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COUPLED ATMOSPHERE, LAND-SURFACE, HYDROLOGY, OCEAN-WAVE, AND OCEAN-CURRENT MODELS FOR MESOSCALE WATER AND ENERGY CIRCULATIONS

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1. INTRODUCTION

Coupled model system was developed to simulate mesoscale water and energy circulations, and test calculations were carried out for the coastal circulations around the Red Sea. The coupled model system consists of the atmosphere, land-surface, hydrology, ocean-wave, and ocean-current models. The models used in this system are the non-hydrostatic atmospheric dynamic model of Pennsylvania State University and National Center for Atmospheric Research (PSU/NCAR-MM5; Grell et al. 1994), detailed multi-layer land surface model (SOLVEG; Nagai 2002, 2003, 2005) and three-dimensional hydrology model (RIVERS; Tsuduki 2003) developed at Japan Atomic Energy Research Institute (JAERI), the third-generation ocean wind-wave model of NOAA, WAVEWATCH III (WW3; Tolman 2002), and the Princeton Ocean Model (POM; Mellor 1998).

In this coupled model system, calculations of the models are carried out as independent parallel processes and a model coupling program (model coupler) controls these processes and data exchanges among models using Message Passing Interface (MPI). This coupling method is very convenient for the construction of this kind of complicated coupled model. The modifications of models are easy, simply adding some modules for data exchanges to each model code without changing each model's original structure. This feature is helpful to make a model code coupling with a community model like MM5, which is updated regularly. Moreover, this coupling is flexible and allows the use of independent time step and grid resolution for each model.

In this paper, the coupled model system and preliminary results of test calculations are described.

2. OVERVIEW OF MODELS

The non-hydrostatic mesoscale atmospheric model MM5 (Grell et al. 1994) is a community model having many users all over the world, and is used for many purposes, even for the official weather forecast by some countries. It has many useful functions such as nesting calculations, four-dimensional data assimilation, and many options of parameterizations for cloud micro-physics, cumulus cloud, planetary boundary layer (PBL), radiation, and land surface scheme.

The land surface model SOLVEG (Nagai 2002, 2003, 2005) consists of one-dimensional multi-layer sub-models for the surface atmosphere, soil, and vegetation, and a radiation scheme for the transmission of solar and long-wave radiation in the canopy. It simulates diurnal variations and seasonal changes of variables in the surface atmosphere, soil, and vegetation canopy, and exchanges of energy and water among these systems, by using meteorological data of the surface layer atmosphere as the top boundary conditions. For coupling with an atmospheric model, one-dimensional model variables are expanded to three-dimensional ones whose horizontal coordinates coincide with those of atmospheric model. However, no interactions in horizontal directions are considered in the model.

The hydrology model RIVERS (Tsuduki 2003) is a grid type distributed runoff model. It consists of three-dimensional grid cells with five vertical layers and river channels. Horizontal and vertical water flows

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among connected grid cells and river channels are calculated from the GIS data (elevation, land-use, soil-type, etc.), and the water content of each grid cell is determined to keep the mass balance.

The ocean-wave model WW3 (Tolman 2002) is known as third-generation wave model that is phase-averaged and stochastic. It simulates temporal and spatial variations of wave growth and decay resulting from the surface wind force, dissipation due to white-capping, and the bottom friction on the water column.

The Princeton Ocean Model POM (Mellor 1998) is a three-dimensional primitive equation model, incorporating a turbulence closure model (Mellor and Yamada 1982) to provide a parameterization of the vertical mixing processes. It calculates the three components of current velocity, salinity, temperature, turbulence kinetic energy, turbulence length scale, and free surface elevation as prognostic variables. It uses a terrain-following sigma coordinate and suitable for the coastal region.

3. MODEL COUPLING

3.1 Coupling method

In this coupling, calculations of five models (MM5, SOLVEG, RIVERS, WW3, and POM) are carried out as independent tasks for different processors and a model coupling program (model coupler) controls these processes and data exchanges among models using Message Passing Interface (MPI) as schematically shown in Fig. 1. This type of parallel calculation is called Multiple Program Multiple Data (MPMD). The model coupler starts at first, and it invokes and controls calculation processes and MPI communicators of five models. It receives 2D or 3D-field data from a certain model and distributes them to other models in arbitrary time intervals, which are prescribed in data exchange setting files for coupled models. If model grids are different between sender and receiver models, the model coupler interpolates 2D or 3D-field data from a sender model on the grid of a receiver model. Therefore, this coupling has flexibility to use different resolution of grid and time step for each model. This coupling is also applicable to the nesting domain calculation, which is the important function used in MM5. Moreover, data exchanges can be cut off and any combinations of models are easily established, for example MM5–SOLVEG–RIVERS, MM5–WW3–POM, etc. The modification of each model code for this coupling is simple and easy, just adding some data exchange routines and put some sentences in the original model code which call the coupling routines, and each model code keeps its original

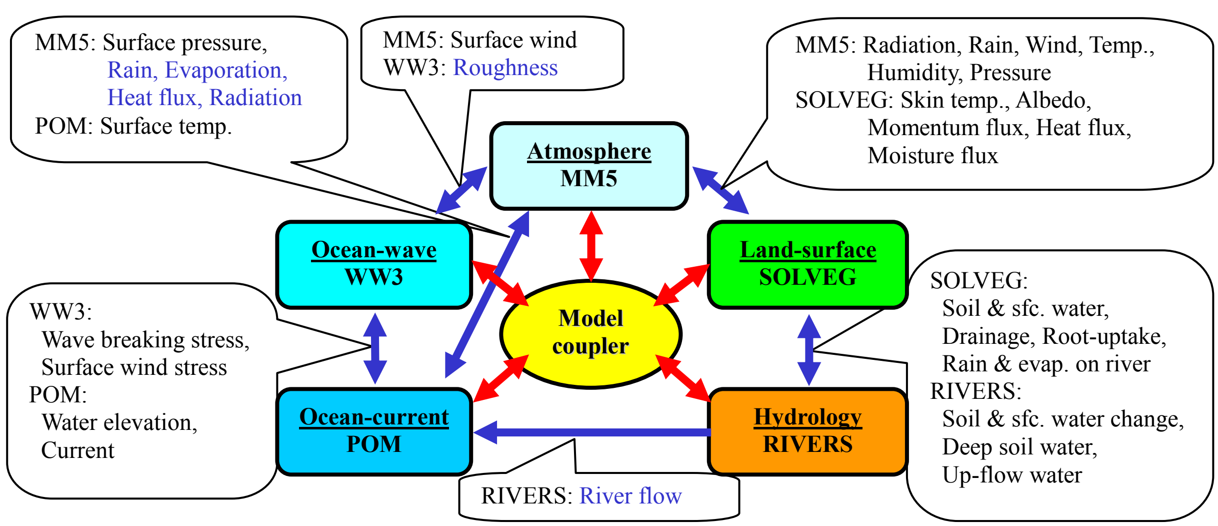

Fig. 1 Data exchanges and interactions among coupled models. Red arrows represent data exchanges via MPI controlled by the model coupler, and blue arrows are interactions among models, respectively. Interactions written in blue letters are planned to be included.

structure.

3.2 Interactions among models

Interactions considered in this coupled model system are briefly described here. As shown in Fig. 1, interactions are divided largely into two parts; the atmosphere-ocean and atmosphere-land. For both parts, interactions occur through the sea or land-surface, and WW3 or SOLVEG play the interface between the atmosphere and ocean or land.

For the ocean part, the momentum exchanges in the wind-wave-current system are schematically illustrated in Fig. 2. The surface wind from MM5 provides the wind stresses; the wave-induced stress (τ_{wave}) and turbulence-induced stress (τ_t) to generate wind-wave in WW3, and the surface stress ($\tau_{surface}$) to generate current in POM. For the wave calculation in WW3, the surface current (u, v) and water elevation (η), which are provided from POM, are necessary as well as the wind stress. Calculated wind breaking stress (τ_{break}) and surface roughness length (z_0) are offered to POM and MM5, respectively. POM calculates the surface current using the wind stress ($\tau_{surface}$) from MM5 and wave

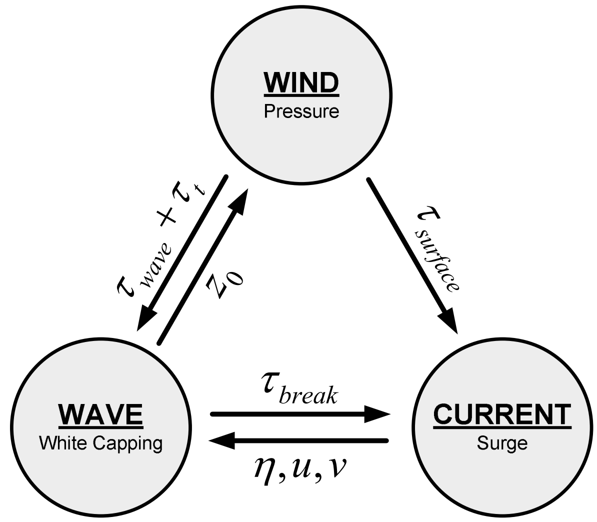

Fig. 2 Interactions in the wind-wave-current system.

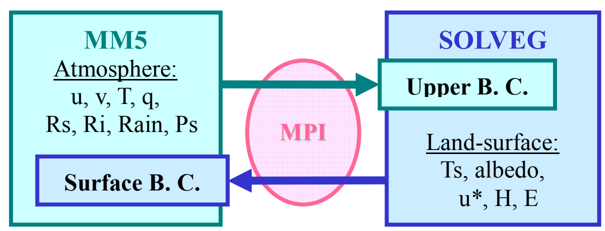

Fig. 3 Data exchanges between MM5 and SOLVEG.

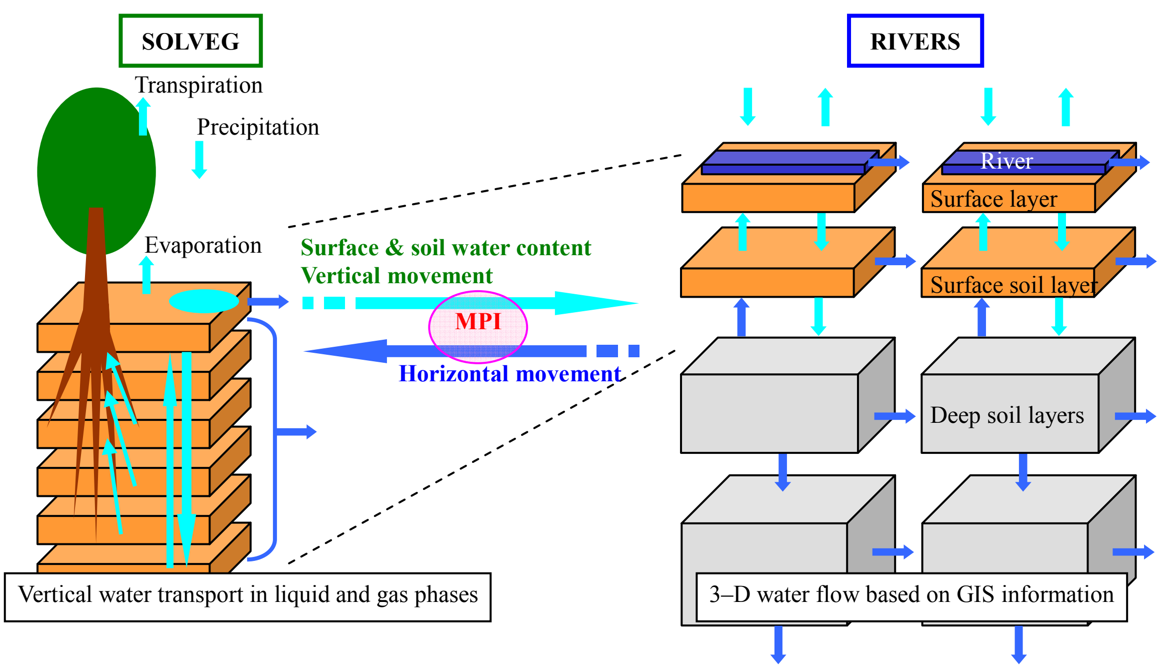

Fig. 4 Calculated water movements in the land-surface model SOLVEG and hydrology model RIVERS and data exchanges. Light blue and blue arrows represent water movements calculated by SOLVEG and RIVERS, respectively.

breaking stress (τ_{break}) from WW3. It also simulates surface water elevation (η) using sea surface pressure from MM5, and this output together with the surface current (u, v) are provided to WW3. Although the energy and water exchanges are also considered in the atmosphere-ocean interaction, only the sea surface temperature by POM is provided to MM5 as the surface boundary condition.

For the land part, the momentum, energy, and water exchanges between the atmosphere and land-surface are considered completely, while only the water exchange is treated in the interaction between the land-surface and hydrology. Figure 3 shows the date exchange between the atmosphere model MM5 and land-surface model SOLVEG. MM5 sends the surface layer variables: air pressure (Ps), radiation (solar: Rs, long-wave: Ri), precipitation (Rain), wind speed (u, v), temperature (T), humidity (q), to SOLVEG at every time steps. With these inputs, SOLVEG calculation proceeds for the same time interval as MM5 and sends its results to MM5: skin temperature (Ts), albedo, momentum flux (u*), heat flux (H), and vapor flux (E). MM5 receives these values in the next time step and uses them as the surface boundary condition in the PBL process. The time step of SOLVEG calculation is usually smaller than that of MM5, and several time steps are carried out for SOLVEG calculation during a single time step of MM5 calculation.

The data exchanges between the land-surface and hydrology are shown in Fig. 4. The land-surface model SOLVEG provides detailed calculations of surface water content, near-surface soil water content, and vertical fluxes of soil water to the hydrology model RIVERS. With these inputs, RIVERS calculates the river flow, deep layer soil water content, and three-dimensional movement of soil water, and the changes due to horizontal water movements are fed back to SOLVEG. These exchanges enable SOLVEG to consider the horizontal movement of soil water, which is not simulated in vertical one-dimensional calculations.

4. TEST CALCULATIONS

Test calculations were carried out to examine the performance of this coupled model system. Target area is the seacoast desert of west Saudi Arabia. This coupled model system is planed to be applied for studies related to the greening project of this area. A heavy rainfall occurred on 22 January 2005, and flash floods caused significant damages in this area. This event was chosen for test calculations. Calculation domains of MM5 are shown in Fig. 5 as the land-use map. Two-domain nesting is used and the other models are coupled with the inner domain of MM5. NCEP/NCAR reanalysis data (provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from the Web site at http://www.cdc.noaa.gov/) was used for the MM5 input. This dataset contains necessary inputs for SOLVEG and RIVERS as well as MM5. For the ocean part, only the Red

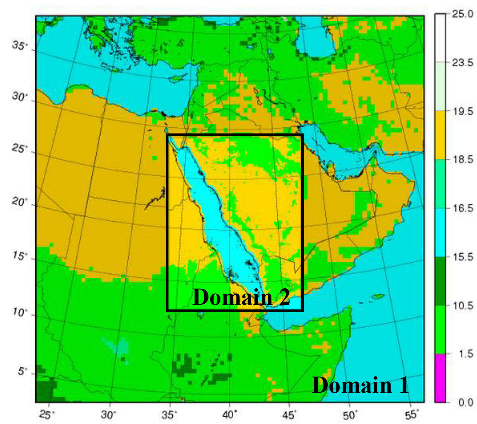

Fig. 5 Land-use map of MM5 calculation domains. Dominant land-use categories are the desert (orange), short vegetation (light green), and tall vegetation (deep green).

Sea is calculated and the climatological data are used as the initial inputs.

4.1 Calculation conditions

Input data and model settings are as follows.

<u>Input data:</u>

- NCEP/NCAR Reanalysis
- Resolution 2.5°×2.5°, 17 pressure levels
- Interval 6 hours (00, 06, 12, 18 UTC)
- Period 4 days from 20 Jan. 2005

<u>MM5:</u> (parallel: 16 CPUs)

Options:

- Cumulus Grell
- Microphysics Reisner2
- Radiation Cloud
- PBL MRF
- LSM Noah-LSM (mother domain)

MM5 mother domain:
- Grid 100×100×23
- Resolution 45 km
- Time increment 90 s

MM5 inner domain:
- Grid 100×130×23
- Resolution 15 km
- Time increment 30 s

SOLVEG: (parallel: 40 CPUs)
- Horizontal grid 100×130 (MM5 inner domain)
- Atmosphere 10 layers, 10 m above the canopy
- Soil 6 layers, 1 m below the land surface
- Vegetation Lower 5 layers of atmosphere
- Time increment 5 s

RIVERS: (single: 1 CPUs)
- Horizontal grid 100×130 (MM5 inner domain)
- Layers Surface + 4 soil layers + river
- Time increment 5 s

WW3: (parallel: 4 CPUs)
- Grid 56×81 (horizontal grid of POM)
- Resolution 22 km
- Time increment 900 s

POM: (single: 1CPUs)
- Grid 56×81×11
- Resolution 22 km
- Time increment 900 s

Data exchanges:
- MM5–SOLVEG 30 s
- SOLVEG–RIVERS 5 s
- MM5–WW3 900 s
- MM5–POM 900 s
- WW3–POM 900 s

SGI scalar-parallel computer Altix3900 was used to execute coupled calculations. Parallel calculations were used for MM5 (16 CPUs), SOLVEG (40 CPUs), and WW3 (4 CPUs). RIVERS and POM calculations were single. The model coupler uses 1 CPU and additional 1 CPU is necessary for MPI full-mode. Therefore, total number of used CPU was 64. The calculation by uncoupled MM5 and those of two different combinations of models, MM5–SOLVEG–RIVERS and MM5–SOLVEG, were also carried out, and the impacts of interactions were examined.

4.2 Results

For four-day calculation of this test case, it took about 3.0 hours by the five-model coupling using 64 CPUs. For the other combinations of models, it took about 1.3, 2.3 and 3.0 hours for the same case by the uncoupled MM5 using 16 CPUs, MM5-SOLVEG coupling using 58 CPUs, and MM5-SOLVEG-RIVERS coupling using 59 CPUs, respectively. For this case, calculation cost for SOLVEG is larger than MM5 and most CPUs are allocated to SOLVEG. However, the parallelization efficiency is not good for SOLVEG calculations, causing the increase of computation time. Frequent data exchanges between MM5 and SOLVEG (every 30 seconds) and those between SOLVEG and RIVERS (every 5 seconds) are also the reason for the increase of computation time. Concerning the ocean part, data exchanges are carried out in 900 seconds interval and times spent for these procedures are negligible. Parallelization scheme of SOLVEG and data exchanges among MM5, SOLVEG, and RIVERS need to be improved to achieve better computational load balance.

Calculated rainfalls for the heavy rain period (12 hours from 12 UTC to 24 UTC on 22 January 2005) by the original MM5 and coupled models; MM5–SOLVEG, MM5–SOLVEG– RIVERS, and all five models, are shown in Fig. 6. The rain pattern changed using the land surface boundary conditions by SOLVEG and POM. Especially, the sea surface temperature by POM affected the rain calculation in MM5 over the coastal area at the north-east part of the Red Sea. It is because that the sea surface temperature calculated by POM was higher than that used in the original MM5, which was constant given as the initial condition. The impact by the land hydrology calculation by RIVERS was almost negligible in this preliminary result. The horizontal movement of land water is not large enough to be recognized in this spatial and time scale. Calculations using higher resolution grid or longer period have to be carried out to examine the impacts by

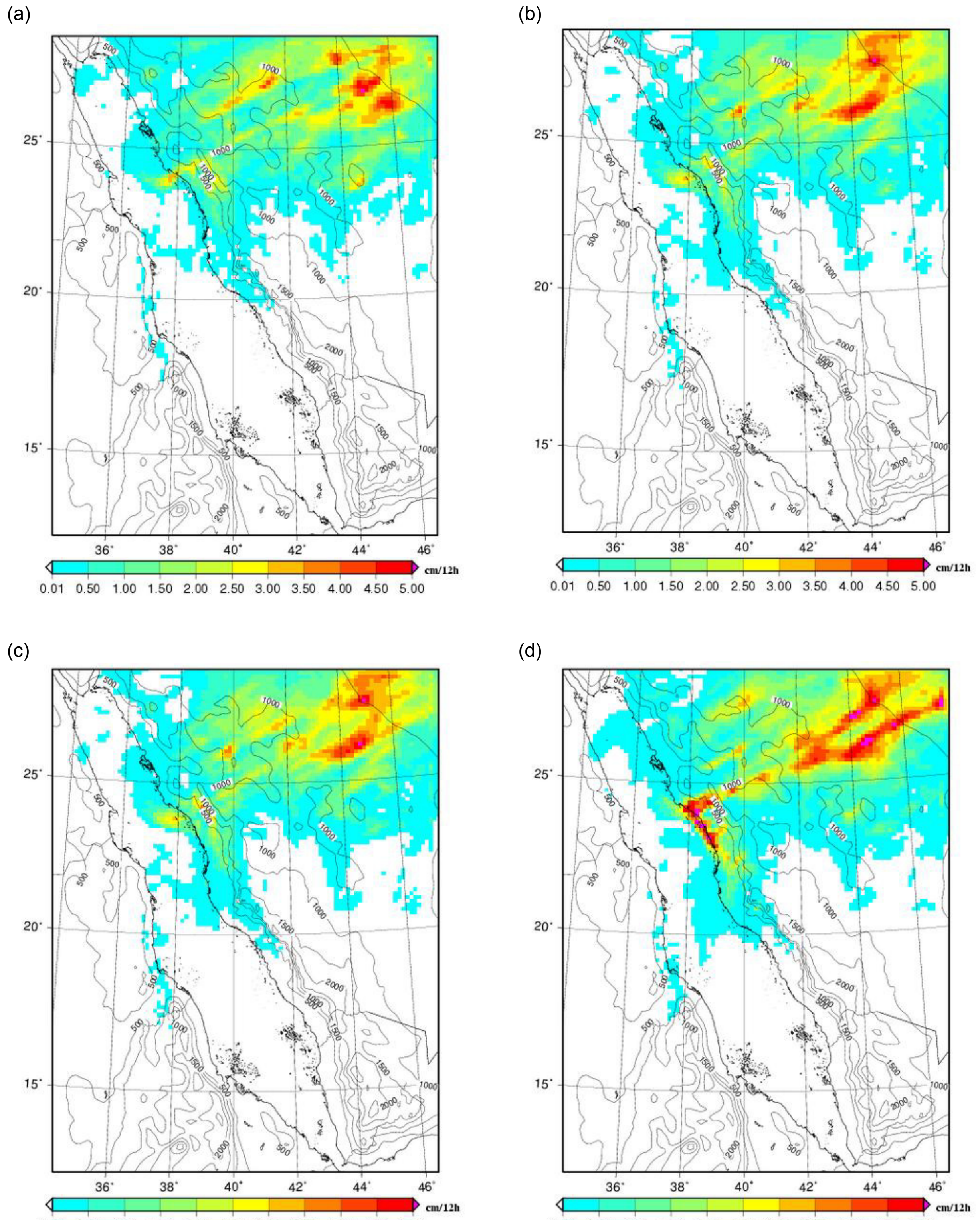

Fig. 6 Calculated rainfalls for 12 hours from 12 UTC to 24 UTC on 22 January 2005 by (a) MM5, (b) MM5–SOLVEG coupling, (c) MM5–SOLVEG–RIVERS coupling, and (d) MM5–SOLVEG–RIVERS–WW3–POM coupling.

the land water movement on the coupling calculations. Besides the higher resolution grid and longer periods, comparison with measured data will be also included in the next step.

5. SUMMARY

Coupled model system was developed and test calculations were carried out for the coastal circulations around the Red Sea. The coupled model system consists of models for the atmosphere (MM5), land-surface (SOLVEG), hydrology (RIVERS), ocean-wave (WW3), and ocean-current (POM), and a model coupling program (model coupler) that controls calculations of these models and data exchanges. Calculations of models are carried out as independent parallel processes and data exchanges among models are handled by the model coupler using MPI. This coupling method is very useful to construct complicated coupled models, easy to modify each model code, and flexible to use independent time step and grid resolution for each model.

Test calculations were carried out for the seacoast desert area of west Saudi Arabia to examine the performance of this coupled model system. Several combinations of models are tested to examine the computational costs and impacts by interactions among models. For the computational aspect, improvements are necessary for parallelization scheme of SOLVEG and data exchanges among MM5, SOLVEG, and RIVERS to achieve better computational load balance. For interactions among models, the sea surface temperature by POM affected much on the rain calculation in MM5, while the impact by the land hydrology calculation by RIVERS was almost negligible. The horizontal movement of land water is not large enough to be recognized in this spatial and time scale. The impact by land water calculations in the hydrology model on the coupling calculations should be examined by calculations with higher resolution grid or longer period in the next step.

REFERENCES

Blumberg, A. F., and G. L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model, In Three-Dimensional Coastal Ocean Model, N. S. Heaps (Ed.), 1-16, American Geophysical Union, Washington, DC.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5), *NCAR Tech. Note, NCAR/TN-398+STR*, 122pp.

Mellor, G. L., 1998: Users guide for a three-dimensional, primitive equation, numerical ocean model, Princeton University, 40 pp.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems, *Rev. Geophys. Space Phys.*, **20**, 851-875.

Nagai, H., 2002: Validation and sensitivity analysis of a new atmosphere-soil-vegetation model, *J. Appl. Meteor.*, **41**, 160-176.

Nagai, H., 2003: Validation and sensitivity analysis of a new atmosphere-soil-vegetation model. Part II: Impacts on in-canopy latent heat flux over a winter wheat field determined by detailed calculation of canopy radiation transmission and stomatal resistance, *J. Appl. Meteor.*, **42**, 434-451.

Nagai, H., 2005: Incorporation of CO_2 exchange processes into a multilayer atmosphere-soil-vegetation model, *J. Appl. Meteor.*, (in press).

Tolman, H. L., 2002: User manual and system documentation of WAVWWATCH-III version 2.22, Tech. Note 222, NOAA/NWS/NCEP/OMB, 133 pp.

Tsuduki, K., 2003: Development of a mathematical model to describe the transport of artificial radionuclides and trace elements in a river watershed, Section 4.1 in Consideration for modeling studies of migration of accidentally released radionuclides in a river watershed, T. Matsunaga, L. Monte, K. Tsuduki, N. Yanase, Y. Hanzawa, and T. Ueno, JAERI-Review 2003-039, Japan Atomic Energy Research Institute.