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

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Outline

The World Ocean

- It is the largest component of global climate system (recall that the cryosphere is the second largest), and has the largest heat capacity of any component [1, 6].
- It covers approximately 70% of the Earth's surface.
- Half of the human population lives within 100 km of the coast; two-thirds within 400 km.
- It affects global precipitation, wind fields, jet streams, and storm tracks (including those of hurricanes and tropical cyclones) [1].
- Salinity affects the polar ice cap extent [1].

Causes of Oceanic Climate Variability

- Natural
  - North Atlantic Oscillation (NAO)
  - Pacific Decadal Oscillation (PDO)
  - El Niño-Southern Oscillation (ENSO)
  - Volcanic activity
  - Ice sheet melting
  - Very low frequency forcings which occur on time scales of several hundred to a thousand years [4]
- Anthropogenic
  - Increases in CO_2, CFCs, and other GHGs in the atmosphere affect the ocean through surface layer mixing [1, 3, 4].

More about NAO and PDO

NAO: Bidecadal-scale air pressure oscillation in which high/low pressure centers over Iceland and the Azores vary in strength. NAO shifted to a positive phase during the late 1970s.

PDO: Quasi-bidecadal oscillation in Pacific water temperatures. During a positive phase, eastern Pacific waters warm while western waters cool. PDO shifted to a positive phase during the late 1970s. PDO and NAO are highly correlated [1].

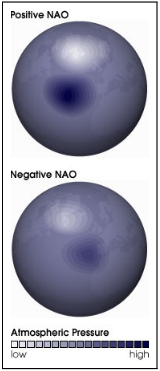

Image courtesy Wikipedia.

NAO at Work

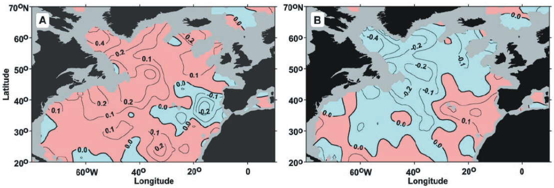

Figure: Temperature difference (in °C) at 1750 m for the North Atlantic for (a) 1970–74 minus 1955–59 and (b) 1988–92 minus 1970–74. Figure taken from [2].

Notice: During a negative NAO phase (e.g. before the late 1970s), much of the North Atlantic warms. The opposite occurs during a positive NAO phase. Temperature changes are most pronounced in the North Atlantic Subpolar Gyre [1, 2].

Outline

1. Brief Introduction
2. Quantifying Heat Content
3. Consequences of Temperature and Salinity Changes
4. Conclusions (and Questions!)

Calculating Changes in Heat Content

The total heat content Q (J) of a substance contained in some volume V can be expressed as

$$Q = \int_V \rho c_p T \, dV,$$

where ρ is the density ($\mathrm{kg} \cdot \mathrm{m}^{-3}$) of the material, c_p is the specific heat capacity at constant pressure ($\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot {}^\circ \mathrm{C}^{-1}$), and T is the temperature (${}^\circ$C).

Since we wish to explore changes in heat content, we must calculate

$$\Delta Q = \int_V \rho c_p \Delta T \, dV.$$

Estimate of ΔQ

As a first-order estimate of ΔQ on a global scale from 1955 to 1996, take

- $\rho = 1027 \text{ kg} \cdot \text{m}^{-3}$ from [8],
- $c_p = 4184 \text{ J} \cdot \text{kg}^{-1} \cdot^\circ \text{C}^{-1}$ from [7],
- $\Delta T = 0.10\ ^\circ\text{C}$ from [1][1], and
- $V = 1.3703 \times 10^{18} \text{ m}^3$ from [8].

Then

$$\Delta Q \approx 5.89 \times 10^{23} \text{ J},$$

which has the same order of magnitude as the Levitus et al. [2] value of 1.82×10^{23} J.

[1] This value is valid only from 1961 to 2003, but will be used here for simplicity.

Oceanic and Global Heat Content

Climate system component	Time period of change	ΔQ (J)
World Ocean	1955–1996	1.82×10^{23}
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: A comparison of the contributions of various global climate system components to changes in global heat content. Table taken from [3] and slightly modified.

Notice that the contribution from the World Ocean *dominates* that from all other climate system components. This is not surprising since

$$c_{p,\text{sea}} \approx 4.2 c_{p,\text{air}} \qquad \text{and} \qquad \rho_{\text{sea}} \approx 850 \rho_{\text{air}}.$$

Spatial Variability of Temperature Changes

Our estimate of ΔQ was crude because spatial (and temporal) variability in ΔT and ρ (more on this later) was neglected. Temperatures (and thus heat content) change on gyre scales:

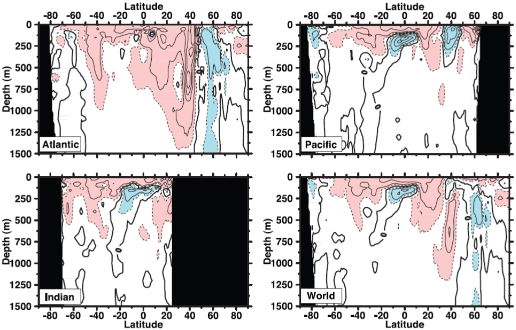

Figure: Longitudinally-averaged temperature anomalies. Red areas indicate warming; blue areas, cooling. Figure taken from [1].

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Equation of State

The following relationship between the density of seawater, temperature, salinity, and pressure holds:

$$\rho(S, T, p) \approx 1027 - 0.15(T - 10) + 0.78(S - 35) + 0.045.$$

This is the equation of state (vastly simplified...the *real* equation of state contains 15 terms!) [8]. Notice that there is no dependence on pressure, since seawater is nearly incompressible. In the equation,

- T is temperature (in $^\circ$C),
- S is salinity (‰), and
- p is pressure (decibar), taken as 10 decibar.

Effects of Temperature and Salinity Changes

- Notice that

$$\frac{\partial \rho}{\partial T} = -0.15 \qquad \text{and} \qquad \frac{\partial \rho}{\partial S} = 0.78.$$

- So, an *increase* in ocean temperature will *decrease* the seawater density (not surprising...thermal expansion!), and salinification will *increase* the seawater density.
- Thus, a decrease in seawater density contributes heavily to sea level rise.
- Changes in salinity can either magnify or mitigate the effects of sea level rise from temperature changes alone. Since much of the World Ocean is freshening, sea level rise is expected to be magnified [1].
- The total change in density is

$$\Delta \rho = \frac{\partial \rho}{\partial T} \Delta T + \frac{\partial \rho}{\partial S} \Delta S.$$

Estimate of Global Sea Level Rise

Using globally averaged ΔT and ΔS from [1], we can (crudely) estimate global sea level rise.

- According to [1], ocean temperatures rose 0.1°C on average from 1961 to 2003, so

$$\Delta T = 0.0023°\text{C} \cdot \text{yr}^{-1}.$$

- Most of the World Ocean is freshening [1, 5]. Using the figure below from [5], take

$$\Delta S = -0.0005 \text{ ‰} \cdot \text{yr}^{-1}.$$

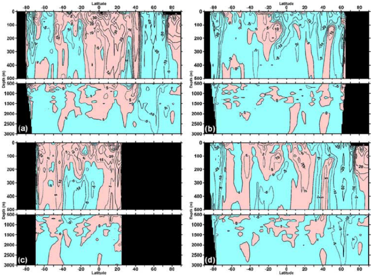

Figure: Longitudinally-averaged linear trends in salinity from 1955–59 through 1994–98 for (a) the Atlantic, (b) the Pacific, (c) the Indian, and (d) the World Ocean. Figure taken from [5].

Estimate of Global Sea Level Rise

- Using these values of ΔT and ΔS,

$$\Delta\rho = -7.35 \times 10^{-4}\ \mathrm{kg} \cdot \mathrm{m}^{-3} \cdot \mathrm{yr}^{-1}.$$

- From conservation of mass,

$$\Delta V = -\frac{V\Delta\rho}{\rho} = 9.807 \times 10^{11}\ \mathrm{m}^3 \cdot \mathrm{yr}^{-1}.$$

- Dividing by the total area of the World Ocean (about $3.61 \times 10^{14}\ \mathrm{m}^2$), global sea level rise is estimated as $2.7\ \mathrm{mm} \cdot \mathrm{yr}^{-1}$.
- The IPCC AR4 [1] quotes a value of $1.8 \pm 0.5\ \mathrm{mm} \cdot \mathrm{yr}^{-1}$ for 1961 to 2003, slightly lower than our estimate (but still pretty close!).

Outline

Conclusions

- The World Ocean is the largest climate system component, so all GCMs *must* model oceanic temperature and heat content anomalies correctly (otherwise the model is wrong!) [1, 4].
- Natural forcings such as NAO, PDO, and ENSO have a tremendous effect on global ocean temperature variability (large drop in temperature around 1980, large "spike" in the mid- to late 1990s) [1, 2, 6]. Anthropogenic forcing very likely contributes to recent temperature, salinity, and thus heat content and sea level trends [1, 3, 4].
- From estimating ΔQ, a 1°C increase in global ocean temperature has almost 3600 times the effect on global heat content as a 1°C air temperature increase.
- Changes in salinity can magnify or mitigate sea level rise in a particular location, so trends in salinity must be taken into account! [1, 5]

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