



# Toward a ground-based and long-term meteorological forcing dataset for South Korea

Kyungtae Lee<sup>1,2</sup> · Do Hyuk Kang<sup>3</sup> · Hahn Chul Jung<sup>4</sup> · Gwangha Park<sup>5</sup> · Changwoo Gye<sup>6</sup> · Sujay Kumar<sup>7</sup> · Edward J. Kim<sup>7</sup> · Christa D. Peters-Adams<sup>8</sup> · EuiHo Hwang<sup>5</sup>

Received: 12 September 2022 / Accepted: 5 April 2023 / Published online: 27 April 2023

© The Author(s) 2023

## Abstract

The Modern-Era Retrospective Analysis for Research and Application version 2 (MERRA-2) is a well-established reanalysis dataset and is widely used for driving global-scale hydrological models. However, owing to its relatively coarse spatial resolution ( $0.5^\circ$ ), the capability of MERRA-2 is repeatedly challenged in regional-scale studies, especially for smaller areas of interest. In addition, the availability of in situ observation data is a pressing issue for generating meteorological forcing. We developed a grid-based high spatial ( $0.125^\circ$ ) and temporal (hourly) resolution meteorological forcing dataset, which can evaluate hydrological processes in South Korea using state-of-the-art meteorological observations from 1980 to 2020. The forcing dataset was created by combining Automated Synoptic Observing System (ASOS) in situ measurement data from the Korean Meteorological Administration and MERRA-2 reanalysis datasets. Five meteorological variables were provided in the ASOS-MERRA2 (precipitation, air temperature, surface pressure, specific humidity, and wind speed). The study demonstrates that the region-based and high spatial resolution of ASOS-MERRA2 is superior to the existing MERRA-2 with improvements of all five weather variables, for example, from 5.6 to 2.8 mm root mean square error of precipitation. The ASOS-MERRA2 was more capable of reducing the biases and root mean squared error by improving the coefficient of determination compared with MERRA-2 for all five variables. The newly developed ASOS-MERRA2 provides an opportunity to drive land surface models to evaluate the hydroclimatic conditions in South Korea.

## 1 Introduction

Comprehensive and reliable meteorological datasets are essential for driving land surface hydrological models (Fang et al. 2015; Guo et al. 2018; Raimonet et al. 2017). In addition, the availability of large-scale, long-term datasets of land surface water and energy states is critical for understanding the global environmental system and water cycle variables (Chun-Lin and Xin 2011; Moradkhani 2008). The Global Land Data Assimilation System and the Famine Early Warning Systems Network Land Data Assimilation System provide a suite of multi-model and multi weather forcing estimates of hydro-climate conditions for data-sparse, food-insecure regions (McNally et al. 2019, 2017; Rodell et al. 2004). As a continuing effort, the North American Land Data Assimilation System has been implemented to produce substantial estimates of land surface hydrology (Mitchell et al. 2004). Specifically, high-quality forcing datasets can be used to identify the onset and demise of droughts and floods (Dong et al. 2011) using the land surface model (LSM). Such datasets can also evaluate historical extreme events and prevent record-setting

✉ Do Hyuk Kang  
dk.kang@noaa.gov

<sup>1</sup> Department of Geographical Sciences, University of Maryland, College Park, MD, USA

<sup>2</sup> Geodesy and Geophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

<sup>3</sup> Weather Program Office, NOAA, Silver Spring, MD, USA

<sup>4</sup> Department of Earth System Sciences, Yonsei University, Seoul, South Korea

<sup>5</sup> Water Resources Satellite Research Center, K-Water Institute, K-Water, Daejeon, South Korea

<sup>6</sup> SELab, Seoul National University, Seoul, South Korea

<sup>7</sup> Hydrological Science Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

<sup>8</sup> Earth Science Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA

disasters in advance by combining effective water resource management measures with model simulation (Lee et al. 2017a). However, consistent observations of land surface water and energy budgets are frequently unavailable over large scales (Sheffield et al. 2006). Thus, the significance of accurate forcing for large-scale land surface modeling efforts was established (Berg et al. 2003; Fekete et al. 2004; Nijssen and Lettenmaier 2004; Sheffield et al. 2004).

Globally, many studies have created several decadal time series of forcing data, including the variables of precipitation, temperature, humidity, and radiation at daily to sub-daily timescales. Most of these products have been based on reanalysis data such as those provided by the National Centers for Environmental Prediction–National Center for Atmospheric Research (Kalnay et al. 1996; Kistler et al. 2001), the European Center for Medium-Range Weather Forecasts ERA-40 and ERA-15 (Gibson et al. 1997; Uppala et al. 2005), the National Centers for Environmental Prediction–Department of Energy (Kanamitsu and Saha 1996), and the National Aeronautics and Space Administration Global Modeling and Assimilation Office (Schubert et al. 1993) reanalysis. In addition to these global datasets, a few datasets have been developed to improve the accuracy of meteorological data on a regional scale, such as the Canadian Land Data Assimilation System (Carrera et al. 2015), the European Land Data Assimilation System (Jacobs et al. 2005, 2008), and the China Meteorological Forcing Dataset (He et al. 2020).

In South Korea, few studies have attempted to develop reliable meteorological forcings. However, high-resolution precipitation and temperature data are necessary to identify detailed spatial drought and flood conditions at a regional scale. The necessity of the development of forcing datasets and hydrologic model was highlighted to meet the full potential of regional land surface modeling as flood and drought monitoring system to provide continuous high-resolution water and energy balance variables in South Korea (Jung et al. 2019). Korea Land Data Assimilation System (KLDAS) has been established for agricultural drought (i.e., soil moisture deficit) monitoring in South Korea (Jung 2021). Soil moisture and evapotranspiration were calculated throughout South Korea using the KLDAS of the Korea-Land Surface Information System to monitor drought (PARK et al. 2021). For instance, the Modern-Era Retrospective Analysis for Research and Application version 2 (MERRA-2) products can represent most inland areas in South Korea with an intermediate spatial resolution of  $0.5^\circ$ . Most recently, Lim et al. (2012) developed meteorological forcing data to drive the LSM at each grid point using analysis-based and observation-based data. The forcing data consisted of temperature, relative humidity, wind speed, surface pressure, and longwave radiation. They were obtained

from the  $0.5625^\circ$  Global Data Assimilation and Prediction System (GDAPS) analysis fields of the Korea Meteorological Administration at 6-h intervals. All variables were interpolated from the GDAPS grid to 10 km for South Korea. For example, precipitation was generated using 6-h accumulated precipitation reports from the World Meteorological Organization Global Telecommunication System and hourly precipitation from the Automatic Weather System over the Korean Peninsula. Precipitation data were then spatially interpolated using Shepard's distance-weighting method (Shepard 1968; Willmott et al. 1985) for South Korea. However, the forcing dataset in South Korea is only available for the 5-year period from 2004 to 2008.

Berg et al. (2003), Ngo-Duc et al. (2005), and Sheffield et al. (2004) showed that there was great potential and advantages for using hybrid datasets that combine reanalysis with observation-based datasets to remove biases. This hybrid approach preserves the consistency and continuity of the reanalysis. Many studies have developed large-scale, long-term datasets using a similar hybrid method (Nijssen et al. 2001; Maurer et al. 2002; Nijssen and Lettenmaier 2004; Livneh et al. 2013). To overcome the current restriction of forcing data availability for South Korea, this study adopted a hybrid dataset of observations and reanalysis data.

This paper aimed to create a 41-year (1980–2020) near-surface meteorological dataset (hereafter called ASOS-MERRA2) with hourly time scales at  $0.125^\circ$  spatial resolution. The ASOS-MERRA2 represents an improvement of the reanalysis dataset (i.e., MERRA-2) in South Korea. An expected advantage of these newly created forcing data is that they should contain temporal and spatial characteristics similar to ground-truth meteorological observations. This study describes the process of creating ASOS-MERRA2 and its validation, including bias and correlation improvements from the existing MERRA-2. In addition, comparison statistics are presented, such as annual, monthly, and daily statistics of precipitation, temperature, pressure, specific humidity, and wind speed from hourly data. The evaluation was carried out in four major river basins in South Korea to explore basin-wide characteristics. The key features of the ASOS-MERRA2 are its long period, reliability, high resolution, and continuity of weather data development.

The remainder of this paper is organized as follows. Section 2 describes the observation data, and Section 3 explains a method to merge MERRA-2 and ASOS. Sections 4 and 5 demonstrate the improvement and comparison statistics of the ASOS-MERRA2 in spatial and temporal scales using the independent stations approach (He et al. 2020). Finally, Sect. 6 concludes with the newly developed, locally available forcing dataset and its potential use for hydrologic modeling.

## 2 Data

This section includes the study area, local weather observations, base meteorological forcing dataset, and a method to merge the observational and reanalysis datasets to create a new forcing dataset for South Korea.

### 2.1 Study area

The study area covers the southern part of the Korean Peninsula between 34–38.5°N and 126–130°E. Over 60% of the domain consists of mixed forests, deciduous broadleaf forests, and woody savannas, whereas 30% is cropland, mainly in the western and southwestern regions. Urbanized areas accounted for 5.2% of the domain (Jung et al. 2020; Sur et al. 2015). This study focused on four major river basins in South Korea. The national water management framework has been mainly oriented to the Han River basin (26,000 km<sup>2</sup>) in the north, Geum River basin (10,000 km<sup>2</sup>) in the west, Nakdong River basin (24,000 km<sup>2</sup>) in the southeast, and Seomjin-Yeongsan River basin (8,000 km<sup>2</sup>) in the southwest of South Korea (Lee and Kim 2007). The geographical regions of the four major river basins are shown in Fig. 1. In Section 5, each forcing was analyzed in the different river basins. Figure 1 shows the spatial distribution of the Automated Synoptic Observing System (ASOS) stations and the availability of data at each station in South Korea.

#### 2.1.1 ASOS

Automated Surface Observing System units (Gang et al. 2016; In et al. 2014; Kim et al. 2020, 2018; Lee et al. 2017b) are automated sensors designed to serve meteorological and aviation observational needs ([www.weather.gov/media/asos/](http://www.weather.gov/media/asos/)). Ninety-four ASOS stations are operated over the four major river basins by the Korea Meteorological Administration in South Korea. Precipitation, temperature, pressure, relative humidity, and wind speed observations were collected to generate a forcing dataset, as described in Section 3. The advantage of the automation of the surface observations is the reduction or elimination of direct human involvement in collecting, processing, and disseminating (transmitting, displaying, and broadcasting) the surface observations. Even though the ASOS is a highly automated and reliable product, quality control has been implemented to ensure the automated product is of a high standard. There are three levels of quality control for ASOS at different temporal and spatial scales. Level 1 is performed on site in real time before an observation is transmitted. Level 2 is completed for a designated area,

usually within 2 h of the scheduled observation transmission time. Level 3 is performed centrally on all aviation routine weather reports nationwide in South Korea.

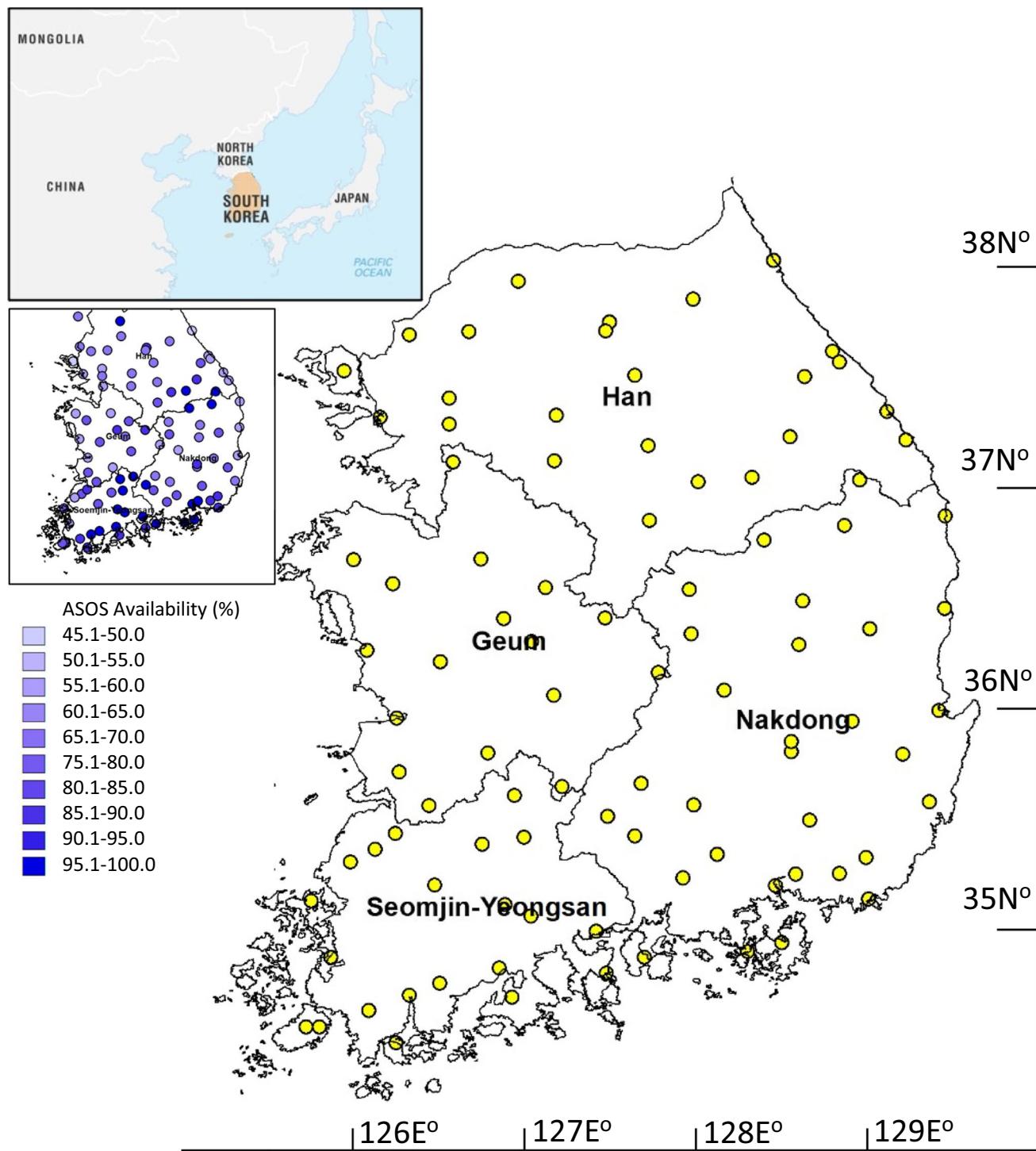
### 2.2 MERRA-2

The MERRA-2 (Gelaro et al. 2017) datasets were used to provide the underlying dataset for ASOS-MERRA2. The MERRA-2 is available globally at an hourly and horizontal resolutions of 2/3° longitude by 1/2° latitude. It was intended as an intermediate reanalysis dataset, which influences recent developments at the National Aeronautics and Space Administration Global Modeling and Assimilation Office (GMAO) in modeling and data assimilation to provide a milestone for GMAO's longer-term goal of developing an Integrated Earth System Analysis. Specifically, the MERRA-2 data product was used to fill the unmeasured station data from the ASOS. The detailed process of combining the data of ASOS and MERRA-2 is described in Section 3.

## 3 Method of generating ASOS-MERRA2

Even though most ASOS stations have continuous and automated observations, some data were missing due to operational issues such as initiation, partial malfunction, and potential maintenance. About 28% (11.5 out of 41 years on average) of the data were neither unmeasured nor unavailable from ASOS stations, and the corresponding MERRA-2 product was used to fill the missing data gaps. Each grid cell of ASOS-MERRA2 at 0.125° and the contained within the MERRA-2 cell at 0.5° are the identical. For example, MERRA-2 cell (38.5N and 129.5E) has value of 1.58 m of precipitation; the corresponding 16 ASOS-MERRA2 cells (the combination of 38.3125N, 38.4375N, 38.5625N, 38.6875N and 129.3125E, 129.4375E, 129.5625E, 129.6875E) are also 1.58 m.

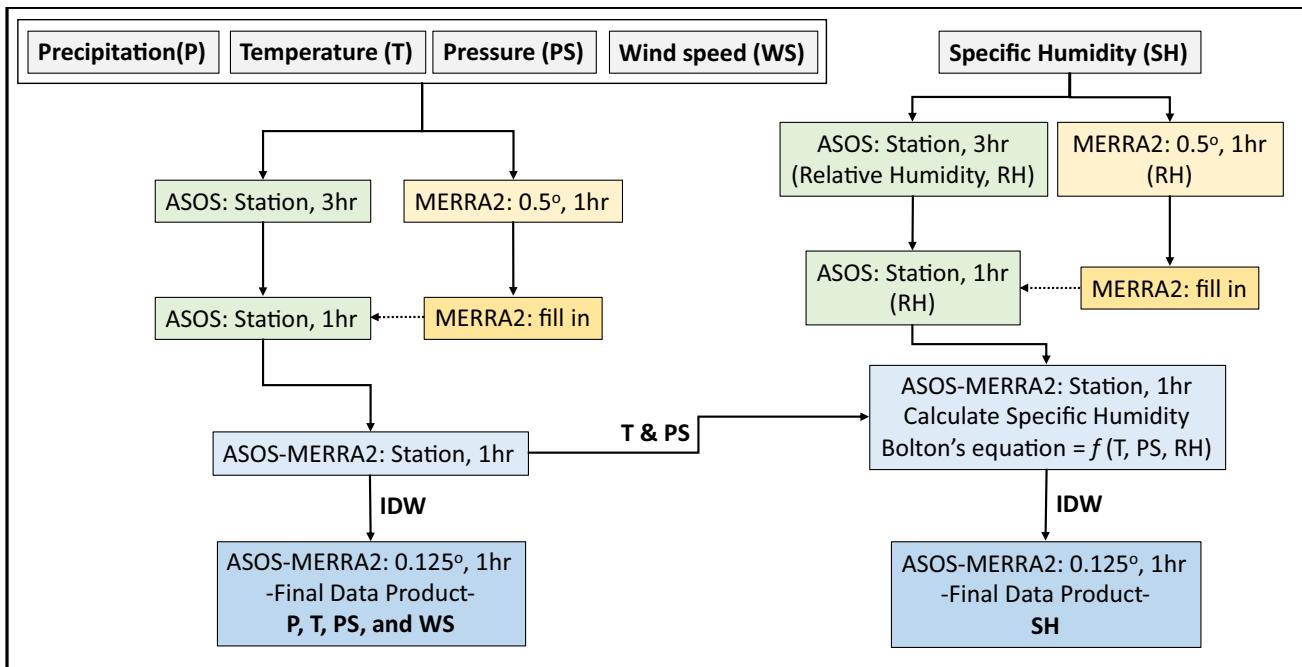
The algorithm for creating the new forcing dataset is shown in Fig. 2. For example, the ASOS station has a 3-h time series of precipitation from January 1985 to December 2020 (the available period). No data were available between January 1980 and December 1984 (the missing period). The first step was to divide the 3-h data into hourly time series. The next step was to find the corresponding MERRA-2 grid precipitation data for the missing period. We then combined the missing period with MERRA-2 and the available period with ASOS in the continuous time series from January 1980 to December 2020. The output time series from this combination is referred to as ASOS-MERRA2. Once we had a continuous 41-year-long time series at each station, these point data were spatially interpolated using the inverse distance



**Fig. 1** Four major river basins and 94 Automated Surface Observing System (ASOS) stations (yellow dots) with ASOS availability (blue dots) in South Korea

weighting method (Shepard 1968) at a grid size of  $0.125^\circ$ . The same procedure was applied to the temperature, pressure, and wind speed data to generate ASOS-MERRA2. Exceptionally, the specific humidity (SH) was calculated from both the ASOS and MERRA-2 relative humidity

(RH), the newly developed ASOS-MERRA2 temperature (T), and pressure (PS). Once we had a continuous time series of RH, T, and PS, the calculation of SH by Bolton's method (Bolton 1980) was applied using the following equations:



**Fig. 2** Algorithm for creating the Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2)

$$vp_{sat} = 6.112 \times e^{\frac{(17.67 \times T)}{(T+243.5)}}$$

(1)  $RH$  = relative humidity(%)

$$vp = vp_{sat} \times \frac{RH}{100}$$

(2)  $SH$  = specific humidity(g/kg)

$$T_d = \log\left(\frac{vp}{6.112}\right) \times \left[ \frac{243.5}{\left(17.67 - \log\left(\frac{vp}{6.112}\right)\right)} \right]$$

(3)

$$vp = 6.112 \times e^{\frac{(17.67 \times T_d)}{(T_d+243.5)}}$$

(4)

$$SH = \frac{0.622 \times vp}{(PS - 0.378 \times vp)} \times 1000$$

(5)

where

$vp_{sat}$  = saturation vapor pressure(hPa)

$vp$  = vapor pressure(hPa)

$T$  = air temperature(°C)

$T_d$  = dew point temperature(°C)

$PS$  = surface pressure(hPa)

Again, the SH point data were spatially interpolated using the inverse distance weighting method at a grid size of 0.125°. The final product of ASOS-MERRA2 was a gridded dataset from January 1980 to December 2020 with hourly temporal resolution. There were 721 ASOS-MERRA2 grids (0.125°) that covered the southern part of the Korean Peninsula, while MERRA-2 only had 65 grids (0.5°) across the same area. The physical definitions of the variables used are given in Table 1.

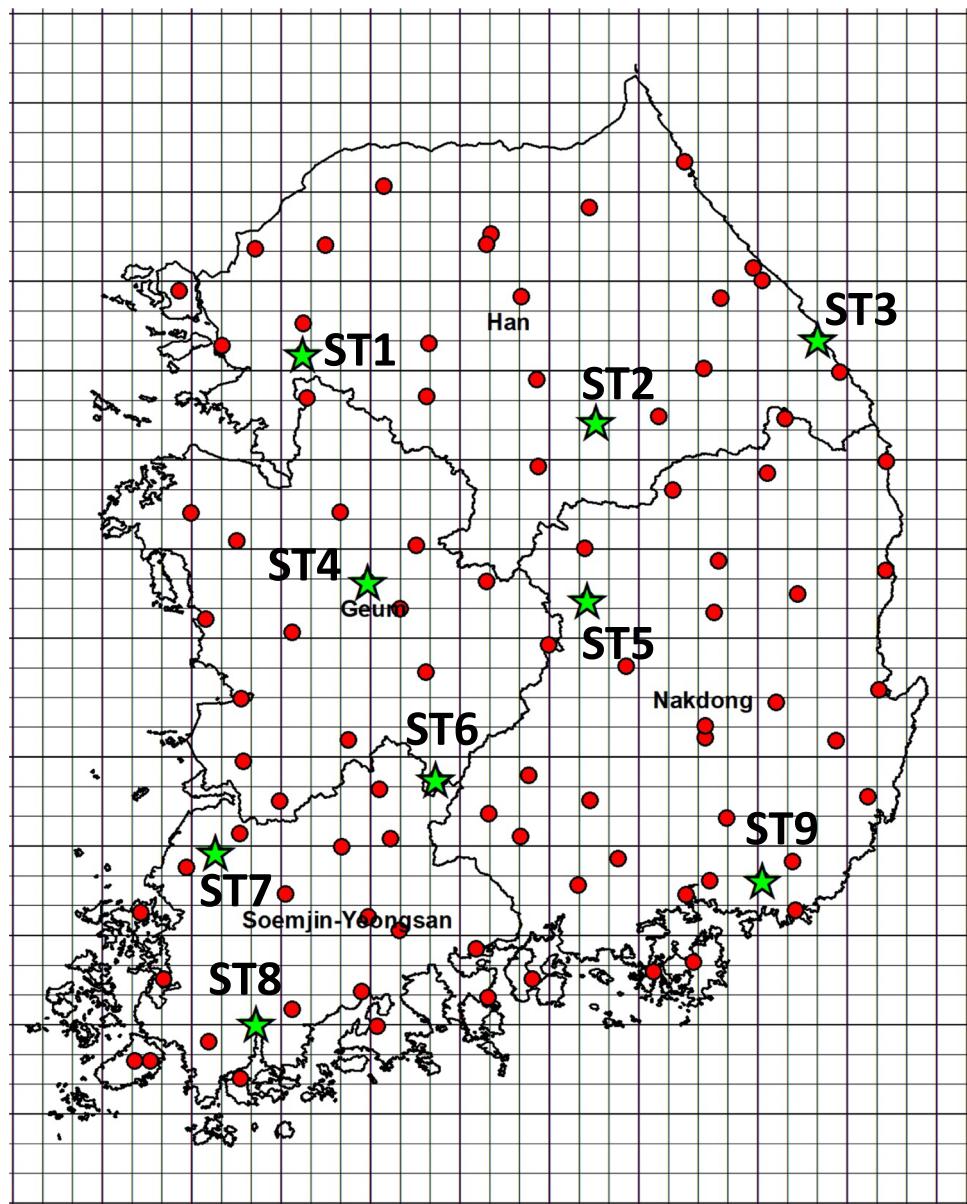
#### 4 Validation of ASOS-MERRA2

The most important question is whether the newly generated ASOS-MERRA2 is better than the existing MERRA-2 datasets, which are widely used globally. To test the robustness of the ASOS-MERRA2, the observational data of nine stations of the 94 stations (about 9.6% of total stations) in South Korea originally used to create ASOS-MERRA2 were intentionally removed, and then the ASOS-MERRA2 forcing was regenerated (Fig. 3). These nine stations were selected

**Table 1** Definitions of the variables used in the Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) forcing data set

Variables	Variable name	Unit	Source
Precipitation	P	mm	ASOS precipitation and MERRA-2 PRECTOTCORR
Temperature	T	K	ASOS temperature and MERRA-2 TLML
Pressure	PS	hPa	ASOS pressure and MERRA-2 PS
Specific Humidity	SH	g/kg	ASOS relative humidity, temperature, pressure, and MERRA-2 QLML Bolton's equation
Wind speed u-direction	WS <sub>u</sub>	m/s	ASOS wind speed, <i>u</i> -direction angle, and MERRA-2 ULML
Wind speed v-direction	WS <sub>v</sub>	m/s	ASOS wind speed, <i>v</i> -direction angle, and MERRA-2 VLML
Wind speed	WS	m/s	$\sqrt{(WS_u)^2 + (WS_v)^2}$

**Fig. 3** Validation of the Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) using hypothetically unknown stations. Green stars: nine ASOS stations excluded from ASOS-MERRA2; red dots: 85 ASOS stations used in ASOS-MERRA2\*. There are three values from each green star: [1] MERRA-2 grid value, [2] ASOS-MERRA2\* grid value, and [3] ASOS station value



based on two criteria: (1) at least two stations were selected within each basin, and (2) those selected stations were at least 80 km apart to avoid overlapping with other validation-purpose stations. This validation method was adopted from the China Meteorological Forcing Dataset (He et al. 2020) and gave us another version of ASOS-MERRA2. Hereafter, the altered version is referred to as ASOS-MERRA2\*, where \* stands for the distinction from ASOS-MERRA2. It should also be noted that ASOS-MERRA2\* is not the released version of ASOS-MERRA2 and is for validation purposes only. Because the observational data from the nine removed stations were not involved in creating the gridded ASOS-MERRA2\*, they could be used as independent observations to evaluate the result of the algorithm of ASOS-MERRA2\*. The statistical error metrics of MERRA-2 and ASOS-MERRA2\* were calculated on a daily scale against local observations from the nine stations, and the results are summarized in Fig. 4. The statistical error metrics of the ASOS-MERRA2\* based on the evaluation at the nine excluded stations were compared with the gridded background (MERRA-2) dataset for 1980–2020. To test whether these two mean values (between MERRA-2 and ASOS-MERRA-2 data for each variable: precipitation, air temperature, surface pressure, specific humidity, and wind speed) were statistically different, two-sample *t*-test (Snedecor and Cochran 1989) was implemented with the null hypothesis that the population mean values were equal for the two samples. Then we did not reject the null hypothesis and concluded that the two-population means were not significantly different at the 0.05 significance level.

For precipitation and temperature, the coefficient of determination ( $R^2$ ) results for ASOS-MERRA2\* were only slightly improved compared with MERRA-2 data from 1980 to 2020. The mean absolute error (MAE) and root mean square error (RMSE) of ASOS-MERRA2\* precipitation and temperature were lower than the MERRA-2 results. Although the  $R^2$  of pressure was somewhat improved from MERRA-2 to ASOS-MERRA2\*, the MAE and RMSE were significantly enhanced with closer-to-zero errors. For specific humidity and wind speed, the overall statistical error metrics ( $R^2$ , MAE, and RMSE) were improved for ASOS-MERRA2\*. The  $R^2$  of wind speed was the lowest for both MERRA-2 and ASOS-MERRA2\* among the five forcings. Because the wind speed value in this comparison was a combination of the wind direction and its magnitude in both the *u*- and *v*-directions, the lower daily  $R^2$  may be due to this compound and sensitive estimation. In conclusion, the algorithm for creating ASOS-MERRA2 can reduce biases and improve correlations in the input gridded data from observations against MERRA-2. Although one validation set may not be enough to say that this sample data and results are valid. To support this idea, we have tested ‘two’ additional sets of validation. A total number

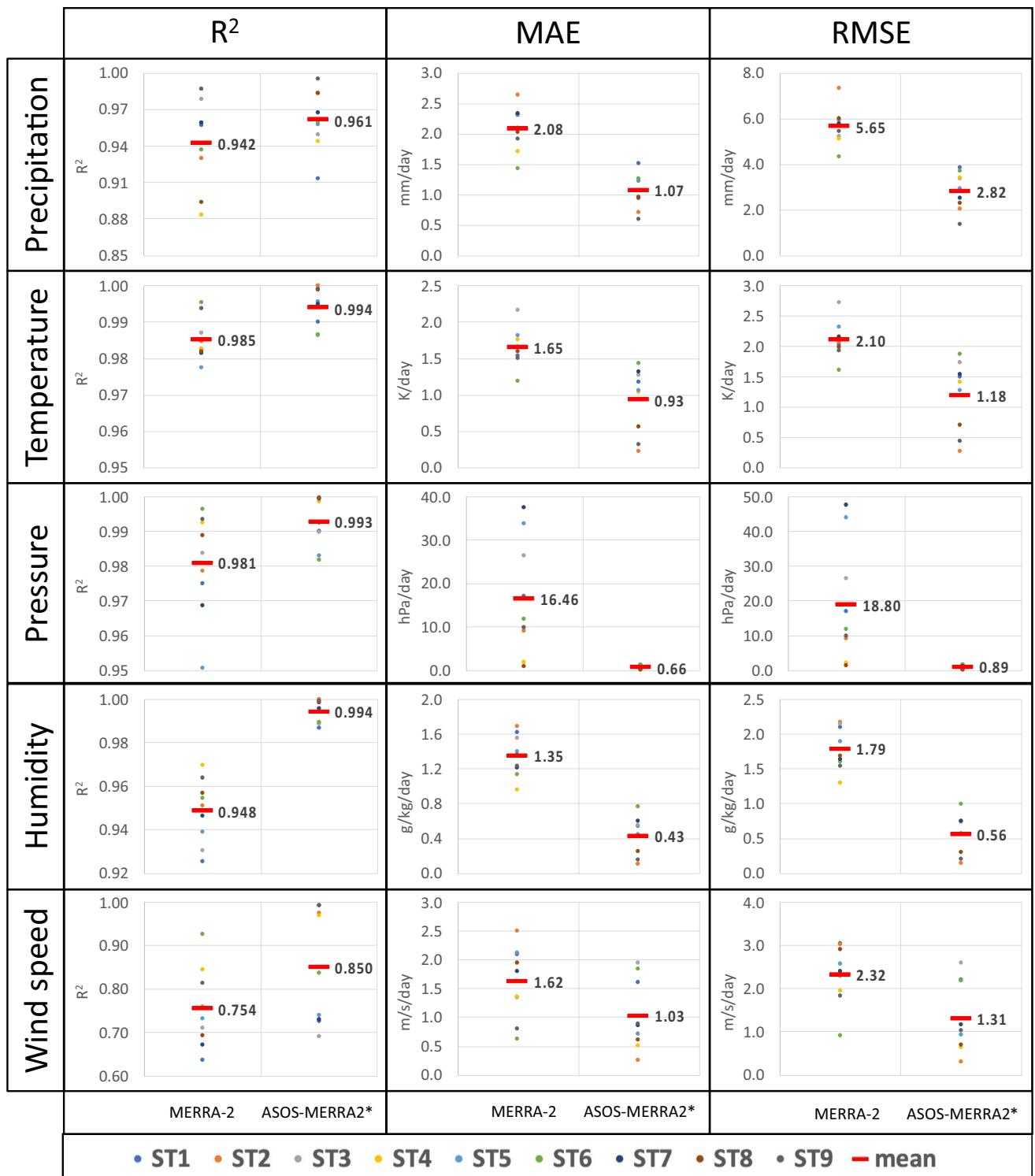
of three different sample datasets was tested in the same validation method. However, two additional validation sets showed nearly the same results in comparison against ASOS ground observation. Since the results were not improved (or changed), the additional validation comparison was not included in this chapter.

## 5 MERRA-2 and ASOS-MERRA2 comparison

### 5.1 Precipitation

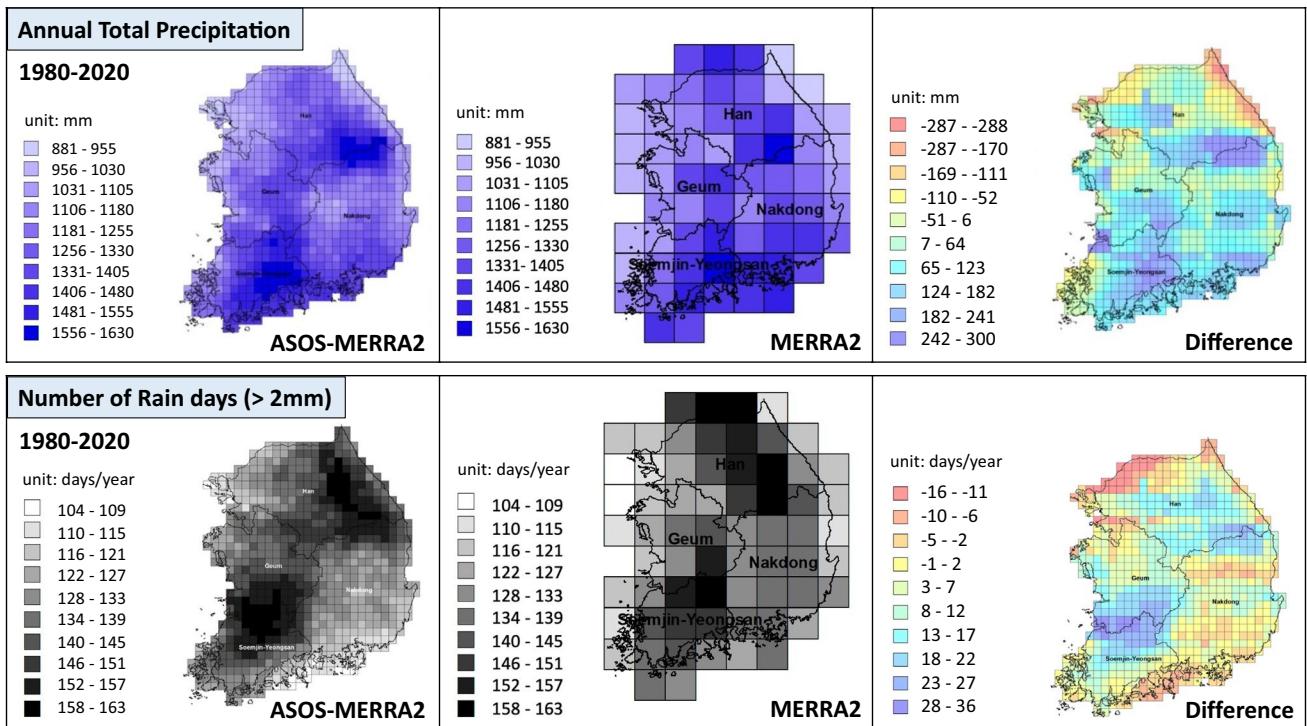
The spatial distribution of precipitation from MERRA-2, ASOS-MERRA2, and their differences are compared in Fig. 5. Each grid cell in the top panel indicated a mean annual total precipitation over 41 years (1980–2020). The overall amount of ASOS-MERRA2 precipitation was greater than that of MERRA-2. The annual total precipitation (ATP) ranged from 993 to 1631 mm in ASOS-MERRA2 and 881 to 1583 mm in MERRA-2. Wetter conditions were found in the Seomjin-Yeongsan River basin, while the Nakdong River Basin had relatively dry conditions for both forcings, indicating a recent severe drought in this basin (Ryu et al. 2002; Yang and Kim 2013). Most regions had more precipitation in the ASOS-MERRA2, except the northern and eastern parts of the Han River Basin, which had less precipitation. The bottom panel of Fig. 5 shows the number of rain days (more than 2 mm precipitation per day) per year for each grid cell. The ASOS-MERRA2 forcing had more rain days in the Geum and Seomjin-Yeongsan River basins, while MERRA-2 had more rain days in the Nakdong River Basin and the northern part of the Han River Basin. The ATP and rain days showed a similar spatial pattern in MERRA-2 and ASOS-MERRA2, yet ASOS-MERRA2 provided more spatially distinctive patterns with the observation-driven data.

The ATP, monthly mean precipitation, and number of rain days were calculated for South Korea and the four basins as a time series (Fig. 6). For the ATP, ASOS-MERRA2 generally had more precipitation than MERRA-2, and the difference between the two forcings was evident in the Geum River Basin. In addition to the difference in the ATP in the Geum River Basin, this basin also did not show good agreement of the rain days between the two forcings. Recent reports have addressed the climatic complexity of the Geum River Basin (Ahn et al. 2018, 2016; Lee et al. 2018), and it appears that ASOS-MERRA2 successfully captures the dynamics of precipitation in this basin. South Korea had high precipitation in summer, which peaked in July. The four basins had nearly identical monthly cycles of precipitation. The number of rain days also showed similar fluctuations and ranges (80–140 days) between MERRA-2 and ASOS-MERRA2.



**Fig. 4** Statistical error matrices for the validation of the Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2).  $R^2$ , coefficient of determination; MAE, mean absolute error; RMSE, root

mean square error; MERRA-2, difference or relationship between [1] MERRA-2 and [3] ASOS observations; ASOS-MERRA2\*, difference or relationship between the [2] ASOS-MERRA2\* and [3] ASOS observations



**Fig. 5** Spatial analysis of precipitation using Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) and MERRA-2, and the

difference between these. To calculate the difference, MERRA-2 grid ( $0.5^\circ$ ) was evenly downsampled to match ASOS-MERRA2 grid resolution ( $0.125^\circ$ )

## 5.2 Temperature

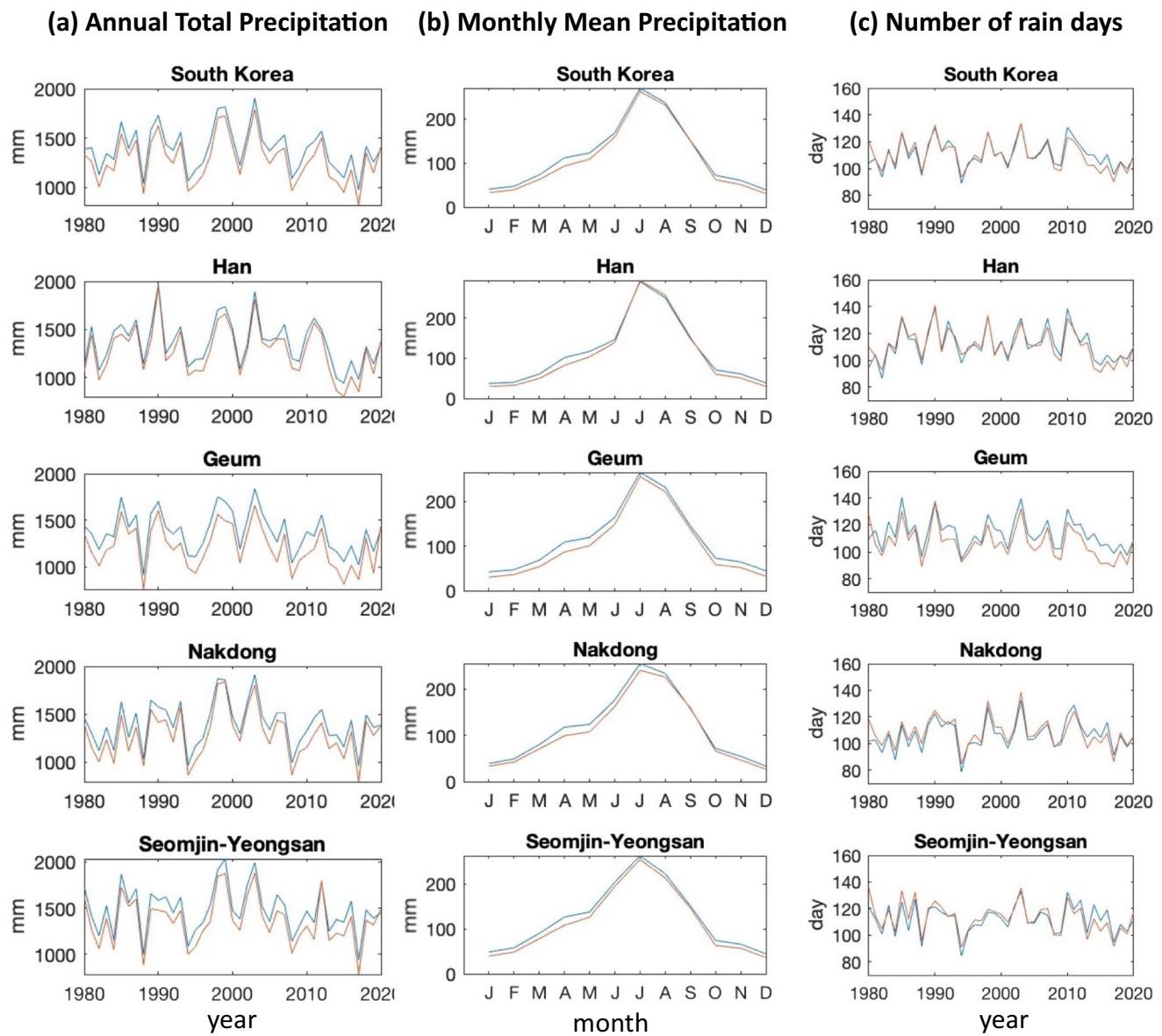
The spatial distribution of the daily mean temperature from MERRA-2, ASOS-MERRA2, and their differences are compared in Fig. 7. For the top panel, the December–January–February (DJF) daily mean temperature (ASOS-MERRA2) was relatively high along the coastline. The inland and northern parts of the Han River Basin had cooler conditions than other areas. This spatial pattern was similar to the MERRA-2 results. The overall DJF temperature from MERRA-2 was slightly higher than that of ASOS-MERRA2. The difference in daily temperature between the two forcings was exceptionally large in the Han River Basin. The bottom panel shows the June–July–August (JJA) daily mean temperature. The spatial pattern of the MERRA-2 results from DJF and JJA were similar, while the ASOS-MERRA2 results from winter and summer were clearly different. The higher spatial resolution of the ASOS-MERRA2 product provided a more detailed spatial pattern of temperature. Unlike the winter temperature, the overall temperature in summer was higher in the ASOS-MERRA2 results.

The annual mean, monthly mean temperature, and diurnal temperature range (DTR) were calculated for South Korea and the four basins (Fig. 8). The DTR was calculated from the difference between the daily maximum and minimum temperatures. This difference was averaged for each month. The

ASOS-MERRA2 annual mean temperature was generally higher than that of MERRA-2, and the difference was primarily observed in the Han River Basin. However, the difference was only up to 1.8 K in this basin, and the temperature fluctuations from both forcings were analogous to each other. The monthly mean temperatures were nearly identical for ASOS-MERRA2 and MERRA-2. There were temperature peaks in July and August in all four basins. The DTR of ASOS-MERRA2 was mostly larger than that of MERRA-2 except in summer (JJA). The ASOS-MERRA2 hourly temperature was a more precise record, while the DTR of MERRA-2 did not demonstrate the actual range of hourly temperatures. The overall temperature results were comparable for both forcings within a feasible range.

## 5.3 Pressure

The comparison of the pressure results was calculated for monthly and daily time steps (Fig. 9). The spatially averaged time series of the mean pressure ( $41 \text{ years} \times 12 \text{ months} = 492$ ) from MERRA-2 and ASOS-MERRA2 were compared in a scatter plot. The least squares line indicated that both forcings were systematically well matched, but the ASOS-MERRA2 results were 22.3 hPa (2.24%) higher than MERRA-2 in South Korea. The Han River Basin had the most considerable pressure difference (34.81 hPa; 3.55%) in the monthly mean pressure and its annual cycle. The winter season had a



**Fig. 6** Temporal analysis of precipitation using Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) and MERRA-2 for all

South Korea and four river basins. The blue line indicates ASOS-MERRA2 and the red line indicates MERRA-2

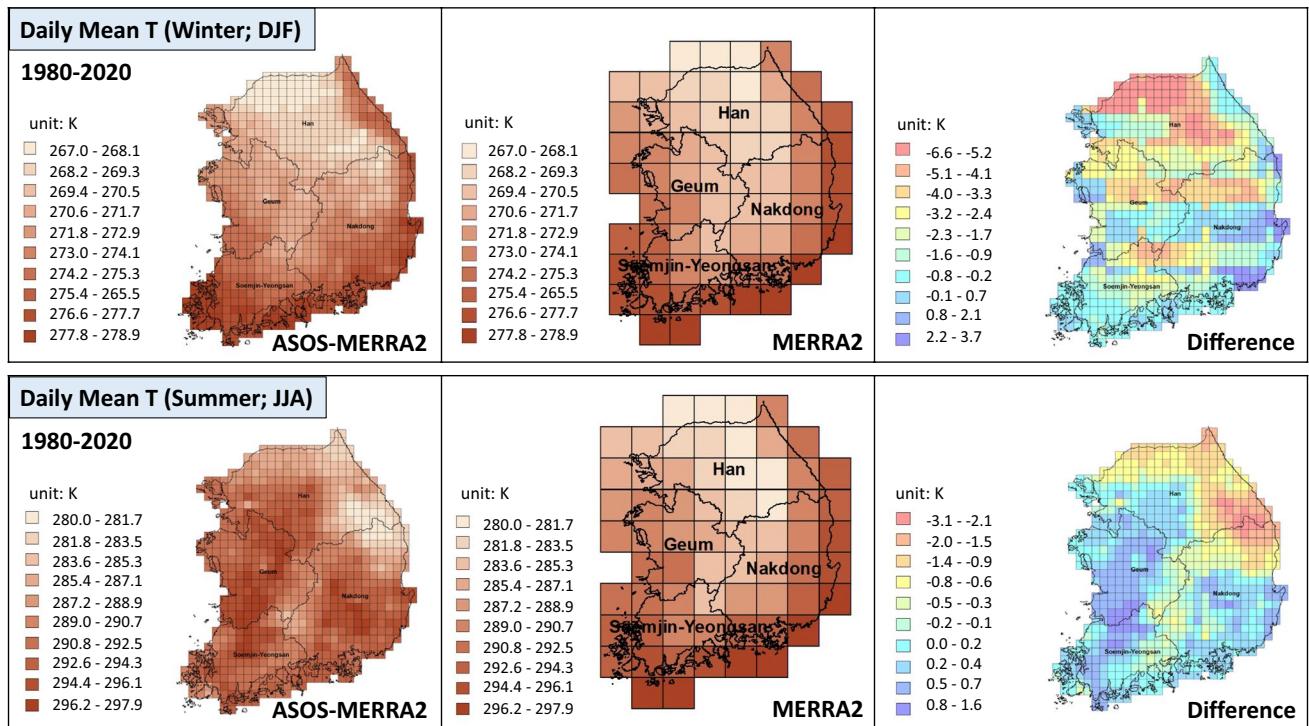
slightly higher pressure than the summer months. However, the monthly mean pressure throughout the year ranged up to 15 hPa in most basins.

The diurnal pressure range (DPR) was calculated from the difference between the daily maximum and minimum pressures from the hourly pressure data. This difference was averaged for each month. Both forcings had nearly identical DPRs, and the summer season had a low DPR in all basins. The pressures from MERRA-2 and ASOS-MERRA2 were systematically biased against each other, but the overall diurnal characteristics from the hourly results were similar. The spatial analysis of pressure between ASOS-MERRA2 and MERRA-2

is described in the Appendix fig. 12. The eastern part of South Korea is a primarily mountainous area (covering Han and Nakdong Rivers). The surface pressure of the two rivers is relatively small 981.39 to 995.61 hPa, while other two rivers (Geum and Seonjin-Yeongsan) are 1001.64 to 1003.15 hPa.

#### 5.4 Specific humidity

The specific humidity results were compared for monthly and daily time steps (Fig. 10). The scatter plot was the spatially averaged time series of the mean humidity from MERRA-2 and ASOS-MERRA2. Compared with the pressure results,



**Fig. 7** Spatial analysis of temperature using Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) and MERRA-2, and

the difference between these. DJF, December–January–February; JJA, June–July–August

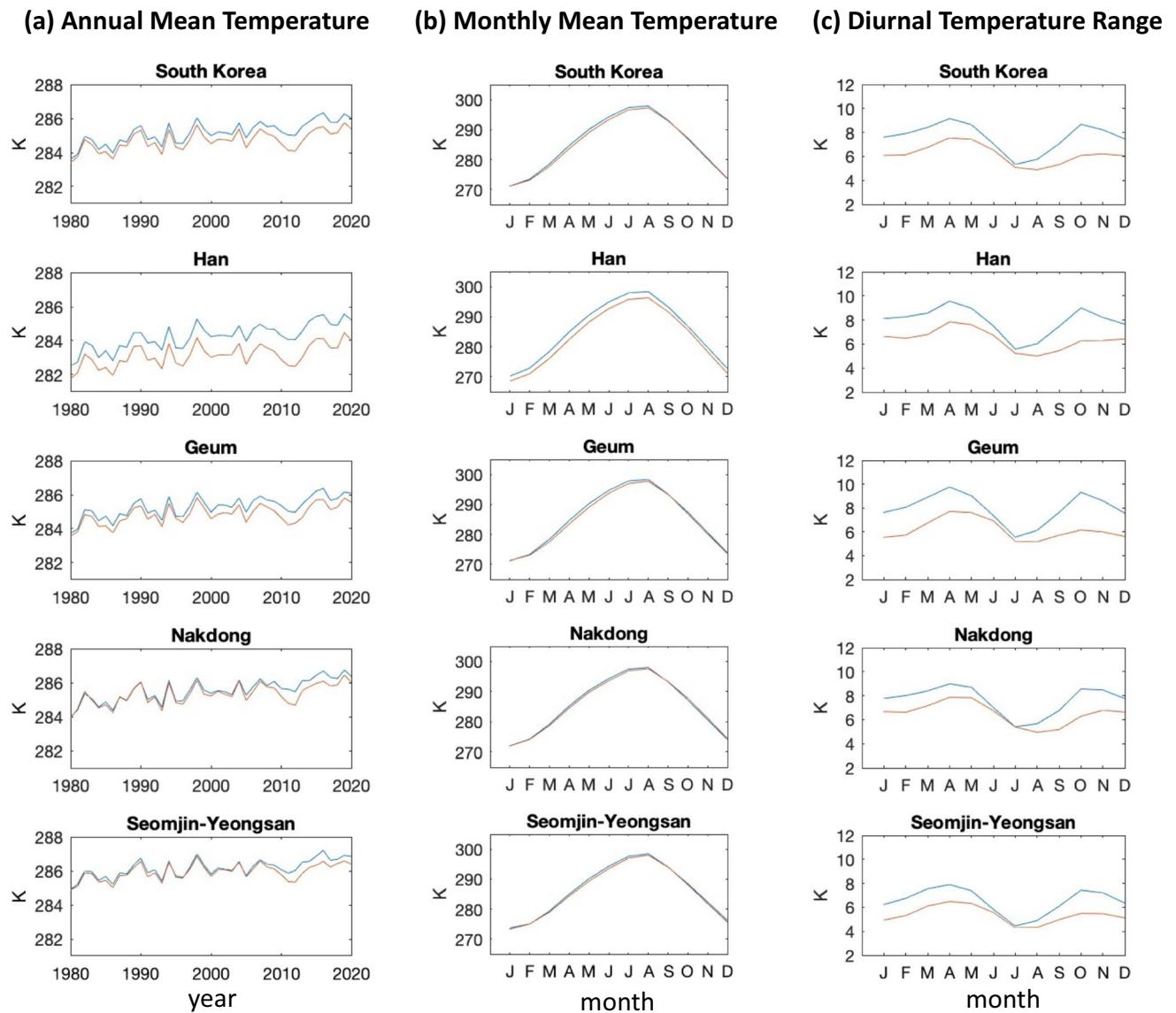
MERRA-2 and ASOS-MERRA2 were close but slightly off from the least square line. This is because the specific humidity was calculated from multiple sources (relative humidity, temperature, and pressure), and Bolton's equation was not a linear relationship among the different sources. The ASOS-MERRA2 results were 0.99 g/kg (13.45%) higher than those of MERRA-2 in South Korea. However, unlike the pressure results, both forcings of the specific humidity were within the same range of 0 to 20 g/kg.

The monthly mean humidity from ASOS-MERRA2 was overestimated from January to June in most basins. However, both forcings had similar annual cycle patterns throughout the year, with humid summers and relatively dry winters. For example, the mean humidity in August (15.0 g/kg) was six times larger than that in January (2.5 g/kg). The diurnal humidity range (DHR) was calculated from the difference between the daily maximum and minimum hourly humidity. In all basins, the DHR from ASOS-MERRA2 was larger than that from MERRA-2 every month. The difference in DHR was captured mainly from April to October when the humidity increased. As a result, the DHR of MERRA-2 flattened throughout the year. The ASOS-MERRA2 specific humidity, as a function of the ASOS-MERRA2 temperature, was affected by the more extensive diurnal range of the ASOS-MERRA2 temperature. As a result, the specific humidity from MERRA-2 and ASOS-MERRA2 was more biased than the results from pressure, and the overall diurnal features

were different for both forcings. ASOS was site-specific result; however, MERRA-2 was downscaled from spatially wide regions. Therefore, ASOS-MERRA2 (containing ASOS results) could provide more sensitive and detailed results of DHR (Diurnal Humidity Range) than MERRA-2 could. The existing bias between MERRA-2 and ASOS-MERRA2 tells us the importance of site-specific forcing development. The spatial analysis of humidity between ASOS-MERRA2 and MERRA-2 is described in the Appendix fig. 12.

## 5.5 Wind speed

The wind speed was calculated from the  $u$ - and  $v$ - directions. The magnitude of the wind speed in both directions was compared at monthly and daily time steps. The wind speeds from MERRA-2 and ASOS-MERRA2 were compared in terms of the monthly mean using a scatter plot (Fig. 11). The overall wind speed from MERRA-2 (5.67 m/s) was faster than ASOS-MERRA2 (3.21 m/s). Both forcings did not have a good agreement, and the difference was most prominent among different forcings (pressure and specific humidity). The annual cycle of the monthly mean wind speed did not vary noticeably throughout the year. Winter (December and January) wind speeds were slightly faster than in other months. The diurnal wind speed range (DWR) was calculated from the difference between the daily maximum and minimum wind speeds



**Fig. 8** Temporal analysis of temperature using Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) and MERRA-2 for all

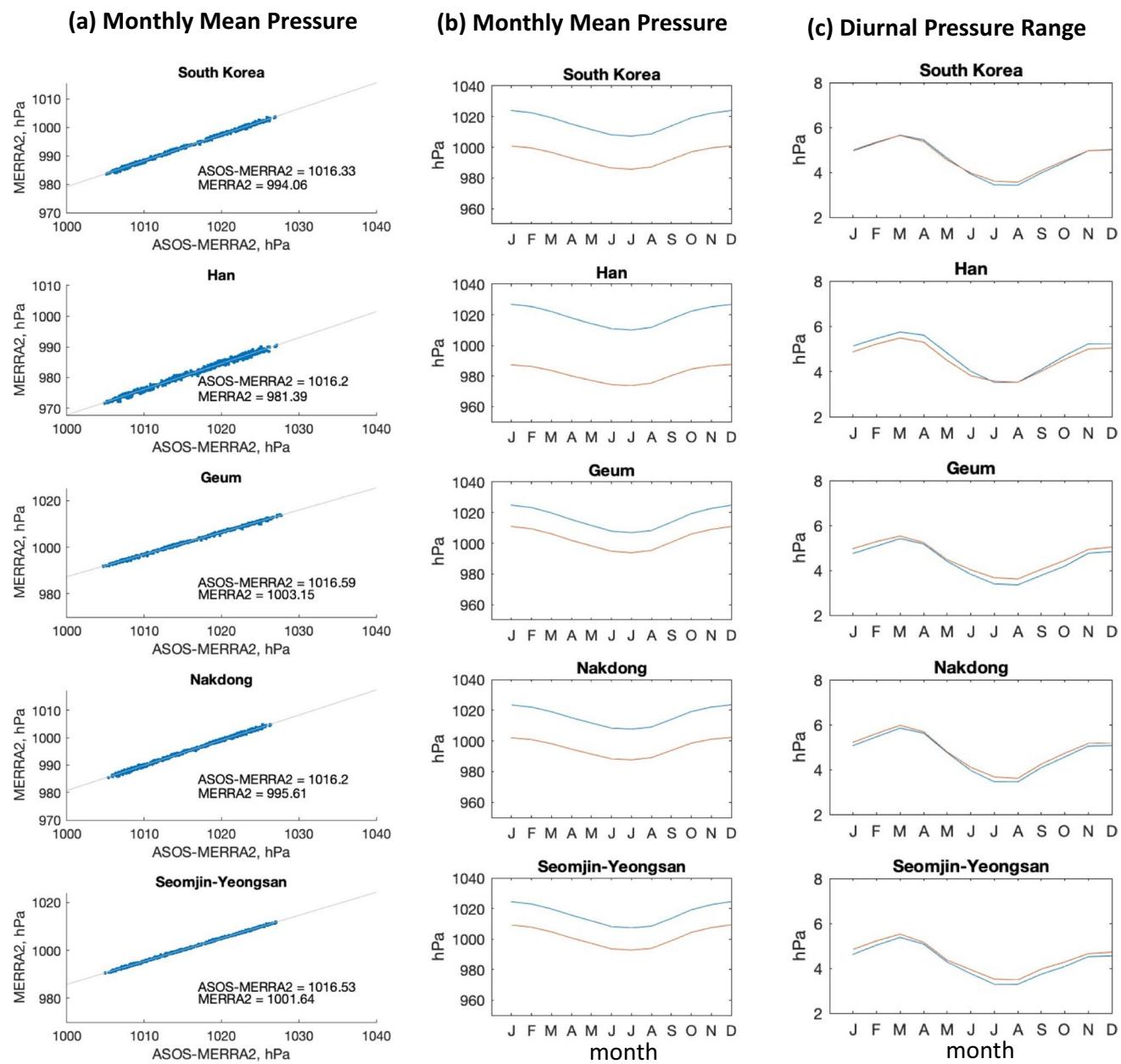
South Korea and four river basins. The blue line indicates ASOS-MERRA2 and the red line indicates MERRA-2

from the hourly data. Unlike the diurnal range of temperature and humidity, the DWR of MERRA-2 was larger than that of ASOS-MERRA2. The DWR was relatively low during the warmer months (from June to August). The spatial analysis of wind speed between ASOS-MERRA2 and MERRA-2 is described in the Appendix fig. 12.

## 6 Conclusion

This study describes long-term (41 years) and high-resolution (hourly and  $0.125^\circ$ ) meteorological datasets that can be used to drive hydrologic models of land surface water

and energy budgets for South Korea. As the necessity for accurate estimates of the spatial and temporal variation in surface hydrology and energy balance is evident, this regional scale dataset was developed for South Korea, including, for the first time, recent observations with quantitative validation. This study is intended to provide a benchmark weather forcing dataset that combines state-of-the-art reanalysis products (MERRA-2) with the most recent meteorological observation-based datasets (ASOS). This hybrid method has potential applications in record-lacking regions, such as South East Asia and Africa, where weather observations are available but for insufficient periods. Below are point-by-point findings from our analysis:

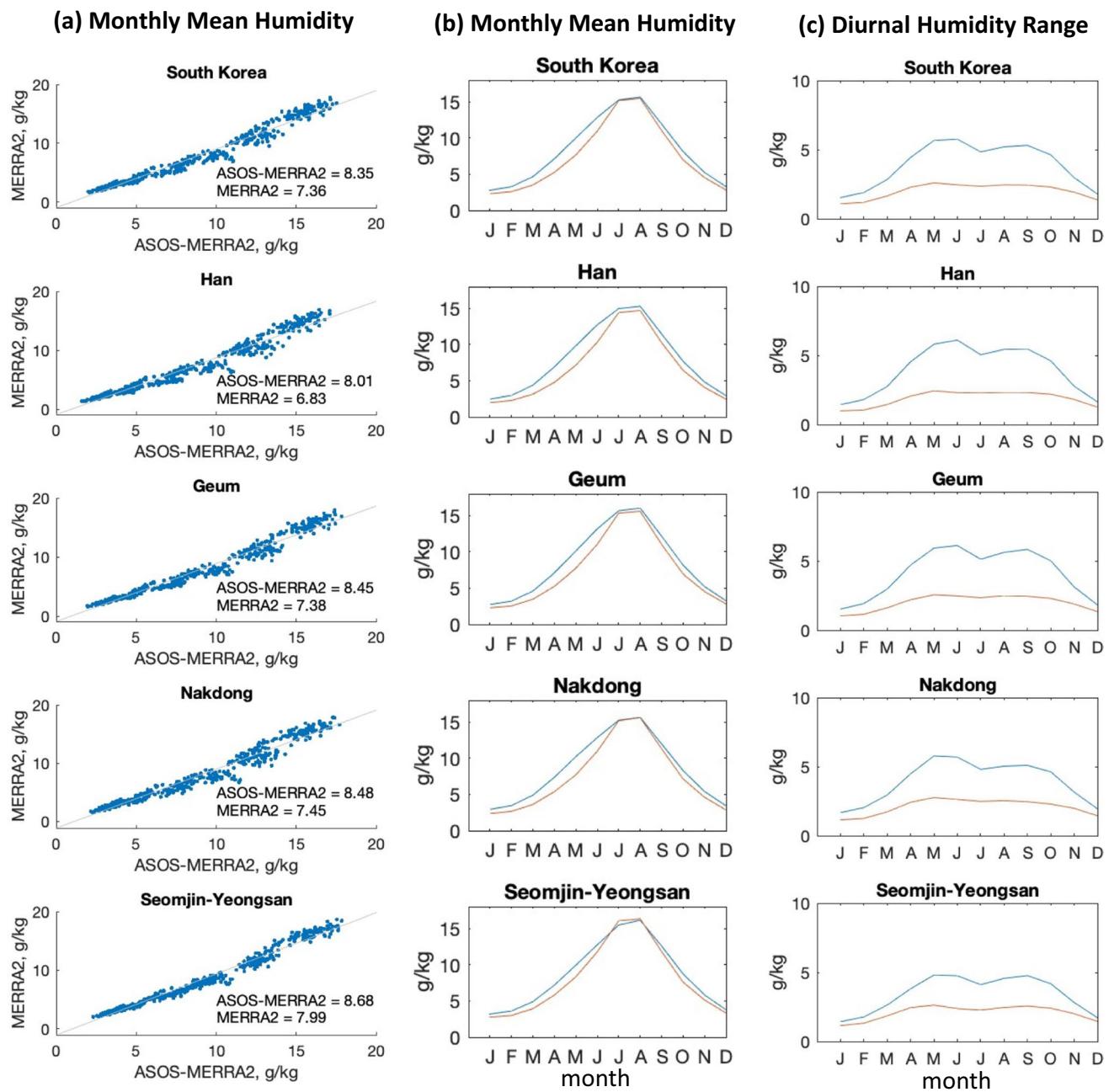


**Fig. 9** Temporal analysis of pressure using Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) and MERRA-2 for all

South Korea and four river basins. The blue line indicates ASOS-MERRA2 and the red line indicates MERRA-2

1. Validations against measured observations show that the region-based and high spatial resolution data of ASOS-MERRA2 are superior (i.e., improved errors and correlations for all five variables) to the existing MERRA-2 data.
2. ASOS-MERRA2 precipitation successfully capture the recent drought in the Geum River Basin (Ahn et al. 2016; Jung et al. 2020; Ryu et al. 2004) and the precipitation effect due to annual typhoons in the headwaters of

- the Han River and Seomjin-Yeongsan River basins (Bae et al. 2008; Kim et al. 2015).
3. The diurnal temperature range in ASOS-MERRA2 was more sensitive than that of MERRA-2. This is because ASOS-MERRA2 avoids the statistical smoothing of MERRA-2 using locally available meteorological observations.
4. The pressure from ASOS-MERRA2 was slightly higher (2.24%) than that from MERRA-2, whereas the specific



**Fig. 10** Temporal analysis of specific humidity using Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) and

MERRA-2 for all South Korea and four river basins. The blue line indicates ASOS-MERRA2 and the red line indicates MERRA-2

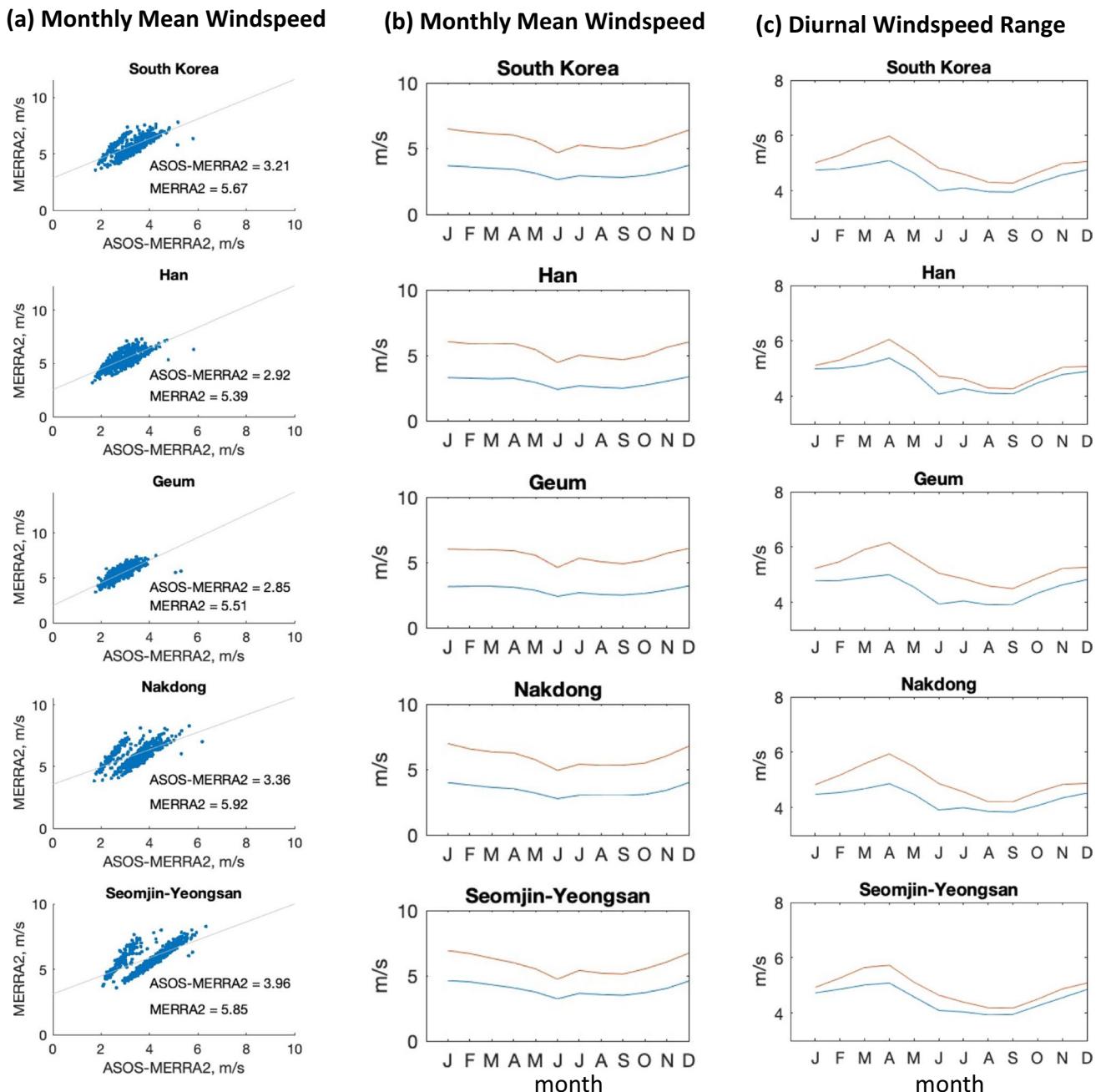
humidity showed good agreement between the two forcing datasets within the same range of results.

5. Among the five forcing components, wind speed had the most significant bias, possibly because of the complexity and sensitivity of data collection from the ASOS network.

Another advantage of ASOS-MERRA2 is the expectation of future extensions from the current status. The final

product of the ASOS-MERRA2 forcings was a ground observation-based gridded dataset that can provide more detailed spatial patterns and diurnal ranges of results. This new dataset significantly improves the original reanalysis product (MERRA-2) and can be used for applications and analytical studies in the hydrological and climatological sciences in South Korea.

The hydrologic model outputs (i.e., soil moisture and evapotranspiration) driven by ASOS-MERRA2 can be used



**Fig. 11** Temporal analysis of wind speed using Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application version 2 (ASOS-MERRA2) and MERRA-2 for all

South Korea and four river basins. The blue line indicates ASOS-MERRA2 and the red line indicates MERRA-2

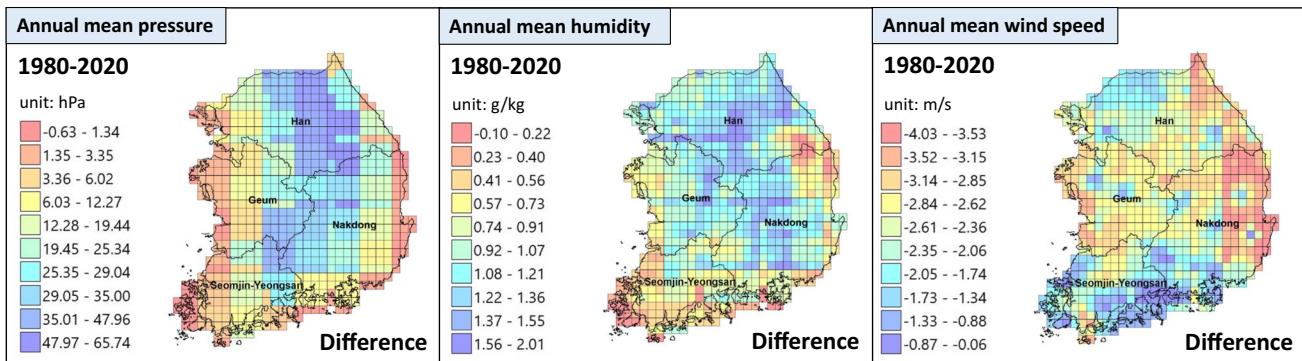
as agricultural drought monitoring tools to improve meteorological forcing. The standardized soil moisture index and standardized precipitation evapotranspiration index approaches can be applied using the updated meteorological inputs and hydrologic variables from the LSM simulated by ASOS-MERRA2. In addition to enhanced agricultural drought monitoring, the simulated hydrologic model is

expected to provide valuable information about heat waves (i.e., temperature and humidity), which directly affect mortality (Kim et al. 2014; Lee et al. 2016; Yeh et al. 2018). Thus, the LSM simulated by the newly developed ASOS-MERRA2 is expected to produce more reliable long-term and high spatial-temporal resolution land surface hydrological outputs in South Korea.

## Appendix

The spatial distribution of the annual mean pressure, humidity, and wind speed using the difference between MERRA-2 and ASOS-MERRA2 was compared in Fig. 12 in the Appendix. [Pressure] The spatial mean pressure of ASOS-MERRA2 was generally higher (22.3 hPa; 2.24%) than MERRA-2 in South Korea. The difference was significantly captured in the inland of the Korean Peninsula. The Han River Basin had the most considerable pressure difference (maximum of 65.74 hPa) in the annual mean pressure. On the other hand, the pressure difference was not considerable along the coast line. [Humidity] The

spatial mean humidity of ASOS-MERRA2 was generally higher (0.99 g/kg; 13.45%) than MERRA-2 in South Korea. The spatial distribution of humidity difference is likewise in the pressure difference map. The overall inland had more humid condition for ASOS-MERRA2 than MERRA-2. The maximum humidity differences (2.01 g/kg) were found in the Han River and the Nakdong River Basins. [Wind speed] The spatial mean wind speed of ASOS-MERRA2 was generally slower (2.46 m/s) than MERRA-2 in South Korea. The eastern part showed the extensive difference, while the southern part of South Korea had fairly good agreement of wind speed values between two forcings.



**Fig. 12** Spatial analysis of pressure, humidity, and wind speed using the difference between Automated Synoptic Observing System-Modern-Era Retrospective Analysis for Research and Application

version 2 (ASOS-MERRA2) and MERRA-2. To calculate the difference, MERRA-2 grid ( $0.5^\circ$ ) was evenly downscaled to match ASOS-MERRA2 grid resolution ( $0.125^\circ$ )

**Author contribution** Kyungtae Lee analyzed and wrote the main manuscript. Do Hyuk Kang analyzed and wrote the main manuscript. Hahn Chul Jung analyzed the data and results. Gwangha Park prepared and provided figures. Changwoo Gye prepared and managed data. Sujay Kumar reviewed the manuscript. Edward J. Kim reviewed the manuscript. Christa D. Peters-lidard reviewed the manuscript. EuiHo Hwang reviewed the manuscript. All authors read and approved the final manuscript.

**Funding** This research was supported by (1) Korea Environment Industry and technology Institute through Water Management Research Program, funded by Korea Ministry of Environment (grant number: 79622) and (2) the National Research Foundation of Korea (NRFK) and funded by the Korean Government (2021R1A2C100578011). Computing was supported by the resources at the K-water Research Institute and SELab in Seoul, South Korea. Funders in this research: Kyungtae Lee, Do Hyuk Kang, Gwangha Park, Changwoo Gye, Edward J. Kim, and EuiHo Hwang.

**Data availability** The newly generated ASOS-MERRA2 products were provided by (Water Hazard Information Platform in Korea (WHAP)). Details of the data and how to request access are available from [http://116.125.66.242:9132/monitoring/klis/WHAP\\_GIS/system/system.html](http://116.125.66.242:9132/monitoring/klis/WHAP_GIS/system/system.html) at Korea Land Surface Information System. MERRA-2 data are

available at [https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data\\_access/](https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/), managed by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

**Code availability** The code that support the findings of this study are available from the corresponding author, D.H. Kang, upon reasonable request.

## Declarations

**Competing interests** The authors declare no competing interests.

**Ethics approval** I declare that the manuscript in part or in full has not been submitted or published anywhere. In other words, the authors should ensure that the manuscript is not a duplicate publication.

**Consent to participate** Not applicable to this research.

**Consent to publication** I have read and understood that the publishing policy, and submit this manuscript in accordance with this policy.

**Conflict of interest** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

Ahn SR, Jeong JH, Kim SJ (2016) Assessing drought threats to agricultural water supplies under climate change by combining the SWAT and MODSIM models for the Geum River basin, South Korea. *Hydrol Sci J* 61:2740–2753

Ahn JM, Kwon HG, Yang DS, Kim Y (2018) Assessing environmental flows of coordinated operation of dams and weirs in the Geum River basin under climate change scenarios. *Sci Total Environ* 643:912–925

Bae D, Jung I, Chang H (2008) Long-term trend of precipitation and runoff in Korean river basins. *Hydrological Processes: an International Journal* 22:2644–2656

Berg AA, Famiglietti JS, Walker JP, Houser PR, (2003). Impact of bias correction to reanalysis products on simulations of North American soil moisture and hydrological fluxes. *Journal of Geophysical Research: Atmospheres* 108

Bolton D (1980) The computation of equivalent potential temperature. *Mon Weather Rev* 108:1046–1053. [https://doi.org/10.1175/1520-0493\(1980\)108%3c1046:TCOEPT%3e2.0.CO;2](https://doi.org/10.1175/1520-0493(1980)108%3c1046:TCOEPT%3e2.0.CO;2)

Carrera ML, Bélair S, Bilodeau B (2015) The Canadian land data assimilation system (CaLDAS): description and synthetic evaluation study. *J Hydrometeorol* 16:1293–1314

Chun-Lin H, Xin L (2011) A review of land data assimilation system. *Remote Sensing Technology and Application* 19:424–430

Dong X, Xi B, Kennedy A, Feng Z, Entin JK, Houser PR, Schiffer RA, L'Ecuyer T, Olson WS, Hsu K, (2011). Investigation of the 2006 drought and 2007 flood extremes at the Southern Great Plains through an integrative analysis of observations. *Journal of Geophysical Research: Atmospheres* 116

Fang GH, Yang J, Chen YN, Zammitt C (2015) Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrol Earth Syst Sci* 19:2547–2559

Fekete BM, Vörösmarty CJ, Roads JO, Willmott CJ (2004) Uncertainties in precipitation and their impacts on runoff estimates. *J Clim* 17:294–304

Gang N-E, Gang H-Y, Sin D-S (2016) Korea meteorological administration: drought information service. *Water for Future* 49:85–91

Gelaro R, McCarty W, Suárez MJ, Todling R, Molod A, Takacs L, Randles CA, Darmenov A, Bosilovich MG, Reichle R, Warman K, Coy L, Cullather R, Draper C, Akella S, Buchard V, Conaty A, da Silva AM, Gu W, Kim G-K, Koster R, Lucchesi R, Merkova D, Nielsen JE, Partyka G, Pawson S, Putman W, Rienecker M, Schubert SD, Sienkiewicz M, Zhao B (2017) The modern-era retrospective analysis for research and applications, Version 2 (MERRA-2). *J Clim* 30:5419–5454. <https://doi.org/10.1175/JCLI-D-16-0758.1>

Gibson JK, Källberg P, Uppala S, (1997). ERA description, ECMWF Re-analysis Final Report Series, 1

Guo B, Zhang J, Xu T, Croke B, Jakeman A, Song Y, Yang Q, Lei X, Liao W (2018) Applicability assessment and uncertainty analysis of multi-precipitation datasets for the simulation of hydrologic models. *Water (basel)* 10:1611

He J, Yang K, Tang W, Lu H, Qin J, Chen Y, Li X (2020) The first high-resolution meteorological forcing dataset for land process studies over China. *Sci Data* 7:1–11

In S-R, Han S-O, Im E-S, Kim K-H, Shim J (2014) Study on temporal and spatial characteristics of summertime precipitation over Korean Peninsula. *Atmosphere (basel)* 24:159–171

Jacobs C, Moors E, ter Maat H, Teuling R, (2005). Validation of ELDAS products using in situ observations, in: *Proceedings of the ECMWF/ELDAS Workshop on Land Surface Assimilation*. pp. 167–177

Jacobs CMJ, Moors EJ, ter Maat HW, Teuling AJ, Balsamo G, Bergaoui K, Ettema J, Lange M, van den Hurk B, Viterbo P (2008) Evaluation of European Land Data Assimilation System (ELDAS) products using in situ observations. *Tellus a: Dynamic Meteorology and Oceanography* 60:1023–1037

Jung HC, (2021). Big data applications in hydrology, in: *International Symposium on Remote Sensing 2021*. The Korean Society of Remote Sensing

Jung HC, Kang DHD, Hwang E, Park G, (2019). Evaluation of global gridded meteorological datasets for land surface modeling in Korean Peninsula, in: *AGU Fall Meeting Abstracts*. pp. H41P-1946

Jung HC, Kang D-H, Kim E, Getirana A, Yoon Y, Kumar S, Peterslidar CD, Hwang E (2020) Towards a soil moisture drought monitoring system for South Korea. *J Hydrol (amst)* 589:125176

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J (1996) The NCEP/NCAR 40-year reanalysis project. *Bull Am Meteorol Soc* 77:437–472

Kanamitsu M, Saha S (1996) Systematic tendency error in budget calculations. *Mon Weather Rev* 124:1145–1160

Kim D-W, Chung J-H, Lee J-S, Lee J-S (2014) Characteristics of heat wave mortality in Korea. *Atmosphere (basel)* 24:225–234

Kim J-S, Yoon S-K, Oh SM, Moon Y-I (2015) Changes in typhoon activities and regional precipitation variability over the Korean Peninsula according to different phases of El Nino. *Adv Meteorol*

Kim M, Choi J, Moon Y (2018) Rainfall analysis considering watershed characteristics and temporal-spatial characteristics of heavy rainfall. *Journal of Korea Water Resources Association* 51:739–745

Kim H-S, Jeon G-I, Lee J-J, Lee Y-S, Kim M-H (2020) Establishment of drought management system with local and people. *Water for Future* 53:8–15

Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V (2001) The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bull Am Meteorol Soc* 82:247–268

Lee K-S, Kim Y (2007) Determining the seasonality of groundwater recharge using water isotopes: a case study from the upper North Han River basin, Korea. *Environ Geol* 52:853–859. <https://doi.org/10.1007/s00254-006-0527-3>

Lee WK, Lee HA, Lim YH, Park H (2016) Added effect of heat wave on mortality in Seoul, Korea. *Int J Biometeorol* 60:719–726

Lee K, Gao H, Huang M, Sheffield J, Shi X (2017a) Development and application of improved long-term datasets of surface hydrology for Texas. *Adv Meteorol*

Lee G, Cha D-H, Park C (2017b) Improvement of extreme summer precipitation over South Korea in APHRODITE data. *European Geosciences Union*

Lee J, Kim C-G, Lee JE, Kim NW, Kim H (2018) Application of artificial neural networks to rainfall forecasting in the Geum River basin. *Korea Water* (basel) 10:1448

Lim Y-J, Byun K-Y, Lee T-Y, Kwon H, Hong J, Kim J (2012) A land data assimilation system using the MODIS-derived land data and its application to numerical weather prediction in East Asia. *Asia Pac J Atmos Sci* 48:83–95

Livneh B, Rosenberg EA, Lin C, Nijssen B, Mishra V, Andreadis KM, Maurer EP, Lettenmaier DP (2013) A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: Update and extensions. *J Clim* 26:9384–9392

Maurer EP, Wood AW, Adam JC, Lettenmaier DP, Nijssen B (2002) A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States. *J Clim* 15:3237–3251

McNally A, Arsenault K, Kumar S, Shukla S, Peterson P, Wang S, Funk C, Peters-Lidard CD, Verdin JP (2017) A land data assimilation system for sub-Saharan Africa food and water security applications. *Sci Data* 4:1–19

McNally A, Verdin K, Harrison L, Getirana A, Jacob J, Shukla S, Arsenault K, Peters-Lidard C, Verdin JP (2019) Acute Water-Scarcity Monitoring for Africa. *Water* (basel) 11:1968

Mitchell KE, Lohmann D, Houser PR, Wood EF, Schaake JC, Robock A, Cosgrove BA, Sheffield J, Duan Q, Luo L, (2004). The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *Journal of Geophysical Research: Atmospheres* 109

Moradkhani H (2008) Hydrologic remote sensing and land surface data assimilation. *Sensors* 8:2986–3004

Ngo-Duc T, Polcher J, Laval K, (2005). A 53-year forcing data set for land surface models. *Journal of Geophysical Research: Atmospheres* 110

Nijssen B, Lettenmaier DP, (2004). Effect of precipitation sampling error on simulated hydrological fluxes and states: anticipating the Global Precipitation Measurement satellites. *Journal of Geophysical Research: Atmospheres* 109

Nijssen B, Schnur R, Lettenmaier DP (2001) Global retrospective estimation of soil moisture using the variable infiltration capacity land surface model, 1980–93. *J Clim* 14:1790–1808

Park G-H, Lee K-T, Kye C-W, Yu W-S, Hwang E-H, Kang D-H (2021) Calculation of Soil Moisture and Evapotranspiration for KLDAS (Korea Land Data Assimilation System) using Hydrometeorological Data Set. *Journal of the Korean Association of Geographic Information Studies* 24:65–81

Raimonet M, Oudin L, Thieu V, Silvestre M, Vautard R, Rabouille C, le Moigne P (2017) Evaluation of gridded meteorological datasets for hydrological modeling. *J Hydrometeorol* 18:3027–3041

Rodell M, Houser PR, Jambor UEA, Gottschalck J, Mitchell K, Meng C-J, Arsenault K, Cosgrove B, Radakovich J, Bosilovich M (2004) The global land data assimilation system. *Bull Am Meteorol Soc* 85:381–394

Ryu J-H, Lee D-R, Ahn J-H, Yoon Y-N (2002) A comparative study on the drought indices for drought evaluation. *Journal of Korea Water Resources Association* 35:397–410

Ryu J, Palmer RN, Jeong S, Lee J, (2004). Drought definitions and forecasts for water resources management, in: *Critical Transitions in Water and Environmental Resources Management*. pp. 1–10

Schubert SD, Rood RB, Pfaendtner J (1993) An assimilated dataset for earth science applications. *Bull Am Meteorol Soc* 74:2331–2342

Sheffield J, Ziegler AD, Wood EF, Chen Y (2004) Correction of the high-latitude rain day anomaly in the NCEP–NCAR reanalysis for land surface hydrological modeling. *J Clim* 17:3814–3828

Sheffield J, Goteti G, Wood EF (2006) Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. *J Clim* 19:3088–3111

Shepard D, (1968). A two-dimensional interpolation function for irregularly-spaced data, in: *Proceedings of the 1968 23rd ACM National Conference*. pp. 517–524

Snedecor GW, Cochran WG (1989) *Statistical Methods*, eighth. Iowa state University Press, Ames, Iowa, p 1191

Sur C, Hur J, Kim K, Choi W, Choi M (2015) An evaluation of satellite-based drought indices on a regional scale. *Int J Remote Sens* 36:5593–5612. <https://doi.org/10.1080/01431161.2015.1101653>

Uppala SM, Källberg PW, Simmons AJ, Andrae U, Bechtold VDC, Fiorino M, Gibson JK, Haseler J, Hernandez A, Kelly GA, (2005). The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography* 131, 2961–3012

Willmott CJ, Rowe CM, Philpot WD (1985) Small-scale climate maps: a sensitivity analysis of some common assumptions associated with grid-point interpolation and contouring. *The American Cartographer* 12:5–16

Yang J-S, Kim I-H (2013) Development of drought vulnerability index using delphi method considering climate change and trend analysis in Nakdong river basin. *Journal of the Korean Society of Civil Engineers* 33:2245–2254

Yeh S-W, Won Y-J, Hong J-S, Lee K-J, Kwon M, Seo K-H, Ham Y-G (2018) The record-breaking heat wave in 2016 over South Korea and its physical mechanism. *Mon Weather Rev* 146:1463–1474

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.