GFDL CLIMATE MODELING RESEARCH HIGHLIGHTS

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

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TAKE HOME POINTS

- The increase of surface air temperatures in response to increasing greenhouse gas levels will not be geographically uniform.
- Computer models indicate that 21st Century warming will occur more rapidly over continents than over oceans.
- The largest warming is expected to occur during the winter months in northern North America and north-central Asia.
- Summer warming over continents may be accompanied by drier soils in many regions.

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Research Highlights, Graphics & Animations
www.gfdl.noaa.gov/research/climate

PATTERNS OF GREENHOUSE WARMING

The term “global warming” is commonly used to refer to surface air temperature changes that are a response to increasing atmospheric greenhouse gas (GHG) concentrations. However, the warming is not expected to be uniform over the globe, nor is it expected to be the same during all seasons of the year.

Computer model simulations conducted at NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL) and elsewhere project that GHG-induced warming will be more rapid over land masses than over oceans. This is seen in the figure below, with red colors indicating greater warming over the continents. White and blue-green colors mark areas with the least warming or slight cooling, found mostly over oceans.

Additionally, the greatest warming is expected during the winter over northern North America and north-central Asia (see the figure on next page and graphics and animations available at www.gfdl.noaa.gov/research/climate/highlights).

► Surface air warming lags over the ocean

Warming over the ocean tends to lag the warming over large land masses in part due to water’s high heat capacity and its ability to mix heat vertically. As water moves vertically in the ocean, water that has been warmed via exposure to the atmosphere at the surface is replaced by colder water from below. The replenished water can then absorb some of the excess greenhouse heat from the air directly above the sea surface, thus moderating the air temperature increase while increasing the heat content of the oceans.

Over both land and ocean surfaces, heat can either warm the surface or be used to evaporate water. The liquid ocean surface allows much of the heat to go into evaporating water, rather than warming the ocean or the air directly above it. In contrast, over land areas a greater fraction of the energy goes into heating

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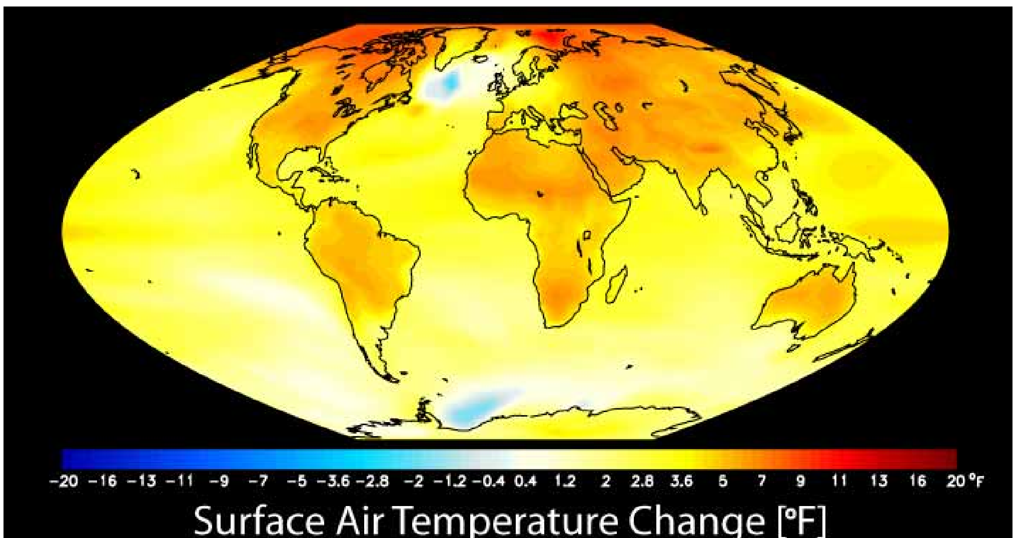


[Above] Projected change in annual mean surface air temperature from the late 20th century (1971-2000 average) to the middle 21st century (2051-2060 average). The change is in response to increasing greenhouse gases and aerosols based on a "middle of the road" estimate of future emissions. This scenario is denoted as IPCC SRES A1B [reference: IPCC, 2000]. Warming is larger over continents than oceans, and is largest at high latitudes of the Northern Hemisphere. These results are from the GFDL CM2.1 model, but are consistent with a broad consensus of modeling results.

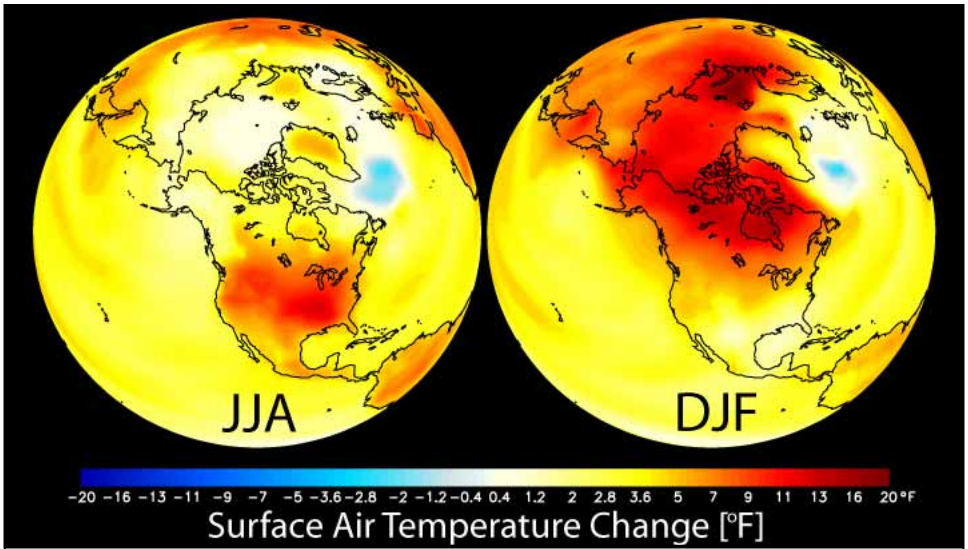
From the IPCC* Summary For Policymakers...

“Projected warming in the 21st century shows scenario-independent geographical patterns similar to those observed over the past several decades. Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean.”

“Eleven of the last twelve years (1995-2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850).”

*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

the air, resulting in greater warming over land than ocean. Over drier regions, such as deserts and areas experiencing drought, there is less water available for evaporation, so that relatively more energy goes to heating the air directly above the surface. This leads to greater warming over dry areas than moist regions. The enhanced warming and evaporation over continental regions can lead to a reduction of soil moisture.



[ABOVE]: GFDL CM2.1 model-simulated change in seasonal mean surface air temperature from the late 20th century (1971-2000 average) to the middle 21st century (2051-2060). The left panel shows changes for June-July-August (JJA) seasonal averages, and the right panel shows changes for December-January-February (DJF). The simulated surface air temperature changes are in response to increasing greenhouse gases and aerosols based on a "middle of the road" estimate of future emissions. This scenario is denoted as IPCC SRES A1B; for details see IPCC [2000]. Warming is projected to be larger over continents than oceans, and is largest at high latitudes of the Northern Hemisphere during Northern Hemisphere winter (DJF).

► Polar amplification of the warming signal

Observations and computer models agree that Arctic surface air temperatures are sensitive to climate change, warming roughly twice as fast as the global average. This is partly due to what is called the ice-albedo feedback (albedo is a term used to describe the fraction of sunlight reflected by an object). In the far north, melting occurs as areas previously covered by snow or ice warm. A highly reflective surface (snow or ice) is replaced by a darker surface (ocean or land). The darker surface absorbs more sunlight, leading to more warming and more melting - a positive feedback. At GFDL, research suggests that the ice-albedo feedback is a significant contributor, but not necessarily the dominant factor, in the polar amplification of the climate change warming signal [Winton, 2006].

► More warming during winter

The patterns and seasonality of the warming response seen in the GFDL climate model results (shown above) are broadly consistent with those simulated at other international research centers. The similarity of the different models' warming patterns, and the highly plausible reasons for the non-uniform warming, led the Intergovernmental Panel on Climate Change (IPCC) to conclude that it is very likely that temperatures will warm most rapidly over continents during the 21st century, especially during winter in the northern latitudes of the Northern Hemisphere. [IPCC, 2007]. The modeled large-scale trends are consistent with observations [Knutson et al., 2006], including that 2006 was the warmest year on record for the United States [NOAA Magazine, 2007].

► Some Related References

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]

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

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]

NOAA Magazine, (2007): , NOAA Reports 2006 Warmest Year on Record fo U.S., online release date: Jan. 9, 2007 (http://www.noaanews.noaa.gov/stories2007/s2772.htm). [LINK]

Stouffer, *et al.* (2006): GFDL's CM2 global coupled climate models - Part 4: Idealized climate response, *J. of Climate*, Vol. 19, No. 5, pp.723-740. [LINK]

Winton, (2006): Amplified Arctic climate change: What does surface albedo feedback have to do with it? *Geophysical Research Letters*, Vol. 33, L03701, doi:10.1029/2005GL025244. [LINK]

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 **"Patterns of Greenhouse Warming"** links at http://www.gfdl.noaa.gov/research/climate/highlights

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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, land 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 seven atmospheric greenhouse gas levels, volcanic aerosols, black and organic carbon aerosols, tropospheric sulfate aerosols, ozone, solar irradiance, and land surface 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, several different 21st century emissions scenarios have been used at GFDL and other climate research centers. In the CM2.1 figures displayed here, we show results from what is known as the SRES A1B emissions scenario - one with a mid-level increase in 21st century greenhouse gas levels [IPCC (2000)]. We display results from the A1B scenario not because it is considered any more or less likely to resemble the emissions scenario that actually will occur in the coming decades, but rather because, even as a "middle of the road" emissions scenario, the model's surface air temperatures show a fairly representative change response that is clearly visible in the graphics.

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 and because the models themselves are imperfect.

The model experiments from which the figures were derived have been documented in peer-reviewed scientific journals (see references below). However, the specific CM2.1 surface air temperature figures presented here have not appeared in the peer reviewed literature.

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 affecting 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.,* (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.

○ NOAA Magazine, (2007): , NOAA Reports 2006 Warmest Year on Record for U.S., online release date: Jan. 9, 2007. (http://www.noaanews.noaa.gov/stories2007s2772.htm/)

⌂ Stouffer, *et al.* (2006): GFDL's CM2 global coupled climate models - Part 4: Idealized climate response, *Journal of Climate*, Vol. 19, No. 5, pages 723-740.

⌂ Winton, (2006a): Amplified Arctic climate change: What does surface albedo feedback have to do with it? *Geophysical Research Letters*, Vol. 33, L03701, doi:10.1029/2005GL025244.

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

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