ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 23, NO. 3, 2006, 442–448

Framework of Distributed Coupled Atmosphere-Ocean-Wave Modeling System

WEN Yuanqiao*[1] (文元桥), HUANG Liwen[1,2] (黄立文), DENG Jian[1] (邓 健), ZHANG Jinfeng[1] (张进峰),
WANG Sisi[1] (王思思), and WANG Lijun[1] (王立军)

[1] *Wuhan University of Technology, Wuhan* 430062

[2] *State Key Laboratory of Numerical Modeling for Atmospherics Sciences and Geophysical Fluid Dynamics,*
Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

(Received 14 March 2005; revised 3 November 2005)

ABSTRACT

In order to research the interactions between the atmosphere and ocean as well as their important role in the intensive weather systems of coastal areas, and to improve the forecasting ability of the hazardous weather processes of coastal areas, a coupled atmosphere-ocean-wave modeling system has been developed. The agent-based environment framework for linking models allows flexible and dynamic information exchange between models. For the purpose of flexibility, portability and scalability, the framework of the whole system takes a multi-layer architecture that includes a user interface layer, computational layer and service-enabling layer. The numerical experiment presented in this paper demonstrates the performance of the distributed coupled modeling system.

Key words: system framework, mesoscale models, distributed coupled modeling

doi: 10.1007/s00376-006-0442-2

1. Introduction

The earth's climate system is extremely complex. It is often considered to be composed of a number of components such as the atmosphere, ocean and land. Typically, the corresponding numerical models are developed separately by different research groups to study the characteristics of the sub-systems. However, the individual models cannot realistically model the interactions between or among the different components. Indeed, the modeling of a complex system requires multiple physical models, at multiple scales and resolutions. Thus, it is a natural approach to develop coupled models that will provide significant advantages over single models in the modeling of complex systems.

A number of global and large-scale air-sea coupled models have been developed aimed at global climate change, seasonal cycles and other large-scale phenomena (e.g., ENSO) (Zebiak and Cane, 1987), for example, the GOALS (Global Ocean-Atmosphere-Land System) (Wu et al., 1996, 1997) and FGCM (Flexible Global Climate Model) (Yu et al., 2002) of LASG (State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics), and the CCSM (Community Climate System Model) (Branstetter and Erickson, 2003) of NCAR (National Center for Atmospheric Research).

However, except for large scale phenomena, many meteorologists are interested in many phenomena that occur on finite spatial scales (or sea basin scales) and short timescales (less than one week generally), such as typhoons that effect coastal zones, explosive mid-latitude ocean cyclones, coastal gales and low-level jets, coastal storm surges, sea fog, meso-cyclogenesis over Kuroshio, coastal frontogenesis, and the Gulf Stream rain band and its meandering in response to cold air outbreaks. The factors influencing these phenomena include the atmosphere, the ocean (including flow, SST and waves) as well as the interactions between them. Hitherto, the understanding and prediction of these phenomena are still largely uncertain. Integrating the interactions between the atmosphere and ocean into the study of these meso-scale phenomena

---

*E-mail: wenyuanqiao@yahoo.com.cn

has significant meaning for disaster weather forecasting in coastal areas. Thus, it is important to develop a coupled atmosphere-ocean-wave model as a modeling tool for theoretical and applied research.

Generally, model coupling includes two aspects: One is how to realize the information exchange between individual models. It is necessary to link the models together so they can exchange information either at boundaries where the models align in physical space or in areas where the models overlap in space. The other is how to describe the scientific problems of the interactions between or among individual systems modeled by the numerical models. Typically, model coupling is performed in one of the four following ways:

The file I/O based model coupling (Hodur, 1996), in which model preprocessors transform the output files from one model into input files for the second model, is a very costly alternative and is only suitable for very slowly varying physics.

The subroutinization method of model coupling can only be used to perform simple information exchange between models through an argument list, because it requires one of the models to be written as a subroutine of the other model. This method significantly reduces the models' performance, requires significant modifications to the sub-models and produces code that is difficult to maintain.

The inter-process communication based model coupling uses a Unix/Linux pipe as the communicator to exchange information between sub-models (Xue and Pan, 2000). Though it is relatively easy to modify the sub-models, it is only suitable for the coupling of two lightweight models since it requires the sub-models to run on the same hardware platform.

The final and more common method for model coupling is through a coupler (Zhou et al., 2004), such as the CSM (Climate System Model) Flux coupler (Bryan et al., 1996) from NCAR, the OASIS coupler (Terray et al., 2000) from CERFACS (European Centre for Research and Advanced Training in Scientific Computation), the MpCCI (Ahrem et al., 1996) from SCAI (The Fraunhofer-Institute for Algorithms and Scientific Computing), and the MCT (Model Coupling Toolkit) from Argonne National Laboratory (Larson et al., 2001). The coupler is a type of software based on MPI (Message Passing Interface), PVM (Parallel Virtual Machine) or OpenMP (Open specifications for Multi Processing). It connects the model components together and allows for the exchange of fluxes and variables between the model components. This method has been widely used in large scale coupling models because this approach requires much less modification of the given applications, allowing for better maintainability of the models, and is feasible to distribute applications over different hardware platforms for improved model performance. However, it is not easy to develop a user-friendly coupler, especially for geophysical scientists.

Recent computer and networking advances, particularly those based on TCP/IP, have made it possible to implement the multi-model coupling in a more straightforward way. This paper describes the framework of a coupled meso-scale atmosphere-ocean-wave modeling system in a distributed computing environment. The system can couple any meso-scale atmospheric model, regional oceanic model or wave model as a research prototype or experimental model that is designed to provide an easy-to-use computing platform for researchers who want to quickly implement a distributed coupling computation. It represents an application of state-of-the-art networking and distributed computing technology to multi-model coupling.

This paper describes the distributed, coupled meso-scale atmosphere-ocean-wave modeling system in section 2 and presents the distributed, coupled modeling system's performance during a numerical case study in section 3. Conclusions are given in section 4.

2. The distributed model coupling system

2.1 *Models in the system*

The models coupled in the system include two mesoscale atmospheric models, two regional oceanic models and a wave model. The atmospheric models can be the LASG-AREM, a regional eta-coordinate model (Yu and Xu, 2004) developed by State Key Laboratory of Numerical Modeling for Atmospherics Sciences and Geophysical Fluid Dynamics/Institute of Atmospheric Physics/Chinese Academy of Sciences (LASG/IAP/CAS), the MM5, a nonhydrostatic primitive equation forecast model (Dudhia et al., 2005), or any other mesoscale atmospheric model. The regional oceanic models can be the Princeton Ocean Model (POM), a three-dimensional primitive equation model designed to simulate marine circulations (Xue et al., 1995) or ECOM-si (Blumberg, 1994), a sigma coordinate non-linear forecasting model employing a hydrodynamic simulation of an estuary, coast, or regional or open sea area. The wave model in the system is Wavewatch III (http://polar.ncep.noaa.gov/waves/), a third generation wave model developed at National Oceanic Atmospheric Administration/National Centers of Environmental Prediction (NOAA/NCEP) in the spirit of the WAM (WAve Modeling) model that solves the spectral action density balance equation for wavenumber-direction spectra.

In the distributed model coupling system, researchers can easily plug in or unplug any sub-models according to their simulation requirements on one or more machines (such as PCs, workstations, or clusters) under identical or differing operating systems. The researchers need only to simply modify the sub-models by using two functions developed for constructing the coupling interface.

2.2 *Model coupling in the system*

The model coupling takes the form of an exchange between the atmospheric surface layer and ocean surface parameters. Each model sends and receives variables, with a recipient model waiting for the necessary information from another before continuing. The coupling occurs between the oceanic area contained in the atmospheric model and the grids of the oceanic or wave models. The models can run concurrently and parameters are exchanged at overlapping model time steps based on the model's synchronous or tightly coupled mode of linkage in the system. The exchange of parameters between models is depicted in Fig. 1 and is described below.

Coupled atmosphere-ocean models: The atmospheric model's input to the oceanic model consists of surface momentum fluxes (such as individual u- and v-component fluxes) and heat fluxes (such as sensible heat fluxes, latent heat fluxes and net radiative fluxes) (Power et al., 1997). SSTs of the oceanic model are transferred to the atmospheric model and become the atmospheric model's surface temperatures, which are usually fixed in time (for example, weekly or monthly averaged SSTs) over the oceanic area.

Coupled atmosphere-wave models: The 10-m wind fields (fractional velocity of the atmosphere) are transferred from the atmospheric model to the wave model. The standard deviation of the water surface elevation for calculating the component of the over-water roughness length associated with form drag, and wave phase speed as well as wave direction, which are used by the atmospheric model in determining wave-relative winds, from the wave model are transferred to the atmospheric model at each coupling time step (Weisse and Alvarez, 1997).

Coupled ocean-wave models: Water level variation and surface currents from the oceanic model are transferred to the wave model. The sea state modified friction velocity from the wave model is then transferred to the oceanic model (Doyle et al., 2002).

The model coupling in the system is very flexible and is fully determined by the researchers' needs. By implementing a user interface, researchers can select different parameters and different time steps to carry out various numerical experiments according to the demands of their research.

2.3 *Framework of the system*

The coupled atmosphere-ocean-wave modeling system is a multidisciplinary application that requires knowledge of atmospheric science, oceanic science, and mathematics, as well as physics. The different models share common parameters and interfaces but each has its own parameters and constraints. Realizing the whole system will require the development of new software for managing the complexity and harvesting the power of the expected high performance computing and communication resources (Walkley et al., 2002).

The design of the framework of the system should allow the following capability: First, the framework should be applicable and flexible to the coupling of various models according to the requirement of researchers. Second, the framework should allow for software reuse in order to achieve lower costs and high quality for the long development period of the numerical models. Finally, the framework should allow users (multidisciplinary cooperative researchers, such as meteorologists, oceanographers, etc.) to solve problems without specialized knowledge of the underlying computer hardware or software. With the help of such a

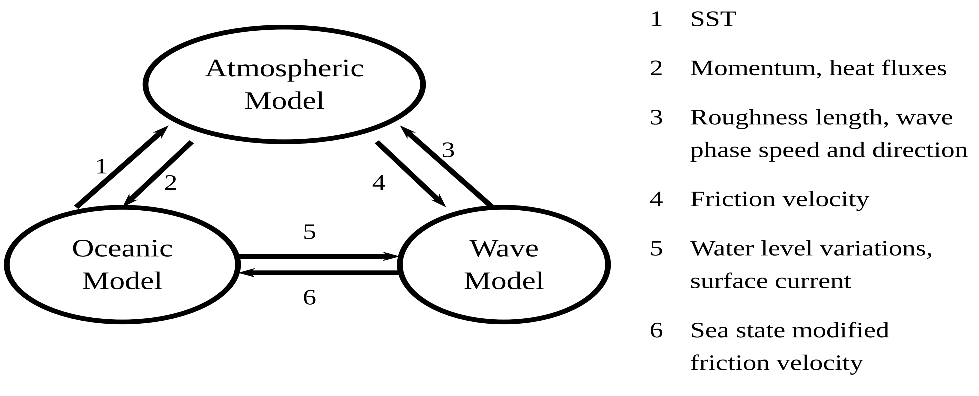

Fig. 1. The exchange of parameters between models.

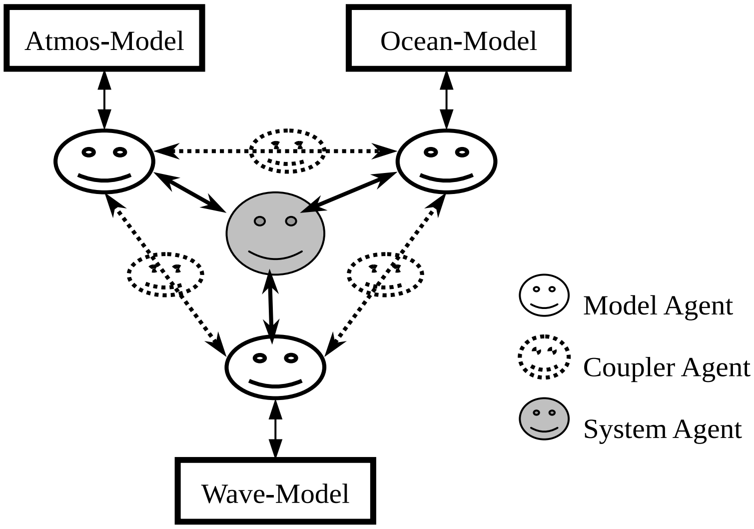

Fig. 2. A hypothetical example of model coupling.

system, the researchers can pay more attention to their own research domain without worrying about the complexity of the computer or the details of the computations themselves (Markus et al., 2000; Lee et al., 2000).

Figure 2 shows a hypothetical example for model coupling. Hypothetically, there are three models in the system: the atmospheric model (Atmo-Model), the oceanic model (Ocean-Model) and the wave model (Wave-Model). The whole system is a multiple software agent (a software agent is an autonomous computer program that operates on behalf of someone or something) system (MAS) (Wen et al., 2004) and consists of four basic components: numerical models, model agents, coupler agents, and a system agent. Each numerical model synchronously works on the same or different machines (PCs, workstations, clusters, etc.) independently to implement their numerical simulation functions. The model agent (MA) is a numerical model's interface to implement the model coupling, and all communications and commands are routed through the numerical model's MA. Thus, the numerical model needs to communicate directly only with its MA. The coupler agent (CA) is used to realize the coupled computing according to the requirements of the model coupling. The system agent (SA) acts in the role of system management and is responsible for the system register, system security, load balance and resource scheduling. All these mutually independent agents (model agents, coupler agents, system management agents and resource management agents, etc.) construct a virtual coupled computing space. Together, they shield the heterogeneity of the system and the complexity of the application environments and allow all users to share a single and transparent working space for their own domains.

2.4 *Software architectural overview of the system*

In this section, an overview of the agents and other components contained in the framework of the entire system are presented. The overall generic software architecture (Fig. 3) is also discussed.

User Interface Layer: The user interface of the framework mainly comprises the coupling specification module and agent dispatcher module. The dispatcher, which has a graphical interface to display its actions, interacts with the specific agents in the underling Aglets platform (http://www.trl.ibm.com/aglets). These agents enable the actual coupling computation in the coupled modeling system. The coupling specification module is used to specify the coupling information, such as the selected model for performing the coupling, the coupled domain of the atmospheric model and the coupled model grids of the oceanic and wave models, coupling time step, interpolation methods, and parameters for exchange, and it does this by using a graphical interface. All information from the coupling specification module is directed to the agent dispatcher module. Then, it dispatches model agents (MAs) to the physical host location for each model to specify the model and to launch the coupler agent using information provided by the resource management agents and the adaptive allocation algorithms for optimizing network connectivity and machine load. The user interface shields the complexity of the coupling simulation with a user-friendly graphical interface. With the help of the user interface, it is very convenient for users to modify the computational parameters and share the

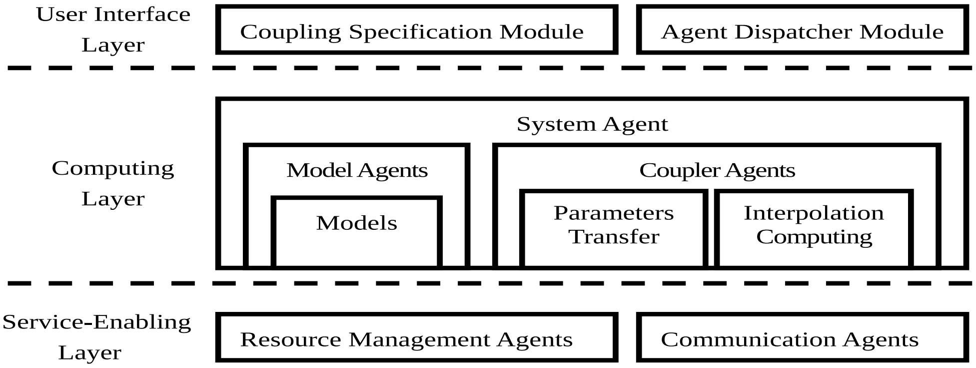

Fig. 3. The software architecture of the system.

transparent workspace, thereby allowing researchers to pay more attention to the scientific problem that they are most interested in, rather than the details of the computation itself.

Computational Layer: In this layer, the model agents and coupler agents are all under the control of the system agent. The system agent communicates with the model agents and controls its running state by monitoring the distributed model agents and coupler agents on each host. The system agent also manages and schedules all available computing resources by interacting with the resource management agents on the target hosts to ensure the computational requirements of the coupling simulation and to keep the system load balanceed. The system agent is the only entrance to the coupling system. For security, users must register and apply for the corresponding authorization before implementing a coupled computation. There is a one-to-one relationship between a numerical model and a model agent. The model agent is the user interface of the corresponding numerical model for the purpose of legacy code. It communicates directly with its numerical model and controls the running state of the numerical model. The coupler agent works to govern the coupled computation (such as interpolation, smoothing computation, flux correction, etc.) and the parameter transfer between two models according to the coupling requirements. The coupling requirements and the interpolation methods in the two models may differ. This suggests that the coupler agents should handle them separately. Therefore, the coupler agent is divided internally into two parts. Each part controls the parameter transfer and interpolation computation of the respective model.

Service-enabling Layer: This layer is mainly used as the foundation facility of the whole system for the management of computation resources, communication, security, and load balancing of the system. Currently, this layer mainly comprises resource management agents (RA) and communication agents (CA). The RA may maintain the information of available computation resources, the usage of the resources, the state of networks and other available resource information needed by the system. The information from the RA facilitates the transparent resource management and usage of the whole system. The exchange of the coupling information (parameters in different models) is realized via a TCP socket, which is one of the most efficient ways of intensive data transfer. The socket programs are encapsulated in the CA. However, it is not necessary for the users to know the details of the communication with the intelligence of the agents.

3. Numerical experiments and system analysis

In the experimental system, the joined models are MM5, ECOM-si and Wavewatch III. The mobile agent execution environment used to implement the system is based on Aglet technology. The coupling specification modules are based on Unix/Linux shell scripting. Sockets are realized in the Java language to allow for the cross-platform feasibility of the system.

Tropical cyclone Rammasun (No. 0205) is presented as an example case study. On 29 June 2002, Rammasun developed as a tropical depression about 250 km northwest of Yap and intensified into a tropical storm on the same day. It moved northwestwards over the Pacific and gradually strengthened into a typhoon on 1 July. Rammasun then headed towards the seas east of Taiwan. On 4 July, Rammasun turned north and moved across the East China Sea. Rammasun weakened into a severe tropical storm on 5 July and changed its course to the northeast. The system then weakened to a tropical storm and became an extratropical cyclone in the Sea of Japan on 6 July.

In all numerical experiments, the domain center of MM5 is at 32°N, 121°E. The atmospheric model has 141×187 grid points in the horizontal with a grid distance of 37.5 km. In the vertical, 27 sigma levels are employed between the ground and 100 hPa. The model has the selected time step of 120 s. The ECOM-si model has 11 vertical sigma layers and 164×202 grid elements with a selected time step of 480 s. The horizontal resolution of ECOM-si is 10 km. Wavewatch III is implemented at the same resolution as ECOM-si with a time step of 480 s.

The oceanic model is driven by heat and momentum fluxes from MM5, which in turn provides SST back to the atmospheric model. The wave induced stress from Wavewatch-III is transferred to ECOM-si, and in turn it provides current velocity and elevation to the wave model. The parameters exchanged between MM5 and Wavewatch III are the u- and v-components of the 10-m wind fields and the wave induced roughness.

The machines utilized in the experiments are an Origin 300 workstation (600 MHz 8 CPU/4 GB Memory, Unix operating system) and two PCs (2.0 GHz 1 CPU/1 GB Memory, Linux operating system). The machines are connected by a 100 Mbps LAN (Local-Area Network). In the first experiment, all models are run on the workstation. In the second experiment, the atmospheric model and wave model are executed on the workstation, while the oceanic model is run on one PC. In the third experiment, the atmospheric model is executed on the workstation while the oceanic model and wave model are run on separate PCs. The last experiment is the single run of the MM5. In all experiments, the models are coupled every 480 s and have a 30-h coupling run. The starting time of the coupling run is 1200 UTC 4 April 2002.

The numerical experiments as described above have been run with the intention of demonstrating the technical applicability, communication efficiency and stability of the coupled modeling system. The system ran successfully in all of the above experiments. Figure 4 simply presents the output of the numerical experiments of the coupling runs and non-coupling run to illustrate the products of the coupled modeling system. However, the analyses of the simulations are beyond the scope of this paper.

The motivations of the second and the third experiments are to prove the feasibility of distributed coupling over a LAN and to show the communication efficiency, as well as to determine the communication cost of the coupled modeling system. The results confirm that the coupled modeling system can indeed operate over a LAN. Thus, it is possible that different disciplines (e.g. meteorologists, oceanographers) can run the coupled model at different places, and thus enhance their long-distance collaboration.

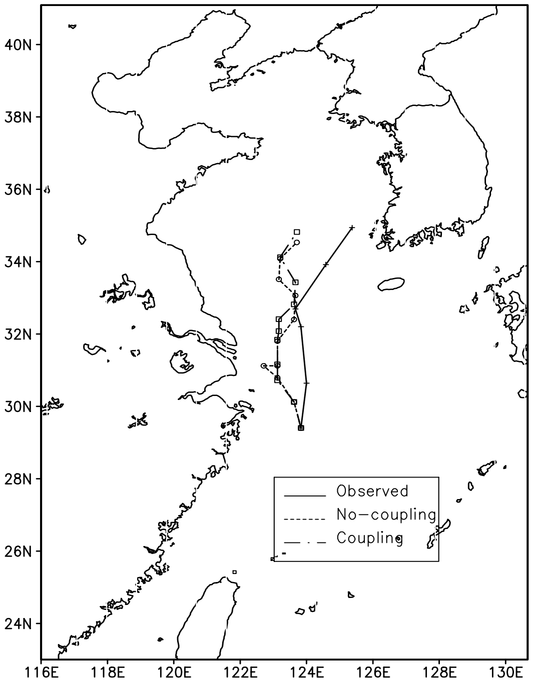

Fig. 4. The central sea level pressure (SLP) of Rammasun in the coupling experiment and no-coupling experiment.

When looking at the results of the coupled simulations, the atmosphere still dominates and it becomes obvious that the simulation time for the coupled experiment has not increased dramatically compared with the non-coupled experiments. The communication cost in the three experiments is 4.6%, 7% and 8.2%, respectively. The communication overhead depends on the exchanged coupling information and the network latency, as well as the synchronicity of the models.

4. Conclusion

Using the modeling of tropical cyclone Rammasun as a case study, this paper demonstrated how the distributed, coupled atmosphere-ocean-wave modeling system can be used to dynamically link different models to realize multi-model coupling. The proposed architecture for the framework provides flexibility and extensibility for the system. The users can extend the system according to their demands at the user interface level by specifying their coupling requirements. By facilitating flexible and easy information exchange between models, the system can be a valuable tool in a wide range of meso-scale air-sea interaction research or application areas. It provides a flexible shared workspace for the cooperation of multidisciplinary researchers in geophysical fluid dynamic modeling and makes it possible for the researchers to implement the multi-model coupling by plugging-in or unplugging the models.

Acknowledgments. This study is supported by the National Natural Science Foundation of China (No. 40275015)

REFERENCES

Ahrem, R., M. G. Hackenberg, U. Karabek, P. Post, R. Redler, and J. Roggenbuck, 1996: Specification of MpCCI. Technical Report 1.2, GMD–SCAI, Sankt Augustin, Germany, 1–78.

Branstetter, M. L., and D. J. Erickson, 2003: Continental runoff dynamics in the Community Climate System Model (CCSM2) control simulation. *J. Geophys. Res.*, **108**, 4550–4566

Bryan, F. O., B. G. Kauffman, W. G. Large, and P. R. Gent, 1996: The NCAR CSM Flux Coupler. Technical Report TN-425+STR, National Center for Atmospheric Research, Boulder, Co., 70pp.

Blumberg, A. F., 1994: A primer for ECOM-si. Technical Report, HydroQual, Inc., Mahwah, 57pp.

Doyle, J. D., 2002: Coupled Atmosphere-Ocean Wave Simulations under High Wind Conditions. *Mon. Wea. Rev.*, **130**, 3087–3099.

Dudhia, J., D. Gill, K. Manning, W. Wang, C. Bruyere, S. Kelly, and K. Lackey, 2005: PSU/NCAR Mesoscale Modeling System Tutorial Class Notes: MM5 Modeling System Version 3, 117pp.

Hodur, R. M., 1996: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscle Prediction System COAMPS. *Mon. Wea. Rev.*, **125**, 1414–1430.

Larson, J. W., R. L. Jacob, I. Foster, and J. Guo, 2001: The Model Coupling Toolkit. *Proc. 2001 International Conf. on Computational Science*, 185–191.

Lee, C., C. Chiang, and M. Horng, 2000: Collaborative Web Computing Environment: An Infrastructure for Scientific Computation. *IEEE Internet Computing*, **4**(2), 27–35.

Liu Xiying, Zhang Xuehong, Yu Yongqiang, and Yu Rucong, 2004: Mean climatic characteristics in high northern latitudes in an ocean-sea ice-atmosphere coupled model. *Adv. Atmos. Sci.*, **21**(2), 236–244.

Markus, S., and Coauthors, 2000: An agent-based netcentric framework for multidisciplinary problem solving environments. *International Journal of Computational Engineering Science*, **1**, 33–60.

Power, J. G., Mark T. Stoelinga, and W. S. Boyd, 1997: Distributed numerical weather prediction via satellite. *Bull. Amer. Meteor. Soc.*, **78**(12), 2755–2770.

Terray, L., A. Piacentini, and S. Valcke. 2000: Oasis 2.4, Ocean Atmosphere Sea Ice Soil: User's Guide. Technical Report TR/CMGC/00/10, CERFACS, Toulouse, France, 73pp.

Walkley, M., J. Wood, and K. Brodlie, 2002: A distributed co-operative problem solving environment. *Lecture Notes in Computer Science*, **2329**, 853–861.

Weisse, R., and E. F. Alvarez, 1997: The European Coupled Atmosphere Wave Ocean Model ECAWOM. Max-Planck-Institut für Meteorologie, Report No. 238, Hamburg, Germany, 35pp.

Wen, Y., S. Yu, J. Zhou, and L. Huang, 2004: Agent based distributed parallel tunneling algorithms. *Lecture Notes in Computer Science*, **3320**, 226–230.

Wu Guoxiong, Liu Hui, Zhao Yucheng, and Li Weiping, 1996: A nine-layer atmospheric general circulation model and its performance. *Adv. Atmos. Sci.*, **13**, 1–18.

Wu Guoxiong, and Coauthors, 1997: Global Ocean-Atmosphere-Land System model of LASG (GOALS/LASG) and its performance in simulation study. *Quarterly Journal of Applied Meteorology*, **8**, Supplement, 15–28. (in Chinese)

Xue, H., and Pan Z., 2000: A 2D coupled atmosphere–ocean model study of air-sea interactions during a cold air outbreak over the Gulf Stream. *Mon. Wea. Rev.*, **128**, 973–996.

Xue, M., K. K. Droegemeier, V. Wang, A. Shapiro, and K. Brewster, 1995: Advanced Regional Prediction System User's Guide. University of Oklahoma, 67pp.

Yu Rucong, and Xu Youpin, 2004: AREAM and its simulations on the daily rainfall in summer in 2003. *Acta Meteorologica Sinica*, **62**, 715–724.

Yu Yongqiang, Yu Rucong, Zhang Xuehong, and Liu Hailong, 2002: A flexible global coupled climate model. *Adv. Atmos. Sci.*, **19**, 169–190.

Zebiak, S. E., and M. A. Cane, 1987: A model El Niño-Southern Oscillation. *Mon. Wea. Rev.*, **115**, 2262–2278.

Zhou Tianjun, Yu Yongqiang, Yu Rucong, Liu Hailong, Li Wei, and Zhang Xuehong, 2004: Coupled climate system model coupler review. *Adv. Atmos. Sci.*, **28**, 993–1008.