Climate Services for Water Resource Management in China: The Case Study of Danjiangkou Reservoir

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(Received June 28, 2020; in final form November 19, 2020)

ABSTRACT

The efficiencies and effectiveness of water resource management are inextricably linked to climate services. This study demonstrates a climate information service for Danjiangkou Reservoir, which is the largest artificial lake in Asia, facing mounting challenges for flood control, water storage, and water diversion. Unlike traditional water resource management on the basis of short-term weather forecast and runoff monitoring, subseasonal to seasonal (S2S) and annual climate predictions as well as long-term climate change projections were well used to support the decision makers in Danjiangkou Reservoir. The National Climate Center (NCC) has projected the changes of future climate and extreme events by dynamically downscaling the Coupled Model Intercomparison Project phase 5 (CMIP5) projections to 25-km resolution for the long-term planning of water resource management in Danjiangkou Reservoir. Real-time climate predictions based on climate models and downscaling interpretation and application methods at different timescales were also provided to meet the specific needs of earlier predictions and spatial refinement for the short-term diversion of the reservoir. Our results show that such climate services facilitated the Diversion Center of Danjiangkou Reservoir (DCDR) to reasonably control the operational water level, increased the ecological water supply to the northern portion of China by 844 million m$^3$, and reduced as much as 1.67 billion m$^3$ of abandoned water in 2019. In the future, it is necessary to develop climate prediction methods to increase spatial and temporal resolutions and prediction skills, and enhance interactions between providers and users.

Key words: climate service, water resource management, climate prediction, climate projection, reservoir

Citation: Wang, Y. J., X. Li, S. Liu, et al., 2021: Climate services for water resource management in China: The case study of Danjiangkou Reservoir. J. Meteor. Res., 35(1), 87–100, doi: 10.1007/s13351-021-0096-0.

1. Introduction

The water resource is highly sensitive to climate. Global warming is likely to change global and regional water cycles, with great impacts on water availability and flood risks (Huntington, 2006; Oki and Kanae, 2006; Biemans et al., 2011; Harding et al., 2011; Haddeland et al., 2014; IPCC, 2014; Reshmidevi et al., 2018; Zhang et al., 2019). China has the world’s most variable climate and the uneven distribution of water resources has been exacerbated in recent decades because of the effects of climate warming (Ding et al., 2007; Piao et al., 2010; Zhang et al., 2010; Wu et al., 2014; Li et al., 2016; Zhang H. et al., 2017; Xi et al., 2018). The high variability of water resources in the context of climate change and the growing conflicts between supply and demand influenced by human activities make water resource management more complicated (Abawi et al., 2000; Ritchie et al., 2004; van Vliet et al., 2015; Ehsani et al., 2017; Feng et al., 2017; Qin et al., 2020).

Water resource management is a day-to-day and also year-to-year activity as well as a long-term strategic plan issue (WMO, 2014). Therefore, there exists an obvious need to develop climate services in relation to the water
resource management on all timescales for water diversion, flood control, hydropower generation, ecological improvement, etc. Climate service refers to the process of generating, providing, and using climate information in such a way as to assist in decision-making (Hewitt et al., 2012). Climate services for water resource management can make the sources to be resilient to climate variability and change, and thus bring significant benefits to the society. The deep integration between climate information and decision-making is critical to water resource management (Kirchhoff, 2013; Koutroulis et al., 2015; van Vliet et al., 2015; Golding et al., 2017, 2019).

However, the use of climate information in water resource management is still limited due to the mismatch between information supplied and needed (Rayner et al., 2005; Lemos and Rood, 2010; Wang et al., 2020). Traditionally, water resource management is mostly carried out on the basis of short-term weather forecast and real-time runoff monitoring, and little has been done to use climate information on a longer timescale such as seasonal and annual climate predictions as well as climate change projections (Feldman and Ingram, 2009; Rice et al., 2009; Abtew and Trimble, 2010). In fact, water storage during high-flow periods and water utilization during low-flow or dry periods can improve the efficiencies and effectiveness of water resource management (Abawi et al., 2000). Therefore, advance climate information would enable users to make more appropriate decisions and adopt strategies to manage the risks associated with climate variability and climate change in water resource management.

The Hanjiang River basin (HRB) is located in the subtropical monsoon climate zone with large precipitation variability and prone to droughts and floods in China and its water system is more vulnerable (Wang et al., 2013; Xia et al., 2015; Liu et al., 2018). Danjiangkou Reservoir is the largest artificial lake in Asia, which is a large water conservancy control project that functions to control floods, adjust water supply, generate hydropower, and provide shipping and other important services in the middle and lower reaches of HRB. At the same time, it is also the source of the middle route of China’s South-to-North Water Diversion Project. Coupled with the steep slope of the upper reaches of the river, floods in this area are characterized by high speeds, skyrocketed fluctuations, and skinny peak tips (Guo et al., 2015). The Danjiangkou Reservoir is facing mounting challenges for flood control, water storage, and water diversion (Zhang et al., 2010; Ban et al., 2018; Chen et al., 2019). The long-term planning and short-term real-time diversion of the Danjiangkou Reservoir are closely linked to climate information, especially precipitation trend predictions for the coming months, seasons, and even longer periods.

In these contexts, we demonstrate here an example of climate services with tailored information available for the Danjiangkou Reservoir. We have focused on the following research questions: What is the impact of climate change on water resources and how climate information can be used for scientific decision-making on water resource management in the area. This study aims to systematically analyze climate information on different timescales for the long-term planning or short-term diversion of water resources and explore the experiences, deficiencies, effectiveness, and prospects of climate services for water resource management in the Danjiangkou Reservoir.

2. Study area and data

2.1 Study area

The Hanjiang River originates in the southern foothills of the Qinling Mountains, and empties into the Yangtze River in Wuhan City, with a length of 1577 km and a drainage area of about 159,000 km² (Fig. 1). The upper reaches of Hanjiang River are the Water Source Area of Danjiangkou Reservoir (WSAD) with a length of 925 km. It accounts for 59% of the total length of the river and covers about 60% of the whole drainage area. Danjiangkou Reservoir is the most important reservoir in the HRB, which functions to control floods and provide water and electricity supplies, and other water diversion tasks. The terrain around the reservoir is high in the northwest and low in the southeast. The reservoir dam is located in Danjiangkou City, Hubei Province, with a height of 176.6 m. The normal water conservation level of the reservoir is 170 m, and the total storage capacity is 31.95 billion m³. The summer flood limit is 160 m (flood limit is the highest beneficial water level allowed in the beneficial impounding), and the autumn flood limit is 163.5 m.

2.2 Data

The climate observation data used in this paper are extracted from “Dataset of Daily Surface Observations Collected at Chinese Surface Meteorological Stations,” which is released by the National Meteorological Information Center of China Meteorological Administration (Ren et al., 2012). The HRB includes 64 national meteorological observation stations, of which 36 are located in the upstream of the Hanjiang River (Fig. 1).

The climate change projection data are derived from a 25-km resolution dataset obtained by dynamical down-
scaling using the regional climate model (RCM), RegCM4.4. The simulated results are bias corrected by using the method of quantile delta mapping, which can reduce the biases in cumulative distribution functions for a variable and preserve the simulated changes in quantiles (Cannon et al., 2015; Tong et al., 2017, 2020; Han et al., 2018). The RCM domain is the same as the domain used in the Phase II East Asia International Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al., 2009), which encompasses the entire continental China and its adjacent areas. This model was driven by the boundary conditions from the historical (1979–2005) and representative concentration pathway 4.5 and 8.5 (RCP4.5 and RCP8.5; 2006–2099) runs of five CMIP5 (Coupled Model Intercomparison Project phase 5) global models, that is, CSIRO-Mk3–6-0, EC-EARTH, HadGEM2-ES, MPI-ESM-MR, and NorESM1-M (acronym definitions can be found at https://pcmdi.llnl.gov/mips/cmip5/). The historical simulation denotes the past climate, and the RCP4.5 (RCP8.5) represents the medium–low (high) radiative forcing scenario with radiative forcing peaking at 4.5 (8.5) W m$^{-2}$ by 2100. A subset of this ensemble experiment has been evaluated and used by different climate projection studies (Han et al., 2017; Zhang D. F. et al., 2017; Gao et al., 2018; Shi et al., 2018a, b; Zhou et al., 2018). In the present study, the average of the five simulations with equal weights is taken as the ensemble mean (ensR). All future projections are reported as the changes from the 1986–2005 reference period to the 2021–2040 future period (next 20 years), which are the urgent requirement of Diversion Center of Danjiangkou Reservoir (DCDR) and can support the near future water resource management of Danjiangkou Reservoir. In this paper, we mainly discuss the projected results under the RCP4.5, which is a more plausible pathway considering countries’ current and pledged climate policies; the RCP8.5 climate will be an unlikely high-risk future, and only general results under this scenario are shown in Ho et al. (2019) and Hausfather and Peters (2020).

The observational dataset of CN05.1 at a resolution of 0.25° × 0.25° (Wu and Gao, 2013) is employed to validate the RCM simulation with a similar resolution (25 km). CN05.1 is an augmentation of CN05 (Xu et al., 2009) and comprises multiple variables (temperature, precipitation, etc.). The RCM outputs were interpolated bilinearly to the CN05.1 grid to facilitate the comparison.

3. Climate information service

As a climate service provider, the National Climate Center (NCC) of China has developed and provided climate information on different timescales to meet the need of DCDR for short- and long-term water resource management, including flood control, water storage, water diversion, and climate change adaptation measures. After discussion and interactions between NCC and DCDR, both made sure that the climate information was appropriate (Wang et al., 2020). Table 1 summarizes the user needs and associated climate information as well as corresponding temporal scales.
Global climate change has imposed great impacts on the hydrological cycle at the upstream of the Hanjiang River, which increases the possibility of drought in water source areas and water-receiving areas at the same time in the future (Fang et al., 2018; Yu et al., 2018; Chen et al., 2019). Based on the demand of DCDR, this study analyzed the climate change impact on water resource management in Danjiangkou Reservoir. Theil–Sen trend analysis is used to estimate the linear trends and the non-parametric method of Mann–Kendall test is used for significance test.

From 1961 to 2017, the annual mean temperature significantly increased at a rate of 0.16°C (10 yr)

\[ p < 0.01; \text{Fig. 2a} \] while the annual precipitation slightly decreased at a rate of 7.2 mm (10 yr)

\[ 1 \] with obvious inter-decadal variation in the WSAD (not significant; Fig. 2b). The annual precipitation experienced 8.4% less than normal in the 1990s. The precipitation in summer flooding season (June–August) accounting for about half of annual precipitation increased by 4.3 mm (10 yr)

\[ 1 \] during 1961–2017 (not statistically significant; Fig. 2c). The precipitation in the autumn flooding season (September–October) accounting for 23% of the annual precipitation is very important for the reservoir water storage. Figure 2d shows that it slightly decreased by 4.6 mm (10 yr)

\[ 1 \] during 1961–2017 (not statistically significant).

Based on the runoff coefficient method (Peng et al., 2019), we calculated the annual surface water resource \( W \) in the WSAD according to the following formula:

\[ W = P \times C \times A, \]

\[ (1) \]

where \( P \) is averaged annual precipitation in the WSAD, \( C \) represents runoff coefficient (average annual inflow divided by average annual precipitation), and \( A \) is the area of the WSAD. Figure 3 shows that \( W \) has slightly decreased at a rate of 345 million m

\[ 3 \] (10 yr)

\[ 1 \] with large interannual variation during 1961–2017 (not statistically significant). The average annual surface water resource during 1991–2017 was 38.21 billion m

\[ 3 \], a decrease of 2.46 billion m

\[ 3 \] compared with that during 1961–1990. This evidence indicates that the annual goals of the South-to-North Water Diversion Project’s middle route might not be achieved within many years, resulting in a broad gap between water supply and demand (Liu et al., 2018).

The occurrence time and intensity of last heavy rainfall at the end of autumn flooding season are closely related to the storage time and capacity of Danjiangkou Reservoir. The heavy precipitation/rainfall is defined as the case when 8 or more of all 36 meteorological stations in the WSAD receive more than 25 mm of daily precipitation at the same time. The intensity index of heavy precipitation \( Z \) is calculated according to the following formula:

\[ Z = \bar{R} \sqrt{s} \sqrt{t}, \]

\[ (2) \]

where \( \bar{R} \) is the average precipitation over the WSAD, \( s \) represents the range of heavy precipitation expressed by the number of stations, and \( t \) is the duration of heavy precipitation. The intensity index of last heavy rainfall shows a weakening trend during 1961–2017 in the WSAD (not statistically significant; Fig. 4a). The date of last heavy rainfall experienced a trend of advance (not statistically significant; Fig. 4b). Therefore, the decrease of precipitation in autumn flooding season, decrease of intensity, and advance of the last heavy rainfall date make it necessary to formulate the early water storage plan of Danjiangkou Reservoir based on accurate climate prediction at subseasonal to seasonal (S2S) timescales (Wang et al., 2014; Guo et al., 2015).

3.2 Simulated and projected climate change

3.2.1 Simulation evaluation

NCC has investigated how well the RCM ensemble
can reproduce the mean climate and precipitation extremes in the HRB during the historical period 1986–2005 (Table 2). The root-mean-square error (RMSE), normalized RMSE relative to observations (nRMSE), and spatial correlation (SCOR) are calculated between the observations and the ensR over the whole HRB and its upper and mid–lower sub-basins (Table 3). The spatial patterns are well simulated over all the study areas by the ensR (figures omitted), with the values of SCOR higher than 0.92. The biases are also acceptable: the RMSE of annual temperature is 0.7°C, and nRMSEs of other variables are less than 12% except DMI (number of drought months), which has a value of 22.1%. The annual cycles of the area averaged temperature and precipitation are well simulated, with the temporal correlations larger than 0.98. The RMSE of monthly temperature is only 0.3°C, and nRMSE of monthly precipitation is 0.1%.

3.2.2 Projected climate and climate change

Based on the projection from CMIP5 global climate models, the NCC has projected the changes of future climate and extreme events over the HRB (Table 2) by dynamically downscaling the CMIP5 projections to 25-km resolution and correcting the simulated errors based on observational data. The products of NCC provide a scientific basis for long-term planning of water resource...
management in Danjiangkou Reservoir.

In the next 20 years, annual mean temperature will increase at all grids within the HRB due to the increase in greenhouse gas emissions, with the magnitude between 0.9 and 1.1°C and the average value of 0.98°C. The most pronounced warming simulated by ensR occurs over the mountainous areas, i.e., Qinling and Dabashan Mountains, which are located mainly at the upper sub-basin of the Hanjiang River. The average temperature increase in the upper sub-basin (0.99°C) is larger than that in the mid and lower sub-basin (0.96°C) (Fig. 5a). For the monthly distribution, the largest temperature increase will occur in August, September, and February, while the smallest will occur in March, April, October, and January. The seasonal mean increases over the whole HRB are 0.90, 1.05, 1.06, and 0.91°C for MAM (March–May), JJA (June–August), SON (September–November), and DJF (December–February), respectively. The spatial variations of temperature increases in each month are quite small, with the range of 25th–75th percentiles mostly smaller than 0.1°C. Same as the annual mean, the temperature increases in the upper sub-basin are larger than that within the whole HRB year-round (except July and September; Fig. 5c). Moreover, the SCORs between seasonal mean temperature increases and annual values are about 0.9, except in JJA (0.35), when the increases over the mountainous area are not so prominent (figures omitted).

The annual mean precipitation will also increase over most regions in the HRB with the magnitude up to more than 60 mm, while decreases mostly less than −15 mm will occur over the lower sub-basin. The largest precipitation increase simulated by ensR occurs over the Dabashan Mountains and Tangbai River basin. Note that the latter is a major food-producing region of China. The averaged increases in the whole HRB and its upper and mid–lower sub-basins are 46.3, 51.3, and 38.3 mm, respectively (Fig. 5b). For the monthly distribution, the precipitation areas averaged over the HRB and its two sub-basins will increase in May–July, December–January, and March, and decrease in February and April (Fig. 5d). For other months, the averaged changes between the upper sub-basin and the mid–lower sub-basin are different. During September–November, the precipitation increases in the upper sub-basin (4.4 mm), whereas it decreases in the mid–lower sub-basin (−9.6 mm). Note that the increases and decreases occur at almost all the grids in each sub-basin (figures omitted). In August, however, the distribution pattern is opposite.

The seasonal mean changes over the whole HRB (upper sub-basin) are 14.3 (13.9), 30.8 (30.9), −1.1 (−9.6), and 2.5 (2.4) mm for MAM, JJA, SON, and DJF, respectively. The spatial variations of precipitation changes in each month are quite large, especially in JJA and SON, with the range up to 11 mm between 25th and 75th percentiles.

The uncertainties of projected changes are also analyzed quantitatively. Two criteria are used (Han et al., 2020): more than 80% of ensemble members agree on the sign of change; signal to noise (SNR) is larger than 1, which is the ratio between the ensR change and the standard deviation of members’ changes (intermodel spread). All five members show a positive annual temperature change over the whole HRB, and more than 80% of members project increased annual precipitation over most part of HRB except the most downstream region with negative changes or small positive changes (Figs. 5a, b). The SNR of temperature changes in each month is greater than 1 (1.1–6.6), and the annual value for the whole HRB (upper sub-basin) is 4.51 (4.79) (Fig. 5e). The SNR of precipitation change averaged over the whole HRB and upper sub-basin is greater than 1 only in

![Table 2. Climate change simulation (1986–2005) and projection (2020–2099) products for the HRB](https://example.com/table2.png)

| Label   | Description                   | Unit |
|---------|-------------------------------|------|
| TAS     | Temperature                   | °C   |
| PR      | Precipitation                 | mm   |
| Rx5day  | Annual maximum of the precipitation amount for the 5-day interval | mm |
| R20     | Annual count of days when daily precipitation ≥ 20 mm | day |
| NCDD    | Number of consecutive dry days | Number of times |
| DMI     | Number of drought months      | Number of times |

![Table 3. Root-mean-square errors (RMSE), normalized RMSEs relative to observations (nRMSE; %), spatial correlations (SCOR), and temporal correlations (TCOR) on annual cycle between ensR and observations during 1986–2005](https://example.com/table3.png)

|               | Annual TAS | Annual PR | R20 | Rx5day | NCDD | DMI |
|---------------|------------|-----------|-----|--------|------|-----|
| RMSE          | 0.7°C      | 28.3 mm   | 0.6 days | 11.7 mm | 0.8 times | 0.4 times |
| nRMSE         | –          | 5.5%      | 6.1% | 11.2% | 5.2% | 22.1% |
| SCOR          | 0.99       | 0.98      | 0.98 | 0.96   | 0.92 | 0.95 |

|               | Monthly TAS | Monthly PR |
|---------------|-------------|------------|
| RMSE          | 0.3°C       | 11.3 mm    |
| nRMSE         | –           | 0.1%       |
| TCOR          | 0.99        | 0.98       |
January, March, June, and July, and the values for the mid–lower sub-basin are less than 1 in all months. For JJA and annual mean changes, the SNR values for the whole HRB are 1.62 and 1.78, respectively, and 1.73 and 1.85 for the upper sub-basin, indicating that the certainties on both the change sign and magnitude are quite low (Fig. 5f).

Compared to the RCP4.5, under the RCP8.5, the averaged changes in annual temperature will rise from 0.98 to 1.09°C, and changes in annual precipitation will increase from 46.3 to 44.1 mm. The spatial distribution of temperature changes is similar to that of RCP4.5 (figures omitted), with SCOR of 0.88. The spatial pattern of precipitation changes is quite different from that of RCP4.5, with positive changes over all the grids in the basin and maximum changes over the mid–lower sub-basin; while there are little changes in features of seasonal mean precipitation changes (figures omitted).

The above features of seasonal mean precipitation changes will add extra challenges to the reservoir operation. With increased precipitation being projected in JJA, more flood protection needs to be considered; with little increase in water storage being projected over the mid–lower sub-basin in September–November, nevertheless, more water needs ought to be catered. Meanwhile, annual mean precipitation averaged over the water intake areas of the middle routes of South-to-North Water Diversion Project is projected to increase by 37.2 mm in the next 20 years, which to a certain degree will reduce the water demand to Danjiangkou Reservoir.

### 3.2.3 Projected changes in extreme climate

In the next 20 years, R20 and Rx5day will all increase
over most regions of the HRB with the magnitude up to more than 2 days and 25 mm, while they will decrease with small magnitudes over the lower sub-basin. The magnitudes of R20 changes are small, and the spatial distribution is quite uniform. The maximum increases in Rx5day will be located at the Danjiang and Tangbai River basins and a small area of Dabashan Mountains (Figs. 6a, b). Future changes in meteorological drought are represented by two indices at daily and monthly scales, i.e., NCDD and DMI, respectively. Both of the two indices show that the frequency of drought will increase over most regions of the HRB. However, the magnitudes are quite small, with less than 1.0 time per year increase in daily-scale drought and mostly no more than 0.5 times per year increase in monthly-scale drought (Figs. 6c, d).

All the extreme indices changes can pass the threshold on agreement over most regions of HRB except the most downstream region. The SNR values for R20 and Rx5day over the whole HRB and upper sub-basin are larger than 1, with the values between 1 and 1.4; while for the two drought indices, the SNR values are less than 1. The results indicate lower uncertainties on all extreme indices’ change sign and flood indices’ change magnitudes but higher uncertainties on drought indices’ change magnitudes (figures omitted).

Compared to the RCP4.5, under the RCP8.5, the averaged change magnitudes in R20, Rx5day, NCDD, and DMI will all increase, with values from 0.95 days, 9.91 mm, 0.41 times, and 0.18 times to 1.49 days, 15.00 mm, 0.55 times, and 0.28 times (figures omitted).

There are few studies focused on future changes in mean and extreme climates over this region. Compared to previous studies on future climate projections over larger regions (e.g., Shi et al., 2018a; Zhu et al., 2018; Lu et al., 2019; Han et al., 2020), the conclusions of positive changes in mean temperature and precipitation and precipitation extremes are similar, which can also support the uncertainty analysis results in our study.

The growth of extreme precipitation at Danjiangkou Reservoir’s catchment area, Danjiang and Tangbai River basins will increase the risk of flood and add more pressure on flood control for Danjiangkou Reservoir. In the meantime, most areas along the Hanjiang River basin will experience more frequent droughts. The above changes impose great challenges for realizing the water diversion goals specified in the South-to-North Water Diversion Project.

3.3 Real-time climate prediction

3.3.1 Annual climate prediction

According to the requirement of the DCDR for formu-

![Fig. 6. Spatial distributions of changes in precipitation extremes: (a) R20 (day), (b) Rx5day (mm), (c) NCDD (number of times), and (d) DMI (number of times). Dotted areas indicate that 80% or more of ensemble members agree on the sign of change.](image)
lating an annual water resource diversion plan, the NCC provides the annual precipitation trend prediction over the HRB before 20 October every year. Analysis of the trends of the El Niño–Southern Oscillation (ENSO) cycle is a key factor for annual climate prediction. First, according to the characteristics of earlier SST evolution combined with several dynamic climate models, the SST evolvement trend in the central East Pacific is predicted. Second, the impact of ENSO cycle evolution on the precipitation in the HRB is diagnosed and analyzed. Based on the similar annual precipitation evolution regularity during the ENSO cycle, the precipitation trend in the next year in the HRB is predicted and its possible impact on the water resource management of Danjiangkou Reservoir is analyzed. For the first time of such a service in 2019, the NCC provided annual quantitative climate prediction on the watershed scale for specific users three months in advance (Table 4).

### 3.3.2 Seasonal climate prediction

In order to control floods in the flooding season and store water in autumn, the seasonal precipitation trend predictions of summer and autumn over the HRB are provided every year before 15 May and 15 August, respectively. China’s Multi-Model Ensemble Prediction System (CMME) developed by the NCC (Ren et al., 2019) has been implemented as the main tool to predict the probability of abnormal spatial distribution of precipitation as well as the likelihood of drought and flood disasters in the HRB in summer and autumn. This probability prediction is different from the previous NCC deterministic prediction, because it can provide users with the probability of abnormal spatial distribution of precipitation in key seasons, which makes it easier to develop appropriate counter measures.

### 3.3.3 Monthly climate prediction

The next-month precipitation predictions are provided before the 15th of each month. The information provides a scientific basis for the development of a monthly water resource control plan at Danjiangkou Reservoir. Based on the large-scale circulation fields predicted by the Climate System Model of Beijing Climate Center (BCC_CSM; Wu et al., 2013) and the test of the prediction ability of the main impact system of monthly precipitation in the HRB, those climate variables with high reliability of prediction are produced by the dynamic model. A downscaling interpretation and application method was developed to predict monthly precipitation in the HRB. Compared with the conventional climate prediction products, on one hand, the HRB monthly precipitation prediction dataset can be provided 15 days in advance; on the other hand, the spatial resolution that has been increased from 100 to 30 km can meet the specific need of earlier predictions and spatial refinement of the climate predictions.

### 3.3.4 Extended-range climate prediction

To address the demand for climate predictions during the impounding period (from 10 September to 10 October) of Danjiangkou Reservoir, an analogue error correction algorithm (using a large amount of historical similarity information to correct the model results) is developed and implemented based on the low-frequency signal of the atmosphere and the NCC’s monthly Dynamical Extended Range Forecasts (DERF 2.0) products (Zheng et al., 2009). The prediction of precipitation process and intensity over the extended range is provided to the DCDR for impounding decisions. Different from the previous climate prediction products over the extended range, the prediction used in the present study is refined to daily scale, making it easier to set specific impounding time.

### 3.3.5 Prediction assessment

This paper introduces the assessment results of climate predictions by taking the monthly precipitation prediction over the HRB as an example. Using the Climate Trend Prediction Test method (Pc) of the China Meteorological Administration, which is the accurate percentage of precipitation anomaly grade prediction (Li et al., 2004), monthly precipitation predictions over the HRB from January to December 2019 are examined. The results are displayed in Fig. 7. It is shown that the average trend test score for the whole year is 61.6%, which reflects a fairly good predicting skill. However, scores of predictions for different seasons and months vary significantly. For seasonal predictions, the score for the critical period of reservoir diversion, or summer (June–August), reaches the highest score of 70.8%, and that for autumn (September–November) and winter (December, January, and February) are 65.1% and 64.1%, respectively. All the scores reflect a high level of predicting skill, especially the score for the critical period of water storage, i.e., October, which reaches 96.9% and is the highest scored monthly prediction. The average score for spring (March–May) is relatively low with the value of

### Table 4. Spatial resolution and methods of climate prediction for the HRB

|                      | Annual          | Seasonal        | Monthly         | Extended-range |
|----------------------|-----------------|-----------------|-----------------|----------------|
| Leading time         | 3 months        | 15 days         | 15 days         | 10 days        |
| Spatial resolution   | 100 km          | 45 km           | 30 km           | 10 km          |
| Prediction method    | ENSO cycle      | CMME            | Statistical downscaling | DERF 2.0      |
46.4%, indicating a poorer skill level of predicting. The lowest value of 32.8% occurs for January. Spring is a transitional season in China, when the climate shifts from the winter monsoon to the summer monsoon, which makes precipitation prediction quite difficult and leads to a low level of prediction skill for precipitation trend in spring. Note that the DCDR also provides real-time inspection results to the NCC regarding the climate prediction products, which greatly contributes to the improvement of climate prediction skills of NCC.

4. Effectiveness of the climate services

With the predictions of precipitation provided by the NCC, which include annual, summer and autumn flooding seasons, monthly, and extended-range predictions, the DCDR has rationally formulated and successfully completed the annual water diversion plan of 2019, and gives a full play of climate information in water resource management such as flood control, hydropower generation, water diversion, and improvement of environment. Given the climate trend fact that there is less rainfall at the upstream of Hanjiang River during summer, the DCDR strictly controls the water supply to Taopen, Qingquangou, and the middle and lower reaches of Hanjiang River before August. The lowest water level of 150.71 m occurred on 23 April 2019, but it was higher than the dead water level (i.e., the lowest water level that allows the reservoir to dissipate under normal operation) of 150 m. As the inflow to the reservoir gradually increased, the water level slowly recovered to 156.68 m on 1 August 2019. Based on the climate prediction information that there would have more rain within the next month and a possible autumn flood, the DCDR increased the water supply for headworks at Taopen and Qingquangou. The water supply for Taopen was increased from 220 m$^3$ s$^{-1}$ on 1 August to 350 m$^3$ s$^{-1}$ on 14 August 2019. The DCDR also launched ecological water supply to water-receiving areas of the middle-route project, and provided water for Yindan irrigation area near Xiangyang City to prevent agricultural drought. On 14 September, combined with the flood control diversion, the DCDR gradually increased the average daily water supply for the middle and lower reaches of the Hanjiang River from 520 to 7180 m$^3$ s$^{-1}$. After the flood, the daily water supply was controlled to be 1200 m$^3$ s$^{-1}$ until the end of the month. At the end of the flooding season, Danjiangkou Reservoir reduced the water supply on time in accordance with extended-range climate predictions. The highest water level reached 166.51 m, the second record high since the records are available, which secured the water supply for the next year with abundant water storage.

According to the projections of future climate change, the autumn precipitation in the HRB would dramatically decrease, which means less natural inflow into the reservoir. Consequently, during the critical period of water storage in autumn, the reservoir would have low storage with less water for diversion. As the use of and demand for water grow, it is impossible to meet the increasing demand for water in the northern portion of China if the water storage of Danjiangkou Reservoir is the only source of water supply for the middle-route project. Considering the development trend of water source and catchment area, the Ministry of Water Resources launched phase II middle-route project of the South-to-North Water Diversion Project. The project plan was approved in December 2019.

Because the climate prediction information was well applied in 2019, Danjiangkou Reservoir reasonably controlled the operational water level, effectively improved the water use efficiency and water supply, secured the diversion of water resource, increased the ecological water supply to the northern portion of China by 844 million m$^3$, and reduced as much as 1.67 billion m$^3$ of abandoned water. Projections of future climate changes effectively facilitated phase II middle-route project of the South-to-North Water Diversion Project to channel the water from Three Gorges Reservoir to the Hanjiang River project. Climate changes would also increase the risks of extreme rainstorms and droughts along the HRB, and the DCDR has been studying mitigation strategies in response to the extreme events.

5. Summary

Providing targeted and refined climate service products for water resource management in Danjiangkou Reservoir is a concrete practice, in which the NCC has transformed its climate science into climate services for water resource management. This is an example of the
cases to implement climate services in the water resource management. The conclusions and discussion of this paper are as follows.

First, in the context of global warming, the annual precipitation, autumn flooding season precipitation, and annual surface water resource over the last six decades in the WSAD slightly decreased at a rate of 7.2, 4.6, and 345 million m$^3$ (10 yr)$^{-1}$, respectively. Evidence also shows the decrease of intensity and advance of the last heavy rainfall date in the WSAD. In the next 20 years, annual mean temperature and precipitation will increase in the HRB while autumn precipitation will decrease in the WSAD. The growth of extreme precipitation at Danjiangkou Reservoir’s catchment area, Danjiang and Tangbai River basins, will increase the risk of flood. The above features of climate changes will add extra challenges to the reservoir operation that needs more flood protection in summer while growing pressure for water storage in autumn. Therefore, climate predictions at the S2S timescale for keeping the reservoir in safe operation and accomplishing the water diversion goals are turning more and more important.

Second, climate information can only be helpful when applied for specific decision-making in water resource management. In this case study, the DCDR well applied the tailored climate prediction information to reasonably control the operational water level in 2019. It effectively improved the water use efficiency and water supply, secured the diversion of water resource, increased the ecological water supply to the northern portion of China by 844 million m$^3$, and reduced as much as 1.67 billion m$^3$ of abandoned water. However, water resource management requires more sophisticated climate service products in terms of time and space, as a scientific basis for long-term planning and short-term real-time diversion of water. Although the NCC has currently made great progress in providing climate prediction products, there is still much work to be done to seamlessly meet the demand of water resource management. For instance, the current density of meteorological observation network is still insufficient, and climate prediction skills, especially for predictions in the spring, need to be improved. To meet the demand of refiner water resource diversion, it is necessary to not only improve the prediction accuracy of precipitation and inflow but also the prediction for a longer lead time. For instance, rotating predictions need to be added in early and mid-June and around mid-September to better serve the need of water resource management for pre-flood water level decline and post-flood storage.

Third, it is fairly necessary for providers and users of climate services to interact and communicate with each other (Golding et al., 2019; Wang et al., 2020). In the application of climate services for water resource management at Danjiangkou Reservoir, the two sides frequently communicated with each other, provided feedbacks, co-inspected the prediction products, and co-developed climate prediction technology. The NCC helped the user to better understand climate prediction and future change projection information, which improved the application efficiency of climate services in decision-making of water resource management. Despite the progress mentioned above, both sides still need to further enhance opinion exchanges and intensify collaborations to improve the availability of climate prediction products and make better use of climate services.

Last but not least, the effectiveness of climate services somehow depends on the progress of climate science. Due to the complexity of the climate system and uncertainties of various climate scenarios, it remains difficult to precisely predict climate variability and project climate changes in the future. Therefore, it is imperative to study and develop a seamless climate predicting method tailored for the HRB. It is especially important to improve the climate prediction skills during the critical periods of flood control and water storage. At the same time, it is necessary to use high-resolution RCMs to dynamically downscale future climate change scenarios and estimate the subsequent climate risks, and strengthen the impact study of climate changes on water resources on the basin scale. Such kind of studies can effectively reduce the vulnerability of the water resource system to climate changes, improve the ability of the Danjiangkou Water Control Project to adapt to climate changes, and make better use of its management functions of flood control, hydropower generation, water diversion, environment improvement, and so on.

Acknowledgments. Thanks go to Dr. Chaoyang Sun for helping draw the figures of the study area and Dr. Rong Gao for helping draw the figures of observed climate changes. We thank the Editor and two anonymous reviewers for providing valuable suggestions for improvement of this manuscript.

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Tech & Copy Editor: Zhirong CHEN