CHANGES IN VENTILATION IN THE SUBTROPICAL SOUTH INDIAN OCEAN ON TIME SCALES OF DECADES

Rana A. Fine[1], Synte Peacock[2], Mathew E. Maltrud[3], Frank O. Bryan[2]

1 Rosenstiel School of Marine and Atmospheric Science, University of Miami, RFine@rsmas.miami.edu
2 National Center for Atmospheric Research
3 Los Alamos National Laboratory

Introduction: Observations of transient tracers - chlorofluorocarbons (CFCs) and sulfur hexafluoride (SF_6) in the ocean have been used to infer ventilation timescales by estimating ages. An age is a timescale that has elapsed between water parcels transiting from the ocean surface into the interior. In recently ventilated waters – on the order of decades, substantial changes in other tracers are also observed (e.g., salinity, anthropogenic CO_2). Changes over time in CFC and SF_6 concentrations due to the changing atmospheric transient (Fig. 1) can be used to quantify variability in ocean ventilation.

If the apparent timescale has changed between two sets of observations spaced years apart, the inference is often made that ocean ventilation itself has either accelerated or slowed down. However, because the ocean is full of eddies and fronts that are characterized by strong gradients in tracer concentrations and ages, a water sample at a given location and given time may not be representative of the temporally and spatially averaged tracer at that location. In order to quantify whether temporal changes in tracer ages at a given location are actually indicative of large-scale ocean circulation changes, it is first necessary to quantify the aliasing errors associated with high frequency internal ocean variability and biases associated with trends in the tracer atmospheric source. To do this we used an eddy resolving model, the Community Climate System Model version 4 (CCSM4) [*Maltrud et al.*, 2010].

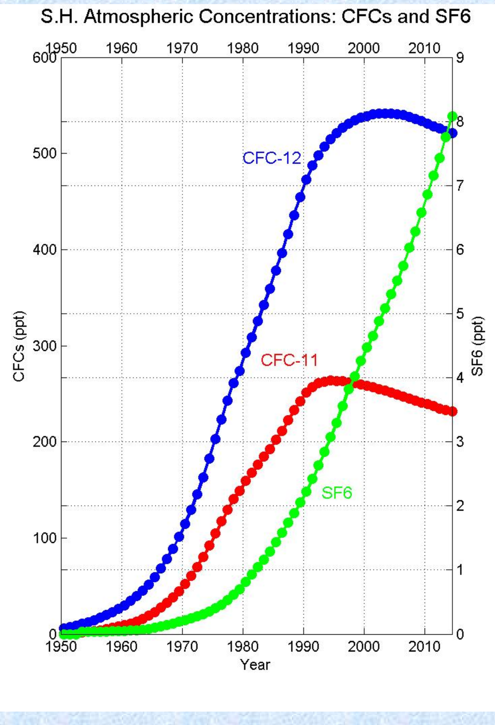

Fig. 1 Southern hemisphere atmospheric time histories of CFC-11, CFC-12, and SF_6 in ppt from http://cdiac.ornl.gov/oceans/new_atmCFC.html.

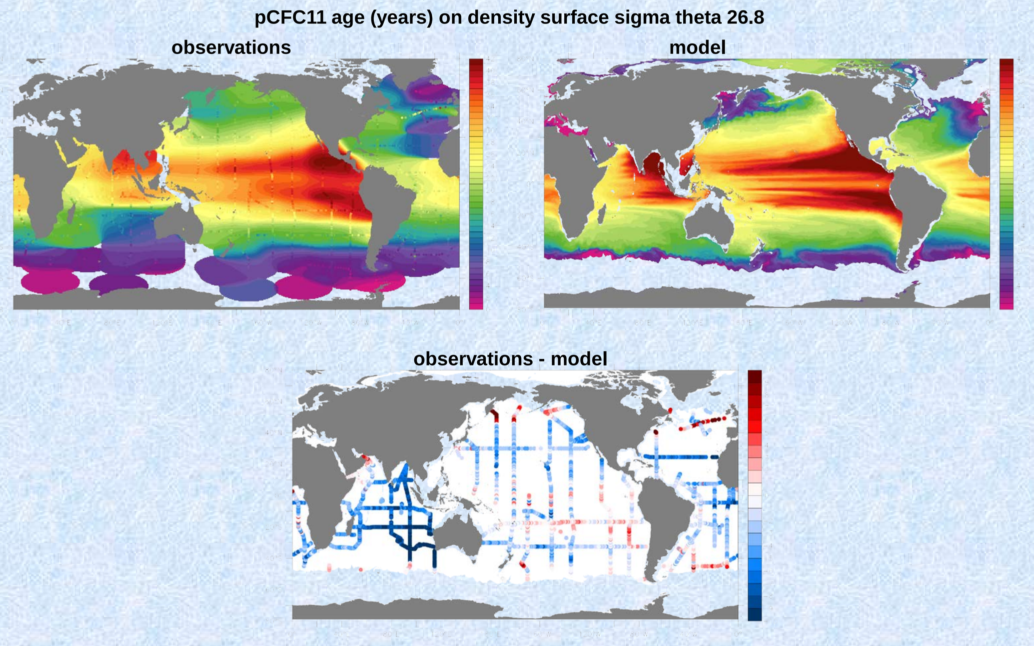

Fig. 2 Global maps from WOCE observations and CCSM4 in 1994 of pCFC-11 age in years for 26.8 σ_θ. Color bar on right shows from 0-50 years. The plots on the left show the observations and the model on the right, below is the difference between observations and model at station locations. Note that 40 years is the maximum age given the analytical capability of CFC-11 measurement technique. Ages in regions showing 40 years could be substantially older.

Data-Model Age Comparison: In mid-thermocline on 26.8 σ_θ, both in the observational and model-derived maps (Fig. 2), the oldest waters are found (>45 years) in the Bay of Bengal and Pacific OMZs. In the southern hemisphere, 26.8 σ_θ roughly coincides with Subantarctic Mode Waters (SAMW). The influence of SAMW is evident as younger water in all three subtropical gyres, [also Fig. 3, e.g., *Fine*, 1993]. Observations in the Indian Ocean are younger than in the model, and differences between observations and model pCFC ages exceed 5 years in the eastern Indian. Differences could be due to model parameterizations and large variability in the throughflow pathway. We find that the effect of model bias having ages older than observations for lower thermocline waters in the eastern South Indian has a minor impact on our comparisons.

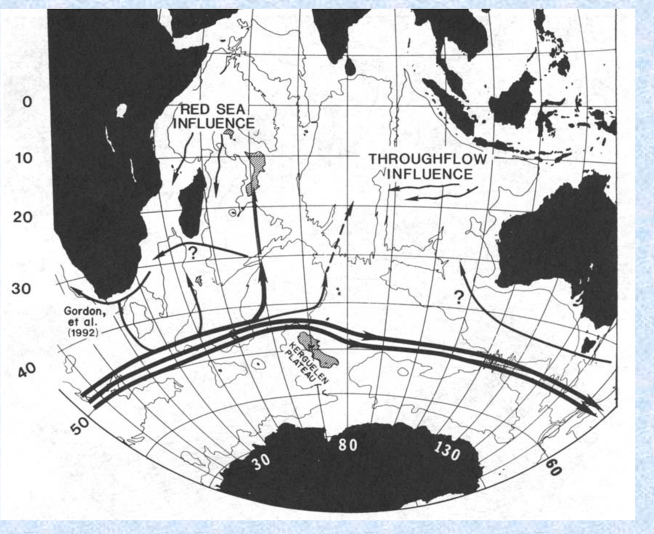

Fig. 3 Map showing the inferred thermocline and intermediate circulation in South Indian (Fine, 1993).

Quantifying Uncertainties and Biases in Tracer Ages:
To estimate uncertainties due to ocean variability using standard deviations, we employ an ensemble of CFC-11 simulations, each subject to identical forcing, but with independent realizations of the mesoscale circulation [*Maltrud et al.*, 2010]. Standard deviations in the interior subtropical gyres are small, less than 0.5 years. On the other hand, the largest eddy induced variability in ages (Fig. 4) occurs in regions of large mean gradients due to fronts and regions with high eddy kinetic energy. Our results indicate that regardless of the year, there are certain high eddy and frontal regions where standard deviations of ages will be relatively large (~4 years), and other regions where standard deviations will be relatively small (<1 year). Based on these results, we will take as a conservative estimate of tracer age eddy noise 2 years for the subtropical gyre regions of interest.

Global maps of mean age trends from the model simulated CFC-11 are presented over the decade 1985-95 (Fig. 5). They show how much the pCFC-11 ages are increasing – due to the effects of non-stationarity of the atmospheric transient when there is mixing. Trend rates vary from 0 to 1 year per year. On 26.8 σ_θ, largest annual increases in ages are in the older waters of OMZs and Bay of Bengal. In general, age trend patterns are quite similar to patterns of the transit time distribution (TTD) and pCFC ages (Figs. 6, 2). Water masses consist of a collection of water parcels of different ages due to their different mixing time histories. A transit time, is a probability distribution of ages, which explicitly accounts for the fact that a water mass contains a collection of ages [e.g., *Waugh et al.*, 2003].

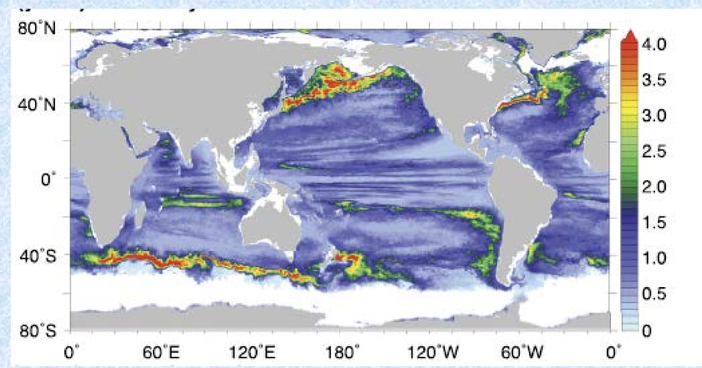

Fig. 4 Global map from CCSM4 of pCFC-11 standard deviations for 1994. Color bar on right shows standard deviation in years for 26.8 σ_θ from 0-4 years. Where pCFC-11 ages exceed 45 years, standard deviations are not meaningful.

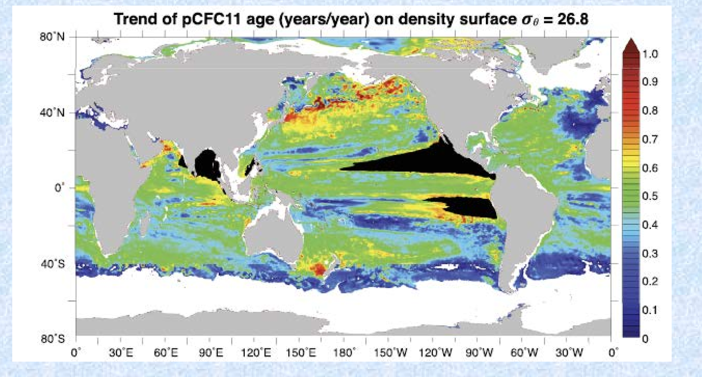

Fig. 5 Global map of pCFC-11 age trends for the years 1985-95 on 26.8 σ_θ. pCFC-11 age from CFC-11 explicitly simulated by CCSM4. Color bar on right shows annual increase in pCFC-11 age in years. Areas are colored black where ages exceed the analytical capability of the technique >45 years.

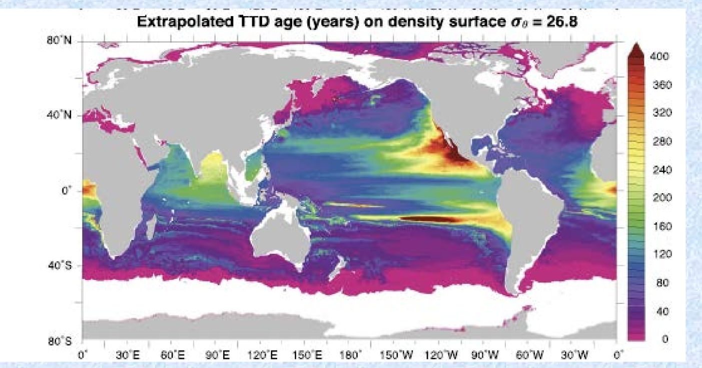

Fig. 6 Global map from CCSM4 of ages derived from extrapolated TTDs. Shown are TTD ages derived from extrapolated TTDs that extend the ~100 year simulation results out to ~1000 years. Color bar on right shows for 26.8 σ_θ from 0-400 years.

References
•Beal, L.M., W.P.M. De Ruijter, A. Biastoch, R. Zahn, and SCOR WCRP/IAPSO Working Group 136 (2011), *Nature,* 472, doi:10.1038/nature09983.
•Fine, R.A. (1993), Circulation of Antarctic Intermediate Water in the Indian Ocean. *Deep-Sea Res.*, 40, 2021-2042.
•Fine, R.A. (2011), Observations of CFCs and SF_6 as ocean tracers, *Annu. Rev. Mar. Sci.*, 3, 173-195.
•Fine, R.A., W.M. Smethie, Jr., J.L. Bullister, D-H. Min, M.J. Warner, M. Rhein, A. Poisson, and R.F. Weiss (2008), Decadal ventilation and mixing of Indian Ocean waters, *Deep-Sea Res.* I, 54, doi: 10.1016/j.dsr.2007.10.002.
•Fine, R.A., S. Peacock, M. Maltrud, and F.O. Bryan (2017), A new look at ocean ventilation time scales, *J. Geophys. Res. Oceans*, 122, 3771–3798, doi:10.1002/2016JC012529.
•Maltrud, M.E. F. Bryan, and S. Peacock (2010), Boundary impulse response functions in a century-long eddying global ocean simulation, *Env. Fluid Mch.,* 10, 275-295, doi:10.1007/s10652-009-9154-3.
•Roemmich, D., J. Gilson, R. Davis, P. Sutton, S. Wijffels, and S. Riser (2007), Decadal spinup of the South Pacific subtropical gyre, *J. Phys. Oceanogr.*, 37, 162-173.
•Schlitzer, R. (2009), Ocean Data View http://odv.awi.de.
•Schmidtko, S., and G.C. Johnson (2012), Multidecadal warming and shoaling of Antarctic intermediate Water, *J. Clim.,* 25, 207-21.
•Tanhua, T. D.W. Waugh, and J.L. Bullister (2013), Estimating changes in ocean ventilation from early 1990s CFC-12 and late 2000s SF6 measurements, *Geophys. Res. Lett., 40*, 927-932.
•Waugh, D.W., T.M. Hall, and T.W.N. Haine (2003), Relationships among tracer ages, *J. Geophys. Res.,* 108, doi:10.1029/2002JC001325.
•Waugh, D.W., F. Primeau, T. DeVries, and M. Holzer (2013), Recent changes in the ventilation of the southern oceans, *Science, 339*, 568.
•Wyrtki K. (1971), *Oceanographic Atlas of the International Indian Ocean Expedition,* National Science Foundation, Washington, DC.

Acknowledgement: Rana Fine thanks the National Science Foundation, Physical Oceanography Program for support, the data originators for the high quality hydrographic, oxygen and tracer data, and Debra A. Willey for programming help with the data and figures. Synte Peacock and Frank Bryan were supported by the National Science Foundation through is sponsorship of NCAR. Mathew Maltrud is supported by the U.S. Department of Energy's Office of Biological and Environmental Research. Computational resources for the simulations used in this study were provided by the National Center for Computational Sciences at Oak Ridge National Laboratory and by the Computational and Information Systems Laboratory of NCAR. The model simulation that produced the output described in Appendix was supported by a DOE INCITE grant at the Oak Ridge Leadership Computing Facility.

Differences in Ventilation Between 2000s and 1990s: With the objective of examining *real* changes in water mass ventilation, differences between pCFC ages from the WOCE decade of the 1990s as compared with the two CLIVAR/GO-SHIP decades of the 2000s and 2010s are presented for sections across the Indian Ocean. The focus here is on the mid to lower thermocline 26.0-27.2 σ_θ to include SAMW and AAIW and for practical reasons.

Both model and observational age differences show ages increasing by up to 10 years between the two occupations (Fig. 7 top panel). Ages increasing with time due to the changing atmospheric source have been well documented. When the model age trend (top panel) is subtracted from observational age differences (middle panel), then in the third panel the result is ages with the residual pCFC-12 age trend removed. On the third panel the light and dark blue boxes are age differences decreasing by more than 2 years, which is the error from the standard deviation. Ventilation changes are also observed in the fourth panel (Fig.7) of difference in AOU between the 2000s and the 1990s. Note that our focus is 26.0-27.2 σ_θ, and in this density range most of the section shows decreasing AOU. In the South Indian I5 section along 32°S (Fig. 7) we infer increased ventilation, most or 64% of the boxes show an age decrease of at least 2 to 10 years, while 76% show a decrease that is greater than zero.

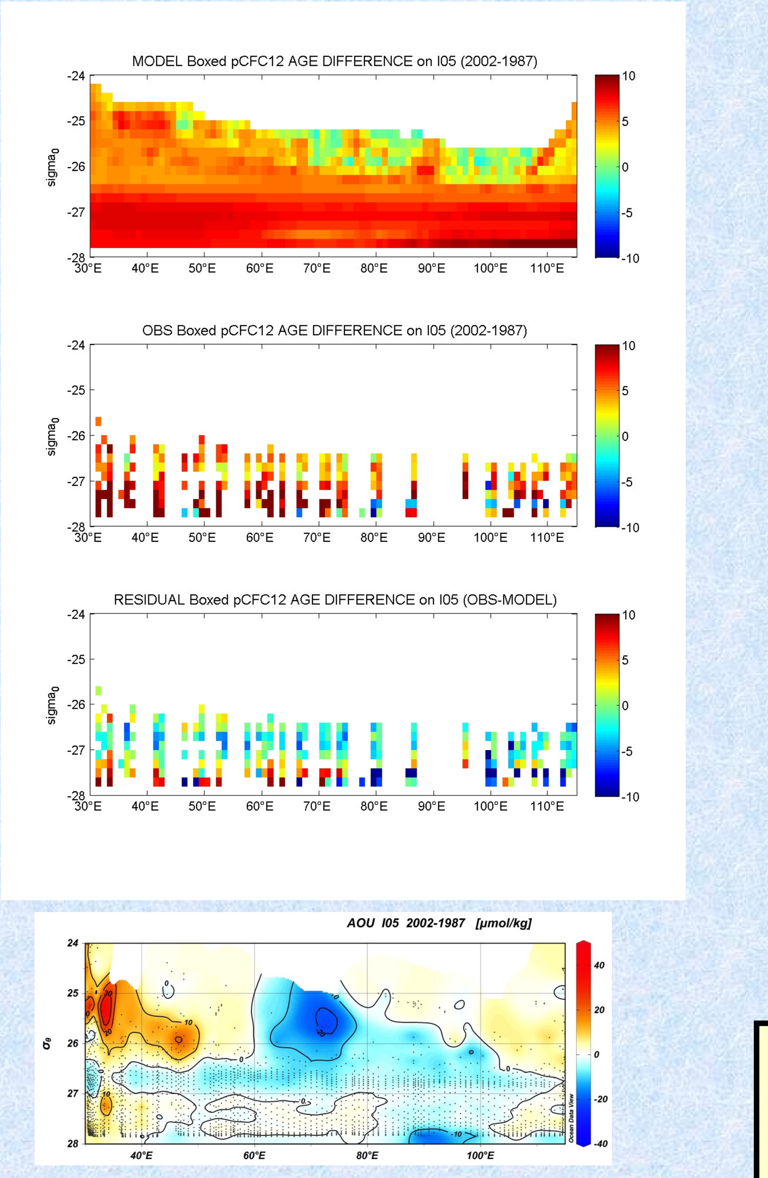

Fig. 7 Sections in the Indian Ocean of pCFC-12 age (top 3 panels) differences versus sigma-theta along 32°S. The I5 sections: 2002 minus 1987. Top panel is pCFC-12 age difference**, which is the age trend and is model derived from TTD projected trends. Second panel is boxed obser**vational pCFC-12 age difference. Third panel is a residual, observational pCFC-12 age difference with age trend removed. Fourth panel is difference in AOU, contour interval is 10 µmol/kg. There are some areas where a few of the AOU difference points may exceed the scale given on right, and still they show as positive or negative. The scale was chosen to emphasize where AOU differences are positive and negative over most of the section. Figure plotted in Ocean Data View [*Schlitzer*, 2009].

Implications for the Entire Indian Ocean: One reason ventilation of subtropical South Indian waters is so important is that they are a major source of ventilated mid-thermocline to intermediate water masses in the entire Indian Ocean (e.g., Wyrtki, 1971; Fine et al., 2008). These southern waters eventually feed the northern open ocean oxygen minimum zones, which are believed to be expanding.

Differences in Ventilation Between 2010s and 1990s: As SF_6 data are available from the beginning of the 2010s decade, we compare them to pCFC-12 ages from 1990s in the Indian Ocean along 32°S (I5 2009 versus 1987, Fig. 8). For SF_6 2009-11 and CFC-12 in mid-1990s, their atmospheric values were still increasing linearly (Fig. 1), and no age trend was applied. Appling no age trend could suggest that the ventilation differences should be considered lower bounds. For the South Indian Ocean, differencing pSF_6 from pCFC-12 ages gives 35% of boxes and 43% in area where ages are decreasing. However, when considering an error of 2 years then ages are decreasing for only 9% of the boxes and 15% of area. The South Indian age differences are least in the west and particularly in the lower thermocline, where AOUs are also increasing (Fig. 8, fourth panel). Note that the AOU differences are considerably more positive between the 2010s and 1990s, as compared with between the 2000s and 1990s.

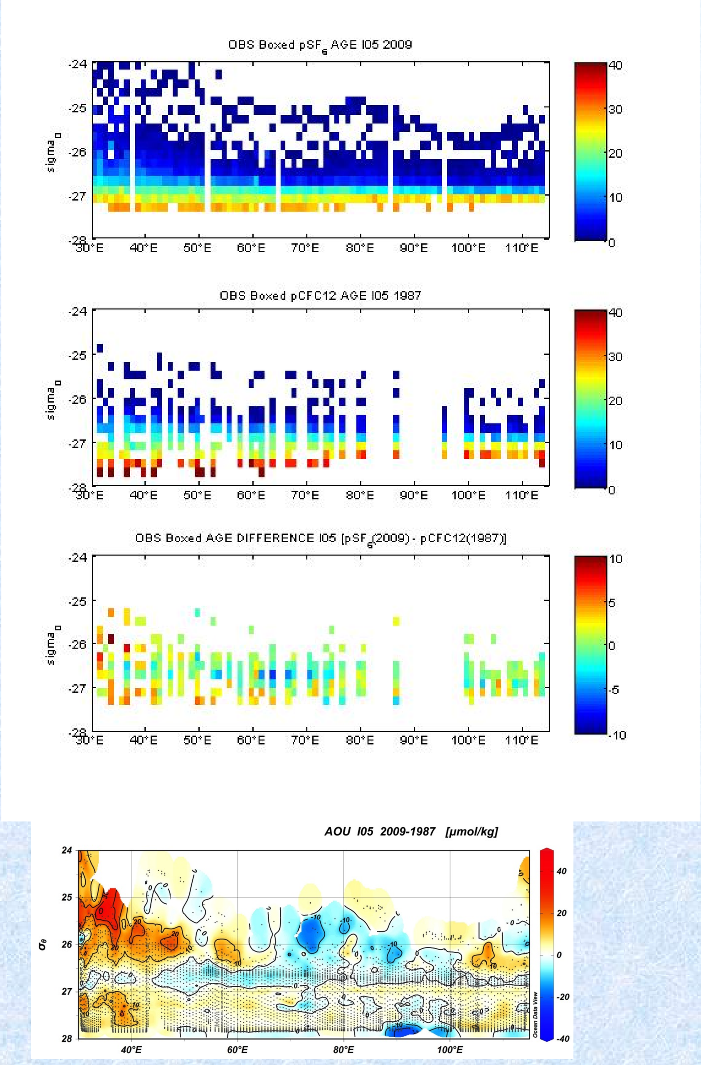

Fig. 8 Sections in the Indian Ocean of pCFC-12 age (top 3 panels) differences versus sigma-theta along 32°S, the I5 sections for 2009 and 1987. Top panel is CLIVAR/GoShip pSF_6 age. Second panel is WOCE pCFC-12 age. Third panel is difference between observational ages 2009/10 pSF_6 age minus 1992 pCFC-12 age. Fourth panel is difference in AOU.

Conclusions: The pCFC ages show that the thermocline is a barrier to interior ocean exchange with the atmosphere on timescales of 45 years, the measureable CFC transient. These do not include parts of the North Indian Ocean lower thermocline and OMZs where the timescales are longer. CFC ages have been assessed: standard deviations to look at uncertainties in tracer ages due to internal ocean variability, age trends to look at biases in pCFC ages due to the effects of non-stationarity of the atmospheric transient when there is mixing. These approaches for assessing uncertainties and biases have promising aspects that should be considered when examining changes in ventilation.

From a comparison of WOCE (1987-1993) and CLIVAR/GO-SHIP decade (2002-2003) pCFC-12 ages – taking into account uncertainties due to standard deviations and biases due to age trends – we infer *real* increases in ocean ventilation. These increases are consistent with decreases in AOU between these decades. A significant increase in ocean ventilation is inferred in the three southern subtropical gyres over the timescale of the specific 2000s decade and 1990s cruises in the layer 26-27.2 σ_θ. Other studies have concluded that increased thermocline ventilation is consistent with changes in the Southern Annular Mode (SAM) and spin up of the gyre circulation [e.g. *Fine*, 2011; *Waugh et al.*, 2013; *Tanhua et al.*, 2013]. However, between 1990s ages and 2010s ages the decreases are not significant, (perhaps except for the South Atlantic Ocean and the South Pacific is questionable). Our finding of no age decrease in the Indian Ocean is consistent with increased Agulhas leakage [*Beal et al.*, 2011] and regional changes in the SAM [e.g., *Roemmich et al.*, 2007; *Schmidtko and Johnson*, 2012]. It is important to note that ventilation changes are specific to the years of the cruises, and also are likely embedded in longer timescale climate trends. Observational programs such as GO-SHIP that measure gases in the global ocean including CO_2, oxygen, CFCs/SF_6 will have an essential role in documenting future ventilation trends.