SUMO - Supermodeling by combining imperfect models

Deliverable 5.1: Report on super climate model with manually chosen connections

Due month 12, postponed to month 18, delivered month 19

Deliverable description: Report describing the super climate model with manually chosen connections (i.e., without a learning algorithm) and its ability to simulate the mean and variability of present-day climate (Tasks 5.1, 5.2 and 5.5) [month 12]

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Summary

To test the super modeling strategy for climate prediction we coupled two atmospheric models with one ocean model. The atmospheric models differed in their convection scheme. As climate models show large sensitivity to convection schemes, this approach may be a good basis for constructing a super model. We performed experiments with a small set of manually chosen coefficients at two different model resolutions. The coupling strategy is able to synchronize atmospheric variability in the tropics, particularly over the western equatorial Pacific, and produce reasonably climate variability. Different coupling weights were shown to alter the simulated mean state, seasonal cycle in the Tropical Pacific, and the El Niño Southern Oscillation. Some improvements were found that suggest a better strategy for choosing weighting coefficients could lead to a more improved simulation. Results with higher model resolution were generally superior. The preliminary results show there is potential to construct a super climate model.

1. Introduction of OASIS3

The main coupling strategy is performed by the Ocean Atmosphere Sea Ice Soil version 3 (OASIS3; Valcke 2010) coupler. The OASIS3 coupler, currently developed in the framework of the EU FP7 IS-ENES project, is software allowing synchronized exchanges of coupling information between numerical codes
representing different components of the climate system. In this work package OASIS is used to couple different component models through 2-dimensional (longitude-latitude) coupling fields.

A key design concept of the OASIS is low-intrusiveness and portability. OASIS3 consists of a separate executable, which main function is to interpolate the coupling fields exchanged between the component models, and a coupling interface library, the OASIS3 PRISM Model Interface Library (OASIS3 PSMILe), that is used to link the component models. The OASIS3 separate executable can be run in parallel, with each processor treating a subset of complete coupling fields; this results in a pseudo-parallelization of OASIS3 on a field-per-field basis. The component models remain separate executables with their main characteristics, such as internal parallelization, untouched with respect to their uncoupled mode. The coupling interface library includes subroutines to receive and send the coupling fields usually implemented within the model time step loop. OASIS3 supports 2D coupling fields only. It has implication that the 3D coupling fields can only be sent to OASIS in 2D format and the vertical interpolation has to be done in the component models.

A simple schematic of the coupling setup is shown in Figure 1. The OASIS performs the static coupling, which indicates all the coupling fields and parameters are fixed initially by the user and defined in an input file, namcouple. The parameter name and the associated grid of the coupling fields have to be well-defined in the component models before compiling but the coupling frequency and interpolation methods are only defined in the namcouple. The associated definition of the namcouple can be found in the OASIS3 user guide [Valcke, 2010].

2. Performance of coupler

It is necessary to limit the time consuming in exchanging information between component models. In general, Earth System Models use 2D coupling and exchange information through the boundary of the component models. The number of coupling fields for climate models is 20 to 40 in general. The coupling fields will be at least twice the number if two or more component models coupled together. The coupling fields will be a huge amount if 3D coupling is achieved on all the vertical model levels. Thus, the time consuming of the coupler has to be evaluated in advance.
The evaluation was done by using COSMOS in two resolutions, T63L31 and T21L19, with two coupling frequencies, once per day and twice per day, and using the serial implementation of OASIS3. The results are shown in Figure 2 and suggest that the time used by coupler is fairly predicable. It also indicates it may take over 10% simulation time to implement the coupling if three 3D fields were coupled in L19 resolution. Using the pseudo-parallelisation of OASIS3 or OASIS3-MCT (OASIS3 embedded with Model Coupling Toolkit) will make the coupling of 3D fields feasible.

3. Model Description

The climate models used in this report are as follows (see also schematics in Figures 3 and 4).

1. **COSMOS**: Community Earth System Models, developed at Max-Planck-Institut für Meteorologie (Germany) in collaboration with M&D and support from CRAY and NEC. COSMOS is a framework to develop and apply coupled atmosphere/ocean/land models for Earth system research. The COSMOS software package allows to build different models including the physical climate model ECHAM5/MPIOM (the European Centre for Medium-Range Weather Forecasts [ECMWF] Hamburg atmospheric general circulation model version 5), and the carbon cycle–climate model ECHAM5-JSBACH/MPIOM-HAMOCC. COSMOS uses the PRISM software for infrastructure. For more information see [http://cosmos.enes.org](http://cosmos.enes.org).

2. **EC-Earth**: developed at the Royal Netherlands Meteorological Institute (KNMI, the Netherlands) in collaboration with 22 academic institutions and meteorological services from 10 countries in Europe. The EC-Earth includes ECMWF’s Integrated Forecast System (IFS) as an atmospheric component, NEMO (Nucleus for European Modelling of the Ocean) as an ocean component and Louvain-la-Neuve Sea Ice Model (LIM2). For more information see [http://ecearth.knmi.nl/](http://ecearth.knmi.nl/).

Therefore we have four major component models: two atmospheric modules (ECHAM5 and IFS) and two oceanic modules (MPIOM and NEMO). Here we seek to synchronize the atmospheric models through coupling two atmospheric models with one oceanic model at the air-sea interface. In this report we use MPIOM.


4. Convection Scheme of Atmospheric models

Convection schemes usually show considerable sensitivities of model results [Arakawa, 2004]. Convection may arise dynamically or thermally or both, and the entrainment and detrainment in one cloud may not happen in the same grids. Furthermore, these processes occur on very small scales. Due to insufficient computer power atmospheric convection is a parameterized process in climate models, i.e., it depends on large-scale fields. Parameterizations require a closure assumption that must hold at each column. Various closure assumptions have been implemented, and these give rise to large model sensitivity.

Both ECHAM5 and IFS use convective parameterization schemes that are based on the Tiedtke scheme [Tiedtke, 1989], but implement different closure schemes. ECHAM5 provides three different choices: original Tiedtke closure, hybrid closure and Nordeng scheme [Nordeng, 1994]. The original Tiedtke scheme uses large scale moisture convergence, the conservation of temperature and specific humidity is considered. The Nordeng scheme uses cloud base mass flux related to the available potential energy (CAPE) relaxation closure. The IFS has only Tiedtke convection scheme using CAPE relaxation closure and some modifications.

The two atmospheric models, ECHAM5 and IFS, have the identical original convection scheme, but differ in their closures. The large model sensitivity to convective parameterizations makes this an ideal process on which to base a super model. Thus, in this preliminary study, we build and test a manually constructed super model from the ECHAM5(Tiedtke), ECHAM5(Nordeng), and MPIOM models. We study the differences that arise from the different closure and test 2D synchronization of the climate model.

5. Numerical Experiments

Three set of experiments were made in this study. The first set was used to evaluate the difference between COSMOS and SUMO when both Tiedtke and Nordeng convection schemes were applied. The second set was applied to evaluate the influence of manual weighted coupling coefficients. The third set was performed to assess the sensitivity of the results to model resolution. The experiments in the first and second set experiments were performed with a
atmospheric spectral resolution of T31L19, which corresponds to approximately 3.75 degrees horizontally; the ocean horizontal resolution was approximately 3 degrees. The third experiments were performed with T63L31 resolution, which corresponds to approximately 1.8 degrees horizontally; the ocean horizontal resolution is approximately 1.5 degrees.

### 5.1 Coupled and Un-coupled Model Variability

The sensitivity of the convection scheme was evaluated through two runs of the COSMOS model, with different convection scheme as shown in Figure 5(a). These two experiments have identical forcing and restart files but with different convection scheme. One is COSMOS-Tiedtke and the other COSMOS-Nordeng. A super-model based on ECHAM5(Tiedtke)/ECHAM5(Nordeng)/MPIOM was built as schematized in Figure 5(b). The two uncoupled simulations form the reference for the supermodel. We use correlation to measure synchronization between the two atmospheric models. The variability of the two uncoupled models is consistently not related to each other (Fig 6), and they can thus be regarded as independent simulations. Differences in the simulated climate are presented below that support the independence of the model physics.

Partial synchronization was found in the results of SUMO(T50N50) shown in Figure 7 when the variability of the atmospheric component models was compared. The symbol T indicates the ECHAM5(Tiedtke) and N ECHAM5(Nordeng). The number indicates the percentage of the weighting coefficient of the coupling fields. The temperature anomaly over tropical column was highly synchronized as shown in Figure 7(a). This implies that the energy variability is dominated by the convective response to ocean variability over tropical zone, for both of moisture convergence and CAPE relaxation closure. The correlation of temperature anomaly drops quickly outside the tropical zone, and suggests the synchronization of the atmospheric dynamics might be weak outside the tropical zone, which can be further seen in Figure 7(b). Only the surface zonal wind stress anomaly of the western tropical Pacific was synchronized through sharing identical ocean surface. This is consistent with many previous studies showing the tight coupling between ocean and atmosphere over the tropical Pacific. It also indicates that the 2D coupling is not able to significantly synchronize models away from this region.

The mean sea surface temperature (SST) from observations and the
differences to that simulated by the models is shown in Figure 8. The SST biases are quite similar to those of other state-of-the-art models. None of the models capture the SST very well over the extra-tropics, especially along the Kuroshio Extension of North Pacific and Gulf Stream Extension of North Atlantic. This is likely because the ocean model resolution of these experiments is too coarse to have a reasonable simulation of the boundary currents. And these boundary currents dominate the heat flux transport over these regions. The resolution has to be finer than 0.5 degree to form the boundary currents. It has implication that the extra-tropic will have cold anomaly along poleward region and warm anomaly along equatorward region if the boundary currents are not strong enough. This is inevitable in this coarse resolution experiments. For the tropical region these three models all have cold anomaly in the equatorial Pacific cold tongue and warm anomalies elsewhere, particularly off the west coasts of the continents. The cold tongue bias causes stronger zonal wind stress, stronger tropical upwelling, and a weakened western Pacific warm pool. Furthermore the near-zero difference of central tropical Pacific of SUMO-T50N50 also suggest the potential that a better choice of model weights could reduce model error, even though both of the individual COSMOS models have similar biases. Besides, the atmospheric component models of the SUMO(T50N50) have strong synchronization over the western Tropical Pacific. Thus, we will focus on this region in investigating the impact of our coupling strategy.

It is very difficult for coupled models to simulate the seasonal cycle of SST in the eastern equatorial Pacific [Latif et al., 2001]. As shown in Figure 9 the COSMOS presents the seasonal cycle reasonably, which has a strong annual cycle in the eastern equatorial Pacific and a pronounced westward propagation of the warm anomaly from eastern to central Pacific. Although the magnitude of the warm anomaly of the models is approximate to that of the observation, the warmest anomaly in the models does propagate more westward than that found in observation. In the observation the maximum anomaly was sourced from eastern Pacific (90°W). However, the warmest anomaly of the COSMOS-Tiedtke and COSMOS-Nordeng are at much near central Pacific than that of observation. Besides, the warmest anomaly was found at June and May for COSMOS-Tiedtke and COSMOS-Nordeng, respectively. This is later than in the observations, even though the warm anomaly starts and ends in observation and the models at the same time. The SUMO inherits the behavior that the warmest anomaly happens later and is at near central Pacific. However, the warmest anomaly of the SUMO is 2.8°C, which is close to that of the observation, which is 2.9°C, and better than
that of both COSMOS-Tiedtke and COSMOS-Nordeng, which has warmest anomaly about 3.2°C.

Figure 10 shows the monthly SST anomalies over Niño-3 region (150W-90W, 5S-5N), which is a good index of the well-known nonlinear climate phenomenon in this region, the El Niño-Southern Oscillation (ENSO), and the associated wavelet spectra. All of the three models, COSMOS-Tiedtke, COSMOS-Nordeng, and SUMO(T50N50), can reproduce several ENSO events and have implication that the ocean-atmosphere interaction is reasonably represented in COSMOS and the phenomenon is not diminished by our 2D coupling strategy. However, the amplitude of the ENSO events of both COSMOS-Tiedtke and COSMOS-Nordeng is stronger than that of the observation, and it seems SUMO(T50N50) inherits this characteristic. Furthermore all the model results have shorter ENSO periods than the observation. It seems SUMO(T50N50) can only inherit these properties and will not approach to the observation without learning.

The Niño-3 index of both the model and observation shows broad spectrum in Figure 11(a), which suggests the COSMOS can reasonably capture the irregularity of the ENSO events. However, they have different peak frequencies, which are five years for the observation and two years for the COSMOS models and SUMO(T50N50). The COSMOS-Tiedtke has highest peak ENSO frequency, and it shows the SUMO(T50N50) is not drifted toward COSMOS-Tiedtke but has peak ENSO frequency much close to that of COSMOS-Nordeng. It indicates that not all the phenomena are dominated by the model that has the stronger signal in the nonlinear system.

The large negative correlation in Figure 11(b) indicates the warm and cold phases of the ENSO events are less asymmetric in the model than that in the observation. The ENSO events should have skewed distribution, which is attributed from flatten troughs (cold phases) and higher crests (warm phases). This can also be found in the time series in Figure 10.

Zero-lag correlation map (Figure 12) of the Niño-3 index and SSTA is used to identify the impaction or the horizontal structure of the ENSO events spatially. The correlation of Pacific has high correlation over Niño-3 region and monotonously decreases toward surrounding region. The negative correlation band over western Pacific is not found in COSMOS-Nordeng and is weak in COSMOS-Tiedtke and SUMO(T50N50). Although this structure is heavily relied
on the resolution of the model, the results of COSMOS-Nordeng imply that the imperfection of this model in this region may lead to this unrealistic feature. It is good that this drawback is diminished in SUMO(T50N50), suggesting the phenomena were self-adjusted when two atmospheric component models were coupled.

**Manual chosen weights**

Three experiments were accomplished to assess the impact of different weighting coefficients of the coupling fields. They are SUMO(T75N25), SUMO(T50N50) and SUMO(T25N75). The symbol T indicates the ECHAM5(Tiedtke) and N ECHAM5(Nordeng). The number indicates the percentage of the weighting coefficient of the coupling fields. The coefficients changes are linear, but one may expect a nonlinear impact on the simulated phenomena.

The global averaged SST shows little differences among the simulated biases in the extra-tropic (Figure 13). The main difference of extra-tropics is the cold anomaly is strong at the California Current in both SUMO(T75N25) and SUMO(T25N75), which suggests the California Current or the equatorward wind stress is strong, thus more cold water is transported from the north and upwelling is strengthened.

The SST of SUMO(T50N50) has the warmest tropical temperature of these three experiments. Adjusting the weighted coefficients entirely toward to one specific scheme seems fail to have a better tropical dynamic because only colder difference has been found in the other experiments, SUMO(T75N25) and SUMO(T25N75). This has implication that the one degree of freedom (the weighting coefficient of coupling fields) is not enough to have a better approach. Varying manual chosen coefficients among coupling fields should increase the degrees of freedom, and in the future we will test if this may lead to an improved simulation.

All of the experiments can simulate the annual cycle at eastern tropical Pacific (Figure 14), however SUMO(T75N25) and SUMO(T25N75) have worse presentation of the annual cycle than SUMO(T50N50). There is a phase lag in the SUMO experiments, which inherits from COSMOS, and the phase lag is larger in SUMO(T75N25) and SUMO(T25N75). The warm anomaly is also increased in
both SUMO(T75N25) and SUMO(T25N75). These results again show strongly that adjusting the entire coupling coefficients linearly may not lead to a significantly improved model.

Strong ENSO events are also inherited by the experiments. For only a short period (model year 10 to 40) is the SUMO(T25N75) simulation more realistic, but the rest of the simulation is still unrealistically strong. SUMO(T50N50) has the lowest peak frequency in the three experiments (Figure 16(a)). The autocorrelation in Figure 16(b) shows the same information that SUMO(T50N50) has the longer self-reproducing period. However, the negative correlation comes too earlier and the large negative correlation indicates they all have smaller skewness than the realistic ENSO.

The experiments have nonlinear changes over global mean SST, annual cycle and the spectral characteristic; however, the zero-lag correlation map of the experiments shows a more linear change. There is no positive correlation found in the Pacific of SUMO(T25N75), as it cannot be found in COSMOS-Nordeng. Also a negative correlation at the western Pacific was found both in SUMO(T50N50) and SUMO(T75N25). The negative correlation is stronger in SUMO(T75N25), which is close to results of the COSMOS-Tiedtke. However, none of the simulations reproduce the horseshoe structure of observations, but this is likely caused by the coarse model resolution.

**Results on different resolution**

COSMOS-Tiedtke, COSMOS-Nordeng and SUMO(T50N50) were run in T63L31/GR15 resolution to assess the degree to which biases may be due to coarse model resolution. T63L31 atmospheric resolution corresponds to approximately 1.8 degrees, which is about twice the horizontal resolution of T31L19 (i.e., approx. 3.75 degrees). The ocean model horizontal resolution was also approximately doubled.

Better results were found in COSMOS-Nordeng, which has only weak warm anomaly found along the extension region of boundary currents and about -1°C anomaly of cold tongue region. Zero anomaly was found in India Ocean and part of the Pacific. However, the temperature was warmer in COSMOS-Tiedtke when the resolution is increasing. Unfortunately the SUMO(T50N50) inherits part of the characteristics of COSMOS-Tiedtke, the warm anomaly is arisen at the India
Ocean and tropical Pacific.

A weakened seasonal cycle was found in the high resolution models, as shown in Figure 19. The warmest anomaly of the three experiments was reduced to less than 2.5°C and also has less warm anomaly intruding into western Pacific. In COSMOS-Nordeng the maximum anomaly at central Pacific is only 0.5°C, which is close to the observation. However, the phase lags are prevailing and has not much difference with the coarse resolution model. A better spatial structure was found in the zero-lag correlation map (Figure 20). The negative correlation of western Pacific is developed in the fine resolution model. A negative correlation or relatively small correlation is found in the tropical India Ocean.

References


Figures

Figure 1. Schematic of the coupling interface. A represents the coupling fields of atmospheric component model and O the ocean component model. The number of exchange fields is not necessary identical, but the conservation law has to be followed.
Figure 2. The performance of OASIS3. The CTS is the coupling frequency, $T_\alpha$ the time used by OASIS3, and $T_M$ by component models. The ratio $T_\alpha/T_M$ is increasing monotonically and linearly.
Figure 3. Schematic of COSMOS. The atmospheric physical/dynamic is implemented by ECHAM5 and the ocean dynamic by MPIOM. These two parts are the main component models used in our SUMO setting.

Figure 4. Schematic of EC-Earth. Only atmosphere physics/dynamics (IFS), aerosols (TM5), and land process (HTESSEL) are going to be used in 2D coupling phase.
Figure 5. (a) Two climate models differing only in the convection scheme used in the atmospheric component model; (b) two ECHAM5 models using the two different convection scheme coupled to the MPIOM. Models were coupled only through the 2D fields of the component models.
Figure 6. Correlation of zonal-averaged temperature anomaly (a) and zonal wind stress anomaly (b) between COSMOS-Tiedtke and COSMOS-Nordeng. Non-significant correlations were set to be blank. It suggests these settings have different performance in variability, and can be regarded as two different models.
Figure 7. Correlation of zonal-averaged temperature anomaly (a) and zonal wind stress anomaly (b) between ECHAM(Nordeng) and ECHAM(Tiedtke) of SUMO. Non-significant correlations were set to be blank. High correlation can be found in tropical region, especially the western Pacific tropic.
Figure 8. (a) Averaged global Sea Surface Temperature from observations (HadISST); (b) the difference of COSMOS-Tiedtke and the HadISST; (c) the difference of COSMOS-Nordeng and the HadISST; (d) the difference of SUMO and the HadISST.
Figure 9. Seasonal cycle of the SSTA of COSMOS-Tiedtke, COSMOS-Nordeng, SUMO and the HadISST over tropical zone (5°S-5°N). The annual mean has been removed to emphasize the seasonal cycle.
Figure 10. Niño-3 monthly SST anomalies and the wavelet spectrum for model period years 831–890 for COSMOS-Tiedtke, COSMOS-Nordeng, SUMO and observation (HadISST). Please note the different scale for observations.
Figure 11. The power spectra (a) and autocorrelation (b) for model period years 31–90 for COSMOS-Tiedtke, COSMOS-Nordeng, SUMO and the observation during 1936-1995.
Figure 12. Zero-lag correlation map of Niño-3 index and the SST of the observation, COSMOS-Tiedtke, COSMOS-Nordeng and SUMO(T50N50).
Figure 13. (a) The difference of SUMO(T75N25) and the HadISST; (b) the difference of SUMO(T50N50) and the HadISST; (c) the difference of SUMO(T25N75) and the HadISST.
Figure 14. Seasonal cycle of the SSTA of SUMO(T75N25), SUMO(T50N50) and SUMO(T25N75) over tropical zone (5°S-5°N).
Figure 15. Niño-3 monthly SST anomalies and the wavelet spectra for model period years 831–890 for SUMO(T75N25), SUMO(T50N50) and SUMO(T25N75) over tropical zone (5°S-5°N).
Figure 16. The power spectra (a) and autocorrelation (b) for model period years 31–90 for SUMO(T75N25), SUMO(T50N50) and SUMO(T25N75).
Figure 17. Zero-lag correlation map of Niño-3 index and the SST of SUMO(T75N25), SUMO(T50N50) and SUMO(T25N75).
Figure 18. (a) The difference of COSMOS-Tiedtke and the HadISST; (b) the difference of COSMOS-Nordeng and the HadISST; (d) the difference of SUMO(T50N50) and the HadISST. A finer resolution, T63L31, was applied in these experiments.
Figure 19. Seasonal variation of the SSTA and zonal wind stress anomaly of COSMOS-Tiedtke, COSMOS-Nordeng, SUMO(T50N50) over tropical zone (5°S-5°N).
Figure 20. Zero-lag correlation map of Niño 3 index and the SST of COSMOS-Tiedtke, COSMOS-Nordeng, SUMO (Super COSMOS), and observation (HadISST).