Climate Working Group
Climate Research and Modeling Program Review

Based on a Review Panel Meeting Held on March 24-26, 2008

Hyatt Regency, Princeton, NJ

Panel Members:

Rit Carbone*, National Center for Atmospheric Research

William Collins, UC Berkeley and Lawrence Berkeley Laboratory

A. Scott Denning, Colorado State University

Masahide Kimoto, University of Tokyo

William Large, National Center for Atmospheric Research

Natalie Mahowald, Cornell University

Jonathan Overpeck, University of Arizona

Joyce Penner, University of Michigan

David Randall (Chair), Colorado State University

Michelle Rienecker, NASA Goddard Space Flight Center

Richard Rood, University of Michigan

Mark Schoeberl*, Goddard Space Flight Center

Eric Wood, Princeton University

* Unable to participate in the Site Review, but provided input for the written report

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Executive Summary

This Report summarizes the first-ever Review of the Climate Research and Modeling (CRM) Program of the National Oceanic and Atmospheric Administration (NOAA). The overarching goal of the CRM Program is to develop, understand, and improve the capability to make intraseasonal, seasonal, decadal, and centennial-scale predictions of climate variability and projections of future climate change on global to regional scales. Current CRM funding is about $78 M per year. The Program is young and rapidly evolving.

CRM draws on NOAA's seven Research Laboratories, twenty-one Cooperative Institutes, six Regional Climate Centers (RCCs), five Applied Research Centers (ARCs), and five climate-related Grant Programs. Dr. V. Ramaswamy of NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) is the Acting Program Manager for CRM.

In brief, this Report concludes that NOAA's CRM Program is producing important, useful, and interesting research that represents a major contribution to the extremely important and now highly visible world-wide enterprise of climate research. NOAA scientists have made many world-class contributions to the scientific investigation of the Earth's climate and global change. NOAA's superb contributions to recent international assessments are particularly noteworthy. NOAA's provision of information on climate variability and the impacts of climate variability on society are also commended. A key challenge for the future is to improve the overall design and cooperative interactions of the many institutional components involved in the CRM Program. Strategic Planning is obviously required to meet this challenge.

Panel 1: Understanding Climate Processes

NOAA continues to make measurements of the long-lived non-CO_2 greenhouse gases, and to quantify the processes that control the abundances of these gases. NOAA has demonstrated that the reduction in ozone depleting substances by 2010 due to the Montreal Protocol will have been equivalent to 7 to 12 years of growth in radiative forcing due to CO_2. Continued monitoring of O_3 and H_2O in the stratosphere and the use of models to explain these changes is required.

NOAA has participated in research to quantify aerosol growth factors as a function of organic mass fraction in aerosols, and to evaluate new measurement techniques to quantify the amount of black carbon in the atmosphere. Intrinsic difficulties of aerosol research arise from the differences between the microphysical scales in clouds and the larger scales represented in global climate models.

Parameterizing convection on the GCM grid scales also continues to be a challenge. At finer grid spacings, parameterizations must be modified. Work on parameterizations for atmospheric models deserves a higher degree of visibility than it received in the presentations to the Panel. The panel was not briefed on the use of cloud-resolving models to test or improve parameterizations. Future Reviews should cover these very important items more comprehensively. Management should emphasize better coordination between measurements and modeling and between small scale process modeling and large scale prediction.

As stratospheric ozone continues to recover, ozone research should evolve away from the ozone hole *per se*. However, understanding changes in stratospheric water vapor and understanding how changes in stratospheric ozone relate to climate changes continue to be important. There is a need for better coordination of the chemical and physical sciences in NOAA.

The CRM Program makes use of three major ocean models: HyCom, primarily used at NCEP (the National Centers for Environmental Prediction); MOM, the Modular Ocean Model, widely used in the climate community; and HIM; an isopycnlal coordinate model. Capabilities of the latter two are to be incorporated into GOLD, a new GFDL ocean modeling framework. However, the Panel was not convinced by assurances that ocean modeling within CRM is coordinated and heading in the same direction and feels CRM's ocean modeling activities need more focus and organization. Again, there is no Strategic Plan only an expectation that GFDL will continue with both MOM and HIM based capabilities within GOLD for the foreseeable future, because neither performs well in all situations. NCEP is now investing in HYCOM, so GFDL and NCEP should collaboratively perform an evaluation of HYCOM's performance as an ocean model. Eddy-resolving versions of both MOM and HIM are being studied in the hope that the results will point the way to improvements in lower-resolution models. This activity will need to be greatly enhanced and perhaps focused on one of the base models if it is to keep pace with developments elsewhere. Science and algorithms developed in the larger community filter into the GFDL ocean models more slowly than they should.

Coordination of research among the many NOAA laboratories and programs was not apparent to the Panel. The relationship between observations and improvement of global models would benefit from a higher level of coordination as well as visibility within the program. Emphasis on understanding basic processes should be balanced with improving the models. A Strategic Plan is needed to define how data assimilation can be used to test parameterizations, on how smaller-scale models can help in the development of parameterizations, and field studies can be used to test parameterizations, and how the development activity will be integrated into an operational capability. As an example, the GFDL-NCEP connection provides a unique opportunity for beginning decadal prediction with the ESMs, but this has not been exploited.

The Panel recommends additional targeted Climate Process Teams (CPTs) to take advantage of the wealth of Earth system observations, process modeling and theory to improve all aspects of CRM modeling. These should follow the structure and guidelines of the CLIVAR CPTs and could be administered by the Grants program. However, sufficient funding cannot be expected from the already strapped grants program, so additional funds need to be secured.

NOAA should continue to push the resolution envelope, at least for decadal-scale modeling. The Panel encourages an exploratory investigation of the results obtained with an eddy-permitting ocean model coupled to a cloud-resolving atmospheric model. For physical and biological systems, improved resolution of coastal systems is vital.

Work on the coupling between the carbon cycle (especially on land) and the climate model appears to be under-funded. CRM carbon modeling would benefit from more vigorous interaction with the observationalists. CRM research should be able to influence the priorities and design of the observing and monitoring system for carbon in the oceans and the atmosphere.

Staffing is sub-critical. Development of the ESM will require additional resources and stable strategic plans to take appropriate advantage of collaborations with the larger community.

Panel 2: Reanalysis and Data Assimilation and Carbon Tracking

The activities being undertaken by CRM encompass the Climate Forecast System Reanalysis and Reforecasting project for the satellite era (the CFSRR), a climate reanalysis with the pre-satellite era observing system (Reanalysis of the 20^{th} Century), ocean data assimilation with both seasonal and decadal prediction goals (Coupled ensemble filter Data Assimilation (CDA), and real-time estimates of CO_2 transport (CarbonTracker) over the U.S.. These are groundbreaking and risky undertakings. The planning of these important activities could have benefited from a more extensive formal scientific review by the external community.

The CFSRR is currently using the resources of the Climate Test Bed, and yet it needs more resources to meet the needs for both analyses and historical forecasts. It should undertake an exercise to demonstrate the performance of the system, and should involve external community early in the evaluation rather than relying entirely on the internal monitoring of the system. The CFSRR should survey the community as part of a process to define the product streams. NCEP/EMC and NCDC should consider a distributed and incremental archiving of the CFSRR and the Reanalysis of the 20th Century, rather than waiting until the results are complete. NOAA management should determine if, when, and how the CDA should transition to CFS, and if not, why it should continue at GFDL.

The Reanalysis of the 20th Century is difficult and less constrained than the past NCEP reanalyses. It is in NOAA's interest to lead and promote external critical assessment of the products.

CDA has an impressive impact on seasonal prediction skill for equatorial SST. The CDA has very close potential links to NCEP CFS, but the models and data assimilation techniques differ. Computing resources are limiting progress.

Carbon Tracker modules currently have no relationship to other CRM models, and there is no institutional mechanism to allow CRM carbon component models to be improved by Carbon Tracker optimization, nor to use the excellent process representations in the ESM to interpret Carbon Tracker output. CarbonTracker should receive rigorous scientific review, and a plan to integrate it more thoroughly with NOAA assets should be developed if it is to be a featured product of CRM. An effort should be made to include ESM component models in the CarbonTracker.

The Panel recommends that NOAA take the lead in forging an interagency partnership to create a national reanalysis program. International collaborations are of course needed, especially for acquisition and quality-control of data. There is a need for more coordination between NCEP/EMC and GFDL in their ocean data assimilation activities. There is a need for Observing System Simulation Experiments, and an assessment of the value added by any proposed new flux towers.

Panel 3: Earth System Modeling, Predictions, and Projections

The Panel was impressed with GFDL's comprehensive coupled climate modeling strategy, which involves development of high-resolution atmospheric and ocean models, and parallel development of an ESM. Over time, the results of the high-resolution studies will feed into the ESM project. GFDL has recently developed a very promising new, nonhydrostatic core based on a "cubed sphere" grid, which provides a relatively uniform resolution. The long-term strategy for studying regional climate and hurricane dynamics is to use the cubed-sphere non-hydrostatic model (or its successors) with high resolution. GFDL is also collaborating with ESRL on the development of a non-hydrostatic geodesic grid version of the Finite Volume core.

GFDL is also developing an ESM that includes representations of the marine and terrestrial ecosystems. It has dynamic vegetation, including species succession, and emphasizes "coupled carbon modeling." Running the carbon system to a steady state is very expensive. The carbon cycle is strongly influenced by the water, nitrogen, and phosphorus cycles. The Panel is concerned that these connections are not receiving enough attention within the ESM effort. Extending the ESM beyond carbon will require additional intellectual and computational resources. A formal pathway should be defined for model components to move from the ESM to the coupled climate model. Coordination between GFDL's ESM and other national efforts such as NCAR's CCSM should be re-examined. GFDL needs to make a strategic decision as to whether or not it wants to take a leading role, nationally and internationally, in ESM development. GFDL and NOAA management should reach a mutual agreement of the relative priorities of Climate Modeling and ESM development. GFDL will not be able to establish or maintain leadership in ESM development without much more extensive collaborations with and contributions from both elsewhere in NOAA and the external community.

GFDL's land-model development activity includes dynamic vegetation, subgrid heterogeneity, and river routing. While some parts are innovative, the bulk of the modeling effort does not appear to be at the cutting edge. Land-ice modeling is a critical area for future development.

NCEP modeling has made strong advances over the past decade. The updated CFS is a major improvement over earlier NOAA forecast systems. The assimilation algorithms are also being enhanced. The current model development and testing cycle will come to a conclusion in 2010. NCEP has a well planned strategy for developing and maintaining the CFS as a fully public national resource. NCEP is to be commended for this open modeling approach, which will be facilitated by NCEP's impending move to the University of Maryland campus.

NCEP will participate in and is committed to Multi-Model Ensembles (MMEs). NOAA needs to lead and develop a *national strategy* for intraseasonal to interannual climate prediction inclusive of MME, data assimilation, and forecast metrics. It is not clear that NCEO has identified the computing resources needed to support the MMEs. The computing requirements for a National MME should be included in the NCEP climate computing request for 2011.

NCEP should give higher priority to understanding climate, as per the draft CRM charge. NCEP should develop more formal and persistent mechanisms for scientific interactions with the outside research community. NCEP is not benefitting from the contributions from the external community at levels anywhere near those at similar facilities abroad. NCEP's move to the

University of Maryland campus will promote interactions with the local university community. NCEP should consider a strategy for supporting visitors who come to NCEP to work directly with the scientists there. Transfer of results from research to operations is hampered by the fact that grants are not administered by NCEP, but the existing grants program should not be cannibalized to support an NCEP grants program.

A state-of-the-art computational infrastructure is critical for the success of NOAA's climate and weather activities. The high-resolution modeling activity provides a strong incentive for a major enhancement of computing resources. The Panel is concerned that more emphasis is needed on the computational system as a whole. Emphasis should be placed on end-to-end systems design anchored on the software of the research and applications suites and data system requirements. Traditionally, NCEP, ESRL and GFDL addressed their computing needs independently. Now the three are working to come up with a strategic, unified procurement. NOAA has also partnered with DOE and NASA in order to pool computing resources. In general, there has been a positive change in NOAA culture towards cooperation and coordinated resource management. Nevertheless, there is a need for far more attention to the planning, funding, acquiring and operation of a robust computational infrastructure to support the links between research, applications, and operations. In this connection, the Panel commends NOAA's active adoption of software frameworks.

The NOAA CRM program activities presented at the Review encompass the operational climate monitoring and prediction products and services and the climate test bed, the CPO Climate Prediction Program for the Americas (CPPA), and the IRI and ARCs. The Climate Prediction Center (CPC) has responsibility for delivering products. CPC is to be commended for the partnerships it has developed with users. The operational climate prediction, with the Climate Test Bed (CTB), is a good partnership between EMC and CPC. Not enough information was provided on the CTB to demonstrate that it is a successful strategy for improving intraseasonal-to-interannual forecasts. The CTB Advisory Panel needs to examine how the CTB is being implemented, and should report to the CWG. No plan was presented for the inclusion of CDA in an MME through the Climate Test Bed.

CPPA focuses on prediction and predictability at seasonal-to-interannual time scales, improved model representation, and scientific issues related to climate predictions useful for hydrology and water resources. All these activities are very important for building NOAA's Climate Services, with effective and continually improving connections with the end users. However, NOAA needs an implementation plan that embraces both climate and water.

CRM management must work to ensure that the transition of research products from labs to operations occurs more effectively. NOAA needs an implementation plan that bridges the gaps between research, operations, and applications. There is currently no mechanism to evaluate the readiness of research results for transition to operations. Conversely, it is not clear how NOAA's operational needs influence the research program priorities and funding decisions.

Each CPO program seems to have its own, idiosyncratic approach to identifying gaps in near-term priorities, and balances between program elements. A more unified strategy would improve effectiveness. Input from the operational elements of NOAA should influence the priorities. The CPO should take care to balance the funding of internal NOAA research groups and Cooperative Institutes with that of the external community to ensure that fresh ideas, perspectives and contributions can be brought forward. The NOAA budget process may not allow the implementation of a long term plan that emphasizes coordination among the labs with the goal of improving operational prediction.

Panel 4: Integration Between and Across Programs and Synthesis of Research leading to Information, and Products and Services

NOAA support for the UN stratospheric ozone depletion assessments, and the IPCC Fourth Assessment Working Group I (AR4 WGI) effort, have superb. The implementation model for the ozone assessments and the IPCC AR4 WGI effort, as well as NOAA's support of these assessments, worked well. NOAA should continue its strong support for the IPCC assessment process. The implementation process used in the ozone assessment and IPPC AR4 worked well and should serve as a model for future assessments. Assessments should be treated as a sustained, strategic element of NOAA's activities. GFDL will need resources to fulfill its future IPCC obligations. Management should determine how much of this can be provided through current and new collaborations, partnerships and linkages. There is a well recognized conflict between basic research and the responsibility to support major assessments. On the positive side, assessments have the potential to *de facto* integrate NOAA's organization units, scientific activities, and services. The CCSP assessment effort contrasts with that of the IPCC in terms political overtones and uneven quality. All policy-influential reports should be reviewed by the National Academy of Sciences in order to remove any possible taint of political bias. NOAA should explore ways to make their success in the policy-oriented scientific assessment process more of a vehicle for cross-CRM and cross-NOAA-climate-program integration. NOAA might benefit from greater engagement with policy scientists, as well as regional climate scientists in this effort to anticipate future assessment needs while at the same time meeting current needs.

The many institutional components of the CRM Program are badly fragmented. Fragmentation is not unique to NOAA; it is characteristic of all Federal Agencies. Fragmentation, like DNA damage, accumulates over time, and often persists despite efforts to eradicate it. Developments at GFDL, NCEP, and ESRL should be more formally coordinated. CRM-relevant research at ESRL was not sufficiently highlighted at the meeting in Princeton. This suggests that the roles of other NOAA Laboratories have not been adequately integrated. In the future, CRM research should involve more collaborations among NOAA laboratories, and also between NOAA and other agencies. High-resolution and decadal time scales are "natural" places for NCEP, ESRL, and GFDL to meet. NOAA-wide integrated budget planning is not apparent in the CRM structure, and the Panel did not see evidence of incentives to link individuals and organizations to NOAA Agency goals.

In particular, the ARCs, Joint Institutes, and Cooperative Institutes need to be reviewed, redefined, and reconsidered in context of a NOAA and CRM Strategic Plan. They should be aligned with NOAA's strategic goals, and balance research and operations. There should be an open competition for groups to meet needs that are clearly identified. Reductions is these areas are a potential source of funding for actions recommend in the Report.

Presentations suggested new directions for the CRM Program in the development of Climate Services. A National Climate Service should be a federated system of existing and evolving assets that recognizes the distributed nature of the generation of climate information as well as the need to incorporate intellectual resources from across society. NOAA is already developing far-reaching and consequential observational and modeling capabilities, products, and services that are intended to serve both NOAA and non-NOAA customers. NOAA’s customers should be more involved in the design and evaluation of these products. NOAA should assume a leadership role in the development of federal-level Climate Services, in a federation with other federal agencies as well as non-governmental organizations.

Panel 5: Decadal Variability and Predictability

There is a growing need for more robust projections of decadal climate change. Considerable progress towards decadal prediction has been made in recent years, and the NOAA scientists' contribution, especially by GFDL, is significant. Whether or not there is any practically useful decadal predictability is not at all clear at present. NOAA, especially GFDL and NCEP, is one of the few organizations that is capable of addressing this question. NOAA should undertake a strategic planning exercise towards (possible) operational decadal predictions. Coordination is needed between GFDL, NCEP, and other research entities on initialization and prediction systems development for decadal prediction. Near-team prediction will soon require considerations of aerosols, chemical species, greenhouse gases, and vegetation, i.e., it will require ESMs. At present, NOAA’s ESM and decadal prediction efforts do not appear to be linked. Computational requirements will also have to be planned for.

Introduction and Overview

On March 24-26, 2008, a Review Panel (hereafter, “the Panel”) convened in Princeton, New Jersey, to review the Climate Research and Modeling (CRM) Program of the National Oceanic and Atmospheric Administration (NOAA). The Review was conducted under the auspices of NOAA’s Climate Working Group (CWG). This was the first-ever external Review of CRM Program. The Program of the Review meeting at Princeton is attached as Appendix A of this Report.

The Review was organized into Sections, defined by topic area. Each Section was addressed by a team consisting of Moderators, a Chair, Panel Members, Presenters, and a Rapporteur. In this Report, the panel reports of each section are organized into Observations, Findings, Recommendations and Concerns. The “Observations” summarize the perceived message of the individual presentations. Naturally these present the NOAA case in an overly positive light with little self criticism. In some cases connections with overall NOAA goals and priorities were made, but the guiding questions posed below were not all directly addressed and only rarely was the panel presented with specific issues to address. The view of the panel is found in the “Findings”. It reflects the expertise of the moderators and other contributing panel members and, therefore, is neither uniformly strong, nor consistent across all Sections. As is to be expected, the “Findings” are often in conflict with the “Observations”. They are followed by specific “Recommendations” that are often aimed at resolving such conflicts. Finally, additional issues are itemized as “Concerns” that NOAA management is asked to consider further.

In an opening presentation, Dr. Chester Koblinsky outlined the structure of NOAA’s Climate Program activities, which he directs. NOAA currently has three climate programs, down from five prior to 2006. The current programs are:

- A Climate Service Development (CSD) Program, which has been created in response to increasing demands for Climate Services to the nation. CSD aims to improve the ability of society to plan for and respond to climate variability and change. CSD includes the International Research Institute for Climate and Society (IRI). Current CSD funding is about $31 M per year.

- The Climate Observations and Monitoring (COM) Program, which is heavily involved with Earth-observing satellites. COM aims to develop and support a predictive understanding of the global climate system The overall purpose is to describe and understand the state of the climate system through integrated observations, monitoring, and data management. Current COM funding is about $150 M per year.

- The CRM Program, whose overarching goal is to develop, understand, and improve the capability to make intraseasonal, seasonal, decadal, and centennial-scale predictions of climate variability and projections of future climate change on global to regional scales. An additional, emerging goal is to attribute observed climate fluctuations, such as droughts, and changes in the Arctic, to specific causes. Current CRM funding is about $78 M per year.

This is the "big picture" within which the CRM Program is being reviewed.

The Panel recognizes that NOAA is a very large, high-profile government agency that is widely distributed across the country, though with pockets of concentrated activities. The Climate Program itself and CRM in particular share these characteristics and are particularly vulnerable to the problems arising from their geographical distribution. For example, GFDL is isolated and more naturally connected with Princeton University than with other NOAA facilities. Complicating these problems is the budget process where multiple NOAA entities receive CRM funding through different streams In cases where CRM issues arise from these greater NOAA circumstances, the panel notes that it is not the appropriate review mechanism.

CRM is broadly based and widely dispersed; it draws on NOAA's seven Research Laboratories, twenty-one Cooperative Institutes, six Regional Climate Centers (RCCs), five Applied Research Centers (ARCs), and five climate-related Grant Programs. The Grant Programs are the Global Carbon Cycle Program, the Climate Variability and Predictability Program, the Climate Prediction Program for the Americas, the Atmospheric Chemistry and Climate Program, and the Climate Dynamics and Experimental Prediction Program. The Panel did not receive a full account of the various roles and responsibilities of these organizations as they relate to CRM.

CRM connects strongly to the COM Program, because modeling is a key to COM's production of observational datasets through data assimilation, and because model evaluation by comparison with COM-supplied observations is a critical activity within CRM. Many activities within CRM rely heavily on NOAA's high-performance computing capabilities.

In addition, CRM must work effectively with other agencies, including DOE (the U.S. Department of Energy) and NASA (the National Aeronautics and Space Administration), which are both heavily involved in climate modeling and observation. CRM recognizes that NOAA cannot do everything in the climate arena.

Dr. V. Ramaswamy of NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) is the Acting Program Manager for CRM. He presented the draft CRM Charter (attached as Appendix B of this Report). Naturally, CRM has a mandate to support NOAA's Climate Mission Goal, as well as other NOAA Goals. CRM produces forecasts on time scales ranging from weeks to centuries. An emerging focus of CRM is natural and anthropogenic variability on decadal time scales.

The Charter clearly articulates the science aspect CRM activities; in particular the goal is to develop, understand and improve climate predictions and projections. Thus, CRM scientists are stakeholders, who should work closely with other stakeholders to identify and generate the products that they need. CRM works to enable national and regional managers to plan for climate variability. In the past NOAA has sometimes "pushed" products to stakeholders, but increasingly stakeholders "pull" products from NOAA.

To achieve its goals, CRM needs a suite of state-of-the-art models, including cutting-edge Earth System Models (ESMs); a strategy for generating the required forecasts; and access to suitable observations. CRM's models are required to achieve a sufficient degree of realism, which can come through resolution and process representation. Uncertainty must be minimized. Prediction of "forced" changes requires quantification of the forcing itself.

Panel 1: Understanding Climate Processes

a) Panel 1a: Climate Processes and Atmospheric Modeling

Observations:

NOAA continues to make measurements of the long-lived non-CO_2 greenhouse gases (CH_4, N_2O, halocarbons, etc.) and to quantify the processes that control the abundances of these gases. For example, studies have shown that global mean OH abundance has been approximately constant (+/- 5%) over the past decade, which is consistent with estimates from atmospheric models. In addition, model studies have shown that CH_4 source estimates are reasonably consistent with observed abundances since 1990, although recent trends in CH_4 may be due to changes in the temperature-dependent CH_4 OH reaction rate or changes in the lightning source of NOx. Tropospheric ozone studies are examining precursor emissions as well as the processes involved in reactions in the troposphere. For example, studies have shown that satellite measurements of NOx and emissions of NOx from fossil fuels over North America are consistent. Model studies have been used to predict transport of CO from polluted regions over the oceans and global concentrations of tropospheric ozone. The goal of stratospheric ozone studies is to quantify the processes that have caused ozone depletion and understand the recovery phase as a result of the Montreal Protocol. NOAA scientists have shown that the ozone hole over Antarctica influences surface temperatures. Changes to ozone and temperature in the stratosphere have been calculated using a 3-D model, and NOAA scientists have made major contributions to the 2006 Scientific Ozone Assessment. Finally, NOAA scientists have continued to work on quantification of water vapor in the UT/LS and on understanding water vapor trends in this region. There has been a significant increase in LS water from 1980 to 2006 that is larger than that which can be explained by increases in methane. These changes are associated with changes in tropical tropopause temperatures that are hypothesized to be related to changes in sea surface temperatures.

NOAA, together with NASA and other agencies, has demonstrated that the reduction in ozone depleting substances by 2010 due to the Montreal Protocol will have been equivalent to 7 to 12 years of growth in radiative forcing due to CO_2. It is important to continue monitoring ozone-depleting substances through the recovery phase associated with the Montreal Protocol. Stratospheric effects on climate and climate effects on the stratosphere involve stratospheric dynamics, stratospheric tropospheric exchange processes, and understanding the connections between temperature changes in the stratosphere and the troposphere on chemical processes. Improved models (through both resolution and parameterized processes) are still needed to better quantify these processes. Continued monitoring of O_3 and H_2O in the stratosphere and the use of models to explain these changes is required. NASA will play a key role in monitoring.

One of the most uncertain aspects of treating aerosols in global models has been to understand the organic aerosol fraction (and its sources) and how organics change the hygroscopic growth of aerosols (and thus their optical properties) as well as how organics alter aerosol/cloud interactions. NOAA has participated in research to quantify growth factors as a function of organic mass fraction in aerosols. They have also pioneered new measurement techniques to quantify the amount of black carbon in the atmosphere, which has been another major uncertainty.

The complexity inherent in aerosol and aerosol/cloud interactions dictates that NOAA adopts a combined field-measurement and modeling approach to improving understanding. Inherent difficulties are due to the difference in scales between the microphysical scales in clouds to the larger scales represented in global climate models. While smaller scale cloud models can be validated using in-situ models, it is not at all clear how to validate the treatment of clouds and their response to aerosols in climate models. For example, satellite measurements of the slope of the relationship between aerosol optical depth (or index) and droplet radius do not match the slopes measured in in-situ observations. Should the global models use the satellite measurements as "validation"? It is not clear what the best strategy here is, but regional networks of observations together with comparison of the global model results with statistical distributions of aerosol properties and cloud/aerosol interactions from both field and large-eddy-simulation models is likely to be needed, with attention to a variety of cloud regimes.

Parameterizing convection on the GCM grid scales continues to remain a challenge. Changes in closure techniques continue to significantly alter results. This is an area where differences in the scales of GCM grid cells and the actual physical phenomena are hampering progress. Observations are needed to evaluate results obtained with high-resolution cloud models.

As models evolve to finer grid spacings, parameterizations must be appropriately modified, and the changes should include the introduction of stochastic, non-deterministic behaviors. Despite the extensive presentations on higher-resolution models, the Panel did not hear any discussion of this important topic.

The largest uncertainty among the topics that NOAA covers is in aerosol/cloud interactions and how to treat these processes within the global models. Climate modeling needs to advance to the point of including effects of air quality.

Findings:

- The topics covered in this session -- troposphere/stratosphere ozone, water vapor in the stratosphere, parameterization of aerosols and aerosol/cloud interactions and convection in global models -- are at the heart of some of the largest uncertainties in climate modeling. Continuing improvement in parameterizations must be emphasized for both conventional coupled models and ESMs.

- Coordination among the many NOAA laboratories and programs was not apparent to the Panel. For example, it was difficult to see any connection between the chemical and physical sciences.

Recommendations:

- As stratospheric ozone continues to recover, related research should evolve away from the ozone hole *per se*. However, understanding changes in stratospheric water vapor continues to be important, and understanding how changes in stratospheric ozone relate to climate changes continues to be important.

- The relationship between observations and improvement of global models would benefit from a higher level of coordination as well as visibility within the program.
- Emphasis on understanding basic processes should be balanced with improving the models.
- Advancing understanding should emphasize decreasing uncertainty in aerosol/cloud interactions and how to treat these processes within the global models, though improvement of the other processes needs to continue to be developed.
- Management should emphasize better coordination between measurements and modeling and between small scale process modeling and large scale prediction. This will be crucial to improve parameterizations in large scale models.
- There needs to be a long range plan that emphasizes how the development activity will be integrated into an operational capability.
- There is a need for better connection of the chemical and physical sciences and the role of chemical science and air quality in NOAA.
- A Strategic Plan is needed, to define how the various activities fit together into a coherent whole.

Concerns:

- There seems to be a lack of overall strategic planning. For example, since the overall goal of NOAA's activities is operational prediction, there should be a strategic plan to reach this goal. The lack of a strategic plan manifests itself in the lack of development of a coherent capability.
- There does not seem to be any Strategic Plan to include data assimilation as a means of improving parameterizations in the models.
- The Panel was not briefed on the use of smaller-scale models to help in the development of parameterizations.
- The NOAA budget process may not allow the implementation of a long term plan that emphasizes coordination among the labs with the goal of improving operational prediction.
- The process for identifying necessary field studies is not apparent to the Panel.

b) Panel 1b: Ocean Processes and Carbon Cycle

Observations

NOAA's Climate Research and Modeling Program has developed a world-class ocean research effort that has made major contributions to understanding, diagnosing, and predicting seasonal, interannual and decadal time scales in the climate system. Three major ocean models are involved: HyCom, primarily used at NCEP (the National Centers for Environmental Prediction); MOM, the Modular Ocean Model, widely used in the climate community; and HIM, an isopycnal coordinate model. Capabilities of the latter two are available within GOLD, a new GFDL ocean modeling framework.

Studies of the effects of ocean eddies using high-resolution simulations revealed a 40% difference in the response of the Atlantic Meridional Overturning Circulation to enhanced greenhouse-gas forcing relative to the response of parameterized eddies at ocean resolution like that used in the simulations done for the Intergovernmental Panel on Climate Change (IPCC). GFDL ocean scientists participated in two CLIVAR Climate Process Teams (CPTs) combining theory, observation, and modeling to study (a) the impact of the Mediterranean outflow on the circulation of the North Atlantic and (b) mesoscale eddies in the mixed layer. A quite different activity in Southern Ocean carbon cycling is unfortunately also referred to as a CPT. Here ,GFDL scientists have conducted interesting and important experiments looking at the response of the ocean biogeochemistry to climate change, and are currently incorporating more sophisticated ocean biogeochemistry parameterizations. NOAA oceanographers at the Pacific Marine Environmental Laboratory (PMEL) have mapped air-sea exchange of CO2 by combining observations made by repeat hydrography with models, and have studied the impact of ocean acidification.

Findings

- The carbon modeling efforts at GFDL suffer from a "not invented here" syndrome, in which science and algorithms developed in the larger community filter into the models more slowly than they should. Carbon modeling in NOAA's CRM program would benefit from more vigorous interaction with the observationalists (e.g., the eddy covariance network, FACE experiments, ocean acidification mesocosm experimentalists, atmospheric constituent observers) to evaluate and improve model components and the coupling to the physical climate system.

- Even within NOAA, there appears to be insufficient interaction between CRM and observing systems. The CLIVAR Climate Process Teams are examples in which observationalists and modelers work together: such collaborations have synergistic advantages beyond just comparing models to observations. CRM research should be able to influence the priorities and design of the observing and monitoring system for carbon in the oceans and the atmosphere.

- The GFDL-NCEP connection provides a unique opportunity for initialization of decadal prediction with the ESMs, but this has not been exploited.

- The Panel was not convinced by assurances that ocean modeling within CRM is coordinated and heading in the same direction, because there is no agreed-upon Strategic Plan.
- The Panel finds that a lack of computer power limits high resolution numerical experiments.

Recommendations

- The CRM Program needs to better integrate with NOAA observational and modeling efforts to improve the observing system, the models, and the predictions. NOAA's program represents a unique opportunity among climate research efforts in US to leverage national investments in observations, operational prediction, and predictive modeling by taking advantages of synergies among them. Past work with CLIVAR Climate Process Teams (CPTs) has been very productive. It has been a part of the integration strategy. The Panel recommends additional targeted CLIVAR CPTs to take advantage of the wealth of Earth system observations to improve operational seasonal to interannual forecasting, initialization of decadal prediction, and climate projection. NOAA should continue to fund NOAA scientist participation in CLIVAR CPTs. Regular meetings among key NOAA CRM researchers from all supported labs (including GFDL, ESRL, PMEL, AOML) and related University research colleagues on specific topics (e.g. ocean carbon) would facilitate such interactions.
- NOAA should continue to push the resolution envelope, at least for decadal-scale modeling. Sensitivity experiments have already indicated that process-level realism can be improved by a transition to eddy-permitting resolution. The Panel encourages an exploratory investigation of the results obtained with an eddy-permitting ocean model coupled to a cloud-resolving atmospheric model. For physical and biological systems, improved resolution of coastal systems is vital.
- The state of understanding of the interactions among coastal upwelling, advection, nutrient cycling, river inputs, and estuarine biogeochemistry and sedimentation remains poor. Progress in this area will likely require experiments at very high resolution in collaboration with experimentalists and data from field campaigns.

Concerns:

- Work on the coupling between the carbon cycle (especially on land) and the climate model appears to be under-funded. Coupled carbon/climate modeling will require a concerted effort if GFDL is going to maintain their "best" model status in the IPCC Fifth Assessment.
- The role of PMEL in CRM is not clear to the Panel. Apart from the discussion above, PMEL was not mentioned anywhere else in the presentations made to the Panel.
- GFDL modelers have taken little advantage of the opportunity to evaluate and prioritize model improvements through collaborations with NCEP, which conducts operational

climate data assimilation and seasonal-to-interannual prediction constrained by a wealth of observations and with an almost completely disjoint set of modeling tools.

- Only two full-time people are currently funded to work on the ocean carbon cycle in the ESM, and one person on the terrestrial carbon cycle (through collaborations at Princeton): this is sub-critical. There may be additional resources available at Princeton and through other collaborations, and there is a large community working on decadal- to century-scale projections of carbon-climate modeling. In addition, there is the effort of Carbon Tracker (discussed below) which could be coupled to the GFDL modeling effort to better use NOAA resources in attaining improved carbon/climate modeling. Development of the ESM will require additional resources in this area and stable strategic plans to take appropriate advantage of collaborations with this larger community.

Panel 2: Reanalysis and Data Assimilation and Carbon Tracking

Observations

The activities being undertaken by CRM encompass the Climate Forecast System Reanalysis and Reforecasting project for the satellite era (the CFSRR), a climate reanalysis with the pre-satellite era observing system (Reanalysis of the 20^{th} Century), ocean data assimilation with both seasonal and decadal prediction goals (Coupled ensemble filter Data Assimilation (CDA), and real-time estimates of CO_2 transport (CarbonTracker) over the U.S. as a service to the research and application communities.

The CFSRR is groundbreaking, and it is being done in a weakly coupled sense – the first guess for the atmosphere, the ocean and the sea-ice comes from a coupled integration. The CFSRR represents collaboration between NCEP/EMC (the Environmental Modeling Center), NESDIS (the National Environmental Satellite Data and Information Service), NCEP/CPC (the Climate Prediction Center), and NCDC (the National Climatic Data Center). The last will distribute the end products to the external users.

The decision to proceed with Reanalysis of the 20th Century has been made. A limited evaluation, primarily of height fields, has shown that the products will be "useful." However, this optimistic assessment applies more strongly to the Northern Hemisphere middle and high latitudes; it does not extend to the tropics, and is lower for the Southern Hemisphere middle and high latitudes. Only two data streams will be provided as input to the assimilation systems: reconstructed sea-surface temperatures (SSTs), and surface pressure. Much of the climate information content will come from the way the reanalysis projects the reconstructed SSTs, in the presence of the surface pressure observations.

The Coupled ensemble filter Data Assimilation (CDA) effort is aimed at advancing ENSO prediction, by mitigating atmosphere-ocean coupling shock. The land and sea-ice components are neglected in the assimilation. This effort is groundbreaking, and is the first apparent breakthrough in several years for improving seasonal prediction skill. The CDA is also being applied to a global analysis of ocean temperature and salinity, which is being applied to initialization of multi-decadal oceanic variability, in particular 20th century ocean climate change and the predictability of climate variability associated with the Atlantic Meridional Overturning Circulation. To date only perfect model experiments have been performed. A two member multi-model ensemble (MME) uses CM2.0 and CM2.1 (versions 2.0 and 2.1 of GFDL's coupled modeling system).

The CarbonTracker is an ensemble data assimilation system that analyzes seasonal carbon fluxes at sub-continental scales by optimizing the fit to CO_2 observations made by ESRL and collaborators. The CarbonTracker is based on process "modules" which predict spatial and high-frequency temporal variations in CO_2 fluxes due to fuel combustion, air-sea gas exchange, terrestrial ecosystems, and wildfire. Each component flux is scaled weekly over relatively large regions (12 for temperate North America) to match observed variations of CO_2 within error specifications. Atmospheric transport is run for five weeks in each ensemble member, and error covariance in the model background is reset in every assimilation cycle (a "cold start" in DA parlance), which limits the ability to estimate uncertainty. The system has a lot of visibility as an outreach product through its beautiful web interface, which publishes global monthly maps of CO_2 sources and sinks on a relatively fine mesh.

Findings

- The CFSRR, the Reanalysis of the 20th Century, the CDA, and CarbonTracker are groundbreaking and risky undertakings. The risks need to be managed. The planning of these important activities could have benefited from a more extensive formal scientific review by the external community, including the intended customers of the analysis products.

- CRM has taken the first step ever towards a fully coupled Integrated Earth System Analysis by coupling the system through the first guess forecast, although the component analyses themselves are uncoupled.

- The schedule for the CFSRR is driven by that of the seasonal forecast application. There is no external scrutiny of the scientific quality of the analysis from a climate time series perspective.

    - The CFSRR is currently using the resources of the Climate Test Bed, and yet it needs more resources to meet the needs for both analyses and historical forecasts required to define the climatological coupled forecast bias.

    - The CFSRR should undertake an exercise to demonstrate the performance of the system, and should involve external community early in the evaluation rather than relying entirely on the internal monitoring of the system.

- The Reanalysis of the 20th Century is difficult and less constrained than the past NCEP reanalyses. There is healthy skepticism towards this project. Significant problems with the products are expected, especially with compatibility between sea-ice and the SSTs.

    - Spurious climate signals should be minimal, but not necessarily negligible. They are expected from changes in the SST and surface pressure global sampling and observational methodologies. There is an implicit faith in the SST reconstructions, and belief that these SSTs can drive the climate with fidelity, but neither is so certain.

    - It is in NOAA's interest to lead and promote external critical assessment of the products, because uninformed usage of unreliable products should be anticipated, but is contrary to the CRM charge, which explicitly says that such reanalyses are to lead to understanding.

    - The project and users need to agree that the proposed estimates of biases and uncertainties are sufficient indicators of product quality, and how these or other quality estimates will evolve to reflect user experience.

- The Coupled ensemble filter Data Assimilation (CDA) development at GFDL is impressive in its impact on seasonal prediction skill of equatorial SST. The impact apparently arises from the improved consistent initialization of the ocean and atmosphere. No analysis was presented of the larger aspects of prediction skill – skill in SST outside the Niño-3 region, and more importantly, skill in surface temperature and precipitation over the continental U.S.

  - No plan was presented for the inclusion of CDA in an MME through the Climate Test Bed.

  - The CDA has very close potential links to NCEP CFS, but the models and data assimilation techniques differ.

  - Investigations into the predictability of climate associated with the Atlantic Meridional Overturning Circulation are showing promise, but are still preliminary. The results of Observing System Simulation Experiments (OSSEs) may be overly optimistic.

  - Computing resources are limiting, as are model biases, but observations less so than before the ARGO floats were deployed. Many biases are likely common to both members of the MME.

- Carbon Tracker modules currently have no relationship to other CRM models, and there is no institutional mechanism to allow CRM carbon component models to be improved by Carbon Tracker optimization, nor to use the excellent process representations in the ESM to interpret Carbon Tracker output. The Carbon Tracker's land model is CASA, air-sea flux is based on Takahashi's climatology, fires are estimated by Prof. James Randerson's group at the University of California at Irvine, and fossil fuel emissions are from a U.S. Department of Energy climatology. The Carbon Tracker calculates weekly regional multipliers on each flux but there is no way for the system to learn over time.

Recommendations

- The CFSRR needs more connections to its customer base, and should survey the community as part of a process to define the product streams.

- The CFSRR should undertake a validation to demonstrate the performance of the system and should involve external community early in the evaluation rather than relying entirely on the internal monitoring of the system.

- NCEP/EMC and NCDC should consider a distributed and incremental archiving of the reanalysis rather than waiting until the entire reanalysis is complete and shipping the end-product to NCDC for archival and distribution. Such an archival strategy would allow broad access to the products and support re-processing if and when problems are found with any portion of the first processing.

- The project and users need to agree that the proposed estimates of biases and uncertainties are sufficient indicators of product quality, and how these or other quality estimates will evolve to reflect user experience.

- The above recommendations also apply to the 20th Century Reanalysis.
- NOAA management should determine if, when, and how the CDA should transition to CFS, and if not, why it should continue at GFDL.
- The CRM Program should recognize that the predictability of the Atlantic Meridional Overturning Circulation will continue to be a research problem, rather than an operational problem, for the foreseeable future.
- CarbonTracker should receive rigorous scientific review, and it should be integrated more fully with other CRM projects.
- An effort should be made to include ESM component models in CT, at least as part of a "MME" for carbon. Rather than simple regional scaling factors, model state variables (e.g., woody biomass, ocean nitrogen) or parameters (e.g., carbon allocation, carbonate ballasting) could be improved over time as the models are repeatedly confronted with atmospheric observations. Such a collaboration within NOAA CRM would improve the Carbon Tracker analyses, might expose weaknesses in ESM, and would help initialize ESM components for decadal prediction.
- Despite workshops that have articulated the need for an ongoing national program to produce periodic reanalyses, no such program has emerged. Since reanalyses have generally been conducted by numerical weather prediction centers/activities, the Panel recommends that NOAA take the lead in forging an interagency partnership to create a national program.

Concerns:

- International collaborations are also needed in connection with the reanalysis activities, especially for acquisition and quality-control of data.
- There is no apparent coordination/interaction between NCEP/EMC and GFDL in their ocean data assimilation activities. As models and data assimilation techniques at GFDL and NCEP diverge, the likelihood of timely convergence with mutual benefits diminishes.
- There is a need for Observing System Simulation Experiments, and an assessment of the value added by any proposed new flux towers. NASA involvement seems natural.

Panel 3: Earth System Modeling, Predictions, and Projections

a) Panel 3a: Modeling Overview

Observations:

GFDL aims to remain a world leader in climate research, and the development of Earth System Models (ESMs). It defines an ESM as a global physical model plus the carbon cycle, namely; atmospheric transport and chemistry coupled to ecology and biogeochemistry both on land and in the ocean.

GFDL has contributed in major ways to the IPCC, especially the Fourth Assessment, and also to U.S. Climate Change Science Plan's Synthesis and Analysis Products, the World Climate Research Plan, and other national and international programs. It is also addressing critical climate problems.

GFDL benefits from numerous collaborations, partnerships and linkages with other NOAA laboratories and programs including NCEP, universities, other U.S. agencies and international institutions.

A major message from GFDL is its "crucial need for dedicated computational and human resources."

There is a conflict between basic research and the responsibility to participate in and support major assessments. This is not unique to NOAA, but it is a problem for NOAA, and for GFDL in particular.

NCEP has a well planned strategy for developing and maintaining the Climate Forecast System (CFS = GFS + MOM3) as a national model. CFS is the end member of a seamless suite of NOAA forecast products spanning climate and weather. Forecasts across all scales include MMEs. A recent increase in forecast skill of U.S. seasonal temperature is unprecedented, but not understood. There is a commitment to accelerate CFS improvements through "Operations to Research" (O2R) and "Research to Operations" (R2O), though there is more emphasis on the former. The crucial ingredient of the latter is the Climate Test Bed, which is limited by design and resources.

Findings:

- GFDL operates, primarily, as a quasi-independent entity within NOAA, and presents its past successes in support of maintaining this status. A number of promising potential NCEP-GFDL collaborations were presented to the Panel only as "opportunities". The strengths of the partnerships with the Cooperative Institute for Climate Science, the Cooperative Institute for Climate Applications Research, and other named collaborators, are not clear.

- Although NCEP-NWS collaborations refer to MOM, NCEP itself is investing in HYCOM.

- GFDL modeling collaborations include work “towards community based modeling framework” and “towards a NOAA common modeling framework for ESMs.” It is not clear how these are related to each other and to the Earth System Modeling Framework (ESMF) used by NCEP.

- Current GFDL priorities seem to be aimed at maintaining its leadership position in climate modeling, but not in ESM development. It was not clear to the Panel whether or not this is a deliberate choice by management.

- NCEP is committed to the MME.

- NCEP is not benefitting from the contributions from the external community at levels anywhere near those at similar facilities abroad, such as the United Kingdom Meteorological Office (UKMO) and European Center for Medium-range Weather Forecasts (ECMWF).

- R2O is hampered by the fact that grants are not administered by NCEP.

Recommendations:

- GFDL and NOAA management should reach a mutual agreement on the relative priorities of Climate Modeling and ESM development. Then the various critical climate problems should be prioritized, and resources allocated accordingly.

- GFDL needs to make a strategic decision as to whether or not it wants to take a leading role, nationally and internationally, in ESM development.

- Management should determine to what extent future IPCC obligations can be supported through current and new collaborations, partnerships and linkages.

- GFDL and NCEP should collaboratively perform an evaluation of HYCOM’s overall performance as an ocean model for use by NCEP.

- NCEP should give higher priority to understanding climate, as per the draft CRM charge. In particular, it should consider whether the empirical result that the MME has improved forecast skill has a satisfactory theoretical basis.

- NCEP should develop the automated metrics that are appropriate to measure the skill of climate predictions.

- NCEP should develop more formal and persistent mechanisms for scientific interactions with the outside research community.

- NOAA management should assess the success of the Climate Test Bed, and develop a strategy for it to reach its potential.

- NOAA needs to lead and develop the national strategy for intraseasonal to interannual climate prediction inclusive of MME, data assimilation, forecast metrics.

- The computing requirements for a National MME should be included in the NCEP climate computing request for 2011.

Concerns:

- GFDL will not be able to establish or maintain leadership in ESM development without much more extensive collaborations with and contributions from the external community.
- CRM-relevant research at ESRL was under-represented in the presentations made during the meeting in Princeton. This point will be raised again later.
- NCEP's move to the University of Maryland campus will promote interactions with the university community, analogous to those between the UKMO and the University of Reading, but the same move may also diminish the impetus for NCEP to collaborate with GFDL.
- NCEP's (appropriate) focus on forecast skill and the CRM's charge to achieve an understanding of climate need not be mutually exclusive.
- The Panel is concerned that NCEP may not have identified the computing resources needed to support the MMEs.

b) Panel 3b: Model Development

Observations:

Model development at GFDL is now strongly constrained by the IPCC cycle. Following the IPCC's Fourth Assessment, GFDL scientists drafted a white paper plotting GFDL model development over the next 5 to 7 years. In addition, the model development leaders get together every quarter to assess progress.

GFDL's model-development strategy involves two activities that are proceeding in tandem:

- development of high-resolution atmospheric and ocean models, and
- development of a comprehensive but low-resolution Earth System Model (ESM).

A. High-resolution modeling

The average grid spacing of the IPCC AR4 atmosphere models is 200 km. This is not adequate to resolve the Earth's surface hydrology. Something closer to 50-km grid spacing is needed to resolve such features. A growing body of experience suggests that 50 km grid spacing should be used in global change research. AM2.1 and NCAR's Community Atmosphere Model are both being run globally with 50-km grid spacing in time-slice mode, using prescribed SSTs, with good results.

The current atmospheric model, AM2, is not suitable for studying hurricanes. Its convection scheme has been modified to simulate hurricanes with observed sea surface temperatures, but the model does not simulate the trend in the reanalysis, as previously discussed. The 50-km grid does a good job of simulating the frequency of hurricanes, although hurricane intensity is not well simulated. Many GFDL scientists would like to use the 50-km model, but limited computational resources prevent this. GFDL needs major increases in computational power to enable additional, immediate useful research with such high-resolution models.

GFDL's research on high-resolution modeling will make use of a range of grid spacings, from tens of kilometers to just a few kilometers. Over time, the results of the high-resolution studies will feed into the ESM project.

As an example of ongoing research with high resolution, the focus of the NARCCAP (North American Regional Climate Change Assessment Program) is to use a 50-km model over North America with model output 8 times daily. As a second example, a regional model with 18-km grid spacing has been used to simulate the Atlantic hurricane season from 1980 to 2006. The model produces excellent simulations of the year-to-year (ENSO-related) variability, and also simulates the observed trend. It is not clear that the trend is being simulated for the right reason, because the reanalysis that is used to force the model gradually becomes more unstable with respect to moist convection. There is an ongoing discussion as to whether this increasing instability is realistic.

AM2's finite-volume core, based on spherical coordinates, has been a community resource for the last ten years or so and was used in three of the top AR4 IPCC models. A need for improved dynamical cores comes in part from the weather forecasting community, and the required fundamental modeling research is done partly at GFDL and ESRL. In particular, because of the need for improved computational efficiency, AM3 (the next generation atmospheric model) needs a new dynamical core. GFDL has recently developed a new, nonhydrostatic core based on a "cubed sphere" grid, which has quadrilateral grid cells. The grid provides a more uniform resolution than a grid based on spherical coordinates. The new core is more scalable, and provides a large performance boost; in particular, it makes tracer transport in the model much more efficient, which is important for atmospheric chemistry. The long-term strategy for studying regional climate and hurricane dynamics is to use the cubed-sphere non-hydrostatic model (or its successors) with high resolution. The goal is global cloud-resolving weather-climate models, and the question is not whether they will be used, but when.

S.-J. Lin showed some examples to demonstrate that the dynamical cubed sphere core does not introduce artifacts (a "grid signature") into the model or affect the physics underpinning the models, and in fact, reduces some of the "code bias" errors seen in previous models and leads to substantial improvements in our ability to represent dynamical fields such as winds and temperature. He also presented some examples of output from prototype very-high-resolution (cloud-resolving) models, and showed the improvements in tropical cyclone simulation gained by increasing resolution. This work is still computationally limited, and more computer resources are needed to make progress at the very high resolution. In the mean time, the new dynamical core is improving both the quality and computational efficiency of GFDL's current-generation atmospheric models.

GFDL is also collaborating with ESRL on the development of a non-hydrostatic geodesic grid version of the Finite Volume core. This work has been done primarily at ESRL. It is not clear how or whether the GFDL and ESRL activities are coordinated. The Panel does not understand how or whether the ESRL work is coordinated with NCEP/EMC.

The eddy-resolving ocean model is being studied in the hope that the results will point the way to improvements in lower-resolution models, but was not compared to alternatives. An eddy-resolving simulation of the Southern Ocean produces many realistic results, but does not respond appropriately to changes in wind stress This activity will need to be greatly enhanced if it is to keep pace with developments elsewhere.

Overall, the presentations carefully avoided measures of fidelity, so there is no way of judging how well the model development is progressing. Model development should involve collaborations among NOAA laboratories, and also between NOAA and other agencies. The CPT framework for organizing a group that consists of both modelers and process researchers to talk about model deficiencies seems to foster such collaborations. The bilateral relationship with universities (e.g., the Princeton University vegetation model) helps to get to improved understanding of the processes in the model and tends to be successful. High-resolution and decadal time scales are "natural" places for NCEP and GFDL to meet. ESRL also appears to be interested in this.

B. Coupled modeling

The Panel was impressed with GFDL's coupled climate modeling strategy. It emphasizes comprehensiveness. The challenge in coupled model development is the balance between competing goals.

Two ocean models are currently being tested. One has a depth coordinate and performs better in weakly stratified regions. The other has a density coordinate and performs better near a sloping bottom. Apparently neither performs well in all situations. GFDL expects both ocean modeling activities to continue for the foreseeable future.

GFDL's land-model development activity includes dynamic vegetation, subgrid heterogeneity, and river routing. While some parts are innovative, the bulk of the modeling effort does not appear to be at the cutting edge. Land-ice modeling is a critical area for future development, but is currently in its infancy. IPCC AR4 could not estimate sea level change arising from altered land ice dynamics though is preferable to estimating it poorly. Future work will include modeling ice shelves, including grounding-line movement.

Model coupling infrastructure requires continuous, parallel development of multiple components. There is a need for fast models, fast computers and long-term observational datasets. Long runs are necessary to characterize model behavior, and to permit simulations of the statistics of slowly varying phenomena, e.g., ENSO. As an example, prior to the implementation of a Convective Momentum Transport parameterization, AM2 produced a weak

ENSO. The Convective Momentum Transport parameterization has improved the zonal wind stress, delayed the ocean adjustment to changes in winds, and shifted the ENSO to a slower time scale.

Current climate models predict large greenhouse gas responses, but uncertainty arises in part because the models do not yet include the global cycling of carbon. GFDL is developing an Earth System Model that includes representations of the marine and terrestrial ecosystems. It has dynamic vegetation, including species succession. It emphasizes “coupled carbon modeling.” It does not currently include an economic model, but it does represent land use. No plans were put forward to include a nitrogen cycle.

C. Earth System Modeling

Earth System Models have many potential applications beyond prediction of the carbon system. The GFDL ESM can address the fate of anthropogenic CO_2; the ecological impacts of increased atmospheric CO_2, ocean acidification, and the attendant climate change; the role of land use in carbon cycling, and the potential effectiveness of CO_2 sequestration strategies.

The development of an ESM requires sustained collaboration across diverse disciplines. There is a need for resolution of physical processes on a wider range of scales. It is necessary to synthesize community knowledge into parameterizations. GFDL scientists follow several approaches to evaluate and build the model, and also engage actively in small projects. For example, a project with the U.S. Department of Energy provides checks on the dynamic vegetation and carbon cycle models by making use of Forest Services inventories and flux towers. A Carbon Process Team has been awarded to Princeton University to develop and evaluate carbon and nitrogen and allows GFDL scientists to take uncertainty and constrain it with data. The magnitude of fertilization determines whether land vegetation is a net carbon source or sink. There is no current consensus on the effects of CO_2 fertilization. The magnitude of the Southern Ocean CO_2 uptake is the big question with respect to prediction challenges on the ocean side. Ocean observations are sparse in winter.

Running the carbon system to a steady state is very expensive. Ocean biogeochemical time scales are on the order of 2,000 years. The GFDL carbon model, currently under development, is run for simulated centuries.

Extending the ESM beyond carbon will require additional intellectual and computational resources. The future of Earth System Modeling includes coupling with atmospheric chemistry, river biogeochemistry, integrating elemental cycles beyond carbon, coastal and estuarine interactions and ecological prediction of hypoxia, harmful algal blooms and fisheries capacity variability.

D. NCEP modeling

NCEP modeling has made strong advances over the past decade. NCEP is now focused on producing a “seamless suite” of forecast products. The Climate Forecast System is being used in the CFSRR, as described earlier. The current model development and testing cycle will come to a conclusion in 2010. All components -- atmosphere, ocean, land surface, and sea ice -- are being upgraded. The assimilation algorithms are also being enhanced, for example to assimilate over a deeper layer of the ocean (2200 m depth, versus 750 m now). The model is being tested in part through CMIP runs with variable CO_2.

NCEP intends for the CFS to become a national resource. NCEP will participate in a multi-model ensemble enterprise, although at this time there is no formal plan or strategy. The multi-model ensemble is being pursued in part through collaboration with COLA. The CFS will be made available to the national research community. An annual CFS workshop is planned. This should lead to faster improvement of the CFS through evaluation by a broader community with a broader range of applications.

All of this will be facilitated by NCEP's impending move to the University of Maryland campus. It has been suggested, however, that the move could actually work against strengthening future collaborations between NCEP and GFDL.

The Panel did not receive a clear explanation of how and whether NCEP modeling activities are coordinated with those at GFDL and ESRL. This issue was also raised under Panel 3a, above.

E. Computing needs

NOAA management has asked for a detailed plan for revitalizing NOAA high-performance computing (HPC) for fiscal year 2010. Traditionally, NCEP, ESRL and GFDL addressed their computing needs independently, which meant that NOAA was going to Congress for computer resources every couple of years. Now the three are working to come up with a strategic, unified procurement for all of NOAA R&D computational needs, under the management of the Environmental Modeling Program. The Panel was provided with the recommendations concerning HPC communicated to VADM Lautenbacher in a letter from David Fluharty on April 4, 2007.

The Panel saw presentations that focused on the computational environments at both NCEP and GFDL. These environments support both production and research. The application suites include codes that require the greatest capability that the computational platform can deliver to a single application as well as ensemble-based applications that require high-capacity computing. The Panel is under the impression (but cannot document) that, compared with ten years, ago the amount of computing available for research relative to operations has improved, although we infer from the presentations that this trend may now have ended.

The computational aspects were presented with a focus on the high-performance computing engine and focused on the need for cycles. The NCEP presentation highlighted the central importance of the operational forecast-assimilation system to their suite of operational and research products. It was stated that more than 1.7 billion observations were being assimilated every day. NOAA has sought and used opportunities to partner with DOE and NASA in order to pool computing resources. The runs performed using these resources were designed to test grand challenge scale problems. The type of collaboration and experimentation is important for specific scientific or computational tests. The experiments also reveal that there are not sufficient marginal resources in the community to sustain the computation needed for these experiments.

NOAA is also working towards unifying software, in part through the use of ESMF. The Panel commends NOAA's active adoption of software frameworks. Both the pioneering efforts of the Flexible Modeling System at GFDL and the incorporation of the Earth System Modeling Framework at NCEP and GFDL have added order to the software development process of key models. During presentations in the Review, software frameworks were credited with helping to maintain and build important modeling capabilities.

Many of these observations represent a positive change in NOAA culture towards cooperation and coordinated resource management.

Findings:

It is evident that for both the generation of standard products and the research and development of future models, there is currently a shortage of computational resources. NOAA is negatively impacted relative to its potential and relative to its competitors. There are enhancements to the suite of products and experiments with advanced models that would benefit immediately from additional computational resources.

Since next-generation models are generally of higher resolution and include more complete and more robust representation of processes, research models are by definition more computationally demanding than current-generation operational suites. Further consideration of the experimentation that is required for development and validation reveals that the need for computational cycles for research computing far exceeds those needed for operations. Then, if there is a desire to broaden the research community to embrace innovation the requirements for research computing scales with the size of the community.

While recognizing the importance of the computational cycles, the Panel is concerned that more emphasis on the computational system as a whole needs to be exposed. The computational attributes for assimilation are different than for century-long climate model experiments. Further, as more and more research instruments are used for routine assimilation, the data acquisition, management, and quality control becomes more challenging.

There were presentations that discussed the need to support the transition of research to operations and the provision of operational algorithms to the research community. An essential element of achieving such connectivity is computational infrastructure. Because of the requirements of testing and validation, this too, contains elements of high-performance computing. The development of the system design to support this closed loop of research to operations to research would place the development of these long-argued for capabilities on a more secure footing. Currently, the process to request a particular computer to support a particular element of this infrastructure appears *ad hoc* and anchored in budgetary opportunity.

Based on the Review, the Panel re-emphasizes the recommendation of Fluharty's April 7, 2007 letter of a need for a more integrated NOAA approach to high performance computing. We emphasize that this does not imply that there should be "centralized NOAA computer." In fact, the heterogeneous nature of the problems and the varying missions in the different organizational units virtually assure that a one-size-serves-all HPC environment does not best serve NOAA. Emphasis should be placed on end-to-end systems design anchored on the software of the research and applications suites and data system requirements. There are key financial gaps, and the needed computing upgrade will cost about $150 million, with sustained expenditures for the foreseeable future. NOAA also has citing problems as the existing facilities cannot house the required computational systems. Given high-performance networking and the development of a resource management strategy, NOAA should consider a centralized facility. (Note: a centralized facility is not the same as a single computational environment.)

Historically NOAA as a whole has not participated as a primary player in the Federal HPC community. The exception has been GFDL at various times over its history. NCEP has in recent years procured computational services. The facility in Boulder has, at times, pursued innovative, productive computational paths.

ECMWF has followed a largely successful model for acquisition of computational services. They have always maintained a strong, strategy-oriented in-house HPC team. They have had an emphasis on software, and a sustained interaction with the HPC vendors through a program called Real Applications of Parallel Systems (RAPS; see http://www.cnrm.meteo.fr/aladin/meetings/RAPS.html). Given that state-of-the-art climate models form a niche in an HPC community which is already a niche in the computational market as a whole, these sustained relations with vendors are important for keeping software execution efficient, indeed, viable.

Recommendations:

A. Modeling

- The high-resolution modeling activity provides a strong incentive for a major enhancement of computing resources.

- The ongoing atmospheric dynamical core development is very promising. Developments at GFDL, NCEP, and ESRL should be more formally coordinated, however.

- The parallel development within GOLD of MOM and HIM based capabilities at GFDL is potentially wasteful, especially when moving into the eddy resolving regime and data assimilation . Clearly both models have merits, so a consensus plan is needed. One of the models might be officially recognized as primary, while the other undergoes development in the background as resources permit. Cross-fertilization between the two efforts, and also with the atmospheric dynamical core activity, should be encouraged.

- The coupled climate modeling activity is critical to future IPCC participation, and to other projects. A formal pathway should be defined for model components to move from the ESM to the coupled climate model. The merits of coordination between GFDL's ESM and other national efforts such as NCAR's CCSM should be reconsidered. NCEP's data assimilation and reanalysis activities are critically important for the study of the climate system and the evaluation of climate models. This needs to placed on a more sound funding and scientific foundation (see the discussion in connection with Panel 2).

- Care should be taken to maintain and enhance ties between GFDL and NCEP as the latter moves to the University of Maryland campus.

B. Computing Needs

- The Panel concurs in spirit and principle with the comments and recommendations in the letter of April 4, 2007 from David Fluharty to VADM Lautenbacher focused on HPC.

  - There is a need for a more integrated NOAA approach to high performance computing. We emphasize that this does not imply that there should be “centralized NOAA computer.” In fact, the heterogeneous nature of the problems and the varying missions in the different organizational units virtually assure that a one-size-serves-all HPC environment does not best serve NOAA. Emphasis should be placed on end-to-end systems design anchored on the software of the research and applications suites and data system requirements. There are key financial gaps are, and the needed computing upgrade will cost about $150 million, with sustained expenditures for the foreseeable future. NOAA’s existing facilities cannot house the required computational systems. Given high-performance networking and the development of a resource management strategy, NOAA should consider a centralized facility. (Note: A centralized facility is not the same as a single computational environment.)

  - NOAA should develop a “core team of HPC expertise.” NOAA needs to take primary responsibility for maintaining the computational viability of its critical software. This is not a problem of simple procurement of computational systems. Again, the emphasis should be on software and data; computational systems are ephemeral.

  - NOAA should establish stronger relationships with the other Federal agencies, as well as the vendor community.

- “System diagrams” that expose not only the need for cycles, but that also capture the requirements for memory, memory bandwidth, the data system, communication, degree of parallelism, etc. should be drawn up to define the computational environment more robustly and contribute to better strategic management and acquisition of computational systems.

- A work flow model for research activities and operations should be built to expose the need for research computing and help to define the requirements for the system. For a sustained, robust activity such as GFDL or NCEP, an operational environment using on the order of 15% of the total computational capacity is robust.

- Given that state-of-the-art climate models form a niche in an HPC community which is already a niche in the computational market as a whole, sustained relations with vendors are important for keeping software execution efficient, indeed, viable. The Panel recommends that NOAA investigate participation in RAPS or a RAPS-like consortium (http://www.cnrm.meteo.fr/aladin/meetings/RAPS.html). This would have significant impact for the U.S.'s HPC culture.

- The Panel encourages continued development of software frameworks and participation in the Federal and academic communities that are developing software infrastructure.

Concerns:

- Very few quantitative measures of success were presented.
- Work on parameterizations for atmospheric models deserves a higher degree of visibility than it received in the presentations to the Panel. Many serious problems remain. The panel was not briefed on the use of cloud-resolving models to test or improve parameterizations, although we know that such work is ongoing. Future Reviews should cover these and related items more comprehensively.
- The carbon cycle is strongly influenced by the water, nitrogen, and phosphorus cycles. The Panel is concerned that these connections are not receiving enough attention within the ESM effort.
- Model development work at ESRL was inappropriately under-represented at the Review.
- The funding, acquisition, and management of NOAA's high-performance computing and networking provides a major challenge that impacts NOAA's current ability to perform. Successfully addressing these challenges is essential if NOAA is to extend itself to Climate Services.

c) Panel 3c: Operational Predictions and Applications

Observations

The NOAA CRM program activities presented at the Review encompass the operational climate monitoring and prediction products and services and the climate test bed, the CPO Climate Prediction Program for the Americas (CPPA), and the IRI and ARCs. CPC is the service center within NCEP that has responsibility for delivering products.

CPC is to be commended for the partnerships it has developed with users and its responsiveness in developing products for users. The CPC-RISA (Regional Integrated Sciences and Assessments) paradigm, where CPC partners with a counterpart from each RISA to develop climate forecast products that are relevant to users, has been very successful. There was interest expressed in establishing similar WFO (Weather Forecast Office) - Climate Service point of contacts in developing a Climate Services strategy. The discussions indicated that elements for a Climate Service delivery system exist, but there is no overall strategy (or funding) for tying the elements together, including with WFO Climate Services personnel and state Climate Services.

The operational climate prediction, with the Climate Test Bed (CTB), is a good partnership between EMC and CPC, with CPC monitoring the quality of the CFS forecast and working with other NCEP centers to deliver a broad range of climate products tailored to end user requirements. The updated CFS has brought an unprecedented increase in forecast skill; the system is one of the best in the world. NCEP/EMC is establishing an agreement to collaborate with its operational European counterparts in an international MME. In an attempt to get community contributions to improve the CFS, CFS will be made fully public. NCEP is to be commended for opening up its model to scrutiny by having others use it. The Climate Test Bed (CTB) operates a grants program to help improve the operational prediction, with of the order of 10 grants expected to be funded in FY08.

CPPA focuses on prediction and predictability at seasonal-to-interannual time scales, improved model representation, and scientific issues related to climate predictions useful for hydrology and water resources. There are many notable activities funded through the CPPA. Recent efforts associated with drought prediction were highlighted. CPPA's contributions to the National Integrated Drought Information System (NIDIS) are the outcome from a long-term commitment to focused research funded by OGP.

All these activities are very important for building NOAA's Climate Services, with effective and continually improving connections with the end users. However, NOAA needs an implementation plan that spans research ←→ operations ←→ applications. It must flow forwards and backwards, and should embrace both the climate and water cross-cut themes. This is presumed to be a core function of the "Climate Service" business model, and the lack of a coherent plan prevents progress. As an example, hydrologic forecasting for drought and water managers falls between operations and applications, with CPPA supporting scientific development but having no obvious transition path. There are elements that are working well, but the overall implementation plan appears lacking.

Findings

A. Operational climate monitoring and prediction products and services, and the climate test bed.

1. The connections among NOAA efforts and organizations are not apparent. For example, there does not seem to be pathway between GFDL's modeling and assimilation developments and NCEP.

2. Not enough information was provided on the Climate Test Bed to demonstrate that it is a successful strategy for improving intraseasonal-to-interannual forecasts. CTB computing resources are being used for the CFSRR, and overall the computing appears to be under-resourced.

3. There is no national strategy for MMEs, and NOAA has not provided leadership to develop such a national strategy. In fact, there is not even a NOAA MME strategy, which is needed given that both NCEP and GFDL undertake seasonal forecasts. Instead, NCEP has reached out to the European community to participate in an international MME.

4. Little information was offered on NOAA's international commitment to GEO (the Group on Earth Observations; http://earthobservations.org/) or GEOSS (Global Earth Observation System of Systems). Although some activities were mentioned (IRI did

some GEO-related studies; CPPA supports some GEOSS work; NCDC supports some data architecture), it seems that the CRM program hasn't thought through the international element of Climate Services.

5. It is not clear that distributing the CFS is the most effective way to benefit from external users. Distributing and supporting the distribution requires additional human and computational resources. A more effective approach may be one that follows ECMWF in having visitors come to NCEP to work directly with the scientists there, with the expectation that developments should transition both into and away from NCEP. This too requires additional human and computational resources.

B. Role of Climate Prediction Program: Improvements to NCEP climate and hydrology forecasts; land-surface processes and their role

6. Although the CPPA does consider R2O transitions, there is currently no mechanism to evaluate the readiness of research results for transition to operations. Conversely, it is not obvious how NOAA's operational needs influence the research program priorities and funding decisions.

7. The transfer from research to operations appears effective through land hydrology process studies. CPPA supports field work (e.g. NAME), and the process studies from the field work get transitioned through involvement of the operational groups in the core project. This is true for the land hydrology component. It is less clear that there is a transition path for other components of the operational models – say ocean processes or atmospheric developments.

C. Role of the IRI and Applied Research Centers

8. The discussions pointed to a multitude of problems related to the funding of the ARCs, Joint Institutes (JI), and Cooperative Institutes (CI). There is a perception that some of these activities are funded through earmarked appropriations, and that their research is not well coordinated with the CPO research priorities or with the NCEP operational and CTB needs and priorities. The ARCs, JIs, and CIs need to be re-defined and reviewed. Although the need to do this is recognized by the CRM Program, no plan has yet been formulated. Reductions is these areas are a potential source of funding for actions recommend in the Report.

Recommendations

A. Operational climate monitoring and prediction products and services, and the climate test bed

1. NCEP is applauded for its efforts to contribute to an international MME. It should be more aggressive and provide leadership in developing a national MME. The path to improving the national (NOAA) climate forecasts will come from the transition of national research efforts to operations.

2. The CTB computer requests should include support for a national MME.

3. Selected CTB activities seem to reflect interest of internal staff (NCEP/CPC) rather than NOAA or CPO programmatic needs. The CTB advisory panel needs to look at how the CTB is being implemented and should report to the CWG.

4. NCEP should consider a strategy for supporting visitors who come to NCEP to work directly with the scientists there, with the expectation that developments should be transition to NCEP systems and also from NCEP to the community as a whole. Computer resource requests should include resources needed for this.

5. NOAA needs an implementation plan that closes the loop between research to operations to applications. There needs to be an objective measure of determining when research is ready for transition, and a plan that spans from basic research to applied research to pseudo-operations to full operational transition.

B. Role of Climate Prediction Program: Improvements to NCEP climate and hydrology forecasts; land-surface processes and their role

6. Each CPO program seems to have its own, idiosyncratic approach to identifying gaps in near-term priorities, and balances between program elements. A more unified strategy would improve effectiveness for coordination across programs. Input from the operational elements of NOAA should influence the priorities.

C. Roles of the IRI, Applied Research Centers, Joint Institutes, and Cooperative Institutes

7. The CPO ought to take care to balance the funding of internal NOAA research groups and Cooperative Institutes with those of the external community to ensure that fresh ideas, perspectives and contributions can be brought forward for R2O transition.

8. The successful CPC-RISA paradigm should be expanded.

9. The ARCs, Joint Institutes (JI) and Cooperative Institutes (CI) need to be reviewed, re-considered, and recompeted in the context of the CTB, the more successful RISAs, and the fact that other NOAA elements and activities from other agencies should be brought together in a strategy for climate prediction products and services. Possible redefinition of these centers and institutes should be considered in context of the review and implementation of a NOAA and CRM strategic plan.

10. CWG should respond positively to Dr. Ropelewski's request for help in formulating a review plan for the ARCs/JI/CI and a strategic plan for better directing their research activities and integrating the results into CRM program priorities. In a time of challenging budgets, the under utilization of these centers and institutes is a problem worth fixing.

Concerns:

- There needs to be stronger management of the CRM element so that transition between labs (e.g. GFDL) and NCEP (operations) occurs more effectively. CRM needs more examples of successful transition and fewer examples of lost opportunities. The inherent conflict of the CRM manager being a lab manager seems to reveal itself (as in the earlier review). This is especially critical in setting priorities among program elements: intraseasonal-to-interannual predictions, decadal projections and long term projects, and the needs for model improvements.
- The process by which resource decisions are made for climate prediction vis a vis climate projections was not very clear to the Panel.
- As mentioned earlier, the role of ESRL was notably absent in the presentations and indicated future directions. This is a significant shortcoming, and suggests that the roles of other NOAA Laboratories have not been adequately considered.
- The CRM Program needs a stronger water component. For many users, hydrology and water availability are the nexus of climate applications. It is unclear how the water cross-cut interfaces with the Climate crosscut, except through CPPA. This needs better articulation.
- Transition from research to operations remains a huge problem at all levels.

Panel 4: Integration Between and Across Programs and Synthesis of Research leading to Information, and Products and Services

Observations

This Panel focuses on two distinct aspects of CRM. The first focus is on the synthesis of research, largely in the form of participation in assessments run by the Intergovernmental Panel on Climate Change (IPCC) and the Climate Change Science Program (CCSP). The second focus is on NOAA as a whole and how the pieces, which the Panel has been shown, fit together.

A. Synthesis of Research

There is little doubt that NOAA's role and visibility in major policy-oriented scientific assessments is large and valuable. In particular:

- NOAA support for the UN stratospheric ozone depletion assessments, and the IPCC Fourth Assessment Working Group I (AR4 WGI) effort, have been nothing short of superb. They are a major service to the nation and the world. Solomon's IPCC leadership and broad NOAA participation no doubt played a key role in the effort being awarded a Nobel Prize. This success built on the strong and commendable level of support for the IPCC that has become a much appreciated tradition for NOAA. NOAA's visibility in this effort is all positive. It is good to see that a NOAA scientist will be co-chair of the 2010 Ozone Science Assessment. It is also good to see that NOAA will provide key technical support for this process, plus continued important scientific research support.

- GFDL support of the IPCC AR4 WGI effort was impressive. Great strides were made in modeling capability and research. The staff and management of GFDL should be very proud of their accomplishments.

- The CCSP assessment effort contrasts with that of the IPCC in terms the political overtones associated the CCSP, as well as the uneven quality of the CCSP assessment reports. Nonetheless, NOAA's efforts are applauded for working hard to make the best of the situation, and in particular, for helping to reach scientific consensus on some particularly vexing issues such as those related to lower atmosphere warming, hurricanes, and climate extremes.

- The implementation model for the ozone assessments and the IPCC AR4 WGI effort, as well as NOAA's support of these assessments, worked well.

- The implementation model for the CCSP assessment process was not optimal and should be improved on if repeated, or extended, into the future.

- The IPCC assessment effort will not be able to provide all of the national-level assessment knowledge needed for national and regional policy- and decision-making. There is a growing need for national efforts that support climate change adaptation. NOAA is well positioned to help lead a multi-agency effort to develop a workable implementation strategy.

B. Integration Between and Across Programs

NOAA is a large entity comprised of Laboratories and Divisions that have traditionally been quasi-independent. The core functions of these elements were originally aligned around specific missions. Some of these missions were based primarily on research and some primarily on operations. The performance of some elements of NOAA is outstanding, and in this decade NOAA has improved the organization and effectiveness of its climate work as a whole.

Overlap across organizations has developed extending the original discipline foci of the organizations; i.e., weather, climate, atmosphere, ocean, fisheries, air quality, simulation, observations, etc. The overlap follows from both the connections between disciplines required to perform thorough research and predictions and the interests of principal scientists and NOAA program offices. The natural result of this history is that, taken as a whole, NOAA is fragmented. This is to be distinguished from distributed. This is no different from other Agencies.

Scientific and programmatic needs have pushed the field to consider the Earth as a system. The desire for the best information about weather and climate and air quality has led to a broad customer base. Budgetary pressure leads to examination of the overlapping activities, which often appears to external examiners, both political and scientific, to be duplicative. There is, naturally, an increasing call for both NOAA-wide and Federal-scale integration of climate research. This requires the consideration of the structured use of the capabilities from multiple parts of NOAA; it requires the consideration of time scales that are longer than budgetary cycles. By definition, NOAA requires more attention to strategic management. This is especially true if there is be the development of a Climate Service.

During the Review it was stated that the CLIVAR Climate Process Teams had contributed effectively to model evaluation and the development of new capabilities. This process also integrated intellectual resources from the community as a large. Other entities, elements of the Regional Integrated Science and Assessment Program and Applied Research Centers, were stated to be effective. In the National Weather Service, the local weather offices were noted as a formal, effective interface to the end-use customers. These activities are characterized by being larger than the effort of an individual researcher, but far smaller and more focused than, for example, GFDL or the Environmental Modeling Center. These are effective strategic elements.

The Panel notes the significant successes of organizations such as the Climate Prediction Center and the National Climatic Data Center to organize and supply application-related products and information to the community.

Findings:

A. Synthesis of Research

- NOAA's leadership roles in important national and international environmental assessments is a major accomplishment, and is much appreciated by the scientific community. The issue of stratospheric ozone depletion paved the way in defining the great utility of effective and iterative scientific assessment. The issue of stratospheric ozone depletion developed rapidly in the 1980's and has led to a well-defined global policy effort to mitigate the problem. Scientific assessment has been essential since that time, making it possible to monitor progress, and also to identify new scientific issues along the way (for example, the interactions with anthropogenic climate change). The series of international agreements on the issue, and tangible reductions in ozone-destroying chemicals, are a clear measure of success. NOAA's leadership has been key over the years, and is deserving of strong praise.

- NOAA's support of the IPCC effort has also been strong and commendable since the 1990's initiation of the process, and there is now little doubt that NOAA is one of the top contributors to the success of the IPCC. Special praise is due Susan Solomon for her leadership of the Nobel Prize winning Fourth Assessment, but also to the many others within NOAA that played key roles as Coordinating Lead Authors, Lead Authors and Contributing Authors; many others in NOAA no doubt played important roles and also should be recognized for one of the most important global scientific efforts yet made.

- As discussed by Susan Solomon, there are a number of elements have been identified that are essential for successful "world-class" policy-oriented scientific assessments:

    - They are not one-time reports, but rather are processes that slowly build strength and impact over time.

    - They must be hard-hitting and focus on policy-relevant scientific advances.

    - They must have a strong process of rigorous review, author selection and approval; the process must be transparent and stringently followed.

    - They must have strong leadership capable of engendering the support and confidence of the science community, as well as the policy community.

    - They should contain content that is useful and credible to both the policy and science communities.

    - They must have clear connection to a policy process.

- Whereas the UN Ozone and IPCC processes, and NOAA's role in these processes, have largely been perfected over time, it appears that the CCSP process is not nearly as optimal. The timing of the CCSP assessments relative to the IPCC taxed the scientific community and precluded some key scientists from participating. The CCSP assessment process is not clear, nor is the degree to which this process was stringently followed. It is also not clear that the CCSP assessment was, or is, connected to a policy process. Thus, even though some aspects of the CCSP assessment were certainly of scientific value, the ultimate utility of the assessments for policy-making is uncertain. Nonetheless, the effort of NOAA scientists and staff in meeting the largely politically-mandated time-line of the CCSP assessments is recognized – no other agency within the US government has the skill, experience and capability to match NOAA when it comes to policy-oriented scientific assessments.

- NOAA's over-all climate research and modeling effort also serves to be one of the best in the world in terms of generating the peer-reviewed science that underpins the policy-oriented science assessment process. NOAA's leadership, scientists and staff should be proud of the prominence that NOAA science has, and gains, via these assessments. Particularly noteworthy are the varied roles that NOAA science has played in improving the confidence in understanding both ozone and climate change issues; this improvement is a successful metric of overall assessment success, and also NOAA's success.

- Although there are many areas where NOAA could improve integration both within CRM, as well as within the overall climate program (see rest of this report), the IPCC AR4 report, in particular, showcases how well NOAA can support a well-integrated whole in a policy-relevant manner.

- There is a need for the CRM Program to operate in a less ad hoc, more strategic manner. This is absolutely essential if NOAA is to provide the foundation for a Climate Service. The organizational units and programs that were presented in the Review showed numerous connections or possible connections. There are efforts to make linkages with some successes. However, for the most part, the organizations that comprise NOAA have quasi-distinct missions and cultures, and there is little incentive to work with more of a character of a cohesive unit. In short, the overhead to generate productive, coordinated activities is larger than the intellectual or financial advantage. This is, in part, related to the stress that exists between budget, human resources, supporting infrastructure, scope of mission, and increasing scope of mission.

B. Integration Between and Across Programs

The following findings are drawn from the Review as a whole.

- NOAA, traditionally, has research and operational activities. Future services often have the characteristic that are better classified as applications. This Application function stands in distinction to both Research and Operations, and will require scientific research to support specific customer goals.

- The historical mission, traditional discipline focus, and culture of the different Laboratories and Division inhibit the development of integrating strategic initiatives.

- Several organizations within NOAA are starved for resources and trying to develop new capabilities and new products, and at times, de facto, to compete with activities such as ECMWF. There is little chance of effective integration in such an environment.

- Budgets are formulated around Programs and goals. The budgets are then submitted by Line Offices. Key elements of NOAA's infrastructure and strategic directions, for example reanalysis, are in and out of budgets, not fully scoped out, and can take several years to obtain scattered startup funding. This budget process undermines the development of strategic goals.

- The lack of clear strategic goals perpetuates the budget process.

- The current fragmentation of NOAA is rational and justifiable strategy given the history and structure of NOAA.

- The development of integrative, strategic directions requires addressing fundamental issues of organizational culture and structure.

- Re-organization is not an adequate response to achieve more effective integration of NOAA.

- Strategic planning and management is required that is pervasive through the organizational units that need to work more collaboratively; for example, ESRL, GFDL, and NCEP.

- A cohesive, stable strategic vision at the Agency level must be formed which has the ability to align resources with strategic goals and that do not, primarily, reward fragmentation. Without this the ability for Laboratories to make significant progress in collaboration is limited.

- Funding and reporting systems that supports integration and the need for Research, Applications, and Operations to inform each other need to be developed.

- The development of new capabilities by integration of existing capabilities will require both a bottom-up and top-down approach.

- Middle-sized, focused activities like CPTs, RISAs, and ARCs, are strategic elements that can stand as an important part of a NOAA-wide, hierarchical strategy.

- The process for selection of middle-sized, focused activities like CPTs, RISAs and ARCs should be reconsidered in light of the review called for by Panel 3c. They should be aligned with NOAA's strategic goals, and balance research and operations and should include competitive awards when appropriate.

- Information technology infrastructure is critical to the success of NOAA. This infrastructure includes web services, high-performance computing, software frameworks, indeed, all aspects of information technology. The lack of planning and design of infrastructure systems inhibits the ability to integrate into cohesive units.

- The successes of organizations such as the Climate Prediction Center and the National Climatic Data Center to organize and supply application-related products and information to the non-scientific communities serve a strategic function.

- The Panel notes that presentations suggested new directions for NOAA in the development of Climate Services. Two examples were the development of an attribution capability and the use of model predictions to inform policy. The Panel is concerned by this apparent expansion of mission when the resources to support the core mission are spread thin, and that several core activities appear to be fragile in places. Furthermore, the real customer and the understanding of how the customer uses climate information are not well defined and understood. This is an example of expanding to perceived mission with out consideration of the end-to-end resources and impacts on the existing, important capabilities.

Recommendations:

A. Synthesis of Research

- NOAA's leadership and support of policy-oriented scientific assessments should continue. In particular, NOAA should continue its strong support for the IPCC. Diligence should be made to ensure that the necessary resources are allocated, so that key NOAA institutions (e.g., GFDL) don't suffer as a result of the tremendous effort that is required to meet these commitments.

- The implementation process used in the ozone assessment and IPPC AR4 should serve as a model for future assessments. NOAA should work hard to support their participation with the funding that is required, particularly in terms of supporting the model development and analysis at GFDL.

- The CCSP assessment process is almost complete, and will continue to be impacted by political agendas. NOAA should strive to make the remaining process and reports as transparent and rigorous as possible. In the future, more clear and uniform demarcation between the assessment participants and the government (e.g., NOAA) leadership should be realized. More clear articulation of the targeted "users" of the assessment is required. NOAA and other government agencies should not both facilitate and author assessments; there must be a clear independence between these two roles. Conflict-free mechanisms should be worked out so that some NOAA scientists can serve as authors in future assessments.

- All policy-influential reports like those produced by the CCSP should be reviewed by the National Academy of Sciences in order to remove any possible taint of political bias.

- Strong efforts should be made to avoid scheduling overlap between the IPCC assessments and any national effort. The CCSP, in particular, may have suffered because of the temporal overlap of the two processes and the inability of the scientific community to support both sufficiently with time.

- NOAA should explore ways to make their success in the policy-oriented scientific assessment process more of a vehicle for cross-CRM and cross-NOAA-climate-program integration. For example, it may be possible to prioritize NOAA climate funding and science on the basis of how well it meets the integrated objectives of the policy-oriented scientific assessment processes. NOAA might also create a more formal process to anticipate the science that will be needed future assessments and the support of policy-making, e.g., as the nation starts to implement large-scale climate change adaptation and mitigation programs – both will require greater NOAA effort, and greater NOAA climate program integration. NOAA might benefit from greater engagement with policy scientists, as well as regional climate scientists in this effort to anticipate future assessment needs while at the same time meeting current needs.

B. Integration Between and Across Programs

- NOAA should lead an integrated multi-agency effort to provide climate services.
- The federal government needs to develop an entity that serves as the “recipient” of climate information that is developed, in part, by NOAA.
- Strategic planning and management is required at all levels in NOAA, to allow the development of integrating activities both internal and external to the agency, and to help fix the current, fragmenting budget process.
- Budget, reporting and incentive mechanisms need to be developed to orient performing organizations with Laboratory and Agency Goals.
- NOAA cannot provide the best Climate Services without well designed partnerships with other Federal Agencies, the academic community, the resource management community, and commercial interests.
- NOAA needs a clear understanding of who its “climate customers” or “climate stakeholders” are. NOAA alone cannot define the stakeholders.
- The Panel suggests that NOAA develop a management strategy that is consistent with modern concepts of open innovation or open communities – a generalization of the open source software culture. (http://climateknowledge.org/figures/Rood_Library/vonKrogh_open_source_2007.pdf.) Success will require the development of community governance models, which include definition of process for building and modifying capabilities.
- Recognizing the successful attributes of the Climate Process Teams, the Regional Integrated Science and Assessment Programs, and the Applied Research Centers, the Panel recommends that NOAA develop an agency-wide strategy that incorporates these middle-sized activities as key strategic elements. Specifically, integrating activities should be focused at the interface between organizations to realize strategic goals. A subset of these activities should be in the spirit of a project, with a finite lifetime to achieve specific goals, and chosen competitively.
- In the spirit of the Climate Process Teams, NOAA should form ad hoc research teams. Funds should be set aside in advance of any team building to ensure that non-NOAA scientists will be part of any given team.
- NOAA must recognize the importance of the information technology infrastructure necessary to support its science-based generation of products and services,including high-performance computing and communications.

Concerns:

- There seems to be a lack of overall strategic planning. For example, since a major goal of NOAA's climate activities is to provide the nation with climate science, applications, services and products that are truly useful and used, there should be a strategic plan to reach this goal. The lack of a strategic plan manifests itself in the lack of development of a coherent capability.

- The NOAA budget process may not allow the implementation of a long term plan that emphasizes coordination among the NOAA groups and other partners with the goal of improving climate science, applications, services and products.
- NOAA and Federal Agencies, in general, don't build effective, and essential, partnerships outside the agency. This is a potential killer of a national Climate Service since climate variability and climate change are only one part of what the nation needs from a national Climate Service.

Panel 5: Decadal Variability and Predictability

Observations:

Understanding decadal climate variability and pursuing its predictive capability is one of the emerging foci in climate research. Especially, there is a growing need for more robust estimates of near-term (i.e., next 10-30 years) climate consistent with projected changes in anthropogenic radiative forcing and with observed tendencies of climate system's variability in recent decades. This involves not only large-scale changes in climate system, but also changes in extremes. Understanding the possibility and predictability of abrupt climate change associated, for example, with oceanic thermohaline circulation is also a closely related research topic.

Observational verification is a critical component of advancing modeling and understanding. Sustained efforts are needed to explore and reconstruct available observations for both the past and present.

Findings:

- Considerable progress towards decadal prediction has been made in recent years, and the NOAA scientists' contribution, especially that by GFDL, is significant. GFDL is playing a leading role in modeling studies of variability in Atlantic Meridional Overturning Circulation. Significant progress has also been made in areas of Atlantic hurricane variability, US droughts and high-resolution modeling, among others.

- Whether or not there is any practically useful decadal predictability is not at all clear at present. Simulated variability should be more rigorously verified against available observations. Decadal predictions must start from the observed state of the climate system, and will be driven by estimates of near-term changes in radiative forcing. The rapidly varying components such as the radiative forcing agents like aerosols and ozone need to be calculated and accurately represented. Whether one can effectively initialize climate models by assimilating observations of the slowly varying components of the climate system is a big scientific issue. NOAA, especially GFDL and NCEP, is one of the few organizations that is capable of addressing this endeavor.

- Possible changes in extremes, including hurricane activities, are an important aspect of decadal predictability. This is a concern, because large-scale climate models have difficulty representing extremes.

Recommendations:

- NOAA should undertake a strategic planning exercise towards (possible) operational decadal predictions.

- While the Atlantic Meridional Overturning Circulation is one of the most important foci for decadal variability and abrupt change studies, the Pacific, polar regions (including recent trends in Arctic and Antarctic ice), and southern oceans, should not be neglected.

- Continental hydrological processes and considerations on cryospheric components of climate should also be focused. Especially, process modeling of the cryosphere should be of considerable importance in advancing the understanding of abrupt climate change.
- Coordination is needed between GFDL, NCEP, and other research sectors on initialization and prediction systems development for decadal prediction.

Concerns:

- NOAA lacks an agency-wide plan for how research progress will be transformed into operational decadal prediction, useful to a wide spectrum of possible users, over the next 5 to 10 years.
- NOAA's ESM and decadal prediction efforts do not appear to be linked.
- NOAA lacks a 5-10 year plan for providing the resources required for high-resolution modeling, including data assimilation.

Appendix A: Program of the Review

Climate Working Group (CWG) CRM Program Review
March 24-26, 2008
Hyatt Regency, Princeton, NJ
Room: Austin/Savannah (Lobby Level)

DAY 1 - Monday, March 24

Welcome
7:30 Breakfast
7:45 **Executive Session Meeting:** Climate Working Group and CRM Review Team -Tony Busalacchi

8:30-10:30 Introduction and Overview
Moderator: Tony Busalacchi

8:30 Welcome, Objectives, and Meeting Logistics --- *Chet Koblinsky*

8:45 Overview and Goals of CRM Review --- *Dave Randall*

9:00 Overview of CRM Program --- *Chet Koblinsky/ V. Ramaswamy*
- NOAA's overall research and modeling strategy
- Institutional responsibilities at each lab or facility
- Q&A at the end of Overview

10:15 Break

Panel 1: Understanding Climate Processes

10:30 – 12:30 **Panel 1a: Climate Processes and Atmospheric Modeling**
Moderators: Joyce Penner and Bill Collins

*Chair**: A. R. Ravishankara***
Panel: Ram, Feingold, Donner, Dunlea [Other experts: Horowitz, Fiore, Chip Levy, Ogren, Ginoux, Yi Ming, Ming Zhao, Golaz]
Rapporteur: Brian Magi

A. Atmospheric Composition and Climate
Non-CO2 long-lived gases, stratospheric and tropospheric ozone, and upper trop/Lower strat water vapor [*Speaker: Ravishankara*] **20 min**
B. Aerosol (direct & indirect) Process Studies: [*Speaker: Feingold*] **15 min**
C. Atmospheric Processes in Climate Models - Aerosols, Convection, and Clouds [*Speaker: Donner*] **20 min**

D. Climate and Air Quality [*Speaker: Ravishankara*] **15 min**

Discussion with Panel - 50 min

12:30 Lunch
- Report out from ESRL Lab Review – [*Speakers: Ravishankara and Butler*]

1:45 – 3:30 **<u>Panel 1b: Ocean Processes and Carbon Cycle</u>**
Moderators: Scott Denning and Nathalie Mahowald

*Chair**: Mete Uz***
Panel: Hallberg, Gnanadesikan, Dick Feely, Ed Harrison [Other experts: Sonya Legg, Steve Griffies, Alistair Adcroft, G. Vallis, Sarmiento, Toggweiler]
Rapporteur: Marian Westley

A. Ocean processes and modeling [*Speaker: Hallberg*] **20 min**
B. Ocean and Carbon Cycle [*Speaker: Gnanadesikan*] **20 min**
C. Role of Global Carbon Cycle Program [*Speaker: Mete Uz*] **20 min**

Discussion with Panel: 45 min

3:30 Break

3:45 – 6:00 **<u>Panel 2: Reanalysis and Data Assimilation and Carbon Tracking</u>**
Moderators: Michelle Rienecker and Bill Large

Chair: ***Chet Ropelewski***
Panel: Tony Rosati, Hualu Pan, Arun Kumar, Gil Compo, Butler [Other experts: Huug van den Dool, Jeff Whitaker, Held, S. Zhang]
Rapporteur: Bill Stern

A. Reanalysis and reforecasting [*Speaker: Pan*] **20 min**
B. Reanalysis of the 20th Century [*Speaker: Compo*] **20 min**
C. Data Assimilation development - ocean model and future plans (including OSSE) [*Speaker: Rosati*] **20 min**
D. Carbon Tracker: its goals and observational needs [*Speaker: Butler*] **20 min**

Discussion with Panel: 55 min

6:30 CWG and Review Team Dinner – closed session

DAY 2 – Tuesday, March 25

7:30 Breakfast

<u>Panel 3: Earth System Modeling, Predictions, and Projections</u>

8:00 – 10:15 **<u>Panel 3a: Modeling Overview</u>**
Moderators: Ricky Rood and Bill Large

Chair: ***Rick Rosen***
Panel: V. Ramaswamy, Brian Gross, Ronald Stouffer, Louis Uccelini, Lord [Other experts: Held, Dixon]
Rapporteur: Will Cooke

A. GFDL strategy and challenges: [*Speaker: Ramaswamy*] **20 min**
- IPCC AR4 experience and future plans for climate projections based on new emissions scenarios [*Speaker: Stouffer*] **15 min**

B. NCEP strategy and challenges;
- Vision for making CFS a public model [*Speaker: Uccelini*] **20 min**

C. NOAA climate computing resources [*Speakers: Gross, Lord*] **20 min**

Discussion with Panel: 45 min

10:15 Break

10:30 – 12:30 **<u>Panel 3b: Model Development in CRM context</u>**
Moderators: Dave Randall and Ricky Rood

Chair: ***V. Ramaswamy***
Panel: Wittenberg, Dunne, Held, Lord [Other experts: Donner, Hallberg, Elena Shevliakova, Chip Levy, Andrew, Toggweiler]
Rapporteur: Lori Sentman

A. High resolution Model [*Speaker: Held*] **20 min**
B. Coupled Climate Modeling (including land-surface) [*Speaker: Wittenberg*] **20 min**
C. Earth System Modeling (land and ocean ecosystems) [*Speaker: Dunne*] **15 min**
D. NCEP Modeling [*Speaker: Lord*] **20 min**

Discussion with Panel: 45 min

12:30 Lunch
- Dynamical core advances in NOAA, and information on HPC strategic developments for running climate simulations [*Speaker: S. J. Lin, Gross*] **30 min**

1:30 – 3:10 **Panel 3c: Operational Predictions and Applications**
Moderators: Eric Wood and Michelle Rienecker

Chair: ***Wayne Higgins***
Panel: Fiona Horsfall, Chet Ropelewski, Jin Huang [Other experts: Rosati, Hua lu Pan, Pedro Restrepo]
Rapporteur: Neil Christerson

A. Operational Climate Monitoring and Prediction Products and Services, and the Climate Test Bed [*Speaker: Higgins*] **25 min**
B. Role of Climate Prediction Program: Improvements to NCEP climate and hydrology forecasts; land-surface processes and their role [*Speaker: Jin Huang*] **20 min**
C. Role of the IRI and Applied Research Centers [*Speaker: Chet Ropelewski*] **15 min**

Discussion with Panel: 40 min

3:10 Princeton University's Collaboration with GFDL [Speaker: Steve Pacala]
3:15 Break

3:30 – 6:00 **Panel 4: Integration Between and Across Programs and Synthesis of Research leading to Information, and Products and Services**
Moderators: Rit Carbone and Jonathan Overpeck

Chair: ***V. Ramaswamy***
Panel: Susan Solomon, Tom Karl, A. R. Ravishankara, Chip Levy, Ron Stouffer, Isaac Held
Rapporteur: Sandy Lucas

3.30 – 4.45 **NOAA's Contributions, Role, and Visibility in Major Assessments**
A. IPCC and WMO [*Speaker: Solomon*] **30 min**
B. CCSP [*Speaker: Karl*] **15 min**
C. Additional Reflections [*Ravi, Chip Levy, Stouffer, Held, Dixon, Barrett]* **15 min**

Discussion with Panel: 15 min

4:45 – 6:00: **Discussion on Program Integration**

Chair: ***Chet Koblinsky***
Panel: Tom Karl, Ramaswamy, Ravishankara, and Wayne Higgins
Rapporteur: Hetal Jain

Speaker: Chet Koblinsky **15 min presentation**
D. Integration within NOAA including the utilization of *in situ* and satellite observations

E. Integration with Universities and external (interagency and international) partners

Discussion with Panel: 60 min

6:15 Executive Session

7:00 Dinner Presentation: "Highlights of CO2 Science: Status, challenges and implications in the context of climate change" [Speaker: J. Sarmiento] **30 min**

DAY 3 – Wednesday, March 26

7:30 Breakfast

8:00 – 10:00 **Panel 5: Decadal Variability and Predictability**
Moderator: Masahide Kimoto

*Chair**: Jim Todd***
Panel: Tom Delworth, Gabe Vecchi, Held [Other experts: Marty Hoerling, Stouffer, Dixon]
Rapporteur: Ken Takahashi

A. Decadal climate variability and predictability, and abrupt change research [*Speaker: Delworth*] **30 min**
B. Role of Climate Variability Program grants in decadal variability and abrupt change research [*Speaker: Todd*] **20 min**
C. Circulation changes and extremes (including droughts etc.) [*Speaker: Held, Vecchi*] **20 min**

Discussion with Panel: 50 min

10:30 Executive Session

Appendix B: Draft Program Charter for the CRM Program

DRAFT PROGRAM CHARTER FOR

Climate Research and Modeling Program

Program Manager: V. Ramaswamy

Climate Goal Team Lead: Chester J. Koblinsky

1. EXECUTIVE SUMMARY

Program Description:

An overarching goal of climate research and modeling is to develop, understand, and improve the capability to make intra-seasonal, seasonal, decadal, and centennial-scale predictions of climate variability and projections of future climate change on global to regional scales. This will enable regional and national managers to better plan for the impacts of climate variability and provide climate assessments and projections to support policy decisions with objective and accurate climate change information. The CRM Program directly supports the other Programs under the National Oceanic and Atmospheric Administration's (NOAA) Climate Mission Goal. CRM also contributes to the other four NOAA Mission Goals, Ecosystems, Weather and Water, Commerce and Transportation, and Mission Support.

A key requirement for predictions and projections is models that embody sufficient realism in terms of process understanding, sufficient spatial resolution, and improved physics. To achieve these goals, continued development of Earth system models is required, especially with regard to incorporating carbon cycle and other relevant chemical processes for making predictions on longer time-scales. The informational output of CRM will enable regional and national managers to better plan for the impacts of climate variability and provide climate assessments and projections to support policy decisions with objective and accurate climate change information.

An emerging focus of the predictions capability is on the decadal time-scales, which will influence infrastructure decisions. Decadal predictions start from the observed state of the climate system, and will be driven by more confident estimates of near-term changes in radiative forcing. To advance decadal predictions, whose acceptance is dependent on the confidence in understanding and modeling, observations of the slowly varying components of the climate system need to be assimilated, and the rapidly varying components such as the radiative forcing agents like aerosols and ozone need to be calculated and accurately represented.

To achieve its goals, this program maintains a suite of operational climate outlooks and implements the next generation operational climate outlooks and assessments by improving climate models, improving forecast generation techniques, and maintaining real-time climate monitoring data sets. This program also maintains and develops leading edge Earth System Models for the understanding of past climate change, interpretation of present climate events and trends, projection of future climate change on regional to global scales, including biogeochemical cycles, as well as developing estimates of future changes in climate radiative forcing agents. Activities under this program are spread across several line offices and NOAA laboratories, and also support, and leverage on, an extensive array of competitively reviewed research.

The Climate Research and Modeling Program maintains capabilities that include (i) understanding climate processes, (ii) Earth System modeling, prediction, and projection, leading to the understanding of climate variations and change and future climate predictions, and (iii) climate analysis and attribution. Activities within these capabilities include (i) operational forecasts and assessments, (ii) applied climate research and development, (iii) measurements and understanding of non-CO_2 climate forcing agents, (iv) understanding the causes of climate forcing, (v) understanding and prediction of the ozone layer recovery, (vi) analysis of the climate system, (vii) characterizing observations for climate models, and (viii) climate attribution.

2. PROGRAM REQUIREMENTS

A. Legislative and Directive Documents establishing needs and requirements:

Legislation:

- *National Weather Service Organic Act* (15 U.S.C. §313): Outlines NOAA's responsibility to produce climate forecasts.
- *National Climate Program Act*, 15 U.S.C. 2901-2908, at 2904(d) (4), et seq.: This act authorizes global data collection, and monitoring and analysis activities to provide reliable, useful and readily available information on a continuing basis. In addition, the act authorizes measures for increasing international cooperation in climate research, monitoring, analysis and data dissemination.
- *Global Change Research Act* (15 U.S.C. §2921 *et seq*.): This act mandates the development of a research program whose goal is to understand climate variability and its predictability. It also mandates research and observation of human activities that may lead to global changes and may adversely affect society (i.e. global warming and stratospheric ozone depletion).
- *Global Climate Protection Act of 1990,* 7 U.S.C. § 6701 et seq.: Requires research in climate change needed to protect the environment. The CRM Program produces results used for the decision support for protecting the environment.
- *Coastal Zone Management Act of 1972* (16 U.S.C. §1450 *et seq*.): Requires understanding and prediction of long-term climate change which may have large impacts in the coastal zone such as global warming and associated sea level rise.

Interagency or International Agreements:

- *Strategic Plan for the Climate Change Science Program (CCSP):* Requires reduced uncertainty in projections of how the Earth's climate and related systems may change in the future. Requires the federal agencies to carry out research to quantify climate forcing by various agents, reduce the uncertainties in their evaluated forcings, produce timely prediction as well as generate synthesis and assessment products (SAPs) on various aspects of climate change.
- *U.S. Ocean Action Plan / Ocean Research Priorities Plan (ORPP):* Presents research priorities that focus on the most compelling issues in key areas of interaction between society and the ocean. Provides guidance on how the various ocean science sectors (government, academia, industry, and non-government entities) can and should be engaged, individually or through partnerships, to address the areas of greatest research priority and opportunity.
- *U. N. Framework Convention on Climate Change (UNFCCC):* Requires better quantification of the agents that force climate change by contributing research results and providing expertise to the assessments.
- *Montreal Protocol on Substances that Deplete the Ozone Layer (and subsequent amendments):* Requires an assessment every four years of the state of the ozone layer, its recovery, and the amounts and origins of ozone depleting substances that drive the ozone layer changes. The influence of climate change on the future of the ozone layer and the consequences of ozone layer changes to the climate also need to be addressed through research and assessments.

B. Mission Requirements

- Understand and predict climate variability on timescales ranging from intraseasonal through seasonal to decadal and beyond *(Global Change Research Act).*
- Monitor, assess, and forecast climate *(National Weather Service Organic Act).*

- Understand and predict long-term climate change and evaluate its impacts on the coastal zone *(Coastal Zone Management Act)*.
- Improve climate models to reduce uncertainty in the projections of Earth's climate *(Strategic plan for the Climate Change Science Program)*.
- Improve knowledge of observed variability and change of the Earth's past and present climate and environment *(Strategic plan for the Climate Change Science Program)*.
- Improve quantification of the forces bringing about changes in the Earth's climate system *(Strategic plan for the Climate Change Science Program)*.
- Monitor and understand changes in the ozone layer and ozone depleting gases and assess the consequences of changes *(Global Change Research Act)*.
- Provide monitoring, assessment, and analysis of the climate system through adequate quality observations and measurements of atmospheric, oceanic, and select terrestrial variables, as well as modeling capabilities *(Global Change Research Act, National Weather Service Organic Act, Coastal Zone Management Act, US Ocean Action Plan)*.

3. LINKS TO THE NOAA STRATEGIC PLAN

A. Goal Outcomes:

A predictive understanding of the global climate system on times scales of weeks to decades to a century with quantified uncertainties sufficient for making informed and reasoned decisions.

B. Goal Performance Objectives

Understand and predict climate variability and change from weeks to decades to a century.

Reduce uncertainty in climate projections through timely information on the forcing and feedbacks contributing to changes in the Earth's climate.

C. Goal Strategies

- Provide the research needed to understand climate processes including information products for an atmospheric composition service. (This includes coordination with the NOAA 5-Year Research Plan.)
- Provide the resolution and accuracy for prediction and projection services on future states of the climate to a scale required to meet user demand.
- Develop Earth system models with advanced assimilation systems to facilitate attribution studies and increase the range of predictability.
- Improve the quantification and understanding of the forces bringing about climate change by examining relevant human-induced increases in atmospheric constituents.
- Develop and contribute to routine state-of-the-science assessments of the climate system for informed decision-making.
- Work with customers in order to deliver climate services and information products involved in health, safety, environmental, economic, and community planning that increase the effective application of this information.

4. PROGRAM OUTCOMES

- Improved understanding of atmospheric carbon dioxide trends for policy support involving quantified estimates of carbon sinks/sources and feedbacks.
- Produce climate change projections in support of making informed policy decisions to mitigate societal impacts of climate trends.
- Produce operational climate outlooks and applications with defined uncertainties on intraseasonal, seasonal, and decadal time-scales to enable national managers to take proactive actions in response to the impacts of climate variability and change.
- Produce information on the climate roles of the radiatively important fine-particle aerosols, with an emphasis on aerosol-cloud interaction (the most uncertain of the climate forcing agents), and non-carbon dioxide greenhouse gases to provide decision support associated with options for potential near-term changes in radiative forcing of climate change.
- Produce information for the verification of the recovery of the ozone layer and the decline of ozone-depleting chemicals in the atmosphere, thereby facilitating compliance with the Montreal Protocol and its safeguarding the Earth's ultraviolet shield.

5. PROGRAM ROLES AND RESPONSIBILITIES

This program is established and managed with the procedures established in the NOAA Business Operations Manual (BOM). Responsibilities of the Program Manager are described in the BOM. Responsibilities of other major participants are summarized below:

A. Participating Line Offices, Staff Office, and Council Responsibilities

- NOAA Office of Oceanic and Atmospheric Research (OAR) is responsible for providing capabilities for climate diagnostics, climate modeling, and climate projections through the Geophysical Fluid Dynamics Laboratory (GFDL). It is also responsible for conducting research and climate observation through its offices, laboratories, and cooperative institutes, including but not limited to the Climate Program Office and Earth System Research Laboratory (ESRL).
- NOAA Weather and Water Goal Air Quality Program is responsible for joint studies on radiation balance and air-quality-health.
- The National Weather Service (NWS) through the Climate Prediction Center (CPC) and Environmental Modeling Center (EMC) is responsible for providing an infrastructure to maintain operational climate predictions on intraseasonal, seasonal, and interannual time scales, and to provide a vehicle for transitioning products developed under the NOAA research to operations.
- NESDIS STAR is responsible for developing algorithms to retrieve carbon gas data from infrared satellite data and for satellite-based ozone-layer and aerosol-radiation monitoring.
- The Aircraft Operations Center provides the fully outfitted WP-3, G-IV, and Twin Otter aircraft platforms, certain key meteorological and navigation data instrumentation, aircrew, and Aviation Project Management for the Climate Forcing Program that produces some of the data required for this performance measure. Specialized air chemistry instruments are provided by NOAA and PIs supported via extramural grants.
- The NOAA Office of General Counsel (GC) is responsible for providing legal services necessary to enable the program to discharge its duties.
- The NOAA Research Council provides guidance on research priorities with different time horizons.

- The NOAA Office of Public and Intergovernmental Affairs communicates findings and results to a variety of audiences via the media.

B. External Agency/Organization Responsibilities

- Intergovernmental Panel on Climate Change (IPCC) established by the World Meteorological Organization (WMO) and United National Environmental Programme (UNEP) coordinates international assessment of scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts, and options for adaptation and mitigation.
- Numerous national and international working groups provide community-based science and implementation planning to guide NOAA's funding of climate variability and change research. These include but are not limited to: Climate Research Committee of the National Academy of Sciences/National Research Council; US Interagency Working Groups for the various Research Element Activities of the US Climate Change Science Program; US Interagency Groups for Climate Variability and Predictability (CLIVAR) and Global Energy and Water Cycle Experiment (GEWEX); World Climate Research Programme, sponsored by the WMO, Intergovernmental Oceanographic Commission (IOC) and the International Council of Scientific Unions (ICSC); US Scientific Steering Committees for CLIVAR, SPARC, and GEWEX.
- Academic and research communities external to NOAA support increased understanding of climate variability and change and development of improved climate prediction techniques via competitive research grants.

6. END USERS OR BENEFICIARIES OF PROGRAM

Products generated by the Climate Research and Modeling Program will benefit the following end users:

- General Public – The program contributes to improved understanding of climate variability and change, including extreme events, enabling the public to plan, anticipate, mitigate, and adjust appropriately. It informs and educates public about climate.
- Businesses – The program provides data, model simulation results, and analyses beneficial to businesses developing and modifying business plans sensitive to weather and climate on timescales from intraseasonal to multiple decades. It provides operational forecasts and outlooks of intraseasonal to interannual variations and intradecadal trends.
- Government – The program supports decision-makers with policy formulation to mitigate climate impacts and reduce costs. It provides information needed to manage natural resources and ecosystems, enhance studies on the spread of climate sensitive diseases, and contribute to mitigating natural hazards along the coast and the interior of the Nation.
- Academia – The program awards funding for extramural research and observation to support these research programs.
- International – The program provides objective information about climate change projections in support of making informed policy decisions for mitigation and adaptation strategies related to global change.