Oceanic Climate Change: Contributions of Heat Content, Temperature, and Salinity Trends to Global Warming

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Abstract

The World Ocean is the largest component of the global climate system, and changes to its heat content, temperature, and salinity have an enormous impact on the current global warming trend. In this paper, these physical changes are discussed in detail, including potential sources of change and spatial and temporal variability, as the observed trends are influenced by location as well as climatological phenomena such as North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and El Niño-Southern Oscillation (ENSO). Long-term trends predicted by the state-of-the-art Parallel Climate Model (PCM) for global oceanic heat content are compared with observations, and a few comments on model reliability are made. Moreover, the almost certain presence of anthropogenic forcing predicted by global climate models (GCMs) is discussed, and the relative strengths of these effects are compared. Long-term trends in ocean temperature and salinity are broken down by basin and depth. Lastly, several consequences of oceanic climate change for the local and global climate are described, including oxygen concentration depletion, which is harmful to marine life, and sea level rise, which is harmful to humans.

1 Introduction

Approximately seventy percent of the surface of the Earth is covered by the world's oceans and seas. These bodies of water occupy an important place in the global climate system: they are the source of most global precipitation, their temperature distribution affects global wind fields and jet streams, and their salinity (together with temperature) can affect the polar ice cap extent. Survival and well-being of all terrestrial life is also affected, either directly or indirectly. The consensus among prominent scientists is that the World Ocean has changed rather abruptly during the previous half-century compared with the previous millennium. Some of this change is natural, and some of it not. Since nearly half of the world's human population resides within 100 km of the ocean (and roughly two-thirds within 400 km), it is of utmost importance to understand which properties of the World Ocean are rapidly changing, as well as possible sources, short- and long-term trends, natural variability on short and long time scales, and consequences for human beings.

Many possible sources of oceanic climate change are listed in [1]. Natural causes include ENSO, which occurs on annual time scales at irregular intervals, as well as NAO, North Atlantic Multidecadal Oscillation (NMO), and PDO, which occur at decadal (or longer, see [2]) time scales. Changes stemming from sea ice and ice sheets are also cited in [1]. Additionally, changes in volcanic and solar activity are shown to contribute to the observed variability in sea water properties [3]. Finally, increased levels of carbon dioxide (CO_2), chlorofluorocarbons (CFCs), and other greenhouse gases (GHGs) in the atmosphere from anthropogenic forcing have markedly affected the World Ocean [2, 3].

The general consensus on oceanic climate change is that there has been a substantial increase in heat content and temperature, an increase in salinity in near-surface waters at low latitudes, a decrease in salinity in subpolar latitudes, a slight increase in acidity, a decrease in oxygen gas (O_2) concentration, and a rise in global mean sea level. The global sea level rise is believed to be caused by thermal expansion, and changes to any of these seawater properties is thought to lead to changes in circulation and transport patterns[1] [1].

The remainder of this paper is as follows. In the next section, the importance of the ocean in global heat content calculations is discussed, followed by a summary of observed and predicted short- and long-term trends in heat content in the World Ocean. Magnitudes of anthropogenic and natural forcing are discussed as well. In section 3, a breakdown of temperature trends by basin and depth are described, while trends in salinity are reviewed in section 4. Other changes observed as a consequence of oceanic climate change are presented in section 5, and some concluding remarks are made in section 6.

[1] According to [1], there is no evidence that any long-term changes to oceanic circulation patterns are currently taking place, since it is *very likely* that such patterns like the Meridional Overturning Circulation (MOC) change only on very short time scales [1]. However, this does not rule out the possibility that the *strength* of the patterns may be changing.

2 Changes in Heat Content

This section is begun with a simple numerical example that shows the importance of the ocean in determining changes to global heat content.

2.1 Quantifying Heat Content

The total heat content of a material is the amount of heat energy stored there. It can be determined by the formula

$$Q = c_p m T, \tag{1}$$

where Q is the total heat content (J), c_p is the specific heat capacity of the material at constant pressure ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), m is the mass of the material (kg), and T is the temperature (K). Thus, we can determine the change in total heat content by relating it to the (measured) change in temperature:

$$\Delta Q = c_p m \Delta T. \tag{2}$$

Since sea water has a (high) specific heat capacity of $c_p = 4184\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$, which is more than four times that of dry air, and because seawater is much denser than air (by a factor of about 800), and since the World Ocean is very large, a 1 K rise in ocean temperature changes the global heat content by three orders of magnitude more than a rise of 1 K in air temperature [7].[2] Thus, contributions to changes in global heat content from the ocean are expected to dominate atmospheric effects. As pointed out in Table 1, it indeed dominates atmospheric effects, as well as all other effects, despite the small observed temperature increase (compared to that of the atmosphere) [3]. That the oceanic contribution to global heat content dominates all other components is also unsurprising, since the volume of the ocean is much larger than that of the other components (besides the atmosphere). Similar comments to this effect are made in [1].

2.2 Anomalies in Selected Basins

Much discussion about heat content anomalies for several basins of the World Ocean is contained in [2]. Data on mean oceanic heat content for the fifty year period from 1948 to 1998 was gathered from the World

[2] The total volume of the World Ocean and that of the air in the atmosphere is of the same order of magnitude.

Climate system component	Time period of change	ΔQ (J)
World Ocean	1955–1996	1.82×10^{22}
Continental glaciers	1955–1996	8.1×10^{21}
Global atmosphere	1955–1996	6.6×10^{21}
Antarctic sea ice extent	1950s–1970s	3.2×10^{21}
Mountain glaciers	1961–1997	1.1×10^{21}
NH sea ice extent	1978–1996	4.6×10^{19}
Arctic perennial sea ice volume	1950s–1990s	2.4×10^{19}

Table 1: A comparison of the contributions of various global climate system components to global heat content. Unsurprisingly, the World Ocean contribution dominates that from the other components. Table taken from Table 1 in [3] and slightly modified.

Ocean Database 1998 (WOD98) and plotted.[3] This plot is reproduced from [2] and is shown in Figure 1. Similar plots for five-year moving averages of heat content appear in [2] and [3].

Notice that in the Atlantic Ocean, there is a very pronounced positive trend in ΔQ, particularly from around 1965 until 1998, whereas no discernible trend can be seen from 1948 until 1965. Most of the more recent positive trend in ΔQ can be attributed to changes occurring in the North Atlantic, since the South Atlantic shows only a small positive trend. In the Indian Ocean, a somewhat positive trend in ΔQ can be seen from about 1965 until 1998, but with greater variability than the Atlantic. Possible reasons for larger variability here and in the Pacific will be discussed in section 2.3. It is noted, however, that most of the changes in Indian Ocean heat content stem from changes observed south of the Equator, as only a weak signal is seen in the North Indian Ocean. Substantial variability on decadal time scales is apparent in the Pacific Ocean, in contrast to the other two basins, and thus a long-term trend is difficult to discern, according to [2]. Lastly, it is noted in [2] that all basins appear to show the highest positive annual mean anomaly around 1998.

Rather than analyzing data from the WOD, the PCM utilized in [4] attempts to hindcast and forecast heat content anomalies. According to [4], the PCM is a state-of-the-art global climate model which incorporates forcing from the atmosphere, ocean, sea ice, and river transport. Using observed and estimated data for greenhouse gases in the atmospheric component, this coupled model was run five times and the results averaged. Decadal trends in oceanic heat content anomalies from 1955 to 2000 were produced, and the

[3] The WOD was updated in 2001 and again in 2005. It would be interesting to see updated trends in heat content anomalies, since then-current data was heavily skewed because of the 1997–1998 ENSO event.

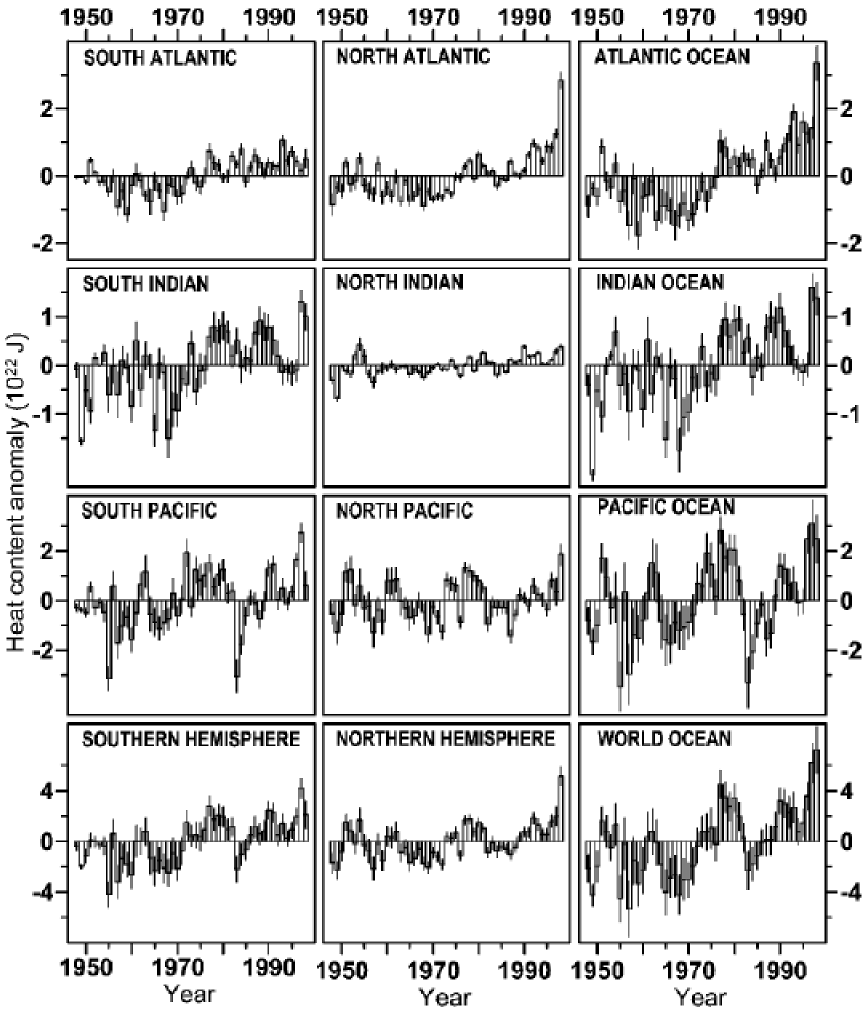

Figure 1: Annual mean oceanic heat content anomalies from 1948 to 1998 for selected basins of the World Ocean. The possibility of spurious variability in these plots from a lack of data in the Southern Hemisphere (SH) before the early 1980s is suggested in [1]. Figure taken from [2].

results of the model runs are shown in Figure 2.

Notice that overall, the results given by the PCM are surprisingly close to the observed trend in all basins [4]. The model appears to do especially well in the North Pacific and Indian Oceans, where the results remain within one standard deviation of the observed trend during the entire 45-year period. In fact, the only basin where the model gives results more than two standard deviations in error is in the North Atlantic Ocean during the mid-1970s. This is the major contributing factor to the overall error observed for the World Ocean. However, it is noted in [4] that the model does not capture observed decadal anomalies, such as that which occurred during the 1970s and early 1980s, and was especially prevalent in the South

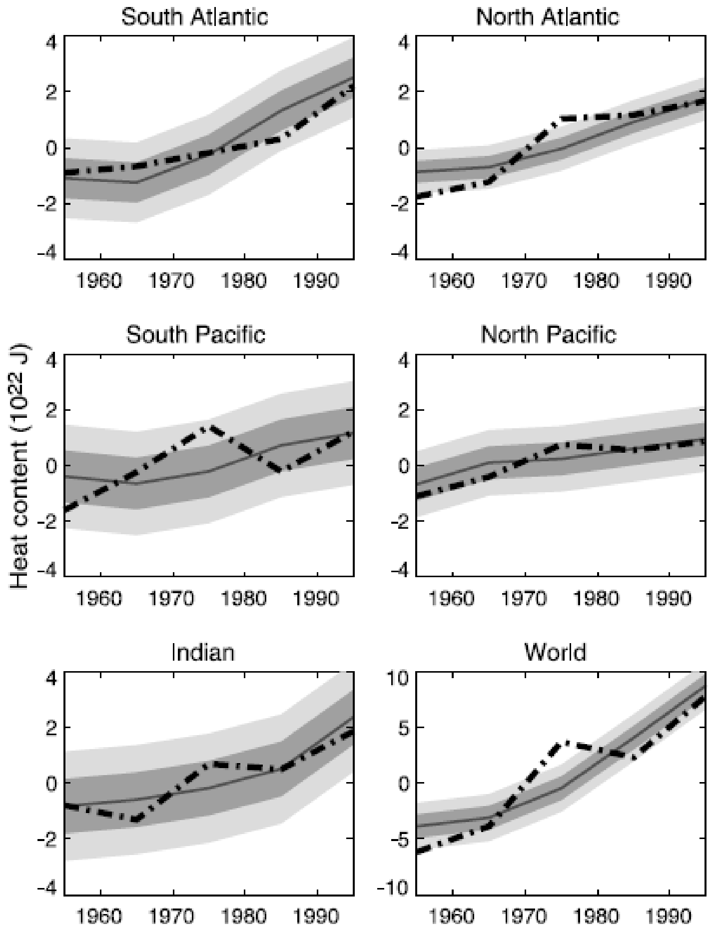

Figure 2: PCM results for oceanic heat content anomalies from 1955 to 2000. The observed decadal trend is depicted by the black dashed line, while the model average is indicated by the solid line. Values within one standard deviation of the mean are denoted by the dark gray area, whereas values within two standard deviations of the mean are shown by the light gray area [4]. Figure taken from [4].

Pacific Ocean. This anomaly will be discussed further in the next section.

2.3 Variability

In Figure 1, a very strong positive heat content anomaly around 1998 is apparent in all basins. According to [2], this coincides with a very strong ENSO event which occurred during 1997–1998, and ended shortly thereafter. Interestingly, ENSO is not cited as a possible source of the sharp drop in heat content which occurred in all basins during the early 1980s.[4]

[4]Chapter 3 of [1] alludes to a major ENSO event which occurred during the early 1980s, as well as to an atmospheric climate shift which occurred in 1976–1977, which coincides with a sharp drop in oceanic heat content worldwide.

As can be seen in Figures 1 and 2, heat content in all basins shows significant interannual and decadal variability, but this is particularly noticeable in the Pacific Ocean. Indeed, it is stated in [2] that "[b]oth Pacific Ocean basins exhibit quasi-bidecadal changes in upper ocean heat content, with the two basins positively correlated."

One of the reasons identified in [2] and [4] for this shift is PDO. PDO is an approximately bidecadal fluctuating pattern of Pacific surface water temperatures (and thus heat content). During a positive phase, eastern Pacific waters warm while western waters cool. The opposite occurs during a negative phase. It is speculated in [4] and also in [1] that the large change in heat content observed during the late 1970s coincides with a shift in PDO from a negative to a positive phase. However, it is stated in [2] that "…it is not clear if the variability we observe in the Pacific Ocean heat content is correlated with this phenomenon or whether there are additional phenomena that contribute to the observed heat content variability."

A similar phenomenon is observed in the Atlantic Ocean during the same time period. According to [2], this is associated with NAO, which is a fluctuating pattern of sea level pressure. During a positive phase, low pressure resides near Iceland while high pressure resides near the Azores. During a negative phase, the opposite pressure distribution occurs. During the late 1970s, NAO shifted from a negative to a positive phase, coinciding with the observed sharp rise in heat content followed a few years later by a drop.

PDO and NAO are at the heart of the shortcomings for the PCM described in [4]. Phase changes in PDO and NAO, which appear to take place over relatively short time scales (about two or three years), fail to be captured by this model. These phase changes are shown to be significant enough to alter the decadal heat content anomalies shown in Figure 2. The PCM appears to "smear out" these decadal anomalies in heat content, and also appears not to capture variability that occurs on very long time scales (centuries to millennia), although this latter problem appears to be mild [4].

In [6], an attempt is made to quantify the variability in heat content during the 1990s. Recall from Figure 1 that during this time, all basins display a strong positive heat content anomaly. As in [2], this variability is attributed to ENSO in 1997–1998, which caused a "spike" in the heat content signal. It is remarked that some of the warmth was due to both the PDO and NAO being in a positive phase, in addition to ENSO [2].

Lastly, the question of whether the observed long-term trend in heat content anomalies in the World

Ocean contains at least some anthropogenic forcing from increased concentrations of GHGs is addressed in [3] and [4]. It seems that two similar approaches were taken to answer this. In [3], it is determined that some human-induced forcing must be involved because the observed and predicted trends could not happen because of natural interactions within the climate system alone—the overall trend is too large. It is concluded in [4] that some anthropogenic forcing is responsible because the model results could not be expected simply by chance—the trend is again too large to be natural.

3 Changes in Temperature

Changes in global oceanic heat content are closely related to changes in seawater temperature. It was observed by several authors that global oceanic heat content shows an increasing long-term trend; an increasing temperature trend should thus be expected as well, by equation (2). Indeed, this is generally the case, but the magnitude of the change are highly location-dependent; not all areas of the ocean are warming. The extent of the change is also dependent on depth; in some areas, the top portion of the water column is warming but the lower portion is cooling, and vice versa. As a result, observed temperature anomaly trends are reviewed by depth.

3.1 Near Surface Anomalies

In the upper 700 m of the ocean, there appears to be a definite warming trend in all basins, as described in [1]. Figure 3 shows the longitudinally-averaged temperature anomalies as a rate of change per decade, as obtained from data for the time period 1955 to 2003.

Consider first the North Atlantic Ocean. It is evident from these plots that tropical and subtropical waters warmed during the past fifty years, as have waters beneath the Arctic polar ice cap. Waters located near the Strait of Gibraltar have warmed as well because of the warming in the Mediterranean Sea; anthropogenic effects are noted to be quite acute in this region [1]. However, waters in the North Atlantic Subpolar Gyre, an area located between $50\,^{\circ}$N and $65\,^{\circ}$N whose circulation is highly dependent on the NAO phase, have cooled during this period. This cooling is attributed to NAO; see, for example, [1, 2]. However, it is noted in [6] that warming over most of the North Atlantic "contributes only marginally to the global trend because [it] only represents a small fraction of the global ocean."

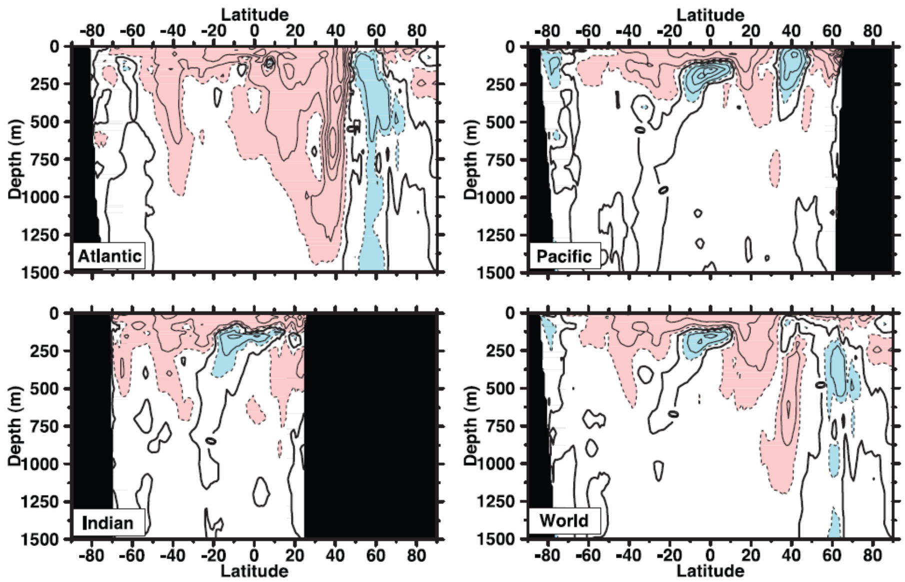

Figure 3: Longitudinally-averaged temperature anomalies as a rate of change per decade. Red areas indicate warming greater than 0.25 °C per decade, while the blue areas indicate cooling greater than 0.25 °C per decade. Figure taken from [1].

The South Atlantic Ocean also shows a warming trend, though not as pronounced as the North Atlantic, and the warming does not penetrate as deep, especially south of 55 °S, near the Antarctic Circumpolar Current. In the Indian Ocean, warming is quite pronounced at all latitudes, except for an area between 20 °S and the Equator at depths between 100 and 500 m, which shows cooling. Again, the warming trend here is not as strong as in the North Atlantic, but it is cautioned that "[t]he delayed warming of the Indian Ocean with respect to the other two oceans may be due to the sparsity of data in the Indian Ocean before 1960" [2].

The Pacific Ocean must be studied carefully, as its waters are subject to ENSO-related events [6]. However, ENSO only affects near surface temperatures, and its effect disappears below 750 m [6]. Figure 3 shows that at depths less than 700 m, most of the Pacific has warmed, especially within the top 250 m of the water column. However, there are three major exceptions. The first is a band centered at about 40 °N, where the waters have cooled markedly. This is associated with the positive phase of PDO [1]. Cooling also occurs in the Equatorial Currents (within 10° of the Equator) at depths between 100 and 375 m, as well as south of 70 °S. Cooling in the latter region may be caused by decreases in sea ice and Antarctic ice sheet melting [1].

3.2 Mid-depth Anomalies

At intermediate depths, which range from about 900 m to between 1200 m and 2000 m, depending on the source (see, for example, [1, 2]), warming and cooling trends differ significantly from the upper ocean. This is because 69% of the increase in ocean heat content (and hence temperature, by equation (2)) from 1955 to 1998 occurred at depth less than 700 m in the World Ocean [1]. Thus, warming or cooling has only penetrated to these depths in a small fraction of the ocean.

Consider Figure 3 again. In the North Atlantic Ocean, significant warming from 1955 to 2003 is indicated in this layer in the North Atlantic Subtropical Gyre, as well as at mid-latitudes. Cooling is indicated in the North Atlantic Subpolar Gyre. The rest of the North Atlantic shows only slight warming. It should be noted that this figure only shows the long-term linear trend; it does not capture variability. Figure 4 shows bidecadal-scale temperature variability by first comparing five-year average temperature data from 1970–74 with that from 1955–59. Another comparison is made for 1988–92 with 1970–74.

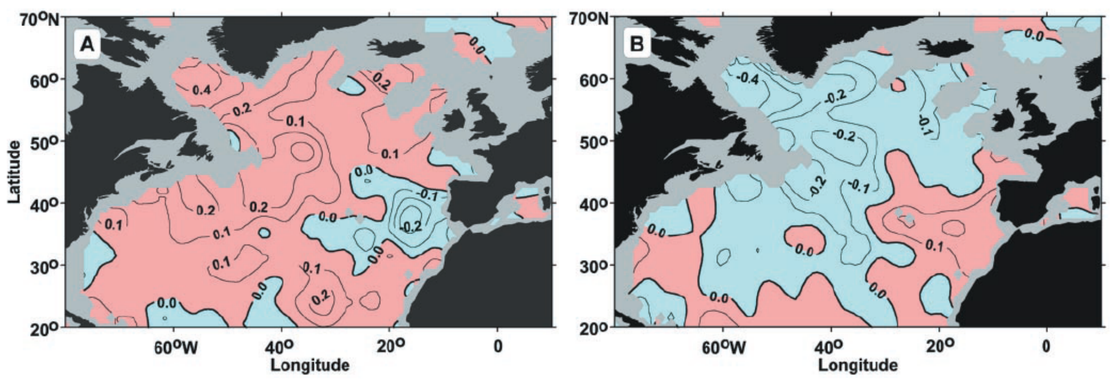

Figure 4: Temperature difference (in °C) at 1750 m for the North Atlantic for (a) 1970–74 minus 1955–59 and (b) 1988–92 minus 1970–74. Figure taken from [2].

Notice in the figure that although an overall warming trend is apparent in [1], this figure from [2] makes it clear that most of the North Atlantic warmed significantly from 1955 to 1974 but cooled from 1974 to 1992. This shows the tremendous effect of NAO on Atlantic temperature trends.

Continuing with the Indian Ocean, little change in temperature occurred during the past fifty years—subject to the caveat noted by [2]. A similar statement can be made for the Pacific Ocean at these depths. This helps to explain the trends for the World Ocean being due almost exclusively to changes in the North Atlantic.

3.3 Deep Water Anomalies

At depths greater than 1500 m (or 2000 m, depending on the source), temperature data is much more difficult to locate, as the majority of samples were taken at depths less than 1000 m [1]. Also, since transport rates are fairly small at these depths, the time scales for the seawater can be on the order of several centuries to as long as a millennium. Thus, temperature changes are quite tiny, and high accuracy in measurement techniques is crucial [1]. Nevertheless, because of the accuracy of current instruments, some data is available.

In the Atlantic, some warming is evident in the North and South Atlantic Subtropical Gryes. This warming is due to deep water convection present at these latitudes [1]. This phenomenon is also somewhat responsible for the very deep penetration of the cooling in the North Atlantic Subpolar Gyre. Also responsible is the changing outflow patterns at the mouth of the Labrador Sea [1].

In the North Pacific, simply stated, "large-scale, significant warming of the bottom 1000 m…on the order of 0.002 °C occurred between 1985 and 1999" [1]. The causes of this warming are as yet unknown, but it is speculated that transport of significantly warmed water from the SH may be responsible [1].

No significant trends appear elsewhere in the World Ocean, except in isolated areas, such as the slight cooling observed near Antarctica. Here, the cooling occurred as a result of the breakup of the Antarctic Ice Shelf, which cools the near-surface waters; this cooler, denser water is in turn quickly transported downward while warmer, less dense water rises to the surface [1].

4 Changes in Salinity

Changing temperature and heat content in the World Ocean is accompanied by changing salt concentrations. Like temperature changes, salinity changes are highly location-dependent [1]. It is important to study trends in ocean salinity when studying global climate change; since seawater is effectively incompressible, its density is independent of pressure, and depends on both temperature and salinity:[5]

$$\rho = \rho(T, S). \tag{3}$$

[5] Equation (3) is often called the equation of state for seawater. The full equation of state for seawater contains fifteen terms, including the pressure terms. Since seawater is nearly incompressible, the pressure terms can safely be neglected. Relationships between T and ρ and S and ρ are for the shorter, approximate equation of state [8].

As T increases, ρ decreases, but as S increases, ρ also increases. Since a large part of the World Ocean is warming, as explained in the previous section, seawater density is expected to decrease, leading to thermal expansion, which contributes to global sea level rise. Therefore, changes in salinity can either magnify or mitigate the amount of sea level rise.

In the Atlantic Ocean, large-scale, deeply penetrating (to almost 2500 m) salinification is seen in Figure 5 in the North and South Atlantic Subtropical Gyres. Strong salinification can be seen at both 40°N and 40°S. This change is attributed to increased evaporation from warming, and possibly from Mediterranean Sea outflow; the Mediterranean is very saline (and is increasing in salinity) [5]. On the other hand, a deep freshening trend is evident in the North Atlantic Subpolar Gyre between 45°N and 70°N [5]. It occurs throughout almost the entire water column because of deep convection patterns in the nearby Labrador and Nordic Seas [5]. In the Arctic Ocean, north of the North Atlantic Subpolar Gyre, the long-term trend is toward more saline seas, but both [1] and [5] caution that much uncertainty exists in this region because of data sparsity. In the SH, freshening has occurred near the Antarctic Circumpolar Current, as well as in the Weddell Sea and near the Antarctic coastline [5]. Interestingly, most of the seawater in the Atlantic appears to be freshening slightly at depths below 2500 m at all latitudes.

Most of the Pacific Ocean is freshening, with only one notable exception. This is the South Pacific Subtropical Gyre, located between 8°S and 32°S, and it is only becoming more saline at depths less than 300 m [1]. The overall freshening trend is particularly strong in the Ross Sea off the Antarctic coast south of 70°S, as well as in the near-surface waters in the North Pacific [5].

In the Indian Ocean, a trend towards salinification is well-defined at almost all latitudes at depths less than 150 m [5]. However, a moderate freshening trend is observed between 40°S and the Equator at depths below 150 m. A 1999 study by Wong et al. claims that the reason for the freshening is decreased evaporation and precipitation in this region [5].

5 Consequences

Although changes to global oceanic heat content, temperature, and salinity can affect many components of the global climate system, changes to oxygen concentration is focused upon, as well as perhaps the most dangerous consequence for humans: sea level rise. A complete and comprehensive discussion of ocean

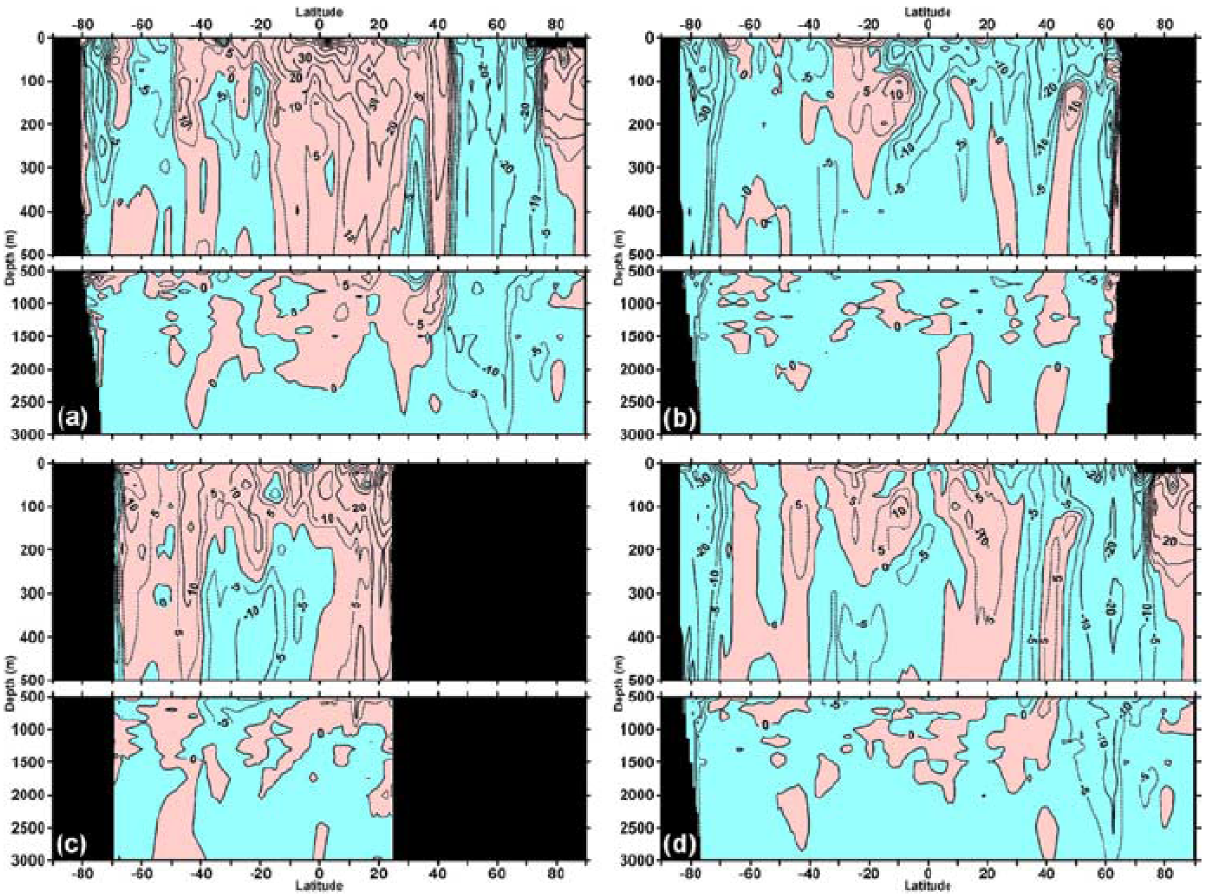

Figure 5: Longitudinally-averaged salinity anomalies as a rate of change per decade from 1955–1998 for (a) the Atlantic Ocean, (b) the Pacific Ocean, (c) the Indian Ocean, and (d) the World Ocean. Red areas indicate salinification, while blue areas indicate freshening. The 2007 IPCC Report uses a slightly modified version of this figure in its discussion of salinity trends, and therefore the IPCC's assessment of the trends for all basins is by and large consistent with that of [5]. Figure taken from [5].

biogeochemical changes is beyond the scope of this paper; see, for example, [1].

Oxygen gas dissolves naturally in seawater. However, its solubility depends strongly on temperature: its solubility decreases as seawater temperature increases. Thus, recent warming trends in the World Ocean discussed in section 3 are expected to lead to decreased worldwide oxygen concentrations in the oceans. This can have negative effects on marine life, as it can cause mass species migration or in some cases lead to extinction.

Decreases from 0.1 to 6 $\mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{yr}^{-1}$ across all basins [1], with decadal variations of ± 2 $\mu\text{mol} \cdot \text{kg}^{-1} \cdot \text{yr}^{-1}$. Moreover, at depths less than 100 m (which affects all coastal marine life), decadal variations were somewhat smaller, at about $\pm 0.5\ \mu\mathrm{mol} \cdot \mathrm{kg}^{-1} \cdot \mathrm{yr}^{-1}$ from 1956 to 1998. Interestingly, the report does *not* attribute these changes to density changes (in effect, changes to temperature and/or salinity). Rather, changes to *local* circulation patterns (from increased levels of anthropogenic CFCs), changes in biological activity, and transport from colder, deeper water are cited in [1] as the more likely culprits. Overall, however, these decreasing concentration trends appear to be quite weak, and with much uncertainty [1].

A clearer picture emerges for global sea level trends. This is because density changes (leading to thermal expansion) are cited as the dominant influence on mean sea level changes [1]. According to a 2002 Antonov et al. study, about 90% of the sea level rise comes from thermal expansion (from increases in temperature), while the other 10% comes from decreases in salinity [1].[6]

Although subject to local and temporal variability, mean sea level has risen in most locations [1]. Results of various studies on globally averaged mean sea level rise are tabulated in Table 2. Results range from $0.33\ \mathrm{mm} \cdot \mathrm{yr}^{-1}$ to $0.40\ \mathrm{mm} \cdot \mathrm{yr}^{-1}$ for long-term studies covering the previous forty to fifty years, while much higher rates are quoted for more recent time periods. It is possible that these data may be underestimates, because of a lack of data in the SH, especially for earlier dates [1].

On regional spatial scales, sea level may rise or fall at several times the rates listed in Table 2. There are several reasons for this. One is that in some regions, changes in salinity play a larger role than in others.[7] The example cited in [1] is the Labrador Sea (near the Atlantic Subpolar Gyre), where the waters have cooled and freshened throughout the water column. In this region, the density has changed little during the past fifty years, since the effect of the temperature drop nearly cancels the effect of the freshening. Other reasons are ENSO, NAO, and PDO, which account for much of the temporal variability, at both interannual (ENSO) and decadal (NAO, PDO) time scales [1].[8] Therefore, it is not clear whether the increased rates of sea level rise in most regions during 1993–2003 are the result of the positive NAO and PDO phases or part of a long-term trend [1].

[6] The figure for thermal expansion includes cryospheric effects such as ice sheet melting in Greenland and Antarctica. However, the effect is substantially lessened by mixing [1].

[7] Salinity changes do not influence sea level rise on a global scale [1].

[8] One reason why sea level has dropped in some locations was discussed in class: glacial melting reduces the weight load on the land, which causes the land to rise, causing local mean sea level to drop relative to the observer. This phenomenon was not, to the author's knowledge, discussed in any reference studied here.

Study	Sea level rise ($mm \cdot yr^{-1}$)	Time Period	Depth range (m)
Antonov et al. (2005)	0.40 ± 0.09	1955–1998	0–3000
Antonov et al. (2005)	0.33 ± 0.07	1955–2003	0–700
Ishii et al. (2006)	0.36 ± 0.06	1955–2003	0–700
Antonov et al. (2005)	1.2 ± 0.5	1993–2003	0–700
Ishii et al. (2006)	1.2 ± 0.5	1993–2003	0–700
Willis et al. (2004)	1.6 ± 0.5	1993–2003	0–700
Lombard et al. (2006)	1.8 ± 0.4	1993–2003	0–700

Table 2: Globally-averaged mean sea level trends. Table reproduced from [1].

6 Conclusions

Changes in global oceanic heat content, seawater temperature, and salinity play an important role in overall global climate change. As the ocean is the largest component of the global climate system, changes to physical properties of seawater must not be taken lightly; although the observed gains in heat content and temperature seem quite small, the effects on the global climate system can be gigantic, simply because of the large specific heat capacity of seawater and the sheer size of the World Ocean.

All trends in heat content, temperature, and salinity are subject to much uncertainty stemming from variability on short and long time scales because of the effects of ENSO, NAO, NMO, and PDO, as well as seasonal effects; see, for example, [1, 2, 5, 6]. This underscores the need for uncertainty quantification, the techniques of which are discussed in detail in [6] for the case of heat content; uncertainty that is too large prevents accurate determination of long-term trends for any quantity. Natural variability demonstrates the importance of the measurement techniques too. Although data in [1] for sea level trends was gathered using measurements from both tidal gauges and satellite altimetry, the former method is subject to bias caused by land movement through plate tectonics, while the latter technique is subject to instrumental errors.

Finally, it is made clear in [1, 3, 4] that anthropogenic forcing from increased atmospheric GHG levels is partially responsible for the observed rises in oceanic heat content and temperature on the global scale. It is shown that these changes are unnatural, and could not have happened by chance. Two lessons should be learned from this. The first is that all current and future GCMs should satisfy the so-called ocean constraint: any climate model that cannot accurately reproduce observed changes in ocean heat content and/or temperature cannot be correct, and should not be relied upon [4]. The second, perhaps more important, is that both natural and human-induced changes can and do affect the state of the World Ocean: any changes, even seemingly small ones, to any part of the oceans will have an enormous effect on the future of the Earth's climate, and could ultimately determine the future and survival of the human species.

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