Hydrographic signatures of thermohaline circulation change: review of some recent results

Curry et al 2003
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Gruber 2004
The question I think I was asked to answer: is the THC changing? (and hint, hint, what is the IPCC going to say on this?)

The question I’d prefer to ask: does the N. Atlantic THC matter?

And…what else might matter besides the N. Atlantic THC and how are these other regions changing?

Framework: Natural variability vs. anthropogenic climate change

Attribution
Workshop survey

- Do you think the THC is changing?
- What do you think is changing about it?
- Do you think it’s in imminent danger of collapse?
- Do you think a collapse matters?
What if the THC collapses?

• This question is almost always posed in terms of the N. Atlantic THC (only)
• Why?
  – Because we are biased to the northern hemisphere and to N. America/Europe?
• Because the time scales and rates of THC ventilation are shortest and largest here, with the greatest potential impact on SST
• But we really mustn’t forget the southern hemisphere and possibly greater impacts of other ocean modes/forcings on SST
• And THC collapse might just be (an important) symptom of the changing climate rather than a primary driver??
• Hydrography:
  – Temperature, heat flux and transport
  – Salinity, freshwater flux and transport
  – Anthropogenic tracers: CFCs and ACO2
• Observed global changes and attribution
• Regional changes (attribution difficult)
  – Defining the thermohaline circulation
  – N. Atlantic/Nordic Seas
  – Pacific
  – Indian and Southern Oceans
• Non-confidential draft findings for this small portion of the IPCC, on regional and N. Atlantic THC changes
Hydrography

Research Ships: full suites of tracers from water sampling bottles

Expendable bathythermograph (from any ship)

Rosette water sampler and CTD

Expendable or free-floating profilers - T, S, (O2), upper ocean only, but great coverage

Profiling floats - global array
Ocean temperature structure

Southern Ocean THC

Atlantic

N. Atlantic THC

Pacific
Temperature structure - what sets it?

Heating and cooling at the sea surface, mixing, and transport of heat from heating to cooling regions.
Salinity

Surface salinity:
Orange high
Blue low

Salinity at 1500 meters: maximum depth of most “deep” convection
(same color scale)
Atlantic layering- salinity

High salinity
North Atlantic waters

Low salinity
Antarctic intermediate and bottom waters
Salinity structure: what sets it? evaporation and precipitation and freshwater transports

Net evaporation-precipitation (red evaporates, blue freshens) (NCEP climatology)
Tracers of anthropogenic influence: where can the ocean respond most directly to changing surface fluxes?

Chlorofluorocarbon inventory: since the 1950s. Most ventilation is at mid to high latitudes, peaks in N. Atlantic

(Willey et al GRL 2004)
Tracers of anthropogenic influence: chlorofluorocarbons in the Pacific

Deep penetration in Southern Ocean.

(N. hemisphere data is of lower quality than similar sections: inexperien ced group)
Tracers of anthropogenic influence: anthropogenic component of dissolved CO$_2$
Ventilation at mid to high latitudes, N. Atlantic hotspot

(Sabine et al Science 2004)
Anthropogenic CO2 (Sabine et al 2004)

Deep penetration in N. Atlantic and Southern Ocean.
- Mid-depth penetration the subantarctic mode waters (southern hemisphere)
Anthropogenic climate change thoughts

• Hypothesis: ACC projects on the natural modes in addition to creating its own pattern.
• (consider a pebble thrown in a pond)
• Natural modes from instrumental record:
  – ENSO, monsoon
  – Decadal are relatively well described: NAO, PDO, NAM, SAM, IDM, etc.
  – Centennial and longer not well determined: AMO has recently been described
• Anthropogenic warming would be evidenced in the part of the water column highlighted by anthropogenic tracers (CFCs, ACO2)
Ocean T/S changes and attribution

- Levitus, Boyer, Garcia results (presented just before this by Hernan Garcia)
- Very large-scale patterns of temperature and salinity change indicate net warming, net salinification of Atlantic and Indian, net freshening of Pacific
- Details of changes - spatial patterns suggestive of natural modes of variability (NAO, PDO, ENSO)
Observed global changes that might be anthropogenic
(presented by H. Garcia)

Ocean heat uptake 0-3 km (1955-1998) = 14.5 x 10^{22} J (~ 0.04°C)

0.037°C warming (0-3000 m)

<table>
<thead>
<tr>
<th>Ocean Layer</th>
<th>Heat Content Linear Trend [x10^{22} J/year]</th>
<th>Heat Storage [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-300 m layer (1955-2003) [Yearly composites]</td>
<td>0.143</td>
<td>0.131</td>
</tr>
<tr>
<td>0-700 m layer (1955-2003) [Yearly composites]</td>
<td>0.228</td>
<td>0.209</td>
</tr>
<tr>
<td>0-3000 m layer (1955/59 to 1994/98) [Pentadal composites]</td>
<td>0.329</td>
<td>0.301</td>
</tr>
</tbody>
</table>

PDO reversal, El Chichón, Mt. Agung
Observed changes: basin-scale temperature
Mostly warming but some cooling (presented by H. Garcia).
Especially note cooling in high latitude Atlantic and Pacific,
tropical Pacific and Indian. Not just noise.

Linear Trend of the *zonally integrated* heat content (x $10^{18}$ J/year) for
100 m thick layers (1955/59 to 1994/98) [Levitus *et al.*, 2005]

![Graphs showing linear trend of zonally integrated heat content for Atlantic, Pacific, Indian, and World oceans.](image-url)
Observed changes: Indian Ocean
(Meyers, personal communication to F. Schott)

Warming since 1970 is greatly accelerated compared with previous 70 years.

Linear Trend in Salinity (x $10^{-4}$ year$^{-1}$) of the zonally averaged pentadal salinity anomaly (1955/59 to 1994/98). Boyer et al., 2005.
Example of attribution of patterns to anthropogenic forcing (Barnett et al. 2005; Pierce et al 2005)

Basin-averaged warming (correlation of observed warming and model fingerprint of warming)

Ensemble with solar/volcanic forcing only.

Ensemble with anthropogenic
Attribution to global warming vs. regional patterns

Model and observation comparisons on ocean basin scales and on global scale indicate that there is an anthropogenic warming signal, at least in the upper ocean (700 m range of data).

So the next question might be whether regional changes can be ascribed to global warming. This is probably too difficult (signal to noise problem) - (D. Pierce, pers. Comm.)

Specifically, the question about N. Atlantic (or other) THC change is a regional question. And there are many other interesting regional changes that don’t have much or anything to do with the Atlantic THC.

Onward to THC and regional patterns...
Thermohaline circulation

- **Broadest definition**: any circulation that is impacted by temperature and salinity change (heating/cooling, evap/precip, diffusion)
- **Broad definition**: any circulation that carries a significant amount of heat (large differences in temperature between inflow and outflow)
- **Moderate definition**: only such circulations that include overturn at very confined locations to intermediate and abyssal depths
- **Narrow definition**: only such circulation that sinks in the northern N. Atlantic/Arctic and in the Antarctic
- **Ridiculously narrow definition**: only such circulation that sinks in the northern N. Atlantic/Arctic
Thermohaline circulation

Atlantic-centric

(ridiculously narrow)


(narrow)
Thermohaline circulation

Cartoon from Schmitz (1996) showing all three oceans and overturn into intermediate as well as deep layers (moderate)
Thermohaline circulation

Deep and bottom water production sites: biggest temperature changes
(narrow THC definition)

Intermediate water production sites: major impacts on salinity
(include in the moderate THC definition)
For observing changes in THC: ocean’s salinity structure is crucial for potential for intermediate and deep overturn.

Density difference from the surface to 1500 meters:

Arrows show largest differences - coincide with deep convection regions.

Density difference if salinity is assumed uniform (i.e. depends on temperature)

Note that N. Pacific, Arctic, much more of Antarctic would overturn.

Creation of fresher surface water compared with deeper waters inhibits overturn. This is a primary focus for concerns about Atlantic THC changes.

Monitoring for any THC (any ocean) changes must include salinity.
Does the THC matter? Does it warm Europe? Compare with N. Pacific which has an extremely weak THC.

Eastern sea surface temperatures and continental temperatures are much closer to each other than the western: this is what led people to suppose that the thermohaline circulation in the N. Atlantic is responsible for warming Europe. But similar SST pattern in the N. Pacific is almost entirely due to wind-driven circulation. Some partial boost from the THC in the N. Atlantic - an (important) couple of °C.
Most N. Pacific heat loss to atmosphere occurs in the Kuroshio; most N. Atlantic in the Gulf Stream.

Seager et al: the relative warmth of Europe/British Columbia in winter compared with Labrador/eastern Russia is due to warming of continental winds when they encounter this Gulf Stream/Kuroshio hot spot, and not due to the relative warmth of the waters in the eastern Atlantic/Pacific.
But winter heat loss is not negligible in the east

120 W/m²
500 W/m²

Sensible heat loss map
Total (winter) heat losses listed; latent is largest, but sensible must be important since the eastern coastal temperatures appear equilibrated to nearly the ocean temperatures.

Latent heat flux
SO, does the ocean matter for European (British Columbian) temperatures?

- Yes.

- Most warming occurs over the Gulf Stream (Kuroshio) (as latent heat exchange), but there is also winter warming all the way across the Atlantic (Pacific).

- Eastern boundary coastal land temperatures are closely aligned with the nearby sea surface temperatures.

- Sensible heat exchange may regulate the temperature after the wind’s initial encounter with the sea (that produces large latent heat loss and also relatively large sensible heat loss).

- Meridional heat transport may be NEARLY irrelevant. However, the ocean temperature distribution of warmer water in the northeast and colder water in the west is absolutely due to the ocean currents.

- But relative importance of THC is debatable since the wind-driven circulation and subtropical ocean heat loss do much of the job.

Drop this here and move on to whether changes have been observed in the N. Atlantic THC ....
N. Atlantic THC: observations to detect changes?

- **Current measurements:**
  - Transport (current) arrays at the deep overflows from the Nordic Seas
  - Transport arrays at 26°N (Baehr talk)
  - Repeat ADCP sections (ferries etc)
  - Surface drifters?? (see next slide)

- **Hydrography:**
  - basin-wide salinity, temperature, oxygen observations
  - From profiling floats, ship observations, satellites and surface drifters for surface values
Surface drifters and the MOC

- One might have hoped that surface drifters would provide useful information about the strength of the surface circulation in terms of the MOC.
- Surface drifters do have an interesting, possibly useful response to the NAO (next slide).
- However, surface drifters do not track the MOC (Brambilla and Talley, submitted).
Observed salinity changes: Atlantic and Nordic Seas
(Curry et al. Nature 2003)
Observed changes:
Freshening of the Atlantic and Nordic Seas
(Dickson et al, Phil Trans Roy Soc 2003)
Observed changes: freshening in the Labrador Sea, formation of cold, fresh LSW in the 1990s (Yashayaev)
N. Atlantic changes: decrease in oxygen at base of the surface layer -> reduction in upper ocean ventilation (concomitant increase in Labrador Sea ventilation) 

(Gruber, 2004; Johnson, 2004; Feely et al 2005)
N. Atlantic oxygen changes: ascribed to high NAO since about 1989, reduced ventilation in the NE Atlantic (Gruber, 2004)
SST pattern for the Arctic Oscillation (or North Atlantic Oscillation or Northern Annular Mode):

High NAO:
- Warm Nordic Seas
- Cool subpolar gyre
- Warm subtropical N. Atlantic
N. Atlantic regional changes: NAO pattern

Levitus et al. (2005) zonally averaged temperature trend

Mid-latitude strong warming and salt increase: Gulf Stream and NAC

Higher latitude cooling and freshening: Labrador Sea
Atlantic summary

• Freshening at high latitudes, salinification in subtropics and low latitudes, reduced oxygen
• Basin-wide net salinity increase (net evaporation increase)
• Increased meridional hydrological cycle: increased trade winds, stronger Icelandic low
• NAO/AO/NAM pattern affects all these regions: Gulf Stream, subpolar gyre, Nordic Seas. Observed changes are consistent with high NAO

Causes? (Curry et al)

• High NAO state can cause this, also can cause the observed temperature and oxygen changes
• Increased evaporation could also be due to simply warming the low latitudes (global warming?)
North Pacific

- PDO strong since about 1976. Strong Aleutian Low strengthens westerlies, changes ocean circulation, and creates cooling/warming patterns:

Adapted from Miller, Chai, Chiba, Moisan and Neilson (J. Oceanogr., 2004)
PDO sea surface temperature pattern (for positive PDO)
Variations in central N. Pacific temperature, salinity and density between 1985 and 2004 (Robbins, pers. comm. 2004)

Changes are consistent with enhanced PDO - surface cooling, subsurface warming (due to stronger Kuroshio); also lots of other similar evidence in time series
Pacific AOU (μmol kg⁻¹) Late 1990s – Mid 1980s

From S. Emerson talk (2005)
AOU has increased and O₂ has decreased particularly north of 40° N

Warmer subpolar surface waters, reduced ventilation

Watanabe et al. (2001)
Ono et al. (2001)
Emerson et al. (2001)
Pacific temperature, salinity and oxygen

Regional patterns:

Changes in temperature, salinity and oxygen are those associated with high PDO (strong Aleutian Low) and enhanced ENSO (slowdown of shallow tropical overturn: McPhaden and Zhang Nature 2002).
Deep Pacific water mass changes: global THC changes?
(Fukasawa et al., Nature 2004)

Repeat hydrography section at 47°N: 1985 to 1999

Warming of deep layer - explanation is slowdown in inflow from South Pacific.
Observed changes: Southern Ocean
(Gille, Science 2002)

Broad warming in southern ocean at about 800 meters

Also note cooling to the north of the warm band
Summary of regional change

- N. Atlantic changes: high NAO plus global warming?
- N. Pacific changes: high PDO (prolonged ENSO state?)

Map on next slide....
Summary of changes over past several decades
(map of E-P da Silva)

Would be useful to subtract basin means to look at spatial patterns in Pacific and Indian
Back to the N. Atlantic THC. What are the freshwater inputs along its path?

- Fresh input from Arctic to NADW/LSW
- Salty input from Mediterranean to NADW
- Fresh input from Antarctic to SAMW/AAIW
- NADW freshens in all three oceans
- Evaporation in Indian and Atlantic -> salty upper ocean input
Northern N. Atlantic freshening: remarkable, deep, prolonged, throughout the subpolar region. Looks bigger than just an extended high NAO? Leads to speculation about THC shutdown.
But global scale changes might suggest counterbalance: Redistribution of freshwater from Atlantic/Indian to Pacific? Exacerbates salinity difference between dense water formation areas and Pacific -> wouldn’t this ultimately pump up the global THC?
Conclusions

• Anthropogenic warming on global scale to about 500-700 m
• Warming especially pronounced in the subtropical upper ocean in all oceans
• Cooling and increased convection in the subpolar N. Atlantic and central N. Pacific
• Saltier upper ocean water masses in subtropics
• Fresher water masses in subpolar and polar regions of both hemispheres
• No evidence of long-term trends in circulation
• No evidence yet of anthropogenic change in THC strength in northern N. Atlantic, but there ARE large changes in freshwater - cannot tell if anthropogenic or natural variability.
• Patterns of warming and cooling suggest some projection on (forcing of?) the natural modes of climate (decadal and possibly millenial)
Questions to grapple with for the N. Atlantic THC

- Would changes in the THC actually affect SST (or ice edges) enough to affect atmosphere?
- Put another way, is heat transport by the THC in the subpolar region large enough to matter? (Wunsch question)
- Put yet another way, how does the THC affect the NAM and NAO?
- The other half of the world is dominated by PDO/ENSO and the SAM. How is it affected by changes in the N. Atlantic THC?
- Is the high latitude freshening attributable to anthropogenic forcing?
- How large does the freshening have to become to significantly affect the THC strength?
- What are the concurrent changes in water masses in the Southern Ocean THC?
PNA North American pattern: suggesting a connection to the Southern Ocean

Pacific North American pattern correlated with sea level pressure: associated with Southern Ocean??

North Atlantic Oscillation pattern correlated with sea level pressure: associated with Arctic (well known)
Observed changes: Southern Ocean
(Bindoff, personal communication)