Comparison of SAMW and AAIW Formation Rates in the South Pacific Between NCAR-CCSM4 and Hydrographic Observations

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Background & Objective

The formation of Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) significantly contribute to the total uptake and storage of anthropogenic gases, i.e. CO_2 and CFCs within the Southern Hemisphere. These water masses play an important role in the earth's heat, freshwater, carbon budgets and resupply of oxygen and nutrients to the subtropical oceans to sustain the marine ecosystem. The South Pacific is a principle formation site of SAMW and AAIW in the Southern Hemisphere.

We conducted a comparison of the large-scale distribution of CFCs in the South Pacific between the World Ocean Circulation Experiment (WOCE) and Climate Variability and Prediction (CLIVAR) hydrographic observations, and the simulations diagnosed from a five member ensemble average of the National Center for Atmospheric Research (NCAR) Community Climate System Model version 4 (CCSM4).

In the model simulations, CFC concentrations within the South Pacific are underestimated compared to observations particularly in the density surfaces that define SAMW and AAIW.

The objective is to quantify this bias by comparing the observed and model formation rates of SAMW and AAIW based on CFC-12 inventories within SAMW and AAIW across the South Pacific.

NCAR-CCSM4 model

The NCAR-CCSM4 model is a global coupled ocean/atmosphere/sea-ice/land surface general circulation climate model. CCSM4 has made significant improvements compared to CCSM3.

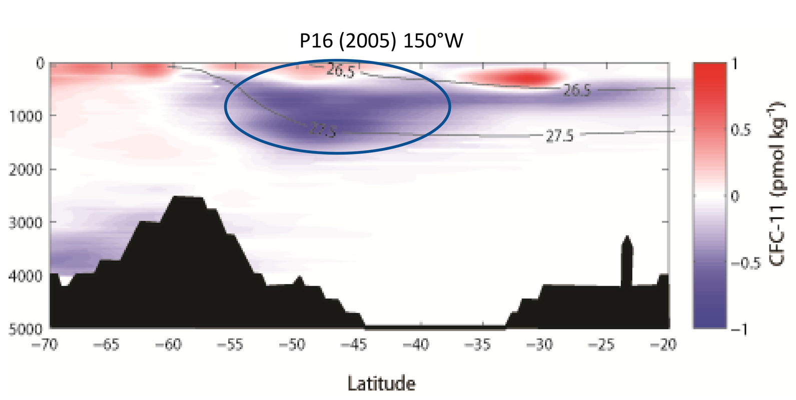

Figure 1: Difference amongst model simulation and observations of CFC-11 concentrations (pmol kg^{-1}) in the South Pacific. Note, the underestimation of CFC-11 in the model between 26.5 to 27.5 σ_0

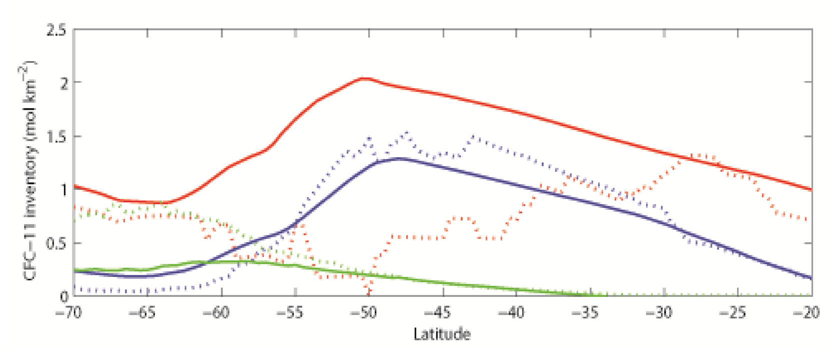

Figure 2: CFC-11 inventory (mol km^{-2}) for 150°W (P16) in 2005 for model simulation (solid) and from observations (dashed). Inventory for different water layers are shown: 0–500 m (red), 500–1500 m (blue), and 1500–5000 m (green).

CFC concentrations within NCAR-CCSM4 are underestimated, particularly at intermediate depths.

Identification of SAMW and AAIW

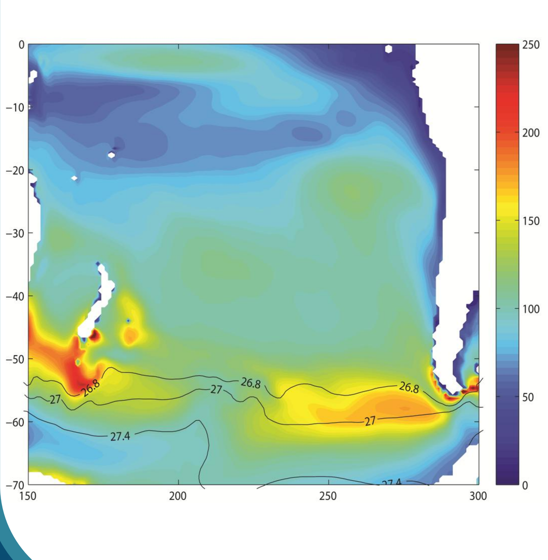

Figure 3: Average winter mixed layer depth (m) from 2000 to 2005, with potential density (kg m^{-3}) contours in black.

We identified ***SAMW (26.8 - 27.0 kg m⁻³)*** based on the deepest winter mixed layers and potential vorticity minimum. ***AAIW (27.0 - 27.4 kg m⁻³)*** is identified by a salinity minimum, poleward of the deepest mixed layers.

CFC-12 Inventories

$$CFC_{inv} = \rho \sum \left([CFC]_{(ij)} A D_{(ij)} \right)$$

Equation (1)

CFC_{inv} = CFC-12 inventory (million moles)
$CFC_{(ij)}$ = CFC-12 concentration (pmol kg^{-1}) at lat(*i*) and long(*j*)
$D_{(ij)}$ = thickness (m) at location (*i,j*)
i = latitude 65°S-0, 65°S-20°N
j = longitude 70°W-150°E
A = area of the grid points (0.534° x 1.125°) in m^2
ρ = water density kg m^{-3}

Observations

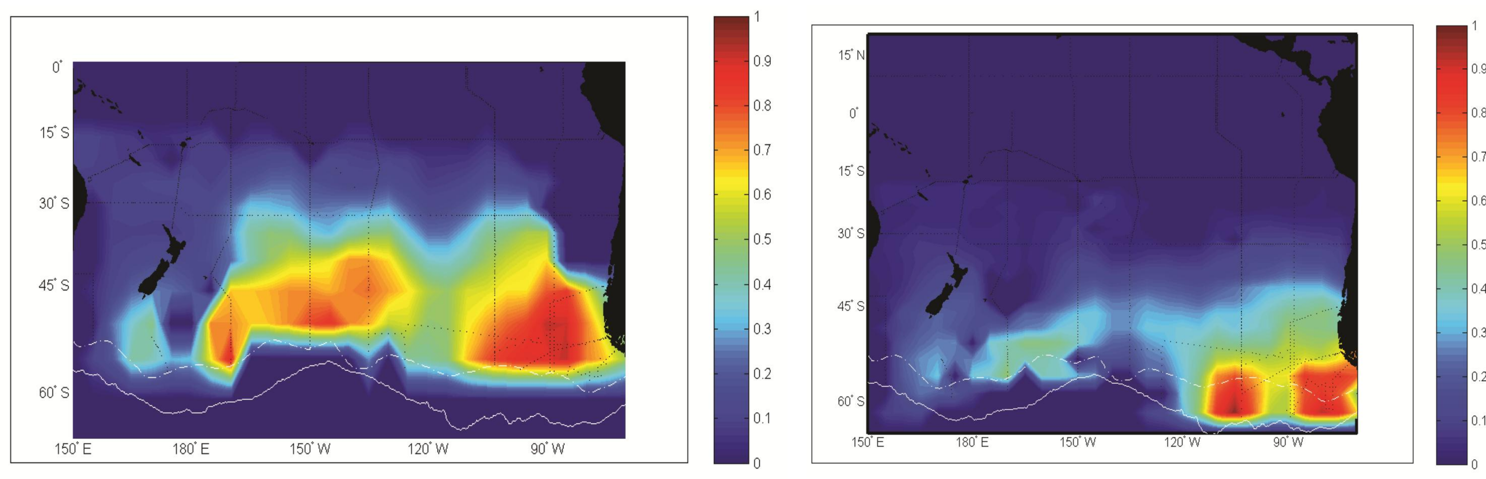

Figure 4: CFC-12 inventory (moles km^{-2}) within SAMW (26.8 - 27.06 kg m^{-3}) and AAIW (27.06 – 27.4 kg m^{-3}), from a combination of WOCE, CLIVAR, and hydrographic data collected in 2005. 2005 data collected as a part of SAMFLOC project under Lynne Talley. Data were normalized to a constant date of January 1, 2005. Lower boundary for SAMW is the Subantarctic Front (SAF, dashed line) and for AAIW is the Polar Front (PF, solid line), taken from Orsi et al., 1995. Figures from Hartin et al (2011).

NCAR - CCSM4

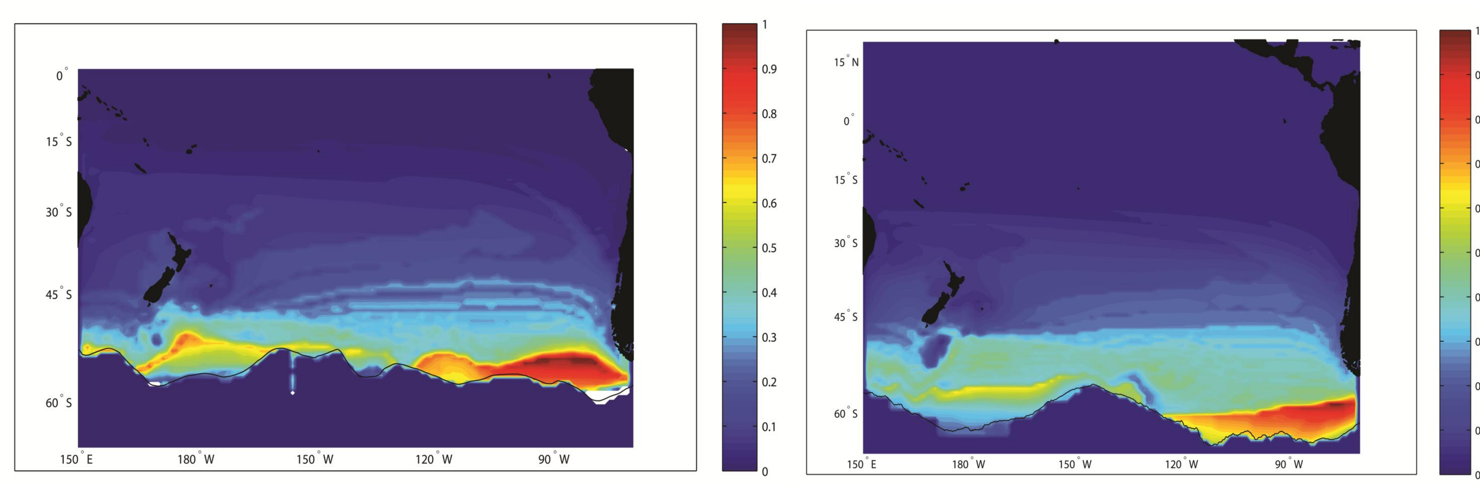

Figure 5: Ensemble average CFC-12 inventory (moles km^{-2}) within SAMW (26.8 - 27.0 kg m^{-3}) and AAIW (27.0 – 27.4 kg m^{-3}) in 2005. As with observations the lower boundary for SAMW is the SAF and for AAIW is the PF, taken from Orsi et al., 1995. Calculation of frontal jets are fairly realistic to the observational data (Weijer et al., 2011). SAF and PF are not typically resolved by climate models. Therefore, we chose to use the observational frontal locations.

Inventories

	Observations (moles)	Model (moles)
SAMW	$16x10^6$	$7.5x10^6$
AAIW	$8.7x10^6$	$11.9 x10^6$

The model inventory distributions for both SAMW and AAIW do a fairly good job at simulating the southeast Pacific as the region with the largest formation and the highest inventories. Another similarity is that the CFCs are contained within the subtropical gyre and reach blank levels as they approach 30°S.

However, in the model the high inventories do not penetrate as far equatorward as the observational inventories do. Inventories for SAMW within the model are about ½ the observations, while AAIW within the model is larger than the observations. Also, in the model the southwest Pacific contains a large region of high CFC-12 inventory - not present within the observations.

References

Hartin , et al, 2011, Formation Rates of SAMW and AAIW in the South Pacific. Deep Sea Research, 58, pp 524-534.
Orsi et al., 1995. On the meridional extents and fronts of the Antarctic Circumpolar Current. Deep Sea Research, 42, pp 641-673.
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Formation Rates

$$R = \frac{CFC_{inv}}{\rho \int_{t_0}^{t_n} [C_s(t) sat] dt}$$

Equation (2)

R= formation rate (Sv Ξ $10^6 m^3 s^{-1}$)
CFC_{inv}=calculated CFC-12 inventory (million moles)
Cs(t)=equilibrium concentration of CFC-12 (pmol kg^{-1}) from 1970-2005
sat= saturation of CFC-12 during formation

CFC-12 Percent Saturation

	Observations	Model
SAMW	95%	90%
AAIW	60%	50%

Average CFC-12 percent saturations for SAMW and AAIW relative to the 2005 atmosphere.

Formation Rates

	Observations	Model
SAMW	7.3 ± 2.1 Sv	2.5 Sv
AAIW	5.8 ± 1.7Sv	6.1 Sv

Average formation rates for SAMW and AAIW between 1970 to 2005 that are circulating within the South Pacific.

Discussion and Conclusions

1. SAMW is underestimated in CFC-12 inventories and formation rates. This may be attributed to:
   a. Mixed layer depths not simulated accurately within the model (Fig 6).
   b. The model not simulating the low potential vorticity signal within SAMW (Fig 7).
2. AAIW has higher CFC-12 inventories compared to observations but the formation rates are within the error of the observations. This may be attributed to:
   a. High inventory within southwest Pacific (Fig 5). Lack of data in observations in southwest Pacific (Fig 4).
   b. Lower percent saturations → increase formation rates (Eq. 2).
3. This comparison is important to understand the strengths and weaknesses of the model, as well as to increase our current understanding of the processes influencing SAMW and AAIW. For example,

   Increased inventory in the southwest Pacific may suggest increased formation there. Sallee at al. (2010), using Argo data also finds the southwest Pacific a region of formation for SAMW. Thus, more observations are needed to fully understand SAMW and AAIW in the southwest Pacific. Fig 6 shows that the model is overestimating the mixed layer depths in the southwest Pacific (150-200°) – a potential reason for increased inventories.

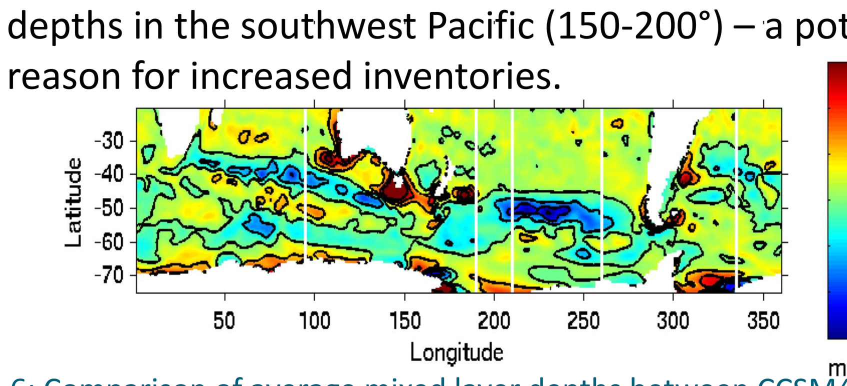

Figure 6: Comparison of average mixed layer depths between CCSM4 and CARS climatology. Note the large widespread underestimation of mixed layer depths within the South Pacific and overestimation in the southwest Pacific. Figure modified from Weijer et al., 2011.

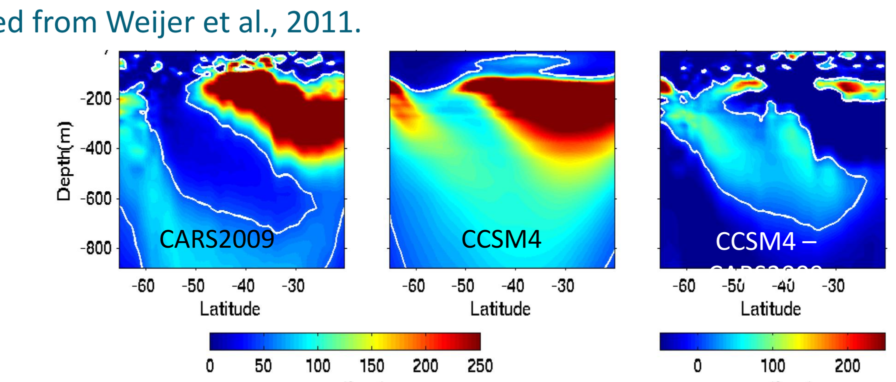

Figure 7: Comparison of winter (August-October) potential vorticity (10^{12} (ms) $^{-1}$)) in the Eastern Pacific (100°W). White contour represents the < $50*10^{12}$ (ms)$^{-1}$. Note the lack of low potential vorticity within the model (middle panel). Figure modified from Weijer et al., 2011.