Hiroyuki Kusaka

Impact of Urbanization on Local Circulation and Precipitation over the Leeward Mountain

Hiroyuki Kusaka[1], Akifumi Nishi[2], Mayumi Mizunari[2]

[1] *Centre for Computational Science, University of Tsukuba, Japan, kusaka@ccs.tsukuba.ac.jp*

2 Graduate School of Life and Environmental Sciences, University of Tsukuba, Japan

1. Introduction

In Tokyo, natural disasters have frequently occurred due to short-time heavy rainfall as a result of the urban structure. This research uses spatially detailed surface rain gauge data to elucidate spatially-detailed distributions of heavy rainfall in Tokyo during the summer. Additionally, the climatic features of their diurnal variations, for a period covering the past 19 years from 1995-2013. Particular focus is placed on short-time heavy rainfall on typical summer days, which is an issue of high social concern. The present study investigates climatology of the short-time heavy rainfall in Tokyo from the spatially detail rain-gauge network and examines relationship between the heavy rainfall and urbanization from the numerical experiment.

2. Climatology of Precipitation in Tokyo

2.1 Data and Methodology

Figure 1 shows the elevation and urban fraction around Tokyo. Elevation is lower in areas closer to Tokyo Bay, and higher on the west side which is separated from the ocean. The city center of Tokyo is located on the plain near the ocean, and the green fraction increases in moving toward the west side.

In this study, two kinds of rain gauge data were used to investigate the precipitation climatology in summer around Tokyo. The first one is measured by the AMeDAS network operated by the Japan Meteorological Agency, and the second one is measured by the Tokyo Prefecture Comprehensive Information System for Water Disaster Prevention (TPCIS) operated by the Tokyo local government. The spatial resolution of AMeDAS and TPCIS networks is about 17 km and 5 km, respectively.

Analysis period of precipitation climatology is summertime (June-September) for 1995-2013.

The analysis of precipitation climatology focuses on spatial distribution and diurnal variation of precipitation for the all days in the applicable period (total of 2318 days) and short-time heavy rainfall days (total of 241 days). As the definition of the short-time heavy rainfall days in this study, it was decided to use days where an hourly precipitation amount of 20mm/hour or more was observed at one of the locations in Tokyo Prefecture, and the time over which that case of precipitation continued was shorter than three hours on typical summer sunny days.

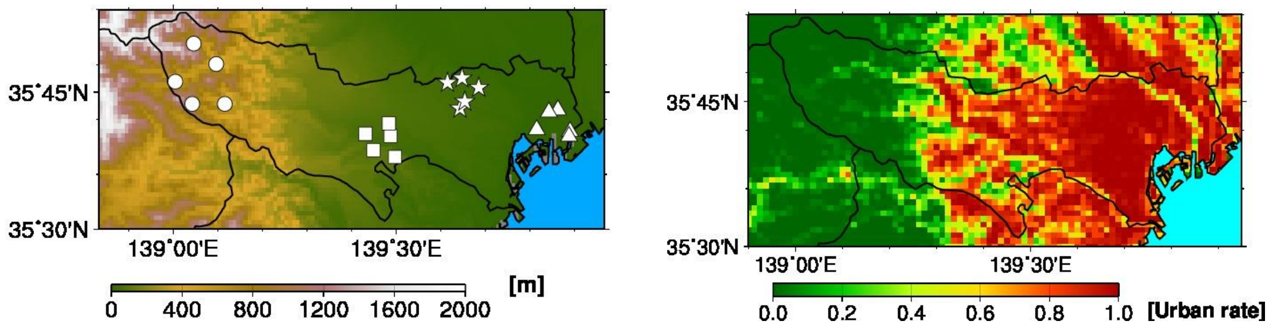

Fig. 1 Terrain height (left) and land-use (right) around Tokyo prefecture.

2.2 Results

Analysis was conducted to prepare the spatial distributions of the total precipitation amount in summertime. A spatial distribution of precipitation occurrence frequency was prepared in the same way.

Figure 2 shows the distribution of precipitation amount and the frequency of precipitation from the observations. It is evident that the climatological mean of the total precipitation amount on short-time heavy rainfall days in Tokyo is lower on the coast of Tokyo Bay, and increases going west. This trend is clearly evident, even in the distribution of precipitation frequency. However, a local maximum of the plain area is found in the Region 3 (Star in Fig. 1) and the precipitation frequency in this area is comparable to that in the mountain areas.

Diurnal variation in the precipitation amount in Tokyo was investigated, as shown in Figure 1, by looking at four areas: the mountainous area to the west (Region 1, Circle), the inland plain area (Region 2, Square), the area located to the northwest of the city center where there was a large amount of precipitation compared to the surrounding area (Region 3, Star), and the area located to the northeast of the city center where the amount of precipitation was small (Region 4, Triangle).

Figure 3 shows, as the precipitation amount by time period, the mean value of the precipitation amount per station in each area. In Tokyo, on days with short-time rainfall, there is a fairly large precipitation amount in the early hours of the afternoon during the day in the mountainous area (Region 1) and evening in the northwest of the city center (Region 3). On the other hand, clear diurnal variation is not evident at the other areas.

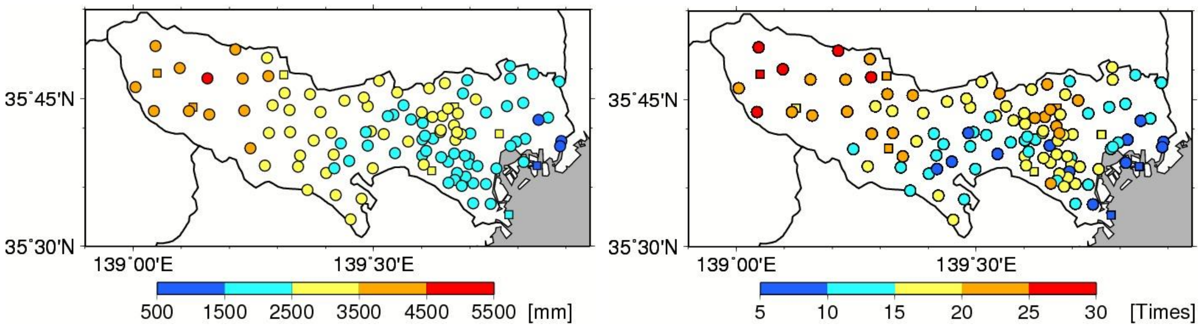

Fig. 2 Distribution of precipitation amount and the frequency of precipitation from the observation on short-time heavy rainfall days in Tokyo.

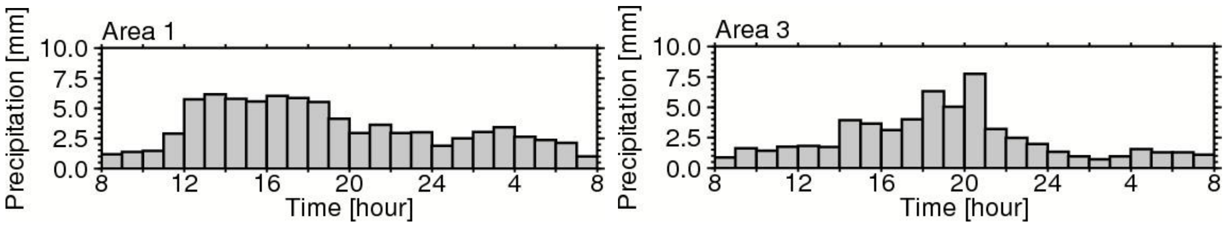

Fig. 3 Precipitation amount by time period at Areas 1 and 3 shown in Fig. 1.

3. Numerical Experiments

3.1 Configurations of the numerical model

Considering the geographical conditions of Tokyo and its surroundings, here is a possibility that tendencies of the spatial distribution and diurnal variation in the short-time heavy rainfall in this region are affected by thermally induced local circulations.

In order to discuss this possibility, numerical experiments were conducted using a regional atmospheric model. Numerical model with idealized atmospheric condition, terrain, and land-use has the advantage of making it easier to generate a physical understanding a given phenomenon and reducing uncertainty due to sensitivity to the model configurations, although there are several limitations and shortcomings in the idealized simulation. Considering these, this study conducts idealized numerical experiments using the two-dimensional version of WRF model.

Figure 4 illustrates the lower atmospheric layer and surface parts of the simulation domain. The simulation domain covers 1,000 km in the east-west direction, and 50 hPa in the vertical direction from ground level. The horizontal grid spacing of the model was set to 1 km. As the purpose of this study is to investigate precipitation in the vicinity of a coastal city with mountains behind it, such as Tokyo, the mountain height, distance from the sea to the mountains, and size of the city were determined with reference to the actual topography and land cover of Tokyo. Differences in land use are expressed by changing the values of the surface parameters for each form of land use.

The initial conditions of atmospheric temperature and humidity were based on the 10-year average of the vertical profile from the Sonde observation at Tateno observatory station near Tokyo during the warm season (June to September). The potential temperature lapse rate was set at 0.004 K/m, regardless of the location. The relative humidity on the ground at the initial time was set at 60%. The initial wind speed value was set at 2 m/s.

A numerical experiment was conducted to assess the impact of the sea and a city on convective precipitation occurring near a coastal city in a summer sunny day. Three experimental cases were prepared: (i) Case U: with the presence of both the sea and a city (this is the control case that refers from the simplified terrain and land-use around Tokyo); (ii) Case S: with the presence of the sea but no city (the city is removed from Case U); and (iii) Case G: all land use as grassland, with no sea and no city (the sea and city are removed from Case U).

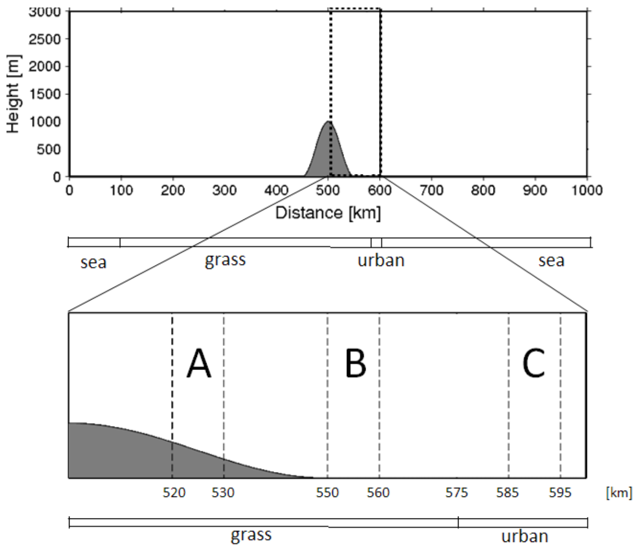

Fig. 4 The lower atmospheric layer and surface parts of the simulation domain. Shading indicates mountain.

3.2 Results of the numerical experiments

Figure 5 shows 12-hours (1200 LT – 2400 LT) accumulated precipitation amount from the three numerical experiments. In the control experiment (Case U), there are two large peaks in the spatial distribution of the accumulated precipitation amount. One peak is appeared in the mountainous area (around x = 530 km) and another is in the inland of the urban area (around x = 570 km). The precipitation amount is relatively small in the inland plain area between the two peaks. It should be regarded that Case U well captures the essential features of observed precipitation distribution, although the precipitation in the inland of the urban area is overestimated. On the other hand, in Case S, the peaks are appeared in the mountainous area (around x = 530 km) and the inland plain area where is far from the coastal area (around x = 555 km). In Case G, there is only one peak in the region, which largely differs from the observations.

Figure 6 shows the time-location cross-section of precipitable water and hourly precipitation from the three numerical experiments. In the control experiment (Case U), precipitation occurs in the mountainous area in the early afternoon, and the precipitation appears around the urban area on the leeward side of the mountains during the several hours after sunset. The most intensive precipitation in the plain is occurred in the inland of the urban area. Eventually, precipitation system moves to the sea though the urban area. From these, it is concluded that Case U clearly reproduces basic features of the observed spatial distribution and diurnal variation.

An experiment with the sea and no city (Case S) produces roughly similar results to Case U, but substantial difference in the precipitation distribution. In Case S, the precipitation system gradually moves to the coastal area from the mountainous area though inland area of the plain over time. During the movement, the precipitation occurs in throughout of the plain area and maximum value of the precipitation is appeared in the inland plain area.

Results from an experiment without sea and city (Case G) largely differ from those of the other two experiments. In Case G, precipitation is limited to the area around the mountain, although the area with precipitable water of 8 mm or over moves in a leeward direction over time.

Figure 7 shows that the urbanization enhances the surface sensible heat flux, which produces an anomalous surface pressure depression in early afternoon. In Case U, the resulting increase in surface heat flux can make the sea-breeze front more clearly defined and increased the time required for the sea breeze to reach inland areas. This modification of the sea breeze should decrease the inland moisture transport while increasing the moisture transport to Tokyo.

Figure 8 shows variation over time in upwind and precipitable water in three areas: the mountain area (Region A), inland area (Region B) and coast area (Region C) from the control experiment (Case U). Looking at variation over time in the mountain region (Region A), it is evident that the precipitable water increases with time during the day, and decreases from evening to night. Precipitation occurs at or after 14:00, when precipitable water has increased, and the peak is at 16:00. On the other hand, the peak in precipitable water at the coastal part of the plain appears somewhat delayed in time relative to the mountain area. Also, this peak is thought to be produced by sea breezes. Looking at Fig. 6 and Fig. 8 together, it can be determined that short-time rainfall during the period 18:00-20:00 at this station is caused by the upwind resulting from the convergence of cold outflow from the mountains and sea breezes, and the increase in precipitable water. It can be conjectured that the reason why the precipitation amount is low in the inland part of the plain near the mountains is that the sea breezes do not reach there, and a strong convergence of cold outflow from the mountains and sea breezes does not occur there.

Comparing Figures 8 and 9 and 10 clearly show that the convergence of cold drainage current and sea breeze shifts the precipitation system from the mountain to the sea over time. It also shows that this sea breeze front converges with the cold drainage current produced by the precipitation system that moved from the mountain, and that the resultant convergence zone moves toward the sea over time. Thus, the modified sea breeze associated with urbanization and cold drainage current from the convective rainfall over the mountain is a key to understand distribution and diurnal variation of short-time rainfall over the coastal city adjacent to mountain.

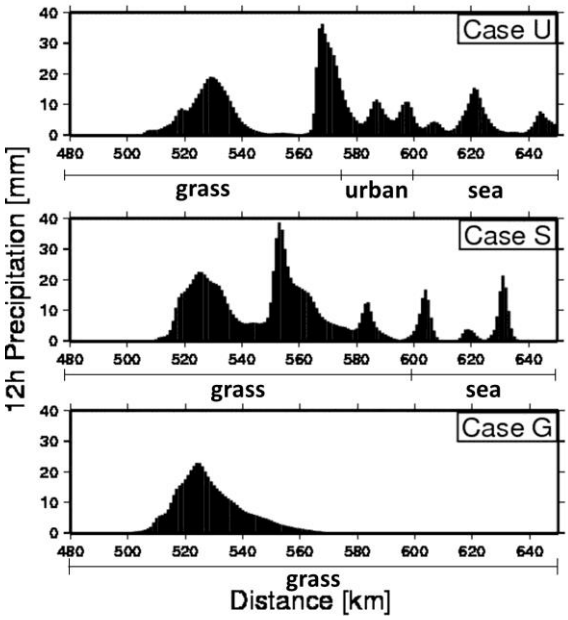

Fig. 5 12-hours accumulated precipitation amount from the three numerical experiments.

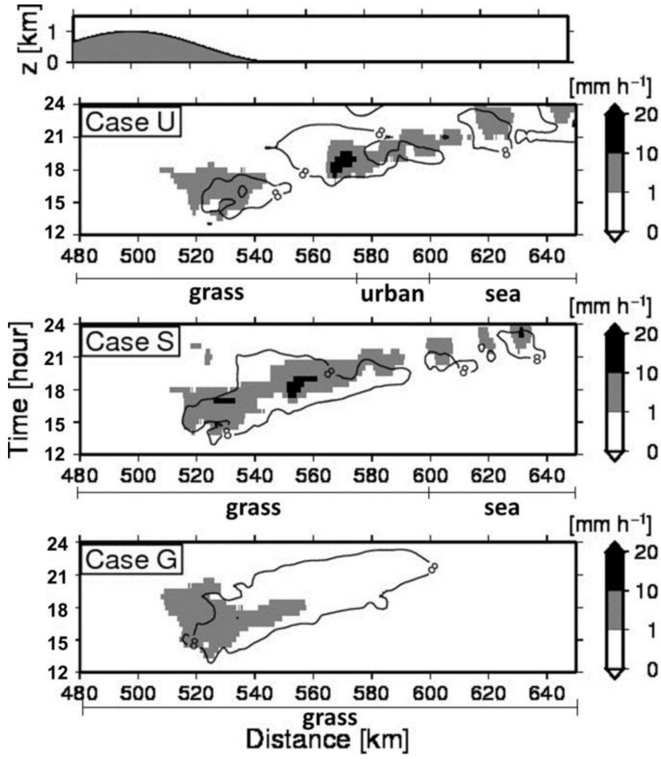

Fig. 6 Time-location cross-section of precipitable water and hourly precipitation from the three numerical experiments.

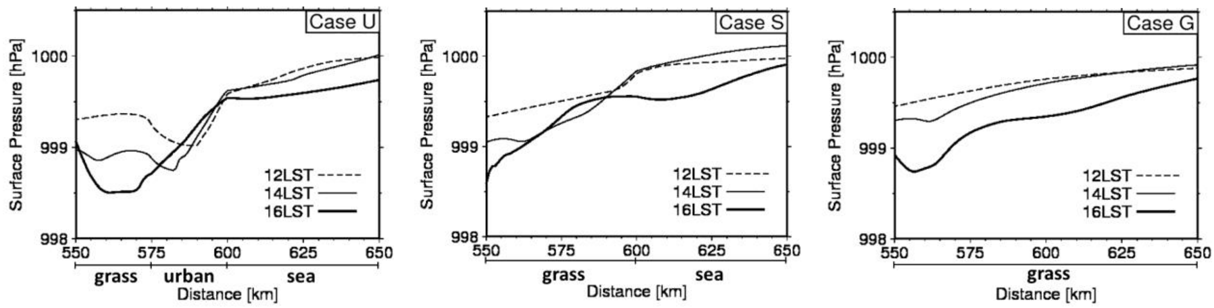

Fig. 7 Temporal and spatial variation of the sea level pressure from the three numerical experiments.

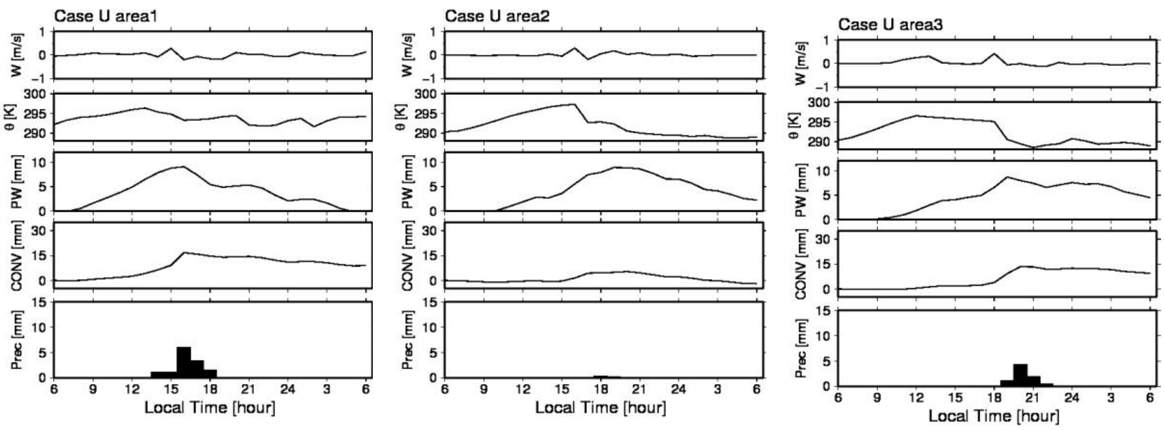

Fig. 8 Diurnal variation of upwind, potential temperature, precipitable water, horizontal convergence of grid-scale moisture flux, and hourly precipitation amount from the control experiment (Case U). Areas 1, 2, 3 indicates Regions A, B, C, respectively.

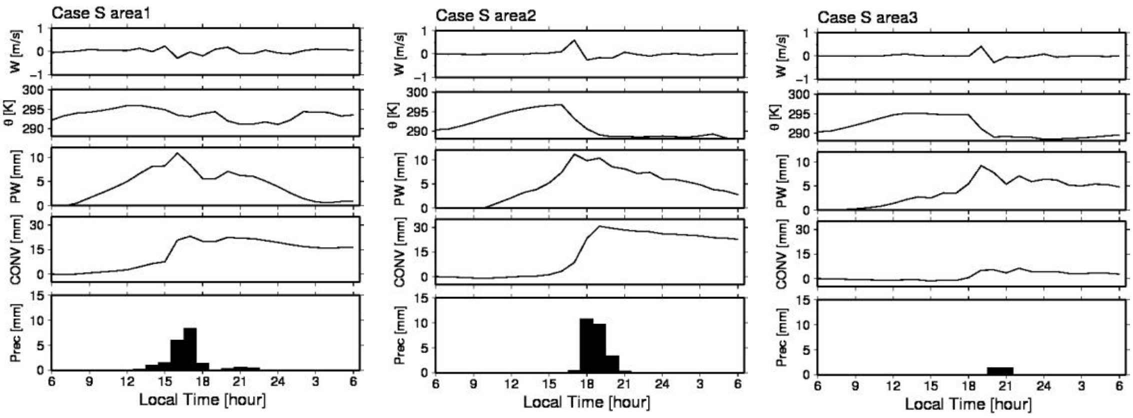

Fig. 9 Same as Fig. 8, but for Case S.

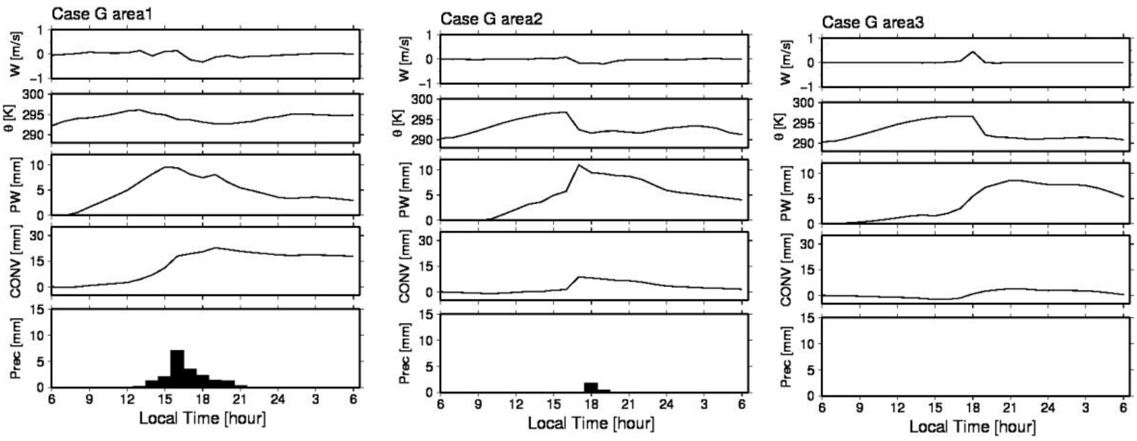

Fig. 10 Same as Fig. 8, but for Case G.

4. Concluding remarks

We conducted research to assess the impact of the presence of the sea and a city on diurnal variation in precipitation occurring in the vicinity of coastal cities with mountains on the windward side and the sea on the leeward side; that is, precipitation observed on the mountain in the daytime and in the coastal urban area in the nighttime.

The experimental results show that daytime rainfall over the mountain occurred due to valley wind circulation, whereas convergence of the cold drainage flow from the convective rainfall and sea breeze produced nocturnal rainfall in the urban area. Additionally, the shift in the precipitation area toward the sea (city), due to the presence of the city, is one of the most important impacts of the city on precipitation.

Thermally induced local circulation, such as valley circulation, sea breeze circulation, or heat island circulation, is generated on sunny days with weak winds in mountainous, coastal and urban areas. A close relationship is known to exist between such local circulations and diurnal variation in precipitation. The experimental results in this study will contribute to local circulation over the complex terrain and land-use as well as urban climate.

Acknowledgment

This research was supported by the Grant-in-Aid for Scientific Research A (13370953) of the Japan Science and Technology Agency (JST), Japan and the Japan Science and Technology Agency's (JST) CREST program entitled "Research and Development of Unified Environment on Accelerated Computing and Interconnection for Post-Petascale Era."

References

Kusaka H., Nawata N., Suzuki-Parker A., Takane Y., Furuhashi N., 2014: Mechanism of precipitation increase with urbanization in Tokyo as revealed by ensemble climate simulations. *J. Appl. Meteor. Clim.*, **53**, 824-839.