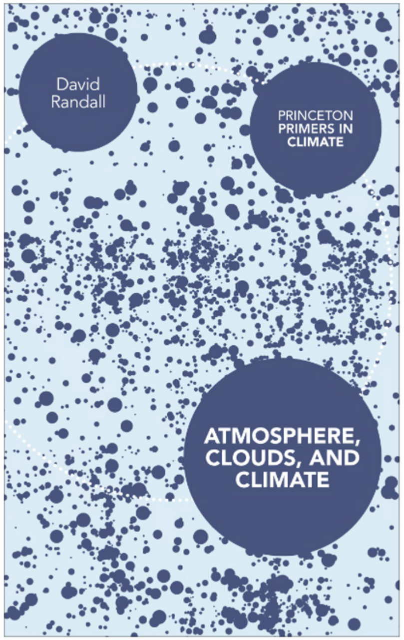
*Atmosphere, Clouds, and Climate*: Chapters 8 & 9

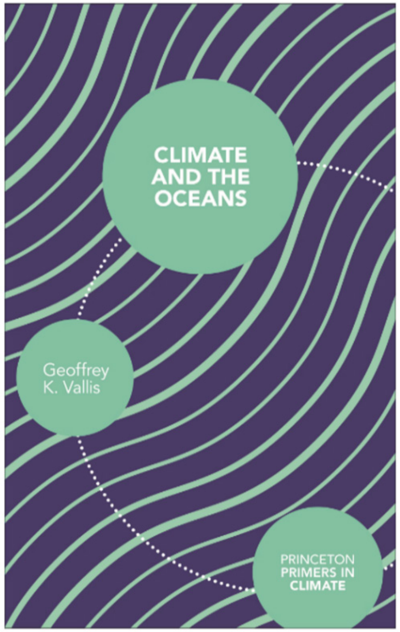
*Climate and the Oceans*: Chapter 2

# AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2024
https://umd.instructure.com/courses/1367293

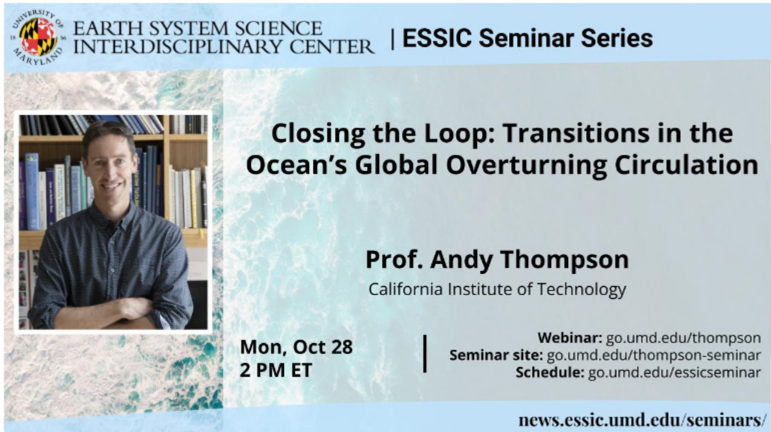



**Lecture 13**

**22 October 2024**

# Announcement 1




**Prof. Andy Thompson**
**California Institute of Technology**
**Monday October 28, 2024, 2 PM ET**

**Abstract:**

The ocean's global overturning circulation connects surface and abyssal waters and thus plays a prominent role in Earth's climate through its regulation of heat and carbon storage. The overturning circulation also exists to deliver water from regions of buoyancy gain, largely at the low latitudes, to regions of buoyancy loss in polar regions. This characteristic, combined with the geometry of the ocean basins, places important constraints on the structure of the overturning circulation for given climate and surface forcing conditions. In this talk, I will discuss the physical processes that control the transient adjustment of the ocean's overturning circulation to surface forcing perturbations over decadal to multi-millennial time scales. A collection of millennial-length GCM simulations is first used to examine the response of the Atlantic meridional overturning circulation (AMOC) to an abrupt quadrupling of atmospheric carbon dioxide. An AMOC weakening or collapse is consistently simulated during the first century in these models, but they exhibit diverse behaviors over longer time scales, showing different recovery levels over a range of timescales. This recovery time scale is shown to sensitively depend on model representations of sea ice and the hydrological cycle. On shorter, centennial, timescales the global ocean response to a perturbation in the AMOC is described, which includes a subsurface warming of the Indo-Pacific basins and a global reduction in upper-ocean nutrient concentrations. Across all of these scales, the three dimensional nature of the circulation as well as dynamical differences between Atlantic, Indo-Pacific and Southern Oceans exert a strong influence on overturning transitions.

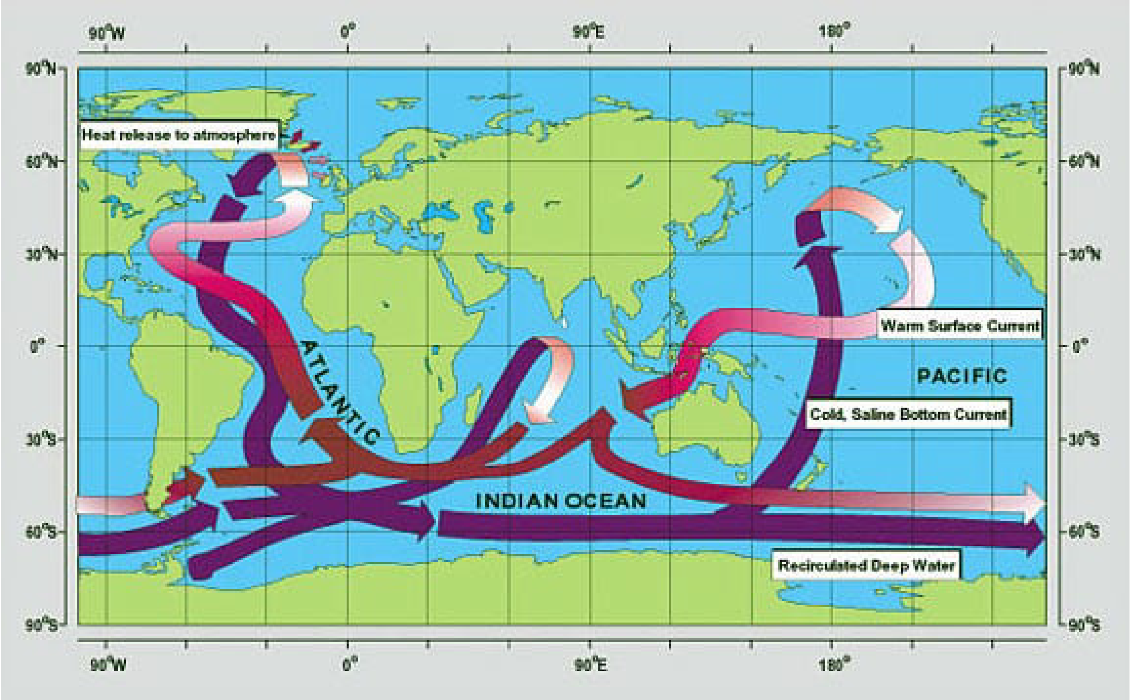
https://essic.umd.edu/events/closing-the-loop-transitions-in-the-oceans-global-overturning-circulation/

# Climate And The Oceans

**2** THE OCEANS:
A DESCRIPTIVE OVERVIEW

There is a sense in which all explanations are really descriptions; what we may think of as an explanation is really a description at a more general level. Nevertheless, the distinction is useful, at least in science: an explanation does not just describe the phenomenon at hand but also provides some more fundamental reason for its properties, and ideally for the properties of a whole class of phenomena. Descriptions are useful because they are the precursor of explanation, and in this chapter our modest goal is to provide a brief descriptive overview of the oceans and their large-scale circulation, focusing on matters that significantly affect climate.

# Ocean Heat Transport

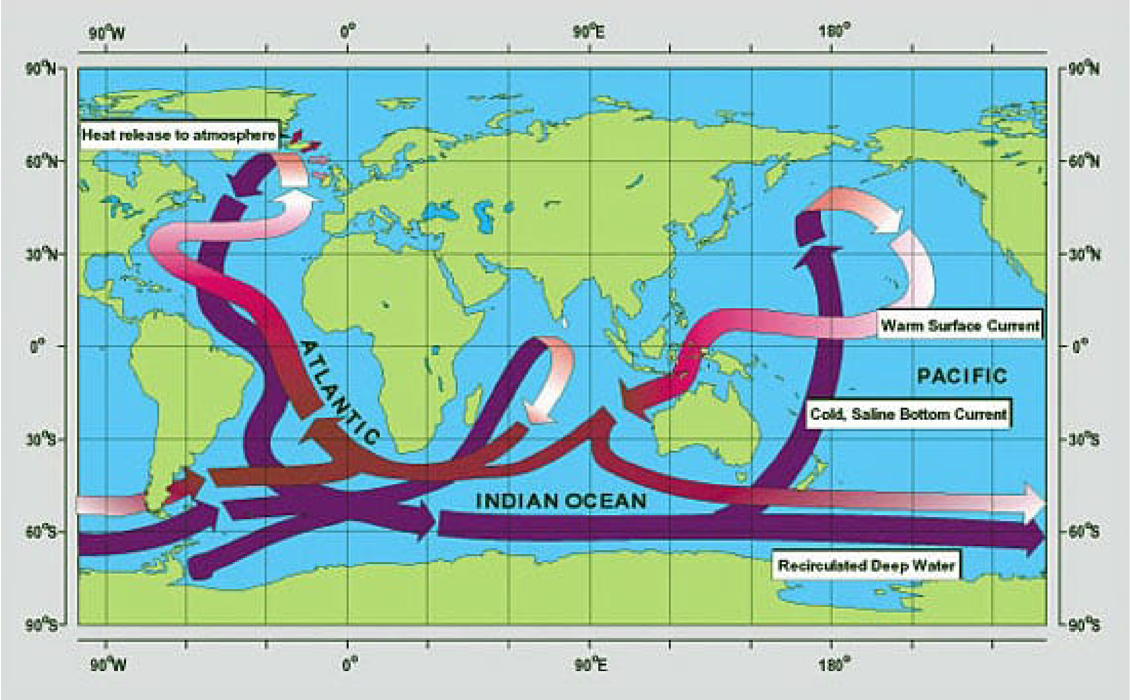



https://www.whoi.edu/oceanus/feature/the-once-and-future-circulation-of-the-ocean

In North Atlantic, cold surface waters sink to the abyss, and salty, warm surface and near-surface currents, including the Gulf Stream, flow northward from the tropics to replace them. When the warm waters reach high latitudes, they release heat to the atmosphere and warm the region. The waters become colder and less buoyant. They sink to continue this grand ocean overturning, which is approximately equal to 20 times the combined flow of all the world's rivers.

This overturning circulation carries a tremendous amount of heat northward, while also generating a huge volume of cold, salty water—which we call North Atlantic Deep Water. After descending, this great mass of water flows southward, filling up the deep Atlantic Ocean basin and eventually spreading into the deep Indian and Pacific Oceans.

# Ocean Heat Transport



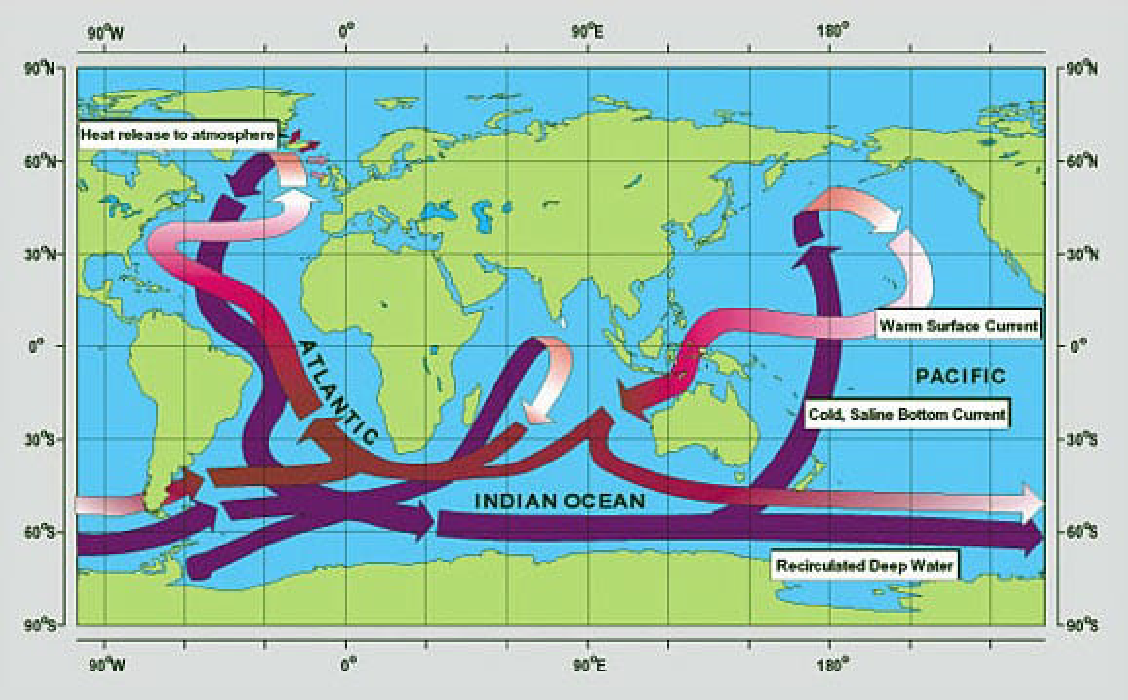

We and other paleoceanographers have found evidence for very different patterns of ocean circulation in the past. This evidence come from clues that are preserved in sediments deposited on the seafloor over tens of thousands of years. The sediments contain fossilized shells of foraminifera—ocean-bottom-dwelling, single-celled organisms the size of sand grains. The shells contain differences in trace elements and carbon isotopes, which reflect different seawater conditions at the times when the foraminifera were alive and growing.

The foraminifera analyses showed us where and when different types of water masses formed in the past. Water masses similar to today's North Atlantic Deep Water seemed to have intensified and diminished in the past—sometimes sinking deeply and spreading to fill the North Atlantic basin and beyond, and sometimes sinking only to intermediate depths and spreading to a far lesser extent.

The carbon isotopes and trace elements, however, don't provide information on how fast or how vigorously these different water masses circulated. To investigate that, we used a different set of clues preserved in deep-sea mud, based on the "clock" inherent in the radioactive decay of naturally occurring **uranium** in seawater to its daughter isotopes, **protactinium** and **thorium**.

https://www.whoi.edu/oceanus/feature/the-once-and-future-circulation-of-the-ocean

# Ocean Heat Transport




Both chemically adhere to particles in the ocean that sink to the seafloor. Thorium is inherently "stickier;" however, so it is removed from seawater within decades, while protactinium remains in seawater for centuries.

As a result, about half of the **protactinium** produced in North Atlantic water today lasts long enough in the water column to be exported into the Southern Ocean by the ocean's overturning system. At times when the rate of overturning circulation slows, the proportion of protactinium buried in North Atlantic sediments increases. Thus, **the ratio of protactinium-to-thorium levels in the sediments tells the story of past changes in how fast North Atlantic Deep Water was produced and exported by the overturning circulation**.

When we compared ocean circulation records to records of climate since the peak of the last ice age 20,000 years ago, we confirmed that the rate of ocean overturning, with its northward heat transport, has a critical influence on climate. When North Atlantic Deep Water filled the deep ocean and spread southward vigorously, the climate of the North Atlantic region was warm and generally stable. When North Atlantic Deep Water filled less of the Atlantic and did not spread southward extensively, the climate was generally cold and more variable.

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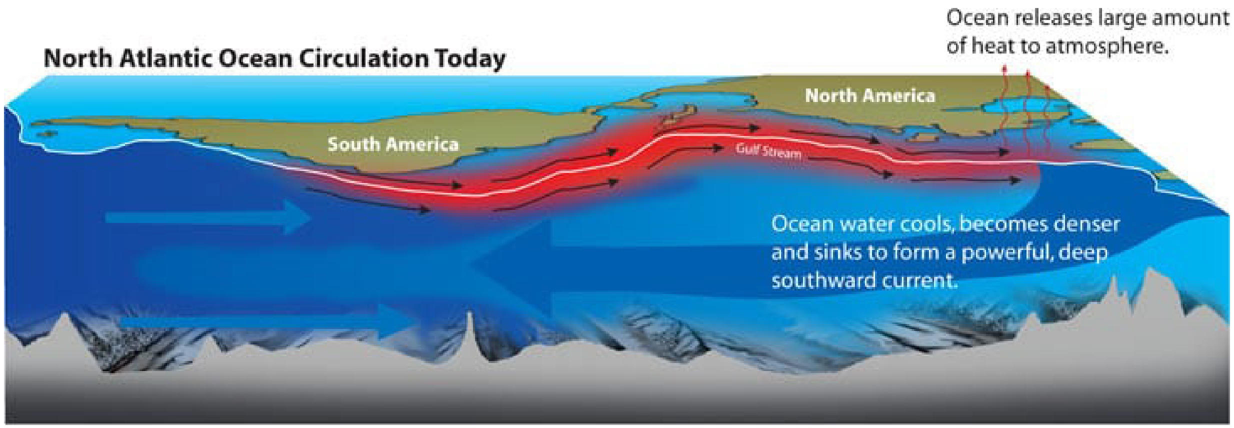
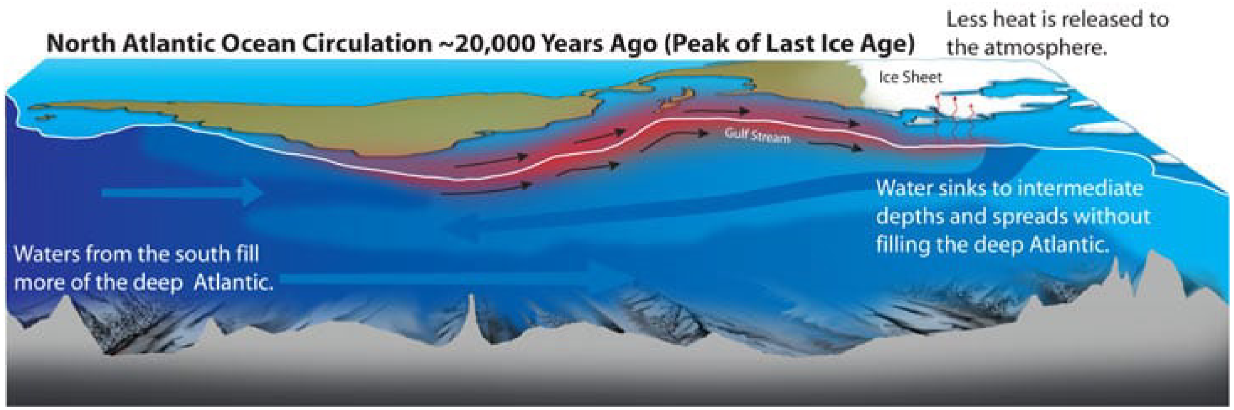
# Ocean Heat Transport




Today (top), the ocean's overturning circulation carries a tremendous amount of heat northward, warming the North Atlantic region. It also generates a huge volume of cold, salty water called North Atlantic Deep Water—a great mass of water that flows southward, filling up the deep Atlantic Ocean basin and eventually spreading into the deep Indian and Pacific Oceans.

Paleoceanographers have found evidence for very different patterns of ocean circulation in the past. About 20,000 years ago (bottom), waters in the North Atlantic sank only to intermediate depths and spread to a far lesser extent. When that occurred, the climate in the North Atlantic region was generally cold and more variable. (Illustration by E. Paul Oberlander, Woods Hole Oceanographic Institution)

https://www.whoi.edu/oceanus/feature/the-once-and-future-circulation-of-the-ocean

# GEOSECS (Geochemical Ocean Sections Study)

478 LETTERS TO NATURE NATURE VOL. 315 6 JUNE 1985

## Direct evidence using tritium data for throughflow from the Pacific into the Indian Ocean

**Rana A. Fine**

Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33149, USA

**Basin-wide exchange between the Pacific and Indian oceans through the Indonesian Archipelago has received attention, both in relation to the oceans' role in the Southern Oscillation[1] and in efforts to balance the salt and mass fluxes of the individual basins[2–5]. Wyrtki[6] made the first indirect estimate using hydrographic data of a mean annual transport from the Pacific to the Indian Ocean of $2\times10^6\ m^3\ s^{-1}$ in the upper 200 m. Recent estimates have been considerably higher: $14\times10^6\ m^3\ s^{-1}$ by Piola and Gordon[2], $10\times10^6\ m^3\ s^{-1}$ by Godfrey and Golding[5], and $5\times10^6\ m^3\ s^{-1}$ by Godfrey and Ridgeway[3]. However, Wunsch *et al.*[4] concluded that, as a result of inverse calculations on sections across the South Pacific, there was a negligible throughflow transport. A meridional maximum in bomb-produced tritium (half-life 12.4 yr) observed in the South Equatorial Current (SEC) of the Indian Ocean is used here to show direct evidence that in the mean there is a net transport (in the upper 300 m) of $5\times10^6\ m^3\ s^{-1}$ from the Pacific into the Indian Ocean.**

The use of bomb tritium, which is found in the oceans in the form of HTO, has become increasingly popular[7–9] as a conservative tracer for oceanic circulation processes with decadal time scales. Decay-corrected tritium data collected during the Geochemical Ocean Sections (GEOSECS) Expeditions[10] are anomalously higher in the South Indian than either the South Atlantic or South Pacific oceans. The presence of the Indian subcontinent at 25° N rules out a North Indian Ocean source, the asymmetric fallout pattern[11,12] rules out a Southern Hemisphere source.

The box model calculation[20] assumes that mass and chemical balances within the box are entirely consistent with pure advection. The first-order physics are:

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{\partial C}{\partial t}-\lambda(C) \qquad (1)$$

where according to convention $u$ is the advection in the east $(x)$/west direction, $v$ is the advection in the north $(y)$/south direction, $C$ is the concentration, $t$ is time, and $\lambda$ is the decay term for tritium. If equation (1) is integrated over the volume $(V)$ of the box then:

$$C_N v_N A_N + C_S v_S A_S + C_E u_E A_E = \frac{\Delta C}{\Delta t}V - \lambda C V \qquad (2)$$

where the $C_i$s represent the average concentrations and the $A_i$s represent the areas along the boundaries of the box. Table 1 gives the actual values for $C_i$s which were obtained by integrating the data[10,19] observed along the boundaries of the box. Equation (2) is written for volume, salinity, temperature and tritium, giving a total of four equations and three unknowns. Using a least squares regression it may be solved for the advective velocities: $v_N$, $v_S$ and $u_E$.

https://www.nature.com/articles/315478a0.pdf?platform=hootsuite

# Rana Fine

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|---|---|
| **Institutions** | University of Miami's Rosenstiel School of Marine and Atmospheric Science |
| **Thesis** | *"High Pressure P-V-T Properties Of Seawater And Related Liquids"* (1975) |
| **Doctoral advisor** | Frank Millero |

## Early life and education [ edit ]

Fine was born April 17, 1944 in New York City to Joseph and Etta (née Kreisman) Arnold.[1] Fine credits her attendance at the Bronx High School of Science for starting her on a career path with science and mathematics.[2]

Fine has a B.A. in mathematics from New York University and a M.A. in mathematics from the University of Miami. She completed her Ph.D. in physical oceanography from the University of Miami's Rosenstiel School of Marine and Atmospheric Science in 1975. Her dissertation was *High Pressure P-V-T Properties Of Seawater And Related Liquids* with Frank Millero serving as her advisor and committee chair.[3]

Upon completing her Ph.D., Fine continued on with the University of Miami's Rosenstiel School in a one-year postdoctoral position in the Tritium Laboratory from 1976-1977.[1][2] She remained was an assistant professor (1977-1980), research associate professor (1980-1984), and associate professor (1984-1990). In 1990, she was promoted to full professor and chair of the University of Miami's Department of Marine and Atmospheric Chemistry.[1]

Fine's research uses measurements of chemicals in the oceans to improve our understanding of the transfer of gases fro the atmosphere to the oceans. Tracers, such as chlorofluorocarbons and sulfur hexafluoride ($SF_6$), have been used to determine a range of oceanic properties, including ocean transport and rates of biogeochemical processes.[2] Fine has secured grant funding to support her research from the National Science Foundation, Office of Naval Research, National Oceanic and Atmospheric Administration, and NASA.[1]

Fine has been active in encouraging and mentoring women to enter the field of physical oceanography. In her biography for The Oceanography Society's *Women in Oceanography: A Decade Later*, she mentions how during her time at the National Science Foundation in the early 1980s, "I was one of only four women considered to be physical oceanographers at academic institutions in the United States." She credits programs such as Mentoring Physical Oceanography Women to Increase Retention (MPOWIR) for increasing the number of women in the geosciences and ocean sciences.[7]

https://en.wikipedia.org/wiki/Rana_Fine
https://aquarius.oceansciences.org/cgi/peo_teams.htm?id=science

# Deep Ocean Temperature

## An empirical model of global climate – Part 2: Implications for future temperature

**N. R. Mascioli[1], T. Canty[1], and R. J. Salawitch[1,2,3]**

[1]Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD
[2]Department of Chemistry and Biochemistry, University of Maryland, College Park, MD
[3]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD

The export of heat to levels of the ocean below 700 m, hereafter the deep ocean, is the source of considerable uncertainty (e.g. Hansen et al., 2011). The associated temperature rise is very small given the mass of the deep ocean, so a long time series of stable temperature measurements is needed to define the rise in OHC of the deep ocean. Section 5.2.2.3 of IPCC (2007) states the rise in OHC, between 1961 and 2003, "accounts for more than 90 % of the possible increase in heat content of the Earth system". If so, considerable heat must be exported from the upper ocean to the deep ocean, because none of the measurements of OHC between 0 and 700 m depth show OHE anywhere close to 90 % of the atmospheric radiative perturbation (i.e. Carton and Santorelli, 2008). Hansen et al. (2011) state "most climate models mix heat too efficiently into the deep ocean" and point to measurements of OHC in the abyssal ocean (Purkey and Johnson, 2010) as evidence for this improper characteristic of GCMs.

Figure 17 is designed to show that if GCMs are indeed placing too much heat into the deep ocean and if the export of heat is a constant fraction of the anthropogenic RF of climate, then the primary consequence will be erroneous determination of equilibrium climate sensitivity. The projection of future $\Delta T$ from GCMs could be unaffected, provided feedbacks are allowed to adjust such that the past climate record is still matched.

https://acp.copernicus.org/preprints/12/23913/2012/acpd-12-23913-2012.pdf

# Deep Ocean Temperature

Climate sensitivity, denoted $\Delta T_{2\times CO_2}$, is defined as “the global annual mean surface air temperature change experienced by the climate system after it has attained a new equilibrium in response to a doubling of atmospheric $CO_2$” (Sect. 8.6.2.1 of IPCC, 2007). In our notation, $\Delta T_{2\times CO_2}$ is expressed as:

$$\Delta T_{2\times CO_2} = \lambda(1+\gamma)5.35\ln\left(\frac{CO_2^{FINAL}}{CO_2^{INITIAL}}\right) \quad (9)$$

where $CO_2^{FINAL} = 2 \times CO_2^{INITIAL}$ and the logarithmic dependence of the $CO_2$ RF is the IPCC (2007) expression originally published by Myhre et al. (1998).

Evaluating Eq. (9) for Models 3 and 4 yields climate sensitivities of 1.50 °C and 1.77 °C, respectively. As the fraction of heat exported to the ocean rises (i.e. Model 4), the temperature found at the time $CO_2$ doubles (year 2053) lies further from equilibrium. Of course, $\Delta T_{2053}$ and $\Delta T_{2\times CO_2}$ also differ because $\Delta T_{2053}$ takes into consideration RF perturbation due to GHGs other than $CO_2$ and aerosols, whereas the notional equilibrium climate sensitivity $\Delta T_{2\times CO_2}$ considers only RF from $CO_2$. The difference between $\Delta T_{2\times CO_2}$ for Models 3 and 4, despite nearly identical projections of future $\Delta T$, is a microcosm of the complication endemic in use of $\Delta T_{2\times CO_2}$ to evaluate GCMs.

$\Delta_{T2\times CO2}$ = 1.5°C $\qquad$ $\Delta_{T2\times CO2}$ = 1.8°C

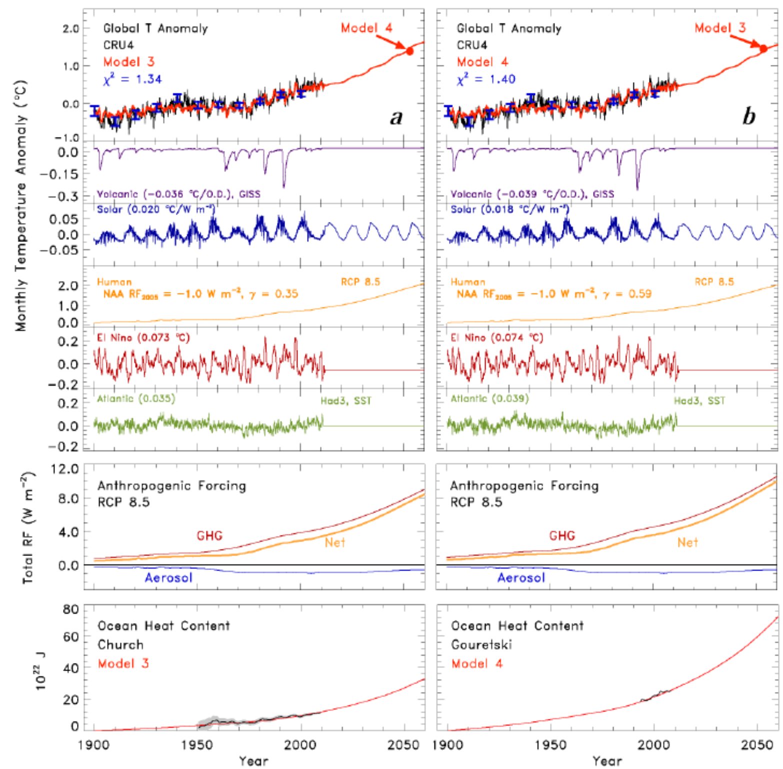


**Fig. 6.** Same as Fig. 5 except for NAA $RF_{2005} = -1.0\,W\,m^{-2}$, the IPCC (2007) best estimate of aerosol cooling. **(a)** Model constrained to match OHC measurement of Church et al. (2011). **(b)** Model constrained to match OHC measurement of Gouretski and Reseghetti (2010).

https://acp.copernicus.org/preprints/12/23913/2012/acpd-12-23913-2012.pdf

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$\Delta_{T2\times CO2}$ = 2.9°C

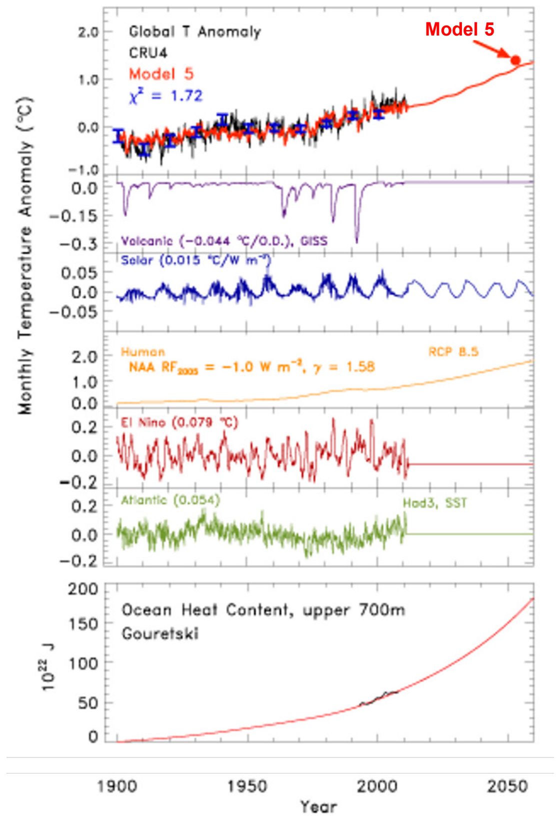


**Fig. 17.** Same as Fig. 6b, except the fraction of anthropogenic RF exported to the ocean, Ω, has been set to 0.72, resulting in a best fit value for $\gamma$ of 1.6 (Model 5). This leads to $\Delta T_{2\times CO_2}$ = 2.9 °C, the IPCC (2007) best estimate of equilibrium climate sensitivity.

https://acp.copernicus.org/preprints/12/23913/2012/acpd-12-23913-2012.pdf