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Changes in Ocean Water Mass Properties: Oscillations or Trends?

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could be bodily transporting core fluid, and thus magnetic field lines (that move with the fluid to a first approximation), from east to west. Such an equatorial jet has previously been suggested in inversions of radial magnetic field change for core flows (*20*), and strong westward (retrograde) zonal flows produced by nonlinear Reynolds stresses have been observed in rotating convection experiments (*21*). Another mechanism that could play a role is an equatorially confined MAC (magnetic, Archimedes, Coriolis) wave (*22, 23*), driven by either convective (*24*) or magnetic (*25*) instability. This phenomenon would produce a series of propagating upwellings and downwellings at the core surface, with motion of associated flux foci. Because equatorial MAC waves would have propagation properties dependent on the strength of the core's hidden toroidal magnetic field, it may be possible to use these waves to estimate this parameter, which defines the nature of the dynamo process. Successful quantification of the relative contributions of these two mechanisms would be a valuable constraint on models of the geodynamo.

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11. For further details on the processing methods, see supplementary material at *Science* Online.
12. It has long been recognized that smaller changes in the magnetic field occur under the Pacific hemisphere than under the Atlantic hemisphere, possibly because of the influence of the deep mantle on core motions (*13*). Here we found that between 1630 and 1950, 50% more RMS variation in the residual field occurred under the Atlantic hemisphere than under the Pacific hemisphere. In movie S3 we observe that the strong equatorial flux foci do not travel into the Pacific hemisphere, hence the mechanism causing the westward motion of flux foci is disrupted under Central America.
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Supporting Online Material
www.sciencemag.org/cgi/content/full/300/5628/2084/DC1
Materials and Methods
Figs S1 to S6
Movies S1 to S3

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Changes in Ocean Water Mass Properties: Oscillations or Trends?

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A new transindian hydrographic section across 32°S reveals that thermocline mode waters have become saltier and colder since 1987. This change almost entirely reverses the observed freshening of mode waters from the 1960s to 1987 that has been interpreted to be the result of anthropogenic climate change on the basis of coupled climate models. Here, we compare five hydrographic sections from 1936, 1965, 1987, 1995, and 2002 to show that upper thermocline waters (10°C to 17°C) changed little from 1936 to 1965, freshened from 1965 to 1987, and since 1987 have become saltier. These results demonstrate substantial oscillations in mode-water properties.

When so few oceanographic sections have been sampled more than once, it is notable that the remote Indian Ocean section across 32°S has now been completely occupied four times. The first transindian section in 1936 was made as part of the Royal Research Ship (RRS) *Discovery* expeditions (*1*). The second aboard Research Vessel (R/V) *Atlantis II* in 1965 was part of the Indian Ocean Expedition (*2*). The third in 1987 was fitted into RRS *Charles Darwin*'s inaugural round-the-world voyage (*3*). The World Ocean Circulation Experiment (WOCE) managed only to reoccupy the eastern and western parts of the section aboard R/V *Knorr* in 1995 (*4*, *5*). In March and April of 2002, we reoccupied the 32°S transindian section aboard *Darwin* with a principal goal to measure the meridional overturning circulation across this southern boundary of the Indian Ocean. In view of the previous sections and because of interest in the use of changes in thermocline mode-water properties as a "fingerprint" for anthropogenic climate changes (*6–9*), our first effort was to examine the evolution of water mass properties from 1936 to the present.

Our station track for the 2002 section followed the 1987 section from the coast of South Africa out to 80°E (Fig. 1), after which we deviated from the 1987 track in order to improve the estimation of the overturning circulation. For this reason, we initially made comparisons between the 1987 and 2002 measurements west of 80°E where the sections coincide. Taking advantage of the tight potential temperature–salinity (θ-S) relationship, which is not affected by the mesoscale eddy variability evident in the large vertical excursions of water masses from station to station, we found the salinity on potential temperature surfaces (*10*) at each station and then examined the salinity difference (between 1987 and 2002) on isotherms along the section (Fig. 2). The changes are remarkably uniform along the section: Upper thermocline waters between 10°C and 17°C are saltier by as much as 0.06, whereas lower thermocline waters between 5°C and 10°C are fresher by as much as 0.03.

It is common to estimate changes in ocean properties on isopycnal surfaces (*11–14*). We found that the change in zonally averaged salinity on isopycnal surfaces achieves a maximum of 0.09 at a neutral density of 26.66 (at a temperature of about 12.9°C). Such an increase in salinity is opposite to the freshening from the 1960s to 1987, which achieved a maximum of –0.12 at a neutral density of 26.75 (*13*). As a result of becoming fresher from the 1960s to 1987 and becoming saltier from 1987 to 2002, the upper thermocline waters now have nearly the same properties they had in the 1960s.

Because the shape of the θ-S relationship lies somewhat parallel to the isopycnals (fig. S1A), changes on isopycnal surfaces can exaggerate trends. We prefer to report the minimum change in water mass

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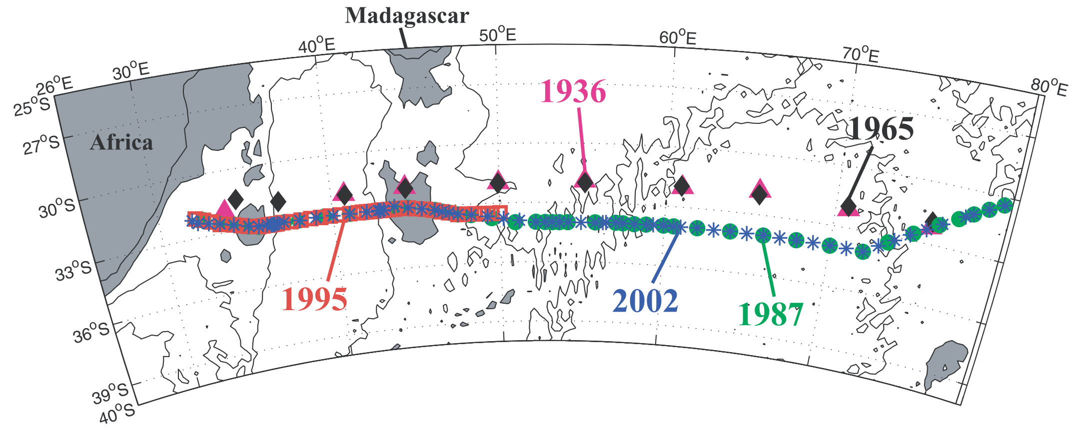

Fig. 1. Positions of the observations used in this study: conductivity-temperature-depth (CTD) stations from the *Darwin* occupation, March 2002 (blue stars); CTD stations from the *Knorr* occupation, June 1995 (red squares); CTD stations from the *Darwin* occupation, November 1987 (green dots); bottle stations from the *Atlantis II* occupation, July 1965 (black diamonds); bottle stations from the *Discovery* occupation, April 1936 (pink triangles). The coastline, 2000-m, and 4000-m depth contours are shown and depths shallower than 2000 m are shaded.

properties by estimating the changes in a direction perpendicular to the θ-S relationship. We used the θ-S relationship from the 1987 section as a baseline and estimated the minimum changes ($\Delta\theta$ and ΔS) from the 1987 properties by finding the minimum "distance" $\sqrt{(\alpha\Delta\theta)^2 + (\beta\Delta S)^2}$ from the 2002 θ-S curve, where α is the thermal expansion and β is the haline contraction coefficient from the equation of state for seawater (fig. S1A). This procedure scales the changes in temperature and salinity relative to their contributions to density. The direction of the change is perpendicular to the 1987 θ-S curve when presented on temperature and salinity axes that are scaled by α and β.

For this minimum change, the 2002 upper thermocline is still saltier than 1987 but only by a maximum of 0.030, a factor of 3 less than the change on isopycnals (fig. S1). The upper thermocline is also colder in 2002 as compared with 1987, by a maximum of 0.07°C. The lower thermocline waters have freshened from 1987 to 2002. On isopycnal surfaces, the greatest freshening is 0.027 at 8.1°C, whereas the minimum-change freshening achieves a maximum of 0.015 at 7.5°C. Such freshening in the lower thermocline is similar in magnitude to the freshening reported for this section before 1987 (*12*, *13*).

To examine changes in water mass properties before 1987, we used the 1965 and 1936 measurements made with discrete Nansen bottle samples of temperature and salinity. To avoid contaminating these point measurements by vertical or lateral interpolation, we estimated the minimum change of each bottle measurement to the 1987 θ-S relationship (Fig. 3). Although there is scatter, the distribution of change versus potential temperature clearly shows that the upper thermocline waters were much the same in 1936 and 1965, so the freshening occurred between the 1960s and 1987 as recently reported (*13*, *15*). In contrast, the lower thermocline waters appear to have freshened primarily from 1936 to 1965 and then to have remained relatively constant from 1965 to 1987.

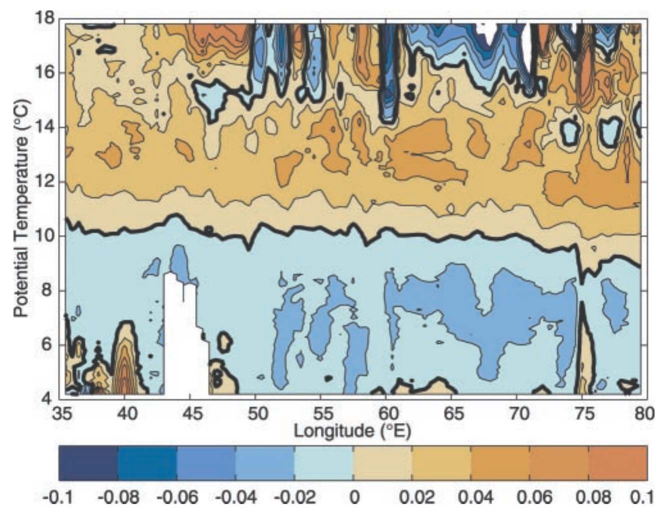

Fig. 2. Salinity change from 1987 to 2002 (2002 – 1987). Vertical salinity profiles were interpolated onto potential temperature levels in tenths of a degree, and then horizontally onto a half-degree longitude grid. No smoothing was necessary. The salinity changes were contoured with an interval of 0.02. (Salinity has no dimensions, but one unit of practical salinity is essentially equivalent to one part per thousand of dissolved salt.) Blue colors denote freshening on temperature levels; yellows and reds denote increasing salinity. Bold contours indicate no change. The temperature range from 18°C to 4°C is equivalent to depths of 50 to 1200 meters. The uncolored area around 45°E is the top of the Madagascar Ridge.

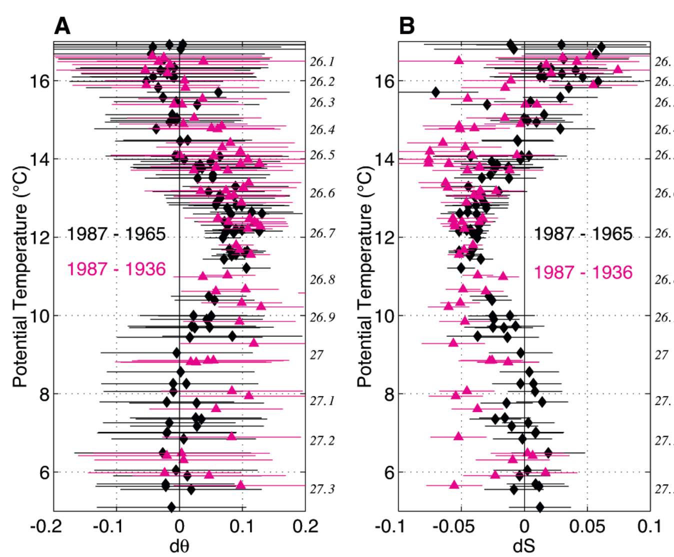

Fig. 3. (**A**) Potential temperature (dθ) and (**B**) salinity (dS) changes in thermocline properties before 1987 for the minimum distance between θ-S curves. Changes are 1965 to 1987 (black) and 1936 to 1987 (pink), so a positive change in θ corresponds to heating (increasing salinity) and a negative change corresponds to cooling (freshening). Differences are estimated between the zonally averaged (on neutral-density surfaces) thermocline properties in 1987 and data from each of the bottles from 1936 and 1965. Horizontal lines represent one standard deviation uncertainty based on the 1987 zonal average profile. Values of neutral density are shown in italics on the right side of each plot.

For the changes after 1987, we included the 1995 WOCE measurements, which are limited to the region west of 50°E. The 1995 θ-S relationship lies between the 1987 and 2002 relationships, from 16°C to 7°C (Fig. 4), indicating that upper thermocline waters warmer than 10°C became saltier both from 1987 to 1995 and from 1995 to 2002 at nearly constant rates and that the lower thermocline waters between 7°C and 10°C consistently freshened.

Thus, there has been an oscillation in the water mass properties of the upper thermocline waters with freshening from 1965 to 1987 and then an increase in salinity from 1987 to 2002, with the properties observed in 2002 close to those observed in 1936 and 1965. The lower thermocline waters have consistently freshened from 1936 to 2002 at a net rate of about 0.01 per decade, though there appears to have been little change in salinity from 1965 to 1987. The lower thermocline waters in 2002 are fresher than those in 1936 by as much as 0.06 (Fig. 4).

Definitions of changes in water mass properties have a degree of arbitrariness and depend on one's conceptual model for the origin of changes. Here, we view the subtropical thermocline as a region that is ventilated through the subduction of surface waters into the thermocline at 32°S over a short time scale of 5 to 10 years. There is no preexisting thermocline structure into which new waters are being mixed. That the mode waters observed in 1987 and 2002 are at different densities suggests that this model of ventilation is more important than one of isopycnal mixing, and it indicates that the isopycnal mode-water formation process observed south of Tasmania (*16*) is not operative in the western South Indian Ocean. Furthermore, the change in density implies that the changes in θ and 5 are primarily forced by changes in air-sea fluxes in the outcrop region. We have used helium-tritium measurements made during the WOCE survey in 1995 (*17*) to estimate the age of the water masses west of 50°E as a function of potential temperature (*18*, *19*) (fig. S2). The age increases from 5 years at 15°C to 40 years at 6°C, reflecting the distance between the 32°S section and the position of the late wintertime outcrop of each water mass.

The greatest change we observed in the upper thermocline was at about 13°C, where the water mass salinity has increased by 0.030 and potential temperature has decreased by 0.048°C from 1987 to 2002. These thermocline waters above 10°C that have increased in salinity and cooled occupy two-thirds of the total thermocline between 6°C and 17°C. In fact, the 13°C water exhibiting the greatest changes ($\theta = 13°C$) is the thermocline mode water (*20*) in this part of the South Indian Ocean, in that it has the greatest thickness and smallest potential vorticity of all water masses between 6°C and 17°C in the thermocline at 32°S. This mode water, with an age of 7 to 8 years, appears to be formed in late winter between 40°S and 50°S in an extensive surface outcrop region north of the Agulhas Return Current (*21*). Assuming a uniform change in properties over 15 years for a 400-m-deep mixed layer at the surface, the surface heat loss and surface evaporation-precipitation (E-P) would have to have increased by 0.17 W m^{-2} and 2.3 cm $year^{-1}$, respectively, to account for the changes we observed in the thermocline. If the changes are the result of wintertime fluxes, the wintertime surface heat loss and E-P increases would be a factor of 4 larger. These changes represent one-tenth or less of the wintertime surface fluxes, demonstrating that changes in thermocline properties represent a sensitive measure of changes in air-sea exchange.

The greatest change in the lower thermocline was at about 7.5°C, where the water mass salinity has decreased by 0.06 from 1936 to 2002 and potential temperature has increased by 0.07°C. The 7.5°C water is not a mode water in this part of the Indian Ocean. Its nearest wintertime surface outcrop occurs near 50°S, but its age of ~28 years may indicate that it has been advected into the 32°S thermocline from its outcrop region in the Pacific sector of the Southern Ocean, where it is the principal subantarctic mode water.

Mode waters are sensitive indicators of ocean climate change, as suggested by recent analyses of coupled climate models (*6*–*9*). With so few repeat observations, there has been a tendency to treat any observed change in water mass properties or circulation as an indicator of ocean climate change (*6*–*9*, *11*–*14*, *22*, *23*). The changes we report here along 32°S demonstrate that water mass changes are not necessarily unidirectional and that there can be substantial oscillations over decadal time scales. Without regular observations, oceanographers have little understanding of the scales of variability in water mass properties.

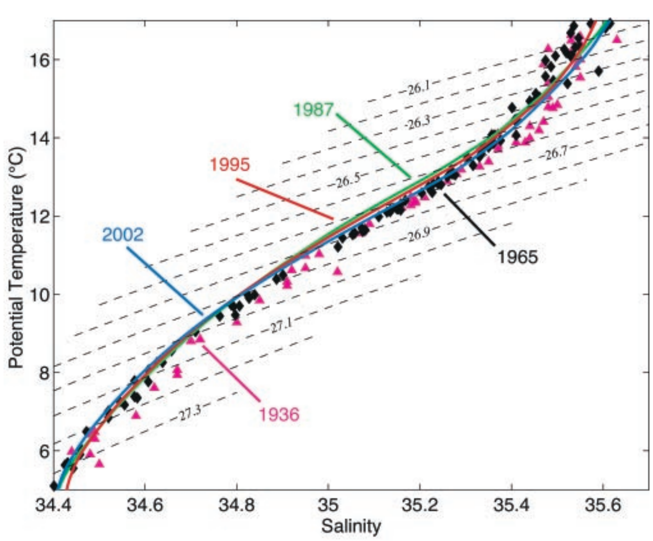

Fig. 4. Potential temperature versus salinity plot for the zonally averaged (on density surfaces) CTD data in 2002 (blue), 1995 (red), and 1987 (green), and for all of the 1965 (black) and 1936 (pink) bottle data. Dashed lines represent lines of constant neutral density.

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Supporting Online Material

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Figs. S1 and S2

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