Mechanism and Predictability of Atmospheric and Oceanic Variations Induced by Interactions between Large-scale Field and Meso-scale Phenomena

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We have been developing atmospheric and oceanic models that run very efficiently on the Earth Simulator. With these models, we performed ultra-high resolution simulations, in which both large-scale field and meso-scale circulation were simulated simultaneously, and interacted with each other. Our ultimate goal is to understand atmospheric and oceanic variations induced by inter-scale interactions. We believe that these simulations, that are possible only with our models running on the Earth Simulator, will result in not only scientifically new knowledge but also contribution to society.

Keywords: The Earth Simulator, ultra-high resolution simulations, atmospheric and oceanic circulation, high-performance computing in meteorology and oceanography

1. Introduction

We have been developing atmospheric and oceanic general circulation models that are computationally well optimized for the architecture of the Earth Simulator. Our atmospheric general circulation model, AFES, is adopted from the CCSR/NIES AGCM 5.4.02 [1]. Our oceanic general circulation model, OFES, is based on the GFDL MOM3 [2]. Our coupled oceanic and atmospheric model, CFES, consists of AFES and OIFES (OFES with a sea ice submodel). PFES, Princeton University POM-based sigma-coordinate ocean model, also has been developed for simulating regional ocean currents.

With these models that are extremely efficient on the Earth Simulator, we are able to perform ultra-high resolution numerical experiments in which both planetary scale fields and meso-scale phenomena are simulated simultaneously. Our goal is a better understanding of mechanism and predictability of variations that are induced by inter-scale interactions.

2. AFES

We performed several ultra-high resolution numerical experiments with AFES. Among these, hindcast simulations of extreme weather events are reported in this section.

In August 2002, heavy rain hit central Europe and caused severe flood there. We conducted a set of hindcast simulations with the so-called T639L48 resolution (horizontally 20 km and vertically 48 layers) targeting the heavy rainfall. Fig. 1 shows comparison between a satellite infrared image (a) and the precipitation fields from the successful 84-hour hindcast (b) when the heavy rain was observed over central Europe. The 84-hour hindcast realistically captures a cut-off cyclone over the Mediterranean Sea and heavy rainfall over central Europe. The hindcast also simulates strong precipitation associated with the front between the Italian peninsula and northern Africa. The longer 156-hour hindcast also simulates heavy rainfall over central Europe (not shown). However the rainfall is associated with the front of a falsely intensified cyclone over Britain, and the cut-off cyclone over the Mediterranean is not simulated very well.

In order to identify the cause of the failure for the longer hindcast, a simple sensitivity analysis was carried out using the 25-member forecast by Japan Meteorological Agency. Fig. 2 shows 48-hour sensitivity analysis of 250-hPa height (Z250). This analysis identifies Z250 anomalies that results in a successful hindcast in central Europe (the rectangular area surrounded by thick black curve). Fig. 2 suggests that not only a pair of cyclone and anti-cyclone over the Atlantic Ocean but also tropical depression Cristobal, identified as the high anomaly in Z250 near the coast of North America, is important for better hindcast. We find that in the successful 84-hour hindcast, Cristobal is located very close to the

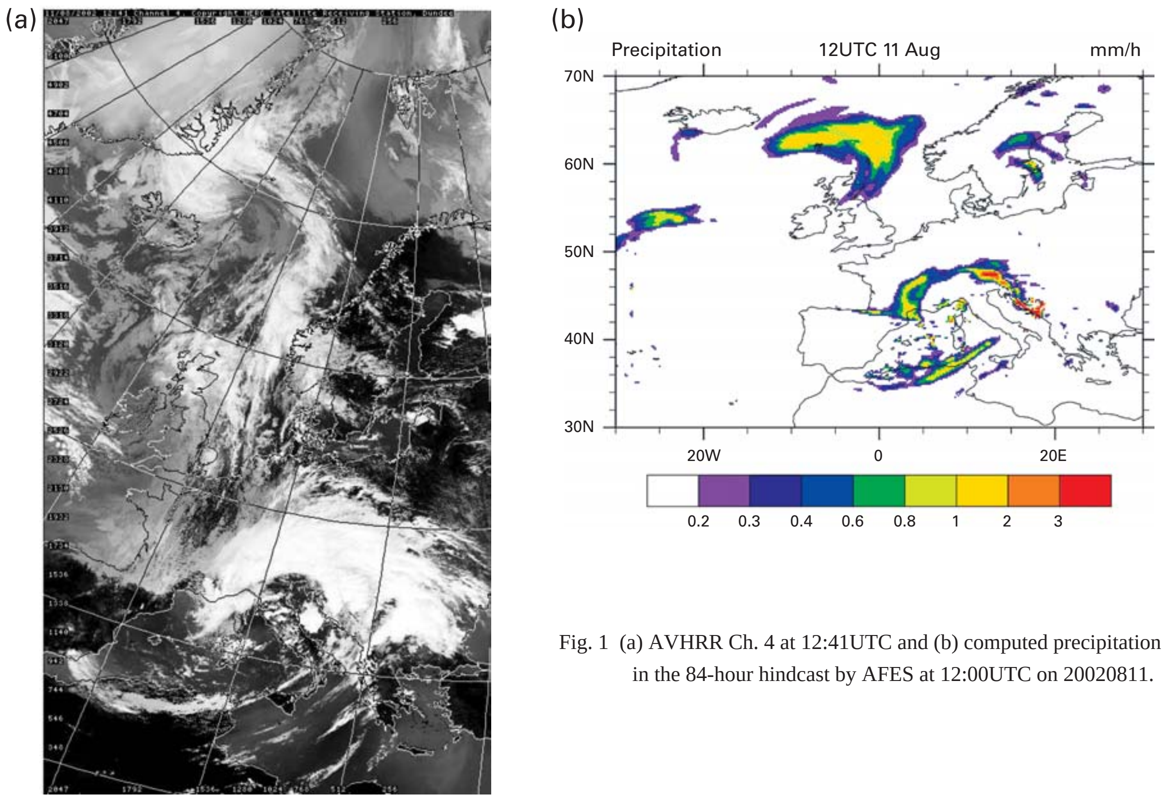

Fig. 1 (a) AVHRR Ch. 4 at 12:41UTC and (b) computed precipitation in the 84-hour hindcast by AFES at 12:00UTC on 20020811.

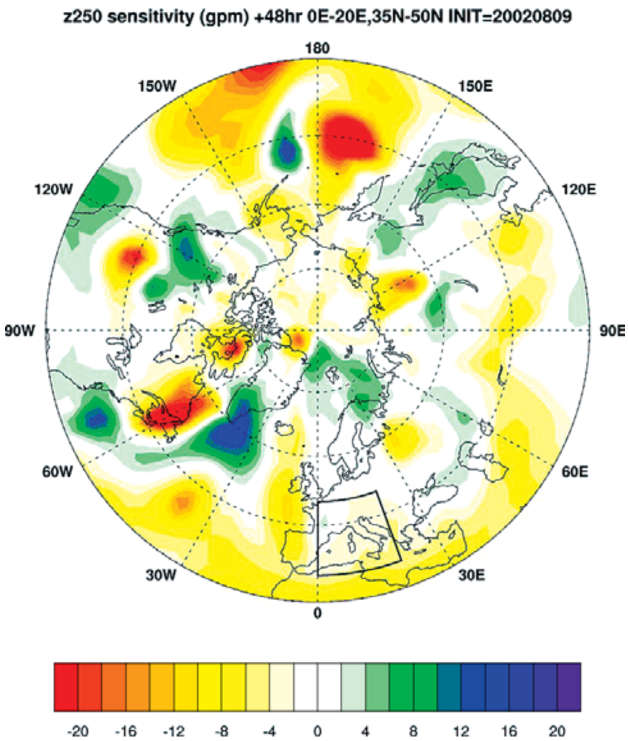

Fig. 2 Simple 48-hour sensitivity map for z250. This figure shows sensitive anomalies in order to have correct disturbance in the thick rectangular area over the Mediterranean Sea.

actual position and may keep the cyclone over the Atlantic at the right location by interacting with the front of the cyclone. On the other hand, in the unsuccessful 156-hour hindcast, Critobal moves to the Gulf of Mexico and cannot keep the cyclone over the Atlantic from moving eastword too fast. We are investigating this possible inter-scale interaction between meso-scale (Cristobal and the cut-off cyclone over the Mediterranean) and large-scale (the cyclone and anti-cyclone over the Atlantic).

3. OFES

Following the successful 50 years eddy-resolving spin-up on the global domain, we started a hindcast covering the period from 1950 to 2003 and a tracer simulation. The computational domain covers near global region extending from 75˚S to 75˚N with the horizontal grid space of 0.1˚ and 54 vertical levels. The spin-up starts from an annual mean field without motion and the surface flux is specified from monthly mean value of NCEP/NCAR reanalysis data, while the subsequent hindcast simulation is forced by daily mean NCEP/NCAR reanalysis.

In our hindcast experiment, there has been a noticeable improvement in the meso-scale eddy activities due to the realistic high-frequency forcing. The frequency of eddy shedding at the Loop Current and at the southern edge of the east Australian current together with subsequent eddy longevity is improved much by the realistic forcing. Unexpected remarkable coincidences of the timing and amplitude of Nino 3 SST (Fig.3) and Dipole Mode Index (Fig.4) encourage us to compare carefully our simulated dynamical fields with observed big events in the 90s.

After 50 years spin-up run, the chlorofluorocarbons (CFCs) have been incorporated into the ocean circulation model to investigate the processes determining the uptake and accumulation of the chemical tracers. The model simu-

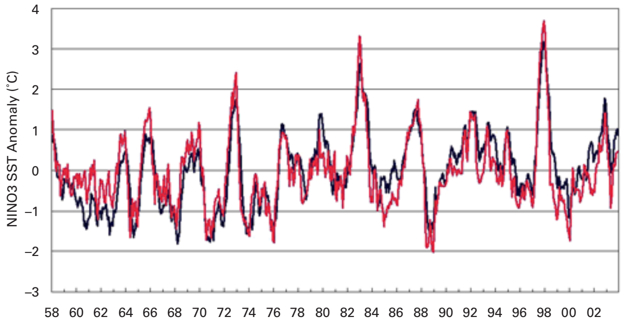

Fig. 3 Nino3 sea surface temperature anomaly (black; OFES, red; observation).

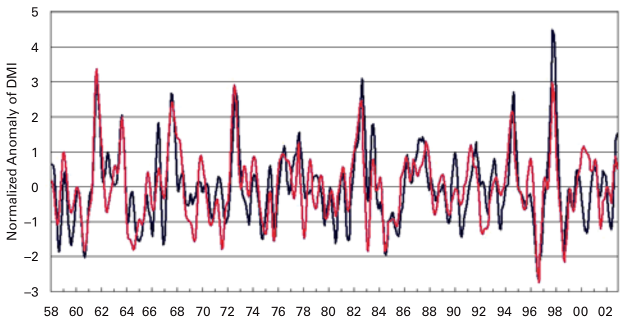

Fig. 4 Normalized anomaly of Dipole Mode Index (black; OFES, red; observation).

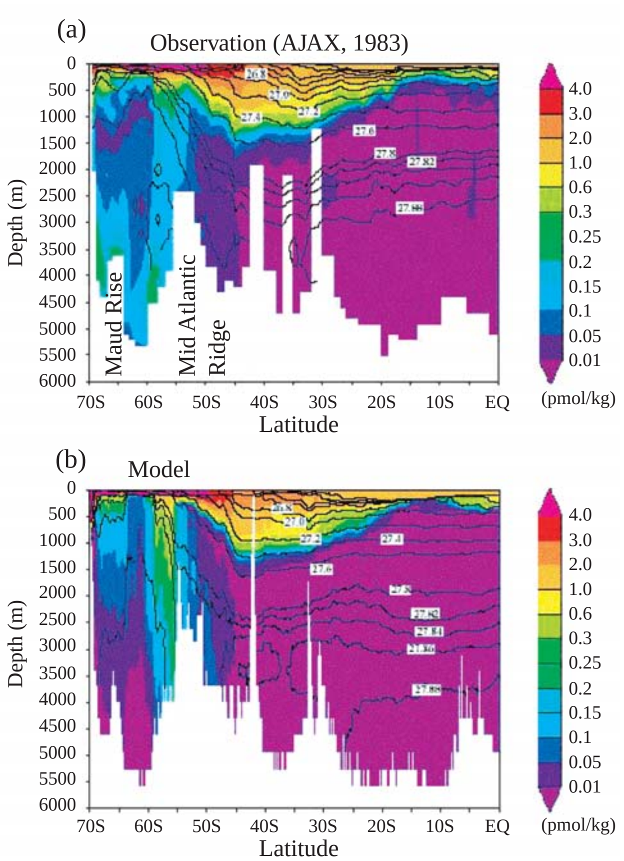

Fig. 5 Comparison of the CFC-11 concentrations (pmol/kg) from (a) observation and (b) model with potential density (solid line) along 0˚E in the South Atlantic (1983).

lates the observed CFC-11 distribution along the AJAX section in the South Atlantic very well especially in the deep layer where the Deep Western Boundary Current (DWBC) ventilates the CFC burdened Antarctic Bottom Water (Fig.5). The CFC-11 distributions capture the realistic pathway of the DWBC in the Western Atlantic. Our realistic results seem to owe much to the employed high-resolution that resolves the bottom topography in a realistic fashion and hence improves the ocean circulation.

4. CFES

In FY2003, we focused our efforts on model improvement and fundamental tuning of CFES. Major improvements from the older version of CFES are treatment of sea-ice concentration and surface fluxes. Current version of CFES deals with the continuous values (from zero to unity) of sea-ice concentration while the older version accepts only zero and unity. At the surface, fluxes between the atmosphere and seawater/sea-ice/land are calculated and then combined according to sea-ice concentration and land/sea ratio in a model grid of AFES. These modifications significantly overcome the cold bias in the polar regions. Now, land surface model MATSIRO (Minimal Advanced Treatments of Surface Interaction and RunOff) [3] is being implemented into CFES as a submodel of AFES. This will be finished in the near future.

Fig. 6 shows a preliminary result of a coupled simulation using CFES. The resolution of AFES is T106L48 and that of OIFES is 1.125˚ in horizontal with 37 levels in vertical. Coupling interval is 1 hour and no flux adjustment is applied. It takes 3 hours for 1 year integration using 9 nodes of the ES.

Recently, we started global ocean/sea-ice simulation using OIFES with the resolution of 0.25˚ in both latitude and longitude in horizontal and of 5 m at the surface with 54 total levels in vertical. It takes about 13 hours for 1 year integration using 45 nodes of the ES under the current setting. In addition, high resolution coupled atmosphere–ocean/sea-ice simulation using CFES has just begun. The resolution of AFES is T106L48 and that of OIFES is the same as described above.

5. PFES

We try to clarify what causes unrealistic representation of the Equatorial Undercurrent in the simulation for the global ocean general circulation using PFES with 0.1˚ horizontal resolution. The conclusion is that the modification of the turbulent closure model level 2.5 [4] with which the dissipation rate of the turbulent kinetic energy (hereafter TKE) is moderated in the case of the strong stratification so that the high TKE level is sustainable, is harmful particularly to the equatorial current system. Because of this problem and also

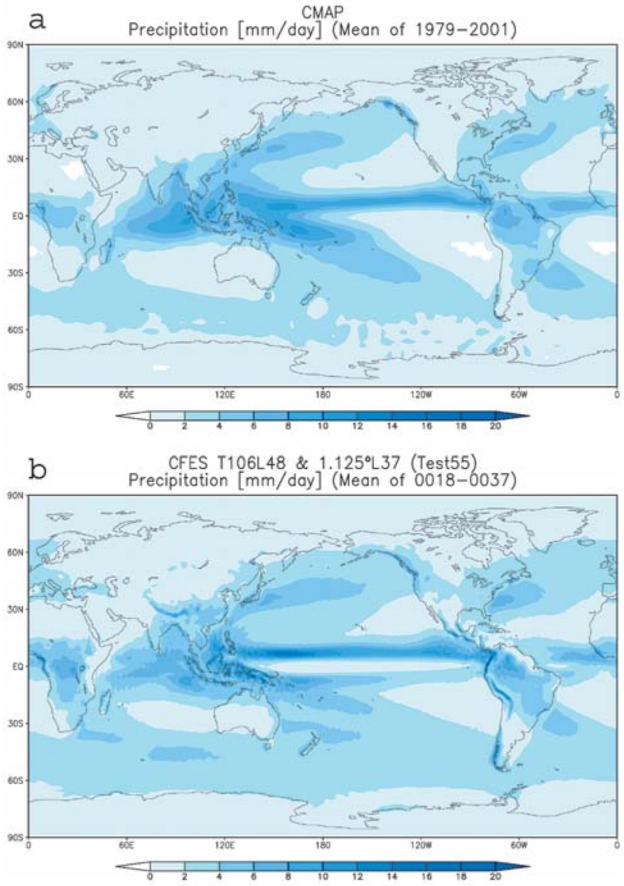

Fig. 6 (a) Observed (CMAP) and (b) simulated (CFES) annual mean precipitation rate [mm/day].

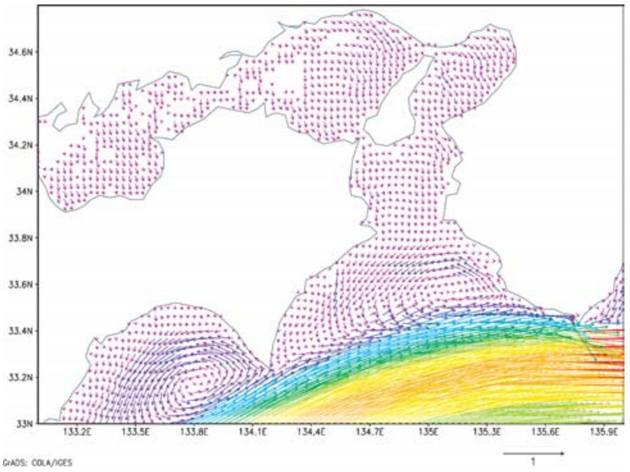

Fig. 7 Simulated surface current in Tosa Bay, Kii Channel and Seto Inland Sea.

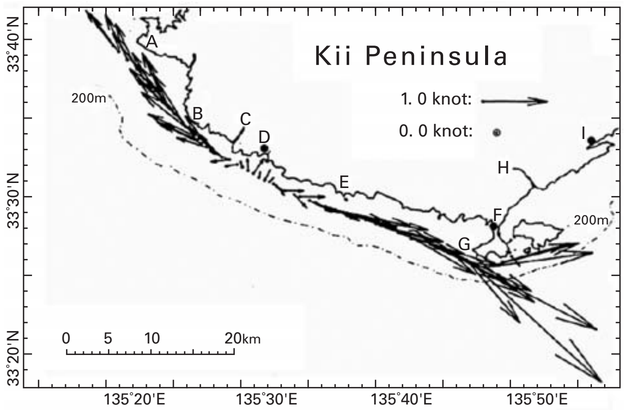

Fig. 8 Observed bifurcation current (called furiwakeshio) at depth 10 m along the western coast of the Kii Peninsula (after [7]).

because the original turbulent closure model level 2.5 [5] has the strong dissipative feature of the TKE in the state of the strong stratification, we implement another turbulent closure model based on Canuto et al. [6] into the PFES for a parameterization of the ocean mixed layer physics. This model successfully represents the strong shear between the South Equatorial Current and the Equatorial Undercurrent that was not sustainable in the previous model.

Using PFES with the above modification, we start to do a very high resolution (0.033˚) simulation for the North Pacific. This model can resolve Seto Inland Sea, Bungo Channel, Kii Channel, Tokyo Bay and so on, and thus enables us to investigate interaction between the Kuroshio and small-scale coastal currents. Note that PFES with the terrain-following vertical coordinate is preferable for it than OFES. Fig. 7 shows the surface current field south of the Kii Peninsula after 35 months integration. The northern part of the Kuroshio attaches the southwestern coast of the Kii Peninsula and bifurcates. The bifurcation current is called "furiwakeshio." This feature is in fact observed in the real ocean (Fig.8). Besides the simulated bifurcation point is almost the same as the observation. This tentative result really encourages us to study on an effect of the Kuroshio on the coastal area and on the predictability of the coastal current.

6. Summary

We have performed ultra-high resolution simulations with AFES, OFES, CFES and PFES. We believe that these simulations, that are possible only with our models running on the Earth Simulator, will result in not only scientifically new knowledge but also contribution to society.

Acknowledgement

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