Universiteit Utrecht

Recent hiatus caused by varying heat sink and the salinity anomalies in the North Atlantic

Huiping Li

Student Number: 5626684

Abstract

The global surface warming started to slow down at the beginning of the 21st century which is recognized as a “hiatus”. Observation-based and model-based analyses have proposed different perspectives to explain where the heat goes and the underlying mechanisms, such as a reduction in radiative forcing or a heat sequestration in deep oceans. This study using the ocean hindcast simulations shows that the increased heat was mostly stored in upper 700 m in global oceans. The Atlantic and the Pacific have the largest contributions in heat rearrangement. In Pacific, it occurred mainly in the upper 700 m layer, dominated by a La Niña pattern in the tropical Pacific during the hiatus; while in the Atlantic, the increased heat has penetrated to 2500 m and was most prominent in the tropical area and the subpolar area. In the subpolar North Atlantic, the salinity anomaly corresponded well with the ocean heat content (OHC) anomaly. The positive salinity/OHC anomaly indicated a weaker Atlantic Meridional Overturning Circulation (AMOC) during the hiatus, and the formation/melting of sea ice also corresponded well with salinity variations.

Contents

1. Introduction

Global warming has been a popular issue for several decades since it was first formally proposed at the First World Climate Conference in 1979. As a huge energy and resources storage container, oceans play an important role in regulating climate changes and heat absorption from and release to the atmosphere. It is shown that the global mean surface temperature has been rising continuously after the 1960s (Hansen *et al*., 2010; Morice *et al*., 2012), but this increasing trend started to slow down at the start of the 21st century, often referred to as a 'hiatus' or 'plateau' (Figure 1). At the same time, the Earth is manifested to be absorbing more energy from the Sun than releasing back to space at the top-of-atmosphere (Church *et al*., 2011), which is mainly because of increasing emission of the anthropogenic greenhouse gases (Stocker *et al*., 2013), with the effects of clouds and aerosols as well (Solomon *et al*., 2010; Solomon *et al*., 2011). The combination of increased energy absorption and a temporal stagnation of surface warming leads to the question where the excess heat was stored.

The incoming radiant energy can be transformed into many forms of energy. This includes temperature-related internal energy, latent energy which is linked to changes in phase of water, and other forms such as potential energy and chemical energy which may play a role in a longer time scale of more than hundreds and thousands of years (Trenberth and Fasullo, 2013). Due to the small heat capacity of the atmosphere, heat is primarily stored in oceans: more than 90% of the extra energy is absorbed by oceans (IPCC, 2007; Trenberth and Fasullo, 2013), leading to the increase of the total ocean heat content (OHC). Although there might be an exaggeration by sampling errors in the study of this warming hiatus (Cowtan and Way, 2014), the slowdown of the global mean surface temperature is however convincing and suggests that the excess heat may have been stored in deeper ocean waters.

Several studies have explained this surface temperature warming hiatus by heat storage in deeper waters. These indicated that faster warming in deeper Pacific Ocean (Kosaka and Xie, 2013), Atlantic Ocean (Chen and Tung, 2014), and Indian Ocean (Lee *et al*, 2015) compensated the slowdown of the surface warming, or there was a combined effect (Drijfhout *et al*, 2014). Most of these studies focused on the internal rearrangement of the heat within the oceans between different water layers. Interestingly, the Argo and the corrected bathythermograph data did not show an apparent increase of the OHC above 700 m depth (Levitus *et al*, 2009; Lyman *et al*, 2010). Indeed, observation-based reanalysis demonstrated a larger contribution below 700 m as well (Balmaseda *et al*, 2013). However, Nieves *et al*. (2015) compared the observational datasets and reanalysis, and they trusted the observational data represented by Argo data and suggested that there was little evidence for changes in warming rates below 700 m between the past two decades, and concluded that the warming in 100-300 m layer in tropical western Pacific and Indian Oceans contributed most. In contrast, Meehl *et al*. (2011) used a global climate model and concluded that the ocean below 300 m absorbed much more heat than that above 300 m in the hiatus period.

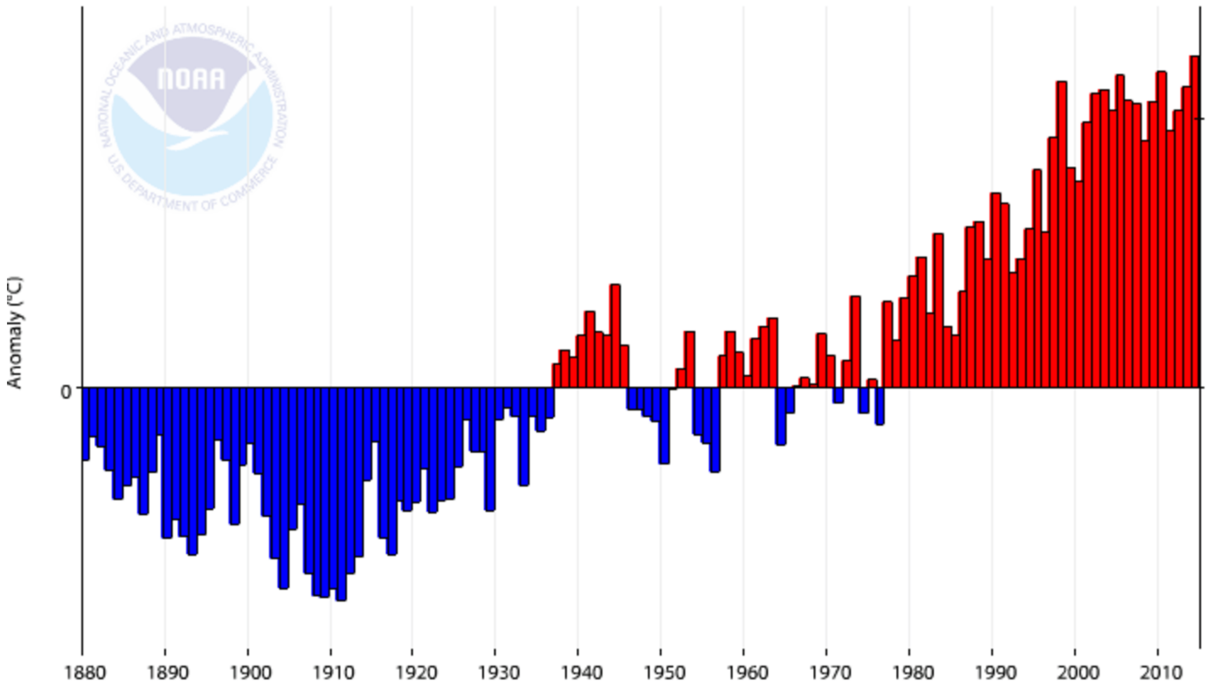

Figure 1. Global mean surface temperature anomalies (℃) for every year from 1880-2014. The average is calculated for each month of the year from 1901 to 2000. (NOAA, 2017)

Regardless whether these insights were based on observational data or modeling results, these different views illustrate the complexity and sensitivity of the climate system. The instruments we use inevitably have different limitations. The Argo floats data are more reliable than the observational techniques applied before, but the limited density of the observations in the deep ocean (Purkey and Johnson, 2010) makes it difficult to detect the changes of the warming rates below 2000 m depth. Furthermore, Argo profiling floats have been put into use from the end of 20^{th} century and were not distributed worldwide until 2005 (Roemmich *et al*, 2009), revealing its spatial and temporal limitations. In this respect, climate models have advantages both spatially and temporally, but the warming hiatus is not reproduced by some free-running models (Watanabe *et al*., 2013), or have lots of statistical errors. However, by combining the existing observational data with an ocean model, the model Ocean Re-Analysis System (ORAS4) from European Center for Medium Weather Forecasting (ECMWF) has produced the surface warming hiatus which is realistic in both magnitude and duration, revealing the increasing ocean heat content during the hiatus period with a more significant effect from the depth below 700 m (Balmaseda *et al*., 2013; Drijfhout *et al*., 2014; Trenberth and Fasullo, 2013). Besides, Drijfhout *et al*. (2014) applied ocean hindcast simulations (Blaker *et al*., 2014), which is forced by atmospheric fields from meteorological reanalysis to detect the variability of the ocean heat uptake, and suggested that increased ocean heat uptake is mainly because of the reduced heat loss with the effect of reduced wind.

But what is the mechanism behind this internal heat redistribution? ENSO (El Niño–Southern Oscillation) is proposed to be responsible for the changes of global mean surface temperature (Trenberth and Fasullo, 2013) and the hiatus period is dominated by La Niña phenomenon

(Meehl *et al*., 2011, Meehl *et al*., 2013), with long lasting easterlies (England *et al*. 2014) and surface cooling in the Tropical Pacific (Kosaka and Xie, 2013). This surface cooling is dominated by Interdecadal Pacific Oscillation (IPO), a prominent decadal sea surface temperature (SST) variability in Pacific. In the hiatus period, the Pacific Ocean is controlled by the IPO negative phase with stronger trade winds and cooler eastern tropical SST (Kosaka and Xie, 2013; Meehl *et al*., 2013), leading to a cooling of 0.1-0.2℃ (England *et al*., 2014). England *et al*. (2014) also proposed that the ocean absorbed more heat below this surface cooling, while Drijfhout *et al*. (2014) took the surface air temperature (SAT) into consideration and suggested that the reduced air temperature resulted in the reduced heat loss from the ocean, rather than in taking in more heat, although the outcome of the increased net ocean heat uptake is the same. By identifying the air temperature variations, they also proposed that the net heat uptake which was caused by reduced heat loss was more prominent in the North Atlantic Subpolar gyre and therefore weakened the Atlantic Meridional Overturning Circulation (AMOC). It is consistent with the finding of Meehl *et al*. (2011) who applied the composite stream function and got a negative trend to support a declining deep convection. Based on observational data, Chen and Tung (2014) proposed that the slowdown of the surface warming was caused by heat transport to intermediate depths in the Atlantic and the Southern Oceans. However, they argued that this transport was forced by a salinity anomaly in the subpolar gyre in the Atlantic, and it enhanced the AMOC. They proved this theory by comparing the salinity anomaly with the ocean heat content in the subpolar North Atlantic from 1950s to 2010s, an extending period for another episode of surface hiatus. Although the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) also play a role in the hiatus period in the Atlantic, their contributions are suggested to be seasonal limited and have insignificant correlation with global temperature (Trenberth and Fasullo, 2013).

Therefore, in this study, I firstly identify the role of the global oceans and different water layers during the hiatus period, and then focus on the Atlantic, investigating how salinity variations and ocean currents have modified ocean heat uptake in the North Atlantic in the last few decades. Because recent researches such as the ones of Chen and Tung (2014) and Nieves *et al*. (2015) drew completely different conclusions based on the observational data, in this study I try to check it out by applying hindcast simulations (see the following part for details). I use ferret scripts to make graphs and postprocess the output of the hindcasts.

2. Methods

The hindcast model forced with the Coordinated Ocean-ice Reference Experiment-2 data set (CORE-2) (Larger and Yeager, 2009) is Nucleus for European Modelling of the Ocean (NEMO) v3.2 (Madec, 2009) in the Global ORCA025 configuration, as the horizontal resolution is 0.25 degree (1442×1021 grid points). The model grid is isotropic Mercator from 20°N to the south and is quasi-isotropic bipolar from 20°N to the north. The horizontal resolution is around 27.75 km at the Equator and becomes increasingly finer to higher latitudes, with 13.8 km at 60°N/S for example. To prevent the numerical instability due to the convergence of the meridians at the geographic North Pole, altered poles are situated in Canada and Siberia. The vertical resolution increases from 1 m near the sea surface to 250 m at the bottom of 5500 m, with 75 levels in total (Blaker *et al*., 2014). The bottom topography is depicted by partial steps and bathymetry set is referred to ETOPO2 (USDC, 2006). Climatological initial conditions for temperature and salinity were taken in January from Steele *et al*. (2001) at high latitudes, from Jourdan *et al*. (1998) in the Mediterranean, and from Levitus *et al*. (1998) in other places. The derivative of the difference between sea surface salinity and climatology with time is controlled by a piston velocity of 33.33 mm/day/psu, to avoid too much drift in global salinity due to the defects in the fresh water forcing (Drijfhout *et al*., 2014). The model runs yearly from 1958 to 2011 (Blaker *et al*., 2014), but in this study the period from 1970 to 2009 is applied due to its stronger reliability.

Compared with other model runs, the hindcast models have the following advantages: because they are constrained by the atmospheric reanalysis, the atmospheric variables are more realistic; the resolution is 0.25°, which is higher than other ocean models with sparse grids of 1° in ocean reanalysis; the heat budget in the hindcast models is closed and one can directly use the heat fluxes to diagnose the places and the mechanisms of the heat uptake variations in the oceans. In other cases, ocean-atmosphere interactions and sea-air heat exchange can be limited by atmospheric general circulation models which regard SSTs as the only key variable (Sutton and Mathieu, 2002) because SST is not only related to SAT, but also under the influence of winds and advection of ocean temperature. Therefore, the hindcasts with a realistic heat flux climatology is less problematic and more reliable. Besides, the comparison with observation-based analysis (Drijfhout *et al*. 2014) suggests that although the error characteristics in numerical simulations are inevitable and are different from those in observations, the estimations of the changes of the ocean heat uptake can still be consistent with state-of-the-art estimations of changes of the ocean heat content (Balmaseda *et al*., 2013), indicating that the ocean hindcasts are trustable, especially with the help of CORE-2 data set which is highly correlated with the observations (Drijfhout *et al*., 2014). In addition to the better consistency it provides, another reason for using CORE-2 data set is that the strength of the salinity re-establishment is appropriate so that the evolution of AMOC can be well developed (Behrens *et al*., 2013).

There are other hindcasts such as ORCA1 with 1° resolution and ORCA12 with 1/12° resolution. They are relatively not good choices because ORCA1 has a coarse resolution and cannot capture heat uptake variations under the impact of changing atmospheric forcing in the North Atlantic subpolar gyre. Although ORCA12 has a higher resolution, it displays a strong trend in the Southern Ocean, diminishing Antarctic Bottom Water formation. In comparison, the ORCA025 simulations perform a high stability over the forcing period, which are more trustworthy and make the analysis in high credibility. The AMOC is slightly weaker than that in observations because of the effect of the Florida Straits transport, but there is no trend (Drijfhout *et al*., 2014). The ORCA025 simulations have been examined in a few researches and there were no serious problems with drift (Blaker *et al*., 2014; Drijfhout *et al*., 2014).

Because the hindcast simulations were running in a higher resolution and a long period (several decades), it is more difficult to use similar-size ensembles for different hindcasts to make sure that the internal variability in the oceans are similar, but the heat-uptake outcomes correspond well between different hindcasts in the Southern Hemisphere (SH) Midlatitudes (50°S-35°S), Tropics (10°S-20°N) and the Northern Hemisphere (NH) Subpolar area (40°N-60°N) (Drijfhout *et al*., 2014). The ocean internal variations are also affected by initial conditions, and for the ORCA025 hindcast forced by CORE-2 dataset, the initial conditions are the ocean analysis from the World Ocean Atlas, with a 5-7-year period at the beginning for model adjustment (Drijfhout *et al*., 2014). For this reason, I chose 40 years from 1970 to 2009 to ensure the feasibility of the analysis in this study.

The hindcast model produced 5-day, monthly and yearly data files of oceanic and atmospheric properties for the whole simulating period. The monthly and the yearly data is the average of all the 5-day data in the month and the year respectively. In this study, I mostly used yearly files to make plots, and verified the rationality and correctness of the results with the 5-day files or the monthly files when it was necessary. The ocean heat content for every year from 1970 to 2009 was calculated by integrating the temperature data of every grid point in three dimensions, added by the effects of sea surface height and sea surface water flux. In the vertical direction, the heat content was integrated from the surface to different depths: 20m (surface layer), 300m, 700m, 1000m, 1500m and the bottom. To make sure that the calculation is correct and the discussion is meaningful, I calculated the heat budget from 1970 to 2009. The sum of the heat content calculated from water temperature and the heat uptake/loss from the variation of sea surface height and surface water flux corresponded well with the heat flux at the sea surface, indicating that the calculation is feasible. From the annual variations of the heat content for different depths, the responses of the surface and deep oceans during the hiatus periods were clearly displayed. With the temperature data, it was also convenient to make figures for zonally and meridionally summed heat content. To compare the climate hiatus with the prior period, I chose two 11-year period respectively: 1999-2009 and 1988-1998, which made it easier to compare the results with that of Chen and Tung (2014) as well.

The study of the heat content was not only in a global scale but also in individual basins. The global oceans are divided to four separate basins: the Atlantic Ocean, the Indian Ocean, the Pacific Ocean and the Southern Ocean (Figure 2). The northernmost point of the Atlantic Ocean is at 82.08 °N, and the southern boundary line is settled at the Cape Agulhas. The sea area to the south of this line composes the Southern Ocean. The western border of the Indian Ocean is the continent of Africa including the Red Sea and the Persian Gulf, and the eastern boundary is the western coasts of Indonesia and Australia. The easternmost boundary of the Indian Ocean which separates it from the Pacific Ocean is at 122.5°E, and the northernmost of the Pacific is Bering Strait.

Besides, zonal and meridional temperature trends for individual basins were also plotted. The four basins and different periods of main interest were selected to study the changes temporally and spatially. The trend was calculated by the regression function in ferret to avoid the strong dependence on the start and the end years. The salinity data was applied to produce plots of vertical salinity in the water columns in the subpolar area (45°N to 65°N) and subtropical area (20°N to 45°N) in the North Atlantic Ocean.

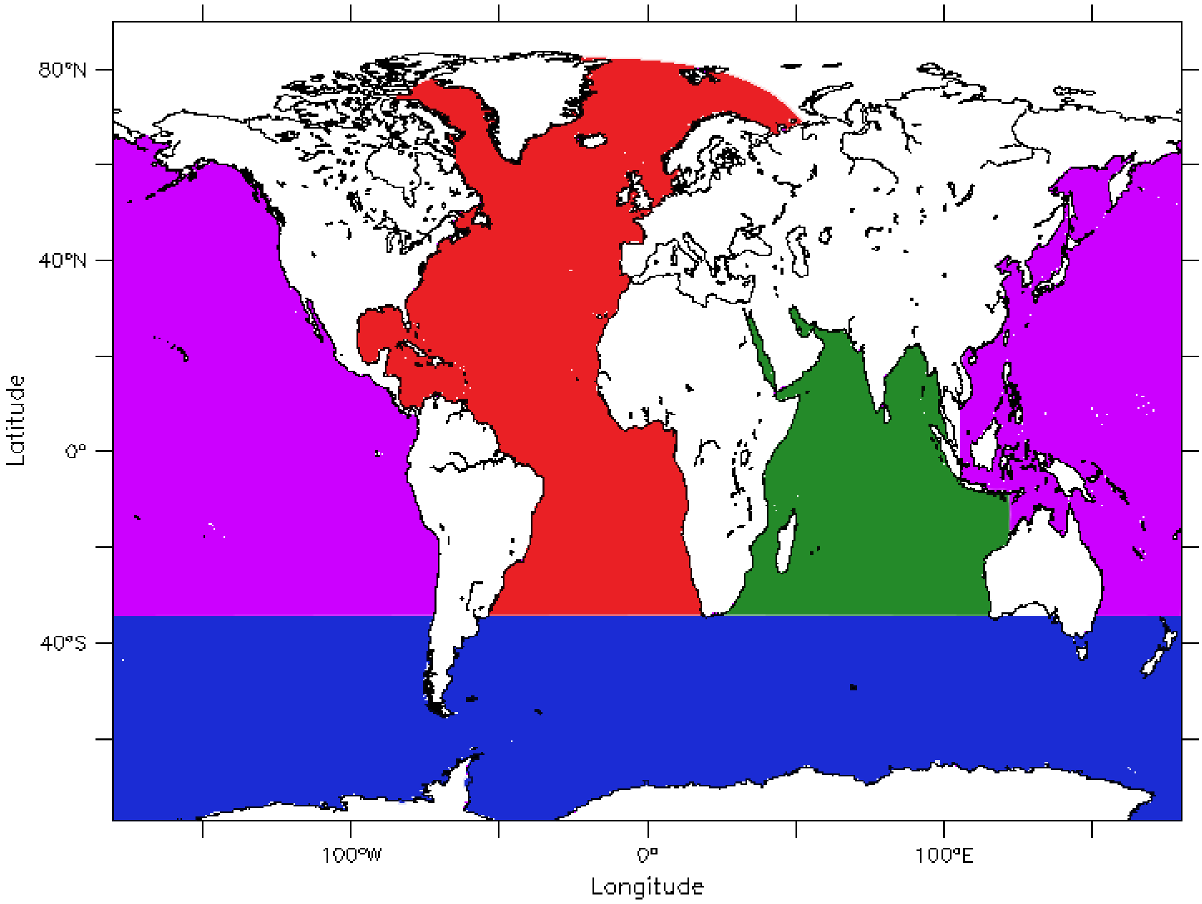

Figure 2. The mask of the Atlantic Ocean (red), the Indian Ocean (green), the Pacific Ocean (magenta) and the Southern Ocean (blue).

For both heat and salinity, the climatology was removed in order to get a more intuitive impression of the changes. The climatology was taken across the whole district and through the full period for each part of the study. In the study of Drijfhout *et al.* (2014), model drift from the CORE-2 hindcast was corrected. The changes resulting from the model drift are relatively small compared to the annual variations, and the temperature and heat flux are already stable from 1970 on. Drijfhout *et al.* (2014) proved that the correction of the model drift did not change the whole picture in quality, therefore, I used the figures which the model drift was not corrected in this study, and these figures corresponded better with the result from observational data (Chen and Tung, 2014) compared with the figures after corrected.

3. Results

3.1 OHC rearrangement

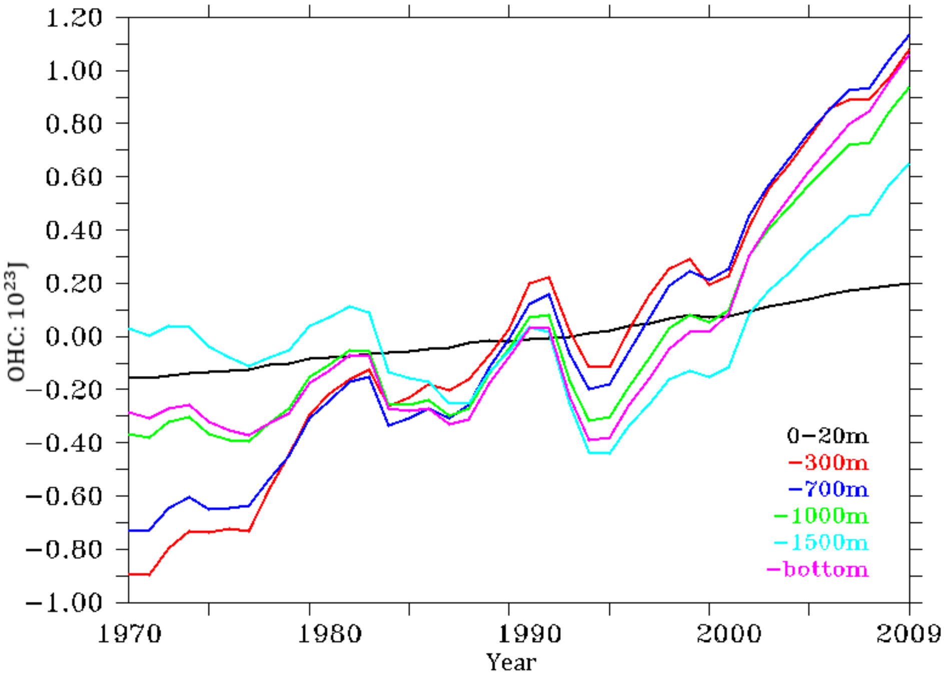

Figure 3. Integrated OHC in the global ocean. Shown is the deviation from the climatological mean of 1970 to 2009 for each layer. The OHCs are integrated from the surface to shown depths.

Figure 3 shows the globally, surface to depths integrated OHC for the years from 1970 to 2009. The climatological mean has been removed and the curves display anomalies, so we focus on the relative changes with time. The hiatus period started at the beginning of the 21st century. During this period, radiative forcing kept growing, so we expected the warming to penetrate deeper into the ocean, while OHC increased less in the upper few meters. As we can see in Figure 3, OHC slowly increased in the upper 20 m over the whole period, corresponding to the continuous global warming from the radiative imbalance at the top of the atmosphere (Church *et al*., 2011). A slowdown of the warming was not clearly visible in the modelled surface layer. After 1995, however, the total, top to bottom integrated OHC (pink line) increased much stronger in the deeper ocean than in any period before. During the whole period, the upper 300 m layer absorbed increasingly more heat (red line), and after 1999, the excess heat went deeper and slightly more heat was stored in 0-700 m layer (blue line) than in the upper 300 m layer. In contrast, the OHC in the 700-1500 m layer was decreasing (the difference between the blue, light blue and green lines), which is contrary to the results of Chen and Tung (2014). But OHC below the upper 1500 m layer was increasing (the difference between pink and light blue lines). This means that the 700-1500 m layer was constantly losing heat and the heat is moving in two directions: to shallower and to greater depth. From these 40-year variations in global OHC, the view that the slowdown of the surface warming is mainly caused by an enhanced ocean sink to the 300-1500 m layer, as suggested by Chen and Tung (2014) is not supported. However, the model hindcast does support the idea that the hiatus period is associated with an enhanced deep ocean sink, only the sink is found even deeper than suggested by Chen and Tung (2014), namely below 1500 m depth.

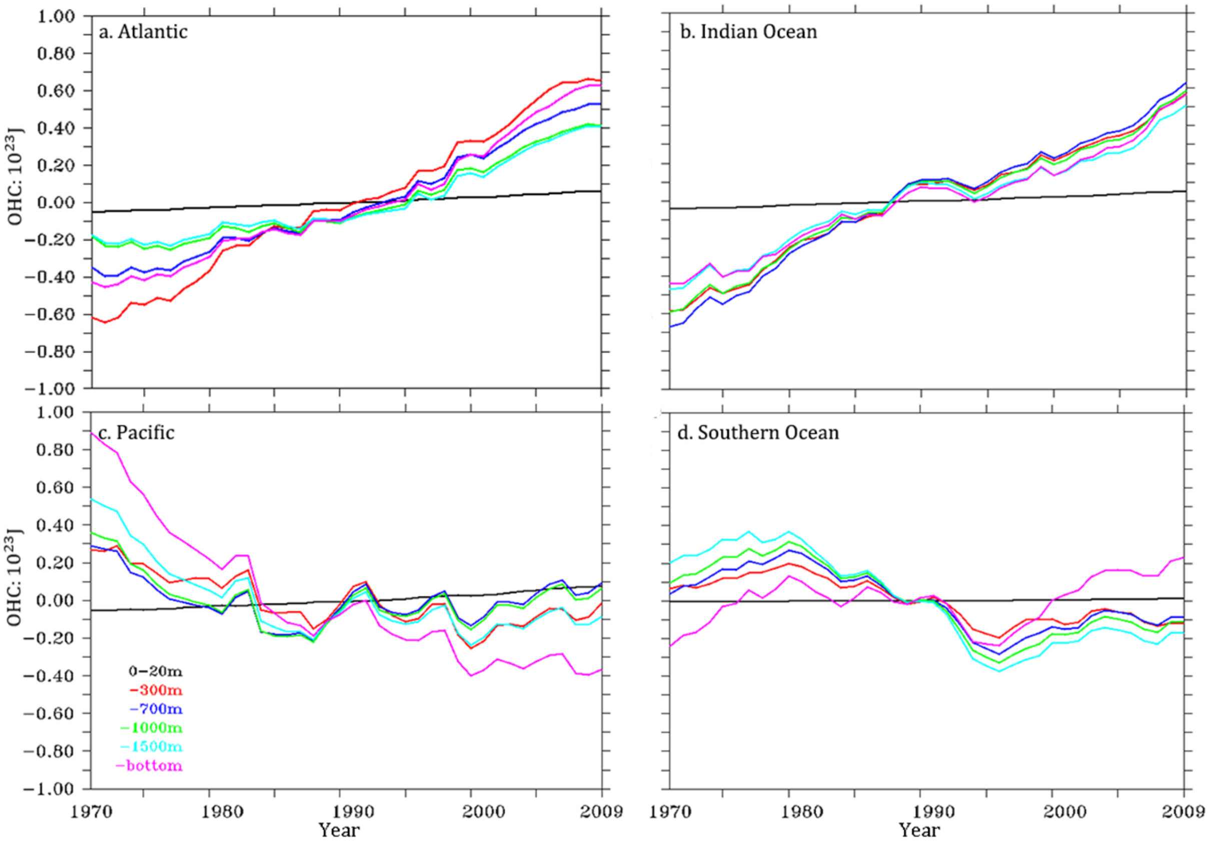

Figure 4. Integrated OHC in the Atlantic (a), the Indian Ocean (b), the Pacific (c) and the Southern Ocean (d). Shown is the deviation from the climatological mean of each basin from 1970 to 2009 for each layer. The OHCs are integrated from the surface to shown depths.

Figure 4 is the same as Figure 3 but for separate basins. The entire OHC (the pink line) experienced a prominent growing trend in the Atlantic and the Indian Ocean, while it reduced significantly in the Pacific. In the Southern Ocean, the increasing trend of the total OHC slowed down and started to decrease from 1980, and it started to increase again after 1995. In the warming context over the whole period, the Pacific was losing heat, especially in the deep water below 1000 m and in the upper layer above 300 m, excluding the surface 20 m layer in which the OHC kept increasing through the time. Except for the Atlantic where there was a strong warming in the upper 300 m, the heat penetrated to the 300-700 m layer and the upper 700 layer had the largest contribution in heat storage above the 1500 m depth in other basins during the hiatus. One can also see that in the upper 1500 m layer, the strongest redistribution of the OHC occurred in the Atlantic, with the largest fan-shaped area made of the curves. The result here contradicts the findings of Nieves *et al*. (2015). They negated the importance of the Atlantic in the hiatus period. The main contribution of the Southern Ocean is also not proved in my study as proposed by Chen and Tung (2014), and in their article, they admitted that the sparse observational data coverage in the Southern Ocean reduced the reliability of their result.

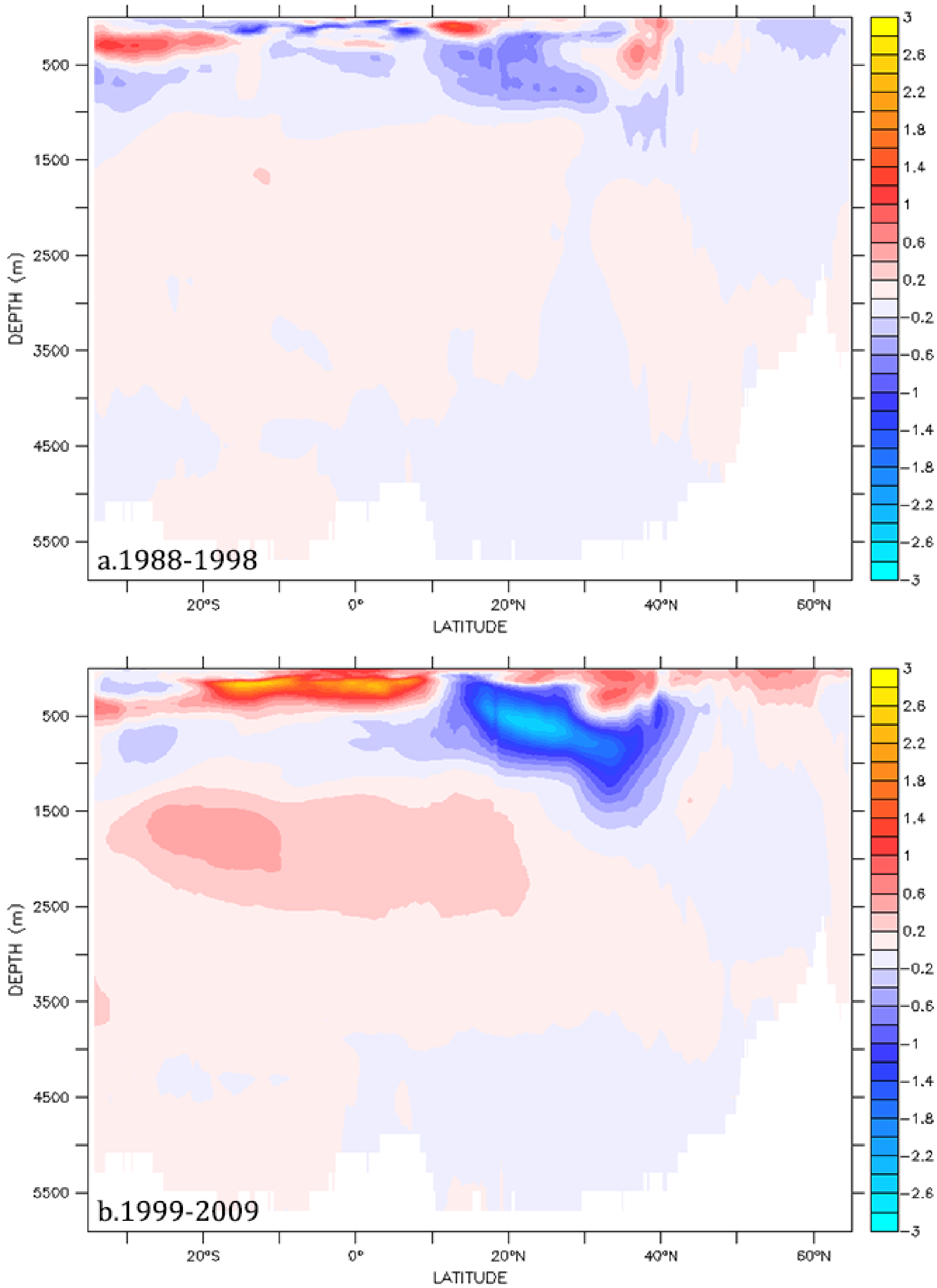

Figure 5. The heat content changes in the Atlantic between the warming period (1988-1998) and the hiatus period (1999-2009). OHC is zonally integrated over the basin as a function of latitude, in units of 10^{18}J. Climatology for each period is removed.

From Figure 2 and Figure 3 we can also see that the redistribution of OHC started in the late 1980s. It was earlier than the result based on observations given by Chen and Tung (2014).

In the Atlantic, significant heat redistribution occurred between the hiatus period (1999-2009) and the prior decade (1988-1998). The heat shift occurred at different depths and at different latitudes. Over a meridional transection of the OHC (Figure 5), the OHC increased dramatically in the upper 300 m layer during the hiatus period. A large amount of heat was stored in the tropical area, while in the past decade it was much cooler than the water nearby. In contrast, the cooling in 300 m-1500 m layer between 10°N and 40°N was more prominent. It corresponds well to the temperature trends shown in Figure 7b. A relatively weaker warming lay in the upper 300 m layer in the North Atlantic above the cooling pool (Figure 5b), and the warming reached 2500 m in the subpolar area (45°N to 65°N), where the North Atlantic Deep Water (NADW) forms. Such a pattern, called a "dipole" pattern, is consistent with the change of the Atlantic Meridional Overturning Circulations (AMOC) (Zhang, 2008). The heat content in the subpolar area in the hiatus period was larger than that in the prior decade, but the temperature trend was only slightly positive or even negative during the hiatus period, while it was more positive during 1988-1998 (Figure 7a-b). The change of the temperature trend in the subpolar North Atlantic in the hindcast model is similar to the trend calculated by observational data in Nieves *et al*. (2015). This result means that the temperature and the OHC reached a high level after a noticeable increase during the warming period, and the slowdown of the warming indeed occurred during the hiatus period.

In the hindcast simulations, the OHC variations correlated well with the AMOC (Drijfhout *et al*., 2014). The AMOC plays an important role on sending extra heat to the deeper water in the North Atlantic subpolar area. As the net ocean heat uptake was higher during the hiatus period, it is more difficult for the surface water to sink, as a result the deep convection was weakened, which is related to a weaker AMOC both in the hindcast (Drijfhout *et al*., 2014) and the observations (McCarthy *et al*., 2012). A weaker AMOC corresponds to a poorer ability of heat transport to the deep ocean, therefore, the warming trend was not as strong as that during 1988 to 1998. This does not agree with the view of a stronger AMOC as Chen and Tung (2014) proposed. Besides, the heat also penetrated to the depth between 1500 m and 2500 m in the tropical area (25°S to 20°N), with the strongest warming at around 20°S during the hiatus period. Such a deep layer was not studied in the articles based on the observational data because of the lack of data, but the research of Meehl *et al*. (2011) got a warming trend in deep Atlantic as well below 1500 m depth based on a global coupled climate model.

Unlike the situations in the Atlantic, the Pacific is the stage of El Niño-La Niña transitions, so the zonal transections (Figure 6) were studied instead of the meridional transections. The OHC changed in a shallower layer above 600 m depth in the Pacific and displayed an ENSO-related pattern. In 1988-1998, an El Niño-like pattern presented in the upper 300 m layer in the Pacific. During this period, the El Niño in 1987/1988, 1991/1992, 1994/1995 and 1997/1998 (a very strong one) together decided the average heat distribution of the Pacific (NOAA, 2015). However, cool water dominated the eastern Pacific during the hiatus period, displaying a La Niña-like pattern and the cold-water jet stretched to the western Pacific and cut the warmer

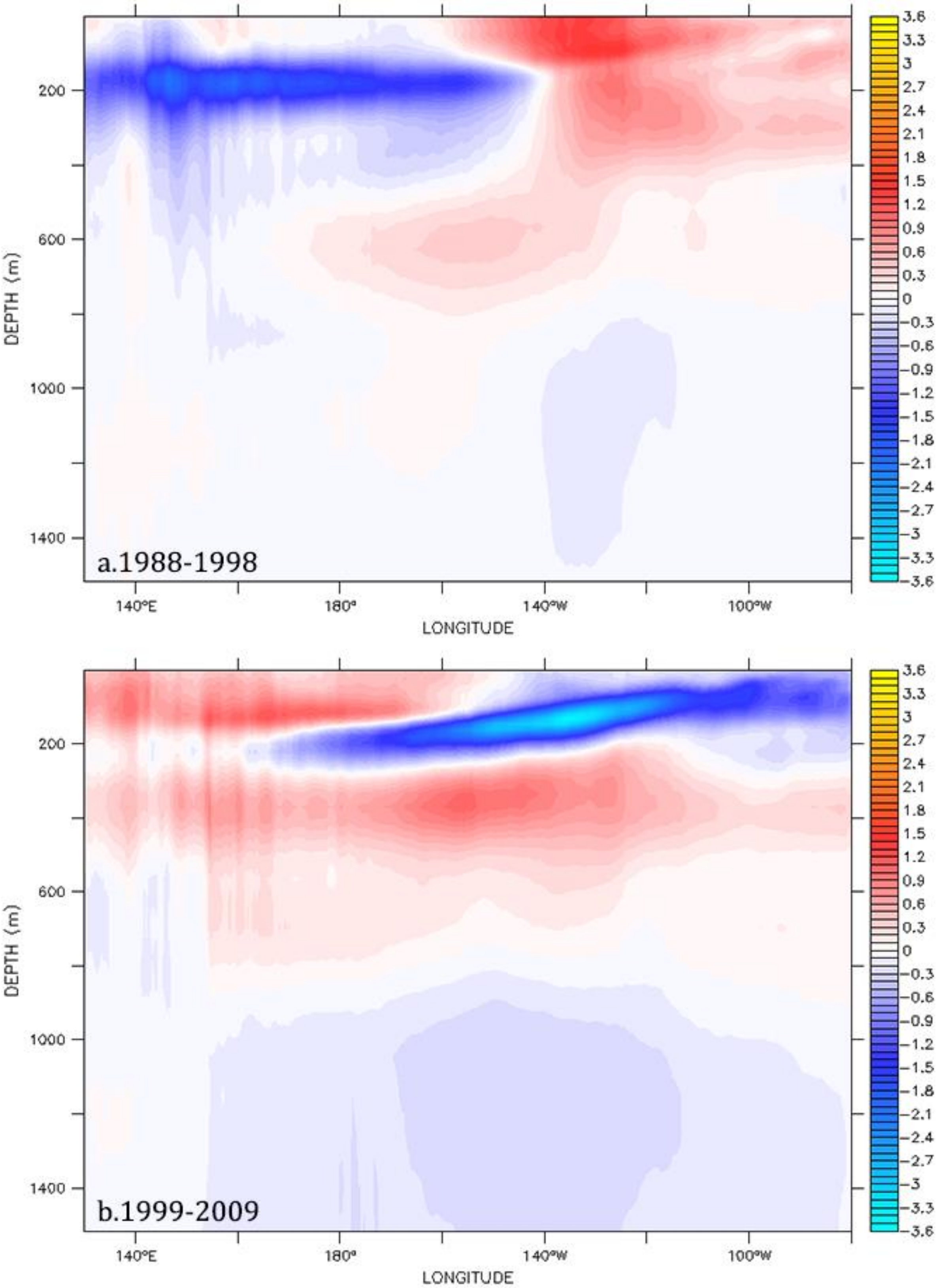

Figure 6. The heat content changes in the Pacific Ocean between the warming period (1988-1998) and the hiatus period (1999-2009). OHC is meridionally integrated over the basin as a function of longitude, in units of 10^{18}J. Climatology for each period is removed.

pool at about 200 m depth. The anomalously strong westward trade wind influenced the surface water in the western Pacific in 1999-2009 (England, *et al*., 2014), bringing cooler water from the eastern Pacific to the west and lying on the surface above the warm water body. However, in deeper layers (300 m to 600 m) the warm water flowed from the west to the east as a compensation of the surface westward flow. The meridional sections of the temperature trend of the Pacific (Figure 6c-d) showed that the heat redistribution mainly occurred in the tropical area (about 20°S to 20°N) and at 40°N, where the equatorial currents and the North Pacific Current dominate respectively. Besides, the Indian Ocean showed a significant positive temperature trend in the hiatus period (Figure 7a-b), not only in upper 300 m layer like the Pacific, but also in deeper layers till 1000 m. The zonally averaged temperature trend in the Indian Ocean was in some extent related to that in the Pacific, as a result of the connection by the Indonesian Throughflow and the leakage through the Tasman Sea (Lee *et al*., 2015). This warming trend in Indian Ocean in the hiatus period was consistent with the result of Nieves *et al*. (2015). As for the Southern Ocean, a slight warming trend below 100 m at 40°S was more visible. The reduced heat loss caused by weaker winds leaded to a warming at 40°S as Drijfhout *et al*. (2014) proposed, and in a hindcast driven by the twentieth century reanalysis, the weaker winds could enhance the Agulhas leakage and then warmed up the Atlantic as well (Lee *et al*., 2011).

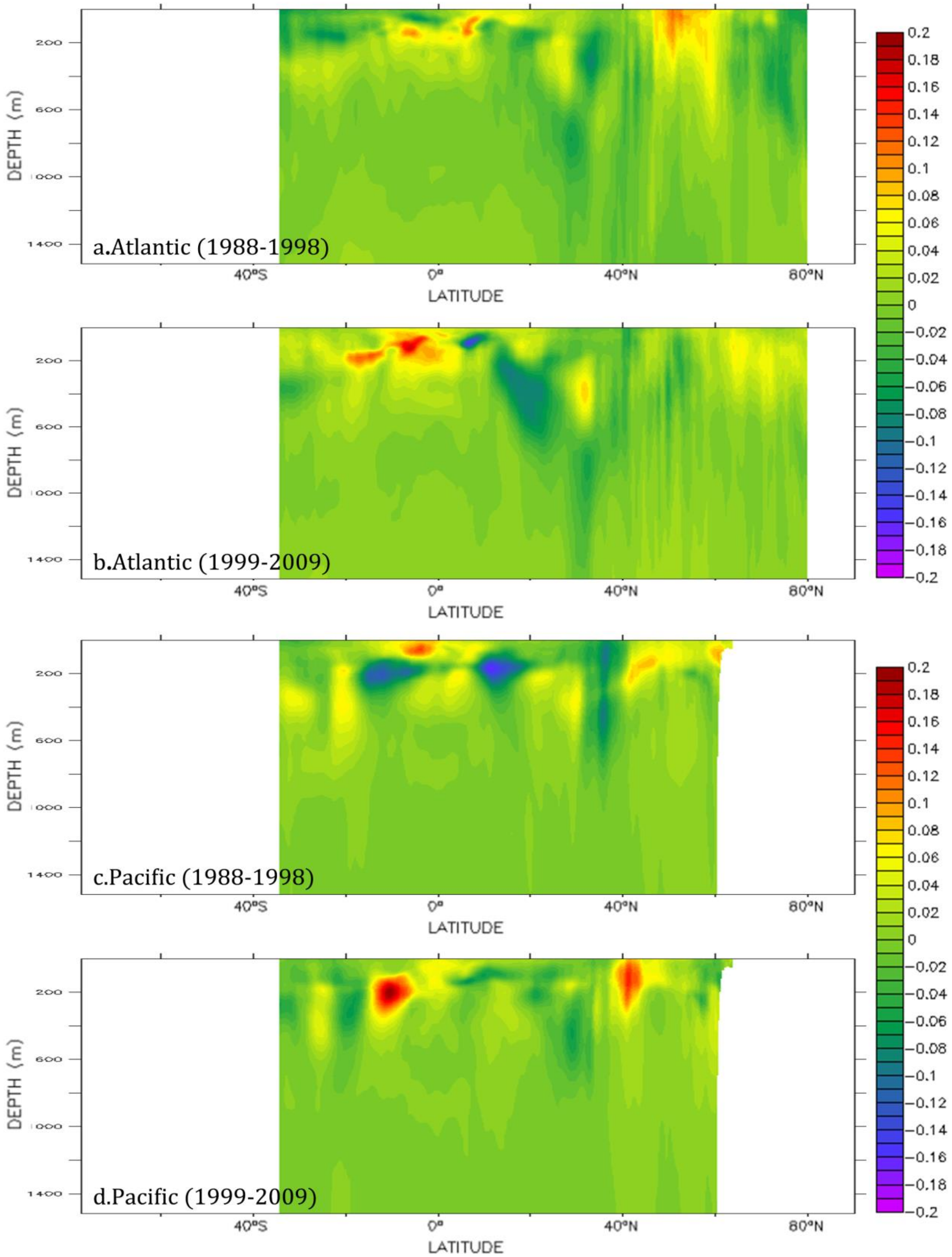

Figure 7. The temperature trends (°C/year) in the Atlantic (a and b) and the Pacific Ocean (c and d) between the warming period (1988-1998) and the hiatus period (1999-2009). The trend is zonally averaged over the basin as a function of latitude.

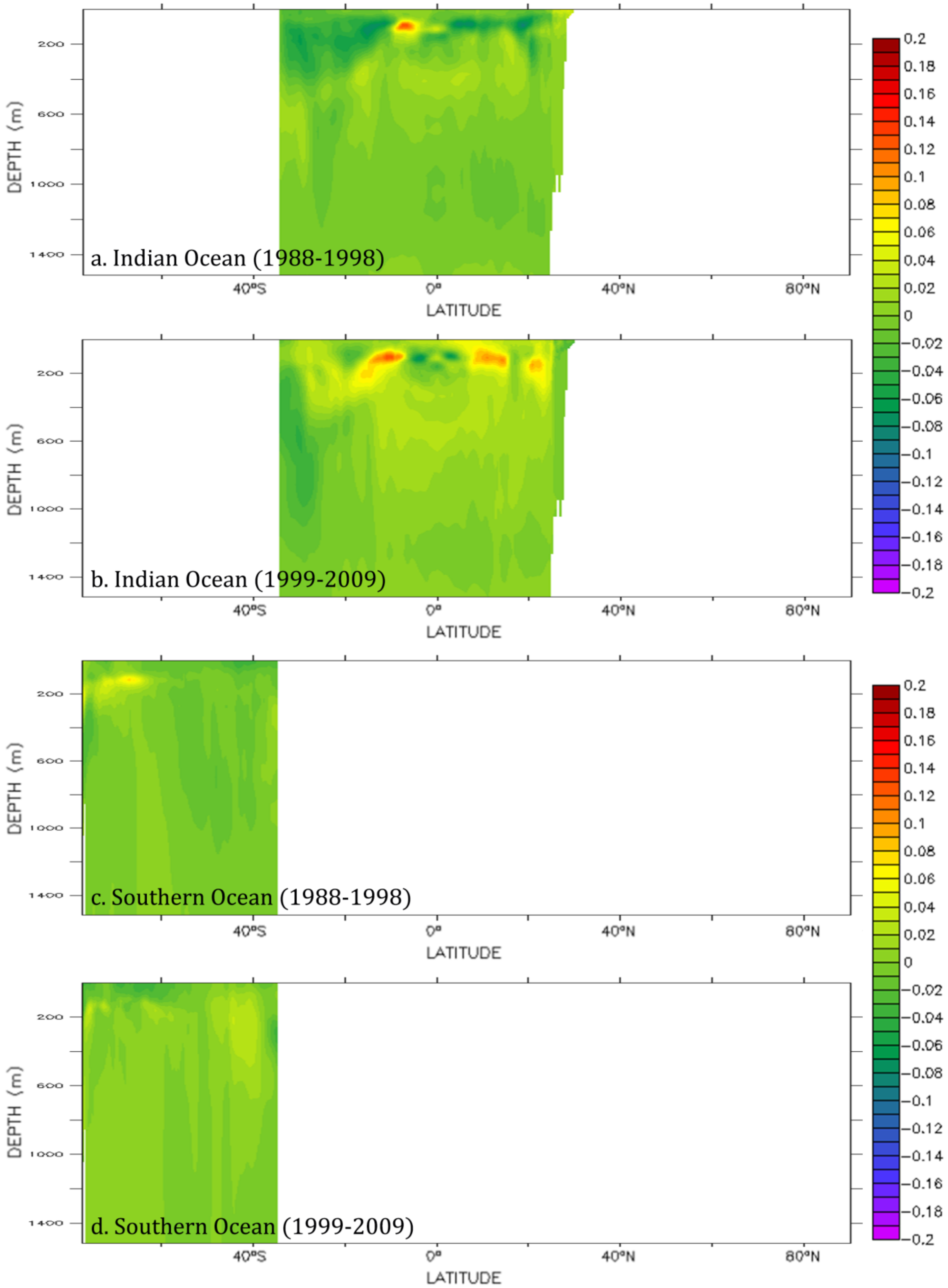

Figure 8. The temperature trends (°C/year) in the Indian Ocean (a and b) and the Southern Ocean (c and d) between the warming period (1988-1998) and the hiatus period (1999-2009). The trend is zonally averaged over the basin as a function of latitude.

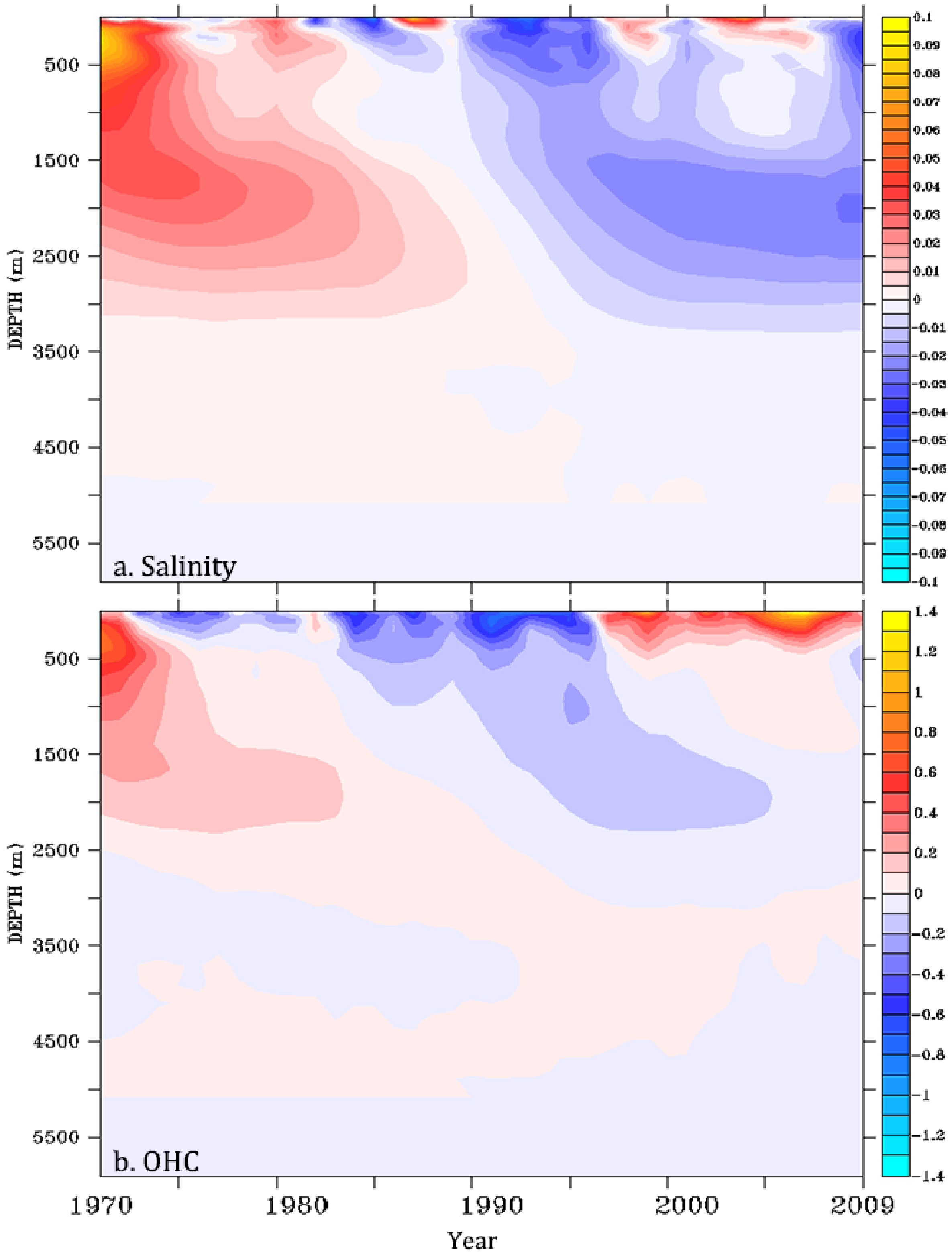

Figure 9. Climate shift in mean salinity (a) and OHC (b) in the subpolar (45°N to 65°N) of North Atlantic, as a function of years, the salinity is in units of PSU; the OHC is in units of 10^{20}J; the climatology for the period 1970 to 2009 was removed.

3.2 The salinity mechanism

As the AMOC plays a significant role in transporting heat to deep oceans, the mechanism of the AMOC is an important breakthrough point for studying the mechanism of the heat penetration in the North Atlantic subpolar area. The AMOC is driven by vertical density differences of the sea water in the subpolar area where the salty and warm water from low latitudes cools down and becomes denser, sinking through convection. As we can see in Figure 9, the salinity (Figure 9a) in the upper 500 m was much larger after 1995 than that in the prior decade, corresponding well with the OHC (Figure 9b). The salinity changed rapidly in the surface, and positive salinity anomalies reached 500 m depth. In deeper layers, the salinity was larger as well during the hiatus period, but it changed much more slowly. This pattern could reach 3000 m depth, and the OHC had a similar pattern with the salinity. In 1970s, a strong positive anomaly in both salinity and OHC occurred as well, and during this period there was another surface temperature hiatus (Chen and Tung, 2014). The salinity and the OHC variations corresponded well with each other and with the variations of the global surface mean temperature as well.

A few different explanations of the salinity fluctuations have been proposed mainly focusing on the AMOC (Chen and Tung, 2014; Jungclaus *et al*., 2005; Polyakov *et al*., 2010; Wyatt *et al*., 2012; Wyatt and Curry, 2014). Among these theories, Chen and Tung (2014) suggested that the AMOC was weakened during the prior warming decades but became stronger in the hiatus period. The reason for the weakening of the AMOC was suggested as a part of the decadal variation (Zhang, 2008), or more well-known as a result of the global warming (Bryden *et al*., 2005; Dima and Lohmann, 2007). Strong evaporation at low latitudes in the Atlantic makes the surface warm water more saline, and after flowing northward to the subpolar area, the warm water cools down and becomes denser by losing heat to warm the cold air. The heat released from the water simultaneously melts more ice (Jungclaus *et al*., 2005), and the fresh water from the melting ice decreases the salinity and the surface water density. Finally, the fresh water overwhelms the extra salt from the low latitudes and the density of the surface water decreases, weakening the AMOC.

Although the air temperature and the SST are increasing continuously globally or in separate basins, the SST in the subpolar region of the North Atlantic did not increase gradually throughout the whole studying period but grew up abruptly after 1995 (Figure 10). This abrupt change also occurred when it came to the surface salinity as Figure 9a shown. Because salt is normally trapped in water, without obtaining or losing through the atmosphere, vertical or horizontal salinity transports and the gain or loss of freshwater could be the reasons for the salinity change. A salinity increase implies that additional salt is added or extra freshwater is removed. In the North Atlantic, most of the saline water comes from the surface between 20°N-30°N due to strong evaporation under the effect of hot and dry easterly wind from Africa, and horizontally there is no other salt source existing in the subpolar area (Curry *et al*., 2003). As seen in Figure 11, the horizontal salt source of the subpolar region--the subtropical area of the North Atlantic (15°N to 45°N) --provided less salty water in the hiatus period than the prior decades, but in the subpolar area the salinity was larger, indicating that northward transport of

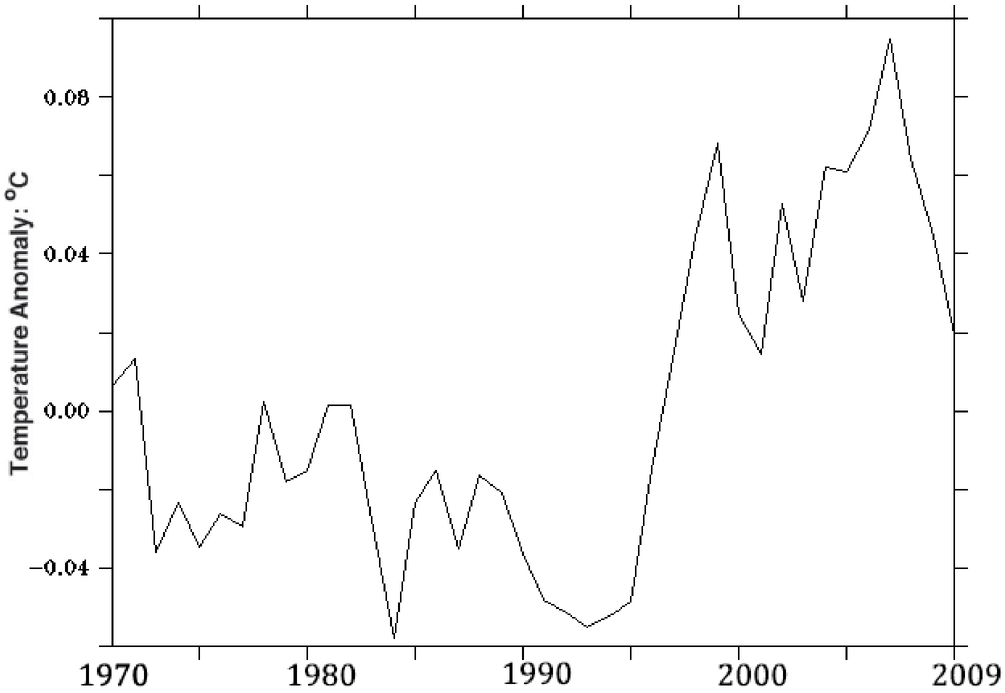

Figure 10. SST anomaly in the subpolar North Atlantic, as a function of years, the climatology from 1970 to 2009 was removed.

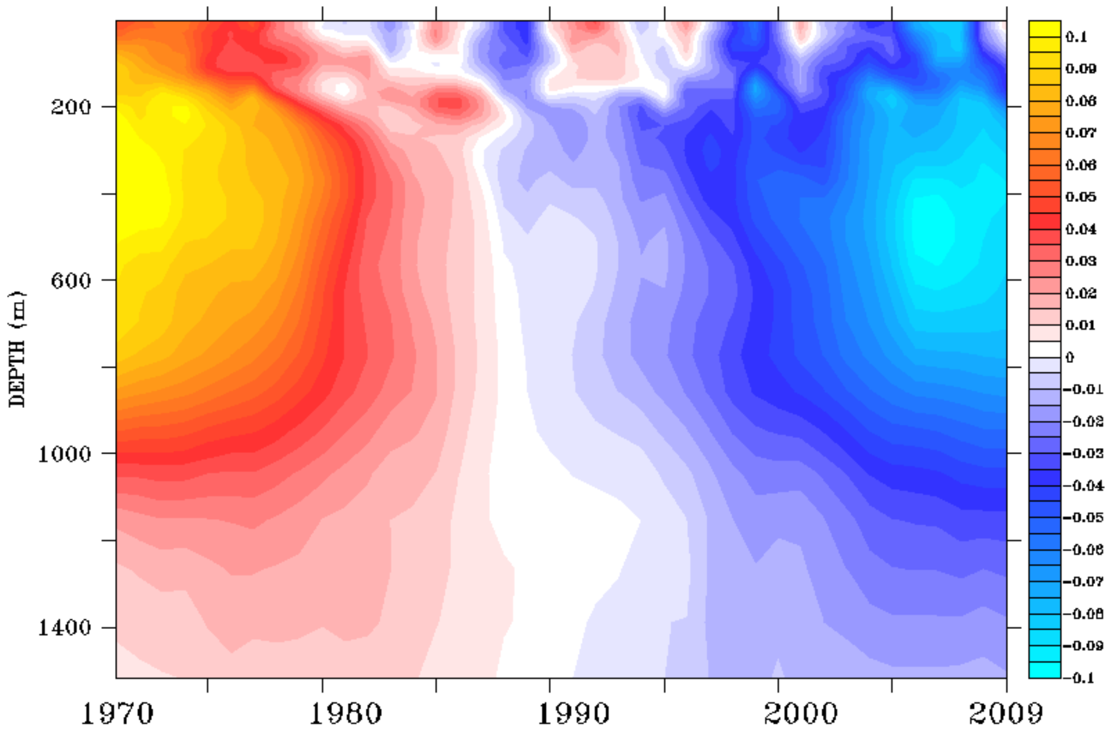

Figure 11. Climate shift in mean salinity in the subtropical (15°N to 45°N) of North Atlantic, as a function of years, the salinity is in units of PSU; the climatology for the period 1970 to 2009 was removed.

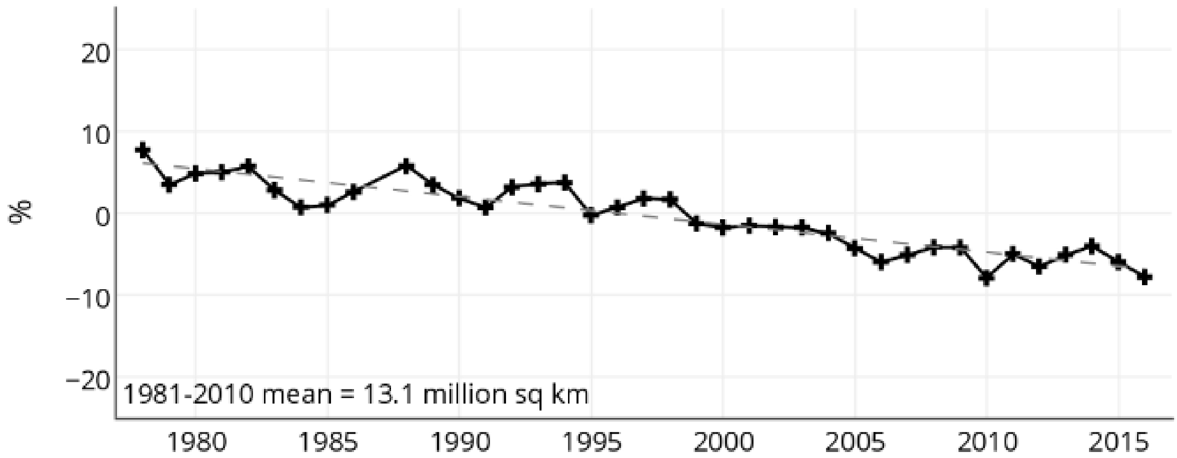

Figure 12. Monthly ice extent anomalies in Northern Hemisphere from 1978 to 2016. The anomaly data points are plotted as plus signs and the trend line is plotted with a dashed grey line (NSIDC, 2017).

salty water was not the reason for the positive salinity anomaly, which contradicted the view of Chen and Tung (2014). Another way to add salt is through vertical transport with deep convection. When denser surface water sinks, the less salty water in deeper layers simultaneously goes up as a compensation. Therefore, during the decade before the hiatus period, the surface salinity was lower than that in deep oceans. In the hiatus period, however, the salty water tended to stay at the surface and trap the salt in surface layers, leading to a lower salinity in deep water. In Figure 9b, the high OHC in the surface made the surface water difficult to be denser and sink, resulting in a weaker AMOC which was related to a less deep convection, keeping salty water near the surface. Therefore, the increase of the salinity during the hiatus period was not because of more salt and heat from the tropical area brought by the enhance of the AMOC as Chen and Tung (2014) suggested, but due to a weaker AMOC and less deep convection.

Another possibility is that the freshwater in the subpolar area was removed. There are a few ways to lose freshwater there. The high surface air temperature in the hiatus period may lead to a stronger evaporation, and in the hindcast run the surface air humidity indeed increased during the hiatus period (Drijfhout *et al*. 2014); another way of losing freshwater is the formation of the sea ice. When sea water is freezing, only the freshwater freezes into ice, leaving most of the brine back into the ocean, thus raising the salinity of the near-surface water. This possibility is supported by the good consistency between the surface salinity variations in Figure 9a and the observed sea ice anomaly in Figure 12: the increase of the salinity was usually followed by an increasing volume of sea ice, and vice versa. The sea ice melting and the formation may not play a significant role on the salinity and the OHC variations in the North Atlantic, but the effect on changing salinity and temperature should not be ignored.

The speed or the strength of the AMOC cannot be easily and accurately detected from a figure like Figure 9, but what can be a reference is the speed of the influences given by surface salinity (or temperature) on deep water. For example, we can see from Figure 9b that in 2006, the surface OHC was around $1.4\times\ 10^{20}$J, and the depth of the $0.1\times\ 10^{20}$J layer was less than 500 m, which was much less than that in 1998 when the surface OHC was around $1\times\ 10^{20}$J, indicating that the AMOC was in some extent weakened. The mechanistic explanation of the salinity and OHC anomaly in the subpolar North Atlantic of Chen and Tung (2014) is not supported by this study, and their reason for the enhanced AMOC is not rigorous.

4. Discussion

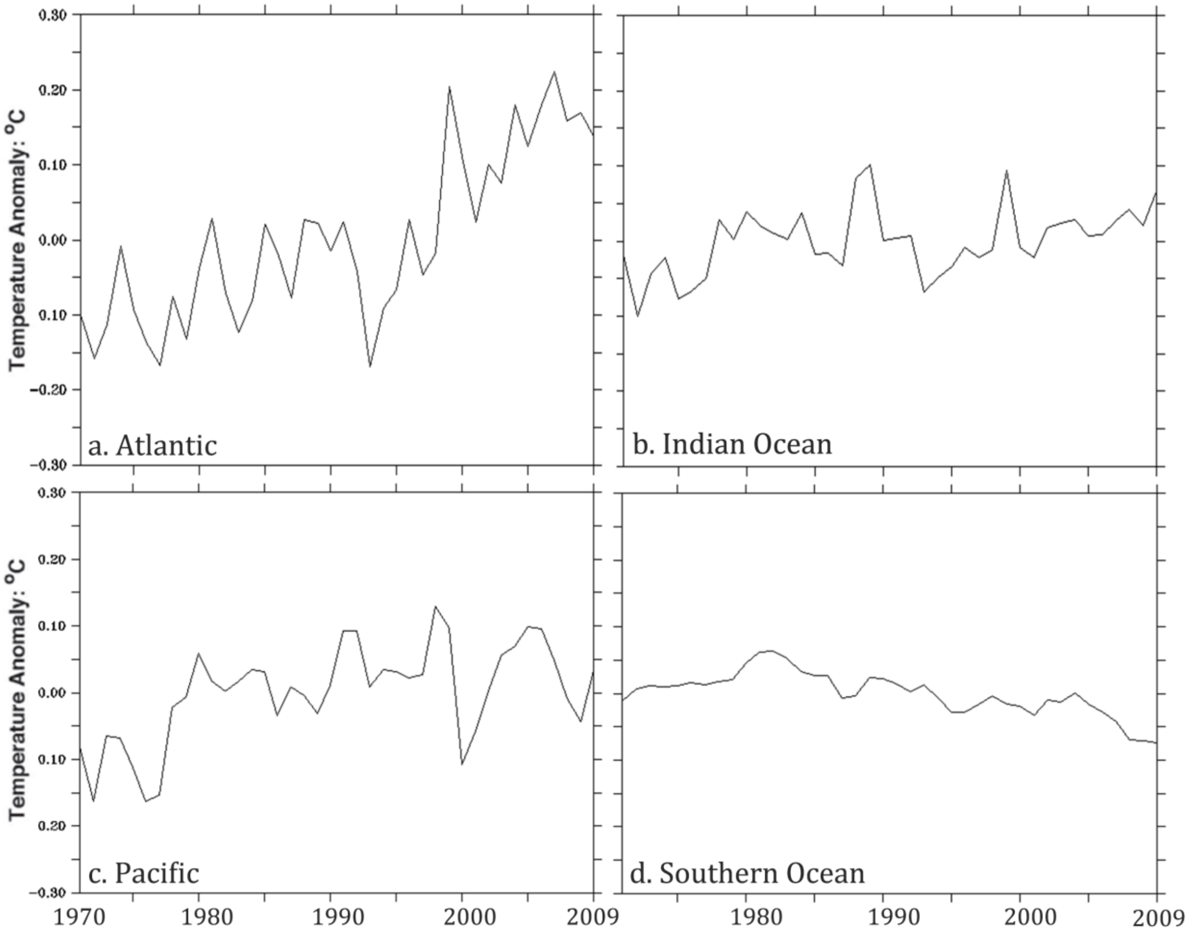

Figure 13. Temperature anomaly in the Atlantic (a), the Indian Ocean (b), the Pacific (c) and the Southern Ocean (d) from 1970 to 2009, as a function of years, climatology from 1970 to 2009 was removed.

The technology of oceanic observations has developed a lot since the 1990s especially after Argo floats were put into use and deployed globally by 2005 (Roemmich *et al.*, 2009). Although the observational data from Argo is highly reliable, spatial and temporal limitations still exist. Other data types based on observations are available before the application of Argo but have all kinds of bias, and the coverage is coarse in deep oceans as well (Chen and Tung, 2014). In this case, the advantages of ocean simulations stand out: the data is available in long periods and to very deep oceans. However, the accuracy of the data can be a problem for simulations. The hindcast simulations are less problematic and more reliable among the models, but bias can hardly be avoided because of the complexity of the reality.

The SST variations for four basins (Figure 13) from 1970 to 2009 from the hindcast corresponds well with that shown by Chen and Tung (2014) based on Ishii data (Ishii and Kimoto, 2009), but the amplitudes of the variation are smaller here. The integrated OHC for different layers shows that there was increasingly more heat in the upper 700 m of the ocean, however, based on Ishii data, Chen and Tung (2014) concluded that the upper 300 m water was losing heat, and that heat was compensated by an increasing heat uptake in 300-1500 m. Their conclusion was contradicted by Nieves *et al*. (2015) who applied Ishii data as well. Nieves *et al*. (2015) proposed that the cooling in the top 100 m layer in the Pacific was caused by the warming in the 100-300 m layer in the Pacific and the Indian Ocean. I agree with the importance of the upper 300 m layer in heat redistribution during the hiatus period, however, I do not agree with the reason they neglected the effect of the deeper oceans below 300 m. In the supplementary material of Nieves *et al*. (2015), the comparison of observation-based datasets with model results were displayed globally and also in different basins. The most reliable data, Argo, showed that the OHC in global oceans changed a lot not only in the upper 300 m but also in deep oceans till 2000 m. In the Atlantic and the Pacific, Argo data demonstrated a decreasing trend of the OHC between 300 m and 1500 m, suggesting that the hindcast simulation in this study did a better job in these two basins. However, the hindcast did not show a good consistency with Argo in the Indian Ocean and the Southern Ocean, where the OHC increased a lot between 300 m and 1500 m based on Argo data.

The importance of the Atlantic in heat redistribution was affirmed both in this study and in the article of Chen and Tung (2014), but the role of the Southern Ocean (Chen and Tung, 2014; Drijfhout *et al.*, 2014) is not confirmed in this study. In Figure 4d and Figure 8c-d, the increase of OHC and temperature were not prominent in the upper 1500 m layer, but it increased a lot below 1500 m depth (pink line in Figure 3d). Using the same hindcast simulation, Drijfhout *et al*. (2014) found that about 30% of the extra heat uptake during the hiatus period occurred in the Southern Ocean, but in this study, the OHC did not increase much in the upper 1500 m layer. This indicates that heat content anomaly is not closely related to heat uptake, supporting the view of Drijfhout *et al*. (2014). On the other hand, the temperature variations in the Southern Ocean was not well simulated in this hindcast model so that it was hard to present the importance of the Southern Ocean in heat rearrangement by OHC alone.

In Figure 3, the global OHC started to rise continuously from 1995, while this monotonically increasing trend started from 1998 in the article of Chen and Tung (2014), indicating that the hindcast simulation may have an overestimation of the starting time of the hiatus. However, the variation amplitudes of the anomalies for the OHC vertical sections of the Atlantic and the Pacific are much smaller than those in the study of Chen and Tung (2014). The supplementary material (Figure S14 and Figure S17) of Nieves *et al*. (2015) suggested that in the Pacific and the Atlantic, both the Ishii data used by Chen and Tung (2014) and the WOA dataset applied by Nieves *et al*. (2015) had large deviations from Argo data in the upper 1500 m layer. Although the hiatus was overestimated by the hindcast in temporally, the heat and temperature variations were not overestimated but even underestimated especially in the Southern Ocean and the Indian Ocean.

The subpolar North Atlantic SST was not simply cooling down during the hiatus period when the extra heat moved to deeper layers. The cooling was from 2006 (Figure 10), and in 2000-2006 the SST and near-surface OHC were increasing with the sea ice melting as well (Figure

12). The effect of the sea ice melting and the formation on salinity change near the surface cannot be ignored. Because the data of the sea ice was not accessible, an observation-based picture (Figure 12) was displayed as a substitute. To get a better result of the correlation between sea ice volume and salinity, the plot of the ice extent anomalies should be made using the result of the hindcast run instead of observational data. The comparison here can be regarded as a reference, more prudent analysis is necessitated in further studying.

5. Conclusions

In the context of the continuously increasing radiative forcing in the atmosphere, oceans play a significant role in absorbing and storing the excess heat to slow down the increasing of the global mean temperature. This is particularly true for a slowdown of the warming at the earth surface at the start of the 21st century, often referred to as a 'hiatus' or 'plateau'. The Atlantic and the Pacific had the largest contributions to the hiatus period in heat redistribution among water layers (Kosaka and Xie, 2013; Chen and Tung, 2014; Drijfhout *et al*, 2014). A La Niña pattern dominated the tropical Pacific during the hiatus, and the heat deficit was compensated by the increased heat in 0-700 m; in the Atlantic, the heat penetrated to 2500 m in the subpolar area but the strongest heat increase took place in upper 300 m depth. The Indian Ocean experienced a continuously warming trend through the 40 years, but the warming in the Southern Ocean was unexpectedly not displayed in this study. The warming in the subpolar North Atlantic in upper 1500 m associated with the anomalously warm SST manifested the importance of the subpolar North Atlantic in the hiatus. The salinity variations corresponded well with the OHC shifts, as Chen and Tung (2014) suggested, corresponding well with the anomaly of the sea ice volume in Northern Hemisphere as well. The significant increase of salinity was due to less deep convection related to a weaker AMOC, and was partly due to the loss of freshwater by the formation of sea ice, but not the increasing salt transport from the tropical area. The view that the AMOC was enhanced was not supported. From the climate shifts (Figure 9), one can also roughly see a weakening AMOC, but considering the complexity of the ocean-atmosphere system, it should be studied further in more detail.

Acknowledgements

I thank Sybren Drijfhout for his assistance in accessing the data on the data achieve of the National Oceanography Centre Southampton, using ferret scripts and improving this manuscript. I thank Appy Sluijs and Lei Yue for suggestions and discussions to improve the manuscript. I thank KNMI for providing a nice working environment.

Reference

Balmaseda, M. A., K. E. Trenberth, and E. Källén (2013), Distinctive climate signals in reanalysis of global ocean heat content, *Geophysical Research Letters*, *40*, 1754–1759, doi:10.1002/grl.50382.

Blaker, A. T., J. J. M. Hirschi, G. McCarthy, B. Sinha, S. Taws, R. Marsh, A. Coward, and B. de Cuevas (2014), Historical analogues of the recent extreme minima observed in the Atlantic meridional overturning circulation at 26°N, *Climate Dynamics*, doi:10.1007/s00382-014-2274-6.

Behrens, E., A. Biastoch, and C. W. Böning (2013), Spurious AMOC trends in global ocean sea-ice models related to subarctic freshwater forcing, *Ocean Modelling, 69*, 39-49.

Chen, X., and K. K. Tung (2014), Varying planetary heat sink led to global-warming slowdown and acceleration, *Science*, *345*, 897–903.

Church, J. A., N. J. White, L. F. Konikow, C. M. Domingues, J. G. Cogley, E. Rignot, J. M. Gregory, M. R. van den Broeke, A. J. Monaghan, and I. Velicogna (2011), Revisiting the Earth's sea-level and energy budgets from 1961 to 2008, *Geophysical Research Letters*, *38*(18), L18601, doi:10.1029/2011GL048794.

Cowtan, K., and R. G. Way (2014), Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends, *Quarterly Journal of the Royal Meteorological Society*, *140*, 1935–1944, doi:10.1002/qj.2297.

Curry, R., B. Dickson, and I. Yashavaev (2003), A change in the freshwater balance of the Atlantic Ocean over the past four decades, *Nature*, *426*(6968), 826-829.

Dima, M., and G. Lohmann (2007), A Hemispheric Mechanism for the Atlantic Multidecadal Oscillation, *Journal of Climate*, *20*, 2706-2719, doi: 10.1175/JCLI4174.1.

Drijfhout, S. S., A. T. Blaker, S. A. Josey, A. J. G. Nurser, B. Sinha, and M. A. Balmaseda (2014), Surface warming hiatus caused by increased heat uptake across multiple ocean basins, *Geophysical Research Letters*, *41*, 7868–7874, doi:10.1002/2014GL061456.

England, M. H., et al. (2014), Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus, *Nature Climate Change*, *4*, 222–227, doi:10.1038/nclimate21 06.

Hansen, J. M., R. Ruedy, M. Sato, and K. Lo (2010), Global surface temperature change, *Reviews of Geophysics*, *48*, RG4004, doi:10.1029/2010RG000345.

IPCC (2007), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T.F. Stocker et al., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ishii, M. and M. Kimoto (2009), Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections, *Journal of Oceanography*, *65*, 287-299, doi:10.1007/s10872-009-0027-7

Jourdan, B., E. Balopoulos, M. Garcia-Fernandez, and C. Maillard (1998), Objective analysis of temperature and salinity historical data set over the Mediterranean basin, *IEEE*, doi:10.1109/OCEANS.1998.725659.

Jungclaus, J., H. Haak, M. Latif, U. Mikolajewicz (2005), Arctic-North Atlantic interactions and multidecadal variability of the meridional overturning circulation. *Journal of Climate*, *18*, 4013-4031.

Knight, J., C. K. Folland, and A. Scaife (2006), Climate impacts of the Atlantic Multidecadal Oscillation, *Geophysical Research Letters*, *33*, L17706, doi:10.1029/2006GL026242.

Kosaka, Y., and S. P. Xie (2013), Recent global-warming hiatus tied to equatorial Pacific surface cooling, *Nature*, *501*, 403–407.

Large, W. G., and S. Yeager (2009), The global climatology of an interannually varying air-sea flux data set, *Climate Dynamics*, *33*, 341–364.

Lee, S. K., W. Park, E. van Sebille, M. O. Baringer, C. Wang, D. B. Enfield, S. G. Yeager, and B. P. Kirtman (2011), What caused the significant increase in Atlantic ocean heat content since the mid-20th century?, *Geophysical. Research Letters*, *38*, L17607, doi:10.1029/2011GL048856.

Lee, S. K., W. Park, M. O. Baringer, A. L. Gordon, B. Huber, and Y. Liu (2015), Pacific origin of the abrupt increase in Indian Ocean heat content during the warming hiatus, *Nature Geoscience*, *8*(6), 445-449.

Levitus, S., et al. (1998), World Ocean Database 1998, *Technical Report NESDIS*, *18*, NOAA Atlas. 346 pp.

Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov (2009), Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems, *Geophysical Research Letters*, *36*, L07608, doi:10.1029/2008GL037155.

Lyman, J. M., et al. (2010), Robust warming of the global upper ocean, *Nature*, *465*, 334–337.

Madec, G. (2009), NEMO ocean engine. Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, *Technical Report, 27*, 1288-1619.

McCarthy, G., E. Frajka-Williams, W. E. Johns, M. O. Baringer, C. S. Meinen, H. L. Bryden, D. Rayner, A. Duchez, C. Roberts, and S. A.Cunningham (2012), Observed interannual variability of the Atlantic meridional overturning circulation at 26.5°N, *Geophysical Research Letters*, *39*, L19609, doi:10.1029/2012GL052933.

Meehl, G. A., J. M. Arblaster, J. T. Fasullo, A. Hu, and K. E. Trenberth (2011), Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods, *Nature Climate Change*, *1*(7), 360-364.

Meehl, G. A., A. Hu, J. M. Arblaster, J. Y. Fasullo, and K. E. Trenberth (2013), Externally forced and internally generated decadal climate variability associated with the Interdecadal Pacific Oscillation, *Journal of Climate*, *26*, 7298–7310.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones (2012), Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, *Journal of Geophysical Research*, *117*, D08101, doi:10.1029/2011JD017187.

Nieves, V., J. K. Willis, and W. C. Patzert (2015), Recent hiatus caused by decadal shift in Indo-Pacific heating, *Science*, *349*(6247), 532-535.

NSIDC (2017), Sea ice index, National Snow & Ice Data Center, retrieved from https://nsidc.org/data/seaice_index/ on January 27th, 2017.

NOAA (2015), Historical El Niño/La Niña episodes (1950-present), United States Climate Predictions Center, retrieved from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml on January 18th, 2017.

NOAA (2017), National Centers for Environmental information, Climate at a Glance: Global Time Series, published February 2017, retrieved from http://www.ncdc.noaa.gov/cag/ on March 11th, 2017.

Polyakov, I.V., V.A. Alexeev, U.S. Bhatt, et al. (2010), North Atlantic warming: patterns of long-term trend and multidecadal variability, *Climate Dynamics*, *34*, 439. doi:10.1007/s00382-008-0522-3

Purkey, S. G., and G. C. Johnson (2010), Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: Contribution to global heat and sea level rise budgets, *Journal of Climate*, *23*, 6336–6351.

Roemmich, D., and the Argo Steering Team (2009), Argo: The challenge of continuing 10 years of progress, *Oceanography*, *22*(3),46–55, doi:10.5670/oceanog.2009.65.

Trenberth, K. E., and J. T. Fasullo (2013), An apparent hiatus in global warming? *Earth's Future*, *1*, 19–32, doi:10.1002/2013EF000165.

Solomon, S., et al. (2010), Contributions of stratospheric water vapor to decadal changes in the rate of global warming, *Science*, *327*, 1219–1223.

Solomon, S. et al. (2011), The persistently variable `background' stratospheric aerosol layer and global climate change. *Science*, *333*, 866–870.

Steele, M., R. Morely, and W. Ermold (2001), PHC: a global ocean hydrography with a high quality Arctic Ocean, *Journal of Climate*, *14*, 2079-2087.

Sutton, R., and P. P. Mathieu (2002), Response of the atmosphere-ocean mixed-layer system to anomalous ocean heat-flux convergence, *Quarterly Journal of the Royal Meteorological Society*, *128*, 1259–1275.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center (2006), 2-minute gridded global relief data (ETOPO2v2), http://www.ngdc.noaa.gov/mgg/global/etopo2.html.

Watanabe, M., et al. (2013), Strengthening of ocean heat uptake efficiency associated with the recent climate hiatus, *Geophysical Research Letters*, *40*, 3175–3179, doi:10.1002/grl.50541.

Wyatt, M.G., S. Kravtsov, and A.A. Tsonis (2012), Atlantic Multidecadal Oscillation and Northern Hemisphere's climate variability, *Climate Dynamics*, *38*, 929-949, doi:10.1007/s003 82-011-1071-8.

Wyatt, M. G., and J. A. Curry (2014), Role for Eurasian Arctic shelf sea ice in a secularly varying hemispheric climate signal during the 20th century, Climate Dynamics, 42, 2763–2782, doi:10.1007/s00382-013-1950-2

Zhang, R. (2008), Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation, *Geophysical Research Letters*, *35*, L20705, doi:10.1029/2008GL035463.