The Reliability of Future Climate Change Projection by High-Resolution Climate Models

Seita EMORI

Frontier Research Center for Global Change
National Institute for Environmental Studies,
16-2 Onagawa, Tsukuba, Ibaraki 305-8506, Japan
Japan Agency for Marine-Earth Science and Technology,
Center for Climate System Research, The University of Tokyo
e-mail: emori@nies.go.jp

Abstract

Recent advancements in the spatial resolution of climate models enable us to provide detailed future climate change scenarios including changes in regional climate and extreme events for impact assessment research. However, impact researchers should be aware that climate models are still burdened with sizable and inherent uncertainty caused by the incompleteness in the representation of physical processes, or “parameterizations.” The prediction of the quantitative amplitude of climate change, such as “climate sensitivity,” remains uncertain because it depends more on physical parameterizations than on resolution. However, some qualitative characteristics of projected climate change, such as geographical patterns, can be regarded as relatively reliable, though they remain at the level of “expert judgment” by climate researchers rather than fact. Criteria for determining the reliable aspects of projections include: a. statistical significance, b. inter-model consistency, c. interpretability, and d. the validity of key processes. It is difficult for impact researchers alone to judge whether these criteria are met by the projected climate change in question for their impact assessments. Therefore, active mutual communication between climate researchers and impact researchers is highly desirable to improve the overall reliability of impact assessment based on the results of high-resolution climate modeling.

Key words: extreme events, high-resolution climate models, impact assessment of climate change, regional climate change, reliability of projection

1. Introduction

Future climate change scenarios produced by climate models have been and, for the foreseeable future, will continue to be the only credible input as the premise for impact assessments of climate change. Hence, the reliability of impact assessments depends largely on the performance of climate models. Climate models are developed at various climate centers in the world and are constantly being improved. The recent advancement of climate models, especially the enhancement of the models’ spatial resolution (the smallest spatial scale that can be resolved by a model) owing to the use of larger computing facilities, enables more advanced, and possibly more reliable, impact assessments. One of the major improvements in recent climate models is a more realistic simulation of extreme events, such as extremely hot days and torrential rain (e.g., Meehl et al., 2000). The analysis of possible future changes in extreme events has also experienced progress. Extreme events are considered to be critical in certain kinds of impact assessments. For example, the impact of heat waves on health and the societal damage of floods can be assessed only by considering extreme events in some way. In this article, I will highlight the advantages of using high-resolution climate modeling in impact assessments, while also bringing up a caution regarding uncertainty issues, which need to be addressed by impact researchers.

2. Recent Advancements in Climate Models

Coupled atmosphere-ocean global climate models (AOGCMs) consist of components such as atmosphere, ocean, land and sea-ice. The atmospheric and oceanic components can each be further divided into two parts; that is, the part that handles the dynamics (dynamical core) and the part that deals with the physics (physical parameterizations). The dynamics part
solves a well-defined physical principle, i.e., a set of fluid dynamic equations. The physics part is an assortment of treatments of various physical processes that cannot be represented by the dynamics part, such as radiation, cloud and sub-grid scale mixing. When the spatial resolution of a model is increased, the performance of the dynamics part is invariably improved, while the physics part is not necessarily enhanced. This is because the physics part is not purely based on physical principles and includes empirical assumptions and approximations (i.e., parameterizations). Improvement of the physics part is done by improving the equations through consideration of more realistic processes taking place in nature.

In recent years, since the IPCC Third Assessment Report (TAR) (IPCC, 2001), considerable efforts have been made to improve the climate models used in various climate centers in the world. Improvements in physics include more realistic parameterizations for radiation, clouds, convection, boundary-layer, ocean mixing and so on, and more realistic interactions among them (e.g., GAMDT, 2004). Some climate models also incorporate an on-line aerosols module and its interaction with cloud and radiation (e.g., Takemura et al., 2005), which is a completely new feature since TAR.

As for the resolution, all AOGCMs at the time of TAR had horizontal resolutions of approximately 300 km or coarser for the atmosphere and approximately 100 km or coarser for the ocean. Recently, however, the ‘Earth Simulator,’ one of the world’s largest computing facilities developed in Japan, dramatically enhanced the computing power that can be used for climate modeling. It enabled a Japanese AOGCM (the ‘MIROC’ model developed by CCSR/NIES/FRGC) to run at the resolution of approximately 100 km for the atmosphere and approximately 20 km for the ocean (K-1 Model Developers, 2004). A global 20 km-mesh atmosphere-only model developed by MRI/JMA has also been running on the Earth Simulator (Mizuta et al., 2006). These high-resolution climate models running on the Earth Simulator have significantly enhanced our ability to represent regional characteristics and relatively small-scale phenomena (such as tropical cyclones, especially for the 20km-mesh atmospheric model (Oouchi et al., 2006)).

3. Uncertainty in Climate Change Projections

However, one should be conscious of general uncertainty issues in climate change projections. Any climate model is inherently incomplete mainly because of the incompleteness of the parameterizations of various physical processes. As mentioned above, the parameterizations do not necessarily improve due to enhancement in resolution. Hence, no matter how high a climate model’s resolution becomes, you cannot naively expect that the uncertainty in climate change scenarios projected by the model will be reduced accordingly.

One major long-standing issue is the uncertainty in the overall amplitude of the change, known as the ‘climate sensitivity’ issue. The climate sensitivity defined by the global mean surface air temperature change in response to a doubling of atmospheric carbon dioxide concentrations is different for different models, ranging from approximately 1.5°C to 4.5°C (an even wider range is suggested in some recent studies (e.g., Stainforth et al., 2005)). Note that a higher-resolution model does not necessarily give a more reliable estimate of climate sensitivity, since the climate sensitivity of a model is largely dependent on physical parameterizations.

However, some of the qualitative aspects of the projected changes, such as the spatial pattern of changes, are considered to be more reliable. Some criteria for a relatively reliable projection, though they remain subjective ‘expert judgments’ rather than fact, can be proposed as follows:

a. The climate change signal is distinguishable from natural variability (statistical significance),

b. The change is found in many different models (inter-model consistency),

c. The physical interpretation of the change is clear and reasonable (interpretability),

d. The key processes to the change are realistically represented in the model and well validated against observational data in the current climate (validity of key processes).

Still another point may be added for some cases.

e. A signal similar to the projected change is found in recent observed record (consistency with observation).

Note that a special care is needed in applying this last criterion because an observed trend may be a part of natural variability and not necessarily indicative of climate change.

Generally, larger-scale spatial patterns of the change can meet these criteria more easily. For example, the well-known patterns in TAR (IPCC, 2001), including greater continental warming than over the sea, greater warming over northern higher latitudes, and an increase in precipitation over high latitudes, can easily be found to meet the criteria in a-d (or a-e). On the other hand, regional changes and the changes in extreme events are generally less likely to meet these criteria. Therefore, we must be especially careful about the uncertainty issue when discussing these detailed changes.

4. Future Climate Change Projection by a High-resolution Model

Some recent work based mainly on the MIROC model results (~100 km atmosphere and ~20 km ocean resolution) is shown here as an example of future climate change projection with a high-
resolution climate model and the related discussion on uncertainty.

4.1 Validation of extreme daily precipitation

Before talking about future projections, I will demonstrate the relationship between the validity of the processes (criterion d) and the model’s spatial resolution. Figure 1 shows the resolution dependence of the simulation of daily precipitation intensity (Kimoto et al., 2005). The frequency of daily precipitation greater than 50 mm/day, as an index of extreme precipitation, simulated by the high-resolution MIROC model (~100 km atmosphere) compares well with a satellite estimate (GPCP (Huffman et al., 2001)), while a lower-resolution version of the same model (~300 km atmosphere) seriously underestimates the frequency of heavy rain events.

Figure 2, on the other hand, shows the physics dependence of the simulation of daily precipitation intensity (Emori et al., 2005). The 99th percentile daily precipitation (approximately the 4th largest event in a year), as another index of extreme precipitation, simulated by the high-resolution MIROC model (precisely, its atmospheric part driven by observed sea surface temperature) compares well with the GPCP satellite estimate. However, the same model at the same resolution (~100 km) seriously fails to simulate heavy rainfall events over low latitudes, if one critical parameter in the convection parameterization is set to a different value, while the mean climate values of the two models are quite similar (figure not shown).

These two results clearly demonstrate that high resolution is a necessary but not sufficient condition for the realistic simulation of extreme precipitation, as it is also strongly dependent on parameterization.

![Fig. 1](image1.png)

*Fig. 1* Frequency of daily precipitation greater than 50 mm/day in summer (June-July-August) over and around Japan.

(a) observed (GPCP satellite estimate), (b) simulated by high-resolution model, and (c) simulated by low-resolution model. (Reproduced from Kimoto et al., 2005)

![Fig. 2](image2.png)

*Fig. 2* Intensity of the 99th percentile daily precipitation.

(a) observed (GPCP satellite estimate), (b) simulated by the atmospheric part of the MIROC model, and (c) simulated by the same model at the same resolution but with the ‘cumulus suppression parameter’ set to zero (set to 0.8 in (b)). (Reproduced from Emori et al., 2005 with modification)
4.2 Regional climate change over Japan

The next example demonstrates “interpretable” regional climate change (criterion c). Figure 3 shows the pattern of climate change from the late 20th century to the late 21st century, over the East Asian region in the summer (June-July-August) projected by the MIROC model (Kimoto, 2005). The contours, arrows and shades denote the changes in 500 hPa height, 850 hPa wind and precipitation rate, respectively. Increased rainfall in the East Asian monsoon frontal rain belt is projected (blue-colored areas extending from Southeast China to Korea, Japan and further to the east). The changes in pressure pattern causing this increased rainfall are identified as follows. A high-pressure anomaly located to the northeast of the Philippines, which is likely caused by El Niño-like tropical Pacific warming, provides moist air to the rain belt. Moreover, another high-pressure anomaly over eastern Siberia and the Sea of Okhotsk, caused by enhanced continental warming, tends to hinder the northward migration of the rain belt (Kimoto, 2005). The El Niño-like warming and the enhanced continental warming are relatively reliable large-scale features, as they are commonly found in many different modeling results (criterion b). Hence, the regional climate change pattern derived from them is also considered to be relatively reliable.

Incidentally, this result suggests that the pressure pattern in the future climate over Japan is more like that in anomalous cool summers (like in 1993 or 2003). However, this does not mean that the summer will be cooler over Japan in the future climate, as the air, continent and sea surface around Japan will be warmed. Figure 4(a) shows the number of ‘tropical days’ for Japan (a day with maximum surface air temperature higher than 30°C in any grid box of Japan) simulated in the MIROC model, which indicates a striking increase in extremely hot days during the 21st century. Figure 4(b) shows the number of ‘torrential rain days’ (days with precipitation in summer greater than 100 mm in any grid box of Japan) for Japan in the summer, which indicates a significant increase in torrential rain frequency in the late 21st century, though the inter-annual variability is large. Note that the magnitude of the changes seen in Fig. 4 is quite uncertain, though the qualitative tendencies are probably robust.

4.3 Future projection of mean and extreme precipitation

The next example is given to try to interpret the projection of changes in extreme events. The geographical pattern of projected change in annual mean precipitation is shown in Fig. 5(a), while that in extreme (99th percentile) precipitation is shown in Fig. 6(a) (Emori & Brown, 2005). These are multi-model en-
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semble averages (including the MIROC model), as similar patterns are obtained from all the model results that have been examined. The change in the mean shows general increases over the tropics and mid to high latitudes and decreases over some subtropical regions, a pattern commonly seen in previous studies (IPCC, 2001). The change in the extreme is basically similar to that in the mean. However, there are some areas mainly in the subtropics where the extreme is projected to increase significantly, while the mean is not.

In general, increased water vapor in a warmer climate is expected to act to increase precipitation. Precipitation will also change due to changes in atmospheric circulation, such as intensity, frequency and track of cyclones. Emori and Brown (2005) called the former ‘thermodynamic change’ and the latter ‘dynamic change,’ and separated the changes in mean and extreme precipitation into these two components. Figures 5(b) and (c) show the dynamic and thermodynamic changes in mean precipitation, respectively, while Figs. 6(b) and (c) show those for extreme precipitation. The distributions of dynamic changes for mean and extreme precipitation are similar to each other, showing an increase over the tropical Pacific and a decrease over the subtropics and almost zero for mid to high latitudes. On the other hand, a clear difference is found in the thermodynamic changes. That is, the thermodynamic change in the mean is almost zero over some areas, mainly in the subtropics, while that in extreme precipitation shows an overall increase. This means that the increase in water vapor does not necessarily increase the mean precipitation, while it does increase the extreme precipitation. Though further work is needed to explain this difference, the investigation of the mechanisms of changes in extremes as demonstrated here is certainly useful to enhance our understanding of projected climate change, leading to the enhanced reliability of the projection.

5. Implication for Impact Assessments

Figure 7 shows an example of advanced impact assessments based on daily data from high-resolution MIROC model results (Hirabayashi et al., 2006).
Figure 7(a) is a future projection of drought risk, defined by the number of days with daily river discharge lower than the 10th percentile, while Fig. 7(b) is a future projection of flood risk, defined by the 100-year return value of daily river discharge. If you were an impact researcher who obtained such results without any information on the corresponding climate change, you would not be able to judge the reliability of these impact assessments. However, if you were given the information in Subsection 4.3 above, you would be able to relate the increased drought risk mainly over the subtropics with a decrease or only a small increase in annual mean precipitation over the region (Fig. 5(a)), together with a general expectation of increased evaporation from the soil in a warmer climate. Similarly, the increased flood risk found mainly over the tropics could be related to the significant increase in extreme precipitation over the region (Fig. 6(a)). In particular, the areas with both increased flood and drought risk roughly correspond to the areas where the extreme precipitation increases but the mean does not. As a result of amalgamating the analysis of climate change results with the data from the impact studies, the resulting impact assessment looks more reasonable. Note that the high-latitude changes in flood risk do not seem to be explained solely by the change in extreme precipitation. Further analysis considering the change in snow processes (e.g., earlier snow melt in a warmer climate) would be needed.

6. Concluding Remarks

High-resolution climate modeling, together with other recent improvements in physics, is undoubtedly beneficial to the impact assessment work of climate change. However, considerable uncertainty still remains and impact researchers must be made aware of this fact. Lack of awareness may result in misleading conclusions in some impact research. In particular, care is needed when using detailed climate change projections such as those for regional climate and extreme events, as it is generally difficult to obtain reliable projections for them compared to large-scale changes. In this paper, my goal was not to discuss the use of high resolution models to predict climate change, but to emphasize that the comprehension and
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interpretation of the results of such predictions plays a crucial role in strengthening the reliability of climate change predictions and, consequently, climate change impact assessment. An understanding of projected climate change as well as other information on uncertainty should be conveyed to impact researchers to improve the overall quality of climate change and impact research. In other words, enhanced communication between climate researchers and impact researchers is highly desirable not only for transferring data, but also for transferring knowledge.

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Notes

1) Center for Climate System Research, the University of Tokyo
2) National Institute for Environmental Studies
3) Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology
4) Meteorological Research Institute, Japan Meteorological Agency

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