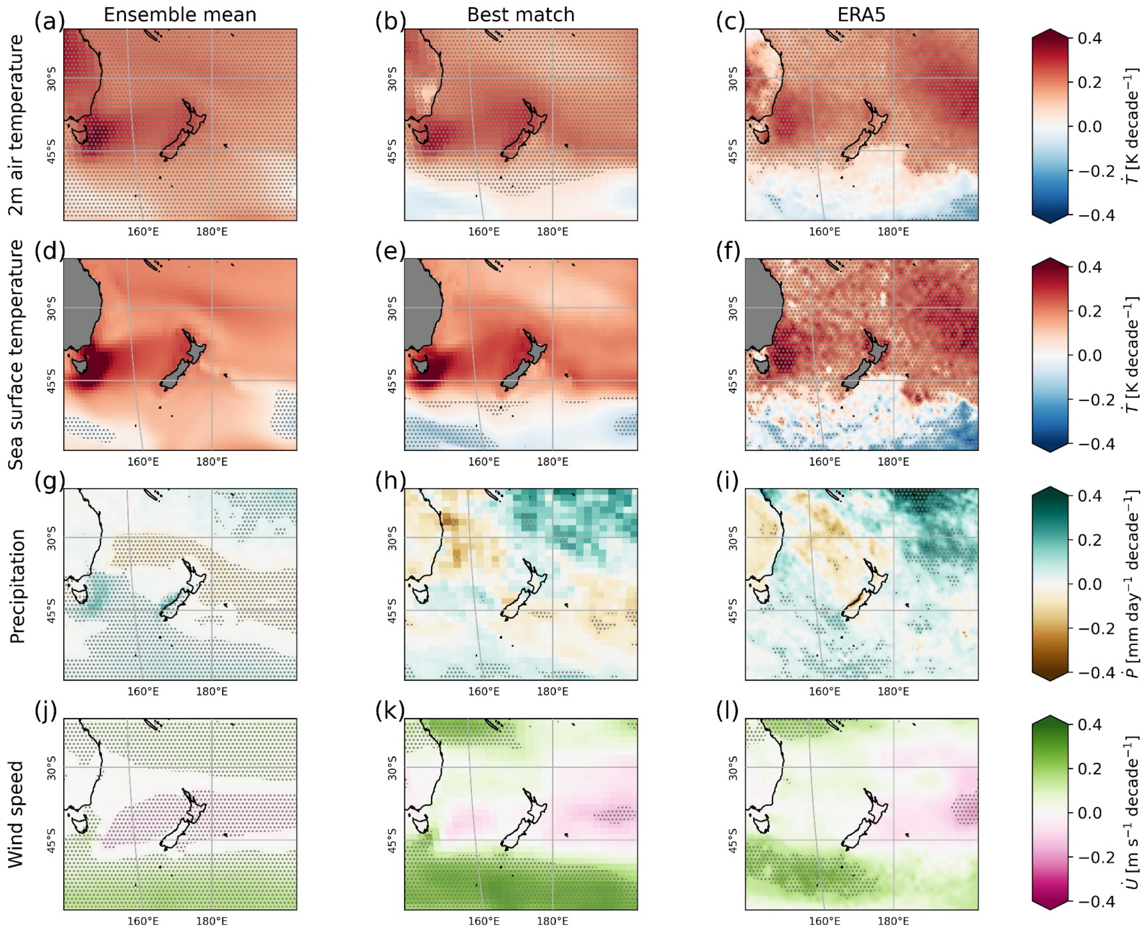


**Figure 2.** Trend in 2 m air temperature, sea surface temperature, precipitation, and wind speed over the period 1979–2020 for (a, d, g, j) the HadGEM3-GC31-LL historical simulation ensemble mean, (b, e, h, k) the HadGEM3-GC31-LL ensemble member with the highest correlation to the ERA5 trend (c, f, i, l) ERA5 reanalysis (repeated from Figure 1 for ease of comparison). Stippling denotes where the trend is statistically significant at the 95% confidence level.

response, indicating that it may be a transient feature of the response that is not present after a few decades. The cooling to the east of New Zealand, extending southeast from the Cook Strait, is also consistent with the decrease in SSH and circulation changes in that region.There is flow from the south into the current flowing east from Cook Strait that brings cooler waters to this region. The cooling to the South of New Zealand shifts the SSH gradient north, resulting in cooling in the region of the current emanating from Cook Strait.

Antarctic meltwater does not have a strong impact on average (see Figure S4 in Supporting Information S1) or extreme (not shown) precipitation for New Zealand. This is perhaps not surprising, given the highly variable nature of precipitation around New Zealand and its lack of response to anthropogenic climate change seen in the reanalysis (Figure 1c). In the CMIP6 ssp585 simulations with no additional Antarctic meltwater the average number of hot days over land (daily maximum 2 m air temperature ≥25°C) increases by about 27 days per year for the period 2081–2100 relative to 2001–2020. The addition of the Antarctic meltwater results in a statistically significant reduction of the projected change by 2.1 days per year on average, with the largest changes in the North Island (see Figure S5 in Supporting Information S1).

Projected changes to near-surface winds are also expected to be an important consequence of a warming climate for New Zealand. Thus, we examine the projected changes in surface wind speed with the addition of Antarctic meltwater. While there is little response in seasonal-mean wind speed over the land of New Zealand, there is a significant increase in wind speed to the south of New Zealand in winter in the *hist-antwater-92-11* experiment (Figure 4c). This change is dominated by an increase in the westerly component of the winds (not shown). This wintertime wind speed increase is also found, albeit weaker and farther south, in the *ssp585-ismip6-water*. This is

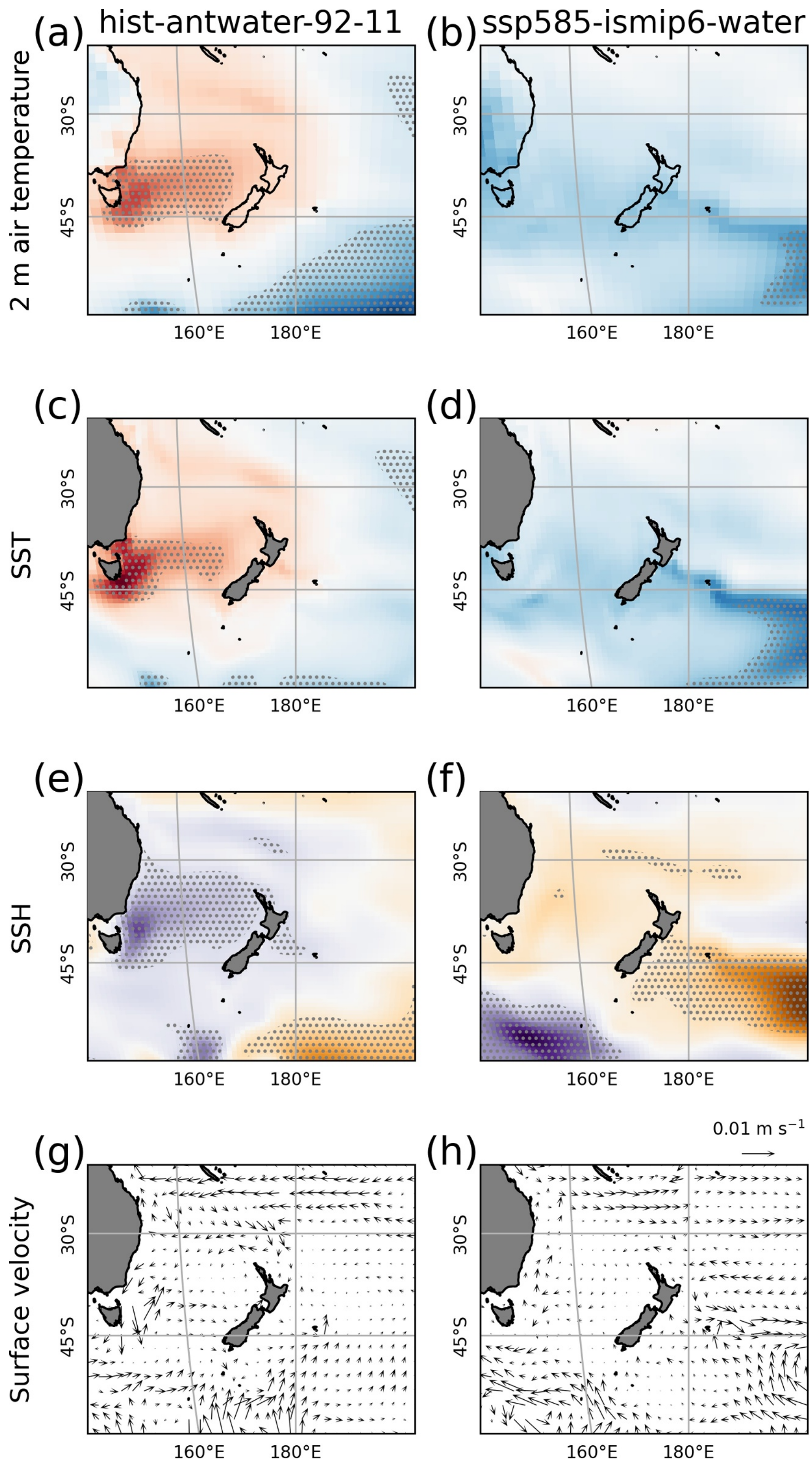


**Figure 3.** (a, b) 2 m air temperature, (c, d) sea surface temperature, (e, f) sea surface height and (g, h) ocean surface velocity response for the *hist-antwater-92-11* and *ssp585-ismip6-water* experiments. The response is computed as the difference between each experiment and its CMIP6 control run with no additional meltwater averaged over 2011–2020 for *hist-antwater-92-11* or 2071–2100 for *ssp585-ismip6-water*. Stippling denotes where the response is statistically significant at the 95% confidence level.

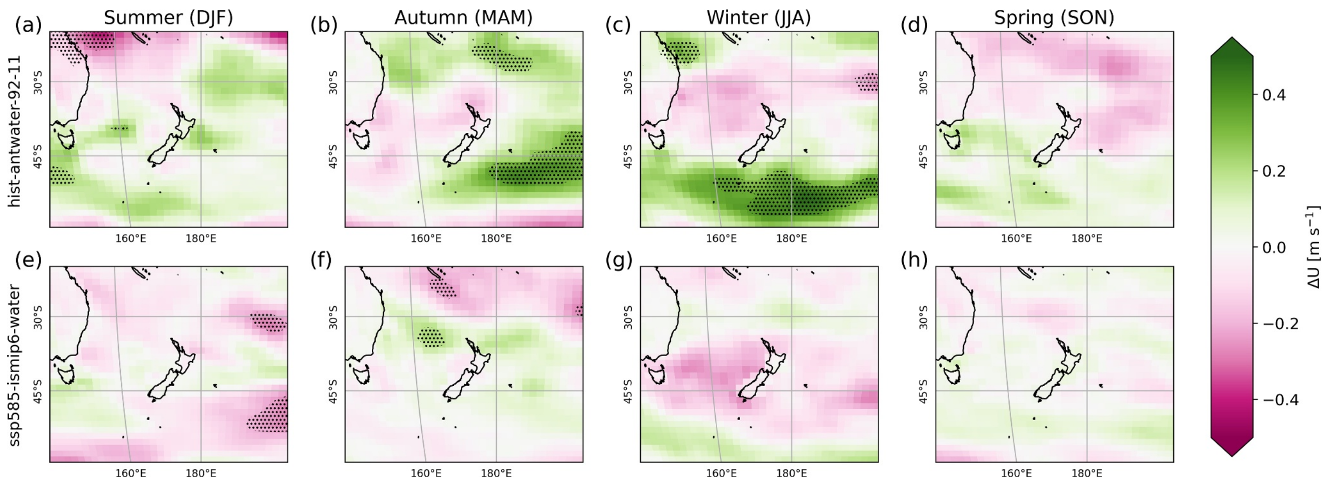


**Figure 4.** Seasonal-mean near-surface wind speed response in *hist-antwater-92-11* (a–d) and *ssp585-ismip6-water* (e–h). Stippling denotes where the anomaly is statistically significant at the 95% confidence level.

consistent with the poleward shift of the westerly winds that is expected as the climate warms (e.g., Perren et al., 2020). The wind-speed increase in *hist-antwater-92-11* is consistent with the increased local meridional SST gradient seen in Figure 3c, which tends to lead to stronger zonal winds due to increased baroclinity (e.g., Hoskins & Hodges, 2005). This increase in local SST gradient is not present in the future scenario, hence we do not see the same change in winds. We also examined wind extremes, by computing the change in the 99th percentile daily-mean wind speed. We found no significant difference in the change in wind extremes by the end of the 21st century with the addition of Antarctic meltwater (not shown).

## 4. Discussion and Conclusions

The cooling to the southeast of New Zealand in response to Antarctic meltwater (Figure 3) is consistent with the response seen in Schmidt et al. (2023). This provides some evidence that this response is robust to the choice of climate model and reinforces the call of Schmidt et al. (2023) for meltwater due to Antarctic ice mass loss to be included as a historical forcing in CMIP7. Omitting this meltwater from historical simulations and future projections will bias temperatures and winds to the south of New Zealand. The studies of Rickard et al. (2016) and Law et al. (2018) highlight the complex nature of the relationship between climate and ocean biogeochemistry in this region, thus model simulations with both added Antarctic meltwater and an active biogechemistry model component are needed to understand the potential impacts on primary productivity.

The model used in this study, HadGEM3-GC3.1-LL, has been found to exhibit spurious open-ocean deep convection in the Southern Ocean (Ridley et al., 2022). The addition of Antarctic meltwater to the Southern Ocean has been shown to substantially reduce this deep convection in models (Chen et al., 2023). To ensure that our results are not influenced by this change in open-ocean deep convection through teleconnections to the New Zealand region, we computed our results with the two historical ensemble members exhibiting substantial Southern Ocean deep convection (out of 10 total ensemble members) removed. This resulted in little change to the response (not shown), indicating that the results presented here are not strongly influenced by spurious deep convection in the model.

There is high uncertainty in the magnitude of the meltwater input used in both the historical and future scenarios presented here. The historical meltwater forcing is based on the observational estimates of Slater et al. (2021). These estimates are sufficiently uncertain that it motivated the SOFIA team to create four different historical meltwater scenarios with varying start dates and rates of change based on the same underlying data. We chose the scenario with the highest rate of increase in meltwater input, in order to provide an upper bound on the response and to maximize the signal-to-noise ratio. We expect that choosing one of the other scenarios would result in smaller impacts in the New Zealand region. The meltwater input for the future scenarios was based on the model output from the Ice Sheet Model Intercomparison for CMIP6 (ISMIP6, Seroussi et al., 2020; Thomas et al., 2023). As can be seen in Figure A1 from Swart et al. (2023), there is a large inter-model spread in meltwater input from

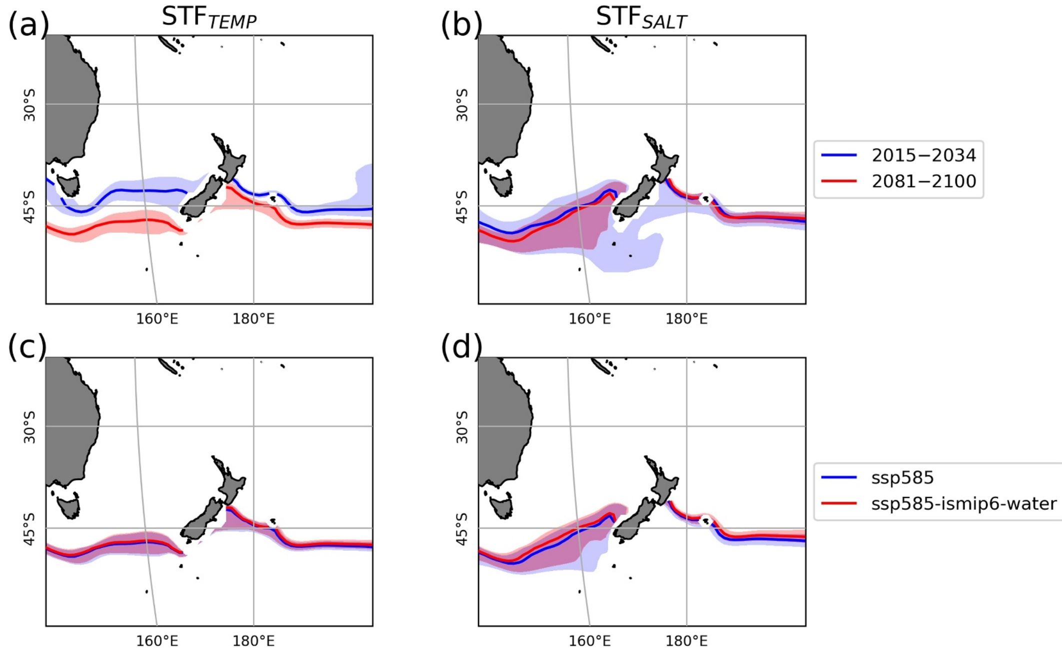


**Figure 5.** Contours defining the sub-tropical front (STF) around New Zealand for (a, b) the first 20 years and the last 20 years of the ssp585 simulations. (c, d) The *ssp585-ismip6-water* experiment versus ssp585 averaged over 2081–2100. The left column shows the STF as defined by the 13°C temperature contour at 100 m depth, and the right column the 34 psu contour at 100 m depth. The shaded region shows the range in STF location given by varying the temperature threshold by ±1°C or the salinity threshold by ±0.2 psu.

the ISMIP6 models, particularly toward the end of the 21st century. The uncertainty in future projections of Antarctic meltwater input can also be seen in the wide range of projections used in previous studies. For example, Bronselaer et al. (2018) used meltwater input from the ice sheet model of DeConto and Pollard (2016), which reaches ~0.6 Sv by the end of the 21st century, about three times that used in this study. While such high estimates of ice sheet mass loss have recently been called into question (e.g., Morlighem et al., 2024), this uncertainty means that the response to Antarctic meltwater could be substantially stronger or weaker than that seen in this study. Continued effort into ice sheet modeling is needed to narrow this uncertainty range. Further uncertainty in future projections of meltwater comes from the choice of emissions scenario. We chose the meltwater input from ice sheet model simulations forced with climate from the SSP5-8.5 scenario, a high-emissions scenario that is likely unrealistic (Hausfather & Peters, 2020). We chose this scenario to provide an upper bound (based on the SOFIA protocol) on the magnitude of the response to Antarctic meltwater and to maximize the signal-to-noise ratio. Choosing a meltwater input from ISMIP6 models forced with a lower-emissions scenario would result in less additional meltwater input to the Southern Ocean and thus a different response for the New Zealand region.

The meltwater-induced cooling to the south of New Zealand may have important implications for the local ocean. New Zealand sits at the boundary between the sub-tropical waters to the north and sub-antarctic waters to the south. The sub-tropical front (STF) delineates these two regions, and the position of this front has important implications for the local ocean conditions around New Zealand, as temperature can vary by 4–5°C, and salinity by 1 psu across a distance of less than 200 km (Belkin & Gordon, 1996). The STF has varying definitions, but is typically defined by the southernmost region meeting a certain salinity or temperature threshold at ~100 m depth (e.g., Behrens et al., 2021; Orsi et al., 1995). Due to both model biases in the mean state temperature and salinity distribution and the substantially warmer ocean in the ssp585 scenario, the temperature and salinity thresholds used here (13°C and 34 psu) differ from those used in Behrens et al. (2021) (11°C and 34.8 psu). These thresholds were chosen to most closely follow the position of greatest temperature or salinity gradient in the model fields. The STF, in particular that defined according to the temperature threshold is expected to move southward as the climate warms (Yang et al., 2020, and Figures 5a and 5b). The inclusion of Antarctic meltwater and its associated Southern Ocean cooling partially offset this shift (Figures 5c and 5d), with the position of the STF slightly farther north in *ssp585-ismip6-water* than ssp585 whether defined by the temperature or salinity threshold. This further highlights the importance of including Antarctic meltwater in climate projections for the New Zealand region.

This study provides the first quantitative estimate of the effect of including meltwater from Antarctic ice-mass loss for New Zealand climate. There is significant cooling in all seasons to the southeast of New Zealand in both historical and future scenarios, while the response over the land of New Zealand is weak. There is also significant warming in the Tasman Sea in the historical scenario that is not present in the future, suggesting a transient impact on the East Australian Current. While wind changes over the land of New Zealand are small, there is a significant increase in wintertime surface wind speed to the south. Including Antarctic meltwater in model simulations of climate is important for regions close to the Southern Ocean in particular, and we echo recent calls for it to be included as a forcing in future simulations, until such time as realistic ice-sheet models can be coupled to state-of-the-art climate models.

## Data Availability Statement

CMIP6 data used in this study is available from the Earth System Grid Federation (ESGF) archive: https://aims2.llnl.gov/search/cmip6. The SOFIA model output data are available at https://crd-data-donnees-rdc.ec.gc.ca/CCCMA/SOFIA (Swart et al., 2023). Code and processed data necessary to reproduce the results of this study are archived at Pauling (2024a, 2024b) respectively.

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