High-Resolution Simulation Studies on the Mechanisms and Predictability of Various Atmospheric and Oceanic Phenomena

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High-resolution simulations and numerical computations are carried out to investigate mechanisms and predictability of various atmospheric and oceanic phenomena. The following topics are reported as examples of this project. 1) A process study on the heat wave in the Tokyo area on July 20, 2004. 2) Research on atmospheric uncertainty and development of a high-resolution singular-vector method for ensemble initial conditions of extreme events prediction. 3) Research and development of the models for studies in climate variation and its impact on anomalous weather events. 4) Ocean ecosystem and tracer modeling.

Keywords: High-resolution simulations of the general circulations of the atmosphere and ocean, Mechanisms of high-impact and anomalous weather events, Predictability of high-impact and anomalous weather events, Climate variation predictability, Oceanic ecosystem and tracer transport modeling

1. Introduction

In addition to the continuing high-resolution simulation studies on atmospheric and oceanic dynamics and predictability using the Earth Simulator [1], the scope of the project has been expanding to include modeling studies of oceanic ecosystem and tracer transport [2].

The simulation models used in the studies are AFES [3], an atmospheric general circulation model, OFES [4], an oceanic general circulation model, and CFES, the coupled atmosphere–land–ocean–sea-ice model that consists of AFES with a land surface model, MATSIRO (Minimal Advanced Treatments of Surface Interaction and RunOff) [5], and OFES with sea-ice component (OIFES) [6]. These models are capable of representing not only planetary-scale phenomena but also meso-scale ones of O(10 km)–O(100 km). Additionally a singular vector computation system developed by the Numerical Prediction Division, Japan Meteorological Agency (NPD/JMA) is used in this project.

2. Process Studies on High-Impact Weather Events

Heat waves, such as those occurred in Europe in 2003 [7] and in Japan in 2004, have large impact to the society. The record-breaking temperature of 39.5°C was observed in Tokyo on July 20, 2004. The convective activity over the Philippine Sea was rather inactive during that month. On the other hand, the westerly over the Asian continent meandered to a great extent. As a result of energy propagation associated with meandering of the jet the subtropical high intensified over southwestern Japan. This is a typical case of intensification of the high in the late summer with "the silk road pattern" [8]. The high was intensified at the location so that northwesterly winds blew over mountains and caused a Foehn in the Tokyo area. The whole process has been successfully reproduced by AFES. The global domain of the model allows the representation of propagation of Rossby waves (Fig. 1a) from the west, and the horizontal resolution of 20-km enables to resolve the local wind and precipitation distributions that caused the high temperatures over the Tokyo area (Fig. 1b). The simulation showed a remarkable predictability of more than 4 days. It implies that the large-scale process that had a long predictability mainly caused the heat wave.

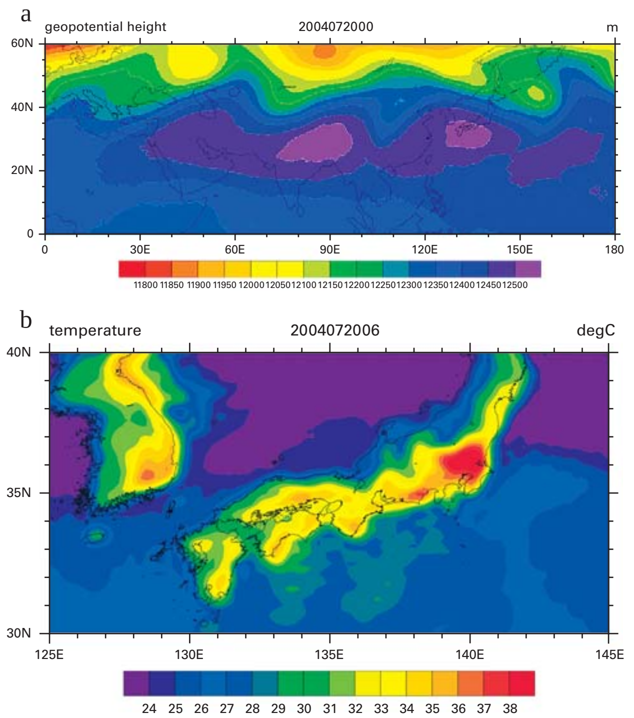

Fig. 1 Simulated (a) geopotential height (gpm) over the Asian continent at 200 hPa at 0 UTC on 20 July 2004 and (b) near-surface temperature (°C) over Japan at 6 UTC (15 JST) of the same day.

3. Predictability Studies on High-Impact Weather Events

Although the above simulations are useful by themselves to understand global-to-regional weather events, more insights would be provided if uncertainty of atmospheric events can be quantified. The following studies in this section aim for this difficult task.

3.1. Uncertainty of atmospheric predictions

It has been pointed out that inaccuracy of initial conditions and model imperfections may be major sources of uncertainty in weather forecasts. The ensemble size (the number of numerical predictions with perturbed initial conditions) of operational ensemble forecasts, for example, is not determined to accurately represent uncertainty but primarily limited by computational cost. In this study the representation of uncertainty is obtained in terms of a probability distribution function by increasing the ensemble size toward 1000. It is also an aim of this research to demonstrate how to extract useful information for more accurate predictions. A 125-member ensemble simulation from 1 March 2004 was conducted to study uncertainty of explosive development of a mid-latitude cyclone off Japan. We have completed the development of a system to generate initial perturbations using a breeding method [9] and generated 100 modes every 12-hour for one month. Lyapunov characteristic numbers for those modes are found to be large enough for the slowest mode to grow in 3-4 days. It is planned to extend this system to include data assimilation by ensemble Kalman filter.

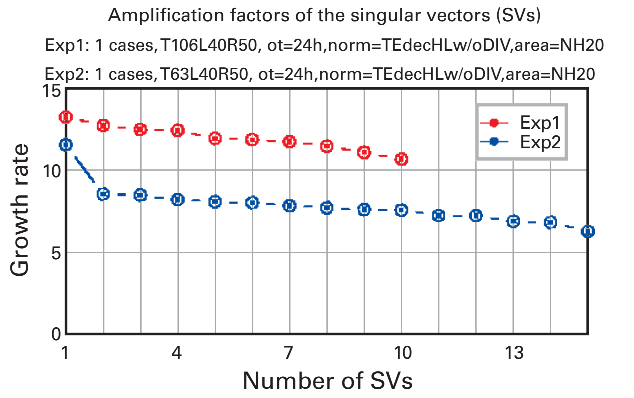

Fig. 2 The growth rates of singular vectors calculated by the high resolution model and low resolution model, respectively. Red line is results from the high resolution model. Blue line is results from the low resolution model.

3.2. Calculations of singular vectors by a high resolution numerical model

An alternative way to calculate initial perturbations for ensemble predictions is to use singular vector analysis. A singular vector computation system developed by NPD/JMA, is used to examine the sensitivity of the characteristics of the singular vectors on the horizontal resolutions with T63 (about 180 km) and T106 (about 110 km) spectral truncations.

The singular vectors are computed as the most growing modes at 24-hour forecast time over the Northern Hemisphere (20°N - 90°N). A linearized model and its adjoint version are used to calculate singular vectors. These models consist of full dynamics (including advection of water vapor) and a simplified physical process (vertical diffusion only). The growth rate of singular vectors is evaluated by the moist total energy norm in the troposphere except the divergence terms.

Figure 2 shows growth rates of singular vectors calculated with the two different resolutions. Singular vectors for each resolution are sorted in the order of growth rate. It is clear that growth rates calculated by the high-resolution model are larger than those by the lower one. This result suggests that it is possible to obtain efficient initial perturbations with large growth rates by using a higher-resolution model for the singular vector calculation. Ensemble forecasts perturbed by such modes with large growth rate may adequately capture rare cases and increase accuracy of a probabilistic prediction for extreme events.

4. Model Developments for Studies on Climate Variation and Its Impact on Anomalous Weather Events

4.1. AFES Development

In order to investigate mechanisms of inter-annual to decadal variations of atmospheric circulations and the relationship between climate variations and anomalous weather events, simulated climate needs to be represented as statistics of such events. For this study, moderately high horizontal resolutions of about 50-km and 80-km are chosen. In

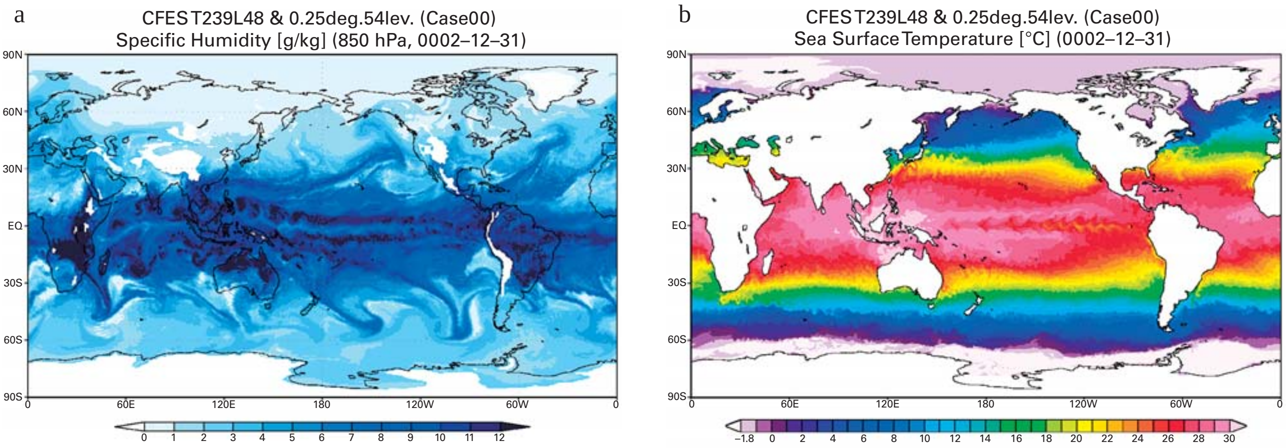

Fig. 3 (a) 10-minute averaged field of 850-hPa specific humidity (g/kg) and (b) snapshot of sea surface temperature (°C) in December 31 of the second model year.

addition a number of physical parameterization packages are upgraded to modern schemes for improvements: MSTRN-X [10] for radiation and a new scheme for convective cloud diagnosis [11]. With these modernized physics, simulations with prescribed sea-surface temperature (SST) are conducted. Simulated results are not only used for studying climate variability but also will be compared against coupled atmosphere–ocean simulations by CFES.

4.2. CFES Development

In addition to upgrades of physical packages of AFES described above, land surface sub-model is upgraded by replacing simple bucket-type model with MATSIRO [5], and this makes significant improvement in precipitation especially over the Eurasian Continent (not shown). Sea-ice component of OIFES is also updated for more accurate computations [6]. As a result, CFES becomes a state-of-the-art coupled atmosphere–ocean GCM.

Using this new version of CFES, we started a coupled atmosphere–ocean simulation with the resolutions of T239 (about 50 km) and L48 (12 layers under 0.8σ) for the atmosphere and 0.25° (about 25 km) and 54 levels (20 levels within upper 200 m) for the ocean. Coupling interval is an hour, and no flux adjustment is applied. It takes about 20 hours for 1-year integration using 60 nodes (30 for AFES and 30 for OIFES) of the Earth Simulator.

Figure 3 shows an example of results from a CFES simulation. Thanks to very high resolution of its atmospheric component, synoptic-scale variability of specific humidity is clearly expressed both in the tropics and extratropics (Fig. 3a). In the ocean part, reproduction of meso-scale variability of western boundary currents such as the Kuroshio and the Agulhas Current is fairly good (Fig. 3b) although the horizontal resolution of the ocean component of CFES is not necessarily enough to resolve extratropical phenomena. This simulation will be carried out for several decades.

5. Studies on Ecosystem and Tracer Transport in the Ocean

OFES with a horizontal grid spacing of 0.1° has capabilities to simulate oceanic fields including meso-scale variations and narrow strong currents due to the high-resolution and realistic presentation of bottom topography [2, 4]. Physical influences on a marine ecosystem in the open ocean are investigated using a simplified four-component ecosystem model [12] embedded in OFES. Distribution of the simulated chlorophyll concentration at the surface, compared with that from the SeaWiFS satellite sensor in spring, shows

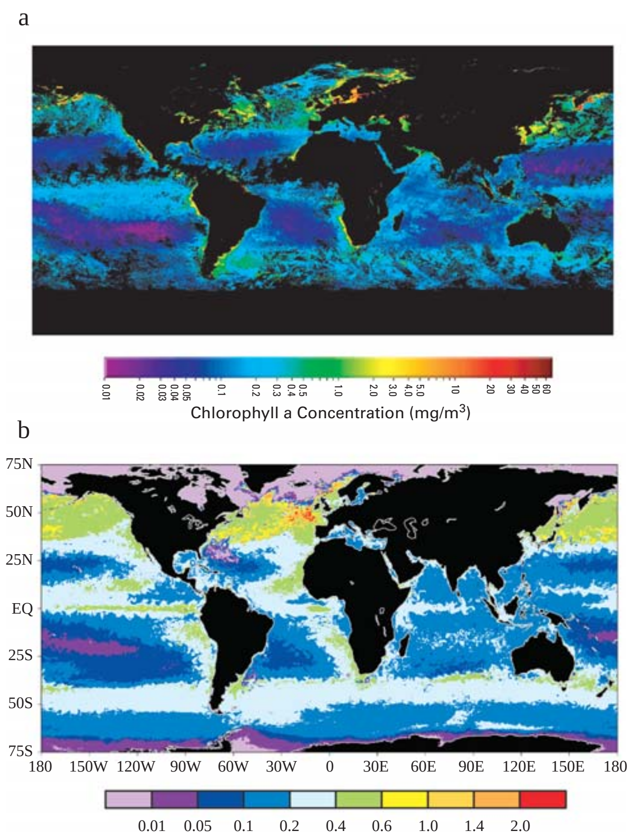

Fig. 4 Comparison of phytoplankton concentration (mmol/m^3) at the sea surface in spring from (a) observation by SeaWiFS (30 Apr 2000 to 07 May 2000) and (b) model (02 May 06).

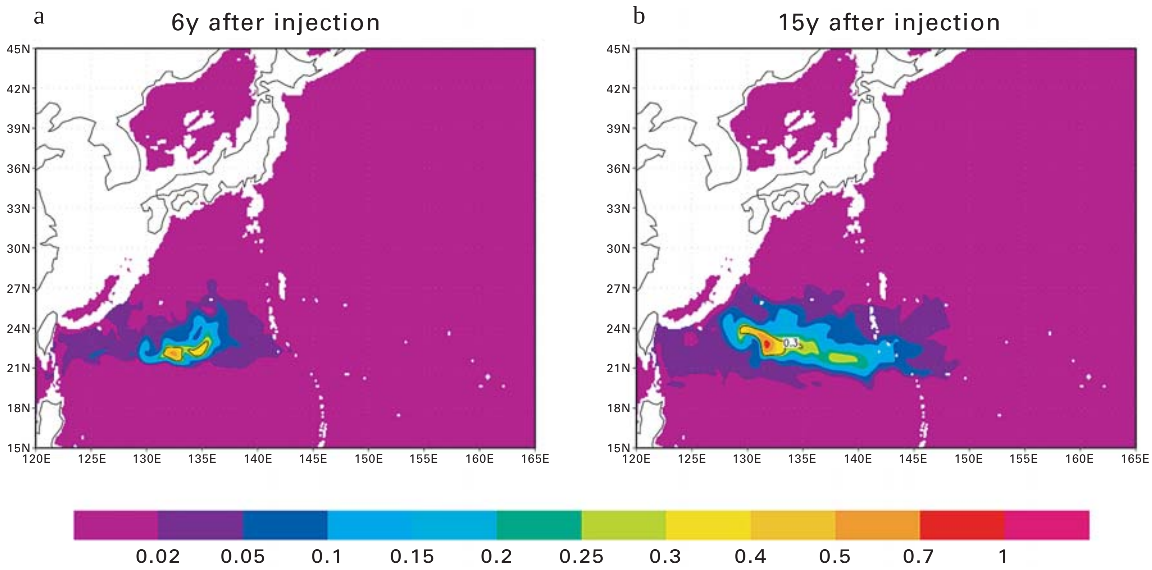

Fig. 5 Distribution of the simulated CO2 concentration (ppm) at a depth of 1185 m in the south of Japan (a) 6 years and (b) 15 years after the beginning of the injection. 1 ppm per year is added in the region (131.4°E–132.4°E, 22°N–23°N, 1000 m–2000 m).

a pattern influenced by the western boundary current and meso-scale variability (Fig. 4). Overall, simulated chlorophyll distribution is in good qualitative agreement with observed chlorophyll, with low concentrations in the subtropical gyre and high concentrations in the upwelling and subpolar gyre. Especially, the distribution shows a pattern influenced by the western boundary current (Kuroshio) and the meso-scale eddy.

The North Pacific regional version of OIFES is used to simulate CO_2 ocean sequestration, which is one of promising ways to mitigate the increasing CO_2 level in the atmosphere. Predictions of the distribution of the injected CO_2 for several decades are necessary to evaluate its environmental impacts. Figure 5 shows distributions of the CO_2 concentrations at a depth of 1185 m at 6th and 15th years in the case of continuous CO_2 injection around 132°E, 22.5°N. The regions of high CO_2 concentration are confined around the CO_2-injected site.

6. Concluding Remarks

This project covers from weather events with the time-scale of a day or two, to decadal climate variations in the coupled atmosphere–land–ocean–sea-ice system. Moreover not only dynamical processes but also bio-geochemical processes are investigated. This diversity is due to the fact that this project has been forming a sort of consortium in the atmospheric and oceanic sciences community. It is hopefully a good development for the entire Earth Simulator project while it may be somewhat necessary to refocus this particular project sometime in the near future.

High-resolution simulations on the Earth Simulator in this project have been producing a huge amount of data. Some of these data have been provided to some research groups and individuals not only nationally but also internationally. It is essential to collaborate with research community outside of this project in order to fully appreciate the simulation results.

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高解像度シミュレーションによる大気・海洋諸現象のメカニズムと予測可能性の研究

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様々な大気・海洋現象のメカニズムと予測可能性を理解するために、高解像度のシミュレーションを含む数値計算を行った。本プロジェクトの例として、このレポートでは以下のトピックスの簡単な紹介をする。

1）2004年7月20日の東京付近での熱波のプロセス研究。
2）アンサンブル手法を用いた顕著現象予測のための高解像度特異ベクトル算出法の開発。
3）気候変動とその異常天候への影響を研究するためのモデル群の研究開発。
4）海洋中の生態系およびトレーサーのモデリング。

キーワード：高解像度大気・海洋大循環モデル，異常災害気象のメカニズムと予測可能性，気候変動の予測可能性，
海洋生態系・トレーサーモデリング