

Warming Oceans Appear Linked to Increasing Atmospheric Greenhouse Gases

Global surface temperatures rose by about 0.6°C in the last century, according to the most recent report from the Intergovernmental Panel on Climate Change.¹ That estimate was based on observations of surface air temperatures and sea surface temperatures—the most commonly used measures of climate change. The IPCC also concluded that the observed warming is caused at least in part by increased greenhouse gases such as carbon dioxide, which absorb the infrared radiation that otherwise would escape from Earth. If the trapped infrared radiation is heating the atmosphere, we might expect it to be warming the world's oceans as well.² Covering nearly three-fourths of Earth's surface and having a high specific heat, the oceans have the greatest capacity to store heat of any component of the climate system. Unfortunately, detailed studies of ocean heat storage have been hampered by the paucity of easily accessible data on subsurface temperatures.

Sydney Levitus and his colleagues have been working for over ten years to correct this problem. Levitus, who works at the National Oceanographic and Atmospheric Administration's National Oceanographic Data Center in Silver Spring, Maryland, now heads an international project under the auspices of the United Nations-sponsored Intergovernmental Oceanographic Commission. Scouring the world, Levitus and his team have added 2.3 million historical temperature profiles (temperatures as a function of ocean depth) to the 3 million profiles that were previously available in electronic form. Many of the newly added data had existed only in manuscript form. The team put the data into a comprehensive, integrated, publicly available scientific database.³

In a report last year, Levitus and three NODC colleagues used⁴ the database to estimate that from 1948 to 1998, the volume-averaged (down to 3000 meters) temperature of the oceans rose by 0.06°C , corresponding to a heat input of $18.2 \times 10^{22} \text{ J}$. Some regions, such as the deep subarctic region of the North Atlantic, had cooled, but each ocean as a whole showed a net warming. (The heat content is calculated on a three-dimensional grid based on the local temperature,

An expanded data set for ocean temperatures has enabled climate modelers to compare predicted heating of the ocean to what has been observed over the past 40 years.

seawater density, specific heat, and the volume represented.)

Recently, three independent groups have compared the changes in ocean heat content seen in the past 40–45 years with the predictions of global climate models that coupled the oceans and atmosphere.^{5–7} In each of the three studies, the modelers found that they could get reasonably good agreement with the observations only when they included the effects of man-made greenhouse gases. Until these recent studies, climate modelers were allowing for heat flux into the oceans but had no way to assess how realistic those heat fluxes were. The newly available ocean data will now act as an important additional constraint on the models.

Different models, similar results

Each climate model has a particular algorithm for calculating the global climate when driven by different forcings—measures of how much the separate atmospheric constituents impact the radiation balance. The three models that were run recently to calculate heat stored in the oceans all had greenhouse-gas forcing but differed in what other forcings were included.

One of the studies was led by Levitus and two colleagues along with researchers from NOAA's Geophysical

Fluid Dynamics Laboratory. They used GFDL's climate model⁵ including forcings from greenhouse gases as well as from sulfate aerosols, volcanic aerosols, and perturbations in the solar irradiance (a constant solar irradiance is the prime driver in all climate models). The NODC–GFDL group made three runs with the same forcings but different initial conditions. In figure 1, the composite of the three runs is compared to the observed anomalous ocean heat content—that is, the difference in the heat content from the average for that 41-year period. The points plotted are five-year running averages; such smoothing helps to compensate for some of the sparseness in the data and background noise while still capturing the lower frequency phenomena such as any possible long-term warming trend. The blue curve, a composite of three runs that excluded the volcanic aerosols and the varying solar input, shows a greater warming, most likely because volcanic aerosols act to cool the climate system.

The red curve closely reproduces the observed heat gain over the 41-year period, although it misses some of the variability on the decadal scale, most notably the peak in the mid-1970s and the dip in the mid-1980s. To check that the same results could not come from normal variations in their model, the researchers did a 900-year control run, with no anthropogenic greenhouse forcing, and could find no 41-year period in that long integration with as large a heat flux to the oceans as was observed.

The second study was done by a group at the Scripps Institution of Oceanography led by Tim Barnett.⁶ The group looked at the changing heat content ocean by ocean, using the Parallel Climate Model (PCM) developed under the leadership of Warren Washington at the National Center for Atmospheric Research. As shown in figure 2, the time variations of heat content are clearly different in each basin, but each basin does manifest a net increase in stored heat. The anomalous heat content determined from the NODC database generally falls within two standard deviations of the curve that represents the average of five runs of the climate model forced with greenhouse gases and sulfate aerosols. (Only ten-year means have been plotted.) The

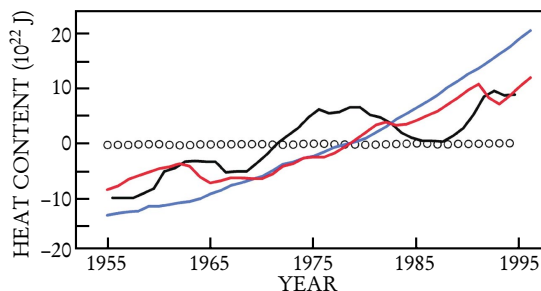
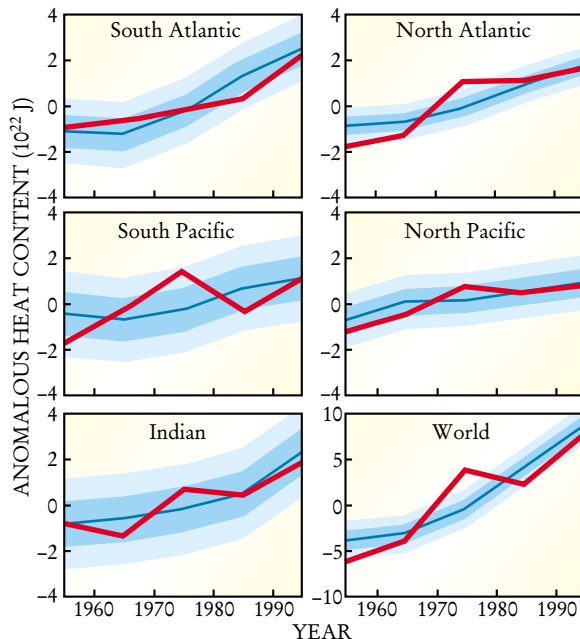


FIGURE 1. GAIN IN HEAT of the world's oceans for 1955–95. Data are 5-year running-means of the heat content relative to the average for the 41-year period. A composite average of three model runs (red) including the greenhouse gases, sulfate aerosols, solar variability, and volcanic aerosols fits the observed heat gain (black). A three-run composite (blue) that excludes volcanic aerosols and solar variability shows too much warming. (Adapted from ref. 5.)

FIGURE 2. HEAT GAIN, ocean-by-ocean. Data are given as 10-year means of the anomalous heat content, measured relative to the average for the 45-year period. The observed values (red) are compared to the ensemble average (blue) of five simulations with greenhouse and sulfate aerosol forcings; they largely fall within the one- and two-standard-deviation ranges (dark and light shadings). (Adapted from ref. 6.)



researchers used a statistical procedure known as optimal detection methodology to examine the likelihood that the observed or model-predicted changes in ocean heat content are produced by natural forcing alone (the chances are less than 5%) and whether the model predictions are indistinguishable from the observations (they are, at the 95% confidence level).

The Scripps group also broadly reproduced the time variation of heat content with depth for the various ocean basins. In both the simulations and the observations, the heat content in most of the oceans increased only slowly with depth, consistent with a diffusive process. The water had been warmed below about 1000 m only in the north and south Atlantic, reflecting strong vertical convection there.

A third study⁷ has just been completed by Bernhard Reichert, Reiner Schnur, and Lennart Bengtsson at the Max Planck Institute for Meteorology in Hamburg, Germany, using their coupled sea-air model.⁸ They made three runs: one having only green-

house-gas forcing, the second adding in direct sulfate aerosol forcing; and the third also including ozone and indirect sulfate forcing. The run that included all forcings gave the best fit to the observations. "With only one run per forcing, however," said Schnur, "it's hard to estimate the uncertainty in our model."

Oceans dominate

Levitus and his group compared the heat stored in the oceans to the heat that has gone into other parts of the climate system over the last 40-odd years. Specifically, they calculated the heat stored in the warmer atmosphere (open circles in figure 1), the heat absorbed in the melting of glaciers, and the heat taken to reduce the extent and thickness of sea ice. All of these terms were more than an order of magnitude smaller than the heat flux into the oceans in the same period. Barnett notes that neither changes in solar

irradiance nor geothermal heating can come close to supplying the heat required to make the changes seen over the last 40 years. "That pretty much leaves anthropogenic sources as our only explanation," he says.

Because of their large thermal inertia, the oceans are clearly the memory of the world's climate system. That result was not unexpected but needed to be confirmed with data. As estimated by a recent paper, even if manmade greenhouse gas emissions were to cease immediately, heat coming out of the oceans would continue to raise atmospheric temperatures by an additional 1°C before the system equilibrated.⁹

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Researchers Uncover the Neural Details of How Barn Owls Locate Sound Sources

As you read this story, your gaze flutters about the page roughly three times a second. But the scene you perceive is fixed firmly in space. Your brain achieves this feat by multiplying the images on each retina by a function that describes where your eyes are pointing. Other examples of sensory multiplication have been found in the animal kingdom. Locusts use it to see and avoid other flying

Barn owls use the neural equivalent of an AND gate to combine time-difference and intensity cues.

objects; humans and owls use it to localize sound.

Where and how does this multiplication take place? Neurons, it's usually assumed, integrate inputs from other neurons. Once the combined

input crosses a threshold, a neuron fires a voltage spike to communicate with whatever cell is next in line, usually another neuron.

In a landmark 1943 paper, the University of Chicago's Warren McCulloch and Walter Pitts proved theoretically that a network of integrating neurons can perform any computational operation, including multiplication.¹ Their formalism underlies the