LONG-TERM VARIATIONS OF SUBANTARCTIC MODE WATER AT 32°S IN THE INDIAN OCEAN

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Long-term variations of Subantarctic Mode Water (SAMW) at 32°S in the Indian Ocean were examined for 1950-2008 using a time-series mapped objectively from historical hydrographics and Argo data. In the lighter SAMW (<26.7σ_θ), saltier water distributed widely in 1960s was replaced with fresher water in the late 1980s after large-amplitude (>0.1 in salinity) oscillations with 5 to 10-year time-scales. After 1995 saltier SAMW occupied again. Freshening trends in the density range were difficult to be conclusively identified now because of the large variations there. Meanwhile, the denser SAMW (>26.8 σ_θ) showed freshening trends clearly; its salinity decreased by over 0.1 since the 1960s. SAMW had a thick pycnostad in 1960s and then became the thinnest in the 1980s. Recently, the thick core recovered and became less dense slightly. These features seem consistent with recent model runs under global warming scenarios.

1. INTRODUCTION

In the South Indian Ocean, a thick pycnostad called Subantarctic Mode Water (SAMW) is distributed widely (e.g., [1]). SAMW originates from a mixed layer fairly developed in winter north of the Subantarctic Front. The properties of SAMW are mainly determined by the long-term accumulation of sea surface heat and freshwater fluxes, which vary quickly and by large amounts. Therefore, examining property changes is suitable for investigating long-term flux changes. Examining variations of the SAMW pycnostad is also important because it is one of the largest reservoirs of heat and freshwater in the global ocean; thus, SAMW plays a crucial role in the climate system.

Recent model studies describe subsurface waters of the South Indian Ocean as one of the areas most sensitive to global warming (e.g., [2]). Furthermore, five full trans-Indian Ocean hydrographic surveys (in 1936, 1965, 1987, 2002, and 2009 recently) and a partial one (in 1995) were conducted around 32°S. Thus, decadal changes of upper water, including SAMW, there were studied directly (e.g., [3], [4]) and indirectly with a "historical" section estimated from numerous observations (e.g., [5], [6]) and it has been clarified that SAMW (and the thermocline water) oscillated its property (freshening/salinizing) on decadal scales.

Meanwhile, recent climate models (e.g., [7], [8], [9]) suggested that upper waters including SAMW become freshening as global warming proceeds, which is partially inconsistent with the observational results. SAMW in the models showed large variations over short time-scales, which may means the trans-Indian observations were too infrequent to resolve the variations there. To Identify variations and trends of observed oceanic changes is therefore increasingly important (e.g., [3]), especially for discussing the effects of global warming.

Here, we discuss long-term variations of SAMW at 32°S using a time-series dataset (1950-present) prepared from historical hydrographic datasets and recent Argo data with an optimal interpolation (OI) technique.

2. DATA AND METHOD

Argo data used in the study were downloaded from the Global Data Assembly Centre at the end of June 2008; about half of the data were quality-controlled (QCed) with the delayed-mode procedure. All data without QC flag of "Good" were discarded. Argo oxygen data were not used in the study because of no oxygen QC in Argo.

For analyses before 2000, the study mainly used Indian Ocean HydroBase ([10]), which is highly QCed. World Ocean Database 2005 (WOD05) is used additionally to fill up a fewer observations of HydroBase, especially in 1990s. Particularly, most CTD data for the analysis were from WOD05.

The time-series dataset at 32°S was reconstructed as follows: Initially, depth, potential temperature (theta), salinity, layer thickness of 0.1 σ_θ interval, dissolved oxygen, and apparent oxygen utilization (AOU) were interpolated every 0.1 σ_θ for 26.0-27.6 σ_θ for all profiles except where were density gaps of 0.2 σ_θ or more between successive vertical layers. Averages and standard deviations (SD) at every 1°×1° gridpoint were calculated from all observations with consideration of distances from the gridpoint. The QCed dataset, in which anomalous data departing from the average by more than 2.3×SD were discarded, was used thereafter.

An initial guess and a signal value for OI were assumed to be the average and SD for all QCed hydrographies and a “climatology” (1°×1° grid) was estimated from the initial guess by OI adjustment with the QCed hydrographic data, regardless of observed year. The correlation function for OI was a Gaussian with a spatial scale of 5° for zonally and 3° for meridionally. The signal-to-noise ratio was 1 for depth and layer thickness and 1.5 for theta and the other parameters, which were determined by preliminary analyses to be representative of the subtropical Indian Ocean. A time-series of the properties (e.g., depth, theta) on isopycnal surfaces at 32°S for 1950–2008 (at 1-year interval) was calculated by OI adjustment. The correlation function for the OI time-series was the same except for an additional time scale of 3 years, meaning that variations shorter than about 5 years were screened out; of course, the density of observations would not resolve any faster variations.

3. LONG-TERM VARIATIONS OF SAMW CORE

Fig. 1 shows variations of the water properties at SAMW core (26.8 σ_θ) along 32°S from 1950 to 2008. In the 1960s, SAMW had a thick core around 80-100°E, then it became thinner to be the minimum around 1980. After 1995, SAMW had a thicker pycnostad again: in recent years, SAMW was the thickest since 1950 and extended eastward to the coast of Australia. The thick SAMW in the 1960s was distributed near the sea surface, but the recent core moved to greater depth.

SAMW was warmer and saltier before 1975, especially east of 70°E. Then, it became colder and fresher with large-amplitude variations (>0.5°C and >0.1) over time scales of 5-10 years to reach a minimum of temperature and salinity in the late 1980s. Afterwards, SAMW retained the cold/fresh properties, with some variations, until now. Ref [11] reported that eastern SAMW became less saline after 2002 in Argo data, which is consistent with our results. Salinity anomaly changes seem to have occurred simultaneously in the whole section. Interestingly, the isopycnal of SAMW core tended to be at deeper depth when colder/fresher water was occupied there and visa versa, which was also simulated in an ocean model of [9]. AOU of SAMW core seemed to increase gradually with variations, but the dissolved oxygen field showed almost no long-term trends (not shown).

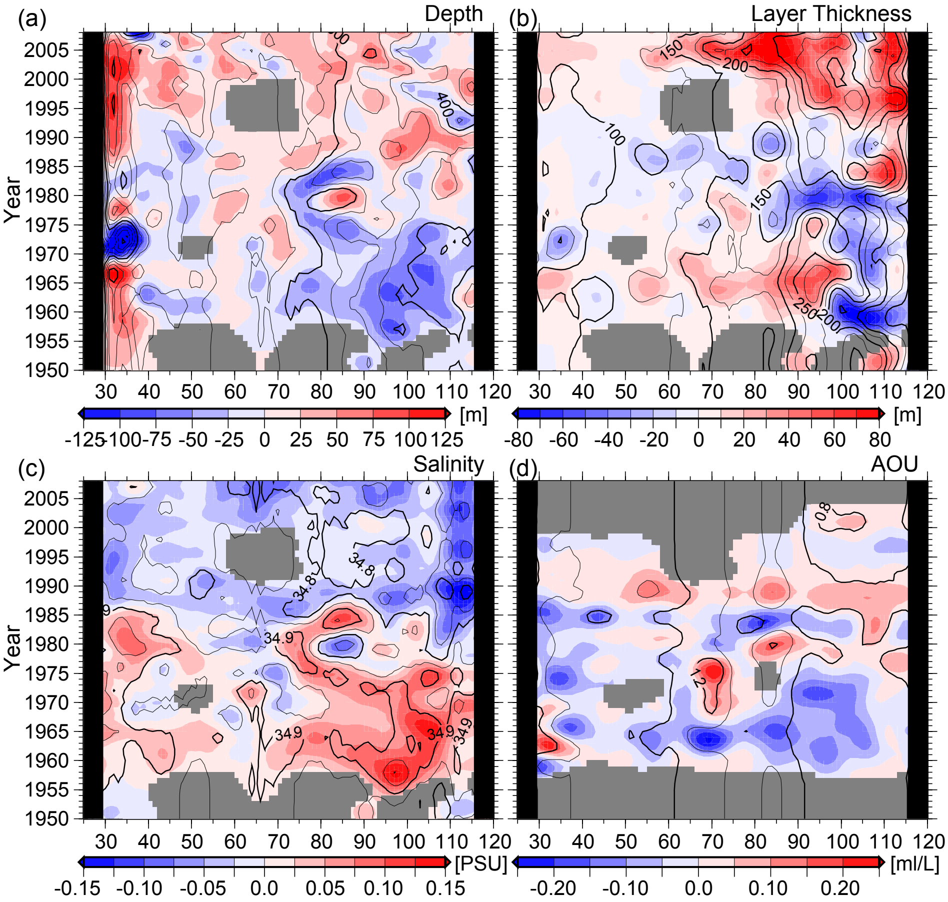

Figure 1. Long-term variations (1950–2008) of (a) depth, (b) 0.1 σ_θ thickness, (c) salinity, and (d) AOU along 32°S on 26.8 σ_θ isopycnal. Contours and shading represent the OI-generated values and the anomalies from the climatology, respectively. Areas with OI errors exceeding 0.9 of the signal (owing to insufficient observations) are masked.

4. LONG-TERM TRENDS AND COMPARISONS WITH HYDROGRAPHIC TRANSECTS AND NUMERICAL MODELS

Fig. 2 shows time-series of the OIed isopycnal properties averaged over the eastern part of the section. It also shows the isopycnal averages of the trans-Indian hydrographies (in 1936, 1965, 1987, 1995, and 2002) for comparisons. The OI results agreed very well with the transects; this may be natural. However, almost the same time-series are reconstructed even in the case of the mapping without all transects (not shown). It means the signals of climate changes found in the trans-Indian sections (e.g., [4]) are observed widely in the South Indian Ocean.

One of the most important features of SAMW's interannual variation was the quick oscillations. They were found in all parameters and their time-scales were about 5-10 years: their lower limits might be determined by the 3-year time-scale used in the mapping. Their amplitudes were very large, sometimes over 0.1 in salinity and 50 m in thickness of the pycnostad. The variability was larger on the less dense isopycnals generally. The most typical example was found in 70-90°E in 1970-1990 (Fig. 1), where the OI errors were relatively small and many observations were conducted. It means such shorter-term variations may exist widely in the subtropical Indian Ocean.

Another important feature was the freshening trends of SAMW. The upper SAMW (<26.7 σ_θ) seemed fresher in the long term: isopycnal salinities in the present were lower by about 0.15 than in the 1960s, the saltiest period in the analysis. To verify the freshening trends clearly future monitoring, however, is needed because of the large variations in the density range. For example, the highest salinity in 2006 was almost as same as that in the 1960s, especially at 26.6 σ_θ and above. Meanwhile, its denser layers (>26.8 σ_θ) showed the freshening trends clearly. Here, the isopycnal salinities decreased from a plateau in the 1960s to a bottom in the late 1980s, and the low salinities continued to the present except for a small rebound in the early 1990s. The freshening trends are further clarified by a comparison with the transect in 1936. The waters in intermediate layers also showed trends towards lower salinity since 1960.

It is also important to note the SAMW core became less dense since 1960 slightly. The pycnostad of SAMW was developed in the 1960s and after 1995 and the thickest layer was always 26.8 σ_θ for the period of analysing. However, the second thickest layer was changed from the isopycnal below the core (26.9 σ_θ) to that above it (26.7 σ_θ).

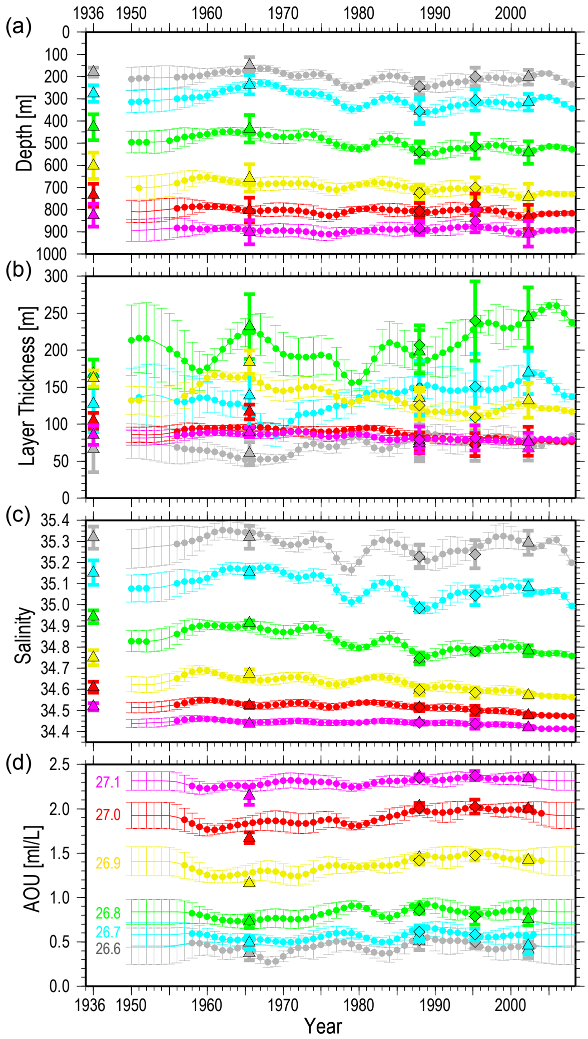

Figure 2. Interannual variations of (a) depth, (b) 0.1 σ_θ thickness, (c) salinity, and (d) AOU averaged over 80-110°E at 32°S for the 26.6-27.1 σ_θ surfaces. Error bars represent root mean square (RMS) OI errors. Reliable estimates (where the RMS error is less than 0.9 of the signal RMS) are shown with solid circles. Triangles and diamonds show averages from bottle sampling and CTD surveys of the trans-Indian hydrographic observations (in 1936, 1965, 1987, 1995, and 2002), respectively.

The above features are consistent with model results in the Indian Ocean (e.g., [7], [8], [9]) that reported simulated SAMW, which is slightly less dense than the corresponding in the real ocean, has large and quick interannual variations. The quick variations are considered one of the natural features of SAMW. Climate models also clearly showed freshening trends in upper layers including SAMW in experiments simulating global warming. The density of the SAMW pycnostad core gradually becomes less dense as well.

One of possible causes of SAMW interannual variations, especially the freshening trends, is an increase of fresher surface water transport owing to stronger westerly over the Antarctic Circumpolar Current ([12]). The strength of the westerly is closely related to the Antarctic Oscillation (e.g., [13]), which has been in a general long-term phase to reinforce the westerly since the 1960s (e.g., [14]). Further investigations of the details of long-term variations are left for future studies.

5. CONCLUDING REMARKS

Long-term variations of SAMW at 32°S from 1950 to the present were examined using time-series properties on isopycnal surfaces reconstructed from historical hydrographies and Argo data with an OI technique. The core (26.8 σ_θ) and the denser part of SAMW clearly showed freshening trends after 1960: the layers were occupied by warmer and saltier waters in the 1960s, which was replaced with colder and fresher waters in latter 1980s. Afterwards, the SAMW retained fresher properties, with some variations, until now. The salinity decreased more than 0.1 from 1960s to 2000s. A comparison with the trans-Indian in 1936 emphasized the recent freshness in the layers. Meanwhile, the lighter part of SAMW (<26.7 σ_θ) was partially different: the low salinity retreated in 1990s and a saltier SAMW was again apparent after 2000 (see Fig. 2). The pycnostad of SAMW on 26.8 σ_θ, which was thick in the 1960s, became thinner to a minimum around 1980. After 1995 the pycnostad greatly developed and extended eastward to the Australia. The pycnostad core became slightly less dense. Note that there were variations of all properties with large amplitudes (over 0.5°C and 0.1 in salinity) and with time-scales of 5-10-years. These SAMW features seem consistent with recent model studies, where water-properties of surface to intermediate layers show very large variations over shorter time-scales due to natural variation and have freshening trends due to global warming.

6. REFERENCES

1. McCartney, M.S. (1977). Subantarctic Mode Water. *Deep-Sea Res.*, **24**, Suppl., 103-119.

2. Banks, H.T. & R.A. Wood (2002). Where to look for anthropogenic climate change in the ocean. *J. Clim.*, **15**, 879-891.

3. Bryden, H.L., E.L. McDonagh & B. A. King (2003). Changes in ocean water mass properties: Oscillation or trend? *Science*, **300**, 2086-2088.

4. McDonagh, E.L., H.L. Bryden, B.A. King, R.J. Sanders, S.A. Cunningham & R. Marsh (2005). Decadal changes in the south Indian Ocean thermocline. *J. Clim.*, **18**, 1575-1590.

5. Wong, A.P.S., N.L. Bindoff & J.A. Church (1999). Large-scale freshening of intermediate waters in the Pacific and Indian Oceans. *Nature*, **400**, 440-443.

6. Bindoff, N.L. & T.J. McDougall (2000). Decadal changes along an Indian Ocean section at 32°S and their interpretation. *J. Phys. Ocean.*, **30**, 1207-1222.

7. Banks, H.T., R.A. Wood, J.M. Gregory, T.C. Johns & G.S. Jones (2000). Are observed decadal changes in intermediate water masses a signature of anthropogenic climate change? *Geophys. Res. Lett.*, **27**, 2961-2964.

8. Stark, S., R.A. Wood & H.T. Banks (2006). Reevaluating the causes of observed change in Indian Ocean water masses. *J. Clim.*, **19**, 4075-4086.

9. Murray, R.J., N.L. Bindoff & C.J.C. Reason (2007). Modeling decadal changes on the Indian Ocean section I5 at 32°S. *J. Clim.*, **20**, 3106-3130.

10. Kobayashi, T. & T. Suga (2006). The Indian Ocean Hydrobase: A high-quality climatological dataset for the Indian Ocean. *Prog. Oceanogr.*, **68**, 75-114.

11. King, B.A., & E.L. McDonagh (2005). Decadal changes in ocean properties revealed by ARGO floats. *Geophys. Res. Lett.*, **32**, L15601, doi:10.1029/2005GL023145.

12. Rintoul, S.R. & M.H. England (2002). Ekman transport dominates local air-sea fluxes in driving variability of Subarctic Mode Water. *J. Phys. Ocean.*, **32**, 1308-1321.

13. Hall, A. & M. Visbeck (2002). Synchronous variability in the Southern hemisphere atmosphere, sea ice, and ocean resulting from the Annular Mode. *J. Clim.*, **15**, 3043-3057.

14. Marshall, G.J. (2003). Trend in the Southern Annual Mode from observations and reanalyses. *J. Clim.*, **16**, 4134-4143.