All for ephemeral life

# KAKUSHIN

## Innovative Program of Climate Change Projection for the 21st Century

MEXT
MINISTRY OF EDUCATION,
CULTURE, SPORTS,
SCIENCE AND TECHNOLOGY-JAPAN

# General Description

Innovative Program of Climate Change Projection for the 21st Century (KAKUSHIN) is being conducted as a 5-year (FY2007 - FY2011) research project with the aim of projecting future climate change by climate models using a super computer, Earth Simulator (ES). Its achievements are expected to contribute to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) scheduled to be made public in 2013.

The forth Assessment Report (AR4) of the IPCC was released in 2007. It describes research findings including the following scientific ones as concluded by consensus among world's experts: "Warming of the climate system is unequivocal."; and "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." Leading policy makers in the world are now making concrete proposals on targets and/or procedures for the emission reduction of greenhouse gases with considerable quotations from the AR4 as bases. For its roles up to such situations, the IPCC was awarded the Novel Peace Prize in 2007 jointly with Al Gore, the ex-Vice-President of the USA.

The AR4 has thus shown a great significance. Japanese researchers had achieved a number of substantial results under the "Kyo-sei Project (Project for the Sustainale Coexistence of Humans, Nature, and the Earth)" that was the predecessor of the KAKUSHIN and made important contributions to the AR4. The Kyo-sei Project intended to make progress of the climate change projection using the ES that was the fastest computing system in the world when it was launched in 2002. Three research groups were formed, each of which developed respective models to conduct global warming experiments for each specific objective. These developed models were then taken over to the KAKUSHIN and have been further improved for new experiments.

Modeling activities and projection experiments under such differentiated roles shown in the above are now to address as follows various challenges related to global warming that are getting increasingly serious and real:

(1) To make long-term climate projection of global environment up to 2300 under concentration pathways including those for stabilization by sophisticating an Earth system model that includes carbon cycle such as land and ocean ecosystem processes; to estimate emission amount that causes stabilization in concentration; and to provide findings as a basis for the emission target in the post-Kyoto emission reduction.
(2) To make short-term climate projection up to about 30 years from now without differentiating emission scenarios focusing on regional scales and ocean currents; to also tackle the challenge of predicting natural climate variability as an aspect of super-long-term weather prediction under considerable dependence on initial values; and to make detail projection by applying higher resolution.
(3) To project extreme events (tropical cyclones, severe rainfall, etc.) in the future under global warming that would cause particularly large impacts on society by further sophisticating a 20 km super-high-resolution atmospheric model; to make further regionally detail projection of extreme events by developing a few km resolution limited area model, providing basis for response policies.

Thus, these projections are playing core roles in the KAKUSHIN. To make closer linkage between their outcomes and response policy making, the KAKUSHIN also includes research groups with experts in impact assessment on natural disasters so that projection outcome data are efficiently utilized to studies in impact assessment and response (see C in page 3-4). On the other hand, it is also required for such actual application of projections that the uncertainly in projection be reduced and quantified. Therefore the KAKUSHIN also includes studis to estimate the possible range of uncertainty in each model projection experiment (see B in page 3-4).

The KAKUSHIN is conducting projections under such a framework as to enable to respond earnestly to the social needs emerging from global warming that is now getting a real issue.

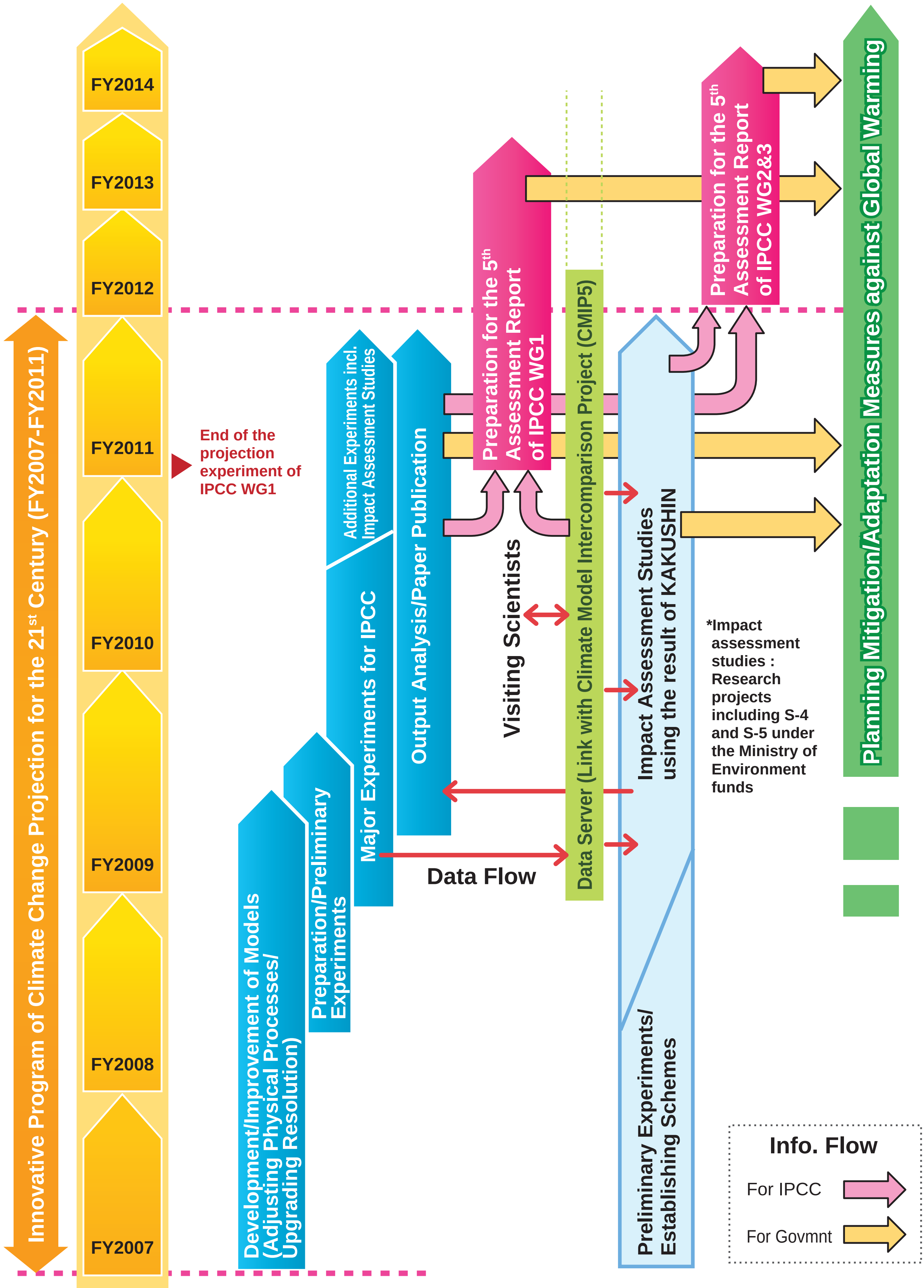
KAKUSHIN

## Logo

The logo design features two planets: the current Earth colored in blue and the future Earth colored in red, with three rising curves representing the temperature tendencies suggested by several emission scenarios and symbolizing a major message of the IPCC.

We have accentuated the "I" in KAKUSHIN to emphasize "Innovation". Our overarching hope is that the achievements of this program will contribute to society.

# Roadmap



FY2014
FY2013
FY2012
FY2011
FY2010
FY2009
FY2008
FY2007
Innovative Program of Climate Change Projection for the 21st Century (FY2007-FY2011)
End of the projection experiment of IPCC WG1
Development/Improvement of Models (Adjusting Physical Processes/ Upgrading Resolution)
Preparation/Preliminary Experiments
Major Experiments for IPCC
Additional Experiments incl. Impact Assessment Studies
Output Analysis/Paper Publication
Preparation for the 5th Assessment Report of IPCC WG1
Visiting Scientists
Data Flow
Data Server (Link with Climate Model Intercomparison Project (CMIP5)
Preliminary Experiments/ Establishing Schemes
Impact Assessment Studies using the result of KAKUSHIN
Preparation for the 5th Assessment Report of IPCC WG2&3
Planning Mitigation/Adaptation Measures against Global Warming
*Impact assessment studies : Research projects including S-4 and S-5 under the Ministry of Environment funds
Info. Flow
For IPCC
For Govmnt

# Research Organization

## Program Coordinators

**Taroh Matsuno**
Special Advisor
MEXT
Principal Scientist
Global Warming Research Project for IPCC AR5/JAMSTEC

**Shuzo Nishioka**
Special Advisor
MEXT

Program Coordinators are responsible for coordinating all of the following to operate the program effectively and efficiently.

- Program management decisions
- Deciding the amount and distribution of funds for each project team
- Improvement of the Program management system (chairing the research coordinating committee, guidance for each team implementation, responsible for correspondence with external reviews, etc)

## Secretariat

**Director : Hiroki Kondo**
Principal Scientist
Global Warming Research Project for IPCC AR5/JAMSTEC

Research coordinating committee is hosted by the Program coordinators and composed of representatives from each research project to promote the realization of targets of each project by collaborating across related projects. Held 3 times a year.

## Teams

### Long-Term Global Change Projection

Long-term global environmental projection using an integrated earth system model

**Representative : Tatsushi Tokioka**
Project Leader
Global Warming Research Project for IPCC AR5/JAMSTEC

Japan Agency for Marine-Earth Science and Technology
http://www.jamstec.go.jp/e/index.html

National Institute for Agro-Environmental Science
http://www.niaes.affrc.go.jp/index_e.html

Department of Urban and Civil Engineering, Ibaraki University
http://www.civil.ibaraki.ac.jp/civil09/english/index.html

| | Research Projects | Organization | Representative |
|---|---|---|---|
| A | Long-term global environmental projection using an integrated earth system model | JAMSTEC | Tatsushi Tokioka |
| A | Development of a global vegetation model | JAMSTEC | Toshihiko Hara |
| A | Reduction in cloud uncertainty using a global cloud-resolving model | JAMSTEC | Masaki Satoh |
| B | Uncertainty estimation for long-term climate change projection using a hierarchy of models | JAMSTEC | Michio Kawamiya |
| C | Evaluation of how natural disasters associated with climate change will affect the stability of major cereal crop production | NIAES | Masayuki Yokozawa |
| C | Long-term global assessment of coastal hazard risks in relation to sea-level rise and global warming | Ibaraki University | Hiromune Yokoki |

### Near-Term Climate Prediction

Near-term climate prediction using a high-resolution coupled ocean-atmosphere general circulation model

**Representative: Masahide Kimoto**
Professor
Atmosphere and Ocean Research Institute, the University of Tokyo

Atmosphere and Ocean Research Institute, the University of Tokyo
http://www.aori.u-tokyo.ac.jp/index_e.html

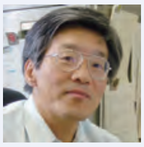
Japan Agency for Marine-Earth Science and Technology
http://www.jamstec.go.jp/e/index.html

Institute of Industrial Science, the University of Tokyo
http://www.iis.u-tokyo.ac.jp/index_e.html

| | Research Projects | Organization | Representative |
|---|---|---|---|
| A | Near-term climate prediction using a high-resolution coupled ocean-atmosphere general circulation model | AORI, the University of Tokyo | Masahide Kimoto |
| A | Improvement of future climate change projection by developing a high-performance ocean model | AORI, the University of Tokyo | Hiroyasu Hasumi |
| B | Development of a technique to quantify the uncertainty in near-term climate prediction using ensemble data assimilation | JAMSTEC | Masayoshi Ishii |
| C | Estimation of changes in the risk of water-related disasters based on near-term climate prediction with uncertainty considerations | IIS, the University of Tokyo | Taikan Oki |

## Extreme Event Projection

Projection of the change in future weather extremes using super-high-resolution atmospheric models



**Representative: Akio Kitoh**
Director
Climate Research Department,
Meteorological Research Institute,
Japan Meteorological Agency

Meteorological Research Institute, Japan Meteorological Agency
http://www.mri-jma.go.jp/Welcome.html
Japan Agency for Marine-Earth Science and Technology
http://www.jamstec.go.jp/e/index.html
Disaster Prevention Research Institute, Kyoto University
http://www.dpri.kyoto-u.ac.jp/web_e/index_topics.html
Global Center of Excellence for Water Hazard and Risk Management, Public Works Research Institute
http://www.pwri.go.jp/icharm/index.html

| | Research Projects | Organization | Representative |
|---|---|---|---|
| A | Projection of the change in future weather extremes using super-high-resolution atmospheric models | JAMSTEC | Akio Kitoh (MRI) |
| B | Quantification and reduction of the uncertainty in climate change projection by super-high-resolution atmospheric models | JAMSTEC | Shoji Kusunoki (MRI) |
| C | Integrated assessment of climate change impacts on watersheds in a disaster environment | DPRI, Kyoto University | Eiichi Nakakita |
| C | Assessment of the impact of climate change on flood disaster risk and its reduction measures over the globe and specific vulnerable areas | ICHARM, PWRI | Kuniyoshi Takeuchi |

## Cloud modeling

**Representative: Kazuhisa Tsuboki**
Associate Professor
Hydrospheric Atmospheric Research Center,
Nagoya University

Hydrospheric Atmospheric Research Center, Nagoya University
http://www.hyarc.nagoya-u.ac.jp/english/index.html

| | Research Projects | Organization | Representative |
|---|---|---|---|
| A | Sophistication of the cloud-resolving model and its coupling with global models | Nagoya University | Kazuhisa Tsuboki |

## Subgrid-Scale Parameterization

**Representative: Toshiyuki Hibiya**
Professor
Department of Earth and Planetary Science,
Graduate School of Science,
the University of Tokyo

Department of Earth and Planetary Science, the University of Tokyo
http://www.eps.s.u-tokyo.ac.jp/index_en.html

| | Research Projects | Organization | Representative |
|---|---|---|---|
| A | High-precision parameterization of marine microphysics using large eddy simulation | EPS, the University of Tokyo | Toshiyuki Hibiya |

## Team Organization

Three teams participating in the KAKUSHIN program are covering these three themes through the following respective foci.

**A**

**Advancing climate modeling and projection** for better simulation of physical and biogeochemical processes by sufficient reflection of feedbacks;

**B**

**Quantification and reduction of uncertainty** for more reliable projections of climate change using model comparisons and other methodologies;

**C**

**Application of regional projections to natural disasters** for better assessments of natural disasters caused by extreme events using sufficiently high-resolution regional projection.

# Long-Term Global Change Projection (- 2300)

## Long-term global environmental projection using an integrated earth system model

### Objectives

The continuing anthropogenic emission of $CO_2$ will worsen global warming. Recent studies have warned that global warming and sea-level increases will continue for more than a century, even if the $CO_2$ concentration could be stabilized at a constant level during this century. Furthermore, achieving the stabilization of $CO_2$ may not be possible if we focus only on anthropogenic emissions because global warming affects various processes of the land (forests and soils) and ocean (nutrient and plankton) ecosystems and the absorption of atmospheric $CO_2$ by the sea surface. We will project global warming using an integrated earth system model and project long-term changes in the global environment under various $CO_2$ stabilization scenarios. We will also estimate the allowable $CO_2$ emissions under $CO_2$ stabilization scenarios based on the results of the global warming projection. Uncertainty estimation of the global warming projection and reduction of the uncertainty will be conducted via additional numerical experiments that incorporate statistical approaches. In addition, natural disaster impact assessment will be conducted based on the global warming projection.

### Advancing climate modeling

Figure 1a shows the evolution of $CO_2$ concentration under a scenario developed for global warming projection. Figure 1b displays the global mean surface temperature projected by our earth system model (ESM) based on the scenario resulting in a 2.8-degree warming relative to the present at the end of the 21st century. Intensive warming is found in the northern high latitudes (Figure 1d). Future $CO_2$ emission path consistent with $CO_2$ scenario in Figure 1a can be calculated by the ESM as depicted in Figure 1c. $CO_2$ emission around the end of the 21st century has to be less than 20% of the current emission, although the warming reaches 2.8 degrees nonetheless. Figure 1e represents the latitudinal distribution of net primary production (NPP)* of trees, illustrating NPP increase in 2090's (blue) compared to 2000's (red). Note however that these are results obtained by a single experiment by a particular model and associated with significant uncertainties.

* Net primary production (NPP):
NPP is the net carbon acquisition by plants, defined as the difference between total carbon assimilated through photosynthesis by plants and that consumed by their respiration. Plants grow on this carbon obtained through NPP.

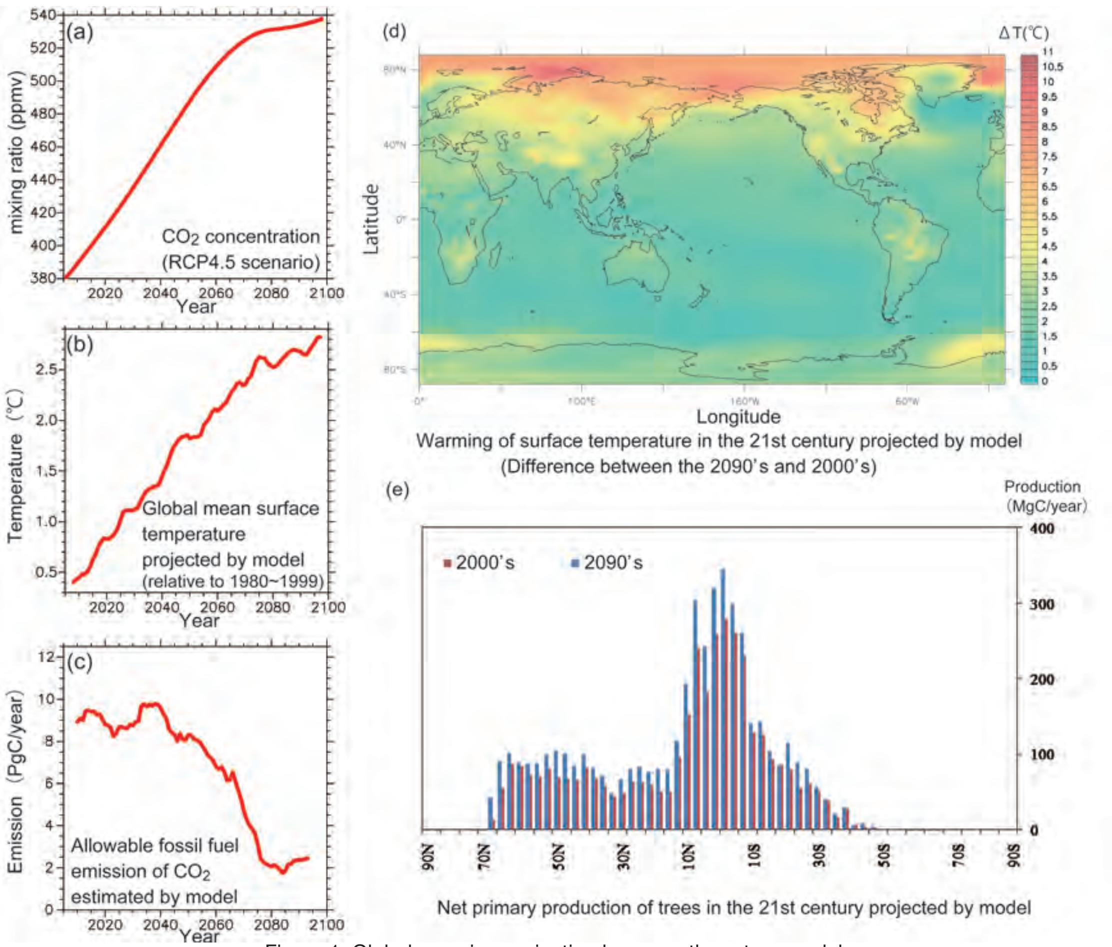



Figure 1. Global warming projection by an earth system model.

## Quantification and reduction of uncertainty

While global warming projections by general circulation models (GCMs) are elaborate, they require huge computer resources. It is therefore extremely difficult to perform enough experiments with GCMs to estimate the uncertainties contained in the projections. Earth system models with intermediate complexity (EMICs) are models that can duplicate fundamental outputs by GCMs while simplifying detailed processes of GCMs, and complementary to GCMs due to their computational speed. We are developing an EMIC that can reproduce the basic behavior of our GCM as shown in Figure 2. In future, various analyses will be conducted using this EMIC in order to obtain quantitative information on uncertainties in global warming projections.

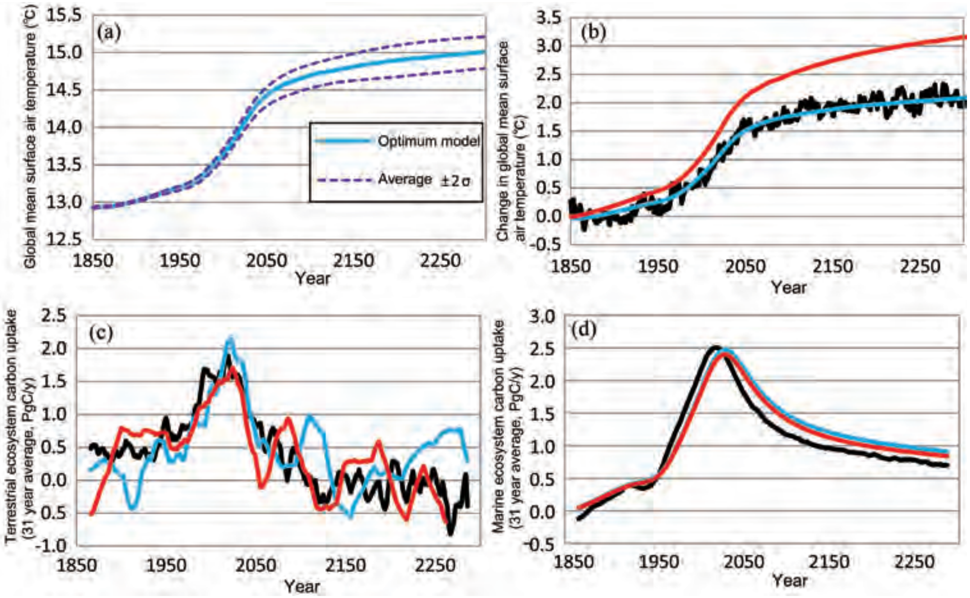



Figure 2. Behavior of the system developed under the present study

(a) Result of an ensemble experiment for the model development (with 300 members under a 450-ppm stabilization scenario). (b)-(d) Temperature (b), terrestrial carbon uptake (c) and oceanic carbon uptake (d) simulated by our EMIC with low (blue) and high (red) climate sensitivities, and our GCM-based earth system model with a low climate sensitivity (black).

## Application of regional projections to natural disasters : Global impact assessment on disasters of storm surges and sea level rise

Storm Surge is sea water that pushed toward shorelines primarily by high winds associated with low pressure weather system, tropical cyclone and so on. Big storm surge causes coastal flooding and takes out people sometimes: for example by Hurricane Katrina in USA in 2006 and Cyclone Sidr in Bangladesh in 2007. If sea level is rise due to global warming, this disaster becomes severer. This map shows the height of past storm surges associated with tropical cyclones calculated by a numerical simulation model. The color from yellow to red shows from low to high heights of storms surge (height above normal tide) along the coastal lines. Estimated potential risk areas of coastal flooding by tropical cyclone are painted in blue color. Test assessment showed that increase in potential risk people by the coastal flooding will become over 500 million by the year of 2100. If intensity of tropical cyclones increase due to global warming, this coastal disaster may also become severer and increase in the number of the risk people.

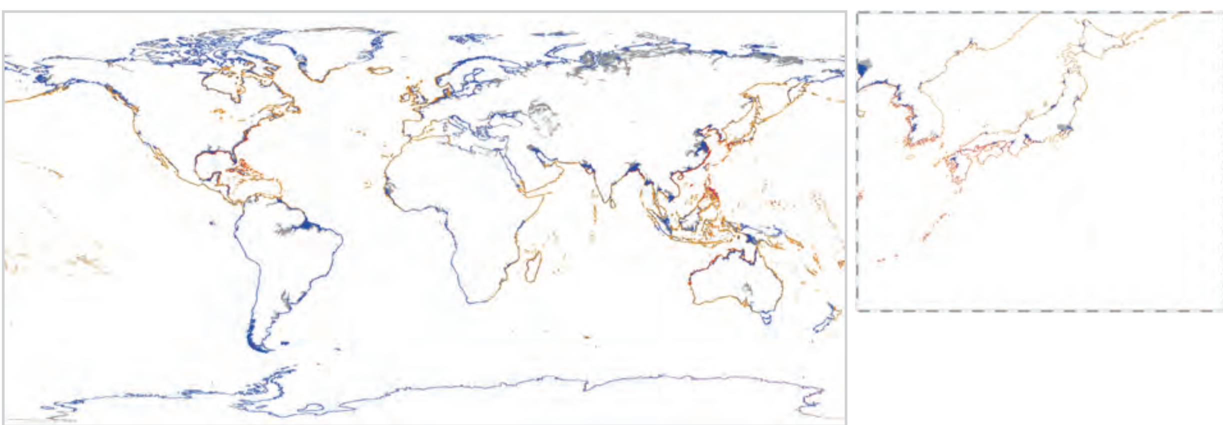


Figure 3. Global impact assessment on disasters of storm surges and sea level rise.

# Near-Term Climate Prediction (20-30 year prediction)

## Near-term climate prediction using a high-resolution coupled ocean-atmosphere general circulation model

### Objectives

According to the future climate projection by the fourth assessment report (AR4) of IPCC, global warming will continue for at least several decades even if anthropogenic greenhouse gases (GHGs, e.g. $CO_2$) emission will be restricted in future. Therefore, it is necessary to predict the climate change during coming decades more precisely with quantitative prediction errors caused by the model uncertainties, and to investigate environmental impacts by the climate change.

The aim of this subject is to build a state-of-the-art high-resolution atmosphere-ocean coupled general circulation model and to predict an anthropogenic climate change up to around year 2030 using the Earth Simulator. In this climate model, not only GHGs but also many climate change factors such as all kinds of aerosols are taken into account. Developing an initialization method for the model to take into account the observed climate variability during the last few decades and an ensemble prediction scheme, the near-term climate prediction including possible changes in extreme weather and water disaster risks will be presented.

The prediction products accompanied by uncertainty estimation will be provided to world-wide impact assessment groups and other interested parties, hoping to contribute to better adaptation strategies.

### Advancing climate modeling

In this subject, we conduct near-term climate prediction experiments focused on the climate change induced by anthropogenic and natural climate variability using an atmosphere-ocean coupled climate model named MIROC (Model for Interdisciplinary Research on Climate), cooperatively developed by Center for Climate System Research (CCSR; reorganized as Atmosphere and Ocean Research Institute (AORI) in April 2010), the University of Tokyo; National Institute for Environmental Studies (NIES); and Japan Agency for Marine-Earth Science and Technology (JAMSTEC). We have finished building a new high-resolution climate model, MIROC4, and a new medium-resolution model MIROC5. MIROC4 has been developed based on the former MIROC3 physics and adopted higher resolution (the atmophere's horizontal grid spacing is about 60km). MIROC5's horizontal grid spacing is about 150km, but most of the model components such as radiation, cloud, boundary layer, ocean, and sea ice, has been replaced by newly developed schemes. Using these new models, we will conduct high- and medium-resolution near-term climate prediction experiments. The high-resolution outputs of MIROC4 should benefit environmental impact assessments while MIROC5 will be used to conduct many experiments to explore the science of near-term climate prediction taking advantage of the relative economy in computation.

The new models show much improved reproducibility, not only of climatological-mean fields but also of natural variabilities which play key roles in the near-term prediction. For example, the El Nino events and associated atmospheric and oceanic anomalies are shown in Figure 1. The amplitude of El Nino events, which was very weak in the previous version of the model, becomes more realistic, and associated upper-ocean thermocline variability, global sea surface temperature, and atmospheric circulation anomalies also show more realistic distributions in the new models.

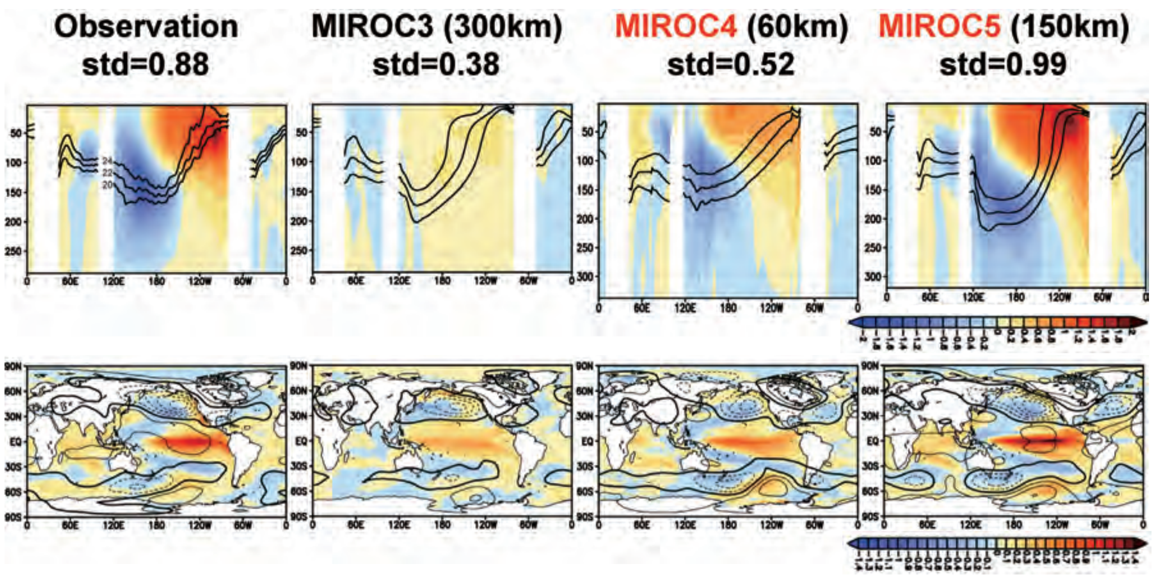



Figure 1. Ocean temperature and atmospheric circulation associated with El Nino events by observations, the previous model (MIROC3), and the new models (MIROC4 and MIROC5). "std" means the standard deviation (amplitude) of sea surface temperature over the monitoring area in the tropical eastern Pacific. The amplitude of the El Nino events becomes more realistic in the new models.
(upper) Longitude-depth cross sections of the tropical ocean temperature anomalies associated with El Nino events (color shades). Black contours show the climatological-mean ocean thermocline. Zonally distributed temperature anomalies along the thermocline are reproduced in the new models.
(lower) Same as upper panels but for the sea surface temperature (color shades) and the height of 500hPa isobaric surface (contours). The ocean temperature anomalies not only in the tropical eastern Pacific but also in the Indian Ocean and eastern Asia region are reproduced better in the new models. For the 500hPa isobaric surface anomalies, the teleconnection effect from the North Pacific to the North America and the Southern Hemisphere also become more realistic.

## Quantification and reduction of uncertainty

For a near-term climate prediction, a scenario of greenhouse gases' concentration and aerosols' distribution in future are required. In addition, the prediction must be started from an initial condition, which is based on observations including decadal natural climate variabilities in order to reduce prediction uncertainties. We implemented a data assimilation scheme for the upper ocean temperature and salinity to the medium-resolution setup of the previous model MIROC3 (horizontal grid spacing is about 300km), conducted climate hindcast experiments. By these experiments, it has been shown for the first time that the Pacific decadal oscillation (PDO), which is the well-known climate variability over the North Pacific region, has predictability of five to six years. Furthermore, we found predictability of a few years, well beyond the usual seasonal time scales, in the precipitation over Brazil associated with a mode of sea surface temperature variability over the tropical Atlantic. We have developed a method to correct historical observational data errors in the ocean temperature and salinity, which are used for the data assimilation and initialization, and a method to produce ensembles that are efficient to reduce prediction uncertainties in the high-resolution climate model. Currently, we are conducting a variety of experiments for the IPCC AR5, using the new models.

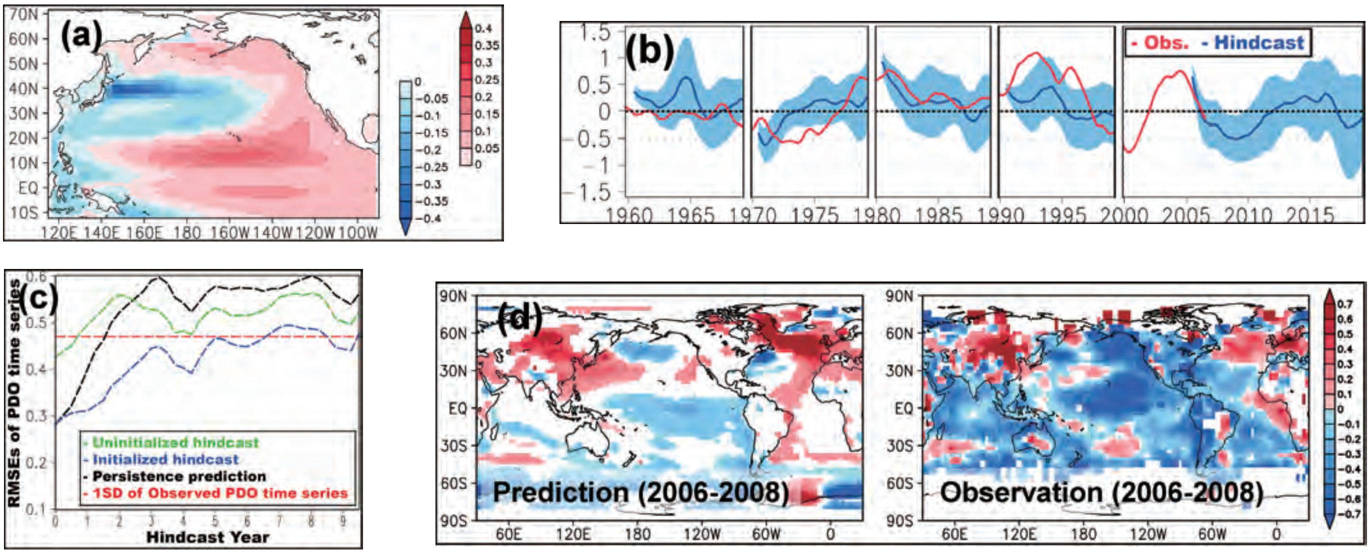



Figure 2.

(a) Pattern of principal mode of variability in the North Pacific VAT300 (vertically averaged ocean-temperature upper 300m depth) deviations from the externally forced variation that is defined using the uninitialized simulations during 1958-2017. (°C) This pattern represents the PDO.

(b) Time series obtained by projecting VAT300 deviations of the observation and the hindcast experiments started from July 1st of 1960, 1970, 1980, 1990 and 2005 on the pattern in panel (a). Red lines are 5-year-running means of the observation. Blue lines and shades represent annual means of ensemble averages and ranges of one standard deviation (SD) of 10-member ensemble experiments, respectively. Plotted values are normalized using the SD of the observations.

(c) Root mean square errorss of the 5-year-mean VAT300 deviations projected onto the PDO pattern in (a). Blue, green and black lines represent the errors in the ensemble-mean states of the initialized hindcasts, the uninitialized hindcasts and the persistence predictions, respectively. Red line represents 1 SD of the observed PDO time series.

(d) The hindcasted (left) and observed (right) ensemble means of 3-year-mean (i.e., during 2006-2008) surface-air-temperature deviations from the externally forced variation. Shaded regins are the significant areas at 90% confidence levels.

## Application of regional projections to natural disasters

Figure 3 shows an estimation of population under flood risk during the 21st century. The actual flood-affected population in the past record taken from the International Emergency Disaster Database (blue line), the flood-affected population derived from climate model outputs of MIROC (solid black line, population under floods with probability of less than once in 50-year in the 20th century), and the output of a Monte Carlo simulation* (shading). Dark shading indicates 95% of the Monte Carlo results. Light shading shows the top and bottom of the Monte Carlo results. Estimation of damages associated with such floods is also under investigation.

* Monte Carlo simulation: A simulation using random numbers. In the present case, the number of cells with floods of once in 50 years or less frequent was counted using the climate model. Then the cell locations were randomly shuffled and the affected population was calculated. This random procedure was repeated 1000 times. The Monte Carlo simulation can represent various hypothetical cases, such as cases in which floods mostly occur in highly populated areas, and cases in which floods mostly occur in less populated areas.

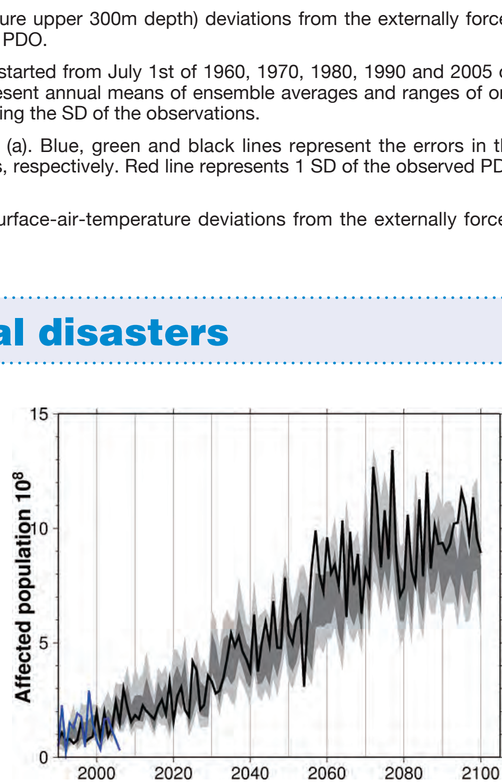



Figure 3. Population under flood risk during the 21st century

# Projection of the change in future weather extremes using super-high-resolution atmospheric models

## Objectives

Using atmospheric models of unprecedented super-high-resolution for global warming projection, we will perform accurate and quantitative climate projection for extreme events which would increase by global warming.With 20-km mesh atmospheric global model (the 20-km model), changes in the number and intensity of tropical cyclones such as typhoon, and changes in the precipitation intensity during Japanese rainy season (Baiu) will be projected. With 5-km, 2-km and 1-km mesh regional model over Japan, changes in heavy precipitation in Japan will be projected. The uncertainty of the projected changes in typhoon and Baiu will be evaluated, quantified and reduced through the multiple simulations of 60-km mesh atmospheric global model (the 60-km model). Using data computed from the model projections, environmental changes that may lead to disasters such as landslides, debris flow, floods, storm surges, and strong winds will be evaluated for Japan. Moreover, flood risk assessment will be extended to a global scale including highly vulnerable regions.

## Advancing climate modeling : Changes in tropical cyclone

A high-horizontal-resolution model is vital to project reliable and possible future changes in tropical-cyclone intensity. The 20-km model is the highest among that of the state-of-the-art global climate models in the world, leading to accurate future projections of tropical-cylone intensity. Figure 1 shows tropical-cyclone mean structures of precipitation and surface wind velocity projected by the 20-km model when tropical cyclones are at their maximum surface wind velocity. For both cases of precipitation and surface wind velocity fields, marked future increases appear at innter-core region within 150 km from the tropical cyclone center, implying increase in disaster risk induced by tropical cyclones in the future.

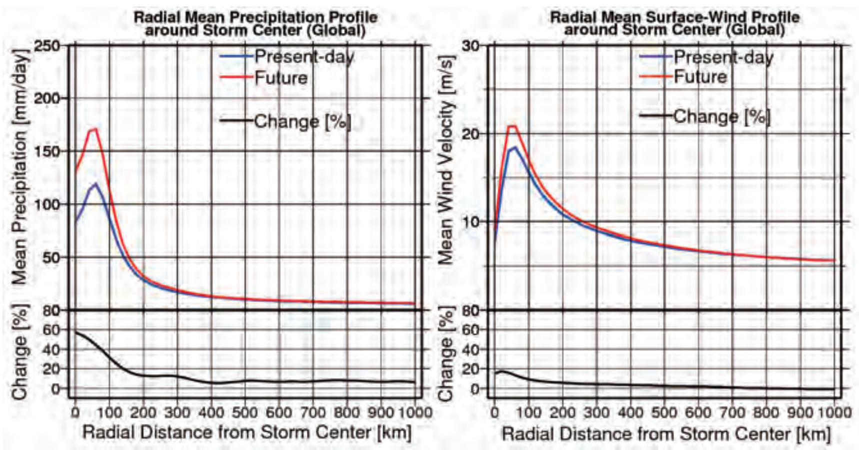



Figure1. Azimuthal mean of precipitation (left, mm/day) and surface-wind velocity (right, m/s) distributions for tropical cyclones at their maximum intensity. The blue lines show the present-day simulations (1979-2003), whereas red lines show future simulations (2075-2099). The black lines show ratio of future change to the present-day value (%).

## Quantification and reduction of uncertainty : Changes in the precipitation intensity

Uncertainty of projection was evaluated by multiple simulations the of 60-km mesh model, because the simulation with the 20-km model is restricted to one case due to the limitation of computer resources. Four different geographical distributions of sea surface temperature (SST) were given to the model, since atmospheric model is strongly influenced by SST. Three different atmospheric initial conditions are also used for each SST simulations so that the total ensemble size is 12. Figure 2 shows the change in heavy rain days for Baiu season. The 20-km model projects slight increase in heavy rain days over Japan. The 60-km model projects increase in heavy rain days almost all over Ease Asia including Japan. Especially, over the southern part of China, increase in heavy rain days is remarkable with both 20-km model and 60-km model, which suggests high reliability of projection over this region.

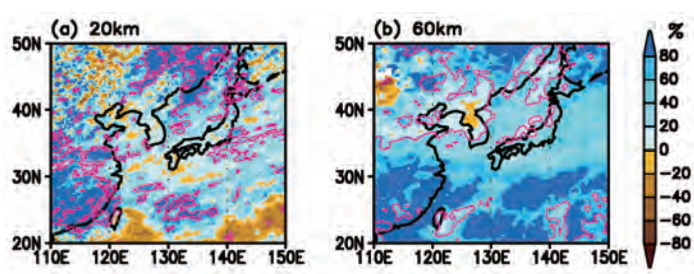



Figure 2. Changes in the number of heavy rain days (precipitation = 30 mm) for Baiu season (June to July). Changes from present-day simulations (1979-2003) to future simulations (2075-2099) relative to present simulation are shown in %. Red contour show 95% significance level. (a) 20-km model. (b) 60-km model.

## Application of regional projections to natural disasters 1 : Flood risk assessment in Japan

The magnitudes of the 100-year flood for the near future and the end of the 21st century were estimated using a 1-km spatial resolution distributed hydrologic model with the input of the climate projections computed by the 20-km model. The left panel of Figure 3 shows the ratio of the magnitude of the 100-year flood between the near future and the present-day simulations; and the right panel of Figure 3 shows the ratio between the end of the end of the 21st century and the present-day simulations. The magnitude of flood increases for the near future in the Hokkaido, the northern Tohoku, the Chugoku-Shikoku, and the northern Kyushu regions. However, it decreases at the southern Tohoku and the northern Shin-Etsu regions where flood is caused by snow melting. This tendency is intensified for the end of the 21st century.

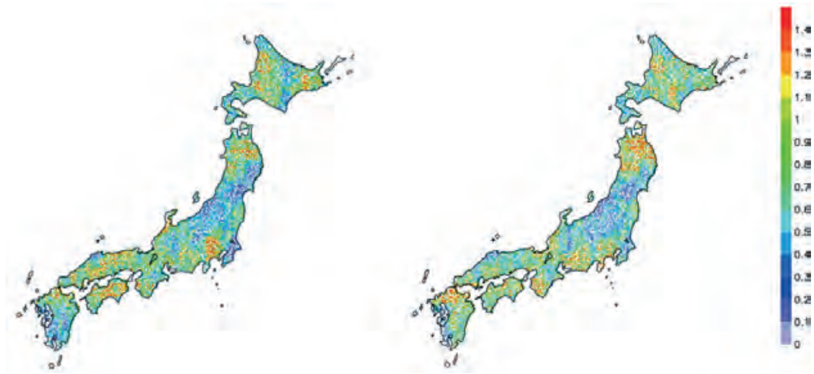


Figure 3. Left: Ratio of the magnitude of the 100-year flood between the near future simulations (2015-2039) and the present-day simulations (1979-2004). Right: Ratio between the end of the 21st century simulations (2075-2099) and the present-day simulations.

## Application of regional projections to natural disasters 2 : changes in future flood risk over the globe and specific vulnerable areas

Based on the 20-km model output, we applied a hydrological simulation system to various basins over the world to evaluate future changes in extreme floods. Figure 4 compares the change ratios between the near future and the end of 21st century for all the grids in future extreme daily discharge (50-year return period). The comparison found that the trend would vary in intense from location to location. It also found most of the regions in the world would generally show an increasing trend in the end of 21st century simulations although the trend would fluctuate in the near future simulations. The results are just an example. However, it is quite important to translate results from state-of-the-art climate change impact studies to basin-scale phenomenon by using systems applicable to basins throughout the world for detailed assessment of future extreme floods and hydrological conditions regardless of locations and basin scales.

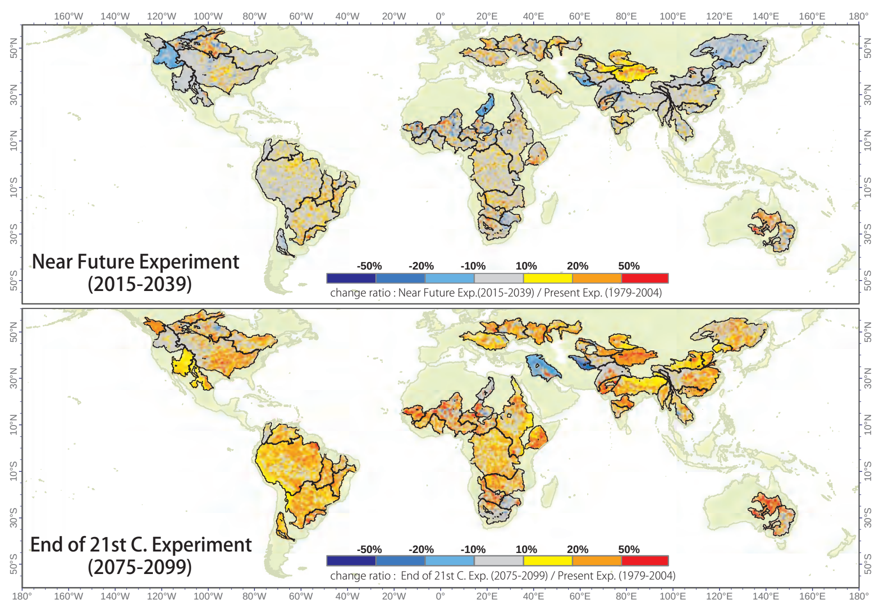



Figure 4. Change ratio of extreme flood discharge (yearly maximum daily discharge, 50-year return period). The area of river basins are equal to or larger than 300,000 km$^2$. Top: Ratio of near future simualtions (2015-2039) to present-day simulations (1979-2004). Bottom: Ratio of the end of 21st century simualtions (2075-2099) to the present-day simualtions (1979-2004).

# Improvement of the cloud resolving model and cooperation with a global model

## Objectives

Cloud physics is one of the key processes in modeling climate change, especially for global warming. The improvement of cloud processes is necessary for accurate simulations. Cloud processes are also core processes in simulations of high-impact weather systems such as heavy rainfalls and typhoons. The cloud modeling team has been developing a cloud-resolving model named the Cloud Resolving Storm Simulator (CReSS). The cloud microphysics and computation scheme of CReSS are improved for accurate and high-speed calculation. Convective clouds in the tropical region and typhoons are important objectives of our team. The CReSS model is also coupled with global models to simulate convective regions. CReSS is used for typhoon research with aims to help verify typhoon simulations made by global models and to produce accurate and quantitative evaluations of typhoon effects on human society under the current and warming climates.

## Cloud modeling and typhoon research

Typhoons occasionally cause a severe disaster owing to heavy rainfall and strong wind. On the other hand, they bring a large amount of water resources to the East Asian countries. Change of typhoon with the global warming, therefore, has a large impact on the human society. Since typhoons are composed of intense convective clouds as well as associated stratiform clouds, cloud-resolving simulation is necessary for accurate prediction of their intensity. In the present study, we have developed a new technique to perform a parallel computation of the cloud-resolving model in an arbitrary-shaped region, which is named the “Tiling Domain Technique”* for CReSS. Using the technique, a simulation experiment with a computation domain along the typhoon track was performed. Figure compares the simulation result at 312 hours from the initial time (09 JST August 25, 2004) with the radar observation provided by JMA (the Japan Meteorological Agency). The position of the typhoon center, eye wall, surrounding spiral rainband and orographically enhanced heavy rainfall are correctly simulated. The simulation shows the sea level pressure at the typhoon center also corresponds to the observation. The result shows that the cloud resolving simulation enable us to predict quantitatively the intensity of typhoon. In the collaboration with the other team of the KAKUSHIN program, our team performed simulation experiments of typhoon in the global warming climate and found that very intense typhoons which never occurred in the current climate will occur in the future climate.

* Tiling Domain Technique for the CReSS model:
An arbitrary-shaped domain is often suitable for efficient computation of simulation. The technique enables us to carry out parallel computation in the arbitrary-shaped domain using many small rectangular domains named “domain tiles”.

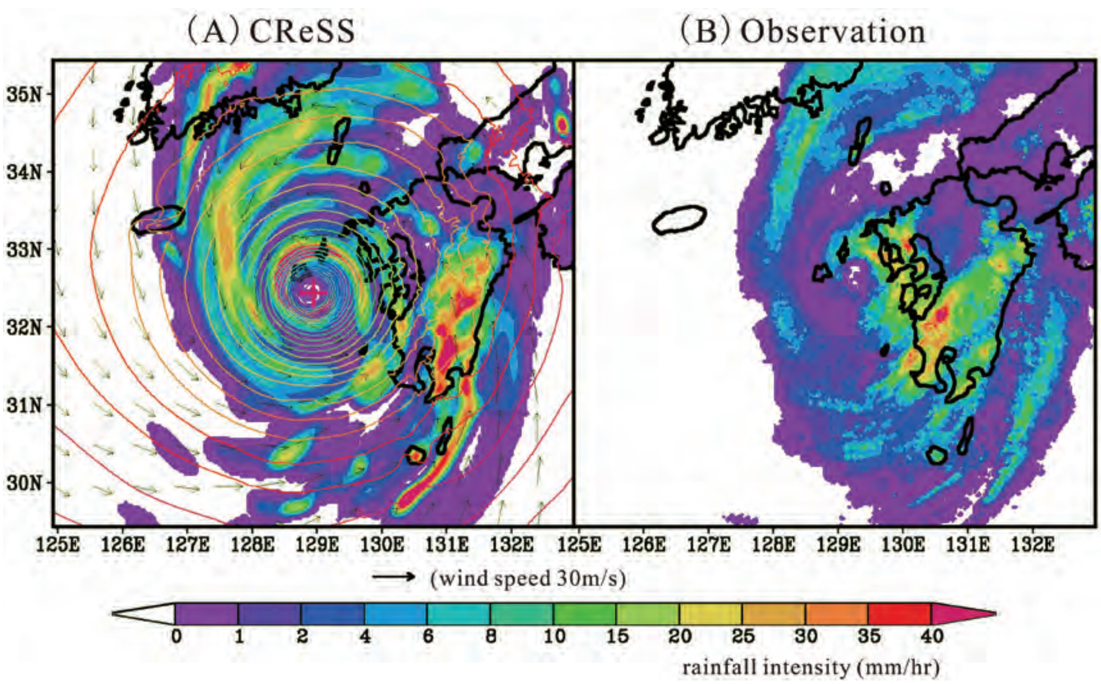



Figure: (A) Simulation result of typhoon No.18 of 2004 using CReSS with the Tiling Domain Technique at 312 hours from the initial time (09 JST August 25, 2004). Color levels are rainfall intensity (mm $hr^{-1}$), contours are sea level pressure and arrows are horizontal velocity. (B) JMA radar observation at the same time of (A). Color levels are rainfall intensity (mm $hr^{-1}$).

# High-precision parameterization of marine microphysics using Large Eddy Simulation (LES)

## Objectives

Sub-grid scale ocean processes in the upper ocean (Figure 1) with scales up to a few meters play a crucial role in determining sea surface temperature, thus controlling air-sea interactions leading to climate changes. Accurate parameterization of sub-grid scale ocean processes therefore must be incorporated into coupled atmosphere-ocean general circulation models.

The final goal of the present study is to improve the parameterization of sub-grid scale ocean processes based on the results of a fully three-dimensional Large Eddy Simulation (LES)*. The improved parameterization scheme will be incorporated into coupled atmosphere-ocean general circulation models to project the interannual variability of the global climate system. By resolving the uncertainty associated with the ambiguity of the existing parameterization schemes, we can expect significant improvement in the ability to predict future climate changes.

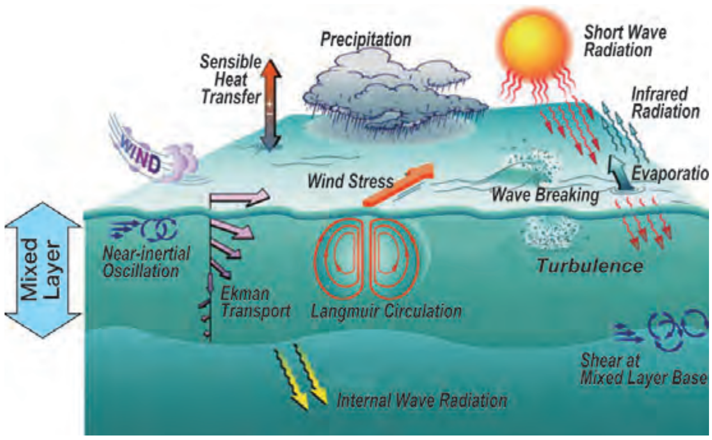



Figure 1. A schematic depiction of the physical processes near the air-sea interface (http://hpl.umces.edu/ocean/).

* LES (Large Eddy Simulation):
Large Eddy Simulation is a numerical technique used to simulate turbulent flows. In LES, the large-scale motions of the flow are explicitly calculated, while the effects of the smaller universal scales (so-called sub-grid scales) are modeled using a physical model. For this reason, LES requires less computational resources than the technique called Direct Numerical Simulation (DNS). While LES has been widely used in the fields of meteorology and engineering since the late of 1960s, it is only about 10 years since the first application to the ocean mixed layer.

## Mixed layer response to typhoons demonstrated by LES

As an example of our calculations, the response of the ocean mixed layer to extremely strong wind forcing such as travelling typhoons is demonstrated in Figure 2a. The LES model clearly demonstrates turbulent mixing of relatively warm surface water and colder thermocline water followed by expansion of the thermocline as well as a decrease of the sea surface temperature.

The upper ocean response calculated using the mixed layer model with the existing parameterization scheme is compared with that obtained using the LES model (Figure 2b,c). We can see that the expansion of the thermocline and the decrease of the sea surface temperature for the former are much smaller than those obtained using the LES model. Figure 2d shows, however, that a slight modification of the existing parameterization scheme in the mixed layer model can produce results comparable to those from the LES model.

In the near future, further LES studies taking into account a wide variety of ocean environments are necessary to improve the existing ocean mixed layer models. A detailed assessment of the coupled atmosphere-ocean general circulation models incorporating the improved mixed layer model is also necessary.

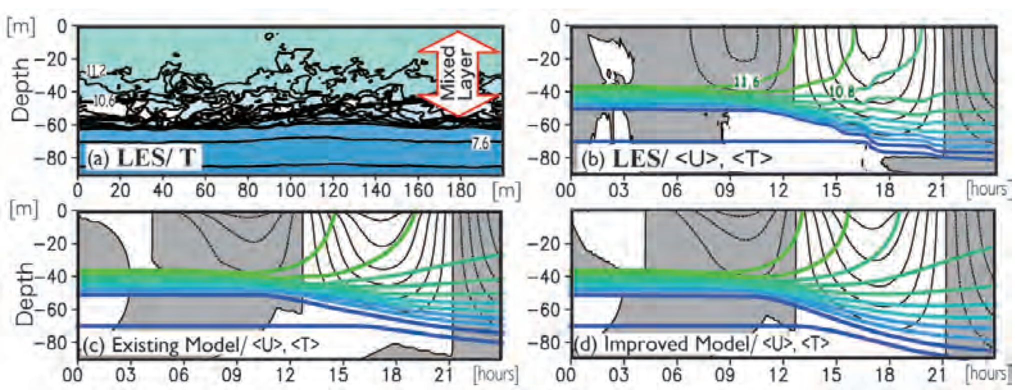



Figure 2. (a) A sample snapshot of the vertical cross section of temperature field simulated by the LES model (contour interval is 0.3 °C). (b-d) The calculated results from ocean mixed layer models incorporating several turbulence parameterizations are compared with the results using the LES model. The blue and green contours denote the temperature (contour interval is 0.4 °C), while black contours denote velocity fields (contour interval is 0.2 m/s), respectively.

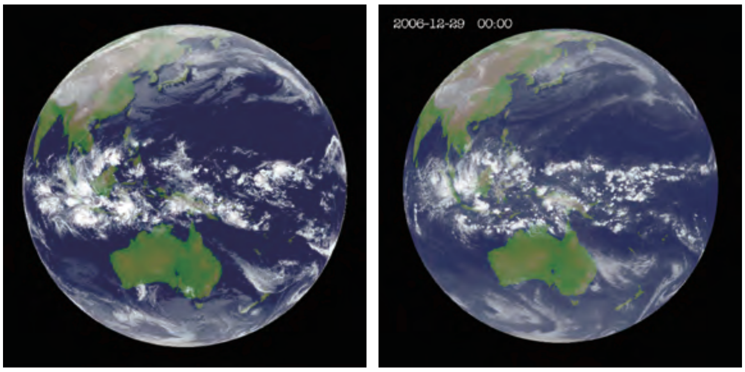
# Emerging New Achievement of Tropical Cloud Simulation

Tropical clouds are one of the important elements in the global environmental system. They drive the global atmospheric circulation and affect the global climate condition. They form a multi-scale structure such as individual cumulus, cloud clusters, and monsoon circulations. Tropical cyclones, which cause serious disasters over the world, are generated from organized tropical cloud systems. Tropical clouds also directly affect weather in Japan by heavy rainfalls especially in the boreal summer season.

The existing climate models cannot directly resolve tropical clouds, since their resolution is about 100km, much coarser than the scale of cumulus convection, 10km. Instead, a semi-empirical method called “cumulus parameterization” is used in climate models to represent tropical convective systems. However, it is known that the use of cumulus parameterization is one of the major causes of the ambiguity of climate models. To overcome this difficulty, we developed a **global cloud-resolving model**, called **NICAM**, which can be run with a mesh size about a few kilometers. This new model directly resolves tropical convective systems without using cumulus parameterizations.

NICAM enables us to represent tropical clouds almost comparable to cloud images by geo-stationary meteorological satellites. As shown by the figure, NICAM captures the multi-scale structure of tropical clouds associated with the Madden-Julian Oscillation, whose realistic simulation has been difficult by the present climate models. NICAM also reproduces the tropical cyclogenesis in the realistic timing and at the precise location in this case.

We expect that NICAM will contribute to more reliable projections of future global warming. NICAM will clarify problems in current climate models and will help reductions of the uncertainties in simulations of tropical clouds. Especially, NICAM will promote studies of future changes in tropical cyclones.



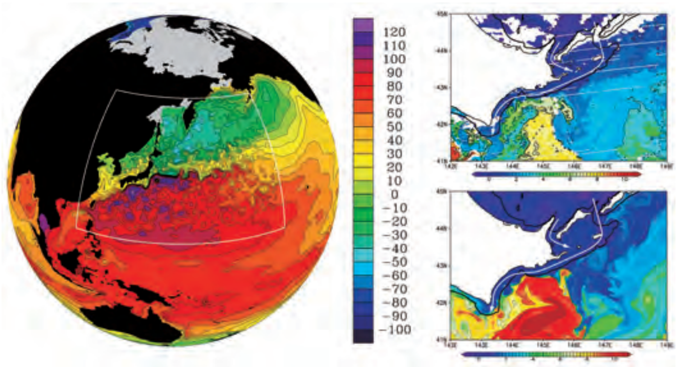
Left: The satellite cloud image from Himawari-6 (MTSAT-1R). Right: NICAM/global cloud-resolving model. Source: (c)JAMSTEC

# Sophistication of Ocean Model in Climate Change Projection

It is unquestionable that the ocean plays an important role in forming mean state and variability of the climate. However, conventional climate models do not adequately represent some climatically important structures of the ocean, such as strong currents and mode waters, which induces uncertainty in climate change projection. A simple solution to most of such problems is to raise horizontal resolution of ocean models up to several kilometers, but it is not feasible, even with expected advances in computational resources over the coming decade, to globally apply such high resolution in the context of climate change projection. This study is aiming at developing a sophisticated global ocean model by combining special high resolution for some selected key regions and sub-grid scale parameterization for other regions. It is also intended to show the impact of such a sophisticated ocean model when it is applied to climate modeling.

In the model being developed, new parameterizations have improved reproducibility of various aspects of mean oceanic structures globally, and both mean structures and variability have significantly been improved in the region around Japan which is selected as the key region for special high resolution. As for the Kuroshio which flows eastward from the southern coast of Japan, for example, not only its mean flow path and transport but also its variability are quite realistically reproduced, such as generation and extinction of large meandering and eddy activities. There also are many other phenomena which are not adequately represented by conventional climate models but are realistically simulated by the newly developed model, such as mode waters which are important in decadal climate variability, and the Oyashio which is important for the fishing environment around Japan and the Pacific intermediate water.

The model developed by this study is surely to contribute to better skill of climate change projection by next generation climate models. It is also expected to become a useful tool to assess impacts of climate change on coastal environment and fishery resources. Such an application would require further high resolution of ocean models for targeted regions. The model will satisfy such requirements under the expected advances of computational resources.



Left: Sea level (whose contours correspond to streamlines of surface currents) simulated by an ocean model with special high resolution around Japan (the region bounded by the white lines). Right: (upper) Satellite-observed and (lower) model-simulated sea surface temperature. The white arrows indicate the path of the low-temperature coastal Oyashio.

# General Description of Major Models

Under the Innovative Program of Climate Change Projection for the 21st Century, climate change models already developed under the Kyo-sei Project are further sophisticated for climate change projections with higher precision and resolution, so that their outcomes would contribute to the Fifth Assessment of the IPCC and climate change impact assessment studies.

Modeling efforts in each team proceed along its respective objective as follows.

| Team Name | Principal Objective | Model Specification | Resolution | | Characteristic Feature | Major Institute Involved |
|---|---|---|---|---|---|---|
| | | | Atmosphere | Ocean | | |
| 1 Long-term | Projection up to 300 years for the basis of options of stabilization targets in Post-Kyoto issues | Integrated Earth system model (covering atmosphere, carbon cycle, land surface, chemistry and ocean) | 280km | 100km | Focused on global climate change; changes in carbon cycle and displacement of vegetation zone are also taken into consideration | JAMSTEC<br>NIES<br>AORI, the University of Tokyo |
| 1 Long-term | Proper simulation of tropical meteorology by directly resolving convective clouds (unique in the world) | Global cloud resolving model (atmosphere-land surface model with given SST) | 14km [7km] | — | Global cloud resolving model (NICAM), original and unique in the world | JAMSTEC<br>AORI, the University of Tokyo |
| 2 Near-term | Near-term detail projection up to 2030 (irrelevant to scenario) | High resolution coupled atmosphere-ocean model (covering atmosphere, land surface and ocean) | 50km | 20km | Projecting changes in sea currents such as Kuroshio; detail geographic differences such as those between Kanto area and Tohoku area in Japan | AORI, the University of Tokyo<br>NIES<br>JAMSTEC |
| 3 Extreme Events | Projection of extreme weather events (typhoons, heavy precipitation, etc. in the near-term future and at the end of the 21st century) | Super-high resolution atmospheric model (atmosphere and land surface model with given SST) | 20km | — | Typhoons, Baiu-fronts, heavy precipitation, etc. are to be simulated with considerable precision | MRI/JMA<br>JAMSTEC |
| 3 Extreme Events | | Dynamic downscaling from the above (limited area model) | 5km [2km&1km] | | | |
| (Reference) Atmosphere-ocean coupled models developed and/or used in Kyo-sei Project | | | 110-280km | 20-140km | | |

(Note) Figures inside [ ] in the column of Resolution show possible resolution cases.

# Updating the Earth Simulator

Since the start of its operation in 2002, the Earth Simulator (ES), a super-computer system installed at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), had been No.1 in the ranking of "the TOP500 list (the list of the 500 most powerful supercomputer systems in the world)" for two and a half years. The Kyosei Project was conducted under the MEXT strategy and funds from FY2002 to FY2006 making the best use of the ES. Outcomes from this project have substantially contributed to the IPCC Fourth Assessment Report.

After 7 years since the launch of the ES, the system was updated in March 2009 to improve its effective performance by more than 2 times. Now, it still maintains practically the highest level performance among supercomputers mainly available for Earth sciences in the world. Further advancement is expected for the research in Earth science fields such as global warming projection.

The *Kakushin Program* has been utilizing the ES and will use the updated new system to further contribute to the IPCC for its Fifth Assessment Report.

Image of the new system started March 2009. Source: JAMSTEC.

**Outline of the new system**
**Type:** vector type processor architecture (shared memory multi-node)
**Peak performance:** 131 teraflops (previous system: 40 teraflops)
**Application sustained performance:** twice of former system (estimation)
**Main memory capacity:** 20 terabytes (previous system: 10 terabytes)

# KAKUSHIN

## Innovative Program of Climate Change Projection for the 21st Century

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