GFDL CLIMATE MODELING RESEARCH HIGHLIGHTS

The National Oceanic and Atmospheric Administration (NOAA)
Geophysical Fluid Dynamics Laboratory (GFDL) - Princeton, NJ

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GREENHOUSE OCEAN WARMING DELAYED BY AEROSOLS

When most people think of global warming, they tend to focus on surface air temperatures. But it is the ocean that is the largest reservoir for storing heat gained by the Earth's climate system. About nine-tenths of the extra heat energy gained by the planet during the second half of the 20th century entered and warmed the ocean and still resides there today [Levitus *et al*., 2001].

Increasing global ocean heat content has implications for both the ocean and the atmosphere. Large scale ocean temperature changes can alter ocean currents and affect global sea level (sea water expands as it warms, contributing to sea level rise). Because heat continually is being exchanged between the ocean and atmosphere, oceanic changes can in turn influence weather and climate.

► Competing effects of aerosols and greenhouse gases

A state-of-the-art computer climate model developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) realistically simulates the observed warming of the global ocean during the late-20th century [Delworth *et al*., 2005] (see figure below), as well as the observed large-scale surface air temperature changes [Knutson, *et al*., 2006]. The success of the model (named GFDL CM2.1) in reproducing observed changes allows the model to be used as a tool to probe the physical factors responsible for the observed ocean warming [Delworth, *et al*., 2005].

The model results (see figure below) reveal that anthropogenic aerosols (airborne pollutant particles produced by human activities, such as burning fuels) likely played a major role in offsetting—at least temporarily—about half of the ocean warming and sea level rise that would have otherwise occurred due to increasing levels of atmospheric greenhouse gases from 1861 to 2000. Cooling due to volcanic aerosols also offset some greenhouse gas-induced ocean warming during this period. The aerosols reflect sunlight back to space, leading to a net cooling of the planet, thereby partially offsetting the warming from increasing greenhouse gases.

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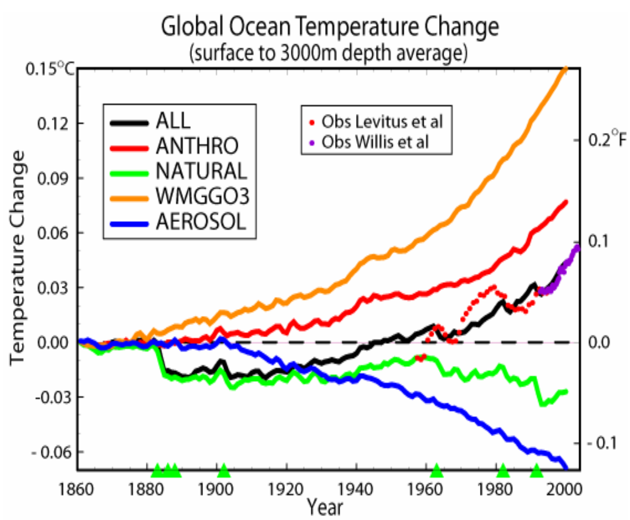

[Left] Global average ocean temperature change from 1861 to 2000 (surface to 3000m depth).
Circles = observations.
Curves = GFDL CM2.1 model results for different combinations of forcing agents.
"ALL" = All climate forcing changes are included (the model version designed to best simulate observations) Includes ANTHRO and NATURAL described below.
"NATURAL" = only includes volcanic aerosols and solar variations.
"WMGGO3" = only includes well mixed greenhouse gases and ozone changes.
"AEROSOL" = only includes aerosol effects from human activities.
"ANTHRO" = includes both the WMGGO3 and AEROSOL forcing agent changes, but not NATURAL.
Green triangles = times of major volcanic eruptions.
See Delworth, *et al*., [2005] for details.

From the IPCC* Summary For Policymakers...

"Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes seawater to expand, contributing to sea level rise."

"It is likely that increases in greenhouse gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place."

*Reference:
Intergovernmental Panel on Climate Change (IPCC) WG1 Fourth Assessment Report, Climate Change 2007: The Physical Science Basis, Summary For Policymakers.
Available online at www.ipcc.ch

TAKE HOME POINTS

- GFDL's CM2.1 model is able to realistically simulate observed warming trends in global ocean temperature from 1950 to 2000.
- Aerosols, both from human activities and volcanic eruptions, have offset approximately 2/3 of the warming that would have occurred solely in response to increasing greenhouse gases.
- This shielding effect of aerosols is expected to diminish in the future, likely leading to an acceleration of ocean warming.

Contact Info:

For this topic:

Thomas Delworth
email: Thomas.Delworth@noaa.gov
phone: 609-452-6565
GFDL Climate Dynamics & Prediction Group

V. "Ram" Ramaswamy
email: V.Ramaswamy@noaa.gov
phone: 609-452-6510
GFDL Atmospheric Physics & Chemistry Group

GFDL media inquiries:
Maria Setzer
email: Maria.Setzer@noaa.gov
phone: 609-452-6643

GFDL main phone:
609-452-6500

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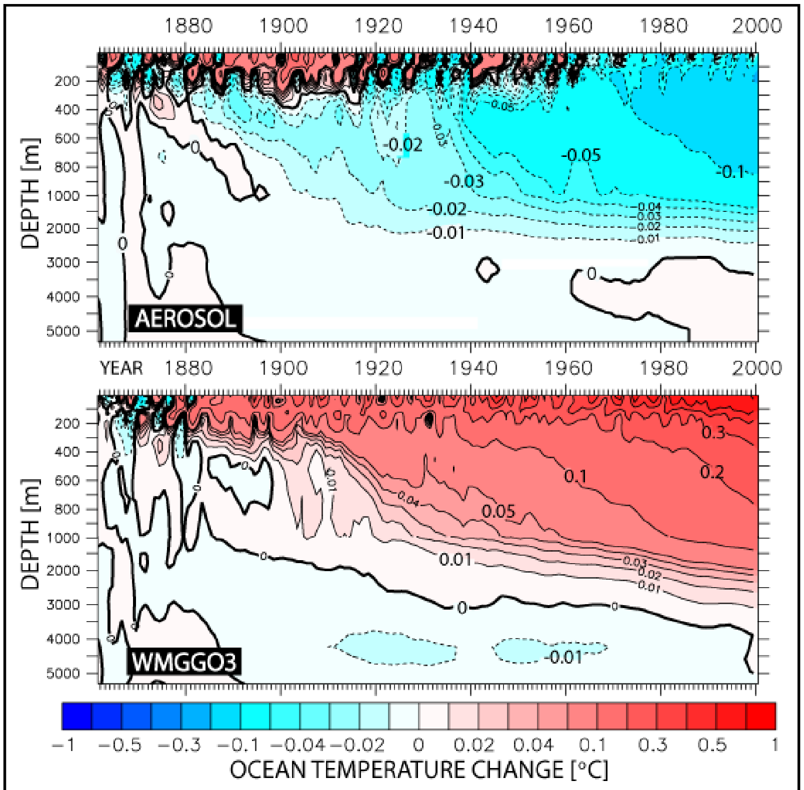
Looked at another way, the GFDL model study suggests that three times more heat would have entered and warmed the ocean from 1861 to 2000 if the observed increases in well-mixed greenhouse gases and tropospheric ozone were the only climate forcing factors to have changed (compare the WMGGO3 and ALL curves in the previous figure).

An important implication of this work is that the combination of volcanic and anthropogenic aerosols has substantially delayed and lessened the total amount of ocean warming—and therefore sea level rise—that would have arisen purely in response to increasing greenhouse gases during the past one and a half centuries. This GFDL modeling study suggests that aerosols offset between 2.4 and 7 cm (1 to 2¾ inches) of sea level rise that would have otherwise occurred due to the thermal expansion of ocean waters.



[Above] Time vs. depth plot of model-simulated global average ocean temperature changes in degrees Celsius (multiply by 1.8 for °F). These simulations show the effect of a single forcing agent on ocean temperature. Note the differing vertical axis scaling above and below 1000m. The upper panel (labeled AEROSOL) shows the steady downward penetration of the cooling signal over 140 years solely in response to increasing aerosols. The lower panel (labeled WMGGO3) depicts the ocean warming signal arising from the effects of well-mixed greenhouse gases and tropospheric ozone changes. The WMGGO3 warming is roughly twice the magnitude of the AEROSOL cooling, though cooling signals tend to penetrate deeper more quickly because of cold water's greater density.

► Long term greenhouse gases vs. short term aerosols

A crucial factor is that aerosols stay in the atmosphere for a much shorter time than greenhouse gases (weeks to a year or so for aerosols, versus decades to centuries for greenhouse gases). For this reason, the cooling effects of the aerosols can be considered relatively temporary compared to the warming effects of greenhouse gases. The aerosols' relatively short residence time suggests that the past situation, in which aerosols offset more than half of the potential greenhouse gas-induced ocean warming, could change rapidly in the future, leading to an acceleration of ocean warming.

Quantitative uncertainties in computed-generated climate simulations such as these remain, in part because our understanding of how aerosols interact with sunlight and infrared energy passing through the atmosphere is incomplete. However, the GFDL CM2.1 model's ability to simulate the 20th century's large- scale atmospheric and oceanic temperature changes can increase one's confidence in its simulation, even as more observations are gathered, theories are refined, and model development continues.

► Some related references

Delworth, *et al.,* (2005): The impact of aerosols on simulated ocean temperature and heat content in the 20th century, *Geophysical Research Letters,* Vol. 32, L24709, doi:10.1029/2005GL024457 [LINK]

Delworth, *et al.,* (2006): GFDL's CM2 global coupled climate models - Part 1: Formulation and simulation characteristics, *Journal of Climate*, Vol. 19, No. 5, pages 643-674. [LINK]

Knutson, *et al.,* (2006): Assessment of Twentieth Century Regional Surface Temperature Trends using the GFDL CM2 Coupled Models, *Journal of Climate*, Vol. 19, No. 9, pages 1624-1651. [LINK]

Levitus, *et al.,* (2001): Anthopogenic warming of the Earth's climate system, *Science*, Vol. 292, No. 5515, pages 267-270.

For more GFDL CM2.1 references, see http://nomads.gfdl.noaa.gov/CM2.X/references

For more information on this topic, including high resolution graphics and animations, please see **"Greenhouse Ocean Warming Delayed By Aerosols"** links at http://www.gfdl.noaa.gov/research/climate/highlights

NOAA GFDL

US Dept. of Commerce
National Oceanic & Atmospheric Administration
Geophysical Fluid Dynamics Laboratory
Princeton University Forrestal Campus
201 Forrestal Road, Princeton, NJ USA 08540

Phone 609-452-6500
Web.................. www.gfdl.noaa.gov
Data Portal .... nomads.gfdl.noaa.gov

About GFDL

Located in Princeton, New Jersey, the Geophysical Fluid Dynamics Laboratory (GFDL) develops and uses mathematical models and computer simulations to improve our understanding and predictions of the behavior of the atmosphere, the oceans, and climate. Over its 50-year history, GFDL has set the agenda for much of the world's research on the modeling of global climate change and has played a significant role in the World Meteorological Organization and Intergovernmental Panel on Climate Change (IPCC) assessments, as well as the US Climate Change Research Program (US CCSP).

The multi-year effort that culminated in the GFDL CM2.1 global climate model used in the research presented here was truly a lab-wide endeavor, and one that supports the National Oceanographic and Atmospheric Administration's (NOAA's) strategic goal to *"Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond."*

For more background information about GFDL, see...
http://www.research.noaa.gov/organization/backgrounders06/gfdl.html

Supplementary Information

<u>Some Fine Print:</u>

More About These GFDL Climate Model Experiments

The Geophysical Fluid Dynamic Laboratory's GFDL CM2.1 coupled model used to conduct the simulations is representative of the state-of-the-art in global climate modeling [Delworth et al. (2006)]. This model became GFDL's workhorse model for studies of decadal to century time scale climate variability and change in 2004 and likely will remain a key tool in climate change studies for a few years. The GFDL CM2.1 computer model of the Earth's global climate system contains atmosphere, ocean, and sea ice components that interact with one another and respond to changes in climate forcings[1].

Regarding the climate forcing scenarios used in the model simulation shown here, for the years prior to 2000, the model includes most of the major climate forcing factors that were observed to change in the real world (e.g., changes in atmospheric greenhouse gas levels, volcanic aerosols, tropospheric sulfate aerosols, black carbon aerosols, land surface changes, and solar irradiance changes). Run in this manner, the GFDL CM2.1 model has been shown to be credible at reproducing the decade to decade variations in global mean surface air temperature observed during the 20th century, though it tends to exhibit somewhat less warming than was observed in the high northern latitudes [Knutson et al. (2006)].

To explore a range of "If ... Then" future scenarios [IPCC, 2000], several different 21st century emissions scenarios have been used at GFDL and other climate research centers. Of course, some uncertainties in model projections of future climate remain and stem from the fact that we do not know how the atmosphere's composition will change in the future (including changes from human activities and those that occur when volcanoes will erupt) and because the models themselves are imperfect. Some model output files from the experiments shown here can be freely downloaded from the GFDL Data Portal (nomads.gfdl.noaa.gov).

[1] A climate forcing (or more properly, a radiative forcing) is the result of a process that directly changes the energy balance of the climate system by altering the balance between incoming solar radiation and outgoing longwave and shortwave radiation. It does not include the effects of feedbacks. A positive forcing tends to warm the surface of the Earth and a negative forcing tends to cool the surface. Forcing agents, such as greenhouse gases, aerosols, and surface albedo changes, are those things that cause variations in radiative forcings.

References:

⌂ symbols identify papers available for viewing online from the GFDL Online Bibliography web page: http://www.gfdl.noaa.gov/reference/bibliography/

○ symbols indicate non-GFDL references.

⌂ Delworth, *et al.,* (2005): The impact of aerosols on simulated ocean temperature and heat content in the 20th century, *Geophysical Research Letters,* Vol. 32, L24709, doi:10.1029/2005GL024457.

⌂ Delworth, *et al.,* (2006): GFDL's CM2 global coupled climate models - Part 1: Formulation and simulation characteristics, *Journal of Climate*, Vol. 19, No. 5, pages 643-674.

○ IPCC (Intergovernmental Panel on Climate Change) (2000): Special Report on Emission Scenarios. Cambridge University Press, U.K. (http://www.grida.no/climate/ipcc/emission/)

○ IPCC (Intergovernmental Panel on Climate Change) (2007): Climate Change 2007: The Physical Science Basis, Summary for Policymakers.
(published online 2 Feb 2007 at http://www.ipcc.ch/)

⌂ Knutson, *et al.,* (2006): Assessment of Twentieth Century Regional Surface Temperature Trends using the GFDL CM2 Coupled Models, *Journal of Climate*, Vol. 19, No. 9, pages 1624-1651.

⌂ Levitus, *et al.,* (2001): Anthopogenic warming of the Earth's climate system, *Science*, Vol. 292, No. 5515, pages 267-270.

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GFDL scientist contacts for this topic:

Thomas Delworth, NOAA/GFDL
Venkatachala Ramaswamy, NOAA/GFDL