MECHANISMS AND EARLY WARNING OF DROUGHT DISASTERS

Experimental Drought Meteorology Research over China

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A major research project in China was launched to measure and model eco-hydrometeorological processes for drought disasters and to disseminate multidisciplinary information by establishing a northern China drought information system.

China is a drought-prone country, and 30% of the economic losses caused by natural disasters in China can be attributed to drought, ranking first among all disasters. In a changing climate, droughts occur more frequently with longer durations and wider affected areas (Zhang and Zhou 2015), and

northern China suffers from droughts the most. To understand drought mechanisms and mitigate drought risk, China launched a series of projects, including the Mechanism and Prediction of Major Weather and Climate Disasters (1998), Northern China Aridification and Human Adaptation (2005),

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and Energy and Water Cycle Variability under Global Warming and Its Impact on Climate Extremes over China (2008). In the past decade, China's drought projects expanded from national to global scales, aiming to obtain global background of regional droughts and aridification (Huang et al. 2016a,b).

Several decades of drought research have identified the variations and variability in the East Asian summer monsoon and Indian summer monsoon, the west Pacific subtropical high and South Asian high, the land surface over Tibetan Plateau, and El Niño–Southern Oscillation as important factors in drought occurrence over China. To monitor and predict droughts, several in situ and satellite observation-based drought indices have been developed [e.g., the comprehensive meteorological drought index (CI), surface water content index (SWCI), and vegetation condition index (VCI)], and meteorological drought prediction techniques have transitioned from statistical methods to numerical model-based statistical–dynamical forecasting methods.

However, most research has mainly focused on the cause and characteristics of droughts from the perspective of abnormal atmospheric circulations and oceanic conditions (Schubert et al. 2009; Hoerling et al. 2014; Trenberth et al. 2014; Wang et al. 2017) without comprehensive observational experiments or drought mechanism research focusing on the understanding of the entire processes, ranging from land–atmosphere interactions to agricultural (ecology) drought formation from a multidisciplinary perspective. Here, the following five research areas are highlighted to promote drought disaster studies:

- 1) Understanding the interactions among atmosphere, hydrosphere, and biosphere with respect to drought onset and recovery as well as the relationship between meteorological droughts and agricultural, hydrological, and ecological droughts that is critical to unraveling the mechanisms of drought disasters. While there are studies on individual types of droughts, the full chain of drought disaster evolution is not well understood.
- 2) Several physical processes that are unique over arid and semiarid regions (e.g., northern China), such as the soil water vapor–heat interaction that affects surface soil moisture variability, the effect of intermittent turbulence on boundary layer energy exchange, and the drought–albedo feedback with variable land cover, are often overlooked by many drought modeling studies.

- 3) The transition from stomatal to nonstomatal control of plant photosynthesis with the increase in drought severity cannot be reasonably represented in drought models without intensive observational experiments.
- 4) Integrated hydroclimate forecasting systems that incorporate both seasonal climate prediction information and initial land surface hydrological memory have become popular in recent years, but their performances need to be rigorously verified over the target areas with comprehensive hind-cast experiments, especially for extreme drought cases.
- 5) Multisource drought information systems built on our understanding of drought disaster mechanisms, advanced drought prediction models, and the reasonable estimation of drought impacts as well as state-of-the-art observation techniques (e.g., radar, satellite remote sensing) have received wide attention among the global drought community, but these approaches are far from perfect given the comprehensive datasets and complicated dialogues across multiple disciplines.

To improve the drought adaptation capability over northern China for arid and semiarid climates, in 2015, China launched the Mechanisms and Early Warning of Drought Disasters over Northern China (DroughtEX_China) project, which is led by the China Meteorological Administration (CMA). Based on a series of regular, intensive, and specially designed observations as well as field experiments on the natural and manually controlled drought conditions, interdisciplinary and comprehensive drought research is being performed. This research will advance the understanding of the complicated dynamic processes of the onset and recovery of drought disasters, the characteristics of the water and energy cycles in the atmosphere–soil–vegetation system at multiple scales, and the relationship among meteorological, agricultural, and hydrological droughts. Moreover, technological advancements in accurate monitoring, risk assessment, and early warning for drought disasters are expected.

The DroughtEX_China project aims to 1) carry out interdisciplinary, comprehensive, and systematic field observational experiments to identify drought disaster mechanisms over northern China; 2) investigate the characteristics of the land–atmosphere interactions from drought onset to recovery and model the link between meteorological droughts and drought disasters; 3) improve the parameterization schemes of land surface processes and atmospheric boundary characteristics for better

FIG. 1. Field observational experiment station network over northern China.

drought modeling; 4) develop an early-warning system based on multisource observational data and advanced hydrology–climate forecasting models; and 5) establish a regional integrated platform of drought monitoring and warning for information sharing and dissemination. This paper will introduce the observational and experimental system; present preliminary results on key processes for modeling drought disasters, especially over arid and semiarid regions; and demonstrate a prototype of a northern China drought information system.

OBSERVATIONAL AND EXPERIMENTAL SYSTEM. *Experimental design.* The observational experiment covers the whole chain of drought development, that is, drought onset–disaster formation–drought recovery. For example, to investigate land–atmosphere interactions during drought, an intensive observation of land surface–boundary layer–atmosphere dynamics is required. Drought damages crops by influencing water supply (soil water content), plant water conditions, photosynthetic processes, biomass accumulation, crop growth, and crop yield, among others. Therefore, drought disaster mechanisms are investigated through a series of artificially controlled field experiments and data analyses.

Experimental area and network configuration. Field observation stations are located across northern China, where the climate is arid and semiarid, and

the ecological environment is vulnerable. The project designed a V-shape station network layout (Fig. 1), which is mainly made up of many existing meteorological, agricultural, and grassland stations as well as several comprehensive observation stations. The stations are operated collaboratively for continuous and automatic (manual) observational experiments and intensive observations during key periods (Fig. 1). The information on the 23 observational experiment stations is listed in Table 1. In addition, several CMA radiation observation stations were used as auxiliary observations stations. The observations started in June 2015, and simultaneous coupled air sounding–intensive observations in multiple experiment regions were carried out in May, July, and September 2017. Preexisting observations were also used for drought analysis.

Experiment components and main instrument. The field experiments consist of three components, namely, land surface processes (Table 2) and atmospheric boundary layer characteristics (Table 3) over arid and semiarid regions, mechanisms for drought disaster onset (Table 4), and the impacts of precipitation on drought duration and recovery (Table 5).

Table 4 shows that the observational elements for the drought mechanism experiment include plant physio-ecological indicators such as the leaf water content, net photosynthetic rate, respiration rate, transpiration rate, stomatal conductance (G_s),

intercellular CO₂ concentration, air temperature of the leaf chamber, photosynthetically active radiation (PAR), leaf area index (LAI), plant height, and dry and fresh yield (crop yield composition). In addition, the artificial soil moisture experiment equipment includes a moisture testing ground with an awning. Table 5 shows the observational elements for investigating the influence of precipitation on drought duration and recovery, where different types (e.g., intensity, durations) of rainfall could be generated artificially and the corresponding water and vegetation responses can be observed.

PRELIMINARY RESULTS ON KEY PROCESSES FOR UNDERSTANDING AND MODELING DROUGHT DISASTERS OVER ARID AND SEMIARID REGIONS. *Impact of soil water vapor–heat interactions on soil moisture variability.* Droughts usually start as a result of rainfall deficits from the atmosphere, but their impacts are reflected

in the land surface (e.g., soil moisture deficit and vegetation damage). Therefore, land surface processes are critical for understanding drought impacts, as well as drought disasters. Over arid and semiarid regions, land surface processes are unique as 1) the surface gradient of temperature and moisture is large and soil water is usually transported in the form of water vapor via diffusion in the surface layers, and 2) the surface evaporation rate is closely related to the water vapor diffusion rate. However, most land surface models (LSMs) do not include the soil water vapor diffusion processes. Here, a fully coupled water–heat transport scheme (FCS) was incorporated into the Community Land Model, version 4.5 (CLM4.5), to improve the simulations of soil water and heat transport (Wang and Yang 2018).

Figure 2 shows the simulation results at the Naiman station. In most LSMs (e.g., CLM4.5), only the influences of the soil heat conduction (H₁) and hydraulic potential gradient (W₁) were considered, while the water vapor–induced transport of sensible and latent heat fluxes as well as water vapor fluxes due to temperature gradient and hydraulic potential were ignored. As shown in Fig. 2, CLM4.5 overestimated the surface soil moisture at the Naiman station, while the new scheme with water vapor impacts (FCS) produced a more reasonable simulation as compared with the observations, especially during dry periods. The results suggest that representing soil water vapor–heat interaction processes improves the simulation of soil moisture variability, which is important for drought modeling over arid and semiarid regions.

Effect of intermittent turbulence on atmospheric boundary layer characteristics and energy exchanges. Soil moisture dynamics can affect the overlying atmosphere through turbulence exchanges. Over arid and

TABLE 1. Information for 23 field observational experiment stations.

No.	Station	Information
1	Tazhong	A land–atmosphere interaction and boundary layer observation station in a desert region in Xinjiang
2	Wulanwusu	Agricultural experiment stations in an oasis region of an arid region
3	Wuwei	
4	Zhangye	Arid and Gobi Desert region observations in the Hexi Corridor
5	Dunhuang	
6	Jiuquan	
7	Minqin	
8	Dingxi	In a semiarid region of the Loess Plateau with farmland and natural soil surfaces
9	Yuzhong	
10	Pingliang	
11	Guyuan	
12	Qingyang	
13	Changwu	
14	Ansai	
15	Yongning	
16	Haibei	A husbandry meteorological experiment station in the Qinghai–Tibet Plateau with an underlying alpine grass surface
17	Naiman	A land–atmosphere interaction and boundary layer observation station with a desert grassland surface
18	Gucheng	A comprehensive observation station with farmland surface
19	Hengshui	An ecological monitoring station in a wetland
20	Xilinhot	A grassland observation station in Inner Mongolia
21	Xiajin	Featuring agricultural field surfaces in a semihumid region
22	Zhengzhou	
23	Shouyang	

semiarid regions, the effect of intermittency on turbulence is obvious, and it should be considered in the estimation of turbulence fluxes. Turbulent motion in the atmospheric boundary layer can be formed by the accumulation of eddies at different spatiotemporal scales, which can be separated by using the spectrum analysis method. The Hilbert–Huang transform (HHT) can reveal the frequency spectrum of turbulence better than the fast Fourier transform (FFT) and can identify obvious intermittent characteristics of the stable boundary layer. Removing the intermittence of turbulence from the original data can better match similarity of the boundary layer. Observational data from the 20-m-high meteorological tower at the Naiman experiment station in a semiarid region were used, and HHT was applied to analyze the turbulence characteristics of the atmospheric boundary layer with a complicated underlying surface. Figure 3 shows that turbulent motion at night has clear intermittency in the Naiman region (Wei et al. 2016). Two fluctuation periods of 4 and 13 min exist and correspond to the oscillation periods of the gust and internal gravity waves.

The intermittency of turbulence occurs frequently owing to strong thermodynamic effects. Figure 4 shows the diurnal cycle of turbulent kinetic energy (TKE), shear and sensible heat fluxes averaged

during 1–15 April 2011, using the original data [Eddy Covariance (EC); without considering intermittency], and the reconstructed data (reconstructed; with the consideration of intermittency). The turbulent fluxes were overestimated because of nonturbulent motion. In classical eddy covariance systems, the typical averaging period used for turbulence measurements is approximately half an hour. In conditions of intermittent turbulence, such a length may not be well suited to stationarity conditions. Therefore, a new estimation that considers intermittent turbulence would be more reasonable for model development, would reduce the overestimation of the hydrothermal exchange between

TABLE 2. Land surface observational elements and instruments.

Observational elements	Experimental methods or equipment
Turbulent fluctuations of 3D wind and temperature, CO ₂ and H ₂ O flux	Ultrasound wind–temperature meter
Sensible and latent heat fluxes	Dual-wave band scintilloscope
Surface radiation	Shortwave radiation gauge (with upward and downward probes)
	Longwave radiation gauge (with upward and downward probes)
	Direct radiation gauge
	Scattering radiation gauge
Soil temperature (0–50 cm)	Platinum resistor thermometer
Soil humidity (0–50 cm)	Automatic soil moisture meter, soil drilling
Soil thermal flux (0–20 cm)	Soil thermal flux board
LAI	LAI gauge
Vegetation condition	Camera
Snow cover	Manual glass thermometer
Snow depth (≥ 1 cm)	Manual observation
Depth of frozen soil	Manual observation
Precipitation	Hyetometer
Evapotranspiration	Lysimeter, ultrasound wind–temperature meter
Evaporation	E601B

TABLE 3. Boundary layer observational elements and instruments.		
Category	Observational elements	Experimental methods or equipment
Flux observation (four-floor tower higher than 20 m)	Temperature	Platinum resistor thermometer
	Humidity	Humidity-sensitive capacitor
	Wind speed	Three-cup anemometer
	Wind direction	Wind vane indicator
	Ground air pressure	Barometer
Profile observation	Wind profile	Wind profile radar, air sounding balloon
	Temperature–humidity profile	Air sounding balloon

TABLE 4. Observational elements and instruments for drought disaster mechanism experiments.		
Category	Observational elements	Experimental methods or equipment
Soil characteristics	Soil moisture (0–50 cm)	Automatic soil moisture meter, soil drilling method
	Farmland evapotranspiration	Lysimeter, ultrasonic wind–temperature meter
	Soil temperature (0–50 cm)	Platinum resistor thermometer
	Soil property	Sample measurement
Plant physio-ecological characteristics	Net photosynthetic rate, respiration rate, transpiration rate, Gs, intercellular CO ₂ concentration, air temperature of leaf chamber, PAR	Photosynthesis apparatus (LI-6400XT)
	LAI	Leaf area apparatus (LAI-2200)
	Density	Manual
	Spectrum characteristics	Spectrometer (FiedSpec Pro FR2500)
	Dry and fresh yield	Electronic scale, balance
	Leaf water content	Drying method
	Plant height	Meter scale
	Canopy temperature	Platinum resistor thermometer, infrared thermometer
	Chlorophyll	Chlorophyll apparatus (SPAD-502)
	Sap flow	Sap flow apparatus (FLOW32)
Meteorological conditions	Temperature, humidity, wind speed and direction	Automatic meteorological station
Configuration for artificial soil moisture experiments	10%–100% of normal soil moisture	Outdoor artificial soil moisture equipment

TABLE 5. Observational elements and instruments for evaluating the influence of rainfall on drought duration and recovery.		
Category	Observational elements	Experimental methods or equipment
Rainfall process indicator	10- and 30-min precipitation	Automatic hyetometer
	Hourly precipitation	Automatic hyetometer
	Precipitation magnitude	Manual
	Precipitation phase	Manual
Water and soil characteristic indicators	Soil moisture (0–50 cm)	Automatic soil moisture meter
	Soil temperature (0–50 cm)	Platinum resistor thermometer
	Surface runoff	Surface runoff gauge
	Soil moisture movement parameters	Laboratory method
	Streamflow	Buoy method, hydrometric propeller method
Vegetation characteristics indicators	Vegetation type	Manual
	Vegetation coverage	Manual
	LAI	Leaf area apparatus (LAI-2200)
	Spectrum characteristics	Spectrometer (FiedSpec Pro FR2500)
	Density	Manual
	Leaf water content	Drying method
	Height	Meter scale
Meteorological condition indicators	Temperature, humidity, wind speed, wind direction	Automatic meteorological station
Rainfall simulation indicators	Rainfall duration varying from 30 to 60 min; rainfall intensity varying from 1 to 4 mm min ⁻¹	Field artificial rainfall simulation device

FIG. 2. Vertical profiles of four components regarding (top) soil heat fluxes (H_1 , H_2 , H_3 , and H_4 ; W m^{-2}) and (middle) soil water fluxes (W_1 , W_2 , W_3 , and W_4 ; mm s^{-1}) from the new scheme considering water vapor (FCS) and the difference with the CLM. (bottom) Time series of the observed and model-simulated surface soil moisture at a depth of 0.05 m. Components H_1 , H_2 , H_3 , and H_4 represent the soil heat fluxes accounting for conduction, convection of sensible heat with flowing water, transfer of sensible heat via the diffusion of water vapor, and transfer of latent heat via the diffusion of water vapor, respectively. The results are for Naiman station in the northeast part of the study domain. Components W_1 , W_2 , W_3 , and W_4 represent soil water fluxes due to the hydraulic potential gradient, soil water fluxes due to the temperature gradient, and water vapor fluxes due to the hydraulic potential and temperature gradients, respectively [modified from Wang and Yang (2018)].

FIG. 3. Intermittent turbulence measured at Naiman station. Change in $\xi(q) - 1$ with order q under (a) unstable stratification and (b) stable stratification, where the black straight line represents $\xi(q) - 1 = q/3$; (c) the time series of horizontal wind speed pulsation U at 0000–0100 UTC 16 Apr [$\xi(q)$ is the Hilbert-based scaling exponent function, and q is the order number (Wei et al. 2016)].

FIG. 4. Diurnal cycles of (a) the TKE, (b) the shear, and (c) the sensible heat flux averaged during 1–15 Apr 2011 at Naiman station. The dashed and solid lines are the estimations without and with consideration of the intermittent turbulence, respectively.

the land surface and atmosphere, and would improve drought simulations and predictions (Howell and Mahrt 1997; Vickers and Mahrt 2003).

Albedo–drought feedback over semiarid regions. In addition to soil water vapor–heat interactions and intermittent turbulence, land-use/land-cover change also has a significant influence on the water and energy cycle, especially during drought periods. To model drought-induced changes in albedo and surface energy balance as well as the interaction between albedo and the atmosphere in a semiarid region (i.e., the Loess Plateau) two severe drought cases (2001 and 2005) were selected. The Weather Research and Forecasting (WRF) Model was used for the simulations, with two albedo datasets as the lower boundary layer conditions, namely, the WRF default climatology albedo (CTL simulation) and the time-varying Moderate Resolution Imaging Spectroradiometer (MODIS) albedo (ALB simulation). Figures 5a–c

show that the albedo reacted to the spring drought in August 2001, especially in the middle and eastern parts of the Loess Plateau, suggesting that the response lag time of the albedo to drought is approximately 3 months over this semiarid region. The response time scale is similar to that over the Murray–Darling Basin in Australia, in which Meng et al. (2014) found that albedo reacted to drought after approximately 3–6 months. Similar changes were found during another drought year of 2005 (Figs. 5d–f). The albedo changes due to drought in 2001 and 2005 were 5.5% and 3%, respectively.

Changes in albedo can affect the surface energy balance, thus affecting the atmospheric state and subsequent precipitation. To investigate the influence of drought-related albedo change on the subsequent summer precipitation over the Loess Plateau, we used a convective triggering potential and low-level humidity index (CTP–HI_{low}) framework developed by Findell and Eltahir (2003) to

FIG. 5. (a)–(f) Differences in the monthly albedo variations during summer between the CTL and ALB simulations in 2001 and 2005. (g),(h) Regional climate model (WRF)-simulated convective precipitation changes due to albedo variations resulting from drought during the summers of 2001 and 2005, respectively.

calculate the albedo-induced convective precipitation changes. The convective triggering potential (CTP) represents a measure of the temperature lapse rate taken between 100 and 300 m above the land surface (i.e., approximately 750 and 550 hPa, respectively, assuming a surface pressure of 850 hPa over the Loess Plateau) and provides insight into the boundary layer response to surface flux development. The low-level humidity index (HI_{low}) was defined by Findell and Eltahir (2003) and Findell et al. (2011) as the sum of the dewpoint depressions 50 and 100 m above the ground surface. Figures 5g and 5h show that the

albedo changes affected convective precipitation with a larger influence in 2001 due to a larger albedo change. On average, the precipitation changes in the affected regions are 27% and 11% for 2001 and 2005, respectively, leading to a positive feedback on the summer drought.

Influence of drought stress on the physiological and ecological characteristics of different crops. The DroughtEX_China project not only focuses on the physical mechanisms of drought (e.g., soil water vapor–heat interaction, intermittent turbulence,

and the drought–albedo feedback introduced above) but also attempts to investigate the mechanisms for drought disasters. Understanding the effects of drought stress on the physiological and ecological characteristics of crops is an important step toward drought impact analysis and drought adaptation. In this project, a set of observational experiments were conducted with measurements of physio-biochemical indicators of wheat, corn, potato, and cotton under irrigation and drought conditions. The changes in

physio-biochemical indicators under different treatments could reflect the crop adaptation to drought. The drought stress mainly caused the degradation of wheat tillering, further resulting in a significant difference in wheat density compared with that under normal irrigation conditions (4 times the irrigation amount for the entire growing period; 105 kg m⁻² each time). Under drought conditions, the LAI for different crops (corn and cotton) was lower than that with sufficient irrigation. Persistent soil drought greatly suppressed potato growth in terms of height and size. Droughts could lead to a remarkable decrease in the crop yield, which could be exacerbated when the drought persists.

Drought stress led to a decrease in chlorophyll concentration, thus resulting in significant differences in the photosynthesis rate and transpiration rate; such reduction would be amplified if the drought intensified. For example, the net photosynthetic rates (Pn) of spring corn leaves had consistent and sensitive reactions to PAR under different drought conditions, showing a tendency to stabilize or decrease after a sharp increase (Fig. 6a). The value of Gs increased rapidly as PAR increased, especially for those without drought stress (Fig. 6b), and the intercellular CO₂ concentration (Ci) decreased significantly as PAR increased and increased slightly when PAR was larger than a certain threshold (Fig. 6c). Under the same PAR, Pn and Gs for spring corn leaves were generally as follows: normal irrigation (CK) ≥ light drought stress (LS) ≥ medium drought stress (MS) ≥ severe drought stress (SS) (Figs. 6a,b). Therefore, drought stress increased the resistance of the stoma and decreased CO₂ absorption and photosynthesis (Jiang et al. 2015).

The observational experiment suggested that leaf water content is a good indicator for the water potential of plants under stress conditions as well as for the water usage of plants (Fig. 7). If there was a drought during the key growth period of corn, the leaf water content decreased gradually with the intensification of drought, whereas the relative saturation deficit and the water absorption rate increased gradually. Meanwhile, the crop water shortage increased, and the drought adaptation capability weakened dramatically. In arid and semiarid regions, the crop water stress index (CWSI), which is defined as $CWSI = 1 - LE/EP$, where LE and EP indicate the actual and potential evapotranspiration, respectively (Shen and Tian 1998), ranged from 0.242 to 0.390 for corn and from 0.305 to 0.342 for spring wheat. In this observational experiment, the CWSI was relatively low, which suggests that the crop's adaptation capability increased.

FIG. 6. Reaction curves of spring corn leaf photosynthesis with respect to PAR under different drought stresses.

A PROTOTYPE OF A NORTHERN CHINA DROUGHT INFORMATION SYSTEM.

Multimodel ensemble drought forecasting. Based on the understanding of the key processes from soil moisture–vapor movement to intermittent turbulence and from albedo–drought feedback to drought’s ecological impact, a better land–atmosphere coupled model for simulating water and energy cycle as well as drought disasters is expected over northern China. However, in order to make a skillful drought prediction at long leads, land–atmosphere coupled models should be combined with oceanic models that resolve large-scale climate variability. To demonstrate the possibility of establishing a drought early-warning system for northern China, we collected six North American Multimodel Ensemble (NMME; Kirtman et al. 2014) ocean–atmosphere coupled models with complete soil moisture hindcast datasets for the period 1982–2010 and assessed their forecasting skill through a comparison with the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) soil moisture data. To enable comparisons among different models, the soil moisture was first standardized. The forecasting skill in terms of anomaly correlation (AC) can be very high without such a standardization procedure (not shown), suggesting strong land surface heterogeneity over northern China. Figure 8 shows the AC of the seasonal mean soil moisture for winter [December–February (DJF)] and summer [June–August (JJA)], with the forecasting skill in winter generally being higher than that in summer. During winter, two Canadian models [Third Generation and Fourth Generation Canadian Coupled Global Climate Model (CanCM3 and CanCM4)] and National Centers for Environmental Prediction’s (NCEP) Climate Forecast System, version 2 (CFSv2), exhibited high skill for the central and eastern parts of northern China, with AC values of 0.3–0.5. Two National Center for Atmospheric Research (NCAR) models did not display good forecasting skill, which might be partly due to the absence of land surface initialization when performing seasonal hindcast experiments. The forecasting skill of the simple multimodel arithmetic mean (NMME1) falls between that of the best and worst models except for the Song–Huajiang River basin in northeastern China. By using an optimization procedure (Zhou et al. 1997; Yuan et al. 2012; Yao and Yuan 2018) to assign different weights to different models that have variable skill, the resulting NMME2 forecasting skill was substantially improved for all of northern China. Note that NMME2 involved an estimation without cross validation; that is, NMME2 is the potential upper limit

of the forecasting skill. A comparison between the simple ensemble mean (NMME1) and superensemble mean (NMME2) showed that there is room for further improvement, especially for the summer season where the low skill in individual models resulted in a low skill in the simple ensemble mean (NMME1).

Similar to other NMME studies (Mo and Lettenmaier 2014; Thober et al. 2015; Yuan et al.

FIG. 7. Measurement of main drought resistance indicators for dryland crops under artificial rainfall (drought stress) conditions during 2015–16. The bar plots with (without) pink diamonds represent the results for severe (moderate) drought conditions. The rainfall conditions for the observational experiments are as follows: that without any natural or artificial rainfall (KWR), natural rainfall only (MR0), and natural rainfall plus 30 (MR30), 60 (MR60), 90 (MR90), and 150 mm of artificial rainfall (IRR). Here, 150 mm of artificial rainfall is considered a sufficient irrigation condition.

2015; Sikder et al. 2016), these NMME climate forecast models did show some skill and may be useful in hydrological forecasting. Therefore, the meteorological hindcasts were downscaled and bias corrected to drive a well-calibrated land surface hydrological model [Variable Infiltration Capacity (VIC)] to provide hydrological drought forecasting for the Yellow River basin in northern China, using an experimental

forecasting system developed by Yuan et al. (2016). A drought case of 2002 was selected to verify the ensemble forecasting of a hydrological drought index, that is, the standardized streamflow index (SSI). Figure 9 shows the ensemble forecasts started from February and June of 2002 for five selected gauges from the upper to lower reaches of the Yellow River basin. In the February SSI forecast, the climatological forecast method [ensemble streamflow prediction (ESP)/VIC] had some positive forecasting skill; however, the method entirely missed the hydrological drought in the June forecast with the ensemble-mean SSIs (blue lines in the left panels of Fig. 9) being close to zero and larger than the drought threshold line of -0.8 . Using the climate-model-based approach (NMME/VIC), a number of ensembles could capture the hydrological drought conditions during summer, with the ensemble-mean SSIs (blue lines in the right panels of Fig. 9) being closer to the reference (black line). This demonstration is just an example showing the potential of the experimental system in hydrological drought forecasting, and more comprehensive evaluations can be found in Yuan et al. (2017).

Integrated multisource drought information platform.

This project integrates and manages data via a shared platform—the Information Integration and Data Sharing Platform of China Drought Information. This project applied a relational database management system (RDBMS) to integrate structured and nonstructured meteorological metadata and all the observational experimental data and products collected by DroughtEX_China and to classify the information and manage the documents in accordance with international standards. With the help of the basic information technology resource from the CMA Cloud Platform, an open data-sharing platform was established utilizing distributed database technology

FIG. 8. AC of the predicted seasonal-mean standardized soil moisture over river basins in northern China at the lead-0 season. The results were calculated using (left) hindcasts starting in Dec during 1982–2010, and (right) hindcasts starting in Jun. The soil moisture predictions were directly generated by six NMME models, including CanCM3; CanCM4; Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1 (GFDL CM2.1); Community Earth System Model, version 1 (CESM1); Community Climate System Model, version 3 (CCSM3); and CFSv2. NMME1 is the simple arithmetic mean of standardized soil moisture from the above six models, and NMME2 is the superensemble mean of six models using an optimization method [see Yao and Yuan (2018) for details].

and a service-oriented architecture system to provide data search and download services. Figure 10 shows the structure of the information-sharing platform. The platform will ensure that the experimental data and products are conveniently utilized by the drought community. After completion of this project, the DroughtEX_China data will be posted on the China Meteorological Data Service Center website (<http://data.cma.cn/en>) for public access with a proper registration.

SUMMARY AND CONCLUSIONS.

DroughtEX_China, a scientific research program focusing on the mechanisms of drought disasters, is aimed at establishing a comprehensive observational experimental system for drought research in arid and semiarid regions in northern China based on existing meteorological, agricultural, and ecological stations and by carrying out interdisciplinary, comprehensive, and systematic drought observations and scientific experiments via regular and intensive observations as well as artificially controlled experiments. Understanding drought disaster mechanisms and improving the simulations of drought-related processes will facilitate the development of a drought early-warning capacity. Since the implementation of the project in 2015, the following progress has been made:

- 1) A comprehensive V-shape drought observational experiment system for understanding drought disaster processes and mechanisms was constructed for northern China, and continuous, automatic (artificial) observational experiments were performed. Intensive observations were carried out during key periods.

FIG. 9. Seasonal ensemble hindcasts of 2002 Yellow River hydrological droughts from upstream to downstream gauges, produced using a climatology method (ESP/VIC) and a climate-model-based approach (NMME/VIC). The vertical axes are the SSI, where $SSI < -0.8$ represents a hydrological drought condition. The solid black lines represent the SSI simulated with the hydrological model VIC with observed meteorological forcings; the green and red lines represent the individual ensemble members from the hindcasts starting from the beginning of Feb and Jun, respectively; and the blue lines denote the ensemble means of the hindcasts.

- 2) Observational datasets were used to investigate soil water vapor–heat interactions and improve soil moisture simulations to study the effects of intermittent turbulence and drought–albedo feedback on boundary layer water–energy exchanges and convection over arid and semiarid regions and to understand the transition processes between the stomatal and nonstomatal control of crop photosynthesis with increasing drought severity.
- 3) A prototype drought information system for northern China was developed, including a multi-model ensemble drought forecast system that provided skillful seasonal predictions of agricultural and hydrological droughts over northern China

FIG. 10. Diagram of the drought information-sharing platform.

and a multisource drought information platform that integrated long-term station observation data and products, drought scientific observations, and an experimental database. The information system includes standardized data products and process flows and a drought-related information-integrating and data-sharing platform for northern China, which represent important contributions to the global drought information system (GDIS).

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