Investigating Antarctic Intermediate Water Changes in the South Pacific Under RCP 8.5 Using CESM1-BGC

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ABSTRACT
Antarctic Intermediate Water (AAIW), formed primarily in the Southern Ocean, is an important water mass responsible for nutrient transport, heat storage, and uptake of anthropogenic CO_2 throughout the global oceans. AAIW is also thought to be the most important global source of O_2 and nutrient transfer to the equatorial regions (Russell and Dickson 2003). In this study, we investigate changes in the surface properties of AAIW in the South Pacific, under historical (1970-1990) and RCP8.5 (2080-2100) scenarios, using the Community Earth System Model (CESM-BGC). These surface properties will then be subducted within intermediate water and distributed throughout the subtropical gyre. AAIW within the South Pacific is identified based on a low salinity of 34.2 psu. This study will investigate changes in AAIW surface properties (e.g., salinity, O_2, NO_3) under the RCP 8.5 (+8.5 W/m^2 from pre-industrial values) scenario. Identifying changes in AAIW can be valuable in diagnosing a changing climate.

INTRODUCTION

a. Motivation

Within the last century, greenhouse gas concentrations, such as Carbon Dioxide (CO_2), have been rising due to the enhanced greenhouse gas effect. According to the Mauna Loa Observatory in Hawaii, current CO_2 levels are at 404.49 ppm and steadily rising. The ocean acts as an important carbon sink, accounting for about 48% of CO_2 fossil-fuel emission uptake (Sabine et al. 2004), mitigating a large portion of anthropogenic CO_2. However, changes in the ocean properties due to climate change could disrupt this uptake and cause further intensification of the greenhouse gas effect.

b. AAIW formation and global importance

The Southern Ocean is home to a water mass that plays a significant role in the global climate system. Antarctic Intermediate Water (AAIW) is particularly important for nutrient transport (e.g. O_2, silica), heat storage, uptake of anthropogenic CO_2, and ventilation throughout the global ocean circulation. The formation of AAIW is the key process to the sequestering of these nutrients and CO_2. AAIW forms from upwelled Circumpolar Deep Water off the coast of

Antarctica. This cold, low-salinity water, which is now at the surface, is referred to as Antarctic Surface Water (AASW). AASW then moves northward due to Ekman transport until it hits the Polar Front. At the Polar Front, the cold, low-salinity water meets warmer waters and subducts into AAIW at the Subantarctic Front (Sloyan and Rintoul 2001b). During this subduction, CO_2 and various nutrients enter AAIW through air-sea flux. Due to this, AAIW is thought to be one of the largest global transports of anthropogenic CO_2 (Ito et al. 2010).

c. Influence of the Antarctic Circumpolar Current

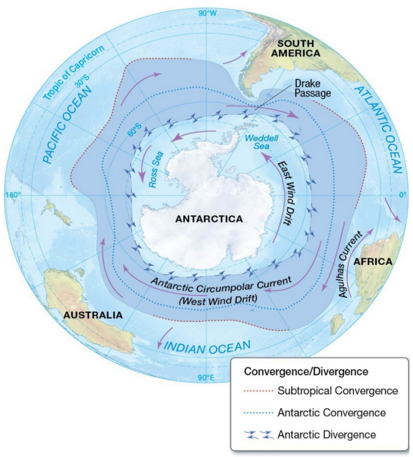


Figure 1. Polar view of Antarctica. Prevailing winds drive convergence and divergence at the surface, creating the Polar (Antarctic Convergence) and Subantarctic Front (Subtropical Convergence). (Pearson Education, Inc. 2011)

The transport of CO_2 and oxygen is facilitated by the Antarctic Circumpolar Current (ACC), a major current found in the Southern Ocean, which feeds into the Southern Hemisphere Subtropical gyres. This allows AAIW to spread and extend as far as 20°N (Talley 1999). The ACC is an eastward flowing current, driven by strong westerly winds, circling Antarctica that varies between the latitudes of 40 and 65 degrees south. The ACC is bounded in the south by the convergence of polar easterlies and the strong prevailing westerlies, or what is referred to as the Polar Front. The north boundary is the Subtropical Convergence, where cold polar water meets warmer equatorial region waters (see **Figure 1**). The ACC is also unbounded by any landmass, with the exception of the narrow restriction at the Drake Passage, allowing for large volume transports and connection with all major ocean basins. The connection to all Southern Hemisphere ocean basins, large nutrient uptake, and CO_2 transport allow this water mass to play a significant role in the climate. A change in the formation and uptake of AAIW could have impacts to the global carbon cycle and be an important tool for diagnosing further change in the climate system.

d. AAIW properties

Water masses are defined by numerous factors, including temperature, salinity, potential density, and nutrient content. AAIW is characterized by a salinity minimum, cold temperatures, and high oxygen concentrations. Preliminary results have identified AAIW to be 34.2 psu (practical salinity units) and a surface density range of 26.6-27.2 kg/m^3. In **Figure 2**, we can distinctly see the low salinity waters, represented by the yellow and green colors, subducting at around 60°S. These values will be used as baseline conditions to compare with mid-century and end-of-century projections. Changes in the physical properties of AAIW could affect the formation of AAIW or nutrient uptake. This study aims to identify and diagnose future changes at important uptake locations, such as Antarctic Intermediate Water, to assess potential decreases in ocean CO_2 and oxygen uptake and their implications.

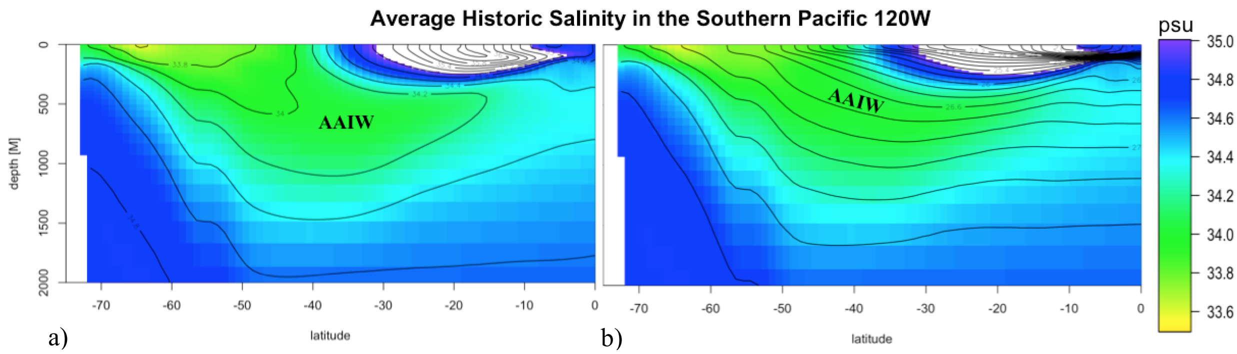


Figure 2. Both figures are showing historic salinity (psu) depth profiles at 120W from the surface to 2km, 80S to the equator. Areas of fresher water (lower salinity) are shown in yellow and green colors; areas of saltier water are shown in blue. a) (Left) Overlaid lines of constant salinity indicate AAIW salinity to be 34.2psu. b) (Right) Overlaid lines of constant density indicate a surface density range of 26.6-27.2 kg/m^3.

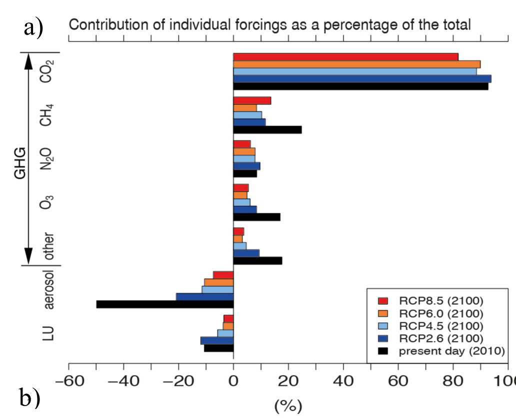
METHODS

a. CESM1-BGC

This study uses the Community Earth System Model - Biogeochemical (CESM1-BGC) output. This is an open-source model developed for the Coupled Model Intercomparison Project, phase 5 (CMIP5) by the National Center for Atmospheric Research (NCAR) through the Department of Energy and the National Science Foundation. CESM1 is the successor of the Community Climate System Model (CCSM4), now offering a more interactive carbon cycle and improved sea ice component for Greenland and Antarctica climate prediction (Long et al. 2013). This is a fully-coupled global climate model, which includes the land, atmosphere, ocean, and sea-ice featuring a 1° by 1° horizontal resolution and 60 vertical layers. The BGC component field was initialized using data-based climatologies and is used to track biogeochemical cycles in the earth system, which will be valuable in tracking changes in AAIW uptake.

b. Representative Concentration Pathways (RCPs)

CESM1-BGC is forced by emission concentrations and run for various radiative forcing scenarios put forth by the Intergovernmental Panel on Climate Change (IPCC). These scenarios, called Representative Concentration Pathways (RCPs), were introduced in the IPCC's Fifth Assessment Report (AR5) and range from 2.6 W/m^2 to 8.5 W/m^2 radiative forcing by the end of the century (2100) (IPCC, 2014). Emission scenarios are trajectories of concentrations of greenhouse gases such as those shown in **Figure 3**. Figure 3 also shows a breakdown of each greenhouse gas and their percentage



b)

RCPs Gases and Pollutants

Greenhouse gases: CO2, methane, nitrous oxide, fluorocarbons, sulfur hexafluoride

Aerosols/chemically active gasses: Sulfur dioxide, soot, organic carbon, carbon monoxide, nitrogen oxides, volatile organic compounds, ammonia

Figure 3. a) Emission contributions of individual forcings as a percentage of the total for RCPs compared to present day contributions. b) List of greenhouse gases, aerosols, and chemically active gases included in RCP projections. (IPCC, 2013)

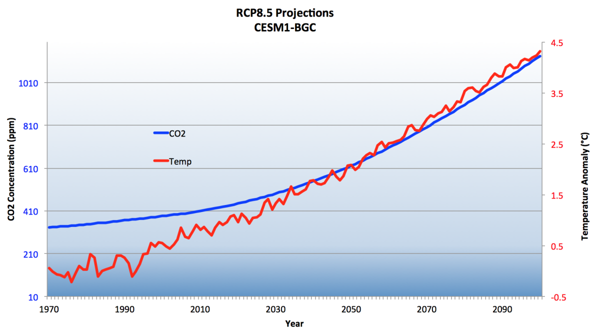


Figure 4. CESM1-BCG RCP8.5 projections for CO_2 and temperature anomaly from 1970 to 2100. Both indicate an increasing trend with $3XCO_2$ of today's value and a 4°C increase by 2100.

contribution to the total forcings. Carbon Dioxide is responsible for about 80% of the total forcings included in RCP 8.5. This study will focus on the RCP 8.5 scenario, which has been described as consistent with no policy changes to reduce emissions. **Figure 4** shows the CESM1-BGC projections for the RCP 8.5 emission scenario from 1970 to 2100. We see a 4°C temperature anomaly and 3 x CO_2 of today's value by 2100. These projections are representative of the factors that influence changes in AAIW, which are evident in the preliminary results.

c. Data Processing

This study will look at changes in AAIW from historic values to mid-century and end-of-century projections using monthly ocean data from 1970-2100. The model output data was collected from Earth System Grid, a climate data distribution portal. We chose historic values to be from 1970-1990, mid-century from 2003-2050, and end-of-century from 2080-2100 (see the summary provided in **Table 1**). Each 20-year time period was then averaged using Climate Data Operators (CDO). CDO offers the ability to format multiple aspects of a data files in one command. The 20-year periods were first selected, then averaged, and finally re-gridded to sort the longitudes to a 0-360° format. The resulting data files were plotted in RStudio using R language. We took depth profiles at four longitudes: 180W, 150W, 120W, and 90W, and surface plots of the South Pacific. This study will focus on 120W for simplicity since this longitude will give us average conditions of the South Pacific as it cuts through the middle of the subtropical gyre. Difference plots were also calculated for the physical surface properties of AAIW to show quantitative changes. These were calculated by subtracting historic values from end-of-century values.

Label	Model	Ensemble	Year
Historic	CESM1-BGC	r1i1p1	1970-1990
Mid-Century	CESM1-BGC	r1i1p1	2030-2050
End-Of- Century	CESM1-BGC	r1i1p1	2080-2100

Table 1. List of averaged time periods with the respective model and ensemble used.

PRELIMINARY RESULTS

Figure 5a shows difference values plotted in the South Pacific Ocean. Preliminary results show a density decrease of AAIW by about 0.3 kg/m^3. The density of seawater is dependent on salinity and temperature properties, so we further diagnose this decrease by also looking differences in salinity and temperature in the area. We see a salinity freshening of 0.2 psu and temperature increase of 2.5°C. The density changes of surface AAIW are concluded to be largely temperature dependent. Isopycnals of the surface properties of AAIW also show a poleward movement through the end of the century, see **Figure 5b**. These changes could indicate a possible expansion of the subtropical gyre (Zhang et al. 2014).

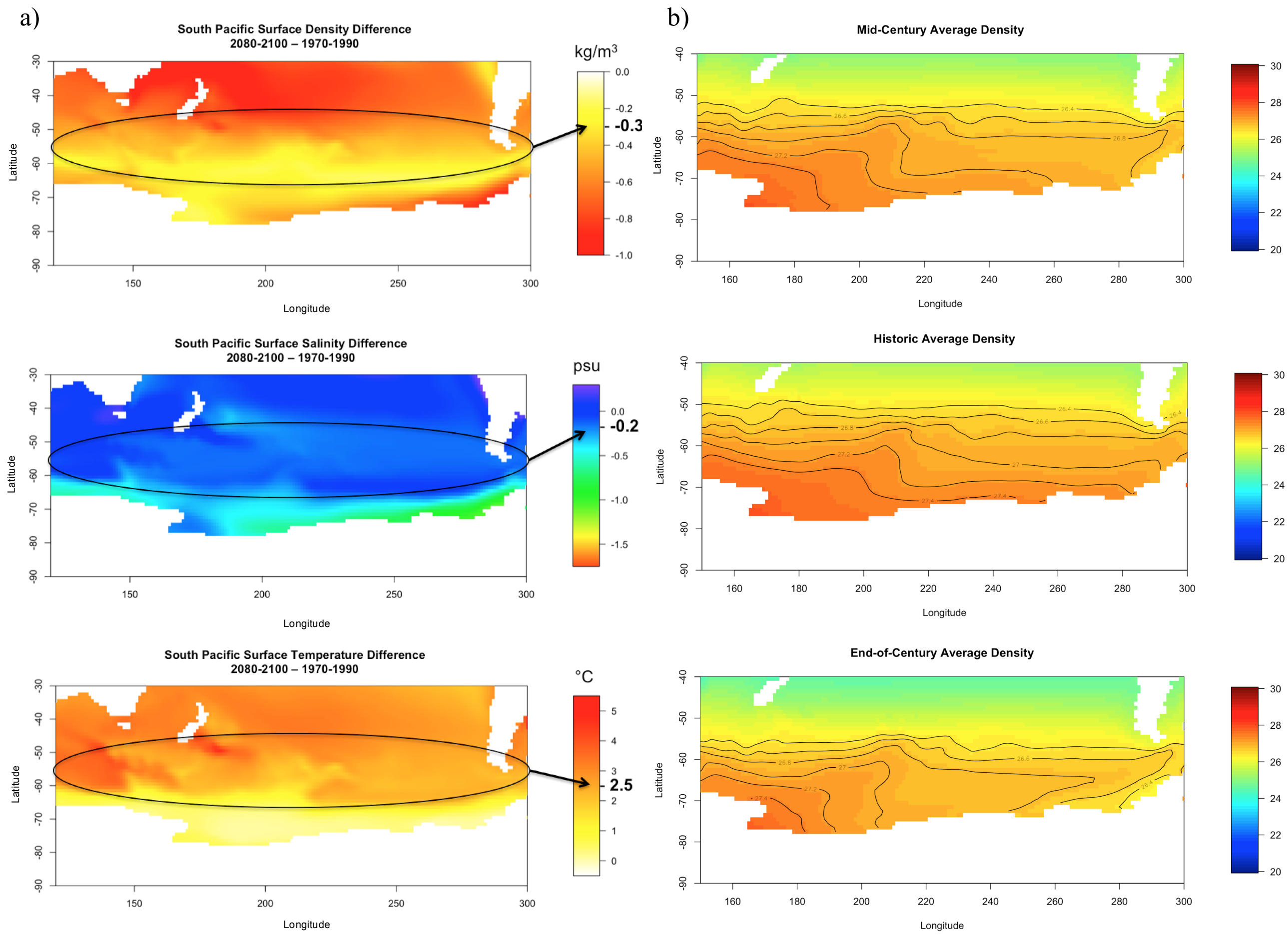


Figure 5. a) Difference plots of the South Pacific calculated for density, salinity, and temperature from 1970-2100. The black circle encompasses surface AAIW based on historic density values. b) Average surface density in the South Pacific through historic, mid-century, and end-of-century. Isopycnals overlaid to show boundary outcropping of surface AAIW.

FUTURE RESEARCH

Future research will involve further analyzing and diagnosing of the changes identified in the preliminary results. This diagnosing will include looking at Evaporation-Precipitation data to determine the cause and location of changes in surface AAIW salinity; as well as investigating sea-ice melt off the coast of Antarctica near the Ross Sea to investigate further changes in salinity due to freshwater flux. Wind stress data will also be analyzed to look at dynamic influences on density changes. Once these changes are fully analyzed, we will ultimately investigate changes in formation rates of AAIW. This can be done by two different methods: a thermodynamic approach and a dynamic approach (Marshall et al. 1999; Hartin 2012).

a. Thermodynamic Approach

The thermodynamic approach involves looking at changes in the ocean properties of density, temperature, and salinity. The annual mean formation rate (M, in Sv) is calculated by:

$$M = -[F(\sigma_{\theta 2}) - F(\sigma_{\theta 1})]$$

Where F is the water mass transformation (subduction) rates. A positive value for M indicates subduction in the density range, and a negative value indicates subduction into a less dense range.

b. Dynamic Approach

The dynamic approach calculates movement of fluid into the permanent thermocline. First, we would need to calculate the annual subduction rate using:

$$S_{ann} = -\bar{u}_{ml} \cdot \nabla h_{ml} - \bar{w}_{ml}$$

where, $\bar{u}_{ml}$ and $\bar{w}_{ml}$ are the monthly horizontal and vertical velocity components at the base of the deepest winter mixed layer (h_{ml}) (Hartin 2012). The values associated with these components are determined by upper ocean motion, which is primarily driven by winds (Karstensen and Quadfasel, 2002). The annual average formation rate (F) is then calculated by integrating the annual subduction rate over the area of surface AAIW isopycnals that we found to be 26.6-27.2 kg/m^3:

$$F = \int_A S_{ann}\, dA$$

CONCLUSION

The decision of which approach to use will be based on the diagnosing of density changes. If wind stress is found to be the primary driver for the changes, the dynamic approach will be most useful; whereas if temperature or salinity is, the thermodynamic approach will be chosen. Formation rates are an important indicator of a change in the uptake of CO_2 and nutrients. A slowing of AAIW formation could imply a disruption of uptake and promote further climate change. The ocean plays an important role in the mitigation of climate, especially that of anthropogenically produced warming.

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