IDENTIFICATIONS AND APPLICATIONS OF COUPLED CLIMATE MODELS

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Contents

Summary

Climate system models are at the core of environmental system models. Identification and application of coupled climate models constitute an important research area of environmental system modeling. They also represent the ultimate challenge to the performance of numerical models for the atmosphere, ocean, land surface, and chemistry. Environmental system models are also characterized by strong interactions among sub-systems. They share concerns and problems similar to those faced by coupled climate models. Therefore, the technologies developed for coupled climate systems pave the way for the future success of environmental system models.

1. Introduction

The Earth climate system consists of several major components, such as atmosphere, ocean, land, and chemistry. Many climate phenomena that have profound impacts on the environment and human society are produced by strong interactions among two or more of those components. The ozone hole depletion involves interactions between chemical processes and the atmospheric circulation; the El Niño and La Niña events are results of mutual forcing between the atmosphere and ocean; and the Amazon deforestation involves not only land surface but also atmospheric processes. In the most challenging problem of global warming, all four components of the Earth climate system are involved.

Coupled climate models, which integrate together models of the individual climate system components and allow them to interact with each other, are powerful tools to study and to predict those climate phenomena. There is a hierarchy of coupled models with varying complexity being developed in the climate research community. Each type of coupled model has its own unique strength. Selection of coupled model type primarily depends on the nature of specific climate problem being addressed and the availability of computational resources.

2. Elements of Coupled Climate Models

There are at least two basic elements in a coupled climate model: component model and coupling interface. For more complex coupled climate models that are computational demanding and generate large amounts of outputs, two additional elements are needed: high-performance computational tools and a model data information system.

A component model is a numerical representation of one climate component in the coupled model. Component models are responsible for simulating the state of that climate component and its responses to forcing from other components.

Interactions within the climate system are represented in coupled models by exchanging simulated state parameters (e.g., atmospheric circulations, ocean temperatures, ozone concentrations, land surface types, etc.) among component models. The back and forth passing of simulated parameters between any two component models constitutes a coupling interface. Coupling interfaces are responsible for coordinating and processing information flow among component models.

Complex coupled climate models solve large sets of partial differential equations to provide comprehensive information on climate states. Furthermore, those complex models are usually developed for studying climate phenomena that have long characteristic time scales. Long integrations of these models are usually needed. It is desirable that those long model integrations can be completed in a reasonably short "wall clock" time. High-performance computational tools are necessary for coupled climate modeling.

Processing and analyzing the huge amounts of output from long-term simulations of coupled climate models can be time-consuming and difficult. An efficient data information system is needed to simplify the use of simulation results See *Data Information System* and *Coupling Interfaces.*

3. Component Models

Various complexities of component models have been developed by the climate research community for the simulations of the atmosphere, ocean, land surface, and chemistry components of the climate system. In general, those models can be categorized into three types: Statistical models, simplified physics-based models, and sophisticated, general circulations models.

3.1. Statistical Type

Statistical models use observational data to empirically determine the state parameters of climate components. They are usually simple and computationally efficient, but cannot provide comprehensive information on climate states. Statistical models are usually used in coupled climate models for generating force to drive another component models. The empirical relationships derived from the present climate situation that underlies these models are not necessary valid when significant changes occur in the climate system. Therefore, statistical component models are not appropriate for coupled climate models that aim at climate change applications.

3.2. Simplified Physics-based Type

Simplified physics-based models solve simplified governing equations. The simplification eliminates equation terms that are of secondary importance to generate specific features in climate components. Many factors can affect how the governing equations can be simplified, such as time scales of the climate feature to be simulated or its spatial scales, geographic location, or dynamic characteristics. Simplified physics-based models are computationally more efficient than complex general circulation models and physically more realistic than statistical models. Shallow-water equation models are one example of simplified physics-based models that are often used in coupled climate models as the component models for the atmosphere and oceans.

3.3. Comprehensive General Circulation Type

Atmospheric and oceanic general circulation models (AGCMs and OGCMs, respectively) offer the most complete representation of atmospheric and oceanic dynamics and are most often used in coupled climate models. GCMs simulate comprehensive three-dimensional information about the atmosphere and oceans by solving the complete sets of the governing equations of these two climate components. GCMs also use parameterization schemes to include the effects of important physical processes that cannot be treated in the governing equations. Among the first AGCMs were those developed in the 1960s at University of California Los Angeles and Geophysical Fluid Dynamics Laboratory. Since then, different AGCMs have been developed and widely used for climate research. Major differences among these models are their physical parameterization schemes, such as cumulus convection scheme, surface fluxes scheme, and cloud-radiative scheme. The performance of an AGCM depends greatly on its physical parameterizations.

OGCMs share many common features with AGCMs, such as the governing equations and numerical techniques. However, OGCMs require fewer physical parameterizations than AGCMs. Major physical parameterizations in OGCMs include vertical mixing parameterization and meso-scale eddy parameterization. Parameterization of radiation transfer is a crucial part of AGCMs but is not needed in OGCMs. As a result of the smaller number of physical parameterizations, the number of OGCMs developed and used in climate research community is much fewer than the number of AGCMs. See *Oceanic General Circulation Models (OGCMs),* and *Atmospheric General Circulation Models (AGCMs).*

4. Coupling Interfaces

Regardless of model type, the parameters to be exchanged to simulate the interactions between climate components are essentially similar.

4.1. Atmosphere-Ocean

The interactions between the atmosphere and oceans occur at the interface between these two large-volume medias. They interact with each other through the exchanges of heat, momentum, and water. The heat exchange is in the form of surface heat fluxes, which consist of four components: sensible heat flux, latent heat flux, shortwave radiation flux, and longwave radiation flux. The momentum exchange is in the form of surface wind stress, which is sometimes referred to as surface momentum flux. The water exchange is in the form of precipitation from the atmosphere and evaporation from the ocean.Atmospheric component models need sea surface temperature information from the oceanic component models to determine the strength and distribution of surface heat, momentum, and water fluxes. Oceanic component models need surface fluxes from the atmospheric component models to force ocean circulations. Therefore, the coupling interface between the atmosphere and oceans consist of four parameters: sea surface temperature, surface heat flux, surface wind stress, and surface water flux. In some climate applications, where only the upper part of oceanic circulation is involved, surface water flux can be neglected. Surface water flux is important when the deep ocean circulation, such as thermohaline circulation, is of concern.

4.2. Atmosphere-Land Surface

Similar to atmosphere-ocean interactions, the interactions between the atmosphere and land surface are also in the form of exchanges of heat, momentum, and water. However, the land surface has much lower heat capacity than oceans, and is much more heterogeneous than the ocean surface due to various vegetation and soil types. Low heat capacity makes the land surface respond to atmospheric thermal forcing at much faster rates than oceans. Different land surface types have different abilities of intercepting, absorbing, and scattering incoming solar radiation. They also evaporate water vapor back to the atmosphere in different ways and rates. Much of the evaporation from the land surface to the atmosphere is through vegetation.For atmospheric component models, information on heat capacity and land surface albedo are needed to calculate its surface energy budget; and information on soil moisture and vegetation type are needed to determine its surface water budget. For land surface models, information on downward shortwave and longwave radiative fluxes, precipitation, surface air temperature and humidity, and surface winds are needed to determine the heat, radiation, and moisture properties of the land surface. Those surface properties determine the forcing of the land surface to the atmosphere, in the form of surface albedos, upward longwave radiation, sensible heat flux, latent heat flux, water vapor flux, and surface wind stress to the atmosphere.

4.3. Chemistry-atmosphere/ocean

The principal way for chemical processes to affect the earth climate is by altering concentrations of certain radiatively-active tracer compounds and in consequence affect the energy balance of the atmosphere. One such tracer is ozone (O_3) in the stratosphere, which plays the important role of absorbing solar radiation in the upper atmosphere. Chemistry models are needed to treat those processes in order to have more realistic and accurate simulations of radiative heating/cooling in the atmosphere. On the other hand, several chemical-active and climate-relevant species, such as ozone (O_3), methane (CH_4), nitrous oxide (N_2O), and the chlorofluorocarbons (CFCs), have their major sources and sinks in the atmosphere. Their chemical reaction processes are affected by the atmospheric circulation and by other physical processes in the atmosphere. The interactions between the atmosphere and chemistry should, therefore, be included for climate system modeling.Chemistry models solve mass conservation equations of tracer gases to simulate evolutions of their concentrations. Two major processes are included in the models: transport and chemical transformation. Such types of chemistry models are often referred to as chemistry transport models. The transport of chemical species is controlled by the general circulation, convection, and mixing processes in the atmosphere. Therefore, chemistry component models need that information from atmospheric component models. The information on solar radiation may also be needed for the treatments of photochemical reactions. Concentration information simulated by chemistry transport models is then passed on to the atmospheric component models for radiation calculations.Oceans are a major sink for CO_2 and a major source of N_2O. Interactions between physical oceanic processes and chemistry are also important to the climate system. It is particular true for understanding the global carbon cycle. The basic treatments of chemistry-ocean interactions are similar to those of chemistry-atmosphere interactions. See *Chemistry transport models.*

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Biographical Sketch

Professor Jin-Yi Yu is an expert in climate system modeling, climate dynamics, and high-performance computing for scientific applications. His research work covers a wide range of climate issues, ranging from global-scale climate changes in the coupled atmosphere-ocean-land system to regional-scale variations in the hydrological cycle. Professor Yu has made important contributions to the understandings of the dynamics behinds several climate phenomena, such as El Nino-Southern Oscillation (ENSO) and jet stream and storm track variations in the atmosphere. His research findings are often cited by studies in these areas. In collaboration with US national laboratories, Professor Yu develops state-of-the-art climate models that combine complex Earth science disciplines and are capable of performing century-long simulations on distributed parallel supercomputers. He is also involved in many other research projects funded by US government agencies and universities, including National Oceanic and Atmospheric Administration, Los Alamos National Laboratory of Department of Energy, Jet Propulsion Laboratory of National Aeronautics and Space Administration, and Water Institute of University of California. Professor Yu has been actively involved in, and has served as program chair, in many international conferences that document the state-of-the-art in the development and application of environmental information technology and promotes the dialogue of science, industry and end-users. Professor Yu received his Ph.D. in Atmospheric Sciences from University of Washington in 1993.