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Global sea level has risen during the past decades as a result of thermal expansion of the warming ocean and freshwater addition from melting continental ice1. However, sea-level rise is not globally uniform1, 2, 3, 4, 5. Regional sea levels can be affected by changes in atmospheric or oceanic circulation. As long-term observational records are scarce, regional changes in sea level in the Indian Ocean are poorly constrained. Yet estimates of future sea-level changes are essential for effective risk assessment2. Here we combine in situ and satellite observations of Indian Ocean sea level with climate-model simulations, to identify a distinct spatial pattern of sea-level rise since the 1960s. We find that sea level has decreased substantially in the south tropical Indian Ocean whereas it has increased elsewhere. This pattern is driven by changing surface winds associated with a combined invigoration of the Indian Ocean Hadley and Walker cells, patterns of atmospheric overturning circulation in the north - south and east - west direction, respectively, which is partly attributable to rising levels of atmospheric greenhouse gases. We conclude that - if ongoing anthropogenic warming dominates natural variability - the pattern we detected is likely to persist and to increase the environmental stress on some coasts and islands in the Indian Ocean.

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Patterns of Indian Ocean sea-level change in a warming climate

Weiqing Han[1]*, Gerald A. Meehl[2], Balaji Rajagopalan[3], John T. Fasullo[2], Aixue Hu[2], Jialin Lin[4], William G. Large[2], Jih-wang Wang[1], Xiao-Wei Quan[5], Laurie L. Trenary[1], Alan Wallcraft[6], Toshiaki Shinoda[6] and Stephen Yeager[2]

Global sea level has risen during the past decades as a result of thermal expansion of the warming ocean and freshwater addition from melting continental ice[1]. However, sea-level rise is not globally uniform[1-5]. Regional sea levels can be affected by changes in atmospheric or oceanic circulation. As long-term observational records are scarce, regional changes in sea level in the Indian Ocean are poorly constrained. Yet estimates of future sea-level changes are essential for effective risk assessment[2]. Here we combine *in situ* and satellite observations of Indian Ocean sea level with climate-model simulations, to identify a distinct spatial pattern of sea-level rise since the 1960s. We find that sea level has decreased substantially in the south tropical Indian Ocean whereas it has increased elsewhere. This pattern is driven by changing surface winds associated with a combined invigoration of the Indian Ocean Hadley and Walker cells, patterns of atmospheric overturning circulation in the north–south and east–west direction, respectively, which is partly attributable to rising levels of atmospheric greenhouse gases. We conclude that—if ongoing anthropogenic warming dominates natural variability—the pattern we detected is likely to persist and to increase the environmental stress on some coasts and islands in the Indian Ocean.

Global mean sea-level rise since the 1950s has been detected using tide-gauge observations and attributed to thermal expansion of sea water and retreat of continental ice[1]. The rise, however, is not geographically uniform[1–5]. Sea-level rise in some regions accompanies a fall in others. Along the coasts of the north Indian Ocean, tide-gauge data show an average rise of 12.9 cm per century (ref. 3). What is the cause and has there been a rise everywhere in the Indian Ocean? Answering these questions is imperative, because Indian Ocean sea-level rise affects the lives of millions of people who inhabit coastal regions and islands. Improving estimates of the spatial variability in future sea-level change is identified as an important research target in coming years[2], which could help to inform adaptation and response options for human society.

Here, for the first time, we systematically investigate the non-uniform sea-level change and its cause in the Indian Ocean region since the 1960s, when warming of the world's oceans has been attributed mostly to increases of human-produced greenhouse gases[4]. We use a combined approach that first integrates the best available *in situ* and satellite observations, reanalysis data (model simulations that assimilate observed data), and then investigates the causes for the sea-level change using general circulation models. We carry out model experiments using two independent ocean general circulation models (the Hybrid Coordinate Ocean Model (HYCOM) and the Parallel Ocean Program (POP)), two atmospheric general circulation models (AGCMs) and a simple ocean model (see Supplementary Information S1 and S2 for details). We also analyse the results from two of the climate models assessed in the Intergovernmental Panel on Climate Change Fourth Assessment Report (the National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3) and the Parallel Climate Model).

Tide-gauge observations[6]—after corrections for land movement from a global isostatic adjustment model[7] and for sea-level pressure change—show that sea level along all Indian Ocean coasts has increased since the 1960s, except for the fall at Zanzibar (Fig. 1; see Supplementary Information S3 for tide-gauge data and analysis of reconstructed data[8]). The observed sea-level trends are reasonably well simulated by HYCOM. The observed (simulated) trends of 13 (10.1) cm per century averaged over stations 1–5 are close to previous estimates for the north Indian Ocean[3].

Most strikingly, sea-level decrease at Zanzibar is in a region of large-scale sea-level fall in HYCOM centred in the southwest region of the tropical (15° S ~ 15° N) Indian Ocean. This is the climatological upwelling zone[9] where mean sea level is low compared with surrounding regions (top panels of Supplementary Figs S1 and S2). The strongest sea-level drop is consistent with the observed subsurface cooling inferred from different data sets[1,10–12]. In contrast, sea-level rise occurs in the south subtropical-midlatitude basin, the eastern equatorial region, the Bay of Bengal and the Arabian Sea. This spatial variation amplifies the climatological sea-level-low region, extends it southward and strengthens the surrounding mean sea-level high especially south to 25° S but not in the north and west Arabian Sea.

Time series of sea level from HYCOM averaged in four representative regions show persistent trends of sea-level fall and rise, and they are not caused by a jump in 1976/1977 when Pacific climate shift occurred. However, the sea-level fall in region A rebounds over the past decade (Fig. 2). They agree well with satellite altimeter data[13] from 1993 to 2008. Sea-level trends for this shorter period do differ markedly from that of 1961 to 2008 (Fig. 2A), as might be expected from natural decadal variability. This is why

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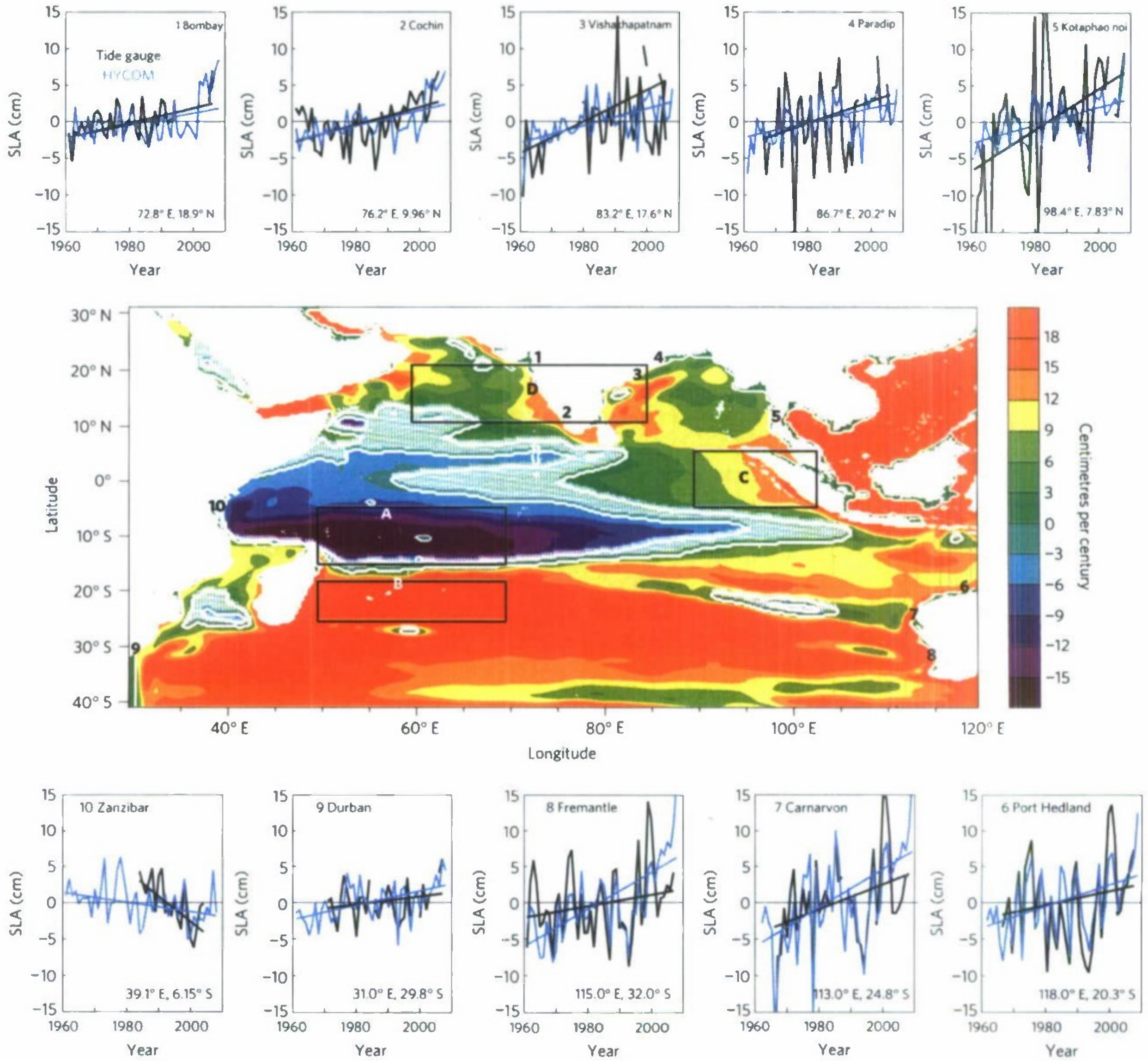

Figure 1 | Tide-gauge-observed and HYCOM-simulated annual mean sea level anomalies (SLAs) and their Kendall Theil trends[26] during 1961–2008. The 10 tide-gauge stations with records longer than 30 years (20 years for Zanzibar) are shown. All trends exceed 95% significance except for stations 6 and 9 tide-gauge data. The middle colour panel shows the Kendall Theil trend of HYCOM SLA for 1961–2008. The light blue/green regions are below and the rest are above 95% significance. Tide-gauge locations are marked 1–10. The rectangles labelled A–D mark regions discussed in Fig. 2.

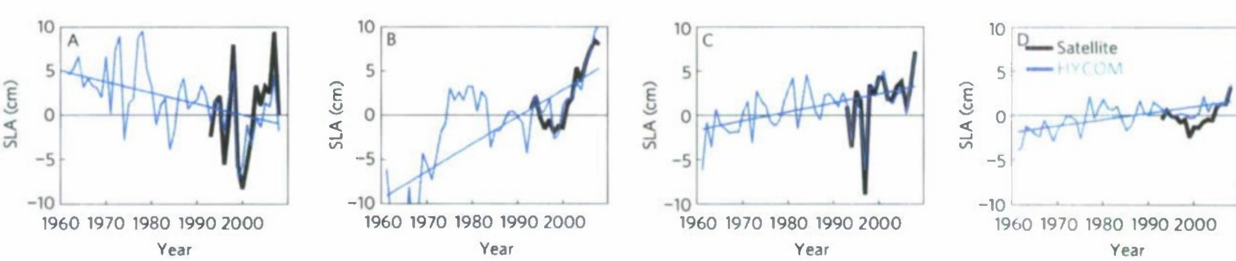

Figure 2 | Time series of annual mean SLA from HYCOM during 1961–2008 and from satellite-observed sea level for 1993–2008. SLA averaged for four representative regions of the Indian Ocean marked A–D in Fig. 1. Data–model correlations are 0.85, 0.93, 0.97 and 0.71, respectively, and are above 95% significance.

much longer records are needed to detect anthropogenic sea-level change[14]. These good model–data agreements suggest that HYCOM has captured some major physical processes that determine the Indian Ocean sea-level change. Freshwater input from melting land ice, however, is not included in any of our models or reanalysis data. It has been estimated to contribute 6.9 ± 7.1 cm per century (ref. 1) (or higher[15]) to global mean sea-level rise. If uniformly distributed this would enhance the Indian Ocean sea-level rise and compensate

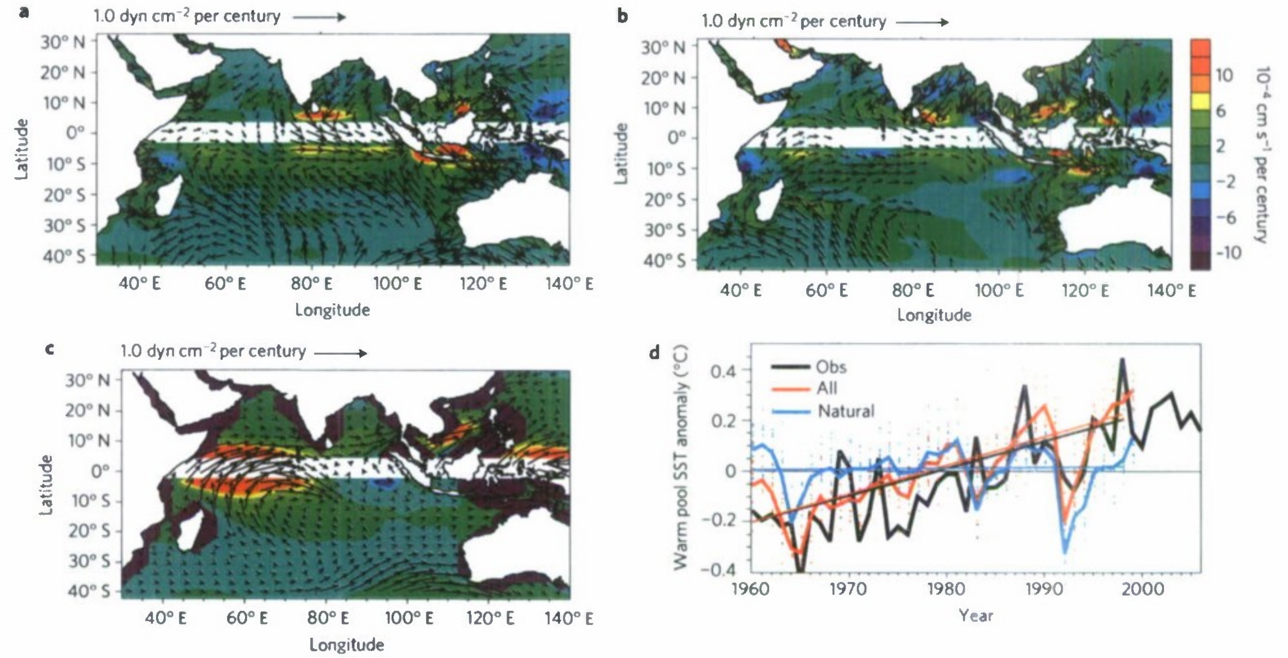

Figure 3 | Kendall Theil trends of surface wind stress, Ekman pumping velocity and time series of SST. Arrows = surface wind stress (>95% significance); colour shading = Ekman pumping velocity, ω_e. **a**, European Center for Medium-Range Weather Forecasts 40-year reanalysis winds for 1961-2001; $\omega_e = \partial/\partial x(\tau^y/\rho_0 f) - \partial/\partial_y(\tau^x/\rho_0 f)$, ρ_0—water density, f—Coriolis parameter, (τ^x, τ^y)—(zonal, meridional) wind stress. **b**, The same as in **a** except for NCEP winds. **c**, Wind stress and ω_e from a 60-member ensemble of the Geophysical Fluid Dynamics Laboratory Atmospheric Model version 2.1 and the Global Forecast System forced by the warm-pool SST trend (Supplementary Fig. S6). The wind speed is scaled up by a factor of 2. **d**, Warm-pool SST anomaly (solid curves) and trend (straight lines) from HadiSST (ref. 27; black) and 9-member ensembles of CCSM3 and the Parallel Climate Model all-forcing (red) and natural-forcing (blue) runs. The dots are SST values from individual members.

substantially for the sea-level fall in the southwest tropical Indian Ocean. Recent studies, however, suggest that ice-sheet melting can cause non-uniform Indian Ocean sea-level change[2,16] (see Supplementary Section S3).

Patterns similar to Fig. 1 are found in other models and data for 1961–2001 (Supplementary Fig. S3), when HYCOM has consistent forcing fields (Supplementary Section S1). The overall pattern appears in the Simple Ocean Data Assimilation products[17], and it results from wind-driven mass redistribution, with global thermal expansion and salinity effects[18] increasing the basin-mean sea level (Supplementary Fig. S3B,D). The importance of wind-driven mass redistribution is also seen from the dynamical sea level of POP (Supplementary Fig. S3C), the ocean model of NCAR CCSM4, forced by different forcing fields from those of HYCOM. A solely wind-driven linear ocean model reasonably simulates the large-scale sea-level pattern, and it is mainly forced by winds over the Indian Ocean (Supplementary Fig. S3E,F). A similar pattern of sea-level trends was reproduced by a reduced-gravity model[19].

Given the importance of wind in driving the sea-level changes, how and why are surface winds changing over the Indian Ocean? The trend of surface-wind stress shows an enhanced convergence into the equatorial ocean owing to the anomalous southeasterly (northeasterly) winds from the Southern (Northern) hemispheres (Fig. 3a,b). Along the Equator, a westerly wind trend enhances the mean (Supplementary Fig. S1). These winds form the positive trends of the Ekman pumping velocity ω_e in the south tropical Indian Ocean (Fig. 3a,h), which is associated with ocean surface mass divergence. Their effects are to either lower the sea level or enhance the upwelling of colder subsurface water, or both. The colder water is denser and thus also lowers the sea level. The amplitudes of sea-level change intensify westward (Fig. 1, Supplementary Fig. S3) when ω_e keeps the same sign zonally. In contrast, negative ω_e in the south subtropical-midlatitude Indian Ocean enhances downwelling and raises the sea level. Near the Equator, westerly wind anomalies cause surface Ekman mass convergence to the Equator and raise the sea level. These high sea-level signals propagate eastward and subsequently into the north Indian Ocean along the east coast of the Bay of Bengal by means of transient equatorial and coastal Kelvin waves and westward-radiating Rossby wave mechanisms, interfering with the sea-level change induced by north Indian Ocean local winds. On multi-decadal timescales, these processes are in quasi-equilibrium.

The enhanced intertropical convergence zone near the Equator is associated with the low-level branch of the strengthened local Hadley cell (the atmospheric meridional overturning cell zonally averaged over the Indian Ocean (Supplementary Fig. S4)). The enhanced surface equatorial westerlies are associated with a strengthened Indian Ocean Walker cell (the atmospheric zonal overturning cell along the Equator) with enhanced upward air motion occurring in the central and eastern equatorial Indian Ocean (Supplementary Fig. S4). This enhanced Indian Ocean Walker cell is also suggested by a recent publication[20]. Whereas the stronger intertropical convergence zone is observed during both summer and winter, the stronger equatorial westerlies occur mainly during the Asian summer monsoon (Supplementary Fig. S1), causing sea-level rise near Sumatra and in the Bay of Bengal (Supplementary Fig. S2D,F,H), thus aggravating monsoon floods in Bangladesh and India. During winter, wind-driven mass redistribution causes significant sea-level increase around Sri Lanka, the northern Maldives and the Lakshadweep islands (Supplementary Fig. S2C,E,G). Similar surface-wind changes are found in five different atmospheric reanalysis products and in the International Comprehensive Ocean–Atmosphere Data Set[21] (ICOADS) for the 1979–2001 overlapping period (Supplementary Fig. S5). An exception is in the northern Arabian Sea, where ICOADS wind changes enhance all phases

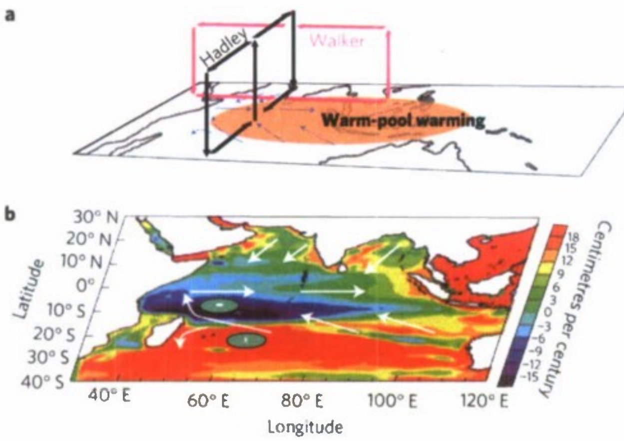

Figure 4 | A schematic diagram showing the mechanisms for the Indo-Pacific warm-pool warming to cause the Indian Ocean sea-level change. Warming enhances the Indian Ocean regional Hadley and Walker cells (**a**); the two enhanced cells combine to form a specific pattern of surface wind change (surface arrows in **a** and **b**) together with the Ekman pumping velocity (positive—circle with dot; negative—circle with x), which drive the distinct sea-level pattern (colour contours in **b**).

of the seasonally reversing monsoons; reanalysis wind changes enhance only the winter monsoon. The upward trend of this ICOADS inconsistency could result from the increased heights of observational platforms[22]. Otherwise the consistencies of all wind products and of changes in sea level demonstrate that signals of both atmospheric circulation and sea-level change exceed cross-model and cross-sampling differences.

Observed trends in surface wind stress and ω_e are similar to those from the 60-member ensemble of idealized experiments (Fig. 3a–c) using two state-of-the-art AGCMs forced by the sea surface temperature (SST) trend of the Indo-Pacific warm-pool region (defined in Supplementary Fig. S6). The patterns of associated local Hadley and Walker cells bear similar resemblance (Supplementary Fig. S4). The SST warming trend in the Indo-Pacific warm pool during the past few decades is caused primarily by anthropogenic forcing, because the natural forcing runs show no trend, as suggested by two Intergovernmental Panel on Climate Change Fourth Assessment Report climate-model solutions (Fig. 3d). (See Supplementary S2 for more analysis and discussion of climate-model solutions.)

The consistent changes of observed/simulated sea level and atmospheric circulation demonstrate that the signals discovered here far exceed model and data uncertainties. Our new results show that human-caused atmospheric–oceanic circulation changes over the Indian Ocean—which have not been studied previously—contribute to the regional variability of sea-level change. This mechanism is summarized in Fig. 4. The caveats are that there are quantitative differences between the observed and AGCM-simulated winds (Fig. 3), which may indicate the role of multi-decadal natural (forced or internal) variability. It is probable that anthropogenic forcing combined with natural variability explains the observed wind and sea-level changes.

These results show the patterns of atmospheric circulation and sea-level change expected if future anthropogenic warming effects in the Indo-Pacific warm pool dominate natural variability. Mid-ocean islands such as the Mascarenhas archipelago, coasts of Indonesia, Sumatra and the north Indian Ocean may experience significantly more sea-level rise than the global mean. Conversely, the Seychelles islands, and the east coasts of Kenya and Tanzania may see little or no sea-level rise. Interestingly, on the basis of all-season records, there is no significant sea-level rise around the Maldives (Fig. 1, Supplementary Fig. S3). However, statistically significant sea-level rise is shown during winter in both ocean general circulation models and Simple Ocean Data Assimilation data (Supplementary Fig. S2), which could have significant impacts on the Maldives because of its low elevation. Our results indicate that warming-induced regional atmospheric circulation changes—although challenging for climate models, especially over the Indian monsoon region—should be considered seriously, together with thermal expansion, melting land ice and natural variability, to achieve reliable regional sea-level and climate prediction. The warming-induced Indian Ocean Hadley and Walker circulation enhancement can have far-reaching impacts on Asian–Australian monsoons, Indonesian floods, African drought and the North Atlantic Oscillation[23–25].

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Author contributions
W.H. led the project and did the main analyses and primary HYCOM experiment, J.T.F. analysed atmospheric reanalysis products, A.H. processed the climate-model results, J-W.W. processed the tide-gauge data, X-W.Q. carried out the AGCM experiments, L.L.T. did the extended HYCOM run, A.W. helped to design and run all HYCOM experiments, S.Y. carried out the POP model experiment and G.A.M., B.R., W.G.L., J.L. and T.S. contributed to the scientific results through stimulating discussions and analyses. All authors contributed extensively to writing the paper and analysing the results.

Additional information
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