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IDENTIFICATIONS AND APPLICATIONS OF COUPLED CLIMATE MODELS

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Keywords: Climate system, climate model, atmosphere, ocean, land surface, chemistry, coupling interface, information exchange

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 Nio and La Nia 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.

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.

5. Computational Aspects of Coupled Climate Models

Coupled climate models need to solve complex mathematical equations to simulate climate. Long-term integrations are always necessary for coupled climate models to have enough samples for studying climate phenomena with long characteristic timescales. These two characteristics of coupled climate models make computational efficiency an important issue in coupled model developments.

5.1. High-Performance Computational Tools

The advance of computer technologies has been one important factor for the progress of climate modeling techniques. Faster and better computers make it possible for climate models to include complex physical processes for more realistic simulations. On the other hand, the need for intense computational power in climate modeling presents a grand challenge to the development of computer technologies. Climate modeling has benefited by the introduction of supercomputer and parallel computing. Both computer techniques have made complex, fully coupled ocean-atmosphere general circulation climate models possible to perform decadal and century-long simulations. In particular, parallel computing provides computational tools that offer high-performance computing with relatively low costs. There is an increasing trend in the climate modeling community to modify existing climate models for parallel computing environments. Several new climates are being developed purposely for parallel computing environments. One example is the Parallel Ocean Project (POP) OGCM developed at Los Alamos National Laboratory.

5.2. Model Data Information System

Another important issue related to the computational aspect of coupled climate modeling is the need for an efficient way to exchange information among different climate components and to process the large amount of output from model simulations. This issue becomes more fundamental as parallel computing has been increasingly adopted as the computational platform for climate modeling. In parallel computing environments, information exchange is a major factor to slow down computational speed. Also model parameters are produced by component models that are executed in distributed computer environments. How to gather information from those distributed locations and redistribute them to other processors is of central importance to coupled climate models.

Software tools have been developed to handle distributed data exchanges between the components in coupled climate models, which are sometimes referred to as a model data information system. In addition to handling information exchanges among component models, model data systems are also designed to validate model simulation against observational data. Observational data sets are usually located at different institutes, collected at various grid systems, and represented in different units. These heterogeneous characteristics are similar to those faced by the coupling interfaces in coupled models. Model data information schemes are also capable of presenting model simulation results in visualizations and other presentational methods. This is designed to help end-users, who are not necessarily familiar with numerical model techniques, model configurations, and data structures, to make use of model results. One example of such a data information system is the Earth System Model Data Information System (ESMDIS) developed at University of California Los Angeles.

6. Important Issues of Climate Model Coupling

Component models are mostly developed separately and were not originally designed to be coupled with other models. Several important technical issues have to be addressed in order for coupled climate models to produce realistic simulations.

6.1. Mismatch of Model Grids

Each climate component has its own characteristic space scales that have to be properly resolved in the numerical model by appropriate grid sizes. Characteristic spatial scales in different climate components can be very different, so are the grid sizes of their component models. For example, characteristic space scales are on the order of a thousand kilometers for atmospheric climate phenomena, but are on the order of hundreds of kilometers for major oceanic phenomena. Atmospheric model grids are usually much larger than oceanic model grids.

When coupling together two component models with very different grid sizes, one grid box in one component model covers several grid boxes in another model. The same information from the larger-size grid have to be distributed to several grid boxes in the model with smaller grid size. At the same time, information from several small-size grid boxes has to be integrated together before being passed to the larger-size grid box. This is often referred to as the mismatch of model grids.

Numerically, grid mismatch affects only information exchanges between two models. This can easily be handled with linear interpolation or more sophisticated weighting methods. Scientifically, however, the grid mismatch implies the interactions between two climate components are not properly simulated in coupled models. In the case of the coupled ocean-atmosphere model, the same atmospheric forcing is applied to several ocean grid boxes, which could have very different oceanic structures and should have received different atmospheric responses. No accurate atmospheric responses are provided for those ocean grids. Even though the impacts of grid mismatch on coupled model simulations is uncertain and case dependent, care should be exercised when grid systems are selected for coupled climate models.

6.2. Frequency of Coupling

Different climate components respond to external forcing at different rates. For example, the general circulation in the atmosphere adjusts itself to changes in ocean surface temperatures on the order of days to months. This is much faster than the time it takes oceanic circulation to respond to the change in atmospheric forcing, which is on the order of months to years. When coupling two climate components with very different response timescales, how often these two components should communicate or interact with each other becomes an important issue.

In the real world, interaction among climate components occurs continuously. In a "perfect" coupled climate model, exchanges of information, or the "communication", among component models, should be performed as often as possible. However, it is computationally expensive to do so. Also, information passing is usually a major factor which slows down computational speed, in particular with high-performance parallel computers. The frequency of coupling, therefore, has to be carefully determined by weighing scientific realism and computational constraints.

6.3. Climate Drift

No numerical model is perfect. Systematic errors, sometimes called model deficiencies, exist for every model. The climate simulated by a model of one climate component is different from that of the real world. Most climate component models are tested with forcing provided from observations. Systematic errors are kept to the smallest level possible during model developments. In most cases, the differences are determined to be small enough and tolerable during those forced model tests. When climate component models are coupled together, the performance of one component model can significantly affect the performance of the other through interactions. Originally tolerable and small deficiencies can, therefore, be amplified in coupled models and gradually lead to unrealistic simulations of climate. The slow trend of drift of the simulated climate state away from the initial climate is referred to as the climate drift. Climate drift is an unwanted phenomenon in coupled climate models and indicates a failure of coupled model developments. In addition to further refinements of individual component models, some coupling techniques have been developed to alleviate the climate drift problem.

6.4. Spin-up Process

The Spin-up process is one of the coupling techniques that is used to reduce the climate drift problem in coupled climate models. The technique intends to reduce the initial imbalance between two climate states by integrating each individual component model to a quasi-equilibrium state before coupling. The simulated conditions from near the end of the spin-up process are used as the initial condition for coupled climate models. This method is widely used in coupled ocean-atmosphere models. The spin-up process also helps to reduce the time to integrate coupled climate model to their equilibrium state in the coupled models, and therefore, reduce the computational costs. This is another advantage of the spin-up process.

6.5. Flux Correction Technique

Flux correction is also referred to as flux adjustment. This is another coupling technique often used in coupled ocean-atmosphere climate models to reduce the climate drift problem. The basic idea of this technique is that the model deficiencies in component models, which cause climate drift, are reflected in the information exchanged between two component models. For the cases of coupled ocean-atmosphere models, they are the surface fluxes exchanged at the atmosphere-ocean interface. The flux correction technique intends to reduce climate drift by "correcting" the flux at the interface.

For the cases of coupled ocean-atmosphere models, this technique first estimates the "true" surface fluxes needed to produce realistic ocean surface temperature in the ocean component model. This step involves using observational data to force the ocean model. The technique then determines the "simulated" surface flux produced by the atmosphere component model, when the model is forced by observed ocean surface temperature information. The differences between the "simulated" and "true" surface fluxes are the amount of flux which needs to be "corrected" at the coupling interface. This amount of flux is added to the surface flux produced by atmospheric component models before they are passed to oceanic component models.

Flux correction is equivalent to adding external forcing to the coupled climate system. If the amount of correction is large, it will make interpretation of model results difficult. The need for flux correction will be reduced as component models become more realistic.

6.6 Centralized Coupler or Distributed Broker

How model parameters are exchanged among component models is of central importance to coupled climate models. The task involves handling information produced at different model grid systems, requested at different frequencies, and represented in different units or forms. The major functions of the coupling device in coupled models are: gathering, redistributing, and converting information. There are two different philosophies in constructing the coupling device. One approach develops a centralized "coupler", which gathers information from all component models, calculates the exchanged parameters at the coupler's own grid system, and then redistributes to component models. For the case of coupled ocean-atmosphere models, surface fluxes are calculated by the coupler, rather than by the atmospheric model. All activities related to coupling are centralized, so they can be performed by the "coupler". Another approach is the distributed "data broker". In this approach, all coupling fluxes are calculated by corresponding component models. The locations and other relevant information of coupling fluxes are "registered" with the data broker.

The data broker converts flux information to the units and grid system of another model that requests those fluxes. In this way, there is no need for component models to know each other. All information passing through is "brokered" by the data broker.

6.7. Model Modulations

Code modulation is aimed at making component models easier to be "plugged in" (i.e., coupled) with each other and has been increasingly adopted by the climate modeling community. The principals of code modulations are to make model code as self-contained as possible, to make the model initializable by a single initialization entry point, and to perform all communication with external software packages through the argument list associated with a single entry point into that package.

7. Hierarchy of Coupled Climate Model

There is a hierarchy of coupled models with various complexities being developed in the climate research community. Depending on how the fundamental dynamics and physical processes of each climate system component are represented in component models, coupled climate models range from intermediate coupled models, hybrid coupled models, to fully coupled general circulation models. Each type of coupled model has its own unique strength. Because of the complexity of physical processes in the climate system that must be represented, coupled climate models need large computer resources. Selection of coupled model type primarily depends on the nature of the specific climate problem being addressed and the availability of computational resources.

Intermediate coupled models consist of component models that use statistical or simplified physics-based models. Hybrid coupled models combine together both complex models, such as general circulation models, and simple statistical or simplified physics-based models. Most complex fully coupled models use GCMs for both the atmosphere and ocean component models. Complex coupled models include more complete physics of various components of the climate system and are potentially capable of producing the most realistic simulations of climate phenomena. Nevertheless, those models have more degrees of freedom (variables) and are more prone to climate drift.

7.1. Coupled Ocean-Atmosphere Climate Model

Many more coupled climate models have been developed for the ocean-atmosphere system. Various complexities of coupled ocean-atmosphere climate models are used for simulation, long-term forecast, and sensitivity studies.

Intermediate coupled ocean-atmosphere models are commonly used for studying El Nio-Southern Oscillation (ENSO) phenomena. This group of models usually uses the shallow water equations models to represent the atmosphere and oceans.

They are computationally efficient and at the same time include the basic feedback dynamics necessary for producing the ENSO phenomena. More importantly, the mean climate states of the coupled ocean-atmosphere models are often prescribed from observations. As a result, there is little problem of climate drift in those models. Intermediate coupled ocean-atmosphere models are important and useful tools for the understanding and long-term prediction of many coupled ocean-atmosphere phenomena.

Hybrid coupled ocean-atmosphere models include two types: one is complex AGCMs coupled with simple oceanic models, and another is simple atmospheric models coupled with complex OGCMs. Two examples of the first group are AGCMs coupled to swamp or mixed-layer ocean models. In both types of ocean models, ocean surface temperatures are determined by considering the surface energy budget and the heat capacity. No ocean dynamics are considered. Those hybrid-coupled models are often used to form the basic assessments of global climate sensitivities or responses to anthropogenic forcings. The type of hybrid models using complex OGCMs and simple atmospheric models are often used to study climate phenomena that have oceanic origins but need atmospheric forcing to determine their evolution. Usually these climate phenomena have long timescales. Examples include ENSO and the thermohaline circulation. For these climate phenomena, the detailed evolution of the atmosphere is of secondary importance. The simple atmospheric component models are sufficient to generate reasonable forcing of the ocean models.

Fully coupled GCMs are extensively used for studying many climate phenomena. This type of coupled models provide comprehensive information on the atmosphere and ocean, and are capable of coupling to other component models from Earth system models for environmental studies. Fully coupled GCMs also have the potential for many other important climate applications, such as data assimilations.

7.2. Coupled Atmosphere-Land Surface Models

AGCMs are often coupled to two types of land surface models. For the simple type, some important land surface properties, such as albedo and roughness, are prescribed. The complex soil-vegetation complex is not considered in detail. In the more complex land surface models, the radiative, thermal, and moisture properties are determined based on the soil-vegetation complex. Two popularly used land surface models of this type are the Biosphere-Atmosphere Transfer Scheme (BATS) and the Simple Biosphere Model (SiB). AGCMs coupled with this type of land surface model have been increasingly popular for climate research and applications.

7.3. Coupled Chemistry-atmosphere/Ocean Models

It is computationally intense for chemistry transport models to solve mass conservation equations for chemical compounds in a realistic global and three-dimensional atmosphere, even with only a relatively small number of chemical species. The hierarchy of chemistry models are structured by spatial discretization of models, ranging from one-dimensional, two-dimensional, to three-dimensional models. Two-dimensional models, as a function of latitude and altitude, are often used to study chemical processes in the stratosphere. Three-dimensional models provide the most realistic representation of the transport of tracer species. AGCMs coupled with three-dimensional chemistry-tracer models are used for understanding the ozone hole depletion problem.

Box models are often used in biochemical ocean models to represent the exchange of chemical species between upper and lower parts of the ocean. They are powerful tools to understand the roles of chemical transport in the ocean. However, three-dimensional chemistry transport models are required to study the carbon cycle problem. See *Flux Correction/Adjustment*

8. Applications of Coupled Climate Models

8.1. El Nio-Southern Oscillation

El Nio originally referred to the warming of ocean surface temperatures in the equatorial Eastern Pacific near South America. The warming occurs quasi-periodically every 3-7 years. This oceanic phenomenon was found to always accompany general circulation changes in the atmosphere, which are characterized by out-of-phase surface pressure oscillations between eastern and western equatorial Pacific. The surface pressure oscillation is referred to as the Southern Oscillation. It is now recognized that the occurrence of El Nio affects atmospheric circulation and produces the Southern Oscillation. The appearance of the Southern Oscillation, in return, affects the evolutions of El Nio. It is now known that El Nio and Southern oscillation are two aspects of the same coupled ocean-atmosphere phenomenon, which is now called El Nio-Southern Oscillation (ENSO). Warm and cold ENSO events are often used to refer to the El Nio and La Nina events, respectively.

El Nio-Southern Oscillation has great impacts on global climate and human society, and is one of the most-intensively studied climate phenomena. Coupled ocean-atmosphere climate models are most popularly used to simulate this phenomenon. Realistic simulations of ENSO become a major test to the performance of coupled ocean-atmosphere models. In the past, intermediate types of coupled ocean-atmosphere models obtained much more success in reaching this goal than fully coupled GCMs. Since the middle 1990s, fully coupled GCM have made significant progress in producing realistic simulations of ENSO, and have demonstrated their capability in performing long-term predictions of ENSO. Many improvements in coupled ocean-atmosphere GCMs are obtained by improving physical parameterizations in AGCMs, such as radiation schemes, cumulus convection scheme, and planetary boundary layer formulations.

8.2. Amazon Deforestation and Sahel Desertification

Both the Amazon deforestation and Sahel desertification problems were originally linked to human activity that changed land surface properties. Deforestation is often referred to as the removal of forests in tropical rainforests. Desertification refers to the removal of relatively short vegetation in semiarid regions. These land surface changes influence the energy balance in the atmosphere through land surface albedo, influence the water budget through soil moisture and evaporation, and influence aerosol amounts in the atmosphere through surface wind. The atmosphere, in return, further affects the deforestation and desertification through hydrological and radiation processes. It is believed that positive feedbacks further intensify the deforestation and desertification problems. AGCMs coupled to sophisticated land surface models, which determine land surface properties by considering the soil-vegetation complex, are being used to understand the sensitivity of the coupled atmosphere-land surface system to changes in land surface use.

8.3. Ozone Hole Depletion

Ozone depletion is a phenomenon that occurs in the stratospheric layer of the atmosphere, primarily over Antarctica. This phenomenon is often referred to as the loss of ozone or the increase of the ozone hole in the region. Ozone concentrations in this region are strongly controlled by the interactions between chemical reactions and atmospheric circulation. During the Antarctic winter, the atmospheric circulation is characterized by a polar vortex that confines very cold air to this region. This cold environment allows polar stratospheric clouds to form and provides an environment suitable for chemical reaction processes to deplete ozone. Sunlight returns to Antarctica in spring to warm up the cold polar vortex. Polar stratospheric clouds are destroyed, and ozone concentrations increase. Ozone is constantly being produced and destroyed through this natural cycle. However, man-made trace gases, such as chlorofluorocarbons (CFCs), upset this balance and increase the ozone hole depletion. These man-made compounds are transported by the atmospheric circulation from the troposphere to the stratosphere. CFCs are photodissociated by ultraviolet radiation and release chlorine atoms, which destroy ozone through chemical reactions. Therefore, ozone levels fall.

Ozone is responsible for absorbing ultraviolet radiation, which is biologically harmful. Depletion of ozone results in more ultraviolet radiation reaching Earth's surface, which may damage human health and certain crops and marine organisms. It also means less solar radiation is absorbed in the upper part of the atmosphere, and more is being absorbed by the surface. Heating associated with radiation can change the atmospheric thermal structure and affect its circulation. There are clearly two major components involved in the ozone hole depletion problem: atmospheric circulation and chemical reaction processes. Coupled chemistry-atmosphere climate models are needed to better understand the ozone hole depletion problem and to project its impacts on Earth's climate and human society.

8.4. Global Warming

Global warming due to man-made greenhouse gases has become a grave concern to human society over the past few decades. To determine how the climate system responds to the increase of greenhouse gases can not be addressed by considering the atmosphere alone. The ocean is a huge heat storage of the climate system, and also plays an important role in transporting heat among different latitudes. Any direct impacts of greenhouse gas increases on the atmosphere can be modified by the oceans. Furthermore, the soil-vegetation complex on land will respond to changes in the atmosphere and change land surface properties. Land surface property changes will affect the energy and water budget in the atmosphere. Chemical processes are certainly also involved in determining the response of the climate to greenhouse gases releases. Therefore, climate system models that consist of at least the atmosphere, ocean, land surface, and chemistry are needed to understand and project the global warming phenomenon.

Acknowledgements

The author would like to thank Professor Akio Arakawa for providing information on the developments of atmospheric general circulation models, and Dr. John D. Farrara for his comments and suggestions.

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Glossary

Climate model :A computer-based numerical tool that simulates the major characteristics of the climate system. It often involves numerically solving a set of physical equations that govern the climate system or a set of statistical relations that best describe the long-term behaviors of the climate system.

Coupling :A two-way interaction that allows different media of the climate system, such as the atmosphere and ocean, to influence and to be influenced by each other.

Desertification :Desertification refers to the removal of relatively short vegetation in semiarid regions.

Weather and Climate :Weather usually refers to shorter-term phenomena of the environment, such as the day-to-day changes of temperature and precipitation. Climate refers to the long-term behaviors of the environment, such as the averaged temperatures and rainfalls in a season, year, or a decade.

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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.

To cite this chapter
Jin-Yi Yu, (2004), IDENTIFICATIONS AND APPLICATIONS OF COUPLED CLIMATE MODELS, in *Environmental Systems*, [Ed. Achim Sydow], in *Encyclopedia of Life Support Systems (EOLSS)*, Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford ,UK, [http://www.eolss.net] [Retrieved October 18, 2006]