Precipitation Changes near Three Gorges Dam, China. Part I: A Spatiotemporal Validation Analysis

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ABSTRACT

In October 2010, the water level upstream of the Three Gorges Dam (TGD) reached the designated 175-m level. The associated inundation and land use–land cover changes have important implications for water resource management, agriculture, ecosystems, and the hydroclimate. Ultimately, it is important to quantify whether the dam-related changes have altered precipitation patterns. Since rain gauges are limited in the region, satellite-based methods are viable. This study is the first to validate NASA Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) data from 1998 to 2009 using 34 national meteorological rain gauges in the Three Gorges region. Areal average satellite estimates are first verified with areal average rain gauge data both annually and seasonally. Then based on empirical orthogonal functions, the study area is divided into two subregions, and similar validation procedures are performed for both subregions. TMPA data are found to have high correlations with rain gauge data for the whole study area, and correlations for the subregions are only slightly lower. The seasonal analysis yields the lowest correlations for winter. Compared with the gauge data, rainfall is slightly overestimated by about 3 mm month\(^{-1}\). At daily scale, satellite data show good agreement with gauge data for all rain intensity categories except light rain (<1 mm day\(^{-1}\)). Spatially, the point-source gauge data are gridded using Thiessen polygons for comparison with satellite data, and the results suggest the satellite-based product may overestimate rainfall in mountainous areas near the reservoir, especially in spring and summer. Overall, the validation results yield strong statistical support for applying satellite rainfall data for hydroclimate studies in this region.

1. Introduction

Since the National Congress of China officially approved the Three Gorges Project in 1992, there have been many ongoing debates and concerns in a variety of fields. After the reservoir started to store water in June 2003, the water level upstream of the dam abruptly rose from 66 to 135 m (above sea level). This project has become the largest hydroelectric project in the world since the water level rose again to 156 m in October 2006. In October 2010, the water level finally reached the designated 175 m. In addition to inundating 19 towns and counties and 24 000 ha of arable land, the project destroyed a tourist region not unlike the Grand Canyon in the United States (Gwynne and Li 1992). Over a million people were displaced from fertile farmland. This change also had serious secondary environmental impacts (Tan and Yao 2006): 1) fragmentation of large, continuous habitats into smaller patches; 2) reduction of biodiversity; and 3) modification of ecological processes like nutrient and water cycling, and eventually other irreparable ecological damage (Edmonds 1992; Shen and Xie 2004). Other issues include the sedimentation problem, reservoir-induced earthquakes, and landslides (Wang 2002). Despite the huge debates and reported negative effects, the Three Gorges Dam (TGD) was eventually built because of the substantial benefits in hydroelectric power generation, flood control, and navigation (Wang 2002).

While the Three Gorges area is a research focal point, little literature exists on the hydroclimatic effects of the reservoir, partly because these effects are less apparent, unlike landslides or reduction in downstream flow. A few previous observational and modeling studies have examined the hydroclimatic effects of TGD and reached contradicting conclusions. Miller et al. (2005) performed two numerical model simulations—control and land use change—for an 8-week period (2 April–16 May 1990) to determine the sensitivity of the local climate around the Three Gorges Dam. Results indicated that strong
evaporation was offset by sinking moist air diverging away from the region, and no net change in precipitation was found. Wu et al. (2006) examined the effects of the TGD on the regional precipitation around the vicinity of the TGD by analyzing the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) rain rate data for an 8-yr period (January 1998–January 2006). They concluded that after the TGD, water level rose abruptly. They also found that rain rate had increased in the northern part of the region between the Daba and Qinling Mountains and decreased in the vicinity of the TGD. A recent study by Xiao et al. (2010) analyzed the decadal variation of annual precipitation in the vicinity of the TGD using daily data from 27 rain gauges from 1960 to 2005, and it was concluded that the variation in precipitation around the TGD shown by Wu et al. (2006) is part of the natural interannual oscillation of precipitation, as a similar change of precipitation was observed before and after 1980.

Motivation

Previous studies are limited because of insufficient data and the complicated circulation patterns and topography of the Three Gorges region. Numerical simulations were also limited because of the resolution of their model, accuracy of input data, and reliability of parameterization. One drawback of Wu et al. (2006) is that they did not tease out natural precipitation variation (noted by Xiao et al. 2010). For example, the 2003 El Niño likely affected the precipitation variability in the region. They also did not use point-source observation data to assess the accuracy of satellite data in this region. On the other hand, the sparse observational records Xiao et al. (2010) used may not accurately depict climate conditions in this region because the point sampling of rain gauges may not truthfully represent the spatial distribution of precipitation in an area with complicated topography. Besides, their observed phenomenon might result from factors like instrumental errors, interpolation methods, and replacement of old rain gauges by new ones. Even if the pattern they observed is accurate, it does not directly answer the unresolved question of whether the TGD has any effects on rainfall, or if the precipitation change is completely related to natural variation. Their disagreements and shortcomings highlight the need for more research in this area.

A better understanding of what TGD might be doing to precipitation in its vicinity over the decadal time scales has implications for both the traditional dam planners—operators and society. Managers of the project need to control the water level in accord with climate conditions and achieve a balance between flood prevention and electricity generation. After a severe drought (in 2006) and an unusual flood (in 2007) occurred in regions near the reservoir, possible drought–flood events in the future have drawn much attention from the public. Possible precipitation change also concerns resettled farmers, whose less-fertile new farms use precipitation as a primary water supply since irrigation systems are sparse and costly, given their uphill terrace topography. All these concerns make it interesting and of practical importance to examine the temporal patterns of precipitation and quantify if and how the project has altered precipitation since the water level rose. It is also useful to resolve the spatial patterns to ascertain how different regions will be affected with different precipitation trends. Overall, the lack of consensus in previous research and the major concerns about TGD highlight the importance of this study.

Though beyond the scope of this manuscript, the objective of this research is to assess the spatial–temporal trend of rainfall based on observation-verified TMPA data as the water level of the reservoir changes. This aspect of the study will be addressed in a forthcoming companion paper. However, it is clear that because of ground-based data limitations, satellite-based precipitation estimates will be a viable resource for addressing the problem. This study seeks to validate that a merged satellite product is significantly accurate to properly quantify changes in the regional precipitation climatology that may be associated with TGD and its associated inundation. To our knowledge, it is the first study to verify the satellite estimates with rain gauges in this particular study region—namely, the TGD-reservoir–mountainous complex. The hypothesis is the TMPA estimates will be relatively well correlated with point-source rain gauge estimates, spatially, temporally, and seasonally. Section 2 provides the research design, data, and methodology. Section 3 presents the results and discussions, and conclusions are given in section 4.

2. Research design, data, and method

The National Aeronautics and Space Administration (NASA)’s Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) rain rate data from 1998 to 2009 are employed. We compare the TMPA data with 34 China national-level rain gauges within the region. Multiple verification procedures are performed to evaluate how well (or poorly) TMPA data correlate with gauge data in the study region.

a. Study area

The Three Gorges study area is defined in the vicinity of TGD (28°–34°N, 106°–112°E). The area is chosen to position the reservoir in the middle and to include major adjacent topographic features that might interact with the reservoir in precipitation processes. The elevation ranges from over 1000 to 50 m in the east. The mountainous
areas are located in the middle of the region, while other parts of the region are mostly hilly areas with a few plains (Fig. 1). Mean annual precipitation is 1200–1400 mm in the middle mountainous areas, and 900–1100 mm in the hilly and plain areas. This study area is identical to previous studies by Wu et al. (2006) and Xiao et al. (2010), which makes it convenient to compare with their results. However, the complexity of the terrain also illustrates why ground-based gauge observations are rather limited.

b. Data

1) Satellite Data

Satellite-based daily rainfall amounts from TMPA between 1998 and 2009 are acquired from NASA’s Goddard Earth Sciences (GES) Data and Information Services Center (DISC; http://mirador.gsfc.nasa.gov). TMPA is a 3-hourly, 0.25° (~25 km) product described in Huffman et al. (2007). This study employs the merged TMPA_3B42 3-hourly and TMPA_3B43 monthly version of the TMPA, composed of available microwave [e.g., TRMM Microwave Imager, Special Sensor Microwave Imager (SSM/I), Advanced Microwave Scanning Radiometer (AMSR), and Advanced Microwave Sounding Unit (AMSU)] and calibrated infrared (IR) estimates.

Note that the merged products like TMPA are so relatively new that there is a lack of intercomparison–validation studies in diverse geographic and climatic regimes. Tian and Peters-Lidard (2010) recently noted that large uncertainties in TMPA-like precipitations exist globally, particularly through the seasons in regions of complex terrain. This makes our study a valuable contribution in itself. Hand and Shepherd (2009), in a 9-yr study around Oklahoma City, Oklahoma showed that satellite precipitation estimates capture spatial rainfall variability as well as traditional ground-based resources of the Oklahoma Mesonet. However, TMPA estimates may not perform equally well in different regions. For example, low values of rain rates in interior tropical Africa, central Asia, and the Great Plains in the United States, as well as higher values in equatorial Amazonia and along the southwestern coast of India, are consistent with known issues with microwave-based estimates in those regions (Huffman et al. 2007). It would be interesting to know how well–poorly the TMPA estimates perform, and if the bias is underestimation, overestimation, or mixed in the study area. Herein, we describe a research version of the TMPA that contains a gauge adjustment. The gauges used for the adjustment may contain some of the gauges used for validation in this study, which would influence the correlations between TMPA and gauge estimates. The gauge adjustment is included in the TMPA for the very reason of improving the product and extending it spatially where gauges are not present. It is worth noting that there is also a real-time version of TMPA available for more immediate analysis, and it does not contain a gauge adjustment (not utilized herein). The resolution of the gauge network is coarse (e.g., the 2.5° Global Precipitation Climatology Center monthly gauge dataset described by Arkin and Xie 1994), and so it would be encouraging if, even with this coarse adjustment, our results using 0.25° data products are still accurate.

2) Rain Gauge Data

Thirty-four China National Meteorological monitoring stations (including the 27 stations used in Xiao et al. 2010) within our study area have been selected. The datasets are from the official source of the homogenized dataset of China Meteorological Administration (CMA)’s National Climate Center (NCC), and they are available on the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). The daily precipitation is recorded by manual observations at 6-h intervals. The error of the rain gauge data is less than 0.1 mm, which would not affect the validation purpose of this study. Further details of quality control, instrumentation used, and data processing are given in the appendix. Daily values from 1998 to 2009 for all stations are used for validation, and there are no missing data or changes of site location in this time period. Daily values from 1961 to 1990 are used to construct a climatology. Note that even when aggregating satellite data into 1° cells, the goal of having at least one station in each grid cell is still not satisfied. For the validation purpose, a Thiessen-polygon-based approach (discussed below in
section 3c) is used to compensate for the number of available rain gauges.

c. Research method

It is hypothesized that the TMPA estimates will be relatively well correlated with point-source rain gauge estimates. The region is poorly gauged in the first place. Even if there are substantially more gauges, point-source gauge methods may not be appropriate for analysis of spatial distributions of rainfall, which, unlike temperature or moisture fields, tends to be highly variant. The point-source–area-average problem is well known in precipitation remote sensing communities and is an ongoing area of research (Hand and Shepherd 2009).

Comparisons between satellite-estimated precipitation and rain gauge data have typically used linear regression analysis as the main analytic tool for assessment (Barrett et al. 1994). Multiple validations are performed to examine the quality of TMPA estimates both temporally and spatially. The first set of correlation analyses are conducted for this study to establish the relative accuracy of areal average point source (gauge) versus areal average satellite (TMPA) rainfall estimates. Areal averages of both estimates for the 144 months from 1998 to 2009 within the $6^\circ \times 6^\circ$ latitude–longitude region are calculated. For TMPA estimates, rainfall per month is averaged from the 576 data grids ($0.25^\circ \times 0.25^\circ$ grids). For gauge estimates, averages are derived from all 34 gauges. Pearson’s correlation between the 144 data pairs is calculated. In addition to TMPA’s performance throughout the year, the 144 pairs are divided into four groups by season, and seasonal correlations are examined. Compared with other validation studies (Hand and Shepherd 2009), a possible shortcoming of this approach is that the large study area would inflate correlation coefficients for these highly aggregated data. One possibility is that the study area could be divided into subregions that have distinct precipitation patterns. TMPA data might have large positive biases in some subregions and negative biases in some others, and these biases might cancel out and result in high correlations for the average values of the whole study area. Thus it is important to divide the whole area into subregions within which the rainfall characteristics are similar, and then compare the areal-averaged TMPA estimates with gauge estimates in each subregion. The empirical orthogonal functions (EOFs) obtained from the annual standardized 12-yr TMPA precipitation data (576 $0.25^\circ \times 0.25^\circ$ data grids) allow recognition of the subregions with different precipitation regimes. EOF analysis is an efficient method widely used in research areas including atmospheric science (see review by Hannachi et al. 2007 for more information). For this study, EOF analysis is used only for the purpose of determining subregions. The daily scale cumulative rainfall and frequency distributions of occurrence of daily rainfall for the whole region are also compared.

The next set of correlation analyses aim to examine how accurate TMPA estimates are spatially. It is most convenient to divide the whole area into 36 $1^\circ \times 1^\circ$ cells, which is close to the number of rain gauges. Previous studies have concluded TMPA data can be successfully validated if average values are compared over larger areas (Fisher 2004; Hand and Shepherd 2009). For this approach, a high-density rain gauge network is essential to reduce uncertainties. However, for the Three Gorges region, the study area is relatively large and the rain gauges have relatively low density. The rain gauge observation averaging approach selected for this study is the Thiessen polygon method (Thiessen 1911), because the simplest averaging technique may have limitations with partial rainfall events and bias (Bedient and Huber 2002). This method is also adopted in Han et al. (2010) for similar reasons. We acknowledge that with such a low-density rain gauge network, there will be considerable uncertainties. However, it is still helpful even if we only get a rough idea of the spatial quality of TMPA data in this region. Note that such a scarce rain gauge network is the very reason that satellite-based rainfall estimates should play a critical role in the hydroclimatic research of this region. The Thiessen polygon method first connects all the rain gauges by dashed lines. Next, perpendicular bisectors of the straight lines are constructed. The bisectors meet at a common point inside or outside of the triangle. The resulting polygons around each rain gauge are known as the Thiessen polygons (Bedient and Huber 2002). In this way, the whole region is separated into many polygons, and each of the 34
gauges would be best to represent the precipitation in its surrounding polygon area. Then the polygons are overlaid on the $1^\circ \times 1^\circ$ grids (Fig. 2); most cells are covered by several parts of the polygons surrounding different rain gauges. As a result, each TMPA $1^\circ \times 1^\circ$ grid could be related with one or more rain gauges. TMPA data are resampled to each $1^\circ \times 1^\circ$ cell, and the related $1^\circ \times 1^\circ$ area-weighted average rain gauge data are derived. Annual and seasonal averages from 1998 to 2009 are calculated for each cell for the two data sources. Mean monthly rainfall estimates from the 36 TMPA $1^\circ \times 1^\circ$ grid cells versus the corresponding estimates from the gauge stations for all seasons are compared to determine how well (or poorly) the rainfall distribution from the TMPA data performs.

3. Results and discussions

a. Region-wide validation

Areal mean monthly rainfall estimates from the 576 TMPA $0.25^\circ$ ($\sim 25$ km) grid cells are compared with the areal averages from the 34 gauges to determine how well the rainfall distribution from the TMPA data correlates with the gauge data. Validations over the whole region yield high correlations both annually and seasonally. The correlation between TMPA ($y$) and gauge ($x$) data over the 144 months (1998–2009) is represented as

$$y = 1.0039x + 2.0879.$$  

The regression lines for both precipitation estimates are located barely above a 1:1 line. The correlation coefficient of determination $R^2$ for the 144-month regression is 0.983, and RMSE is 9.1 mm month$^{-1}$ (figure omitted). Over the study area, the TMPA product slightly overestimates the precipitation recorded by gauges, but the mean bias (2.4 ± 8.8) is well within the range (from $-1.0$ to 1.0 mm day$^{-1}$, or $-30.0$ to 30.0 mm month$^{-1}$), noted by Tian et al. (2007). When grouping the 144 months into four seasons, the correlations are still high, although a little lower than before. Figure 3 is the scatterplot of satellite
versus gauge precipitation estimates for the four seasons in the study area. TMPA overestimates precipitation compared with gauge estimates in all seasons but winter.

b. EOF analysis and subregional validation

The temporal and spatial variations of mean annual precipitation in the study area are analyzed by the EOF method. Figure 4 shows the first and second leading modes of the EOF, including their spatial patterns. The results indicate that the first EOF mode (Fig. 4a) accounts for 46.8% of the total variance while the second mode (Fig. 4b) explains 30.0% of the total variance. The spatial and temporal patterns obtained from the TMPA data are similar to the EOF results presented by Xiao et al. (2010). The EOF analysis shows that the dominating factor of precipitation has some consistency throughout the region (same sign for the first mode). The time variances (Figs. 4c,d) show that large-scale patterns are not fluctuating severely in the 12-yr study period, which is encouraging for an epoch analysis. Based on the north–south pattern from the second mode, the region is divided into north and south subregions. No further dividing is necessary as any mode other than the first two explains less than 10% of the total variance.

The correlations over 144 months for both the north and south subregions are still high (regression lines close to 1:1, $R^2 = 0.9771$ for north and 0.9737 for south, RMSE = 11.5 for north and 12.3 mm month$^{-1}$ for the south subregion; figures omitted). Over the north subregion, the TMPA product overestimates the precipitation...
recorded by gauges; the mean bias (5.2 ± 10.3 mm month$^{-1}$) is larger than averaging over the whole study area, but still well within the range of ±30.0 mm month$^{-1}$ noted by Tian et al. (2007). Over the south subregion, TMPA only slightly overestimates the precipitation with a lower overall bias (0.6 ± 12.3 mm month$^{-1}$). When examined in four seasons, winter is found to have the lowest $R^2$ values in both subregions (Figs. 5 and 6). Overall, the correlation results suggest that while averaging over a smaller region does make the correlations a little lower with larger biases and RMSE errors, it is not substantial enough to conclude that TMPA performs poorly when validated with smaller regions.

c. Daily scale frequency analysis

The distribution of TMPA is also correlated with gauge data at daily scale for over 4000 days, and the correlation coefficient is found to be significantly lower ($R^2 = 0.4594$), as one might expect for this type of product. The frequency distribution of occurrence of daily rainfall totals in the ranges 0–0.005 (trace), 0.005–0.1 (very low), 0.1–1 (low), 1–5 (moderately low), 5–10 (moderately high), 10–25 (high), and >25 (extreme) mm is produced. The results from both satellite and gauge estimates show that the area-averaged high and extreme rain days (area-averaged daily rainfall totals exceed 10 mm) occur less than 9% of the time. The two estimates have good consistency for

Fig. 5. As in Fig. 3, but for just the north subregion.
occurrence of rainfall in the categories over 1 mm day\(^{-1}\) (Fig. 7). This indicates that TMPA does not bias the rainfall distribution of moderate or higher intensity. Below this threshold, TMPA has much fewer days with <0.005 mm day\(^{-1}\) precipitation, and compensate in the other two categories. This is probably because the rain gauges are confined by minimum measurement, thus having many more “0” readings. Also, since satellite estimates include infrared data sources, these may mistake cold cirrus clouds for precipitation. Note that this portion of precipitation is not likely to be substantial and useful for agricultural production.

d. Spatial validation

Mean monthly (averaging from 1998 to 2009) rainfall estimates from the aggregated TMPA 1° × 1° grid cells are compared with the corresponding estimates (area-weighted conversion from the Thiessen polygons) from the gauge estimates to determine how well the rainfall distribution from the TMPA data correlates with the gauge data. TMPA is found to be spatially correlated well with gauge data. The correlation coefficient is \(R^2 = 0.91\) annually and the bias is 3.3 ± 5.6 mm month\(^{-1}\) with a RMSE of 6.5 mm month\(^{-1}\). Spatial correlations are not as high in summer and fall (\(R^2 = 0.8054\) and 0.8498, respectively) compared with spring and winter (\(R^2 = 0.9387\) and 0.9536, respectively). Figure 8 presents the spatial difference maps for four seasons (TMPA – gauge). Less than 1/5 of the whole area is found to have a difference higher than 15 or lower than –10 mm month\(^{-1}\) in any season. The quality of TMPA data is found to be more satisfactory in fall and winter (although the difference is small in winter, it is probably due to low winter
precipitation in this region). Overall, there are many more positive biases, and they are mostly seen over mountainous regions near the reservoir. All the results of the verifications suggest that the TMPA estimate of precipitation is quite robust in this area. Although rain gauge data are used as a reference (ground truth), they do have some biases of their own. Additional weaknesses are inevitable when converting point-source data to data grids, as noted in a precipitation analysis over Australia converting from up to 6000 gauges to 25-km grids (Weymouth et al. 1999). The quality of the analysis depends on the density of gauge reports (sparse data imply larger errors), the complexity of the local terrain (because gauges in mountain areas are generally sited in valleys and, therefore, underreport the true areal average rainfall), and undercatch (Huffman et al. 2007). Because gauges are spatially less dense and tend to be located on relatively low and flat ground in the study area, it is likely that many topographically induced precipitation events will not be captured by the rain gauges. Therefore, the point-source gauge data might underestimate precipitation in the mountainous regions. The large positive “bias” of TMPA might represent the true precipitation conditions.

FIG. 7. Frequency distribution of both TMPA (dark gray) and gauge (light gray) area-averaged daily rainfall estimates from 1 Jan 2002 to 31 Dec 2009.

FIG. 8. Spatial differences (TMPA − GAUGE) overlaid with topography in (a) spring, (b) summer, (c) fall, and (d) winter. Red indicates overestimations, blue indicates underestimations, and light yellow indicates areas with few differences.
4. Conclusions

Multiple correlation analyses indicate TMPA rainfall data have good quality in the study area. Overall, TMPA tends to overestimate rainfall by about 3 mm per month. Temporally, TMPA estimates correlate less well with gauge data in winter. Spatially, compared with gauge data, noticeable TMPA overestimates are found in some mountainous regions adjacent to the reservoir, especially in spring and summer. A closer examination at the daily scale shows the relatively low correlation between TMPA rainfall and gauge data at the daily scale is mostly due to large discrepancy in the frequency of very light rain days (<1 mm day⁻¹). Similar frequencies are found for other categories with rainfall greater than 1 mm day⁻¹, where the rainfall is more agriculturally–economically meaningful.

The results presented herein provide quantitative evidence that the TMPA analysis is quite viable for studying regional hydroclimate changes in the TGD region. This study has provided an understanding of spatiotemporal and seasonal biases in using satellite-based methods to interrogate the regions precipitation climatology. Future work (Part II) will use the TRMM dataset and an epochal analysis to investigate precipitation variability before, during, and after the TDG construction. This work is also useful for algorithm developers and scientists anticipating improved 3-hourly precipitation estimates from the Global Precipitation Measurement Mission.

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APPENDIX

Details of the Rain Gauge Measurements

Every rain gauge has an inner diameter of 20 cm. The most common type of rain gauge is SM1 made in Shanghai. Rainfall is collected in a glass container through a funnel, which can reduce evaporation. Moreover, an extra observation is done after heavy rainfall in the warm season to minimize the effect of evaporation. In the snowy season, the funnel is removed and snow can fall directly into the container, it is brought indoors to make the snowmelt, and then the amount of resulting water is measured. The collecting surface of rain gauges is 70 cm over the ground, and they are installed in open ground. Such location can reach satisfying accuracy as indicated by Experimental Research on Rain Gauges Installation Location, which is a national wind tunnel test carried by 16 provincial hydrological stations (National Hydraulic and Hydroelectric Industry Standard of China 2005). In the late 1980s, manual reading procedure has started to be continuously changed to an automatic one by installation of a siphoning type of rain gauges. The most common type is SJ1 made in Shanghai. The inner diameter is unchanged, the installation locations are chosen in the same manner as previous ones, and the new gauges can measure rainfall intensity within the range of 0.05–4 mm min⁻¹. The accuracy of precipitation measurements is 0.05 mm. Implementation of this transformation of the reading did not implement change of time to which the reading is attributed.

Precipitation measure occurs daily at 0800 Beijing time (UTC +8). All data undergo strict quality control by CMA NCC. Errors from relocation, measurement, and other reasons are corrected, and the datasets are homogenized. However, the corrections applied did not include wind correction. The error is less than 3% as indicated by the result of experiment.

REFERENCES


