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Long-term variations of surface and intermediate waters in the southern Indian Ocean along 32°S

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Summary:
Variations of water properties in surface and intermediate layers along 32°S in the southern Indian Ocean were examined using a 50-year (1960–2010) time series reproduced from historical hydrographic and Argo data by using optimal interpolation. Salinity in the 26.7–27.3σ_θ density layer decreased significantly over the whole section, at a maximum rate of 0.02 decade^{-1} at 26.8-26.9σ_θ, for the 50-year average. Three deoxygenating cores were identified east of 75°E, and the increasing rate of AOU in the most prominent core (26.9–27.0σ_θ) exceeded 0.05 ml/l decade^{-1}. SAMW pycnostad and AAIW salinity minimum shifted slightly toward the lighter layers. Comparisons with trans-Indian Ocean survey data from 1936 suggest that the tendencies found in the time series began before 1960. Interestingly, cores of many prominent trends were located just offshore of Australia in the SAMW density range (26.7–27.0σ_θ). A spectrum analysis revealed that two oscillation components with time scales of about 40 and 10 years were dominant in the subsurface layers. Our results are fairly consistent with, and thus support, the oceanic responses in the southern Indian Ocean to anthropogenic climate change predicted by model studies.

Data:

Argo data: Downloaded from GDAC in Feb. 2010. About 55% of data was proceeded with delayed-mode QC. All data lacking QC flags of 1 (good) were discarded. All oxygen data were removed due to no QC in Argo.

Historical hydrographic data: Used a composite data set of Indian Ocean HydroBase (Kobayashi & Suga, 2006) mainly and WOD05 secondly. The additional use of WOD05 decreased the data gap around 2000.

50-year time series reproduction by OI

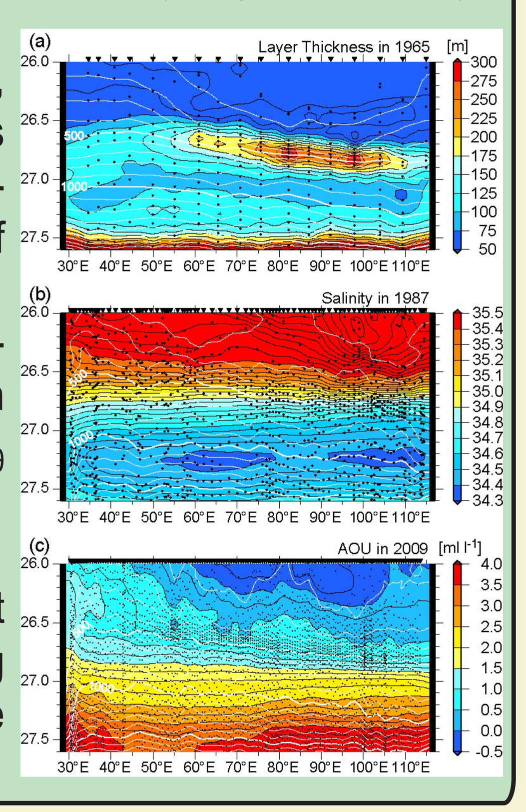
1. Depth, salinity, 0.1σ_θ layer thickness, and AOU on isopycnals (every 0.1σ_θ in 26.0–27.6σ_θ) were interpolated for all profiles.
2. Average and standard deviation (SD) at 1°x1° grid were calculated from all observations considering the distances from the gridpoint. The QCed data set, in which the observations with larger deviation from the average than 2.3xSD were discarded, were used thereafter.
3. The climatology on isopycnals in the Indian Ocean (1°x1° grid) was estimated objectively from the QCed historical data. A Gaussian correlation function was used for the OI, with spatial e-folding scales of 5° zonally and 3° meridionally. The signal-to-noise ratio was estimated at each gridpoint; the value fell roughly within the range of 0.7–1.3.
4. Time-series of the isopycnal properties at 32°S during 1960-2010 were calculated every 1-year by the OI adjustment from the climatologies with all data. Temporal correlation was a Gaussian of 3-year e-folding scale.

Reconstruction of the trans-Indian survey sections

Zonal sections gridded at intervals of 1° zonally and 0.05σ_θ diapycnally were reconstructed by OI for each of the trans-Indian hydrographic surveys due to the differences in station intervals.

The sectional structures of the depth, salinity, and AOU were reconstructed. The thickness was calculated later from the reconstructed isopycnal depths. The OI calculation consisted of two steps, following Roemmich (1983).

1. Large-scale features of the section were estimated using a Gaussian correlation function with e-folding scales of 12° zonally and 0.2σ_θ diapycnally. The signal-to-noise was set to 1 uniformly.
2. Finer structures were adjusted from the first estimation using parameters at e-folding scales of 2° and 0.1σ_θ and a signal-to-noise ratio of 1.5.



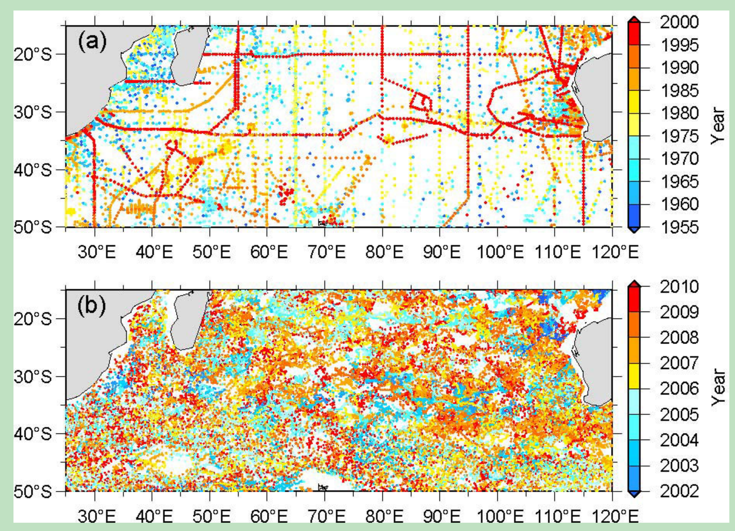
Background: Oscillations or trends? (by Bryden et al. 2003)

The surface and intermediate waters at 32°S in the Indian Ocean became fresher and less oxygenated over 25-year period ('1962'-1987) by comparing the observation in 1987 with a reconstructed section in '1962'. (by Wong et al. (1999), etc.)

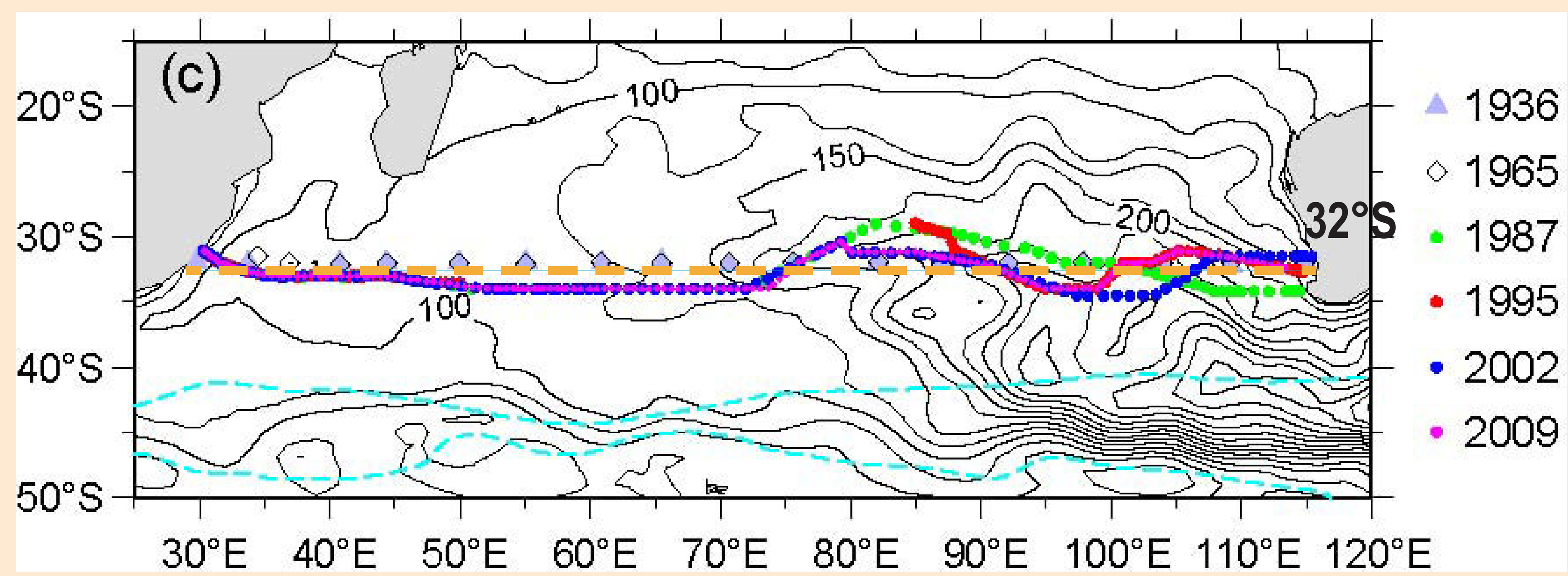
Meanwhile, Bryden et al. (2003) and McDonagh et al. (2005), by direct comparisons of the trans-Indian Ocean surveys, clarified that the property variations at 32°S were more complicated than the simple scenario: the direction of change of the water properties was sometimes different between the lighter and the denser parts of the thermocline, and the direction (e.g., freshening or salinizing for salinity) also alternated over time.

We examined the detail features of the long-term variations at the 32°S section with time series of the water properties reproduced from the historical and Argo data with an optimal interpolation (OI) technique on isopycnal surfaces.

(Revised in Journal of Oceanography)

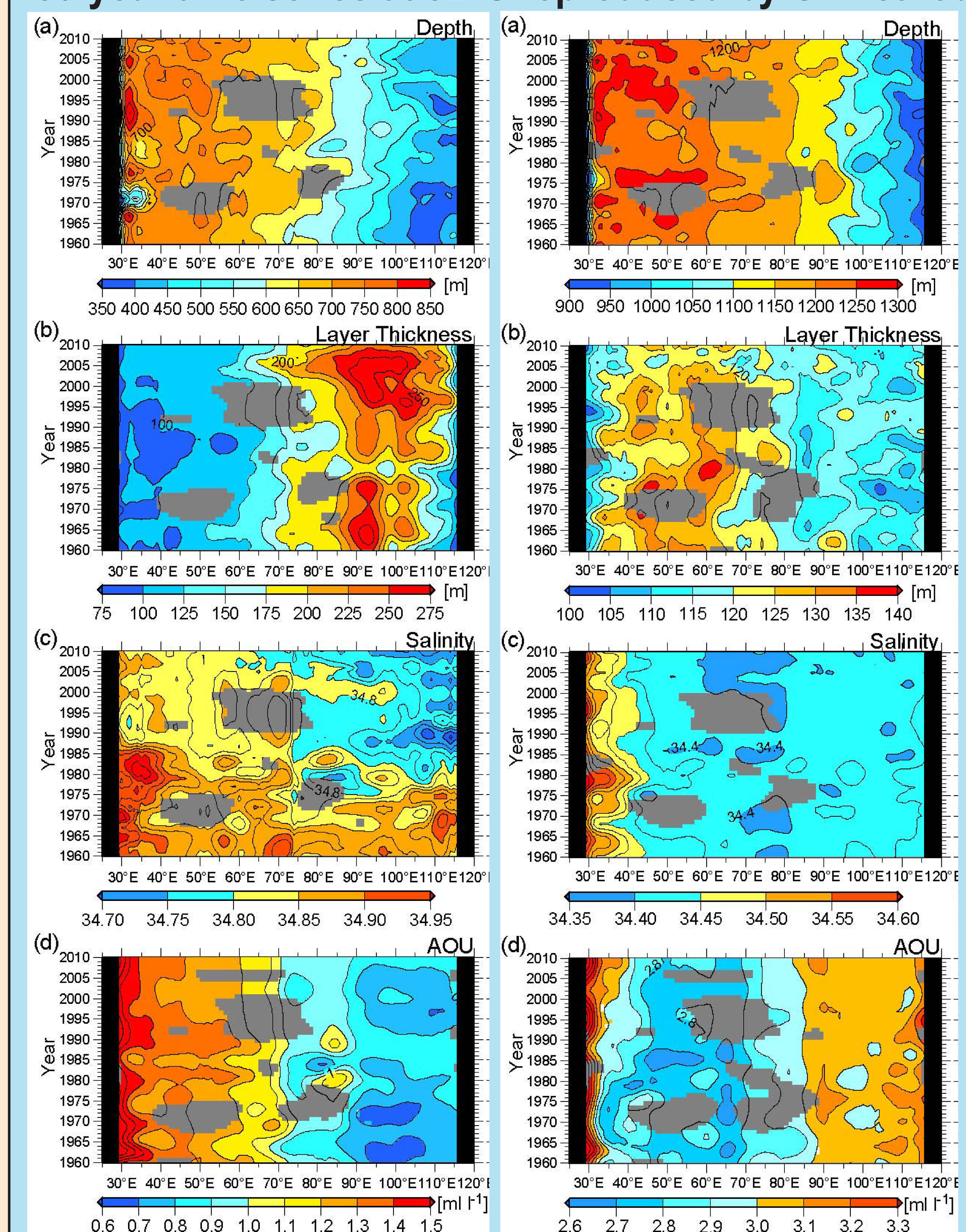


Distribution of (a) historical hydrographic and (b) Argo data on 26.8σ_θ surface used for the study.

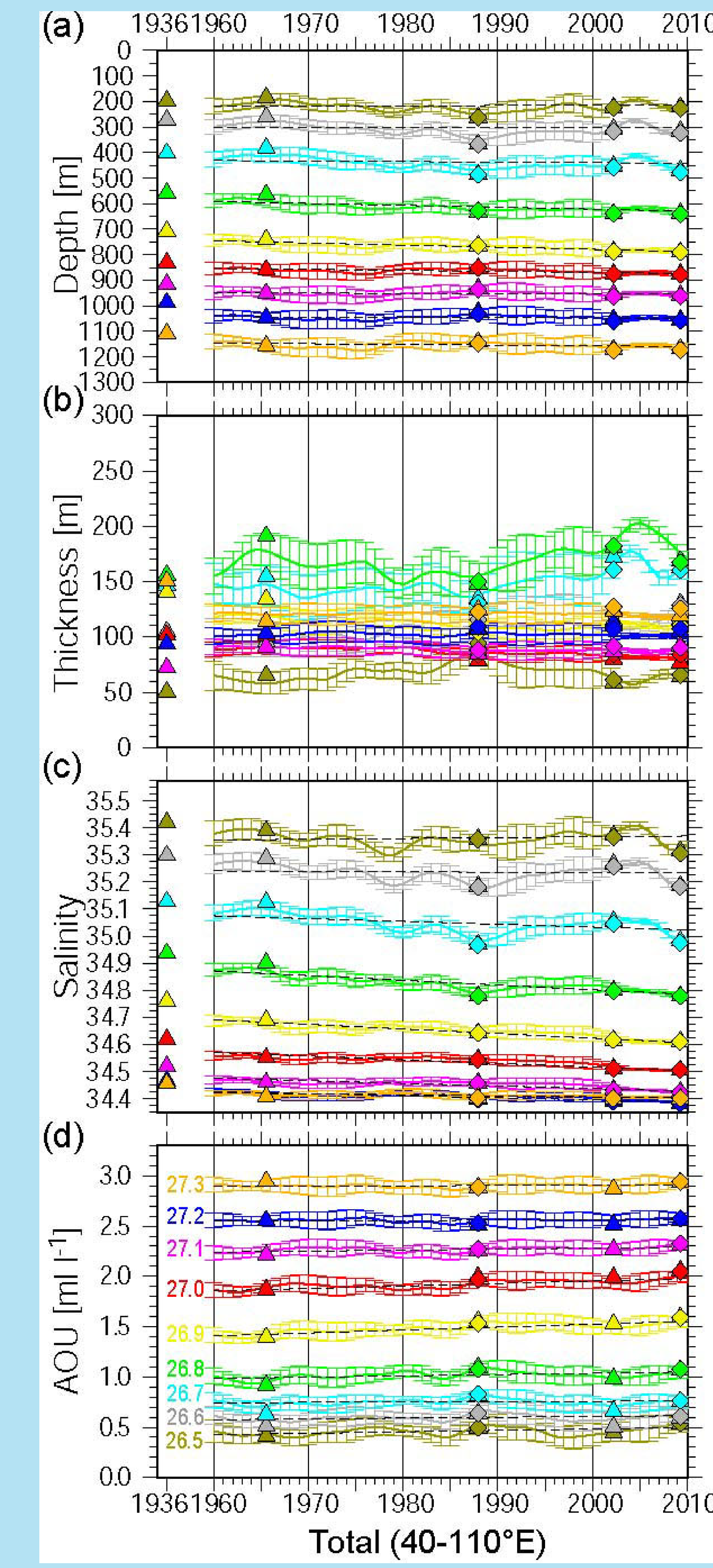


Location of the 32°S section examined in the study and six trans-Indian hydrographic surveys around the section over the climatology of 0.1σ_θ layer thickness at the 26.8σ_θ surface.

50-year time series at 32°S reproduced by OI method

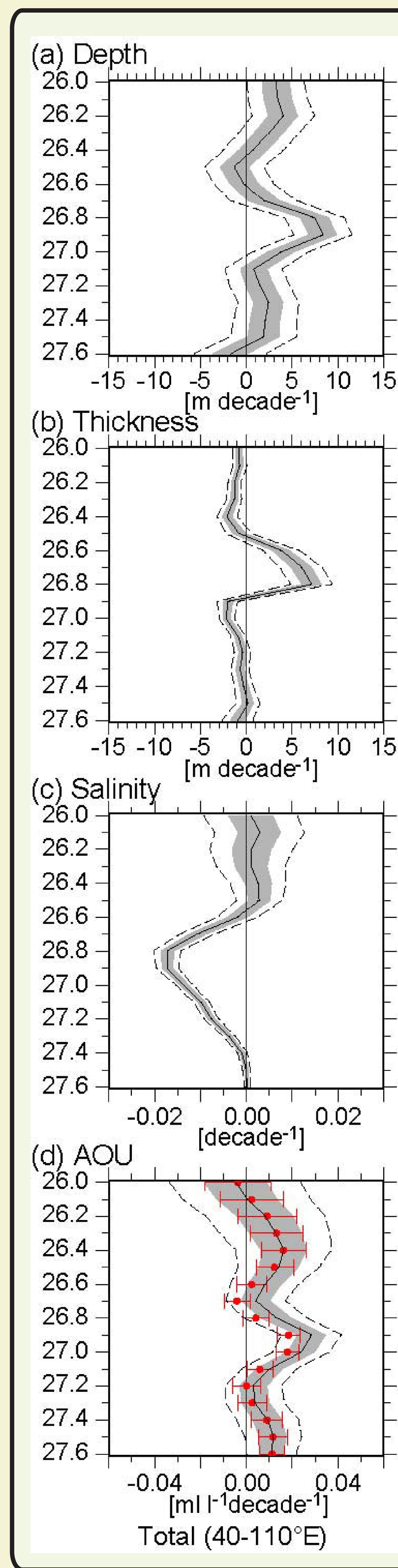


50-year variations of depth, thickness, salinity, and AOU at (left) 26.8σ_θ and (right) 27.3σ_θ along 32°S during 1960-2010. The areas with larger OI error than 0.8xSD (due to fewer observations) are masked.



Variations and typical OI errors of depth, thickness, salinity, and AOU averaged over 40–110°E for the 26.5–27.3σ_θ isopycnals. The dashed lines represent the linear trends for 1960–2010. Triangles and diamonds show the trans-Indian Ocean surveys.

Linear trend components in the variations



Linear trends in depth, thickness, salinity, and AOU from 1960 to 2010 for the averages over 40–110°E. Solid lines and shaded areas represent the trends and the standard errors. Dashed lines represent the upper/lower limits of the 95% confidence intervals.

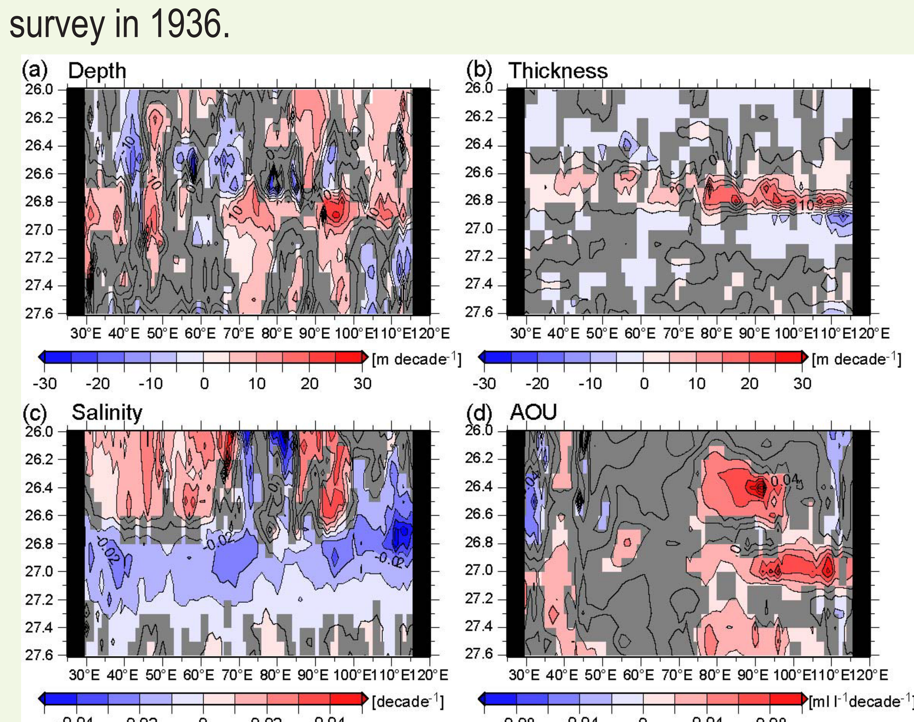
Many of prominent cores are located just offshore of Australia in SAMW density range (26.7-27.0σ_θ).

Freshening: Zonal uniformly in 26.7-27.3σ_θ. (the maximum rate: 0.02 decade^{-1} at 26.8-26.9σ_θ: similar level of model results).

Deoxygenizing: three cores east of 75°E (the maximum rate: 0.05 ml/l decade^{-1} in the middle core)

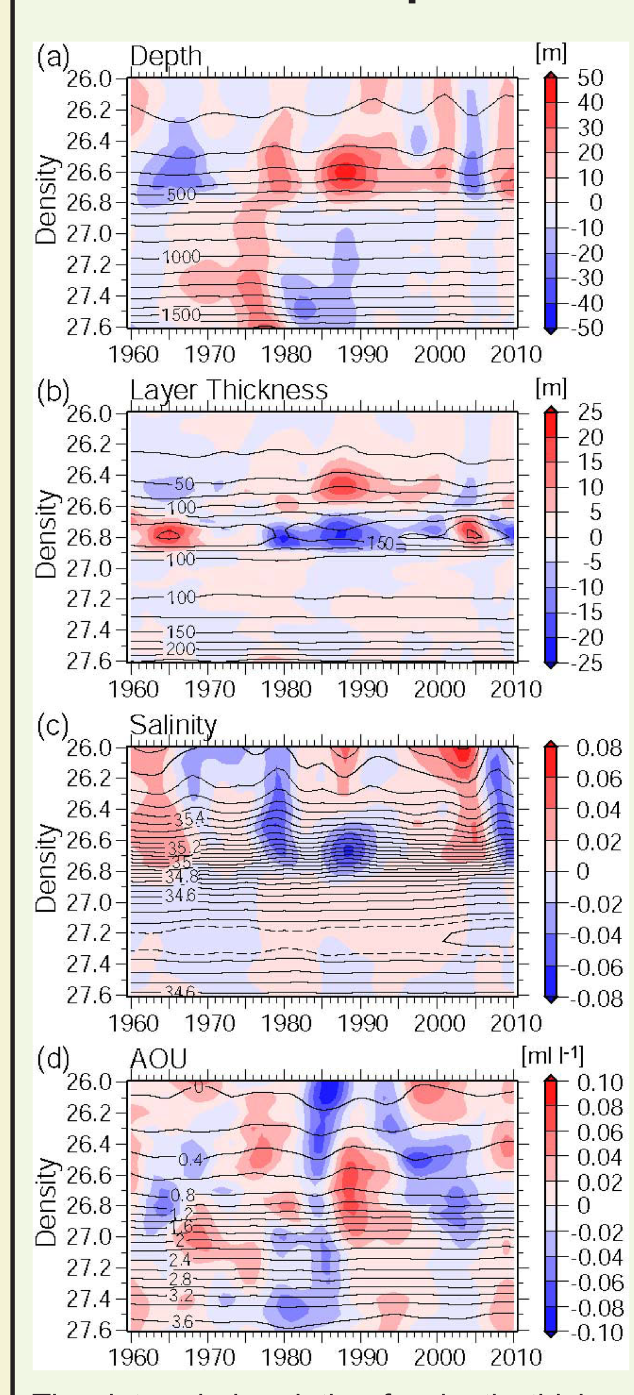
SAMW pycnostad and AAIW salinity minimum shift toward the less dense layers.

=> Such tendencies began before 1960 by the comparison of the survey in 1936.



Distributions of linear trends in depth, thickness, salinity, and AOU for 1960–2010 along 32°S. Colored shading shows areas where the trends are statistically significant at the 5% level.

Oscillation components in the variations

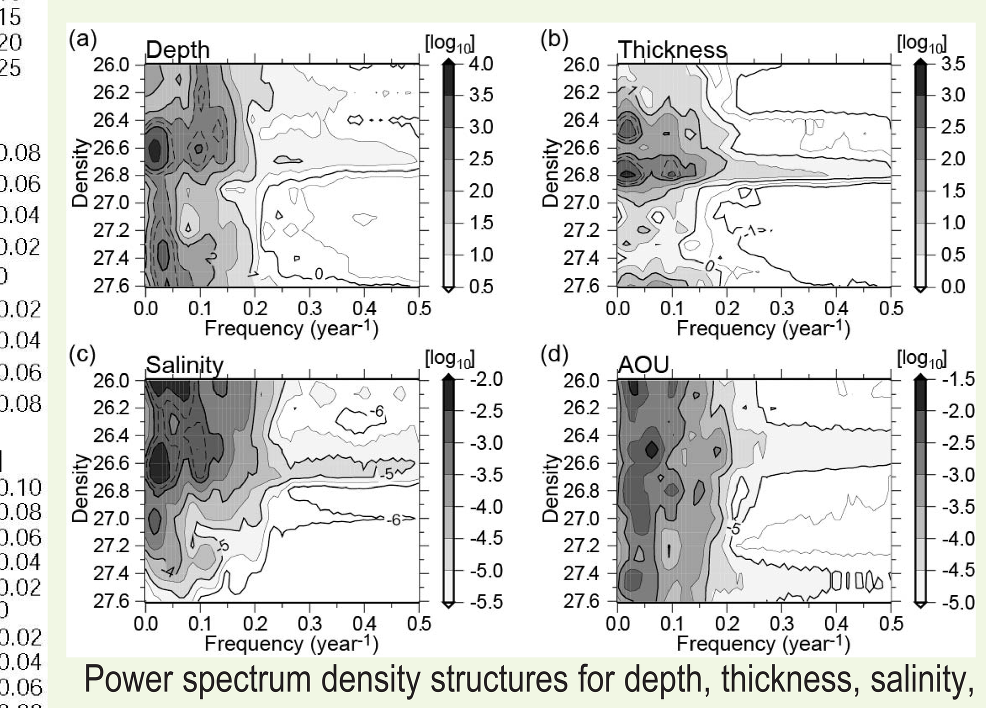


The detrended variation for depth, thickness, salinity, and AOU averaged over 40–110°E for 1960–2010. Contours and color shading in the left panels represent the averaged OI values and the anomalies.

Oscillation components with time scales of about 40 and 10-years are dominant in the lighter layers than 26.8σ_θ.

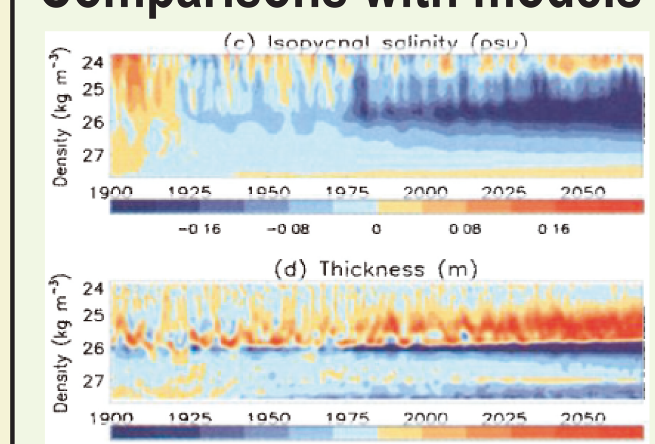
40-year oscillation: during 1985–1990 (1965–1970 and 2003–2007) the water at 26.6σ_θ became fresher (saltier) when the isopycnal surface deepened (shallowed) and the SAMW pycnostad became thinner (thicker).
(consistent with the Maurry's ocean model results)

10-year oscillation: many of model studies reported oscillations with time scales of 5-15 years in salinity or so.

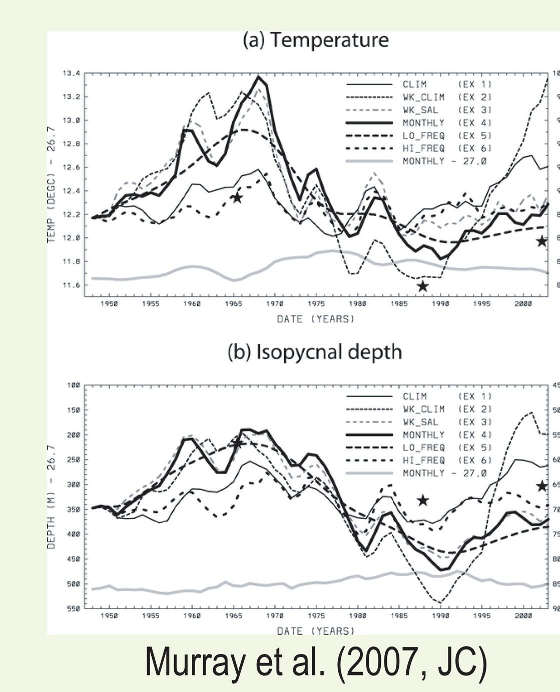


Power spectrum density structures for depth, thickness, salinity, and AOU, averaged isopycnally over 40–110°E for 1960–2010.

Comparisons with models



Banks et al. (2000, GRL)
A climate model run with IPCC B2 scenario. Zonal average along 32°S on isopycnal surfaces. SAMW as thick pycnostad in the model is reproduced around 25.8σ_θ



Murray et al. (2007, JC)
An ocean model run forced by NCEP winds and Hadley SSTs.