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NOTES AND CORRESPONDENCE

An Attempt to Estimate of Probabilistic Regional Climate Analogue in a Warmer Japan

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Abstract

Regional climate projections associated with global warming are of great importance for the development of mitigation and adaptation strategies but are subject to a variety of uncertainties. This study developed a probabilistic strategy to consider every conceivable uncertainty in a climate analogue with the use of a pattern-scaling methodology and bootstrap resampling. The uncertainty of the regional climate model (RCM) simulations, which is associated with the physics and dynamics of the RCMs, is comparable to the uncertainties due to emission scenarios of the greenhouse gases and the transient climate responses of the general circulation model. Comparison of the projections between the probabilistic and deterministic viewpoints demonstrated a benefit of the former method in applications to impact studies.

1. Introduction

Projections of climate changes at the regional scale are of great importance for the assessment of climate change impacts on human society and eco-systems. General circulation models (GCMs) are the most fundamental tool for understanding climate, but their grid spacing is generally too coarse for the examination of regional climate change. Regional climate models (RCMs) complement GCMs by allowing more detailed simulation of regional conditions. A comprehensive description of future climate is a "climate analogue", a region whose present climate is likely to be a reasonable analogue of the future climate of a specific city or region (Parry and Carter 1989; Darwin et al.

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1995; Hallegatte et al. 2007; Kopf et al. 2008). This type of projection is intuitively understandable and can permit a systematic assessment of adaptation requirements. Such a projection should be more useful, for example, than a projection of changes in temperature or precipitation only, especially for impact assessments and adaptation strategies.

Future climate projections are subject to considerable uncertainties (e.g., Giorgi and Francisco 2000). Generally sources of uncertainty in RCM projections include the emission scenario of the greenhouse gases (GHGs), GCM and RCM formulation, and sampling uncertainties. This fact underlies the motivation for use of multi-model ensembles to identify and quantify uncertainties, which provide an estimate of the plausibility of model results and would be of value in the application of simulation results to risk and policy analysis (Tebaldi and Knutti 2007).

Recently, ensemble-based probabilistic climate projections that are often represented by probability density functions (PDFs) have gained popularity not only for short- and medium-term forecasts (Palmer et al. 2000; Richardson 2000) but also for climate change projections (Räisänen and Palmer 2001; Palmer and Räisänen 2002; Giorgi and Mearns 2002; Luo et al. 2005; Dettinger 2005). Probabilistic climate analogues are potentially applicable to a variety of studies of impact and adaptation such as cost-benefit analysis of adaptation options because of their flexible quantification for drawing inferences. They can also provide a probabilistic representation of uncertainty, which is desirable when combining different sources of uncertainty.

Although there is recognition that the sensitivities of climate projections to each source of uncertainty are informative for impact assessment, there has so far been insufficient examination of the uncertainties associated with climate analogue. Uncertainty assessment is difficult because resource limitation makes it impossible to perform simulations for all available GCM-RCM combinations.

The purpose of this study is to develop a probabilistic strategy to consider every conceivable uncertainty in a climate analogue of a warmer Japan with the use of a pattern-scaling method (e.g., Santer et al. 1990; Mitchell et al. 1999; Shiogama et al. 2010) and bootstrap resampling technique, even though there are few available combinations of GCM and RCM. Pattern-scaling, which is described in detail in the next section, can create climate projection scenarios by scaling a spatial response pattern from a GCM (Mitchell 2003) and has been widely accepted especially in impact assessment studies. By incorporating the results of three RCMs nested in one GCM, we use this method to attempt to deal with four kinds of uncertainties: the first associated with the emission scenarios of GHGs and aerosols, the second with the transient climate response (TCR) of the GCM, the third with the physics and dynamics of the RCMs, and the fourth with the constraints associated with sampling from a limited number of years. To examine the dependency of the analogue on each source of uncertainty, we apply this method to a Japanese city.

2. Methods and data

We use dynamically downscaling products generated by three high-resolution RCMs nested in a single GCM (MIROC3.2h; K-1 Model Developers 2004), which we forced with an historical emissions scenario (20C3M, 1981–2000; Nozawa et al. 2005) and SRES A1B future emission scenarios (2081–2100; Nakicenovic et al. 2000). We conducted these experiments as a part of the Environment Research and Technology Development Fund of Ministry of Environment S-5-3 project in Japan. This project uses a single GCM to first provide an intercomparison of multiple RCMs with high spatial resolution around Japan. These RCMs are all non-hydrostatic models with the acronyms NHRCM, NRAMS, and TWRF. Iizumi et al. (2011) and Ishizaki et al. (2011) describe the model configurations, all of which have a grid spacing of 20 km. The RCMs successfully represented the spatial pattern of the temperature of the present climate. Model errors in the monthly surface temperature were no more than -2 to 2°C, which is similar to the range of errors in the simulation driven by JRA-25 reanalysis (Ishizaki et al. 2011). The RCMs show more than a 4°C warming by the end of the 21^{st} century (Fig. 1). The temperature increase is larger over land and high latitudes than over the ocean and low latitudes. There are no obvious differences between rural and urban areas. The model predicted that annual precipitation would increase by 6–19%, whereas winter precipitation would decrease, especially over the coastal region bordering the Japan Sea.

There are several ways to fill a GCM-RCM matrix (e.g., Kendon et al. 2010; Déqué et al. 2011). In

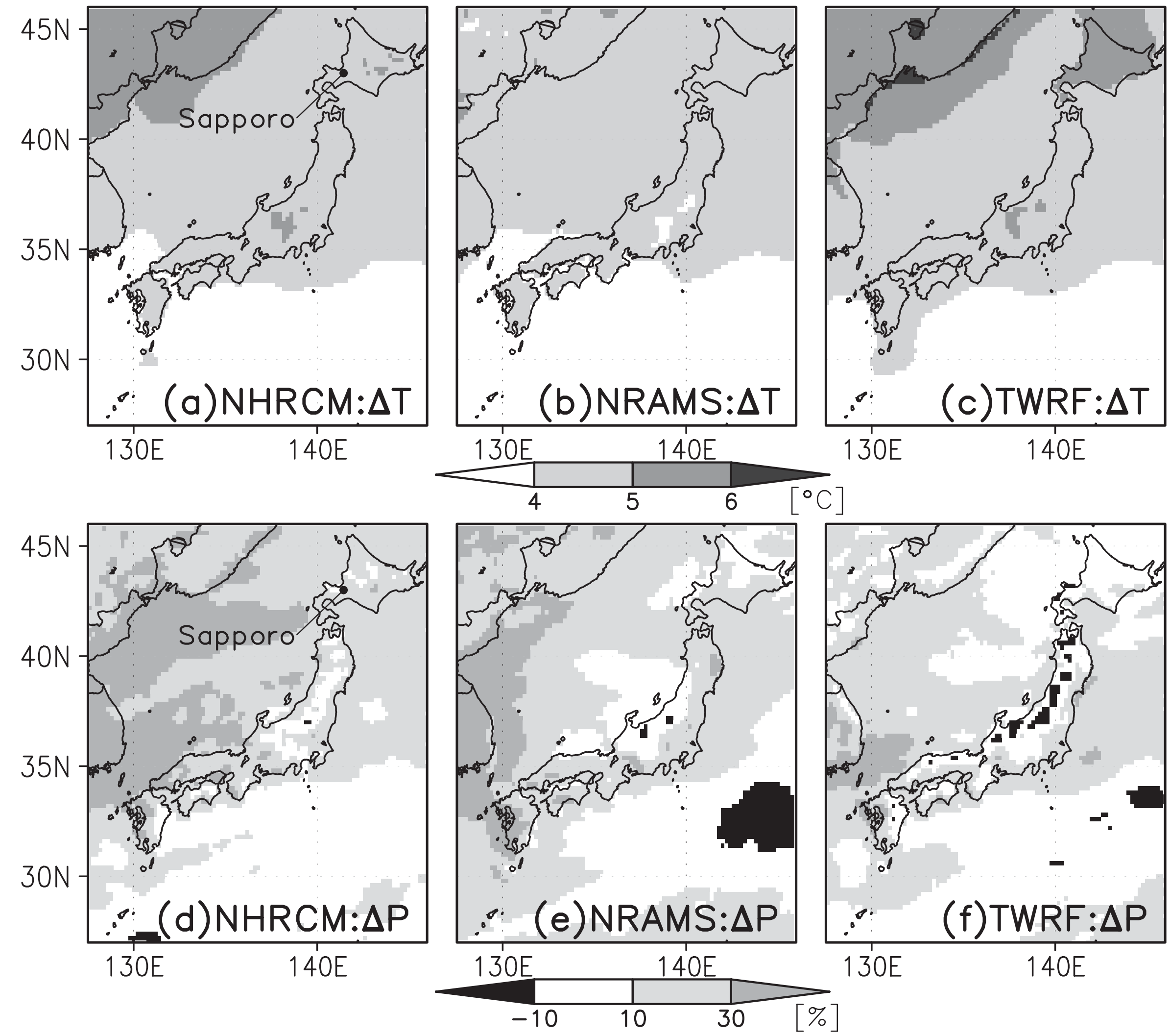

Fig. 1. The future changes at the end of the 21st century between A1B and 20C3M of the annual (a–c) surface temperature and (d–f) precipitation for (a,d) NHRCM, (b,e) NRAMS, and (c,f) TWRF.

this study we apply pattern-scaling to reconstruct the projected climatological temperature T and precipitation P by using the results of three RCMs driven by only one GCM, as follows:

$$T(x,m,s,g,r,p) = T_{Obs}(x,m) + S(s,g,p) * (T_{Mf}(x,m,r) - T_{Mp}(x,m,r)), \tag{1}$$

$$P(x,m,s,g,r,p) = P_{Obs}(x,m) * (S(s,g,p) * (P_{Mf}(x,m,r) - P_{Mp}(x,m,r))/P_{Mp}(x,m,r) + 1), \tag{2}$$

$$S(s,g,p) = \langle \Delta T(s,g,p) \rangle / \langle \Delta T_{Mf} \rangle, \tag{3}$$

where the projected climatological temperature and precipitation vary according to the location x, month m, emission scenario s, driving GCM g, driving RCM r, and time period p. In Eq. (3), $\langle \Delta T \rangle$ denotes the global mean temperature rise, and S is a scaling factor. The suffixes Mp and Mf indicate the climatological modeled value directly nested in MIROC3.2h for the end of the 20th century in the historical run and 21st century with A1B emission scenario, respectively. We use the Meshed Climatological data (Shimazu et al. 2003), which is estimated from surface observations from 1971 to 2000 by multiple regressions based on geographical and urban factors with 1 km × 1 km grid

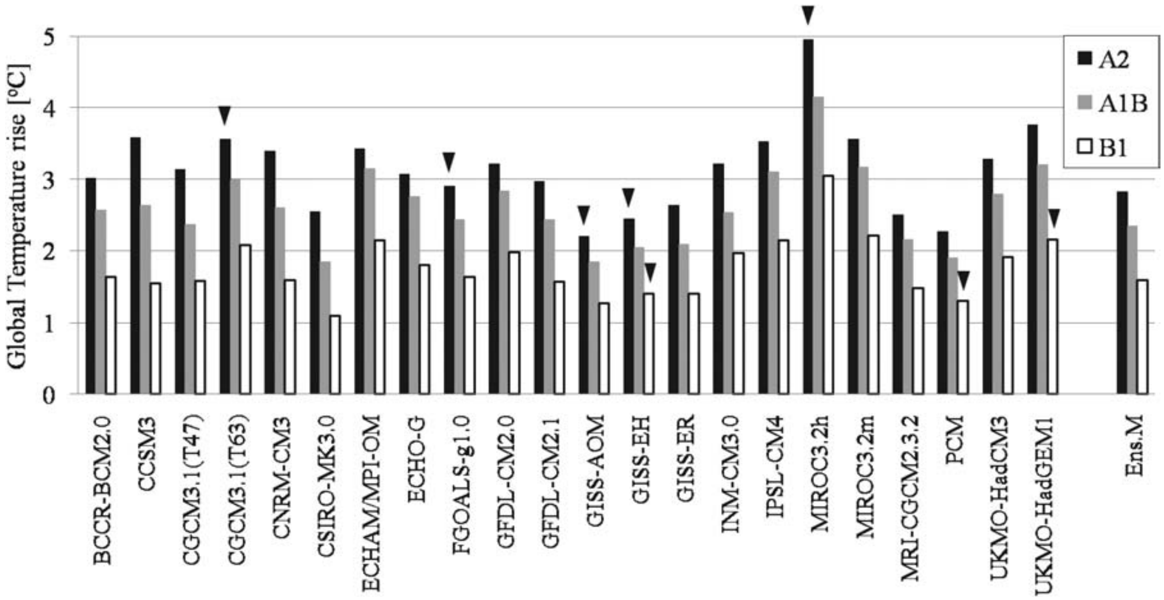

Fig. 2. Global temperature rise at the end of the 21st century for 22 GCMs forced by three GHG emission scenarios. Black triangles indicate use of the multi-model ensemble mean to estimate the global temperature increase.

across Japan. The RCM results and Meshed Climatological data are interpolated at the same grid spacing of $0.2° \times 0.2°$. We derive the spatial pattern of climate change only from the downscaling simulation driven by MIROC3.2h. We utilize the global mean temperature change to define a scaling factor for every 10 years of 20 years of climatology from 2000–2020 to 2080–2100 obtained from the 22 GCMs that contributed to the fourth assessment report of the Intergovernmental Panel on Climate Change (Meehl et al. 2007) under the A2, A1B, and B1 emission scenarios (Nakicenovic et al. 2000). The global temperature rise at the end of the 21st century, $\langle \Delta T(s,g,p) \rangle$ of Eq. (3), ranged from 1.09 to 4.95°C (Fig. 2). If a model had A1B projection data but not A2 or B1, we estimate $\langle \Delta T(s,g,p) \rangle$ of A2 (B1) by inflating the A1B projections of the model by the ratios between A2 (B1) and A1B projections of the ensemble mean (black triangles in Fig. 2). The local changes of temperature and precipitation around Japan are linearly correlated with the global mean temperature rise in MIROC3.2h, and their increase/decrease spatial patterns are consistent with those of many other GCMs. In addition to pattern scaling, we perform bootstrap resampling 1000 times to configure the climatological data set from a limited number of years (20) for present and future. These procedures produce 198,000 different climate scenarios in each period (3 emission scenarios, 22 GCMs, 3 RCMs, and 1000 resamplings).

Constructions of climate classification generally use a combination of parameters associated with temperature and moisture (Kopf et al. 2008; Köppen 1936; Holdridge 1947). In this study we identified regional climate analogues based on the combination of seasonal variations of temperature and precipitation. For each climate scenario, we define climate analogues for up to ten grid points in which the root mean square difference (RMSD) between the target city in the future climate and each grid in the present climate is less than 1°C for the monthly mean temperature and less than 1s for the monthly precipitation. The reconstructed scenarios of temperature and precipitation provide a range of possible climate analogues instead of a single deterministic climate analogue. We are therefore able to estimate the contribution of several uncertainties in the regional climate analogue: the uncertainty associated with the emission scenarios of GHGs and aerosols, the uncertainty of a TCR of the GCM, the RCM uncertainty associated with the physics and dynamics, and the uncertainty associated with sampling a limited number of years.

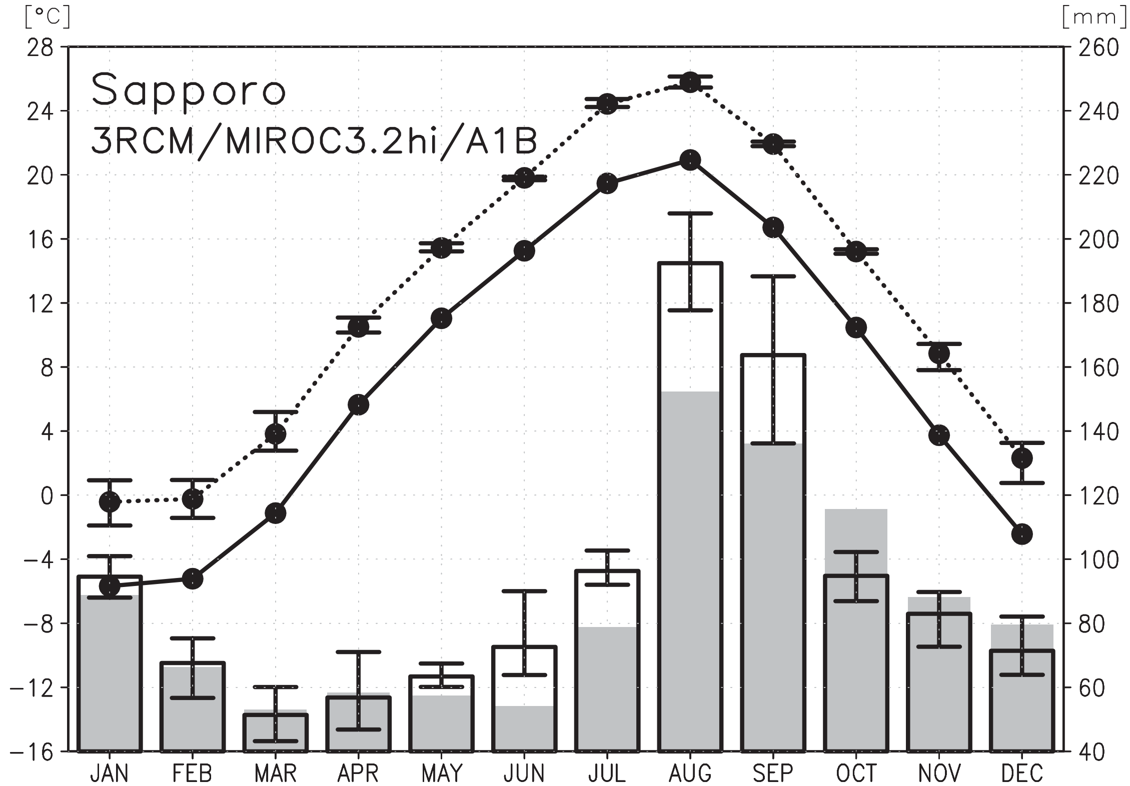

Fig. 3. Observed (solid line or gray bar) and projected (dashed line or outline bar) temperature and precipitation. Modeled values are derived from the simulation nested in MIROC3.2h with the A1B scenario and their biases are corrected with Eqs (1) and (2). Error bars indicate the range between minimum and maximum values among three RCMs.

3. Results

Sapporo, which is typified by agriculture and snow, is the capital of Hokkaido Island (Fig. 1) and has a population of 1,900,000. The projected temperature in Sapporo will be 4.4–5.3°C warmer by the end of this century, and the winter temperature will be approximately 0°C because of global warming driven by the MIROC3.2h with an A1B emission scenario (Fig. 3). Although the amount of precipitation is predicted to show little change, the temperature change implies that there will be a decrease in the amount of snow, which is crucial for agriculture and water resources (Barnett et al. 2005). On the basis of these preliminary results, this study targets the change and uncertainty of the Sapporo climate analogue.

We identified climate analogues for Sapporo in the 2030s, 2050s, and 2090s (Fig. 4), in each case based on the climatology of 20 years (the 2090s for 2080 to 2100, for example). In Fig. 4, colored grids are regarded as the analogues for Sapporo and color in each mesh indicates the percentage of total of climate analogue candidates for 198,000 climate scenarios. The possible climate analogues in the 2030s are spread widely over northern Japan, with the most likely area being in the northern part of the largest island of Japan (Honshu). Precipitation from August to October accounts for almost 40% of the annual rainfall in Sapporo. Because of the similarity of this seasonal pattern of precipitation, the best climate analogue is on the Pacific Ocean side of Honshu, not on the side bordering the Japan Sea, which has much rainfall during the winter. Another feature of the extent of the analogue is the concentrating distribution in lowlands because of restrictions in the definition of temperature. This condition reflects the fact that most cities in Japan, including Sapporo, are located in plains. With increasing global warming, the climate analogue for

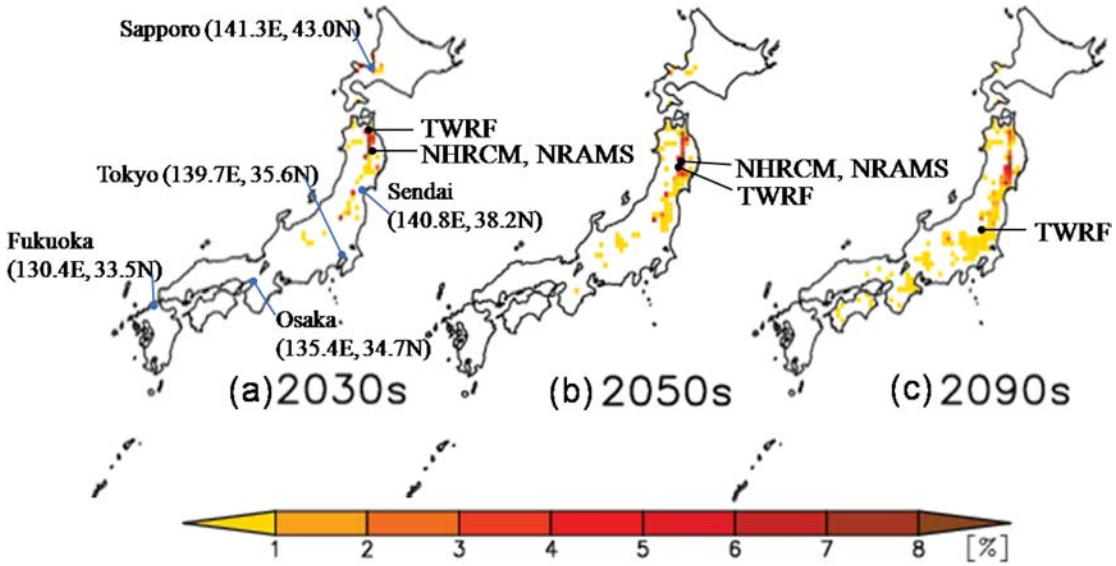

Fig. 4. The geographical distribution of probabilistic distribution of climate analogues for Sapporo in the 2030s (a), 2050s (b) and 2090s (c). Model names indicate the deterministic climate analogue derived without pattern scaling or a resampling process. In 2090s, NHRCM and NRAMS do not have a deterministic climate analogue of Sapporo.

Sapporo spread southward (Fig. 4b,c). Although the most analogous (i.e., peak) region shifts southward gradually, there is a considerable areal extent of the probabilistic analogue to the south of the peak. A similar pattern is evident for other major cities in Japan (figure not shown). Compared to the deterministic climate analogue in the 2090s derived from a single RCM nested in the MIROC3.2h with an A1B emission scenario, the probabilistic projection shows that the climate analogue exists over a wide region. The fact that the NHRCM and NRAMS have no analogue in the deterministic approach for the 2090s is due largely to high climate sensitivity of their parent GCM (Fig. 4c). Nevertheless, it is quite important to discuss several uncertainties in the climate projection even in the case of regional climate.

We examine each source of uncertainty embedded in the climate analogue. As described above, four different sources of uncertainty contribute to the spatial distribution of the climate analogue in this study. To identify the effect of these uncertainties, we examined the latitudinal probabilistic distribution of the climate analogues in the 2090s with one of the uncertainty sources fixed (Fig. 5). For example, the PDF of each of the three emission scenarios consists of 22 (TCRs) $\times$ 3 (RCMs) $\times$ 1000 (resampling) of climate scenarios. The total PDF with all the analogue members for Sapporo peaked at 39.5°N. The bootstrap resampling process indeed yields a wide range of potential analogue areas, and the mean variance exceeds 65% of the total PDF variance (figure not shown). Nonetheless, we find remarkable differences in PDFs due to the other three uncertainty factors. When we apply the ensemble mean of the 22 GCMs as a scaling factor (red line in Fig. 5a), the climate analogue PDF is very similar to the total PDF. However, some GCMs produce PDFs with quite different shapes. Even though this method does not consider differences in the spatial pattern of the projections due to different GCM formulations, differences in the TCR of different GCMs produce a large diversity of climate analogues.

Although the PDF peaks are almost the same, differences due to emission scenarios are remarkable, especially between 40° and 42°N, an indication that regional climate change strongly depends on the emission of GHGs. The differences mainly reflect the large diversity in the range of temperature increases. Because emission scenarios are directly linked to increases in global temperature, it naturally follows that emission scenarios have a

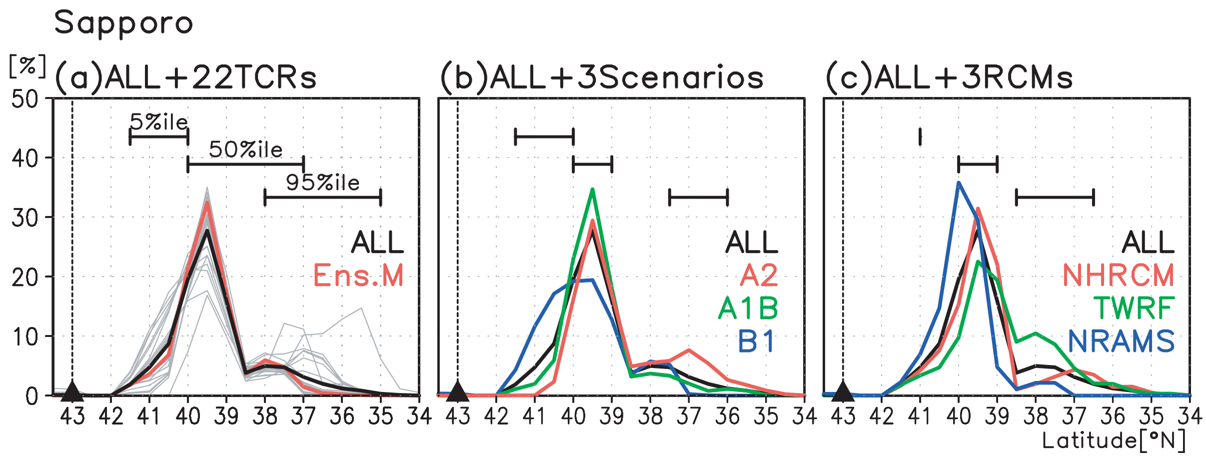

Fig. 5. Latitudinal PDFs of climate analogue for Sapporo in the 2090s. Black lines show the PDF that considers all uncertainty sources. Other lines indicate PDFs with indicated uncertainty sources fixed: (a) TCR of GCM, (b) emission scenarios, and (c) RCMs. Ordinate units are %. Error bars show ranges of the 5th, 50th, and 95th percentile in each PDF.

large impact on the distribution of surface temperatures and the consequent PDFs of climate analogue.

The ranges of warming in the projections are similar among the different RCMs. Differences of RCM simulation are especially evident in patterns of precipitation because of the different presentations of orography or physical schemes. These differences in presentations resulted in considerable differences among PDFs for each RCM (Fig. 5c). Some previous studies have also reported the existence of large uncertainties in RCM simulations of precipitation (e.g., Christensen et al. 2001; Déqué et al. 2007). The uncertainty due to RCMs cannot be neglected even with state-of-the-art models. This fact implies a need to utilize multiple models even for regional climate modeling.

Analysis of the spatial patterns of climate scenarios from the 22 GCMs shows that the pattern scaling method reproduces only a part of the variation in the range of precipitation, whereas it represents a range of variation in surface temperature comparable to the original. This result suggests that GCM-related differences could be larger than is apparent from this study and may be a major uncertainty in future projections, as shown by other studies (e.g., Rowell 2006; Ruosteenoja et al. 2007). Owing to the large computing resource needed for RCM downscaling, it is hard to perform nested RCM runs in many GCMs. Newly developed inflation methods still have problems, especially for precipitation (Kendon et al. 2010; Déqué et al. 2011). Although some recent projects such as NARCCAP have proceeded to address the uncertainty issue comprehensively (e.g., Wang et al. 2009), they have addressed only a part of the available GCM ensemble. Providing more useful information for impact assessment and mitigation studies will require the advancement of studies targeting uncertainties due to RCMs and GCMs systematically and quantitatively.

Figure 5 also shows the range of 5^{th}, 50^{th}, and 95^{th} percentile for each PDFs. For example, 5^{th} percentile for TCR of GCMs indicates the northernmost and southernmost location of 5^{th} percentile for 22 PDFs of TCRs. The range of uncertainty percentiles is rather narrow for emission scenarios and RCMs (Fig. 5). Differences in emission scenarios and RCMs yield similar ranges for the 5^{th}, 50^{th}, and 95^{th} percentile. In contrast, the range becomes larger in the southern area for the PDFs of RCMs. This result is associated with a large difference in the precipitation projection of the RCMs; TWRF provides many climate analogue candidates around 37–39°N, where NRAMS has few analogue regions.

4. Summary and discussions

This study developed a new method to demonstrate regional climate projections with every conceivable uncertainty with the use of a pattern scaling method and bootstrap resampling technique. The uncertainty associated with the transient climate response (TCR) of GCMs was relatively large compared to the emission scenario and RCM uncertainties. Even though the future temperature increase was similar among RCMs, there were considerable uncertainties in the climate analogue due to differences in the precipitation projection of RCMs. For the regional climate analogue, RCM uncertainty cannot be neglected, like the uncertainties associated with TCR of GCMs and emission scenarios, and it is due to physical scheme or given orography and resultant precipitation feature. Investigation of the uncertainty of spatial patterns of GCM projections will require more computing resources and further efforts.

This style of projection enabled us to investigate the sensitivity of regional climate projections to each uncertainty. Furthermore, the strategy is applicable to various impact assessment studies such as the identification of regions suitable for cultivation, the probability of health hazards, and areas vulnerable to flooding. For example, a study of the analogue for satisfactory cultivation of rice will help to predict the change of total paddy yield and rice-paddy acreage in the future. The model results will also help policy makers make informed decisions with regard to the design of cities in a warmer climate.

We did not investigate the reliability of each climate change scenario. In other words, we assigned equal weight to each emission scenario, each GCM, each RCM, and each bootstrap sample. Considerations indicate that we cannot determine differences among the likelihoods of three emission scenarios (Schneider 2001). The likelihood of each bootstrap sample also warrants equal consideration in long-term climate projections. Climate scientists are actively investigating the reliability of projections from GCMs and RCMs and exploring the implications of weighting the projections (e.g., Giorgi and Mearns 2002; Tebaldi et al. 2004). However, determining the reliability of climate change projections is far from trivial (Knutti 2010; Shiogama et al. 2011). The ensembles of GCMs and RCMs used in this study were collections of carefully configured "best models" made by limited numbers of modeling centers and, of particular note, did not reflect attempts to sample the range of all possible models. It is therefore unclear whether the range of uncertainty associated with the projections of these "ensembles of opportunity" should be interpreted to reflect the full range of uncertainty of our knowledge (Knutti 2010).

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