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Key Points:

- Heat uptake increased in the Southern, Atlantic, and Indian Oceans
- The increase of 0.5–1 W/m^2 in ocean heat uptake is enough to explain the hiatus
- Tropical Pacific SST is not the only way to change global ocean heat uptake

Supporting Information:

- Readme
- Text S1–S4 and Figures S1–S6

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Surface warming hiatus caused by increased heat uptake across multiple ocean basins

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Abstract The first decade of the 21st century was characterized by a hiatus in global surface warming. Using ocean model hindcasts and reanalyses we show that heat uptake between the 1990s and 2000s increased by 0.7 ± 0.3 W m^{-2}. Approximately 30% of the increase is associated with colder sea surface temperatures in the eastern Pacific. Other basins contribute via reduced heat loss to the atmosphere, in particular, the Southern and subtropical Indian Oceans (30%) and the subpolar North Atlantic (40%). A different mechanism is important at longer timescales (1960s–present) over which the Southern Annular Mode trended upward. In this period, increased ocean heat uptake has largely arisen from reduced heat loss associated with reduced winds over the Agulhas Return Current and southward displacement of Southern Ocean westerlies.

1. Introduction

Reconstructions of global mean surface temperature [*Hansen et al.*, 2010; *Morice et al.*, 2012] show rising values after the 1960s but a slowing of the warming in the 2000s, even though atmospheric greenhouse gas concentrations continued to increase. This hiatus in warming may have been exaggerated by sampling errors [*Cowtan and Way*, 2014], but a significant slowdown is evident. Changes in radiative forcing have been suggested as an explanation [*Solomon et al.*, 2010; *Kaufman et al.*, 2011; *Fyfe et al.*, 2013]. An alternative possibility is increased ocean heat uptake. Unfortunately, direct observation of such acceleration is difficult; there are limited repeat observations in the deep (>2000 m) ocean [*Purkey and Johnson*, 2010] and observation-based heat content estimates show a large spread [*Trenberth et al.*, 2014]. However, a recent evaluation of an Ocean Re-Analysis System, (ORAS4), indeed suggests accelerated increase of ocean heat content in the hiatus period, with a large contribution from the deep ocean below 700 m [*Balmaseda et al.*, 2013]. The increased heat uptake has been linked to surface cooling in the Tropical Pacific evident over this period, associated with persistent easterlies and greater prevalence of La Niña relative to El Niño [*Meehl et al.*, 2011; *Kosaka and Xie*, 2013; *Meehl et al.*, 2013; *England et al.*, 2014].

Current free-running climate models do not simulate the hiatus of the 2000s (e.g., fewer than 5% of the climate change scenario runs [*Watanabe et al.*, 2013]). Sea surface temperatures (SSTs) in the Tropical Pacific have therefore been prescribed [*Kosaka and Xie*, 2013] in a climate model and ocean heat content compared with a historical run where SSTs were free to evolve. In a similar procedure [*England et al.*, 2014], winds were prescribed instead of SSTs. In both cases, surface air temperature (SAT) decreased over the eastern Pacific and global mean SAT was strongly affected.

An alternative way to estimate ocean heat uptake, which has not been probed until now, is to diagnose changes in heat uptake from ocean hindcast simulations [*Blaker et al.*, 2014] forced by atmospheric fields from meteorological reanalyses, but with SSTs that are free to evolve though partly constrained by SAT and winds. Here we discuss hindcasts that were forced with the Coordinated Ocean-ice Reference Experiment-2 data set (CORE-2) [*Large and Yeager*, 2009] and with the European Centre for Medium-range Weather Forecasts Re-Analysis (ERA)-Interim meteorological fields [*Dee et al.*, 2011]. Other forcing sets were discarded (see supporting information for a discussion of the experimental setup).

2. Methodology

The model is described in *Blaker et al.* [2014]; see supporting information for further details. Model drift was assessed from the CORE-2 hindcast. The CORE-2 hindcast was repeated with the same initial condition

Table 1. Heat Uptake Anomaly Per Region[a]

Area	NCEP	ORAS4	CORE-2	ERA-I	Mean
World Ocean (W m^{-2})	0.4	1.1	0.6	0.8	0.7
Southern Ocean (%)	46	−35	15	16	11
SH Midlatitudes (%)	**26**	**21**	**10**	**16**	**18**
SH Subtropics (%)	−46	19	23	6	0
Tropics (%)	**19**	**26**	**47**	**25**	**29**
NH Subtropics (%)	−11	11	−26	0	−7
NH Subpolar (%)	**31**	**45**	**39**	**35**	**38**
Arctic (%)	35	13	−8	2	11

[a] (first row) Globally integrated heat uptake change between 2001–2009 and 1992–2000. (subsequent rows) Heat uptake change integrated over various regions in the atmospheric reanalysis (NCEP), ocean reanalysis (ORAS4), and hindcast runs, forced with CORE-2 and ERA-I meteorological fields, respectively. Southern Ocean is defined as south of 50°S, SH midlatitudes as 50°S–35°S, SH subtropics 35°S–10°S, Tropics 10°S–20°N, NH subtropics 20°N–40°N, NH subpolar area 40°N–60°N, and Arctic north of 60°N. The right-hand (sixth) column displays the unweighted average of columns 2–5. Bold font indicates the three regions showing good agreement between the different hindcasts/reanalyses.

but now forced by unchanging normal year meteorological forcing [*Large and Yeager*, 2004]. In the latter run, any changes in heat uptake are due to model drift. These changes are relatively small compared to the interannually varying signal, and heat uptake stabilizes after 7 years (1965) for both globally averaged and for the zonal averages and basin-wide scales defined in Table 1 (Figures S2a and S3 in the supporting information). From Figure S2b we conclude that the correction does not qualitatively change the picture: only 15% of the increased heat uptake in the CORE-2 forced hindcast is related to model drift, largely in the Southern Ocean, while the remaining heat uptake increase is associated with changes in meteorological fields. In the following, all fields, ocean heat uptake, ocean temperature, etc., are drift corrected. We divided the CORE-2 hindcast into five 9 year periods and the ERA-I hindcast into two 9 year periods.

3. Results

The hindcast simulations display year-to-year variations in globally averaged heat uptake of similar magnitude to the ORAS4 estimate [*Balmaseda et al.*, 2013], and all estimates indicate that ocean heat uptake in 2001–2009 was larger (Figure 1a) than in any previous decade. Figure 1b shows the field of ocean heat uptake change between 2001–2009 and 1992–2000. Colder eastern tropical Pacific SSTs stand out (Figure 1c), but the increased heat uptake in the area is less prominent, confirmed by heat flux estimates from reanalyses. This is partly due to a fall in SAT that partially offsets the fall in SST. Note that the air temperature variation is not directly included in the earlier studies that modify SST or wind speed only. We also see a strengthening of the shallow meridional cells in the tropical Pacific in our simulation, consistent with the findings of *England et al.* [2014]. Other areas with notably increased heat uptake include the North Atlantic subpolar gyre. Increased heat uptake in the North Atlantic, besides the tropical Atlantic and Pacific, was also suggested in a retrospective prediction with a coupled climate model using the ORAS4 reanalysis to initialize the ocean model component [*Guemas et al.*, 2013].

Although global mean SAT increased little over the hiatus period, changes in atmospheric circulation strongly warmed SAT and moistened air over the subpolar North Atlantic (Figure S1). SST warmed less than SAT, reducing sea-air temperature difference (Figure 1d). Consequently, turbulent heat loss from the ocean reduced, leading to increased net ocean heat uptake. At these high latitudes, where deep waters are being formed, the extra heat input can readily be sequestered deep into the ocean (see text in the supporting information). This heat absorbed into the upper 2500 m between 40°N and 70°N is evident in the plot of zonally averaged temperature increase (Figure 2a). The net heat uptake, caused by reduced heat loss due to less deep convection, was associated with a weaker Atlantic meridional overturning circulation (AMOC) in the hindcasts, consistent with the observed downward trend in the AMOC at 26°N [*McCarthy et al.*, 2012].

Decadal changes in heat content anomaly in the subpolar gyre have previously been attributed to the AMOC, excluding the Ekman component [*Williams et al.*, 2014]. It was inferred that the AMOC responded to

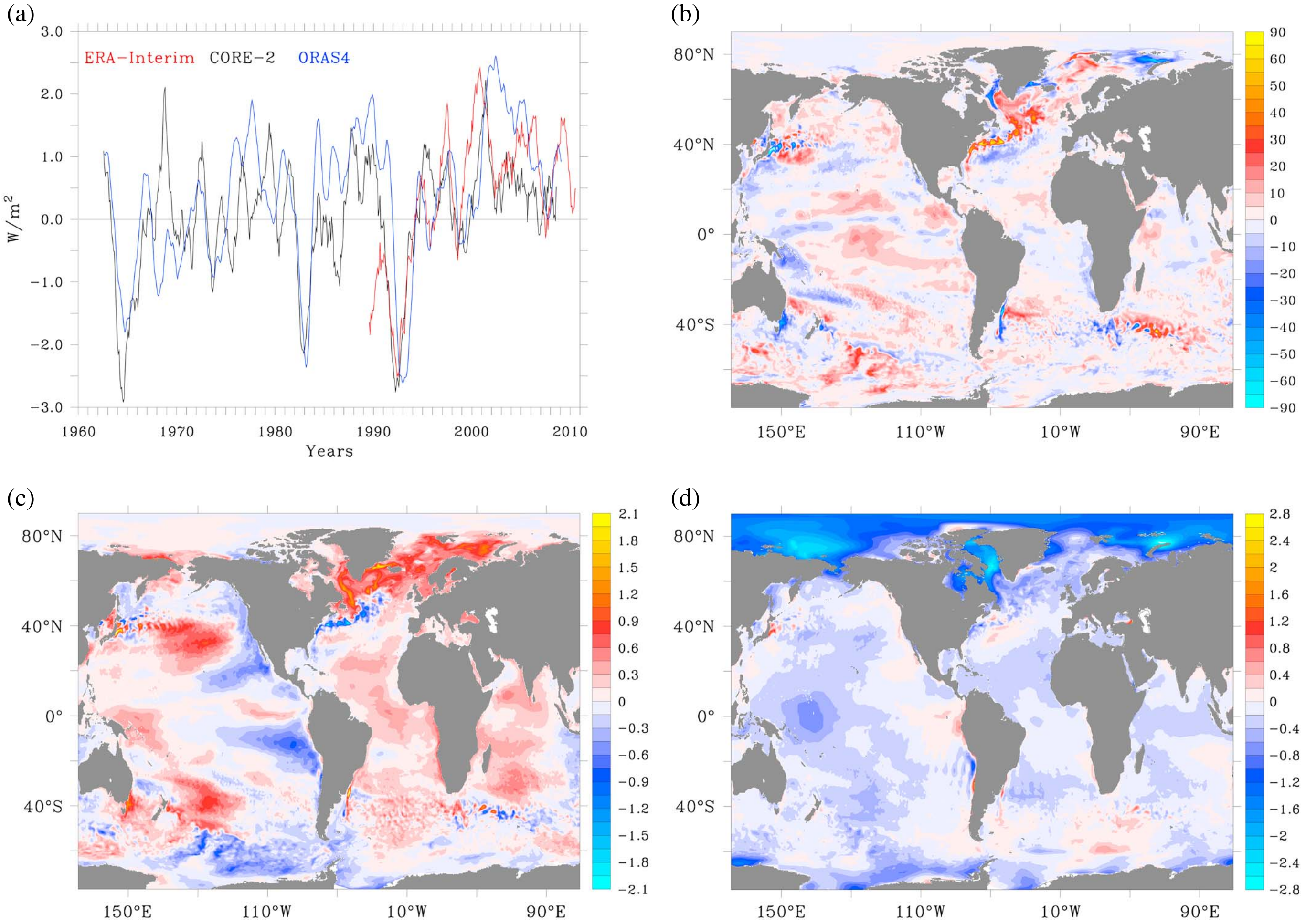

Figure 1. Globally averaged ocean heat uptake and changes at the air-sea interface during the hiatus period. (a) Globally averaged ocean heat uptake over the last 50 years estimated from hindcasts of ORCA025 forced by CORE-2 (black) and ERA-Interim (red), and from the ORAS4 reanalysis product (blue). Changes in (b) ocean heat uptake in W m^{-2}, (c) SST in °C, and (d) in sea-air temperature difference between the 9 year periods 2001–2009 and 1992–2000 in the CORE-2 forced hindcast in °C. The heat uptake from the CORE-2 hindcast has been corrected for model drift (Text S2).

wind changes, primarily via changes in east-west thermocline tilt due to altered upwelling or downwelling. This would explain the opposing signs of AMOC change in the subtropical and subpolar gyre. The change in subpolar gyre heat uptake is not directly related to heat content anomaly and shows a different phase relation with the AMOC (Figure S6). In the hindcast run, subpolar heat content changes indeed correlate with the AMOC, with a correlation coefficient of 0.8 when the AMOC leads by 8 years. Subpolar heat exchange and AMOC variations have a maximum correlation of −0.6 at lag zero, suggesting other (atmospheric) influence as well as influence from the AMOC. Given the strong relation between NAO and AMOC/Atlantic Meridional Oscillation [*Knight et al.*, 2006], we conjecture that both are important in determining subpolar gyre heat exchange. There is some correlation with atmospheric temperatures (0.4), which decrease after applying a 5 year Welch filter, while correlation with the AMOC increases with increasing timescale (0.8 with a 5 year filter). Correlations between subpolar gyre heat uptake and subpolar SST and heat content are even lower than the correlation with SAT.

We infer that, as SAT and SST tend to be in equilibrium on longer timescales (more than a year), subpolar gyre SST will respond to changes in meridional heat transport (by the AMOC), leading SAT, which results in increased net heat uptake when the AMOC decreases and reduced net heat uptake when the AMOC increases. The relation between subpolar gyre heat uptake with increasing/decreasing AMOC holds, regardless of the sign and amplitude of the subpolar SST and SAT anomalies. Such a model is consistent with the findings of *Gulev et al.* [2013] and *Keenlyside et al.* [2008]. The latter predicted a weakening AMOC with lower Northern Hemisphere temperatures that more than offset global warming for the coming decades. Their

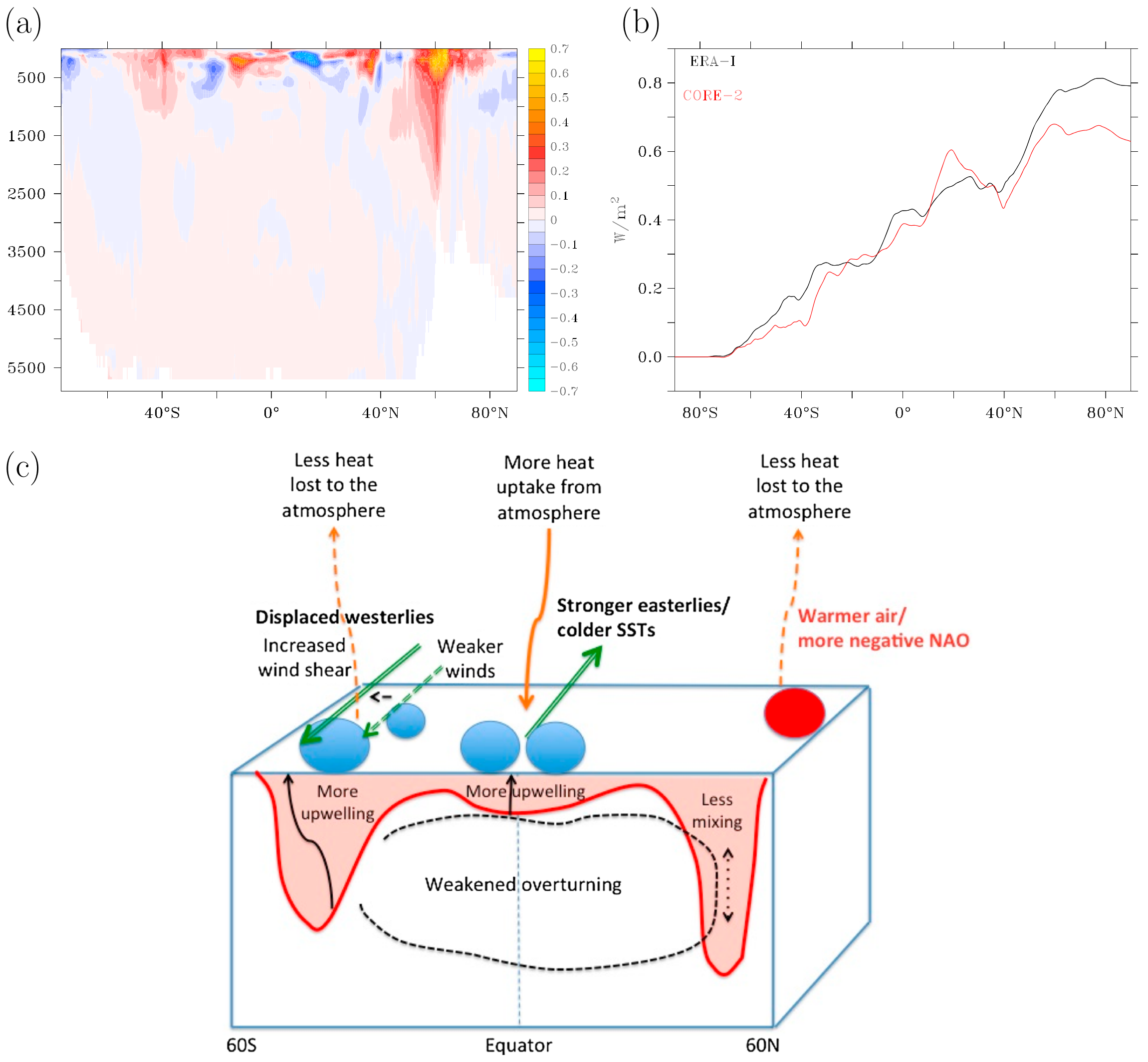

Figure 2. The regional variation of extra heat uptake during the hiatus period. (a) Zonally averaged ocean temperature increase between 2001–2009 and 1992–2000 for the drift-corrected CORE-2 forced hindcast in °C. (b) Scaled cumulative latitudinal sum of zonally integrated heat uptake increase between 2001–2009 and 1992–2000 for the CORE-2-forced hindcast (red) and the ERA-Interim-forced hindcast (black). (c) Schematic of processes governing the change in ocean heat uptake.

forecast implied that the AMOC is the main driver for interdecadal variations in global mean SAT and heat uptake. Our results point to a multibasin explanation for the hiatus, but we agree on the important role for AMOC-induced variations in heat uptake. In parallel with our study, *Chen and Tung* [2014] carried out an observation-based investigation of changing ocean heat content over the period of the hiatus using temperature data in the upper 1500 m from a single data set. They also found that the North Atlantic and Southern Oceans played an important role in the global surface warming hiatus. We do not agree, however, with their mechanistic explanation for the North Atlantic anomaly. They hypothesize an increasing AMOC and stronger vertical mixing associated with increased heat uptake, contrary to our findings and those of *Keenlyside et al.* [2008] and *Gulev et al.* [2013]. In the subpolar North Atlantic the heat uptake anomaly arises from reduced heat loss to the atmosphere, partly associated with atmospheric circulation changes and partly with less vertical mixing and a declining AMOC.

In agreement with this model is that the correlation of heat uptake with the subpolar gyre index is also much lower than the correlation with the AMOC (0.3). Correlation with SST in the tropical Pacific taking the box average of *Kosaka and Xie* [2013] is only −0.2, indicating a negligible influence of tropical SST on heat flux exchange in the subpolar North Atlantic.

Another major region of decreased ocean heat loss lies at latitudes of ~40°S (Figure 1b) along the northern flank of the Antarctic Circumpolar current. In particular, heat loss decreased notably over the Agulhas Return Current, east of South Africa, as a result of weaker winds (Figure S1). In response to wind changes, the subtropical gyres in both the western South Atlantic and Indian Ocean weaken and shift southward with reduced heat loss where Mode and Intermediate waters are formed. Associated with reduced heat loss is a warming signal at 40°S penetrating to ~1000 m (Figure 2a). *Lee et al.* [2011] found that similar wind changes may drive enhanced Agulhas leakage and further warming of the Atlantic in a hindcast driven by the twentieth century reanalysis.

To estimate the relative contribution of each area we calculated the cumulative sum over latitude of zonally integrated anomalous heat uptake, scaled by total ocean area. The integral over the longitudinal width of the ocean equals the increase in globally averaged heat uptake between 2001–2009 and 1992–2000; the cumulative sum shows how this anomaly builds up with latitude. Figure 2b shows this calculation for the hindcasts. They agree on a heat uptake increase of 0.6–0.8 W m^{-2} over 2001–2009 relative to 1992–2000. About 30% of the increased heat uptake takes place in the Southern Ocean and Southern Hemisphere (SH) Midlatitudes, 35% in the subpolar Northern Hemisphere (NH) (dominated by the North Atlantic), and 35% in the tropics and SH subtropics.

The heat uptake increase for the hindcasts is compared with corresponding values from atmospheric and ocean reanalyses for various key regions in Table 1. Good agreement between the values is evident globally (an increase of 0.7 ± 0.3 W m^{-2}, mean and standard deviation across all four data sets), and these values are large enough to explain the hiatus in global surface warming [*Trenberth et al.*, 2009; *Hansen et al.*, 2010]. To completely offset global warming, ocean heat uptake must balance the sum of (i) the rate of increase in energy in the Earth system due to increased greenhouse gas concentrations (0.35 W m^{-2}; [*Solomon et al.*, 2007]), and (ii) the committed warming by the slow ocean adjustment to previous twentieth century greenhouse gas emissions; giving a total globally averaged estimate of 0.6 W m^{-2} [*Levitus et al.*, 2009; *Hansen et al.*, 2011]. Our estimate of 0.7 ± 0.3 W m^{-2} heat uptake increase has to be multiplied by the surface fraction of the oceans, resulting in a 0.5 ± 0.2 W m^{-2} contribution to a global top of atmosphere radiative imbalance, leaving 0.1 W m^{-2} for reduced solar radiation, increased atmospheric aerosols, and melt of land ice, consistent with previous estimates of these contributors [*Hansen et al.*, 2011; *Trenberth et al.*, 2014].

Comparing this result with heat flux climatologies from meteorological reanalysis is not straightforward. Atmospheric reanalyses contain biases in surface radiation arising from difficulties in representing clouds, as well as biases in surface state variables because they are not constrained by coupling or conservation. They typically give an ocean heat budget imbalance of 20–30 W m^{-2} in the global mean, while in reality the budget should be close to 1 W m^{-2} at decadal and longer timescales [*Josey et al.*, 2013]. Surface fluxes are also available from ocean syntheses (e.g., ORAS4). These are typically forced by the meteorological data, after which the ocean fields are adjusted by the data assimilation scheme [*Balmaseda et al.*, 2013]. The data assimilation, however, generates considerable spatial structure in the low-resolution estimate of ocean heat uptake (Figure S4), making it less suited for estimates on smaller, regional scales.

In three key regions (highlighted bold), the increase is caused by the robust processes summarized in Figure 2c. In these cases the signal is larger than the uncertainty measured by the difference between the various estimates. Differences between the values are larger in the other regions, where the signal is not significant. In the Southern Ocean the presence of sea ice may be a factor leading to differences between reanalyses and hindcasts. Overall, three important aspects of the hindcast runs are supported by the reanalyses: (1) A large contribution (38 ± 6%) from the subpolar North Atlantic to the increased ocean heat uptake, (2) an increase in the Tropics (29 ± 12%) that by itself does not control decadal changes in global mean uptake, and (3) an increase in uptake in the SH midlatitudes (18 ± 7%). The contributions from 1 and 3 have not previously been recognized. Thus, our analysis reveals for the first time a multiple ocean basin origin for the recent surface warming hiatus that is robust across ocean model hindcasts and leading ocean and atmosphere reanalyses.

When anomalies relative to a longer period are considered, a somewhat different picture emerges. The Southern Ocean and SH midlatitudes now appear as the dominant contributor, accounting for 50% of the total (Figure 3a). The main reason for the difference between Figures 2b and 3a is that the tropical Pacific and subpolar North Atlantic heat uptake featured opposite anomalies in the last and penultimate 9 year periods, so these areas dominate the signal over the last 18 years, while heat uptake by the Southern Ocean

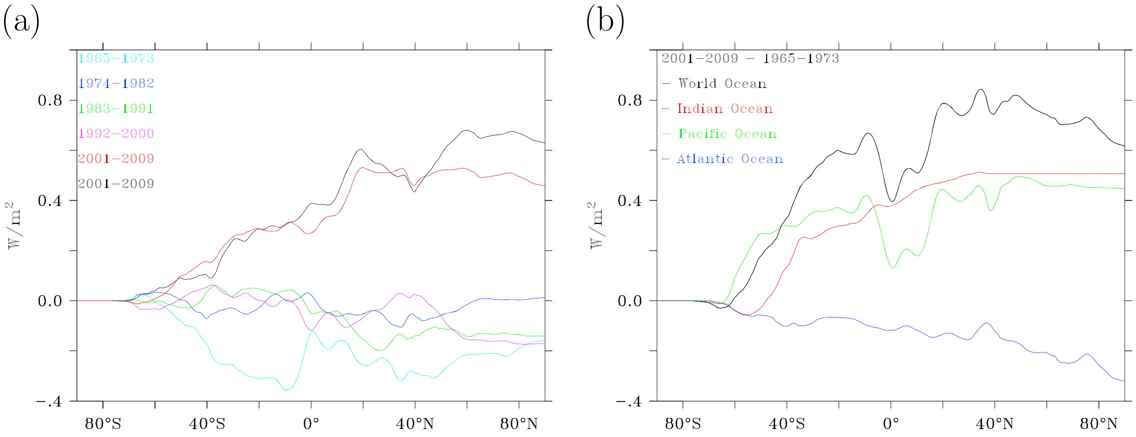

Figure 3. The long-term trend in ocean heat uptake. (a) Cumulative sum of zonally integrated heat uptake anomaly for each 9 year period relative to 1965–2009 in the CORE-2 hindcast, corrected for model drift. The black line is the anomaly of 2001–2009 relative to 1992–2000. (b) Difference between 2001–2009 and 1965–1973 (red minus light blue in Figure 3a), decomposed into contributions from Indian (red), Pacific (green), and Atlantic (blue) Oceans.

has steadily increased since the 1960s. In Figure 3b the difference in cumulative sum over latitude of zonally integrated heat uptake between the last and first 9 year periods is plotted, yielding the footprint of the long-term trend in ocean heat uptake. The global signal is dominated by the Pacific sector south of 50°S and the Indian Ocean sector between 50°S and 35°S. The trend since the 1960s is consistent with the southward shift of the Southern Hemisphere westerlies associated with the long-term upward trend in the Southern Annular Mode (SAM), attributed to the deepening of the ozone hole [*Polvani et al.*, 2011] and to global warming [*Swart and Fyfe*, 2012] (see text in the supporting information).

4. Conclusions

The contrasting results for the past 18 years and the 45 year interval since the early 1960s reveal the ability of the ocean to generate major variations in the heat budget of the global climate system through different sets of basin-dependent mechanisms. The recent hiatus has significant contributions from multiple ocean basins while the SH middle-high latitudes dominate the longer-term signal. Unpicking these contributions and thereby separating the effects of internal variability from anthropogenic warming thus requires an understanding of processes operating across the global ocean. Especially, the large heat uptake increase in the subpolar North Atlantic is remarkable, as SSTs were anomalously warm in the area (Figure 1c). This underscores that SST anomalies cannot be simply associated with heat uptake anomalies of the opposite sign and so heat uptake anomalies cannot be inferred from SST anomalies alone. A similar conclusion holds for the Pacific. The La Niña-like SST pattern in the tropical Pacific dominated global SST, but the tropical Pacific heat uptake anomaly was much less prominent. The changes in heat uptake in the North Atlantic and Southern Oceans are associated with the North Atlantic Oscillation and SAM (see text in supporting information). Freshwater discharge from the Antarctic ice sheet may also play a role in cooling Southern Ocean SSTs, leading to reduced heat loss there [*Bintanja et al.*, 2013]. The hypothesis that the recent changes in ocean heat uptake can be understood by the cool tropical eastern Pacific SSTs is only partly supported by our analysis.

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