Understanding and Forecasting High-Impact Phenomena in the Atmosphere and Ocean

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Impact of a sea surface temperature front on the atmospheric circulation is clarified by sensitivity experiments using a global atmospheric model. Submesoscale eddies and filaments along the Kuroshio and Tsushima Warm Current are successfully simulated using a high-resolution ocean model with a sea-ice process to enable investigation of their impact on large-scale circulations. Preliminary results of long-term integrations of coupled models at two different resolutions show a significantly improved climate due to accumulated improvements of the model components. Impact of Arctic buoys is investigated using an atmospheric data assimilation system using an ensemble technique to show the importance of these buoys in order to capture storm activity in the Arctic region. Tornadoes in the winter in Japan are successfully simulated using a cloud resolving model to study their formation process and structure.

Keywords: sea surface temperature front, submesoscale eddy, atmosphere-ocean interaction, arctic storm activity, tornado

1. Introduction

In this project high-resolution simulations are conducted using atmosphere, ocean and coupled atmosphere-ocean models to better understand and predict high-impact phenomena in the atmosphere and ocean. This project is composed of process studies of atmosphere, ocean, and their coupled system using simulation output, improvement of a high-resolution coupled model, development of an advanced data assimilation system, and predictability studies of high-impact phenomena. This report summarizes the achievements made in the first half of fiscal year 2008.

2. Atmospheric responses to the heat from the Gulf Stream

The fact that the heat from the Gulf Stream warms air in the midlatitudes to cause significant updraft has been revealed by recent satellite observations, operational analysis, and numerical experiments [1]. The atmospheric responses to the Gulf Stream sea surface temperature (SST) gradient are investigated using AFES (atmospheric general circulation model for the Earth Simulator) with 50 km horizontal resolution. A precipitation band is trapped along the Gulf Stream in the satellite observation (Fig. 1a) and in a simulation with observed high-resolution SST data (CNTL, Fig. 1b), while the rain band disappears in a simulation using a smoothed SST distribution (SMTH, Fig. 1c). Strong vertical velocity also penetrates the upper troposphere along the Gulf Stream in the operational analysis data and AFES CNTL run (not shown).

CFES (coupled atmosphere-ocean general circulation model for the Earth Simulator) "standard" simulation (see Sec. 5 in this report) also captures the atmospheric responses to the Gulf Stream. Figure 2 is a three dimensional visualization of atmosphere-ocean interaction along the Gulf Stream. Above the Gulf Stream of 1000 m depth along the western boundary of the North Atlantic, the associated updraft reaches about 10 km above sea level in this simulation.

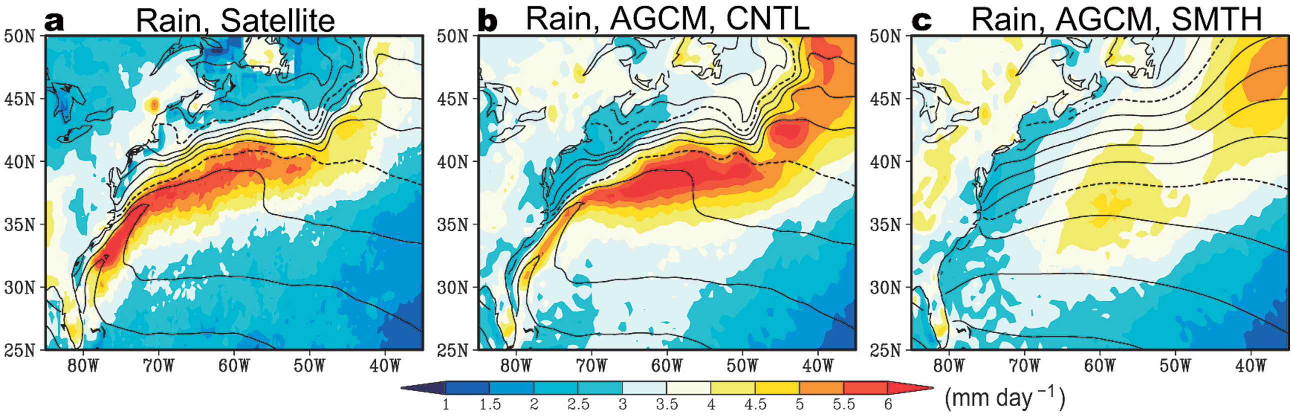


Fig. 1 Annual climatology of rain rate (color) in (a) satellite observation, and in simulations with (b) observed and (c) smoothed SST using AFES with 50 km horizontal resolution. Contours are SST (2°C interval and dashed contours for 10°C and 20°C). From Minobe et al. (2008) [1].

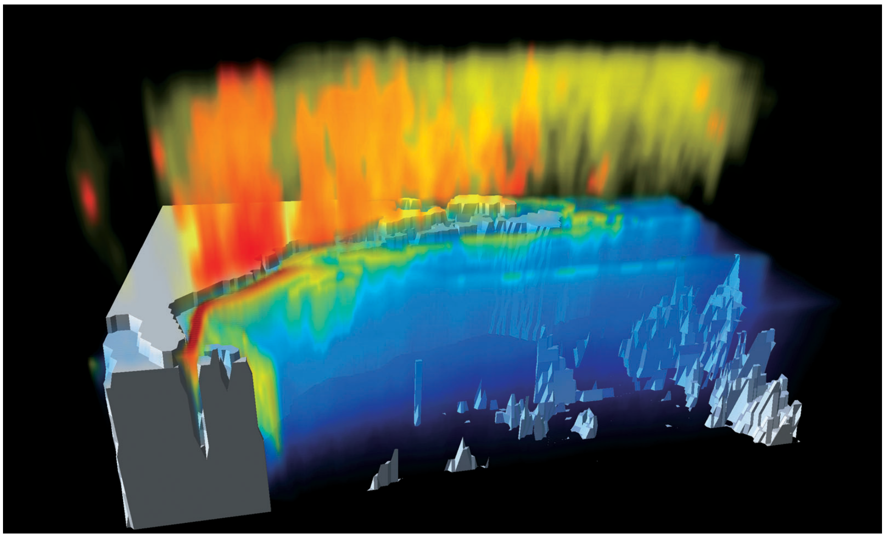


Fig. 2 Annual mean atmospheric vertical velocity and ocean current speed in the simulation with CFES standard.

3. Submesoscale structures in the high-resolution North Pacific OFES

Recent satellite observations of SST and ocean color capture the submesoscale structures (≤30 km) smaller than mesoscale eddies (≈100 km) in the ocean. Some idealized modeling studies (e.g. [2]) suggest that vertical motion induced by submesoscales around density fronts could influence large-scale oceanic field in the surface and subsurface. In the next generation of OGCM (Ocean General Circulation Model) that simulates realistic basin-scale circulation, submesoscales need to be resolved or parameterized.

An experimental North Pacific simulation with the 1/30° (about 3 km) horizontal resolution using OFES (OGCM for the Earth Simulator) with a sea-ice process [3] has been conducted to simulate submesoscales. A snapshot of relative vorticity (left panel in Fig. 3) shows that submesoscale eddies and filamental structures ubiquitous along the Kuroshio and the Tsushima Warm Current are successfully simulated, although the oceanic field is not enough to be spun up due to only 4 month integration from the initial condition without motion. It is suspected that strong vertical motions (right panel in Fig. 3) penetrating into the deep ocean may be induced by the surface submesoscale eddies. The vertical motions could enhance vertical mixing of tracers including biological materials. This successful test simulation encourages us to perform a long-term spin-up simulation to see the details and variation of three-dimensional submesoscale structures and their influence on the large-scale oceanic field.

4. Improvements of AFES

The two dimensional semi-Lagrangian tracer advection has been implemented and optimized for the Earth Simulator. Several options are provided for interpolation including the spectral bicubic method [4]. Preliminary tests imply slightly increased humidity near the subtropical boundary layer. Impacts on the model climate need further investigations.

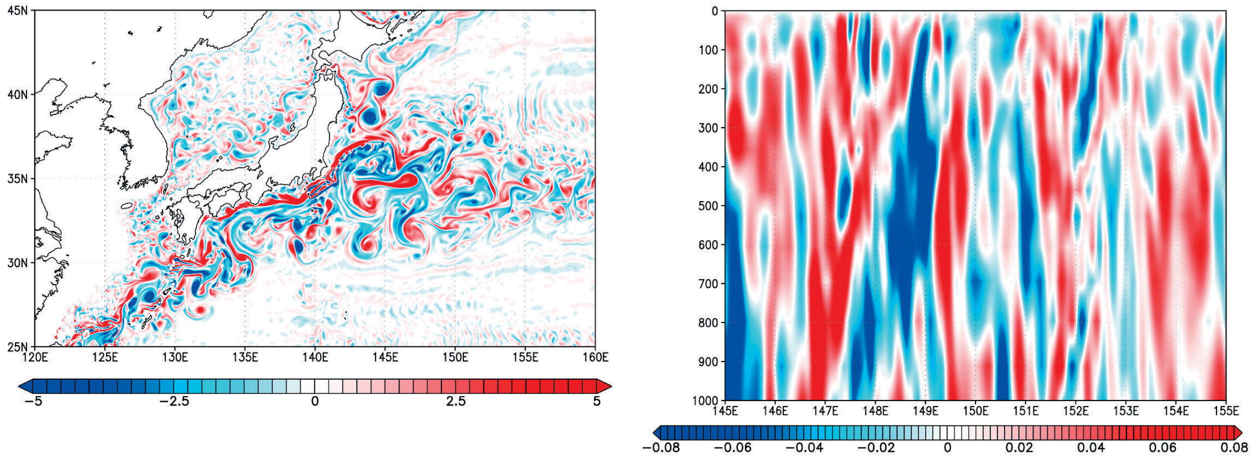


Fig. 3 Snapshots of (left) relative vorticity (10^{-5} s^{-1}) at the depth of 100 m and (right) vertical velocity (10^{-2} m s^{-1}) from 145˚E to 155˚E along 35˚N on May 1 in the model first year based on the 1/30˚ OFES.

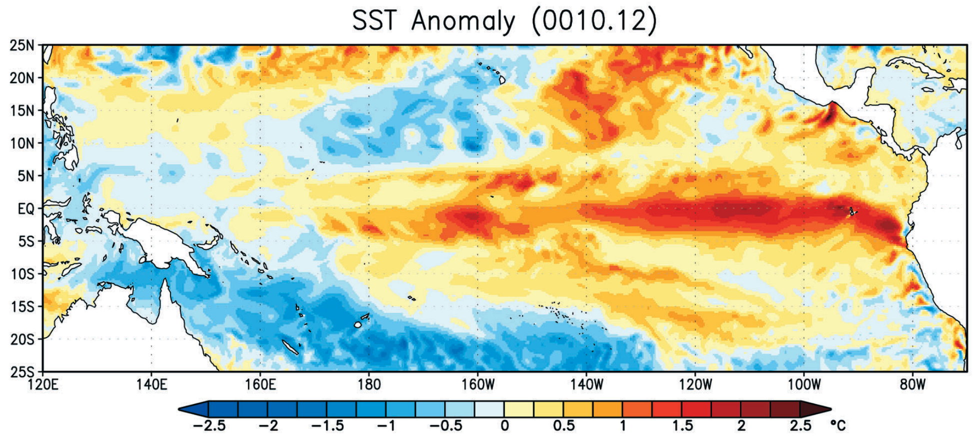


Fig. 4 SST anomaly [˚C] on December of the 10th model year from the 10-year (from 6th through 15th year) averaged field.

In order to improve the mean state and variability of the tropical convection from the diurnal cycle to intraseasonal variations, the Emanuel convection scheme is being overhauled. The definition of the cloud top has been modified to suppress unrealistically high cloud top heights. The vertical profile of the mixing ratio with environmental air has been modified to enhance mixing near the boundary layer top. These improvements contribute to a significantly better representation of the intraseasonal variations.

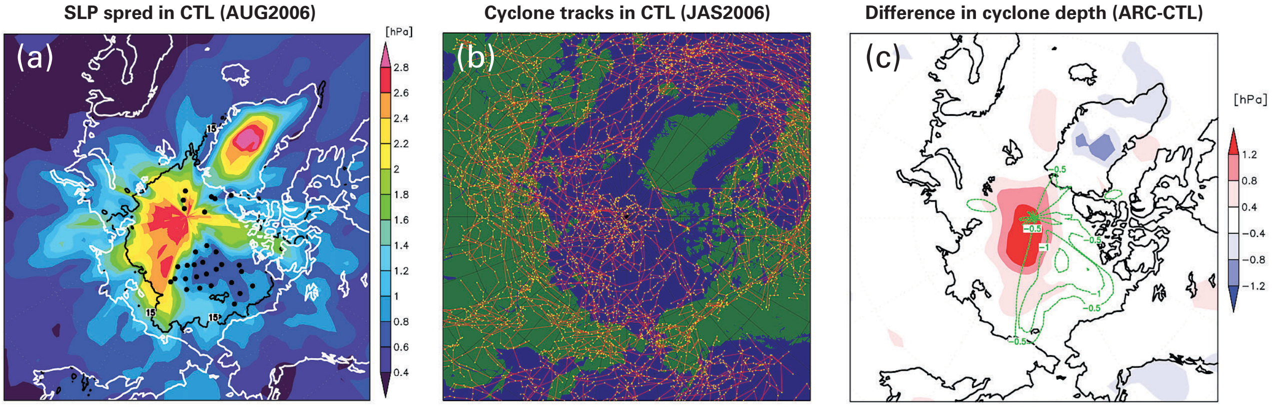
5. Coupled simulations using “CFES standard” and “CFES mini”

Long-term coupled simulations have been started using the latest version of CFES [5] with two different horizontal resolutions. This version of CFES has many improvements from the previous one including a new large-scale condensation scheme in AFES for better representation of low level clouds [6]. The higher resolution version, called “CFES standard,” has the resolutions of T239 (about 50 km) and L48 for the atmosphere and 0.25˚ (about 25 km) and 54 levels for the ocean. The lower resolution version, called “CFES mini,” has half the horizontal resolution of CFES standard and will be used for centennial-scale and ensemble simulations.

At this moment, 15-year integration with CFES standard and 40-year integration with CFES mini have been completed. Interannual variability such as El Niño and Southern Oscillation (ENSO) is reproduced fairly well in both runs. Figure 4 is an example of ENSO warm event simulated in CFES standard. In addition, some decadal signals such as decadal modulation of ENSO and Pacific Decadal Oscillation (PDO) are found in CFES mini.

6. Development of advanced data assimilation techniques

The AFES-LETKF (LETKF: local ensemble transform Kalman filter) ensemble data assimilation system is used to investigate the impact of surface pressure observations by Arctic buoys. These observations provide a reasonably good coverage in the Arctic sea-ice covered region, where meteorological stations are sparsely located. Due to recent abrupt sea-ice decrease [7], however, it is anticipated that many buoys exit the Arctic Ocean through the Fram Strait by the Transpolar Drift Stream (e.g. [8]) and lost during the summer “Blue Arctic” and that the analysis error is much


SLP spred in CTL (AUG2006)

Cyclone tracks in CTL (JAS2006)

Difference in cyclone depth (ARC-CTL)

Fig. 5 (a) Analysis ensemble spread of sea level pressure (SLP) on August 2006 in CTL with position of the Arctic drifting buoys (dots) and ice concentration larger than 15 % (black contour), (b) All cyclone tracks in CTL from July to September 2006, and (c) Difference in summer (JAS) average of cyclone depth (ARC–CTL) with difference in analysis ensemble mean SLP (green contour: hPa).

increased in the Arctic to deteriorate forecast skills.

Impact of Arctic buoys is evaluated in an observing systems experiment (OSE). ALERA (AFES-LETKF experimental ensemble reanalysis [9]) is regarded as the control run (CTL). In the test run (ARC), the same observational data set except for the surface pressure observations north of 70°N is assimilated using the same system that produced ALERA.

The analysis error measured by the ensemble spread is much smaller in the region with many buoys (Fig. 5a). Cyclones during summer over the Arctic region are very important for moisture transport as well as sea-ice retreat along Eurasian coast. Figure 5b shows the cyclone tracks from July to September 2006 as calculated from CTL. In ARC, cyclones become less frequent (not shown). The difference of the average cyclone depth between ARC and CTL (color shades in Fig. 5c) shows that cyclones become deeper due to lower values of the ensemble mean sea-level pressure (contours in Fig. 5c). This result can be interpreted that cyclones are less numerous, deeper and larger without Arctic buoys since small cyclones are not captured.

7. Tatsumakis associated with a winter snowstorm

Both tornadoes and waterspouts are called a "*tatsumaki*" in Japan. Many tatsumakis occur in coastal regions of the Japanese Islands. In particular, they are often observed in association with a snowstorm along the coast of the Sea of Japan in winter. The mechanism and process of formation are not revealed because of the difficulty of observation. In the present study, we performed simulation experiment of a tatsumaki associated with a winter snowstorm using the cloud-resolving model to clarify the process and structure of the tatsumaki and the characteristics of the parent cloud.

The model used in the present study is the Cloud Resolving Storm Simulator (CReSS). Triple-nested simulations with horizontal resolutions of 4 km, 400 m and 70 m were performed in one-way manner to resolve the tatsumaki. The grid numbers of the 70m-model are 2819 and 2307 in horizontal and 67 in vertical. The initial and lateral conditions were provided by the Regional Spectral Model output of the Japan Meteorological Agency. The computation was performed using 128 nodes of the Earth Simulator.

The simulation showed 21 intense vortices of tatsumaki along the front of the cold air-outbreak (Fig. 6). The order of the vorticity is 0.2 s^{-1} and the associated wind speed is about 30 m s^{-1}. The lifetime of the tatsumakis is less than 10 minutes. The most intense tatsumaki had a wind speed of 34 m s^{-1} and moved NNE-ward at a speed of 22 m s^{-1}. The tatsumaki was formed below a shallow convective cloud, which is a non-supercell type (Fig. 7).

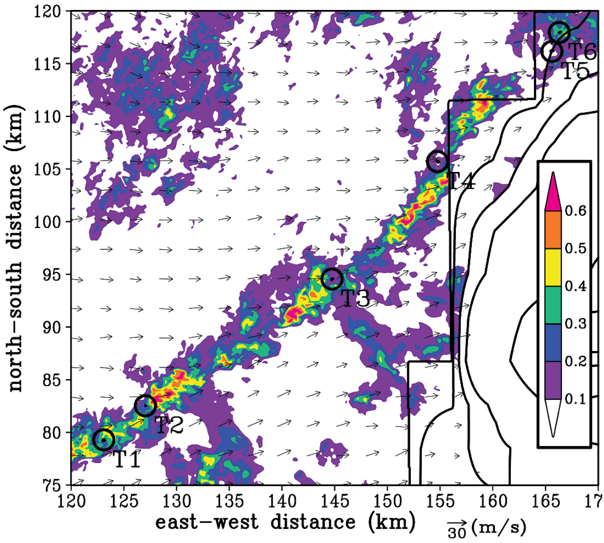


Fig. 6 Horizontal distributions of precipitation mixing ratio (color scales; g kg^{-1}) and horizontal wind (arrows) at a height of 66 m obtained from the 70 m-model at 1900 JST, 25 November 2005. The contour lines are topography of the coastal region near the Mt. Chokai in Yamagata-Akita Prefectures. The circles with names of T1-T6 indicate the tatsumakis in the simulation.

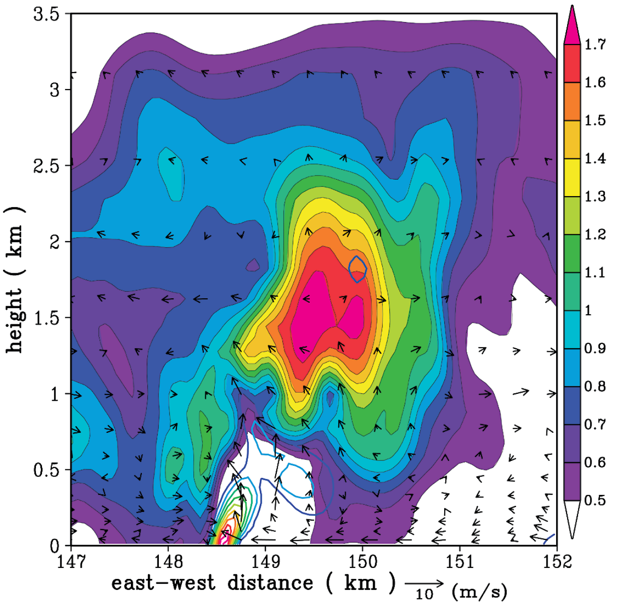


Fig. 7 Vertical cross-section of precipitation mixing ratio (color scales; g kg^{-1}) and vertical vorticity (contour lines) which indicates the tatsumaki. Arrows are velocity in the cross-section (u and w components).

Although the spatial and temporal scales of the winter tatsumaki are small, it occasionally causes severe disaster owing to the associated strong wind. The snowstorm of the present study caused a train accident on 25 December 2005. The very high-resolution simulation shows a possibility to contribute an investigation of disaster and prevention/reduction of disaster caused by winter tatsumakis as well as to study the formation mechanism and structure of tatsumakis associated with snowstorms.

8. Concluding remarks

We briefly reported process and predictability studies of high-impact phenomena in the atmosphere and ocean and development of the coupled atmosphere-ocean model during the first half of the fiscal year 2008. The AFES and CFES simulations reveal the impact of SST front along the Gulf Stream on the atmospheric circulation. OFES simulation with the horizontal resolution of 3 km is able to resolve submesoscales of eddies and filaments ubiquitous along the Kuroshio and the Tsushima Warm Current. An OSE using AFES-LETKF has been performed to investigate the impact of surface pressure observation by Arctic buoys. Understanding of formation process and structure of the winter tatsumaki simulated using CReSS is expected to contribute to prevention and mitigation of disasters. Long-term integrations using CFES at two resolutions have a potential to open a new frontier of atmosphere-ocean interaction studies.

Acknowledgement

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大気・海洋顕著現象の理解と予測

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海面水温前線の大気循環に対する影響を大気大循環モデルを用いた感度実験により明らかにした。黒潮や対馬暖流に沿って存在するサブメソスケールの渦やフィラメントを海氷過程を含む高解像度海洋モデルを用いて再現することに成功し、サブメソスケール現象が海洋大循環に与える影響についての研究を可能にした。数々の改良を取り込んだ結合モデルを用いて二つの解像度の長期シミュレーションを開始した。この結合シミュレーションでは、以前のバージョンと比較して気候再現性が格段に向上している。アンサンブル手法を用いた大気データ同化システムを用いて極域ブイによる気圧観測の影響を評価した。日本における冬季の竜巻を雲解像モデルを用いて再現することに成功し、竜巻の形成過程や構造について調べた。

キーワード：海面水温前線, サブメソスケール渦, 大気海洋相互作用, 極域の低気圧活動, 竜巻