

Simulations of the Indian summer monsoon with a coupled ocean–atmosphere model on PARAM Padma

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Simulations with climate models is a computationally challenging problem. It is even more challenging when a coupled model of ocean and atmosphere is used. In this article, we report the implementation of a coupled ocean–atmospheric model on the PARAM Padma, a high-performance computer developed by Centre for Development of Advanced Computing, Bangalore and results from a 100-year simulation with this model. This is perhaps one of the largest computational experiments in the field of climate modelling conducted in the country. The computation took about 27 days of computer time on 104 processors spread over a period of three months.

We find that the simulations of the Indian summer monsoon with the coupled model are more realistic than with the atmospheric component alone. We also find that the simulation of ocean state is reasonable, although the simulated sea surface temperature is colder than the observed climatology.

Keywords: Coupled ocean–atmosphere model, Indian summer monsoon, PARAM Padma, simulations.

THE monsoon is a manifestation of complex interactions between land, ocean and atmosphere and the simulation of its mean pattern as well as variability on interannual scales is one of the challenging problems in climate studies¹. The problem of simulating the Indian monsoon is compounded by the presence of steep orography to the north of India and vast ocean on its three sides. Thus, it is imperative that it be studied with a coupled land–ocean–atmosphere model. However, simulations with a coupled model are about four orders of magnitude more compute-intensive than with an atmosphere model alone and this has been a major bottleneck in studies with a coupled model. Recently, the Centre for Development of Advanced Computing (CDAC), Bangalore developed a computer called PARAM Padma with a peak speed of about 1 teraflop which is capable of handling such problems. With the availability of this computer system, it is now possible to venture into this challenging field of climate modelling using a coupled model.

We have conducted simulations with the National Center for Atmospheric Research (NCAR) Community Climate

System Model Version 2 (CCSM2)² on PARAM Padma to study the atmospheric and oceanic aspects of the monsoons with the coupled model simulations. The implementation of CCSM2 on PARAM Padma may perhaps be one among the largest achievements in numerical modelling of the coupled ocean–atmosphere within the country. The major objectives of this exercise are:

- To assess the ability of the coupled system to realistically simulate the mean pattern and seasonal cycle of Indian summer monsoon³.
- To understand the variations of the Indian summer monsoon on interannual (i.e. variation from year-to-year) and intraseasonal (variation within a season) scales.
- To assess the model's ability to simulate the seasonal cycle of SSTs in the Indian region.
- To study the simulated circulation pattern both in the ocean and atmosphere.
- To study the heat budget of the Indian Ocean.

The Community Climate System Model

CCSM2 consists of four sub-models, each of them running an independent executable program. The subcomponents are the atmospheric model, the ocean model, the land-surface model and the sea-ice model. These interact with each other through the coupler. The schematic picture of CCSM2 is shown in Figure 1. The atmospheric model, the Community Atmospheric Model (CAM2) was run at T-42 resolution, i.e. an approximate resolution of about 280 km. It has 26 vertical levels. The model uses a reduced grid at higher latitudes for computational efficiency. We have used Eulerian dynamics with semi-Lagrangian moisture for our simulation. The parameterization of cumulus convection is done using the Zhang–McFarlane scheme⁴. Shortwave computations are done using the method of Breigleb⁵. Details of the model are given in Kiehl and Gent².

The ocean model used in CCSM2 is the Parallel Ocean Program (POP)⁶, which interacts with the atmospheric model through the coupler, once a day. The longitudinal resolution in the model is approximately 1°. The grid spacing is variable in the meridional direction. It is 0.27° at the equator, decreasing to 0.54° at 33° and remaining at this value at higher latitudes. The model has 40 vertical levels,

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the thickness of which varies from 10 m in the top 50 to 250 m in the deep ocean. The horizontal mixing scheme in the model uses spatially dependent meridional and zonal viscosity coefficients^{7,8} and the K-profile parameterization⁹ is used for vertical mixing. Further details of the ocean model may be found in Smith and Gent⁶.

The land model used here is the Community Land Model version 2.0 (CLM2.0) and was run at the resolution of atmosphere, i.e. T-42. It includes biogeophysical parameterizations. It has a ten-layer model for soil temperature and soil water. It distinguishes between liquid and ice phase in the soil water. It has a river run-off scheme to route streamflows. More details of the CLM2.0 can be found in Bonan *et al.*¹⁰.

The sea-ice is modelled using the Community Sea Ice Model, Version 4 (CSIM4). This uses the elastic-viscous-plastic rheology. Thermodynamic computations include explicit brine-pocket parameterization. Details of CSIM4 can be found in Briegleb¹¹. The sea-ice model was integrated at the oceanic resolution.

These separate sub-models interacted with each other through the coupler. Schematically, the coupling between various components is shown in Figure 1. The land-atmosphere coupling occurs at every time step of the atmosphere (every 20 min), coupling between ocean and sea-ice occurs every 1 h and between ocean and atmosphere every 24 h.

The spin-up problem for the ocean was eliminated using a pre-spinup condition obtained from NCAR. This reduced the computational requirement by almost 300%. The spin-up integration for a period of 350 years, had been conducted at NCAR with ECMWF analysis corresponding to 1 September 1990. The integration on PARAM Padma was begun with the restart data from this spin-up run conducted at

NCAR (the dataset was available from the NCAR website, <http://www.cesm.ucar.edu/models/ccsm2.0.1/>).

Parallel implementation and prototyping

The work on parallel implementation was carried out in phases. The first phase of initial implementation began on older generation of machines at CDAC, when the PARAM Padma was still being integrated. The second phase was its actual migration to the PARAM Padma cluster. Details of this implementation, testing and validation are discussed in this section.

Prototyping on PARAM 10000

The initial prototyping of the climate system facility was initiated during the development of PARAM Padma (as part of CDAC's third mission). The model as released initially by NCAR was supported only on the IBM SP2 and Origin 3000. Since the PARAM Padma was still under development, it was decided to conduct initial prototyping of CCSM2 on the PARAM 10000 supercomputing system. PARAM 10000 is a loosely coupled parallel computing system based on Sun Ultra 450 nodes. Each node is a four-way SMP system running with individual processor clock speed of 300 MHZ under the Solaris operating environment. The peak performance of PARAM 10000 is 100 Gflops. The nodes are interconnected through the PARAMNet switch (designed and developed by CDAC), the Myrinet Switch and Fast Ethernet (100 Mbps). CCSM2 was not supported on the Solaris platform, hence an extensive re-porting exercise of the software was undertaken. The execution logs of CCSM2 on PARAM 10000 were shared with the Software Engineering Group of NCAR for verification. NCAR too shared its execution logs on IBM SP2 and Origin 3000 systems. This helped in detailed verification of the port.

One of the major problems with a coupled model is the testing of the coupler architecture (coupler is the interface through which different stand-alone components exchange information). Initially, this was tested on PARAM 10000 with data model configuration. This configuration is provided with CCSM2 and is mainly used for testing sub-models. In this configuration, instead of computing with actual models, data are specified from a file to the coupler and hence it is called a 'data model'. This specification drastically reduces the computational time and is thus helpful in verification and validation exercises. For the purpose of validating the coupler, the data models of the four components, viz. atmosphere, land, ocean and sea-ice were used (datm, docn, dlnd, dice respectively). This configuration is termed as 'configuration A'. Each of these 'data models' is a uniprocessor program which communicates to the coupler using MPI (Message Passing Interface).

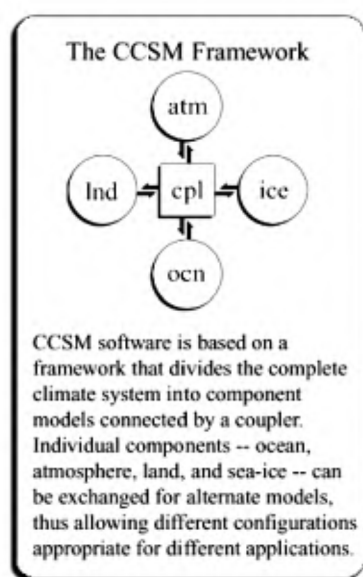


Figure 1. Schematic of community coupled climate system model version 2 (<http://www.cesm.ucar.edu/models/ccsm2.0.1/>).

Next, each of the active sub-components of the CCSM2 was implemented on the PARAM 10000. For this purpose the following configurations were used:

1. H configuration: Active atmosphere and coupler with data models for ocean, sea-ice and land. These interacted with each other through the coupler. This was used to test the porting of the atmospheric component.
2. C configuration: Active ocean with data models for atmosphere, sea-ice and land interacting through the coupler. The oceanic component was tested with this.
3. D configuration: Active sea-ice model with data models for atmosphere, ocean and land interacting through the coupler.
4. I configuration: Active land-surface model coupled with data models of atmosphere, ocean and sea-ice interacting through the coupler.

Once the individual components were tested, all the active components were integrated. For initial porting on PARAM 10000, CCSM2 was executed with the processor configuration shown in Table 1.

This processor configuration is identical to that used by NCAR and this facilitated intercomparison of system logs on PARAM 10000 and NCAR computers. It should be borne in mind that modifying processor configurations does not produce bit-accurate results¹². CCSM2 uses the MPMD (Multiple Program Multiple Data) model which was not supported on the MPICH. For this purpose Sun MPI was used, which in turn did not support Myrinet or PARAM-Net (faster communication channels on the PARAM 10000), but only the 100 Mbps fast ethernet. One day of integration of CCSM2 using active sub-models for all the components took about 40 min of wall-clock time on PARAM 10000. However, this prototyping exercise did provide valuable insights to the actual porting of the climate system model on the PARAM Padma.

CCSM2 on IBM Regatta p690

The second step in the climate system implementation was its porting onto the IBM Regatta p690. This is a 32-way

Table 1. Processor configuration on PARAM 10000

Module	CAM2	POP	Land	Sea-ice	Coupler
Procs	32	40	12	16	4

Table 2. Processor configuration on IBM Regatta

Module	CAM2	POP	Land	Sea-ice	Coupler
Procs	8	8	4	4	4
Task type	4 MPI × 2 OpenMP	MPI	2 MPI 2 OpenMP	4 MPI	4 OpenMP

SMP system with a CPU clock speed of 1.1 GHz. In this phase of implementation, run-time environments like memory stack and optimization levels were fine-tuned. We also found during the course of this exercise that accelerated vector libraries could not be used, as they caused an unacceptable deviation in the results of the simulation. The process of implementation discussed in the previous was repeated on the IBM Regatta. The fully coupled dynamical model configuration was implemented on this machine with the configuration given in Table 2. One day of the simulation took 147 s. Experiments were also conducted with eight threads, increased from four, for the coupler. This did not improve the timings. The CCSM2 was then run in a pure MPI mode (i.e. threads/OpenMP option was not used). This improved the timing to 127 s.

Migration to teraflop cluster

The next step was the migration to the teraflop cluster (PARAM Padma). The previous two exercises, viz. implementation on PARAM 10000 and Regatta had given us useful insights into the behaviour of the climate system and hence this step became relatively easy and straightforward. However, there is a major architectural difference between Padma and the Regatta. While Regatta is a SMP machine, Padma is a 248 processor cluster made up of four-way p630 processors with a speed of 1 GHz (relatively slower than the p690s) and interconnected with gigabit Ethernet¹³. Inside a four-way node (i.e. four processors inside a single node) communication is done using the memory channel. Various configurations were tried and two of these are shown in Tables 3 and 4 with respective timings. For the configuration shown in Table 3, the timing was 63 s/day and for the configuration shown in Table 4, the timing was 69 s/day. Thus increasing the processor configuration did not appear to increase the speed and hence processor configuration 3 was used for longer integra-

Table 3. A Processor configuration tried on PARAM Padma. This configuration took 63 s/day of simulation and used 104 processors

Module	CAM2	POP	Land	Sea-ice	Coupler
Procs	32	40	12	16	4
Task type	8 MPI × 4 OpenMP	40 MPI	3 MPI × 4 OpenMP	16 MPI	4 OpenMP

Table 4. Another processor configuration tried on PARAM Padma. This configuration used 180 processors. But with higher number of processors, it took 69 s/day of simulation

Module	CAM2	POP	Land	Sea-ice	Coupler
Procs	64	64	16	32	4
Task type	16 MPI × 4 OpenMP	64 MPI	4 MPI × 4 OpenMP	32 MPI	4 OpenMP

tions. Using this configuration had an added advantage, viz. that only half the PARAM Padma system was dedicated for this simulation, the rest being available for other scientific and engineering applications. The demand for dedicated nodes being lower, resulted in a decrease in wait-time and a faster turn-around time for the execution. Additionally the same configuration was used by NCAR and hence it was easy to compare the system logs. Computer time used by this experiment is about 639 h, which corresponds to about 26 days of time on the 104 nodes (CPU time is about 2704 days, i.e. computer time \times no. of CPUs).

The atmospheric model is highly compute-intensive. This component took 48s/day on the Regatta and 54 s/day on the Padma cluster, when using 16 processors. To ascertain whether the implementation had reached saturation (i.e. increasing the number of processors), we increased the number of processors for the atmospheric code to 32. This reduced the timing to 48 s/day on the Padma.

Resources used

We have carried out a 100-year simulation with CCSM2 on PARAM Padma. The total computation is estimated at 25,550 teraflop (10^{12} floating point operations). The entire 100-year integration was conducted over a three-month period. In addition, we have carried out a ten-year atmosphere-alone simulation to understand the impact of coupling. The atmosphere alone simulation takes about 48 s/day. The simulations are not only computationally intensive, but I/O requirements are also large. Typically, for a one-year simulation, the output is about 14 GB. Over a 100-year simulation, this adds up to 1.4 TB. We would like to note that we have kept the model output to the bare minimum. Only a few selected variables such as rainfall have been output once a day, most other variables being output as monthly averages. Restart datasets are written out once a month.

Analysis of such an output itself presents problems in datamining. This is of particular importance, as we would like to determine signatures of El-Nino, Indian Ocean dipole and monsoon strength (i.e. strong and weak monsoons) from these datasets. This is currently being done manually, but creating techniques to identify these signatures in large datasets would in itself be a challenging problem in the field of pattern recognition.

Results

Initial results from the simulations are encouraging and analysis of the 100-year simulation is still continuing. Here we present the behaviour of the model on seasonal (the mean pattern of rainfall over the Indian region), interannual (variation from year-to-year) and intraseasonal (variations within a season) using atmospheric variables from the coupled

model. The monthly mean pattern of sea surface temperature (SST) is analysed to understand the simulated behaviour of oceans.

Behaviour of atmospheric variables

Seasonal mean pattern: We find that the mean seasonal simulation of the monsoon improves in the coupled simulation (Figure 2, top). The most striking feature is the northward shift of the rainband over the Bay of Bengal with the use of coupled model. This feature of high rainfall over northern Bay of Bengal is not simulated by most atmospheric GCMs (General Circulation Models). It also realistically simulates the low rainfall over the southeastern coast of India. This clearly indicates that the evolution of SST and its gradients in conjunction with atmosphere plays a crucial role in determining the seasonal mean pattern. In the atmosphere alone simulation (Figure 2, middle), SST is not computed by the model but is specified externally (as a time-varying boundary condition), leading to absence of feedbacks between ocean and atmosphere. This in turn forces the atmosphere to respond to the external forcing (in this case the SST). Thus the response is unrealistic *vis-à-vis* observation (Figure 2, bottom)¹⁴. In a coupled system the two evolve together and hence the coupled re-

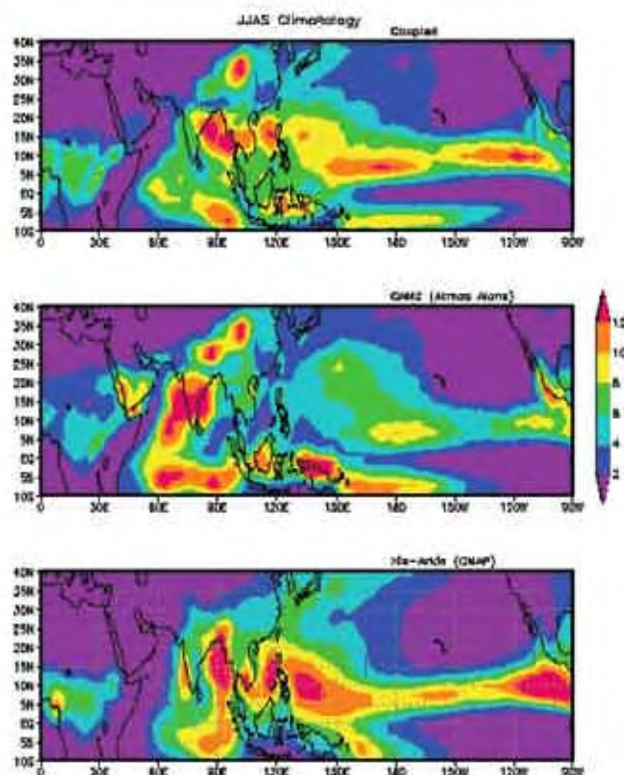


Figure 2. Rainfall (mm/day) during the June–September period. (Top) Coupled model simulation; (Middle) Simulation from atmosphere alone model; (Bottom) observations¹⁴.

sponse is different from the response in a stand-alone system. This perhaps makes the simulation more realistic. The cause of this realistic simulation of rainfall while the SST simulation is less realistic is related to the precipitable water–rainfall relationship of the model, this relationship being largely determined by the cumulus scheme used in the model. We find that this relationship, in the present model, overestimates the precipitation for a given precipitable water. Thus with lower SST and lower precipitable water, we get a realistic simulation of precipitation. A detailed discussion of this is given in Nanjundiah *et al.*³.

Interannual variability of rainfall: It is well known that rainfall over the Indian region during the monsoon season varies from year to year. Analysing the simulated rainfall over the Indian region by the coupled model, we notice a pattern of years of high rainfall interspersed with years of low rainfall. For comparison, in Figure 3, we show the first twenty-five years of simulated rainfall from CCSM2 with the observed rainfall from Global Precipitation Climatology Project (GPCP)¹⁵. It is worth noting that we are comparing simulated climate of the model (simulations are not predictions, but an idealized realization of the ocean–

atmosphere systems behaviour) with observation and hence the comparison can at best be qualitative. We find that while the model simulates cycles of strong and weak monsoons, variability is much higher than observed, the standard deviation of rainfall being much higher at about 1.6 mm day^{-1} *vis-à-vis* the observed value of 0.8 mm day^{-1} for the twenty-five years of GPCP rainfall (it is worth noting the mean value of rainfall during the June–September season in the simulation is lower at about 6.2 mm day^{-1} compared to 7.0 mm day^{-1} in GPCP observations). We note that other years of simulation also show a similar behaviour as seen in Figure 3.

Preliminary analysis shows that some of the simulated monsoon failures are associated with the occurrence of El-Nino. Further analysis to understand the mechanism of these associations in the context of the simulated climate of the model is currently underway.

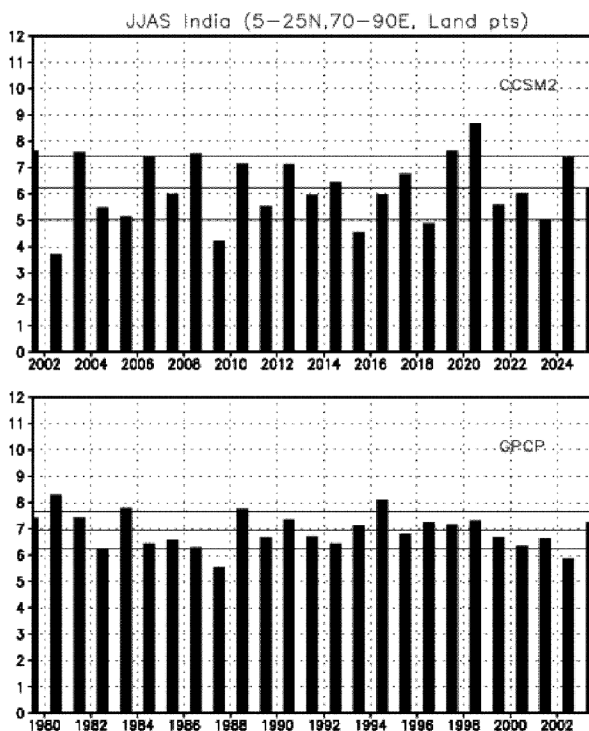


Figure 3. Comparison of June–September rainfall (mm/day) over the Indian region ($5\text{--}25^\circ\text{N}$, $70\text{--}90^\circ\text{E}$, land region only) for the first twenty-five years of model simulation with the observed GPCP rainfall for the period 1979–2003. Note that time on x-axis for the CCSM2 is purely notional and not indicative of any forecast. The three horizontal lines indicate long-term mean (middle line), mean + standard deviation (upper line) and mean – standard deviation (lower line). Mean value for CCSM2 is about 6.2 mm day^{-1} and for GPCP observations is 7.0 mm day^{-1} .

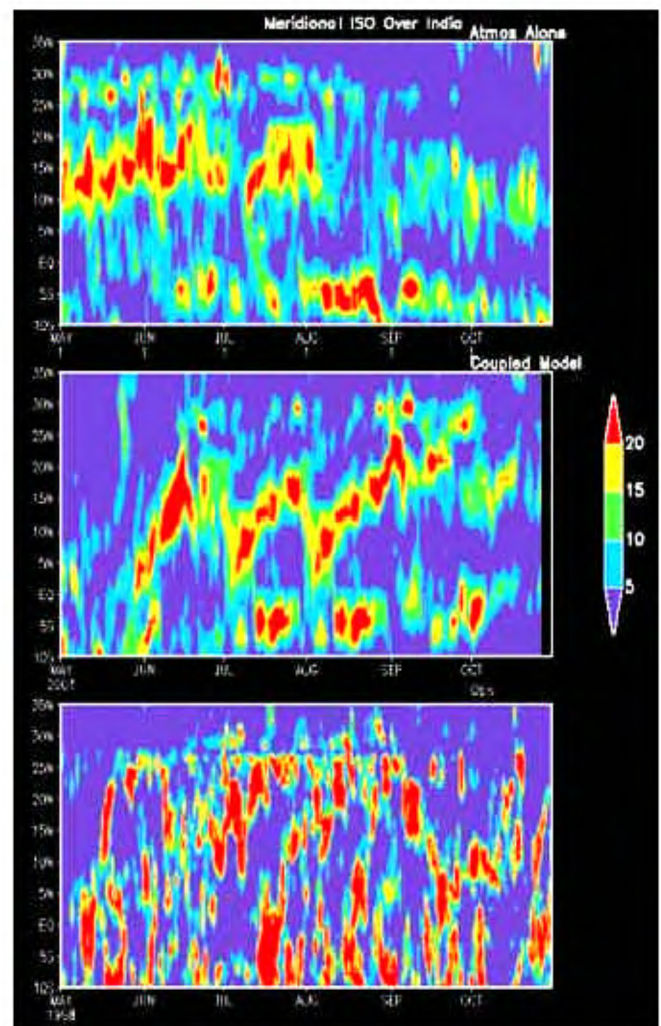


Figure 4. Latitude–time variation of rainfall (mm/day) over the Indian region. (Bottom) Observed intraseasonal structure. (Middle and Top) Same for coupled and atmosphere model alone.

Intraseasonal variations: Rainfall during the monsoon season has cycles of low and high. Additionally, it has been found that organized rainbands over the Indian region have, a rich space-time structure. It has been seen¹⁶ that these rainbands originate over the equatorial Indian Ocean (5°S) and move northwards and culminate over the monsoon trough region (~ 25°N). The period between such northward-moving events is about 25–40 days (Figure 4, bottom). Simulation of the northward propagation of rainbands is a major challenge for most climate models. We find that when the atmosphere model is integrated with observed SST as a lower boundary condition, these northward propagations are not simulated (Figure 4, top). However, when ocean and atmosphere are simulated interactively with the coupled model (Figure 4, middle), the structure of rainbands is more realistic. Poleward propagations of rainbands and the typical interval of about 25–30 days is realistic. Such poleward propagations are not simulated in the atmosphere-alone simulation. This intraseasonal pattern is simulated in quite a few seasons of the 100-year simulation. The presence of such poleward propagations in the coupled simulation and its absence in stand-alone AGCM simulation clearly indicates that the rich intraseasonal structure of rainfall variation over the Indian region is a result of complex air-sea-land interactions. The mechanisms governing poleward propagations in the coupled system and their absence in atmosphere-alone simulations is currently being studied. It is noteworthy that not all the coupled models simulate this intraseasonal oscillations better than their stand-alone atmospheric AGCMs.

Oceans

We present here a comparison of the seasonal climatology of SST in the coupled model with observed climatological data. Figure 5 *a, b* shows the comparison of the seasonal cycle of SST in the Indian Ocean between the model and observations¹⁷ are based on the climatology of WOA2001. During April (Figure 5 *a, b*), a warm pool¹⁸ occupies a major part of the Indian Ocean. Similar to the observations, a warm pool is also seen in the model results. However, there are several differences between the model and data. The spatial organization of the warm pool in the western part of the basin is different in the model; the western and northern parts of the Arabian Sea are cooler in the model than in the observations. Also the eastern equatorial Indian Ocean off Sumatra is warmer in the model than in the observations. Interestingly, the model captures the mini warm pool in the southeastern Arabian Sea^{19,20}. On the whole, around the periphery of the warm pool, the SST in the model is rather cooler than in the observations.

In July (Figure 5 *c, d*), the western Arabian Sea cools under the influence of the monsoon winds. This cooling of the Arabian Sea appear to be stronger in the model than in the observations. The SST around India is also cooler in the model than in the data. In the western Arabian

Sea, the great whirl and the southern gyre appear to be resolved fairly well by the model and the cold-water regions associated with these features can be clearly seen in Figure 5 *c, d*. In the east, the SST in the Bay of Bengal and in the eastern equatorial Indian Ocean off Sumatra is warmer by about 1°C in the model than in the observations.

During the post monsoon season (October, Figure 5 *e, f*) the equatorial Indian Ocean in the model is warmer than in the data. However, most that Arabian Sea and Bay of Bengal is cooler in the model, which is most probably due to the strong summer cooling in the model. The effect of the summer cooling appears to persist for a longer period in the model. The northeast monsoon also showed a cooler ocean in the model than in the data (Figure 5 *g, h*). The northern parts of the Arabian Sea and the Bay of Bengal have much cooler SSTs in the model. The Indonesian throughflow brings warm water into the Indian Ocean in the model and consequently, a zonal band of warm water can be seen along 10°S and off the coast of Sumatra.

In brief, the seasonal simulation of the SST in the model compares reasonably well with the climatological data. The life cycle of the warm pool and the summer cooling in the Arabian Sea are realistically simulated by the model. The model SST, however, appears to be cooler than the observations, particularly in the Arabian Sea during both summer and winter. The reasons for the cooler SST simulation in the model need to be investigated in detail.

Challenges

We have conducted simulations with a coupled ocean-atmosphere model, the CCSM2. This is perhaps the largest numerical and computational experiment in the field of climate modelling undertaken in the country. The results are encouraging. We find that the simulation on seasonal and intraseasonal scales is more realistic with the coupled model (i.e. when both ocean and atmosphere are integrated interactively) than in an atmospheric model.

The seasonal pattern of rainfall during June–September shows higher values over the northern and central Bay, whereas the atmosphere alone shows maxima located more southward. On the interannual timescale, the coupled model is able to simulate years of high and low rainfall. The variation is, however, larger than observed. On the intraseasonal scale, poleward propagations occur only when the ocean and atmosphere are integrated interactively. This clearly suggests that seasonal mean rainfall over the Indian region during the monsoon season and intraseasonal variation of rainfall during the monsoon season are a manifestation of ocean-atmosphere interaction and need to be studied further with coupled models. This result could have major implications for seasonal and intraseasonal forecasting of monsoon rainfall.

Simulations of the ocean state in the vicinity of the Indian region are quite realistic. The model reasonably simulates

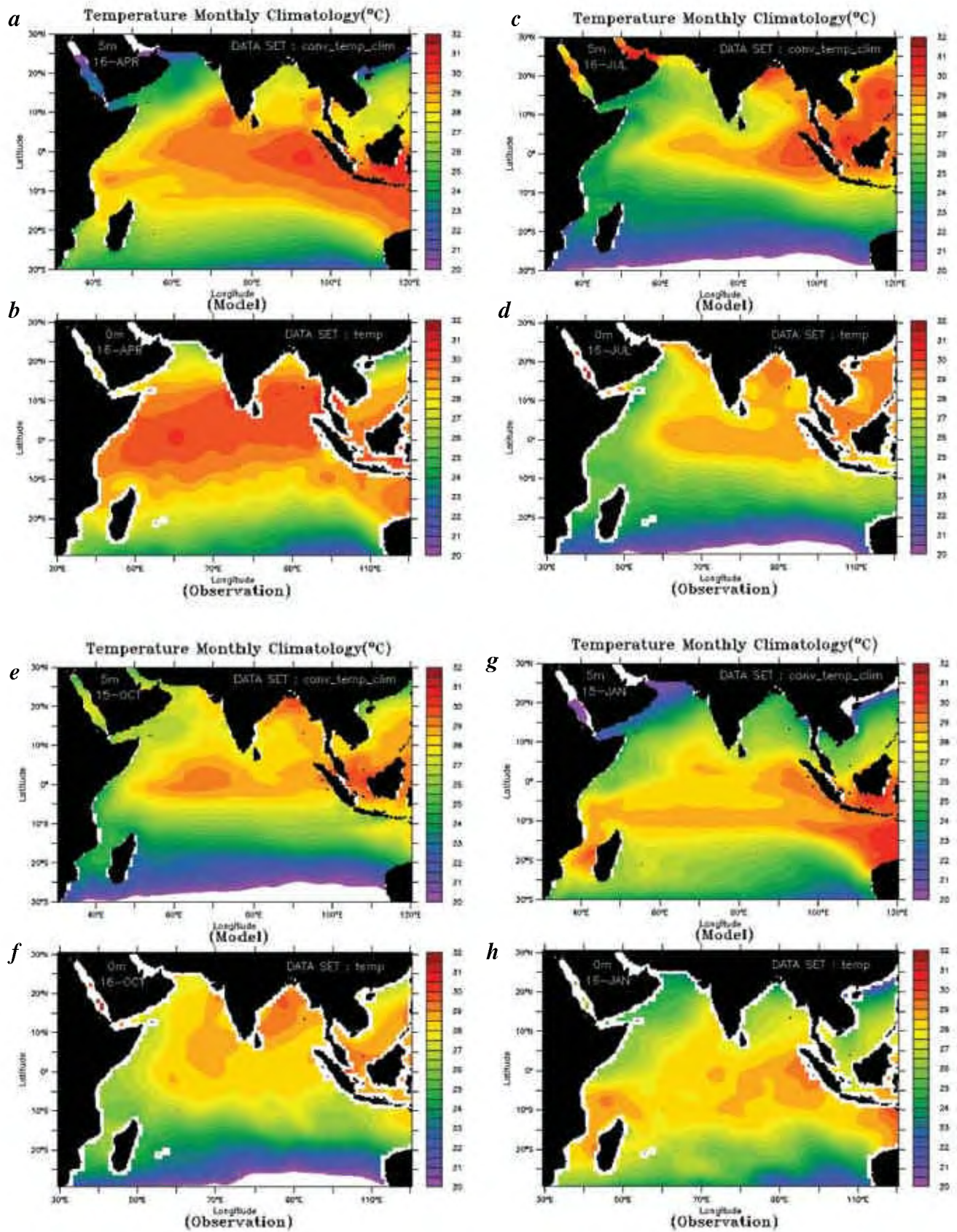


Figure 5. Comparison of SST simulated by the model with observed climatological SST from WOA2001 for the month of April (*a, b*), July (*c, d*), October (*e, f*), and January (*g, h*).

the annual cycle of SSTs although the actual magnitudes of SSTs, are underestimated.

Our experience has thrown up some interesting questions, some related to the science of monsoons as a manifestation of coupled ocean–atmosphere interactions and others related to computational requirement. Questions related to atmosphere and ocean, such as the improvement of seasonal mean simulation of rainfall and SST, variability on intraseasonal and interannual scales and circulation in the ocean and atmosphere in the vicinity of the Indian region are currently being addressed. However, the computational challenges also need to be looked into. Some computational science-related issues are:

1. Can the throughput of the models be increased? Higher throughput could help in more numerical experiments. The scalability of the atmosphere and oceanic components needs to be studied systematically. The throughput of this coupled system depends on many factors. Loadbalancing of the individual components will be crucial to get a higher throughput. Also, for a larger processor configuration, performance of the communication substrate needs to be improved. Gigabit Ethernet will not be adequate for such purposes, as low latency will be crucial for higher throughput and scalability.
2. Huge amounts data are generated by these simulations. Effective tools need to be developed to mine the data for patterns. Currently, this is being done manually based on past experience.
3. Graphical tools also need to be developed to visualize the data in three-dimensions. Currently, simple 2D plots are being used. Three-dimensional pictures might bring out hitherto unknown features.

In summary, experimentation with coupled systems has just begun. We look forward to challenging times ahead.

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