

# How Sensitive is Climate to Greenhouse Gases?

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**G**eorge Boer is on the forefront of research into climate's "sensitivity" to greenhouse gases. He is a lead author of the chapter "Projections of Future Climate Change" and a contributing author to three other chapters in *Climate Change 2001: The Scientific Basis*, the latest report of the Intergovernmental Panel for Climate Change (IPCC). A senior research scientist and former Chief of the Canadian Centre for Climate Modelling and Analysis, Boer has worked with his colleague **Norman McFarlane** and others since the early 1980s on developing and applying the Canadian Climate Model, which was one of the models used for the global warming studies in the IPCC report.

Boer's visit to the IPRC during February and March 2003 gave us the opportunity to ask him what he considers to be the leading issue in climate modeling research. "The focus should be on climate as a system and how sensitive the climate is to perturbations," was his reply. "By climate sensitivity I mean the magnitude and pattern of the temperature increase in response to the radiative forcing resulting from a perturbation such as an increase in CO<sub>2</sub>."

"If a relatively small perturbation results in a large temperature increase, then the climate system is 'sensitive,' and we need to worry; if a large perturbation results in little temperature change, we can say, 'So what!' But we don't know how sensitive the climate system is. The models used for predicting climate change vary quite a bit in sensitivity, and this is the basis for much of the argument on whether we should do something about global warming."

"For instance, there is a lot of scatter in the climate response to a doubling of CO<sub>2</sub> in the models, with results differing by a factor 2 or more." He points to a graph in the IPCC Report (p. 560), in which, depending on the model, the predicted increase in global surface temperature ranges from 2° to 5°C, and the global precipitation increase ranges from less than 2% to 15%. The Canadian Model is in the middle range of the temperature increase predictions.

The difference of 3°C in mean-temperature increase among models is significant since the change plays out

very differently in different parts of the world. In simulations with versions of the Canadian model (for a description of these models see <http://www.cccma.bc.ec.gc.ca/models/models.shtml>) from 1900 to 2100, some regions warm dramatically, others actually cool. Generally, there is greater warming in the higher latitudes of both hemispheres, though this is slowed somewhat in the Southern Hemisphere due to mixing of the surface ocean with the deep ocean. In the tropical ocean, there is a mean warming rather similar to an El Niño state. Not all models, though, produce this mid-Pacific warming.

"It is very important for us to understand why models differ and what determines their climate sensitivity," Boer believes, "and the key to determining the climate's sensitivity to greenhouse gases lies in the feedback processes operating in the climate system." An example of a positive-negative feedback system is the following sequence: as the atmosphere warms, it holds more water vapor, but water vapor is a greenhouse gas (the most prevalent one) and heats up the atmosphere even further (positive feedback); Earth's surface, on the other hand, as it warms further, radiates more heat back into space (negative feedback).

One hint of the critical role of feedbacks is that the nature and pattern of radiative forcing does not strongly determine the resulting temperature pattern: whether, for instance, solar radiation or greenhouse gases are changed in the model experiments, the results show similar overall sensitivity and patterns of temperature increase. "This tells us that the patterns in temperature change depend in the first order on the feedback processes and not on the nature of the forcing."

To understand these patterns, Boer has separated feedback processes into those associated with clouds and those associated with the cloud-free atmosphere and surface. He is examining each of these feedback's regional contributions to changes in longwave, shortwave, and total radiation. His analyses show that depending upon the region, the feedback processes have different effects on long- and shortwave radiation. For example, in higher latitudes



George Boer and Kevin Hamilton studying results of model simulations.

clouds decrease net shortwave heating, but the surface-atmosphere feedback overrides their cooling effect. This positive feedback comes mainly from the melting of snow and sea-ice, resulting in more absorption of incoming shortwave radiation.

Of great interest to Boer is an area of overall positive feedback in the mid-Pacific surrounded by negative feedback in much of the rest of the tropical band. This positive feedback supports a mean El Niño-like response due to positive radiative forcing, which is absent in simpler climate models without a dynamic ocean.

While at the IPRC, Boer has begun to compare simulations from the Canadian model with those made at the IPRC by **Kevin Hamilton** and **Weijun Zhu** using the numerical model from the National Center for Atmospheric Research (NCAR). The NCAR simulations show a generally similar positive feedback distribution, for example, over the higher latitudes and in the mid-Pacific, but negative feedbacks are generally stronger and positive feedbacks weaker, indicating that the model is less sensitive than the Canadian model (indeed, the NCAR model is one of the least sensitive of current climate models). Preliminary analyses suggest that the positive water vapor feedback is weaker in the NCAR model. Boer speculates that this may have to do with differences in moisture distribution.

Boer can well have some confidence in the validity of the Canadian Climate Model and in its sensitivity to green-

house gas and other forcings. Colleagues at his centre have simulated conditions during the Last Glacial Maximum. The model was initialized with CO<sub>2</sub> levels and increased glacial topography existing during the Last Glacial Maximum. As the model approached a new equilibrium, a La Niña pattern with cool sea surface temperatures had developed in the mid-Pacific and the thermohaline circulation in the North Atlantic had slowed. The sea surface temperature and thermohaline findings corresponded to those reconstructed independently by paleoclimatologists with paleo data from the Last Glacial Maximum. The fact that the feedbacks are robust when the climate system is cooled provides convincing evidence of the importance of the geographical feedback patterns in determining the pattern of temperature change.

The next version of the Canadian model is already on the production line and is expected to be released within a year. This model will have more sophisticated cloud parameterization and radiation and convection schemes, and it will include treatments of the sulfur and carbon cycles. With this new model, George Boer will continue to look further into how our climate responds to radiative forcing arising naturally and from human activities.

## Publication available

The lectures from the School on the Physics of the Equatorial Atmosphere, directed by Kevin Hamilton at the International Centre for Theoretical Physics in Trieste (*IPRC Climate, 2*, Fall), have been published. *Physics of the Equatorial Atmosphere*, edited by **L. Gray** and **K. Hamilton**, is aimed at an advanced graduate student audience. Copies are available on request from Library and Information Services, Rutherford-Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, United Kingdom.

# What's New at the Asia-Pacific Data-Research Center (APDRC)?

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<http://apdrc.soest.hawaii.edu>

As you read this article, a huge amount of climate information is being generated. This information exists in many formats and at many locations, making it arduous to use. The APDRC is there to help scientists access such information quickly. Since first featured in the *IPRC Climate* (2, No.1), the APDRC, under the leadership of Peter Hacker, has been actively developing and widening the scope of its servers, has made new products such as those from WOCE and Argo available, and has begun exciting collaborations with GODAE, Frontier, and the Earth Simulator activities.

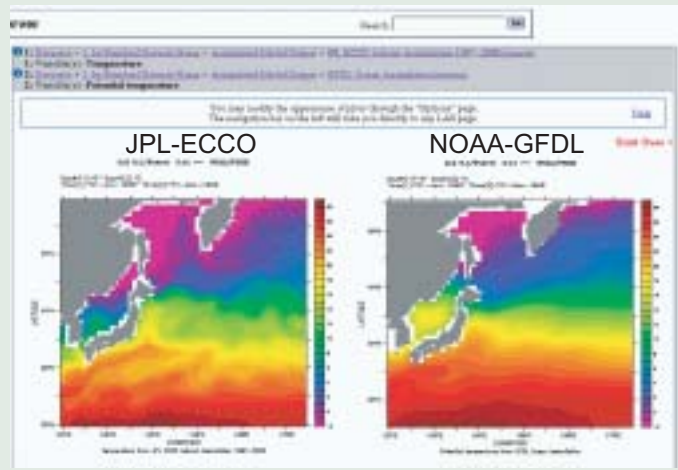
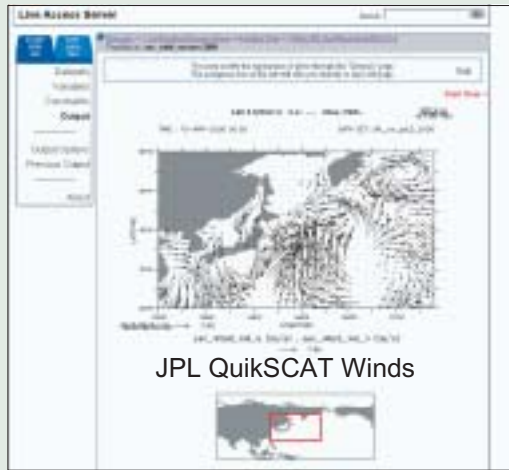
The most challenging task we have taken on at the APDRC is to make the massive model products now being generated by supercomputers, such as the Earth Simulator in Japan, accessible to researchers in an easy and manageable fashion. Data Server Manager **Yingshuo Shen** has been grappling with how to make servers provide efficient access to both local and remote products. The side-panel (p. 20) details some of the technical issues and current solutions. The vision is to develop a system whereby users can select, with only a few clicks on the monitor screen, those specific data products from the vast global data sets that they need for their research. Toward this end, we are greatly increasing the storage capacity of the servers so that a portion of the Earth Simulator and other model products can be stored at the APDRC. Moreover, Shen and his colleagues are working on the concept of "sister servers", in which servers at other institutions store parts of the data sets, yet users will be able to access the diverse data sets seamlessly at the APDRC site without noticing that the data resides on different servers around the world. This past November, for instance, visitors **Kazutoshi Horiuchi** and **Yutaka Oyatsu** from IPRC's Japanese sister institutions worked with Shen to prepare the transfer of the IPRC server systems (LAS, EPIC, and CAS) to Japan as a first step in setting up such connections between the computers.

We have begun at the APDRC to make plans on how to best help in the delivery and evaluation of products associated with the Global Ocean Data Assimilation Experiment (GODAE), which has started its demonstration phase. GODAE will usher in a new era of oceanography — an era of now-casting and forecasting of the ocean state, much like weather forecasting. Specifically, GODAE is

working to provide, with the help of ocean data-assimilation models, real-time and forecast products for temperature, salinity, sea level, and currents frequently and at high spatial resolution. This information will be of great importance for a wide range of research activities and applications, such as fisheries, public safety, resource management, and adaptation to climate change. Our servers can facilitate the use and evaluation of the GODAE products and are already serving the following assimilation-based products: JPL-ECCO products, NOAA-GFDL products, and the Naval Research Laboratory (NRL) Layered Ocean Model (NLOM) products (Figures 12 and 14). The Live Access Server (LAS, version 6.0) allows comparison between two different products from two remote sites. The NLOM product is a real-time research product that has been created operationally by NAVOCEANO. Convenient premade output is available at the NRL website ([http://www7320.nrlssc.navy.mil/global\\_nlom/index.html](http://www7320.nrlssc.navy.mil/global_nlom/index.html)). The output files of this model, however, are huge and the task of downloading and filtering through the data for individual use is difficult. Thus, we are currently downloading the real-time surface layer products globally and serving them on the public LAS (6.0), allowing any user — climate, or reef-coral researcher, or fisherman — to easily prepare custom plots of real-time information for their region of interest.

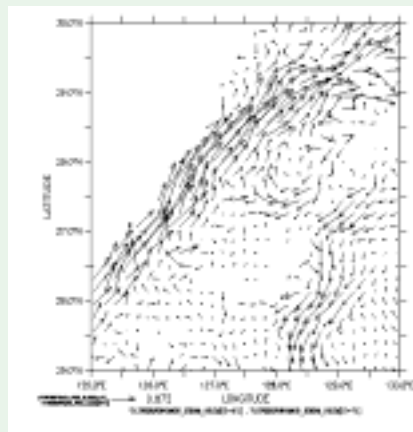
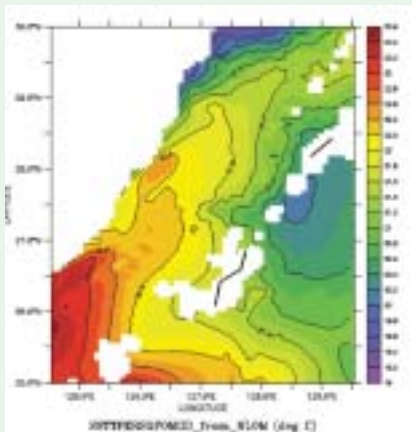
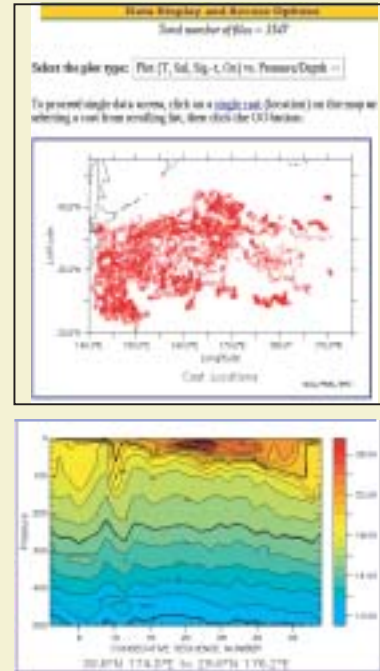
Our server homepage, <http://apdrc.soest.hawaii.edu>, has been updated, and **Gang Yuan** has provided easy access to several in-situ data sets served on the local EPIC servers. The servers provide web-based access to thousands of WOCE CTD stations, Upper Ocean Thermal profiles, and current-meter records. Argo profiles from the Global Data Assembly Centers at US GODAE, Monterey, and IFREMER, France, are also available on a test server. These records will be updated regularly. The EPIC server provides easy sampling of information by region, time, and float, and creates graphic representations of the sampled data (Figure 13). Try the Argo server and tell the APDRC about your experience.

The Integrated Modeling Research Program (under Professor **Toshiyuki Awaji**) at Frontier is developing a cutting-edge 4-dimensional atmosphere-ocean-land coupled data-assimilation system on the Earth Simulator computer for a reanalysis of data from the 1990s. The IPRC, led by **Takuji Waseda**, is assisting with the establishment of an international data network for the project by identifying



**Figure 12.** The Live Access Server (LAS) version 6.0 at the APDRC serves QuikSCAT level 3 wind velocity data from JPL (left) and allows model product comparison from two different sites, JPL/ECCO adjoint output and NOAA/GFDL output (right) for fields such as ocean surface temperature.

**Figure 13.** The EPIC server for in situ ocean data now serves WOCE data, as well as Argo float data (on a “test” site). If you pick “Pacific Ocean Argo Float Data” from the APDRC’s EPIC server, you will get the left panel (11,120 profiles). Select a drag-and-drop subregion in the North Pacific and you get the upper right panel. You can view individual profiles, or select a specific float and see the temperature (shown) or salinity data from a sequence of profiles as on the lower right panel.



**Figure 14.** We recently began serving the NRL NLOM, 1/16°, global surface layer product. The figure shows sea surface temperature (SST) on the left and surface layer velocity vectors on the right associated with the Kuroshio for 8 March 2003 near Okinawa, Japan.

and collecting global ocean, atmosphere, and land-surface data, by providing quality control and value-added information, and by conducting data analyses. The IPRC, moreover, will participate in Earth Simulator experiments conducted with an advanced ocean model (OIFES) and a coupled ocean-atmosphere model (CFES) specifically developed for the large capacity of the Earth Simulator. The coupled model is the same as that for the data-assimilation project described above. For both the Integrated Modeling Research Program and the Earth Simulator Center collaboration, the APDRC's data serving capacity based on the LAS, CAS, and GDS infrastructure (see side panel) should become invaluable for serving the large model output (many tera-bytes) efficiently.

Finally, **Humio Mitsudera** has moved to the University of Hokkaido. We wish him all the best in his new position, though his active role is much missed. We would like to thank **Klaus Wyrтки** for his comments on model-based products (below). As more of these products become available and used, it is essential that their error fields are readily available and that the actual data or observation content of the products can be tracked.

## Letter to the editor:

Data have always been of great interest to me. So when I saw an article "Go Data Shopping" (*IPRC Climate*, 2, No. 1), I became very excited. My eyes immediately focused on the map of the eastern Pacific and the adjoining diagram of temperatures to the west of the Galapagos Islands (Figure 8). The diagram shows temperatures from the surface to 400 m and from 1950 to 2000. I am sure there are almost no temperature measurements in this location between 1950 and 1960, and very few in the following decade; thus these data must have been synthetically generated.

When I hear "data," I think of course of observations, measurements. But today the term "data" is too often used for information generated from model outputs. Scientists should, of course, know the difference and make a proper distinction between different kinds of data: observed, interpolated, model output, and simulated — or what I call "invented data." As long as that is done, it is not a problem; but it becomes scary if outsiders, like environmentalists, use these data in place of observations to draw conclusions. It might, therefore, be useful to warn "shoppers of data" that these are synthetic data and not observations.

Klaus Wyrтки  
Professor Emeritus

## APDRC Server Infrastructure

This note focuses on the OpeNDAP (formerly DODS) infrastructure at the APDRC. Three types of OpeNDAP servers are running; each has specific capabilities and potential.

First, the cgi (common gateway interface) on an Apache server is used to obtain in-situ data with the EPIC "Pointer File" option. The cgi also translates HDF files (a common format for satellite products) into OpeNDAP to support other client applications, such as APDRC's serving of JPL's SeaWinds data (QuikSCAT satellite level 3 data), shown in Figure 12. Technology from Unidata called NcML will enhance this service.

Second, the servlet type server running on a Tomcat server has the capability of an aggregation server (AS) to configure OpeNDAP products stored locally, remotely, or both. As more products become available on OpeNDAP (e.g., NCEP daily reanalysis data from <http://www.cdc.noaa.gov/>, GFDL assimilation model output from <http://nomads.gfdl.noaa.gov/>, and ECCO's assimilation model output from <http://ecco.jpl.nasa.gov/>), the AS at the APDRC makes their access easier and user friendly. The AS can also combine remote and local data into a dynamic distributed-data storage system (an intelligent distributed-data system): client access feedback adjusts data configuration, increasing access speed while keeping local storage at a minimum. The APDRC and Frontier in Japan are working on this capability and doing benchmark testing in order to manage and serve large sets of model- and satellite-derived products emerging from the Earth Simulator activities.

Third, the GrADs DODS (a.k.a. GDS) server, also a servlet type OpeNDAP server, allows different file types to be configured on the server. Any file that GrADS can access may be configured into OpeNDAP, avoiding the conversion of other formats to netCDF (binary to netCDF, GRIB to netCDF, as examples). Another advantage of GDS is its ability to serve large products, such as those from the Earth Simulator. Current GDS model output files are 13 Gb.

The Live Access Server, LAS, at the APDRC is a flexible interface between user and data servers; all datasets on the OpeNDAP server can be accessed with LAS. Our server also supports Ferret and GrADS (two common applications), as well as IDL, Matlab, Fortran, C, Java, and others.

# New International Center for Climate and Society

**L**orenz Magaard, Executive Associate Director of the IPRC, has received approval for his proposed International Center for Climate and Society within the School of Ocean and Earth Science Technology (SOEST) at the University of Hawai'i at Mānoa, and has been appointed the center's director. The mission of this sister center of the IPRC is to develop improved methods of utilizing economic innovation to mitigate and adapt to climate fluctuations and climate change. The idea of the center grew out of a project of **Lorenz Magaard, Wolf Dieter Grossmann, and Hans v. Storch**, described in *IPRC Climate*, 2, No. 1, p.12. The premise for the center is that the New Information and Communication Technologies are turning our society into an "information society" with a "new economy" characterized by "globalization." These technologies are eliminating ever more jobs in the mature industry, which uses energy and materials as its main resources. At the same time, across the globe, new companies are being founded that use information as their prime resource. The mature industry is thus being transformed by advanced information and communication technologies for gathering information, producing and distributing parts, products, and services. Examples of new information-based industries are seen in multimedia industries, cellular phone networks, genomics, and the health-products industry.

The transformation of mature industries and the rapid emergence of a new, information-based economy provide a unique opportunity for dealing with environmental problems arising from climate change. The challenge is to learn what societal adjustments to make based on this new economy in order to decrease present and future environmental problems. Making such adjustments while the economic restructuring and new developments are underway may allow certain environmental problems to be solved at little additional cost, and sometimes with gain.

Magaard and his group have completed a study in which they used a systems model to test policies that capitalize on the new economy in order to help mitigate and adapt to climate fluctuations and climate change. They found several instances in which such policies enhanced economic growth and at the same time solved problems of climate change. The outcome of this study is promising. It will be much more difficult, however, to make societal

adjustments once this economic metamorphosis has been completed. In other words, there is a rather small window of opportunity and that window is *now*.

During his recent visit to the IPRC, Grossmann (UFZ Center for Environmental Research, Leipzig/Halle, Germany) gave examples of how such restructuring can be made cost effectively in industries that are most related to greenhouse gas emissions, namely, power plants, housing, transportation, and forestry. Speaking on "Using Economic Innovation for Mitigation of Global Climate Change," Grossmann presented ways to reduce greenhouse gases in a cost effective manner by replacing the existing infrastructure with new technologies at the most strategic time in the life cycle of each industry. The group now plans to calculate both the cost effectiveness and the reduction in greenhouse gas emissions expected from present large-scale economic restructuring.

The center will conduct basic research to study the options and the costs and benefits associated with certain societal adjustments that make use of the information-based economy. A dynamical systems approach (e.g., Katok and Hasselblatt, 1995) will be used in this research to model interactions among the economy, environment, human knowledge, human attitude, and climate parameters. Moreover, the center will conduct applied research on a) managing natural resources such as energy, fisheries, coral reefs, and tropical forests; b) managing environmental risks; and c) developing policies for decision makers in government and in the private sector. The center will also take part in graduate education programs within SOEST.



Core members of the center, from left: Wolf Dieter Grossmann, James Marsh, and Lorenz Magaard.