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A COMBINED DYNAMICAL/STATISTICAL DOWNSCALING APPROACH FOR ASSESSING FUTURE OF WATER RESOURCES IN THE TONE RIVER BASIN, JAPAN

Mohamed RASMY[1], Maheswor SHRESTHA[1], Toshio KOIKE[2], Masayuki HARA[3], Mikiko FUJITA[3], and Fujio Kimura[3]

[1]Member of JSCE, Ph D., Research Associate, Dept. of Civil Engineering, University of Tokyo (Tokyo, Japan)
[2]Fellow of JSCE, Dr. Eng., Professor, Dept. of Civil Eng., University of Tokyo (Tokyo, Japan)
[3] Japan Agency for Marine-Earth Science and Technology (JAMSTEC), (Kanagawa, Japan)

Dynamical downscaling is a promising tool to assess the future fate of water in a catchment. To overcome strong biases in Coupled Ocean-Atmosphere General Circulation Models (CGCMs), the Pseudo Global Warming Downscaling (PGW-DS), which combines climatology differences (future-past) of CGCM ensembles and Reanalysis Dataset (RD) was proposed as a reliable and efficient method, but biases originated from downscaling of RD was not addressed. Hence, this study evaluated the results from a long-term, high-resolution Downscaled Precipitation (DP) derived from a RD over the Tone river basin. DP showed strong bias over mountainous regions owing to resolution enhancement. DP and CGCM precipitations were merged with Statistical Bias Correction methods (SBC) to obtain a comprehensive outlook on biases and the most appropriate SBC. Characteristics of biases were quite different in DP and CGCM, which performed very poor for extreme rainfall intensities and thus required an explicit treatment. Seasonal inconsistency in extreme events of CGCMs affected the corrected rainfall and discharges significantly. Conversely, a simple cumulative gamma method was successful for DP to represent climatology, extreme statistics of rainfall and discharges owing to the use of RD, which generated lesser bias compared to CGCMs. The proposed method will be applied to PGW-DS to obtain reliable information of future changes of water in the basin.

Key Words: *Dynamical downscaling, statistical bias correction, combined downscaling method, precipitation*

1. INTRODUCTION

The climate change is inevitable and adversely impacting on a range of natural and socio-economic systems1). Though CGCM is a primary tool to assess the future precipitation changes, several features/processes, which influence character and severity of the basin scale consequences, are overlooked in the model. As policy makers have a critical opportunity and a timely need to assess the climate change impacts at regional/basin scale, two major techniques (i.e. *Dynamical Downscaling (DD)* and *Statistical Downscaling (SD)*) have been used to bridge the gap between CGCMs and basin scales; the merits and drawbacks of each have been documented extensively2).

When evaluating climate change in an island like Japan, DD is a promising approach over SD as it exploits Regional Climate Models (RCMs) and high-resolution datasets to resolve finer-scale features (e.g. cloud convection and orography) consistent with larger scale phenomena of parent CGCMs3)4). However, DD still contains biases inherited from parent CGCM as well as shortcomings from RCM itself. It was reported that DD outputs were strongly influenced by parent CGCM bias6), which is the largest obstacle for DD of climate change. In fact, DD does not modify the larger-scale processes derived from CGCMs. Rather it adds regional/local details in response to regional/local scale forcing (e.g., topography)5) and thus certain CGCM systematic biases cannot be removed simply by increasing resolution. As a result, DD of CGCM failed to simulate stronger rainfall events and the northward movement of Baiu front over Japan 7),8).

Recently, the use of long-term reanalysis (based on real world data) products was recommended to overcome the aforementioned issues of CGCM biases in climate change researches (e.g. Pseudo Global Warming Down-Scale (PGW-DS))7),9). Studies showed that PGW-DS reduced large scale model bias, allowed estimating climate difference between past and future with significantly reduced the computational cost, and had high success downscaling future climates7),9),10).

However, reanalysis data should not be fully equated with “reality" because of biases in observations and models used. Moreover, RCMs can also be a source of additional bias, depending on physics schemes, parameterizations, the season, and the types of climatic elements[7]. There were a few studies[11),12)] that analyzed the PGW-DS at basin scale. Though, these studies reported the issues of downscaled results, unfortunately, did not address the methods to improve the uncertainties of downscaled results to obtain reliable climate change information and their impacts.

In contrast to DD, Statistical Bias correction (SBC), which was considered as an alternative to DD, is computationally inexpensive but requires a long-term observations, which are available in the study domain adequately. Merging these two methods is a newly emerging approach to produce value added climate dataset and to obtain reliable scientific information on climate change, which is the primary objective of Research Program on Climate Change Adaptation (RECCA). It would reduce the computational burden of so-called super-high-resolution simulations and improve the biases in RCMs by utilizing long-term observations, while maintaining the effect of finer scale features (e.g. orography) and spatial/temporal continuity simulated by RCMs. Having realized the merits of a combined method, it is crucial and timely required to identify the nature of biases in the downscaled precipitation, which is derived from reanalysis data and to find out an appropriate SBC method (comparing with CGCM) to account for the bias prior to evaluating impacts of climate change.

Accordingly, this study performed a long-term high-resolution historical RCM simulations using reanalysis dataset over Japan. The output was investigated at basin scale using a high density in-situ network. Three bias correction methods were tested to account for the bias in DD rainfall. In addition, hydrological responses to precipitation outputs were evaluated using a distributed hydrological model to address basin scale integrated validity of the value added dataset.

2. METHODS AND DATA

(1) Study Area

This study focused on the Tone River basin, which has the largest catchment area (16,840 km^2) in Japan. The critical importance of this basin is very apparent as it also supplies water to the Tokyo Metropolitan area, which is the political and economic center of Japan and has high population density (27 million). As a result, future water issues are a major concern in this basin under the framework of RECCA because any marginal changes in precipitation will make the country more vulnerable to disasters.

(2) RCM Domains and setup

Fig.1 depicts a topographic structure of selected domains for dynamical downscaling experiments.

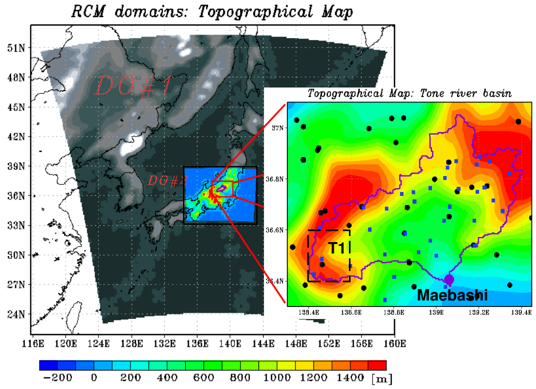

Fig.1 Selected model domains for RCM simulations and the upper Tone river basins (right), color shading, black dots and blue dots depict the topographical structure, AMeDAS locations, and MLIT data locations, respectively.

Table 1: Configurations of domain 1, 2 and 3

Parameters	Domain 1	Domain 2
Number of grids	121X131	149X149
Boundary conditions	ERA-Interim	Domian 1
Spatial resolution (km)	24	6
Time resolution (s)	120	30
Microphysics scheme	WRF Single-Moment 6-class scheme (WSM6)	Same as domain 1
Cumulus scheme	Kain-Fritsch	None

RCM simulations were performed using Weather Research and Forecasting (WRF) version 3.3.1[13]. The models configuration and applied physics were summarized in **Table 1**. WRF historical simulations were performed for 30 years (1980-2010). The initial conditions and boundary conditions were obtained from the ECMWF Re-Analysis (ERA-interim) data, which is the latest global atmospheric reanalysis produced by the ECMWF and covers the period from 1979 onwards[14]. 5-day running mean of 2 m air temperature was used as a lake temperature to avoid the usage of SST over inland lakes. Boundary conditions for sub-domains were obtained from domain 1 by one-way nesting.

(3) Statistical bias correction method

Three kinds of SBC approach were tested. The first is Extreme Correction (EC), in which daily precipitations greater than the 99th percentile were classified as extreme events and the Generalized Pareto Distribution (GPD) was used to model Partial Duration Series (PDS) (values above the threshold of 99th percentile regardless of time of occurrences) of observed and WRF's extremes[15]. The bias corrected WRF extremes, X'_{WRF} were calculated as

$$X'_{WRF} = F^{-1}_{Obs.}\left[F_{WRF}(x)\right] \tag{1}$$

Where $F^{-1}_{Obs.}$ is the inverse GDP function of observation, and F_{WRF} is GPD function of WRF.

In the second approach, Extreme and Gamma Correction (EGC) extreme rainfall was treated explicitly as mentioned above, whereas the rest of the rainfall was corrected with a two-parameter cumulative gamma distribution16). In the third approach the entire dataset was bias corrected by the same two-parameter gamma distribution (GC). For better comparison of SBC methods, two CGCMs (i.e. Miroc3.2_hires and GFDL.CM.2.1) selected for S-8 scenario and PGW-DS were also included in the analysis.

(4) Hydrological modeling and set-up

Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM) was used and the details of model set-up and parameters of Tone river were given in Wang et. al17). Natural flow conditions (without dams) were assumed and hypothetical observed discharges were estimated using observed rainfall to analyze the effect of rainfall bias correction method on whole catchment area using the basin integrated discharges. Discharge analysis was done for peak and monthly climatology at Maebashi outlet.

(5) Rainfall data

Observed rainfall data (1980-2010) collected from Automated Meteorological Data Acquisition System (AMeDAS) of JMA and gauges installed by Ministry of Land, Infrastructure and Transport (MLIT) (Fig. 1) were merged together to better represent the reality of the basin. Inverse Distance Method (IDW) was applied to gauge data to obtain gridded and continuous (missing was filled) records to compare with WRF output.

3. RESULTS AND DISCUSSION

This section was divided into 3 subsections: (a) climatology of dynamical downscaled results at the basin scale, (b) investigation of the statistics and bias correction methods at a location, and (c) analyses of corresponding discharges from WEB-DHM.

(a) Climatology at basin scale

Fig.2(a), Fig.2(b), and Fig.2(c) are climatology plots of annual precipitation WRF-24km, 6-km, and observation. As shown in the figures, though WRF-6km (hereafter WRF) captured better spatial distribution compared with observation (Pearson's correlation coefficient=75%) and WRF-24km owing to resolution enhancement and inclusion of finer scale features, the error statistics were much higher (Mean Bias Error (MBE) = 882 mm/yr; RMSE=1080mm/yr) and precipitation amount was overestimated, especially at high altitudes, exceeding 1500 mm/year (~annual amount). To obtain insight on monthly characteristics, monthly climatology differences between WRF and observation are showed in **Fig.3.** As it can be distinguished clearly; WRF model overestimated the monthly climatology of precipitation at higher altitude regions for all months. As the higher altitude region receives snowfall during winter period (Dec.-Mar.) in this basin, a significant portion of the overestimation can be attributed to observational errors owing to the under-catch of snowfall by the tipping bucket type rain gauges.

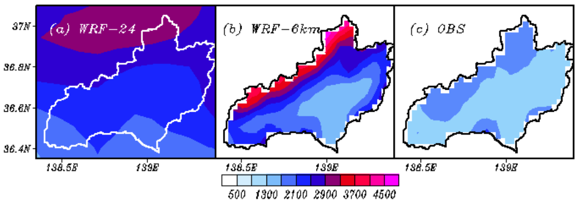

Fig.2 Annual climatology (mm/year) for (a) WRF-24km, (b) WRF-6km, and (c) observation.

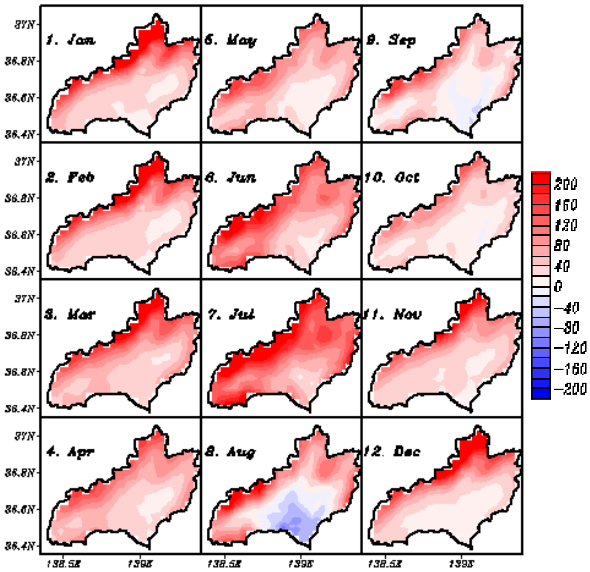

Fig.3 Monthly climatology differences of precipitation (mm/month) between WRF and observation.

However, overestimation of rainfall during other months especially during Jun.-Aug. must be attributed to model errors suggesting that WRF model has high sensitivity to topography, which affects on precipitation dynamically and thermodynamically. The dynamic role includes the triggering and enhancement of the convection and rainfall, whereas the thermodynamic role results in thermal contrast (daytime heating and nighttime cooling), which produces local circulation. Similar overestimation over high attitudes in Shikoku Island was reported in our study18) suggesting that the issue is general to all of Japan. Our initial investigation found that wind speed and relative humidity (10m) was much higher in WRF suggesting further investigation.

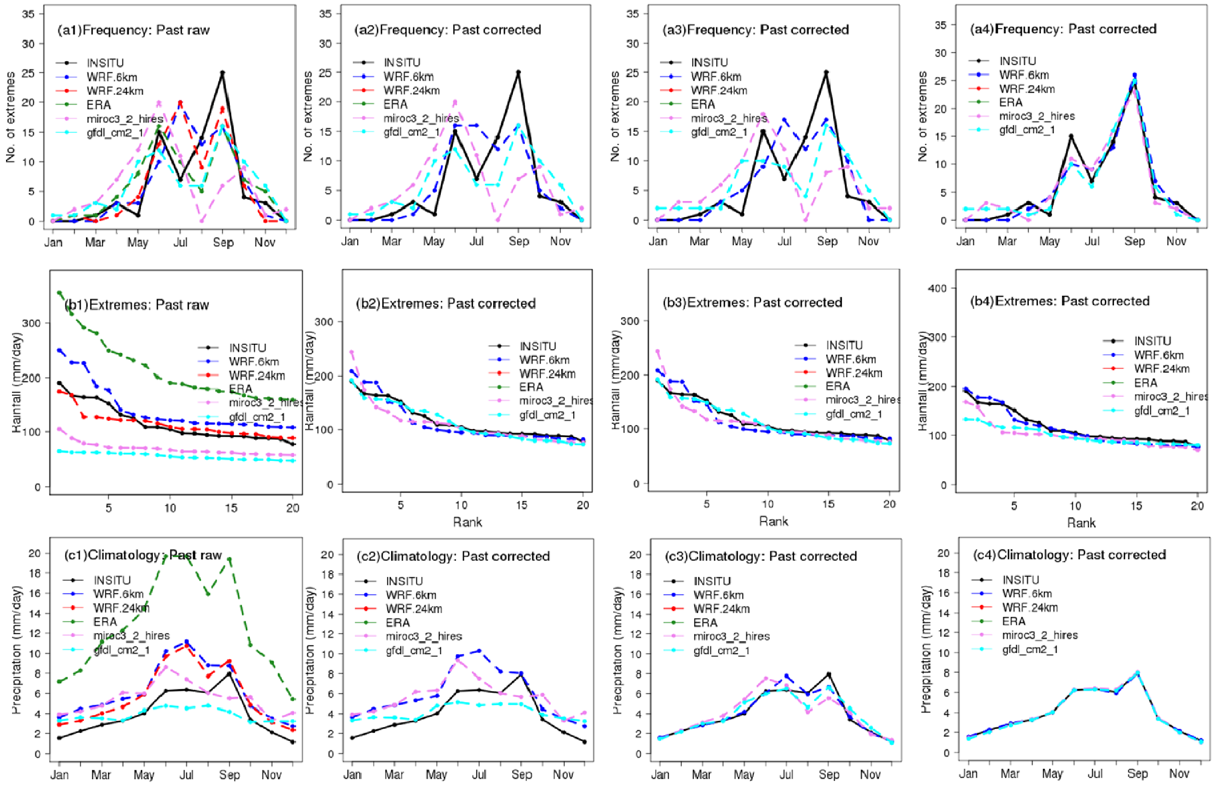

Fig.4 Statistics of raw and bias corrected rainfall at T1 location for (a) frequency distribution of extreme events > 99 percentile, (b) ranking plots for top 20 extreme events, and (c) monthly climatology: first column is for raw data, second column is for only extreme correction (EC), third column is for extreme and gamma correction (EGC), and forth column is for only gamma correction (GC).

In addition, rainfall during August and September was underestimated at lower altitudes in WRF, which may have been caused by underestimation of heavy rainfall events associated with typhoon events. This problem must be related to the representation of typhoon systems in ERA-interim reanalysis data and an investigation is included in the next section. In summary, the above findings indicate that dynamically downscaled precipitation has strong bias especially over mountainous regions due to resolution enhancement and inclusion of detailed topography that must be taken into account to achieve reliable assessments of future climate change.

(b) Statistics and bias correction methods

As point observations cannot be compared with the WRF gridded output, gauge observation was gridded to WRF resolution at first and then both WRF and observation were scaled up to 20km resolution. A grid (T1 at Agatsuma sub-basin in **Fig. 1**) was chosen for this manuscript to show the topography effect on the simulated rainfall considering the number of gauges within the grid and the high-altitude characteristics.

At first, the representation of extreme rainfall was investigated. In addition to two CGCMs (i.e. MIROC and GFDL), forecast from ERA-interim was also included to investigate the extreme rainfall distribution. Note that the procedures to obtain precipitation are different in the CGCMs, the ERA-interim, and this research.

As shown in **Fig.4(a1)**, ERA-interim showed that the number of extreme rainfall during August as being smaller than observation, which clarifies that reanalysis data has a problem in representing heavy rainfall or typhoon events especially in August, resulting in underestimation of WRF extreme rainfall events. Both CGCMs, especially MIROC showed higher number of extreme in June and very few extremes in August owing to early ending of Baiu and poor representation of typhoon events.

Fig.4(b1) is the ranking plot for the top 20 daily rainfall events. As shown in the figure, both climate models underestimated the intensity of extreme rainfalls due to coarse resolution of the models and the absence of orographic effects. The intensity of extreme rainfalls in the WRF model is higher than WRF-24km as well as observation. Moreover, climatology simulated by the WRF model is also higher than WRF-24km, which confirmed that spatial resolution enhancement produced higher rainfall compared to low-resolution over mountainous regions.

Hereafter, WRF and two CGCMs were analyzed to evaluate bias correction methods (other outputs were out of the scope of this study). **Fig.4(a2)**, **Fig.4(b2)**, and **Fig.4(c2)** are for Extreme rainfall Correction (EC) using GDP method. Although EC method successfully fit the model with observation, there is a very little improvement in monthly climatology ((**Fig.4(c2)**) suggesting that EC alone is inadequate to improve biases.

Fig.4(a3), **Fig.4(b3)**, and **Fig.4(c3)** are for the Extreme and Gamma Correction (EGC) method. Results shown in **Fig.4(b2)** and **Fig.4(b3)** are the same due to identical treatment in both methods, whereas improvements in climatology can be seen but are not fitted well (**Fig.4(c3)**). The climatology of MIROC was overestimated during Apr.-Jun. and underestimated during Aug.-Sep. owing to a problem in the frequency distribution of extreme events. The statistical method only considered ranking, and did not consider seasonal characteristics of observed rainfall (**Fig.4(b3)**). A similar argument is valid for the underestimation of GFDL during Aug.-Sep.. These results suggest that when CGCM are bias corrected directly using EGC method for impact assessments studies care must be taken in comparing the changes in climatology.

Fig.4(a4), **Fig.4(b4)**, and **Fig.4(c4)** are for application of simple Gamma Correction (GC) method. As shown in **Fig.4(c4)**, perfect matches were observed for WRF and both GCMs in terms of climatology and frequency of extreme rainfall distribution. However, as shown in **Fig.4(b4)**, the corrected intensity of CGCM extremes was underestimated significantly owing to excessive underestimation of intensity of extremes in raw data (**Fig.4(c1)**), whereas extremes of WRF were fitted well compared with observed extreme rainfall intensities. These results demonstrate that characteristics of biases in CGCMs rainfall and downscaled rainfall from reanalysis data are completely different. CGCMs biases should be treated with explicit separation of extreme events, whereas WRF does not require such an explicit treatment and biases can be treated with a simple Gamma bias correction method, which not only improves seasonal climatology and frequency distributions of extreme rainfall but also improves intensities of extreme rainfall events.

(c) Analysis of discharges

The previous section investigated the nature of the biases existing in CGCMs as well as WRF precipitation at a selected grid point at high altitude and proposed a simple method for WRF bias correction. However, there is necessity to validate the method at each and every grid of the basin to find out its robustness and drawbacks. As a result, hydrological reposes of the Tone river basin to the bias corrected rainfall from CGCMs by EGC and from WRF by GC were investigated by simulating discharges at Maebashi outlet (Fig. 1), which provides overall performances of the proposed methods by integrating the information from all the grid points.

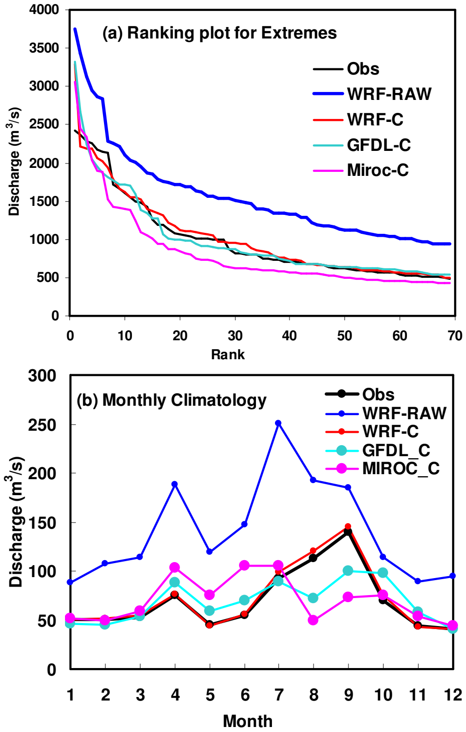

Fig.5 Discharge plot for (a) top 70 daily peak events and (b monthly climatology at Maebashi outlet.

Fig. 5(a) demonstrates the ranking plot for the top 70 daily extreme discharges simulated by the WEB-DHM model for the aforementioned bias corrected inputs. Daily extreme discharges corresponding to the WRF-raw precipitation dataset showed a significant overestimation throughout the period of ranking as similar to rainfall results shown in the previous section indicating that the majority of the grids in the basin overestimated the daily extreme rainfall. Discharge simulated for WRF-corrected (WRF-C) precipitation were in good agreement with that obtained for observed precipitation, which confirms the robustness and applicability of the bias correction method proposed in this study. Moreover, discharges obtained for CGCM based corrected precipitations also followed the observed ranking trend along with underestimation in MIROC. In addition, it is also noted that in all bias corrected rainfall events, the top one or two events are highly overestimated. In the case of CGCM, it is due to ranking correction method, which corresponds to the correction of each and every grid point's top events to the top event in CGCM (one or grids covered the whole basin). In the case of WRF, as the correction method was based on climatology, unprecedented heaviest rainfall occurred in the model during Aug. 1982 was not corrected well.

Variation of monthly averaged discharges is shown in **Fig 5(b)**. CGCM based discharges for bias corrected precipitation are unable to track the monthly variation owing to problems in frequency distribution of extremes (**Fig.4(a3)),** climatology (**Fig.4(c3))** as well as the absence of spatial/temporal continuity in the corrected dataset. In contrast, WRF-C discharges matched quite well with hypothetical discharges (coefficient of determination of 0.99), confirming the validity of the proposed method.

4. CONCLUSION

This study examined the characteristics of biases in DD precipitation from reanalysis data and compared with that of CGCM to find out the nature of biases and an appropriate statistical bias correction method for WRF using long-term high-resolution simulation and observation at the Tone basin.

DD results showed that significant bias over mountainous regions owing to resolution enhancement. Results further concluded that climate models have severe problems in simulating heavy rainfall intensities that demanded explicit bias correction procedures for extremes rainfall events for better representation of extreme rainfall statistics. In addition, the current method (EGC) still has issues in fitting seasonal climatology values of CGCMs with observation due to large differences in seasonal frequency distributions of extreme events and discharges. Therefore care must be taken when using bias corrected results of CGCMs.

On the other hand, WRF precipitation downscaled from reanalysis data showed better representation of extreme rainfall intensities and frequency distributions as compared with CGCMs and observation. As a result, simple gamma correction method fitted the results with observation well. Discharge analysis at Maebashi outlet added further confirmation and validity for the proposed combined method.

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