Identifying climate analogues for cities in Australia by a non-parametric approach using multi-ensemble, high-horizontal-resolution future climate projections by an atmospheric general circulation model, MRI-AGCM3.2H

Tosiyuki Nakaegawa1, Kenshi Hibino2,1 and Izuru Takayabu1
1Meteorological Research Institute, Japan Meteorological Agency, Japan
2Institute of Industrial Science, The University of Tokyo, Japan

Abstract:
Climate analogues for 17 Australian cities in the current climate (1979–2003) were identified by using a non-parametric climate analogue approach and multi-ensemble future climate projections in the late 21st century (2075–2099) made with the Meteorological Research Institute’s atmospheric general circulation model, version 3.2H under the Special Report on Emissions Scenarios A1B scenario with a horizontal resolution of about 60 km. By using this approach, climate analogue cities could be identified within the uncertainties of the multi-ensemble future climate projections. A similarity score as a metric of climate analogue is evaluated with the threshold as the quantified uncertainties in nonparametric manner. Ten of the identified climate analogue cities were in Australia, even in a global search, and the other seven analogue cities were in other continents: five in Africa, one in Mexico, and one in Argentina. In an in-country search, climate analogues for the seven target cities whose climate analogues were identified in other parts of the world in the global search were identified in Australia, although the similarity scores were low. Very low similarity scores imply that the future climate of the target city will be novel, that is, a climate that no city is currently experiencing.

KEYWORDS climate analogue; future climate projection; Australia; surface air temperature; precipitation; multi-ensemble

INTRODUCTION
Recent global warming due to the highest anthropogenic emissions of greenhouse gases ever recorded (Intergovernmental Panel on Climate Change [IPCC], 2013) has had impacts on human and natural systems in many sectors. Global features of the warming effect are clear, but regional ones are less so because of the complicated nature of the Earth’s systems. However, regional climate projections are very important because future climate changes in a specific place affect both human and natural systems there. Dynamical and statistical downscaling methods are widely used to produce future climate projections with high horizontal resolutions of 5 to 50 km (e.g. Ishizaki et al., 2012b) by downscaling projections with horizontal resolutions of 100 to 200 km, which are typical for coupled atmosphere–ocean general circulation models (CGCMs). These projections have then been used as inputs to sector-specific process-based models used to assess impacts on human and natural systems, such as crop yield, flood inundation, and ecosystem models. This approach is very promising for impact assessments because it uses the sector-specific process-based models and future climate projections based on state-of-the-art techniques. However, there are inherent uncertainties in this approach. Dynamical downscaling cannot avoid numerical model biases and statistical downscaling has to assume the relationship obtained for the current climates remains the same for the future climates.

The climate analogue approach is an empirical impact assessment approach that has been employed, particularly in the agricultural sector, to identify suitable crops for a target region. This approach identifies a climate analogue city with well-known sector-specific characteristics that has a current climate which is analogous to the future climate of the target city, which has unknown sector-specific characteristics (Nuttonson, 1955) such as phenology and design water level against flooded river discharge. Parry and Carter (1989) applied this method to the assessment of the impacts of future climate changes on agriculture.

How do we identify a climate analogue city with a climate similar to that of the target city? Many approaches have been used, although some employ subjective metrics (e.g. Hallegatte et al., 2007; Kopf et al., 2008; Ishizaki et al., 2012a). Hibino et al. (2015) proposed an objective and quantitative non-parametric climate analogue approach that considers interannual variations in climate variables. Another feature of this approach is that it includes the uncertainties of the climate projection for the climate analogue city or other candidate climate analogue cities.

The Australian continent formed by separation from Gondwana, the southern supercontinent (Blewett et al., 2012), and as a result of its isolation, it became home to unique fauna, flora, and microbiota (Pascoe, 1991). In the agricultural sector, Australia is the world’s largest producer of wool, the sixth largest producer of wheat, and the eighth largest producer of wine (Malcolm et al., 2009). Therefore, it is crucial to assess the magnitude and frequency of the impacts of climate change on both the ecological and agri-
cultural sectors of Australia, including the impacts that a novel climate might have.

CSIRO and Bureau of Meteorology (2015) developed a climate analogue tool for Australia which interactively provides a climate analogue city for a target city with a variety of options: region, time period, emission scenario, and variables. These results are also compiled as a report for each region to assist regional decision makers in understanding future climate projections.

In the present study, we used the non-parametric climate analogue approach of Hibino et al. (2015) to perform climate analogue searches for 17 Australian cities, after first conducting a future climate projection with an ensemble atmospheric general circulation model (AGCM) experiment under the A1B scenario of the Special Report on Emissions Scenarios (SRES). The climate analogue cities identified by this approach differ from those identified by other approaches mentioned above because the 1-year seasonal cycles of surface air temperature and precipitation are considered as time series.

DATA AND METHODS

Climate analogue

We defined a climate analogue as a region where the seasonal cycle of monthly mean surface air temperature and precipitation resembles that of the future climate of the target city. We quantified this definition by using the root-mean-square difference \( r_j \) of the surface air temperature \( T \) defined as Equation (S3) in Text S1 according to Hibino et al. (2015), where \( j \) is index of the samples from the current climate simulations that range from 1 to the number of years in the current climate periods \( N_j \). Instead of the conventional root-mean-square difference in climatological monthly means for each month, one-year time-series of monthly means are used for computing the root-mean-square difference. We evaluate the uncertainties as the root-mean-square difference \( R_j \) in surface air temperature among the ensemble members defined as Equation (S4) where \( k \) is same as in \( j \) but for the future climate simulations in the future climate periods \( N_f \). The detailed method about climate analogue is described in Climate analogue in Text S1. We assume that a city is a climate analogue candidate if \( r_j \) is smaller than the uncertainties of the future climate projections. We defined the similarity score for surface air temperature \( (S_t) \) as the ratio of the number of cases with \( r_j < R_j \) to the number of samples in the future climate simulations, divided by the number of current climate samples:

\[
S_t = \frac{1}{N_f} \sum_{j=1}^{N_f} \frac{\#[r_j < R_j]}{N_f}
\]  

where \#[A] denotes the number of samples satisfying condition \( A \). A similarity score for precipitation \( (S_p) \) can be obtained in the same manner. We defined the integrated score \( (S) \) for both surface air temperature and precipitation as the product of the individual scores:

\[
S = S_t \cdot S_p
\]

In searching for a climate analogue city for the target city, both the actual seasonal cycles of the observations and those of the opposite phase (6-month delay) were used in order to remove the difference in seasonal cycle between the Southern and Northern Hemispheres. This procedure enabled us to identify potential analogue cities in the Northern Hemisphere with similar seasonal cycles, though of opposite phase, to the Australian target cities.

Ensemble simulations

We performed 25-year climate simulations (i.e. \( y = 1 \) to 25 for both the current (1979–2003) and future (2075–2099) periods) with the Meteorological Research Institute Atmospheric General Circulation Model (MRI-AGCM3.2H; Mizuta et al., 2012). We performed 24-member ensemble simulations (i.e. \( e_i = 1 \) to 24) for the future climate by using combinations of four SST datasets, three convection schemes, and the two different initial conditions. Therefore, \( N_y = 25 \times 24 = 600 \). The future rise in global mean surface air temperature is projected to rise 2.5°C by the late 21st century under SRES A1B in the future climate simulations (e.g. Nakaegawa et al., 2013). These simulations allowed us to evaluate the expression within the square brackets on the right-hand side of Equations (S1) to (S4). Ensemble simulations in Text S1 provides outlines of MRI-AGCM3.2H, the ensemble simulations, and its capabilities (e.g. Fábrega et al., 2013; Nakaegawa et al., 2013; Nakaegawa et al., 2015a).

Observations

Observed gridded monthly mean datasets of surface air temperature \( (T) \) and precipitation \( (P) \) for the current climate prepared by Mitchell and Jones (2005) were used for the current observed climate from 1979 to 2003, which is the same as in the current climate simulations. These datasets were constructed by the anomaly method; that is, anomalies instead of absolute values were spatially interpolated (e.g. Nakaegawa et al., 2015b). They have a monthly temporal resolution and horizontal resolutions of 0.5° of latitude and longitude. The current observation period was set to be the same as that of the current climate simulation.

Target cities and period

We selected 17 target cities in Australia for which to identify climate analogues (Table I). We selected the 10 largest cities in Australia by population (Sydney to Wollongong in Table I) and then selected the remainder so as to cover the entire country geographically (Figure 1). The model grid is mapped to city locations by choosing the nearest grid point. The future climate period for the climate analogue was set to be the same as that for the future climate simulations (2075 to 2099); thus, the scaling factor \( (K) \) on the right-hand side of Equations (S1) and (S2) as the ratio of the global mean surface air temperature during the target time period to that during the future simulation period between the target time period and the future climate simulation period, was unity.

RESULTS

Global search

In the global search, the climate analogues for 10 of the 17 target cities were identified in Australia (Figure 2 and Table

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The climate analogues identified for the five target cities along the southeastern coast of Australia were also located along the eastern coast, but more equatorward. For example, surface air temperature in Sydney was projected to rise by 2.5°C in the future climate, and precipitation was projected to increase in the austral summer and to decrease in the austral winter. High temperature similarity scores were confined to a very small area along the eastern coast of Australia equatorward from Sydney because the climate analogues had to have both a similar seasonal cycle and a similar rise of surface air temperature in the future climate (Figure S1a). High precipitation similarity scores were distributed along the coast of Victoria State near Melbourne (Figure S1b), but high integrated scores were found in a very small area, mainly corresponding to the area with high surface air temperature similarity scores (Figure S1c). Although the location of the highest integrated similarity score, and thus the climate analogue city, for each target city is pointed to by the arrows in Figure 2, the geographical distribution of the integrated similarity score obtained by our method means that it can be used to identify additional possible analogue cities (Figure S1c). These distributions also reflect the uncertainties in the future climate projections due to the convection scheme, the projected SSTs used, and the internal variability of the climate system.

The identified climate analogue cities for Hobart, Adelaide, and Perth were on the coast adjacent to each target city but more equatorward (Figure S3). The relationship between each of these pairs can be interpreted in the same way as for the five target cities along the southeastern coast. In the case of Hobart, which is on the island of Tasmania, no climate analogue city was identified on the Australian continent, although it had high precipitation similarity scores there. In contrast, the precipitation similarity score clearly contributed to the identification of the climate analogue city for Adelaide, because the surface air temperature score was constant along the western coast of the Great Australian Bight. The climate analogue city for Perth was determined by both scores, because the highest similarity scores of both temperature and precipitation were along the western coast of Australia between Perth and Shark Bay.

The climate analogue cities for two inland cities, Alice Springs and Wiluna, were identified in the northern part of the Simpson Desert. For Alice Springs, the highest temperature similarity scores were distributed in an area just east of Alice Springs (Figure S2a), whereas the precipitation scores

| Name         | State                   | Population | Latitude (°S) | Longitude (°E) |
|--------------|-------------------------|------------|---------------|----------------|
| Sydney       | New South Wales         | 4,840,628  | 33.87         | 151.21         |
| Melbourne    | Victoria                | 4,440,328  | 37.81         | 144.96         |
| Brisbane     | Queensland              | 2,274,560  | 27.47         | 153.03         |
| Perth        | Western Australia       | 2,021,203  | 31.95         | 115.86         |
| Adelaide     | South Australia         | 1,304,631  | 34.93         | 138.60         |
| Gold Coast   | Queensland              | 614,379    | 28.00         | 153.43         |
| Newcastle    | New South Wales         | 430,755    | 32.93         | 151.78         |
| Canberra     | Australian Capital Territory | 422,510 | 35.28         | 149.13         |
| Wollongong   | New South Wales         | 289,236    | 34.42         | 150.89         |
| Hobart       | Tasmania                | 219,243    | 42.88         | 147.33         |
| Cairns       | Queensland              | 146,778    | 16.92         | 145.77         |
| Darwin       | Northern Territory      | 140,386    | 12.46         | 130.84         |
| Alice Springs| Northern Territory      | 28,605     | 23.70         | 133.88         |
| Port Hedland | Western Australia       | 15,044     | 20.31         | 118.61         |
| Esperance    | Western Australia       | 9,919      | 33.86         | 121.88         |
| Tennant Creek| Northern Territory      | 3,062      | 19.65         | 134.19         |
| Wiluna       | Western Australia       | 681        | 26.59         | 120.22         |

Figure 1. Seventeen target cities in Australia. The color scale shows elevation above sea level (m). More information about each city is listed in Table I.
were highest southwest of Alice Springs and near the Great Australian Bight (Figure S2b). The distribution of the integrated scores for Alice Springs resembled that of the temperature score; the scores were highest to the east of Alice Springs (Figure S2c). The elevations of Alice Springs and Wiluna are almost the same, about 530 m. The short distance between Alice Springs and its climate analogue city is due to the elevation difference of about 400 m between them, which corresponds to a surface air temperature difference of about 2.6°C. The climate analogue city for Wiluna was identified in a location near to that of Alice Springs. The long distance separating Wiluna from its climate analogue city can be attributed to the fact that the area around Wiluna is all at about the same elevation.

Climate analogues of the other seven target cities were identified in Africa and Mexico and Argentina. The climate analogue cities for Melbourne, Canberra, Cairns, and Esperance were near Cape Town (South Africa), Bahia Blanca (Argentina), Angoche (Mozambique), and Port Elizabeth (South Africa), respectively. Each analogue city is located in the Southern Hemisphere and at a similar latitude to its target city. As an example, the global geographical distribution of the integrated similarity scores for Melbourne are shown in Figure 3a, and the South African region where the highest scores were distributed is shown in Figure 3b. The climate analogue cities for the other three target cities are located at a similar latitude to the target city but in the Northern Hemisphere: Lazaro Cardenas, Mexico, is the analogue for Darwin; Boutilimit, Mauritania, is the analogue for Port Hedland; and Inékar, Mali, is the analogue for Tennant Creek. Of course, the seasonal cycle at these climate analogue city locations was reversed.

In-country search

As mentioned in the Introduction, climate analogue identifies a climate analogue city with well-known sector-specific characteristics that has a current climate which is analogous to the future climate of the target city, which has unknown sector-specific characteristics. It is often difficult to obtain the characteristics outside a country. If a second best or lower is identified in the country, it is easy to do so.

We next identified the best climate analogue cities for the 17 target cities by an in-country search (Figure 4). For the seven target cities with climate analogue cities on other continents in the global search, seven alternative climate analogue cities were identified in Australia in this search. The methodology used in this study facilitated these identifications because all grid points were evaluated on the basis of the integrated similarity score. The Australian climate analogue for Melbourne was identified on the northern boundary of Cape Arid National Park near Esperance (Figure 3c). In the global search, high integrated similarity scores were found in two regions, near Cape Town and near Esperance (Figure 3b, 3c). Thus, although the best climate analogue city for Melbourne was near Cape Town, Esperance would also be a reasonable climate analogue city because the differences in the integrated similarity scores between the Cape Town area and the Esperance area were small, and the integrated score at Esperance, although lower than that at Cape Town in the global search, was still high.

The vectors originating at the three target cities in northwestern Australia, Darwin, Port Hedland, and Tennant Creek, point to the area around 125°E, 18°S, the hottest zone in Australia with an annual mean surface air temperature greater than 33°C. This area is drier than the target city locations, however. Therefore, the integrated similarity scores for these three target cities were much lower in the in-country search than in the global search.

DISCUSSION

Climate zone

In the global search, non-zero integrated similarity scores were distributed in separate areas of several continents. The similarity scores for Melbourne (Maritime temperate cli-
mate in the Köppen classification; Cfb; Figure S4), for example, were distributed around land areas along 35°S: the southeastern coast of Western Australia (humid temperate with a hot summer: Cfa); southern South Africa (Cfa), and Uruguay and central Argentina (Cfa). It is reasonable that the climate analogue for Cfb would be Cfa as long as precipitation is projected to change little (in the Köppen classification system an “a” in the third position indicates that the warmest monthly mean surface air temperature is >22°C, and a “b” indicates that it is <22°C). The climatological monthly mean surface air temperature at Melbourne in the future climate was projected to exceed 22°C in January (Figure S5); thus, the climate zone is projected to change from Cfb to Cfa.

Non-zero integrated similarity scores for Melbourne were also distributed in the Northern Hemisphere, namely, in southern Portugal and Morocco (Warm Mediterranean climate; Csa), the southern part of inland China (Humid subtropical climate; Cwa), and the Mexican Plateau (Csa and Cwa). It is reasonable that the climate analogue for Cfb in the Southern Hemisphere is Csa or Cwa in the Northern Hemisphere because in summer the Csa and Cwa climates are warm and humid.

Time evolution

Ishizaki et al. (2012a) used the pattern scaling method (e.g. Ishizaki et al., 2014) to show the time evolution of a climate analogue city. The method projects future climate changes as the spatiotemporally separable product of the spatial patterns of future changes in climate variables and a time-dependent function \( K(t, m) \), in which \( K \) is a function of only the global mean surface temperature and the time period (see Equations (S1) and (S2)). The time-dependent function can translate the future rise in surface air temperature in MRI-AGCM3.2H into that of each CGCM, allowing us to infer a possible climate analogue for a possible future climate change. Because the spatial patterns of future changes in surface air temperature and precipitation remain the same over time in this method, one may consider that the climate analogue for a target city at any given future year between the current year and the late 21st century intuitively should be located along the vector from the target city to the analogue city in Figure 4, as a first approximation. However, elevational change along the target-analogue vector is not always uniform and patterns of future seasonal changes in surface air temperature and precipitation in seasonal change may not be the same. It is unlikely that the time evolution of the in-country climate analogues for all target cities can be approximated as a dividing point. Instead, the climate analogue approach is required to identify a climate analogue city of a target city after projecting a future climate of the target city using the pattern scaling method.

Inappropriate climate analogue cities

The climate analogue cities for Darwin and Esperance may be inappropriate for practical use owing to the low integrated similarity scores of the identified climate analogues. This result suggests that people living in Darwin and
Esperance in the future will experience a novel climate that nobody living in the current climate has yet experienced, as discussed previously by Williams et al. (2007). A sector-specific process-based model must therefore be used to perform a future impact assessment for each sector in these cases, with inputs from future climate projections made with AGCMs and CGCMs (e.g. Hanasaki et al., 2008; Imbach et al., 2012). However, the identified climate analogue cities for these two cities may still be useful for reference. For example, the surface air temperature in a hot year in the climate analogue city in the current climate probably resembles the future climatological mean surface air temperature in the target city.

Comparison with different approach

Whetton et al. (2013) performed climate analogue for Australia’s major cities by using annual maximum surface air temperature and annual precipitation for least, mid, and hottest scenarios under +4°C global warming from the pre-industrial climatology. Climate analogue cities for Sydney under three scenarios: Tewantin, Bundaberg, and Rockhampton: are located on the eastern coast of Australia equatorward from Sydney according to the future rise in surface air temperature. This feature can be inferred from Figure S1 although the global warming is different between Whetton et al. (2013) and the future climate simulations in this study. The climate analogue for the other cities on the east coast except for Cairns are identified in a similar manner. Climate analogue cities for Melbourne in Whetton et al. (2013) are located in the southern inland region of New South Wales. Although the best climate analogue city for Melbourne in this study is different in both global and even in-country search, the three climate analogue cities for Melbourne in Whetton et al. (2013): Cowra, Wyalong, and Leeton: are included in or very close to shaded area with colors. This suggest that our approach can support other climate analogue approach from the viewpoint of the similarity of seasonal cycle of surface air temperature and precipitation.

CONCLUDING SUMMARY

We identified climate analogues for 17 Australian cities by using a non-parametric climate analogue approach after obtaining future climate projections with MRI-AGCM3.2H under SRES A1B. The climate analogue approach used in the present study can identify a climate analogue city within the uncertainties of the future climate projections. Ten climate analogue cities were identified in Australia in the global search, and the other seven were found on other continents: five in Africa, one in Mexico, and one in Argentina. We also performed an in-country search to identify climate analogues in Australia for the latter seven target cities, although the integrated similarity scores of these in-country climate analogues were lower. A low integrated score suggests that the target city will experience a novel climate in the future, one that no city is experiencing at present. There are many approaches to identifying a climate analogue city. The present approach, however, can identify several possible climate analogues because it considers the 1-year seasonal cycle of surface air temperature and precipitation as time series.

In the present study, we treat multi-ensemble simulations with four SST datasets, three convection schemes, and the two different initial conditions as a set of simulations. These options may influence the uncertainties in climate analogue with different degrees. This should be addressed in a further study (Pinzon et al., 2016).

The climate analogue approach provides useful information for impact assessments of climate changes in each sector. However, it may be difficult for policies and effective adaptations to climate change impacts to be shared between a target city and its climate analogue (Kellett et al., 2015), particularly if they differ with regard to culture and traditional practices (e.g. Kuehne and Bjornlund, 2008). Nevertheless, the identification of climate analogues provides useful information for policy making, because most climate analogues in the present study are based on the seasonal cycles of monthly mean surface air temperature and precipitation. As Kopf et al. (2008) suggested, the identification of climate analogues that take into account temperature and precipitation extremes, such as extremely hot days and heavy precipitation events, would be helpful for policy making and should be explored in a future study.

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SUPPLEMENTS

Text S1. Methods about climate analogue and ensemble simulations
Figure S1. Geographical distribution of normalized similarity scores for the climate analogue region of Sydney
Figure S2. Same as Figure S1 but for Alice Springs
Figure S3. Geographical distribution of normalized similarity integrated scores for climate analogue regions
Figure S4. Global Köppen climate classification in the current and future climates
Figure S5. Seasonal cycles of surface air temperature and precipitation at Melbourne, the target city, and its identified climate analogue city
Table S1. Analogue city for each target city in global and in-country search
Table SII. Maximum integrated, surface air temperature, and precipitation scores for each target city in the global search

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