BAMS Article

# The U.K.–China Climate Science to Service Partnership

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**ABSTRACT:** We present results from the first 6 years of this major U.K. government funded project to accelerate and enhance collaborative research and development in climate science, forge a strong strategic partnership between U.K. and Chinese climate scientists, and demonstrate new climate services developed in partnership. The development of novel climate services is described in the context of new modeling and prediction capability, enhanced understanding of climate variability and change, and improved observational datasets. Selected highlights are presented from over 300 peer reviewed studies generated jointly by U.K. and Chinese scientists within this project. We illustrate new observational datasets for Asia and enhanced capability through training workshops on the attribution of climate extremes to anthropogenic forcing. Joint studies on the dynamics and predictability of climate have identified new opportunities for skillful predictions of important aspects of Chinese climate such as East Asian summer monsoon rainfall. In addition, the development of improved modeling capability has led to profound changes in model computer codes and climate model configurations, with demonstrable increases in performance. We also describe the successes and difficulties in bridging the gap between fundamental climate research and the development of novel real-time climate services. Participation of dozens of institutes through subprojects in this program, which is governed by the Met Office Hadley Centre, the China Meteorological Administration, and the Institute of Atmospheric Physics, is creating an important legacy for future collaboration in climate science and services.

**KEYWORDS:** Atmosphere; Asia; Climate prediction; Seasonal forecasting; Climate variability; Climate services

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Six years ago, we set up a partnership between climate scientists at the United Kingdom's Met Office Hadley Centre, the China Meteorological Administration, and the Institute of Atmospheric Physics in Beijing via the U.K. Government's Newton Fund. This Climate Science to Service Partnership (CSSP) is building a strong network of collaborating U.K. and Chinese climate scientists through an enhanced joint climate science program. The partnership focuses on collaborative research and innovation to provide a solid foundation for the challenging but crucial task of developing new climate services that can support climate-resilient economic development and social welfare in both countries. Hence the project is called the Climate Science for Service Partnership.

Here we describe highlights and challenges from the many U.K. and Chinese scientists working toward these aims and we emphasize some of the principles and guidelines that help make the partnership a success. The work is jointly administered and resourced by the three institutes. In the United Kingdom, around half of participants are based at the Met Office Hadley Centre and half are at U.K. universities and other research centers. The philosophy of the partnership is to encourage research in a wide range of climate science topics, but always with a view to development of climate services and generation of new actionable information and products (Belcher et al. 2018). As we show below, this project spans the whole process from fundamental observations, understanding and modeling, through to providing real-time climate services to decision-makers.

## Climate monitoring and attribution

The basis of climate science is an interplay between observations and theory. However, observations of climate are limited by the length and quality of existing records and much work is still needed to make best use of new and historical observations, not least in testing our theoretical (computer) models. Our work on climate observations falls into two areas: the recovery, digitization, and assimilation of historical climate observations into modern climate records and the attribution of observed changes in climate to anthropogenic forcing.

***Enhancing observational data.*** Plentiful historical global weather observations are essential to extend analyses and weather reconstructions back over the twentieth and into the nineteenth centuries. This provides an enhanced historical perspective that is necessary to understand vulnerability to costly extreme weather and climate events. Historical climate observations are collected under our Atmospheric Circulation Reconstructions over the Earth (ACRE) China subproject, which is a regional focus of the international ACRE initiative (Allan et al. 2016; www.met-acre.net).

ACRE China identifies, sources, and digitizes historical terrestrial and marine instrumental weather observations in and around China. This allows improvements in the historical weather and climate record and data coverage across Southeast Asia and provides the basis for better observational and forecasting products and assessments of regional climatic variability and change (Williamson et al. 2018). As can be seen in Fig. 1, for the 2019–20 cycle of CSSP, ACRE China scanned and digitized a substantial volume of the historical surface terrestrial and marine weather data recovered, imaged, digitized, archived, and curated by


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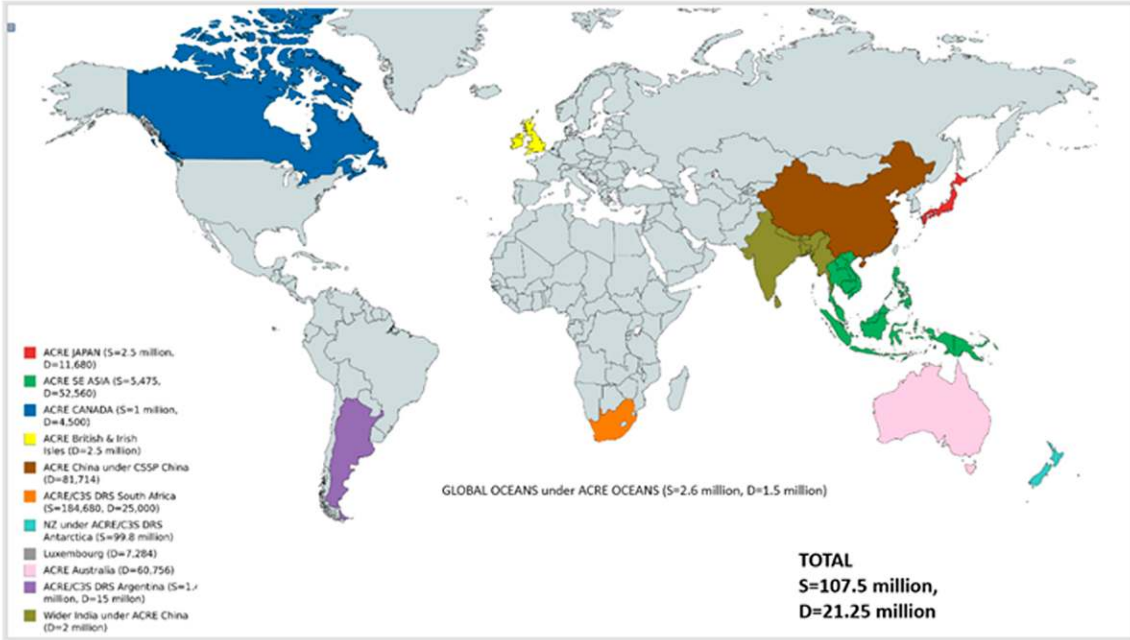


**Fig. 1. Numbers of historical terrestrial and marine weather observations that were scanned (S) and digitized (D) during 2019–20. More than 80,000 historical observations were digitized under CSSP China this year.**

the full ACRE initiative. This included historical observations over China, the South China Sea and across India (Fig. 1).

These activities are carried out jointly by U.K. and Chinese scientists and are aided by a series of joint data rescue workshops in Southeast Asia involving other ACRE activities and the EU Copernicus Climate Change Service (C3S) Data Rescue Service. ACRE China is specifically providing a new data baseline for the Twentieth Century Reanalysis which in turn provides comprehensive fields of other weather variables that can be fed into a wide range of applications to improve the basis for decision-making (Compo et al. 2011; Slivinski et al. 2019). The Twentieth Century Reanalysis data have also been used in CSSP to drive a regional climate model to produce a new 160-yr dataset for 120 meteorological variables at hourly to monthly temporal resolution and 25-km spatial resolution over China (Amato et al. 2018, access and more information about this dataset is available at https://github.com/microsoft/AIforEarthDatasets#uk-met-office-cssp-china-20crds). The resolution of this dataset is currently unmatched by existing gridded observational datasets over China such as the CN05.1 and APHRODITE datasets (0.25°; Wu and Gao 2013; Yatagai et al. 2012), reanalysis datasets, such as ERA5 (30 km; Hersbach et al. 2020), ERA-20C (125 km; Poli et al. 2016), MERRA-2 (~50 km; Gelaro et al. 2017) and Twentieth Century Reanalysis (2°; Compo et al. 2011) and it therefore provides unique long-term climate information for research and services.

Effort has also been made to improve existing station records, including homogenization of surface air temperatures (Cao et al. 2017; Yan et al. 2020) and relative humidity (Li Z. et al. 2020), which has resulted in a significant increase in estimates of observed climatic trends over China. CSSP is also exploiting and developing new observational datasets from satellites. Data from the China's Fengyun satellite program are now routinely monitored and assimilated by the Met Office numerical weather prediction (NWP) system, which both improves Met Office forecasts and underpins the development of Fundamental Climate Data Records (Carminati et al. 2018, 2019, 2021).

***Attribution to climate change.*** Many of these observed climate records already contain detectable signs of climate change that is altering the risk of extreme events. The attribution


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of these events to climate change therefore provides an important early warning of what might occur in future. CSSP has carried out many studies on the causes and attribution of extreme climate events in the East Asia region, including assessments of modeling uncertainty in attribution results (Sparrow et al. 2018), new modeling tools for attribution (Ciavarella et al. 2018) and the effects of changes in land use on East Asian climate (Lott et al. 2020). However, in the interests of developing collaborative networks, it also ran a series of innovative workshops involving China-based scientists and led by attribution specialists. Figure 2 shows photos from the first three of these workshops. Their aim was to build capacity in China for researchers to carry out attribution studies of recent weather and climate events in the region. Such studies seek to determine to what extent anthropogenic

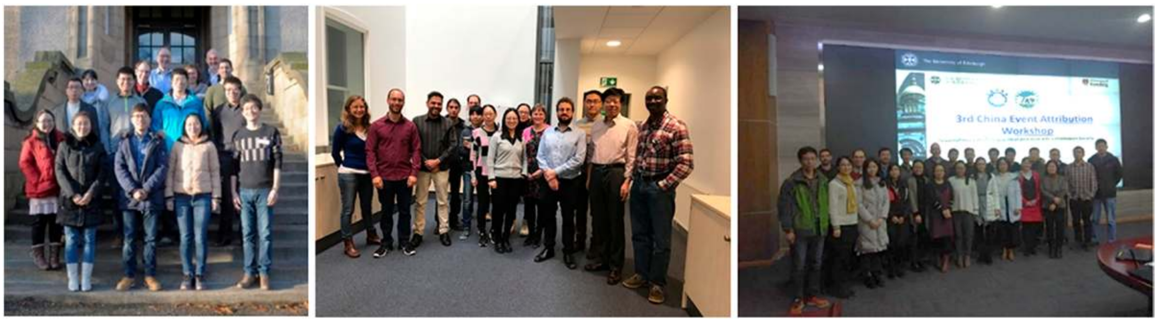


**Fig. 2. Participants and tutors at U.K.–China climate attribution workshops held in Edinburgh (December 2016), Oxford (January 2018), and Beijing (December 2018).**

emissions of greenhouse gases and other pollutants have changed the likelihood or intensity of the extreme events in question. During the week-long workshops, participants learnt the principles of event attribution and analyzed recent extreme events using data from the Met Office attribution system which is based on the U.K. Unified Model (see model development activities below). These workshops encouraged and facilitated the rapid development of an enhanced capability in China to carry out event attribution studies and resulted in peer-reviewed publications describing the extent to which recent climate events and trends can be attributed to anthropogenic forcing (Li et al. 2018a; Qian et al. 2018; Chen et al. 2019; Ren et al. 2020, L. Zhang et al. 2020; W. Zhang et al. 2020).

## Climate dynamics and predictability

In addition to observing and attributing climate, improving our understanding of the dynamics behind climate variability underpins our explanations of extreme events, points the way forward for model development and increases our confidence in climate predictions. Some of our chosen topics in climate dynamics have also led surprisingly quickly to new climate services, as described below.

***Dynamics and predictability of the East Asian monsoon.*** A major theme in our climate dynamics work is the East Asian summer monsoon (EASM). The annual poleward migration of summer rainfall in China is essential to regional agriculture, hydropower, and water supply. However, the EASM also exhibits strong interannual variability which is linked to flooding events in eastern China and catastrophic loss of life and livelihoods. Theoretical work on understanding the fundamental dynamics driving the EASM has been carried out in the CSSP. A hierarchy of model complexity was used to probe idealized EASM simulations and how these relate to the seasonal Hadley cells and the intertropical convergence zone (Geen et al. 2020, manuscript submitted to *Rev. Geophys.*). This work examined the onset of the monsoon, starting from aquaplanet simulations and adding increasingly realistic orography (Geen et al. 2018). Important questions relating to the poleward migration of the monsoon


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and the dynamical feedbacks that control the observed sharp poleward jump in the seasonal transition of the monsoon have been addressed (Geen et al. 2019) where tropical moist static energy (MSE) buildup is identified as a key precursor to monsoon onset. By applying this dynamical understanding, an explanation of real-world skill in prediction of monsoon onset over the South China Sea has been demonstrated (Geen et al. 2020) with skill comparable to that found in latest seasonal prediction systems (Martin et al. 2019).

Despite this predictability of the monsoon onset, seasonal mean rainfall is still difficult to predict for the EASM. Nevertheless, during the early development of CSSP, collaborative work identified skillful seasonal prediction of the EASM rainfall over the Yangtze River basin (Li et al. 2016). The newfound skill for EASM rainfall led us directly to a new climate service: predictions of the Yangtze River basin seasonal rainfall, started in early 2016 (Bett et al. 2018) and described in more detail in the context of climate services below. Subsequent collaborative work between China Meteorological Administration (CMA), IAP, and Met Office scientists (Liu et al. 2018) showed that large-scale dynamical indices of the EASM based on lower tropospheric zonal wind could be used as an improved predictor of Yangtze River seasonal rainfall and this has since been implemented (Bett et al. 2020), extending prediction lead times and providing predictions on a smaller, subbasin scale that are better tailored to user requirements (see climate services below).

This predictability of year-to-year variations in the EASM originates in part from a lagged response to El Niño–Southern Oscillation (ENSO) and understanding such sources of skill provides confidence in predictions. Work in CSSP has therefore examined the evolution of major ENSO events and how these are predicted with varying success by different forecast systems, as happened in 2014/15 and 2015/16 (Ineson et al. 2018); how predictability varies with ENSO type between central Pacific and east Pacific events (Ren et al. 2016, 2018; Zhang et al. 2019); and how predictions represent the ENSO teleconnection to the monsoon (Hardiman et al. 2018). Finally on monsoon predictions, recent work in CSSP demonstrates that skillful predictions of ENSO beyond the seasonal range allow skillful predictions of monsoon rainfall on longer time scales (Dunstone et al. 2020) and prediction skill for other variables and in other seasons (Lu et al. 2017; Li et al. 2018b; Lockwood et al. 2019), including for the extratropics (Nie et al. 2019, 2020; Wu et al. 2020). These findings offer further prospects of new and extended climate services.

***Global teleconnections.*** A second theme in our dynamics work is the impact of remote teleconnections on regional climate. Tropical rainfall variability and associated heating has long been known to drive changes in vorticity and trigger poleward propagating Rossby waves and our work has shown that this mechanism leads to skillful seasonal predictions of extratropical circulation (Scaife et al. 2017a). Similar Rossby wave trains appear in our studies of the mechanism by which variability in East Asian anthropogenic aerosol emissions generate remote climate influences (Wilcox et al. 2019) and they are also implicated in extreme hot summer months over southeast China (Thompson et al. 2019). The latter is illustrated in Fig. 3 where a prominent Rossby wave, also known as the "Silk Road pattern" can be seen

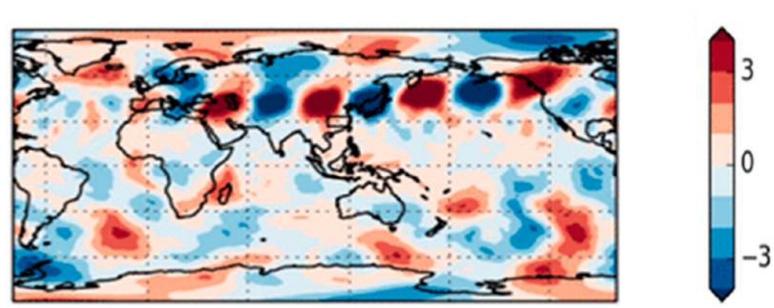


**Fig. 3. Silk Road pattern dynamically implicated in half of simulated unprecedented extreme hot summer months over southeast China (black box). Composite meridional wind anomalies (ms$^{-1}$) are plotted at 250 hPa for extreme modeled summers showing a prominent eastward propagating Rossby wave. Adapted from Thompson et al. (2019).**


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propagating eastward from the Mediterranean across the globe to the east Pacific in extreme summer months in southeast China. Similar mechanisms have even been identified on decadal time scales, where the impact of Atlantic multidecadal variability (AMV) on East Asian climate again reveals eastward propagating Rossby waves, and the potential for skillful multiyear prediction of temperature variability over northeast Asia (Monerie et al. 2018).

These examples illustrate a recurring theme that emerges from this project; that the profound influence of climate phenomena such as ENSO affect not only East Asian climate (Li et al. 2016) but also extend to U.K. climate (Hardiman et al. 2018, 2019). Stark examples have occurred during the project when the major El Niño event in 2015/16 was linked to extreme U.K. flooding in December 2015 (Scaife et al. 2017b) and then in the following early summer of 2016, to flooding in the Yangtze River basin (Bett et al. 2018). It can also be shown that joint forecasting capability can improve predictions of some of these modes (Lu et al. 2018). Hence, while the United Kingdom and China are physically separated by over 8,000 km, both regions can be influenced by teleconnections to the same global modes of climate variability. Collaborative effort can improve our dynamical understanding and simulation of these global modes and their teleconnections and improve climate predictions in both regions.

## Extremes and climate change

Climate extremes such as drought frequently hit China and affect the livelihood of millions of people. They also have devastating impacts on agriculture and water resources, particularly in northern China and there are urgent questions about the future of such extremes under climate change. We therefore try to understand the mechanisms of climate extremes from short duration events to multidecadal climate change and to assess the potential for new climate services.

***Extreme events.*** The intensification of climate extremes on the background of global warming has diverse societal impacts across both the United Kingdom and China. Research carried out under CSSP finds that both extreme summer temperatures and precipitation have been increasing in China due to human activity. J. Wang et al. (2020) found that, in addition to individual hot days and hot nights, compound hot extremes throughout day and night have significantly increased across the Northern Hemisphere in both frequency and intensity. For rainfall, Xiao et al. (2016) found that maximum summer hourly rainfall intensity had increased by over 10% across China for the period 1971–2013. Ma et al. (2017) have shown a detectable anthropogenic shift toward heavy precipitation over eastern China, while W. Zhang et al. (2020) showed that the influence of anthropogenic forcing on heavy rainfall depends on event time scales.

An important step to gain better understanding of such rainfall extremes is to understand the moisture budget. A moisture tracing technique has been employed to identify the major moisture sources and their roles in the East Asian water cycle (Guo et al. 2017, 2019). The Eurasian continent appears to be a source of moisture for many areas of China outside the southeast, which is more strongly influenced by the Indian and Pacific Oceans. The Mediterranean and the inland Eurasian seas (Black Sea, Caspian Sea) are moisture sources for the semiarid regions of western China. These moisture sources vary considerably with the phase of ENSO (for tropical and subtropical East Asia) and the NAO (for midlatitude East Asia). Tropical cyclones are also important for the moisture budget and contribute ~20%–30% of summer mean precipitation over coastal China, as well as about 50% of extreme precipitation (Guo et al. 2017).

Drought research is usually focused on long lasting events that have major impacts on crops and water resources, but global warming has prompted new challenges in "flash drought."


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Flash droughts refer to a type of drought with rapid onset and intensification. They are driven by a lack of precipitation in combination with anomalously high evapotranspiration due to high temperatures that occur in humid regions. The increase in heatwaves because of global warming has significantly raised the threat of flash droughts. Collaborative research under CSSP finds a rising trend in flash droughts in China, even during the so-called global warming hiatus (Wang et al. 2016) and the risk continues to increase under anthropogenic climate change (Yuan et al. 2019). Predicting flash drought therefore poses a new challenge and ongoing CSSP projects are exploring novel new methods to meet this challenge.

***Decadal variations and climate change.*** As noted above, the East Asian monsoon is influenced by ENSO and the Atlantic may also exert some influence (Monerie et al. 2018; Stephan et al. 2019) but the Pacific still appears to play a dominant role in decadal precipitation variability over China. Analysis in our project by Yang et al. (2017) used idealized model experiments forced by different combinations of observed SST modes provided by the U.S. CLIVAR Drought Working Group to show that the atmospheric response to the leading Pacific SST pattern is a circulation anomaly in the lower troposphere occupying the entire northern North Pacific. During the warm phase of the SST pattern, a cyclonic response with northwesterly wind anomalies over northern China advect the monsoon front to the south and result in a rainfall pattern characterized by "southern floods and northern drought." During the cold phase, the circulation anomaly and rainfall patterns reverse. As this circulation anomaly extends across the whole North Pacific, it affects North China and southwest United States in the opposite sense, leading to an interdecadal seesaw of precipitation anomalies between the two (Yang et al. 2019). It has also been found that ENSO transitions from La Niña to El Niño often drive prolonged spring–summer drought over North China (Zhang et al. 2018) and local effects of air pollution and increased aerosol loading can exacerbate drought (Zhang et al. 2017).

The western North Pacific subtropical high (WNPSH) atmospheric circulation system is intimately connected to the EASM. Along with other factors such as changes in heating over the Tibetan Plateau (He et al. 2019), it will also play a role in the long-term future of Chinese drought as it is closely related to the strength and position of the mei-yu/baiu/changma front and the trajectories of typhoon and western Pacific tropical cyclones. However, models participating in the fifth phase of Coupled Model Intercomparison Project (CMIP5) do not agree on even the sign of future changes in the WNPSH and some studies find that, on average, modeled changes in the WNPSH contribute little to EASM climate change (He et al. 2020). Chen et al. (2020) find that such uncertainties may be the result of systematic biases in individual models. Ultimately, we aim to reduce these biases (see below) but the relationship between bias and projected changes appears to be strong enough to constrain simulations using atmosphere only simulations. The models then tend to agree on a future intensification of the WNPSH with 45% of the uncertainty reduced and a more confident projection of a stronger East Asian summer monsoon with increased rainfall but reduced typhoon landfall over East Asia.

## Climate modeling

CSSP aims to demonstrate innovative new climate services, and these often depend on skillful climate predictions which are in turn dependent on accurate computer modeling using global climate models. However, systematic errors in the EASM are long-standing in climate models and in some cases they limit the skill, for example, in rainfall over land (Li et al. 2016; Liu et al. 2018).

***Diagnosing systematic errors.*** Errors in the EASM in climate models are often associated with a weak WNPSH (Fig. 4a). This error causes a weakening of the monsoon flow over East


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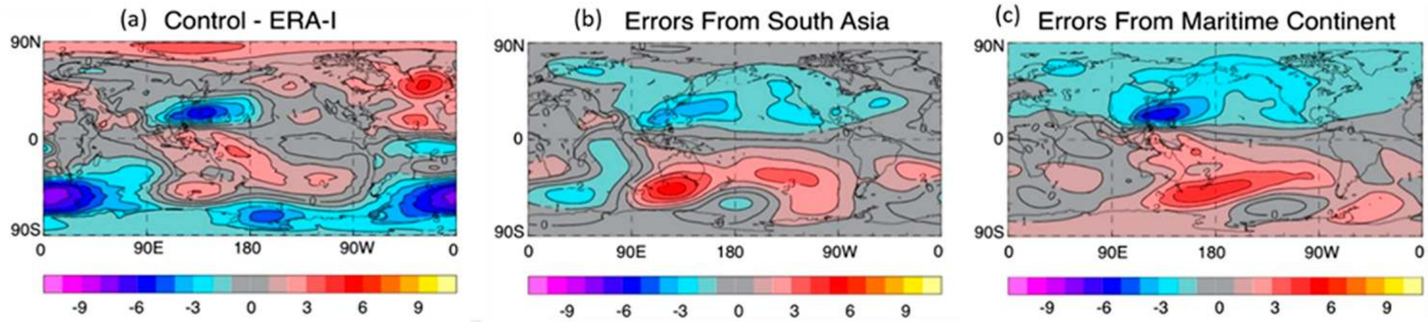


**Fig. 4. Sources of mean state error in climate simulations. (a) Total bias in 850-hPa streamfunction in atmosphere only simulations over 1982–2007; (b) impact of South Asian nudging, showing the error forced from the South Asian monsoon region (60°–100°E, 5°S–20°N); (c) impact of Maritime Continent nudging (90°–150°E, 10°S–10°N). Streamfunction is in units of $10^6$ m$^2$ s$^{-1}$. After Rodríguez et al. (2017).**

Asia and a dry bias. As described above, systematic errors like this can also affect climate projections of the monsoon. Researchers in CSSP are therefore trying to understand the source of these errors, with the aim of improving models. Rodríguez et al. (2017) applied a regional atmospheric nudging technique to estimate the effect of tropical climate model errors on the East Asia summer monsoon. Figure 4 shows the inferred impact of the equatorial Indian Ocean and Maritime Continent. The striking similarity between the total-error pattern and the Maritime Continent forced error highlights the need to better understand tropical model errors in that region, and the mechanisms by which tropical–extratropical teleconnections propagate such errors into the WNPSH.

***Convection-permitting models.*** Even if the large-scale biases discussed above were reduced, it is likely that a range of errors would persist on smaller scales. Model biases in eastern China are particularly important for flood predictions for the densely populated cities along the Yangtze River and errors on the eastern Tibetan Plateau (Figs. 5b,d,f) are of importance for water resources because precipitation falling in this region feeds the headwaters of several major rivers. P. Li et al. (2020, 2021) use convection-permitting-resolution (0.04°) simulations over East Asia with rain gauge observations and a lower-resolution simulation with parameterized convection (Fig. 5) to show that the clear improvement in the convection-permitting configuration is due to improvement in the frequency of heavy rainfall events.

The performance of convection-permitting models is closely related to their ability to represent the diurnal cycle of precipitation. Li et al. (2021) have shown that the excessive precipitation over the eastern Tibetan Plateau in the parameterized convection simulations (Fig. 5f) is linked to an inability to simulate afternoon to early evening precipitation. We therefore performed a comprehensive assessment of the effects of explicit-versus-parameterized convection on the diurnal cycle over the East and South Asian monsoon regions, using high-resolution (global) climate simulations. Explicit-convection simulations improve the diurnal cycle over most areas but especially in regions where observed rainfall events exhibit nocturnal maxima. This work highlights the weaknesses of convection parameterization in regions such as the eastern lee of the Tibetan plateau, where nocturnal triggering of deep convection is the dominant heavy-rainfall producing mechanism.

***Improved model capability.*** Collaboration between U.K. and Chinese researchers has also dramatically improved climate models on global scales. The quasi-biennial oscillation (QBO) impacts both the Asian monsoon and extratropical North Atlantic regions on interannual time scales. Despite this, very few models participating in CMIP5 were able to simulate a realistic


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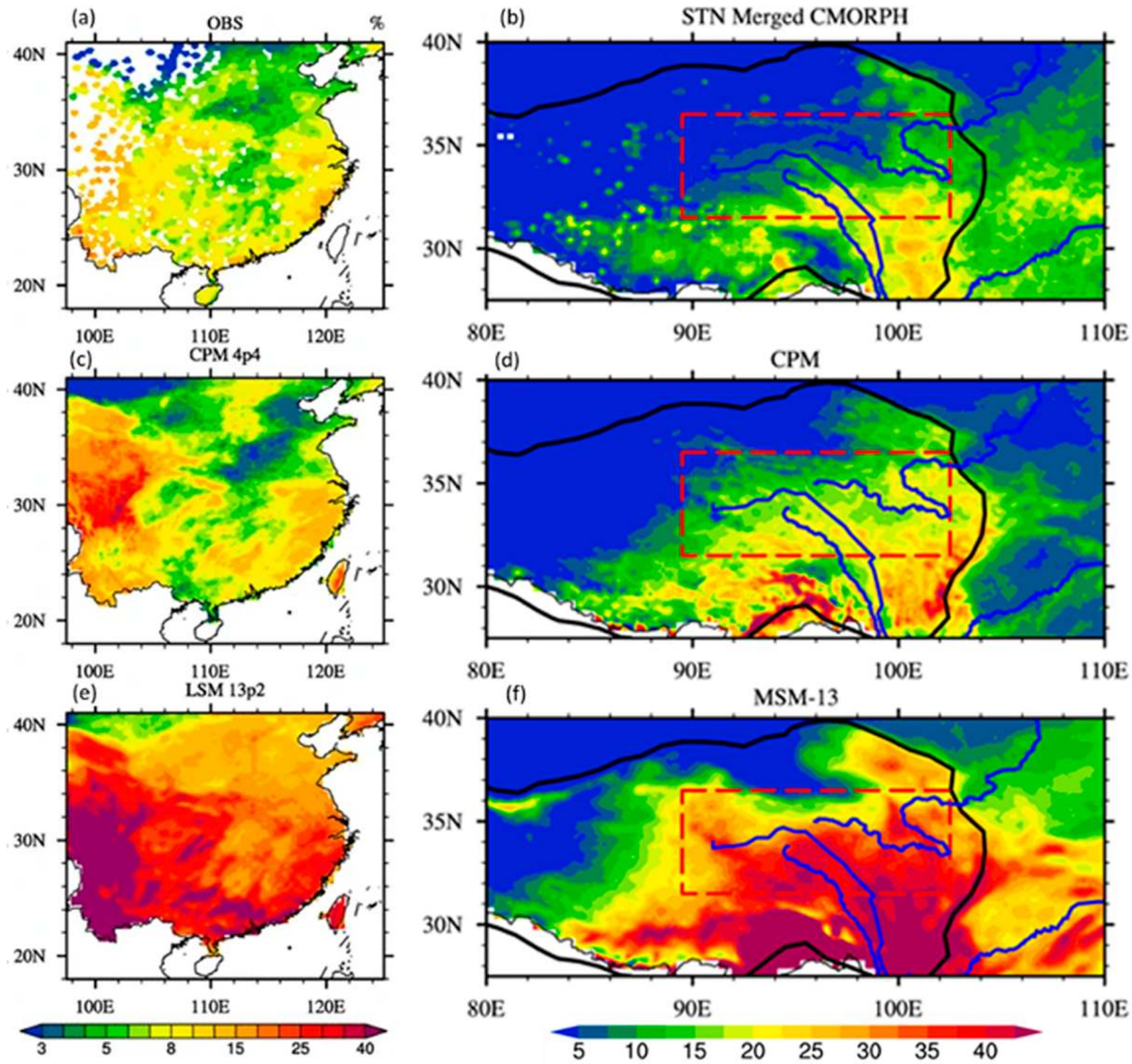


**Fig. 5. Improvements in precipitation frequency at convection-permitting model resolution. Precipitation frequency (%) in summer 2009 over (a),(c),(e) eastern China and (b),(d),(f) the Tibetan Plateau in the "three-river's source" region (red box). Rain gauge observations merged with satellite data are shown in (a) and (b), convection-permitting model simulations (0.04° resolution) in (c) and (d), and lower-resolution model simulations (0.12° resolution) with parameterized convection in (e) and (f). After P. Li et al. (2020) and Z. Li et al. (2020).**

QBO and a major advance for the Beijing Climate Centre (BCC) Climate System Model between CMIP5 and CMIP6 has been the generation of a realistically simulated QBO (Lu et al. 2020; Wu et al. 2019). Figure 6 compares the observed QBO to that simulated by versions of the BCC model. The simulated QBO in the CMIP6 configuration is a result of the inclusion of a parameterization of the zonal force from dissipating nonorographic gravity waves (Fig. 6d) and improved vertical resolution (Fig. 6c). The wave driven accelerations of the zonal-mean flow are at least as large as those due to resolved equatorial waves in these simulations, confirming that convective gravity waves are an essential prerequisite for a realistic QBO, in agreement with work on the U.K. model (Scaife et al. 2000).

CSSP is now producing multiple real improvements in climate models at both Chinese and U.K. prediction centers and other examples include use of regional radar measurements of severe storms over South China to improve modeled cloud microphysics (Furtado et al. 2018, 2020). This long-term work on climate model development is the foundation for improving predictions and generating new climate services.


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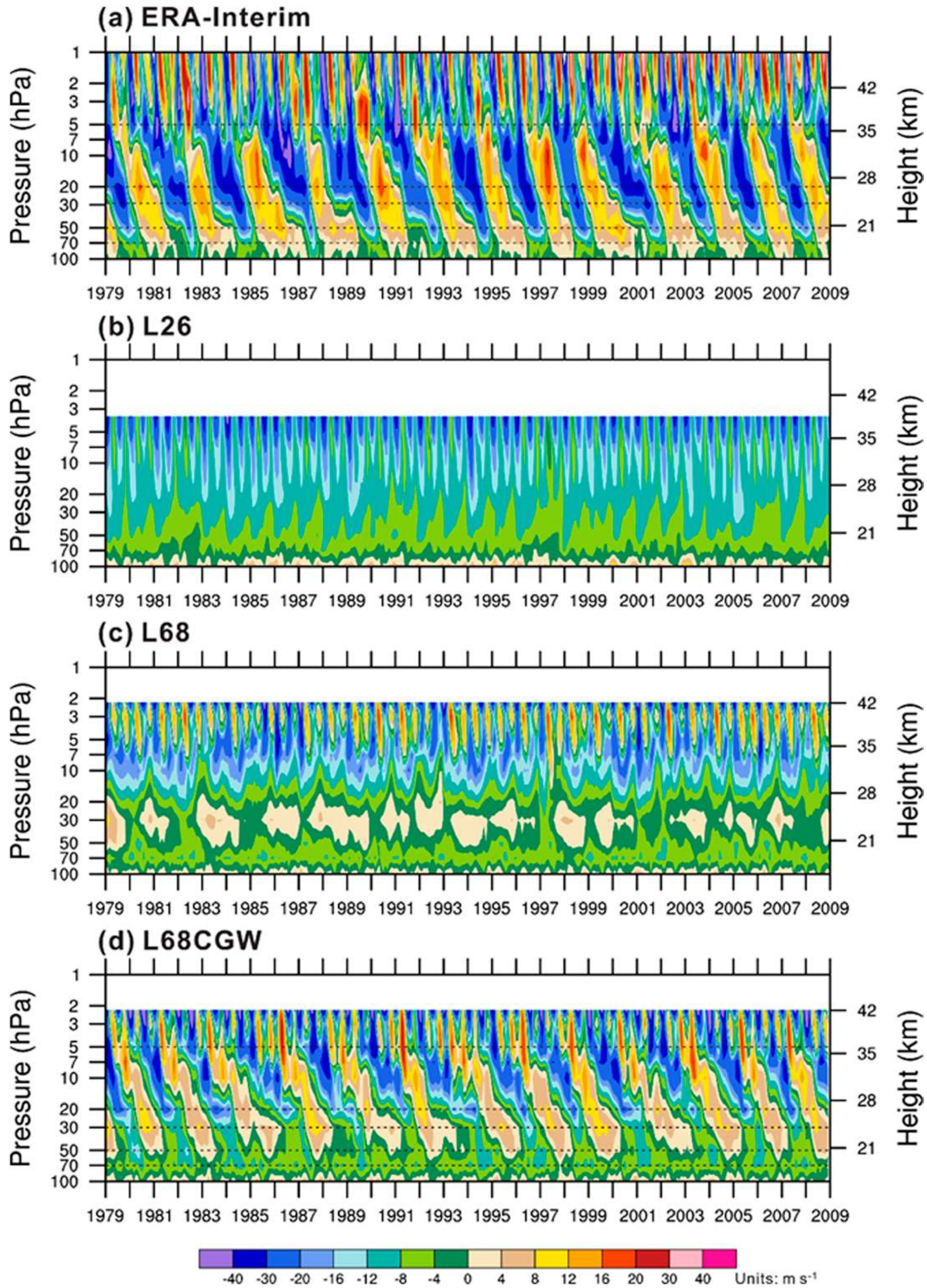


**Fig. 6. Improved simulation of the quasi-biennial oscillation. Time–height cross sections of the monthly tropical zonal winds (ms$^{-1}$) between 5°N and 5°S in the lower stratosphere for (a) observational reanalysis, (b) 26-level (CMIP5) version of the BCC model, (c) 68-level BCC model, and (d) 68-level model with parameterized nonorographic gravity waves. Reproduced from Lu et al. (2020).**

## Climate services

The data and knowledge generated in CSSP, combined with new and evolving collaborations between China and the United Kingdom, offer new opportunities to help society better manage risks and opportunities arising from climate variability and change (Golding et al. 2017). However, it is rarely the case that raw data and knowledge allow proper risk management


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and there is an important need to aid users in the uptake and use of climate information for decision-making through the codesign, development, and delivery of climate services (Hewitt et al. 2020a; Khosravi et al. 2021).

The approach successfully being used in CSSP is to support the China Framework for Climate Services (Y. Wang et al. 2020) by bringing scientists as providers of climate services together with users to develop services and meet decision-makers' needs together. This codevelopment is being done by trialing prototype climate services with users, seeking feedback and then iterating the prototypes which are issued with CMA. The ultimate aim is to create services of demonstrable value for decision-making.

***Regular climate services.*** Several prototypes are being developed and trialed, covering various parts of China and differing user needs and sectors (Hewitt et al. 2020b). The most advanced is the real-time probabilistic forecast for summer rainfall in the Yangtze River basin. This service emerged from advances in dynamical understanding and prediction skill described above, the identification of user needs, and the development of a major El Niño event in late 2015, which we identified as an opportunity to present a clear forecast for the wet start to summer that followed (Bett et al. 2018).

This is intended for use primarily by the operators of large reservoirs along the Yangtze River for flood control, water resource management and hydropower generation, including the Three Gorges Corporation. Early season reduction of water levels needed for flood prevention is linked to reduced hydroelectric power production and early user engagement identified the Three Gorges Corporation as a potential user that would benefit from early warning of extreme summer rainfall. The product gives text and graphical descriptions of the probabilistic rainfall forecast for the summer flood season in the Yangtze River basin and is updated monthly (Fig. 7, left). It is issued to China's National Climate Centre for onward dissemination to regional and provincial centers along the Yangtze River. This service was further codeveloped in 2019 to give subbasin information and to extend the range of predictions, as requested from interaction with users (Golding et al. 2019). To achieve this, the Yangtze basin was split into the "upper reaches" and the "middle and lower reaches," with the Three Gorges Dam near the boundary and using a predicted dynamical monsoon index rather than explicit rainfall (Liu et al. 2018; Bett et al. 2020).

At the time of writing, the sign of the forecast issued for 2020 (Fig. 7) appears to verify against latest observations as there has been extreme summer monsoon rainfall in the Yangtze River valley this summer (Zhang et al. 2021).

More recently trials have begun for predictions of tropical cyclone landfall risk for East China, after significant levels of skill were identified in seasonal climate predictions (Camp et al. 2019). This product follows a similar format to the Yangtze rainfall product and provides probabilistic information about likely numbers of landfalling tropical cyclones in eastern China. The trials of this prototype are at an earlier stage, but forecasts are being issued (Fig. 7, right) and potential users are being consulted, including flood management, agriculture, and infrastructure to better understand applications.

***Collecting evidence of impact.*** A further important aspect of climate services is the measurement of impact through the effect of the service on decisions made. This is very difficult to assess, but examples are emerging, including an initial evaluation of the usefulness of the Yangtze River valley summer rainfall service (Golding et al. 2019). It is difficult to obtain objective quantitative measure of benefit of these services, but surveys of users from the disaster risk reduction, agriculture, water resources, and hydropower sectors provided testimonials of the utility of these real-time seasonal forecast services, reporting that "we developed a positive flood control plan, effectively stopping the flooding, and reducing the flood pressure on


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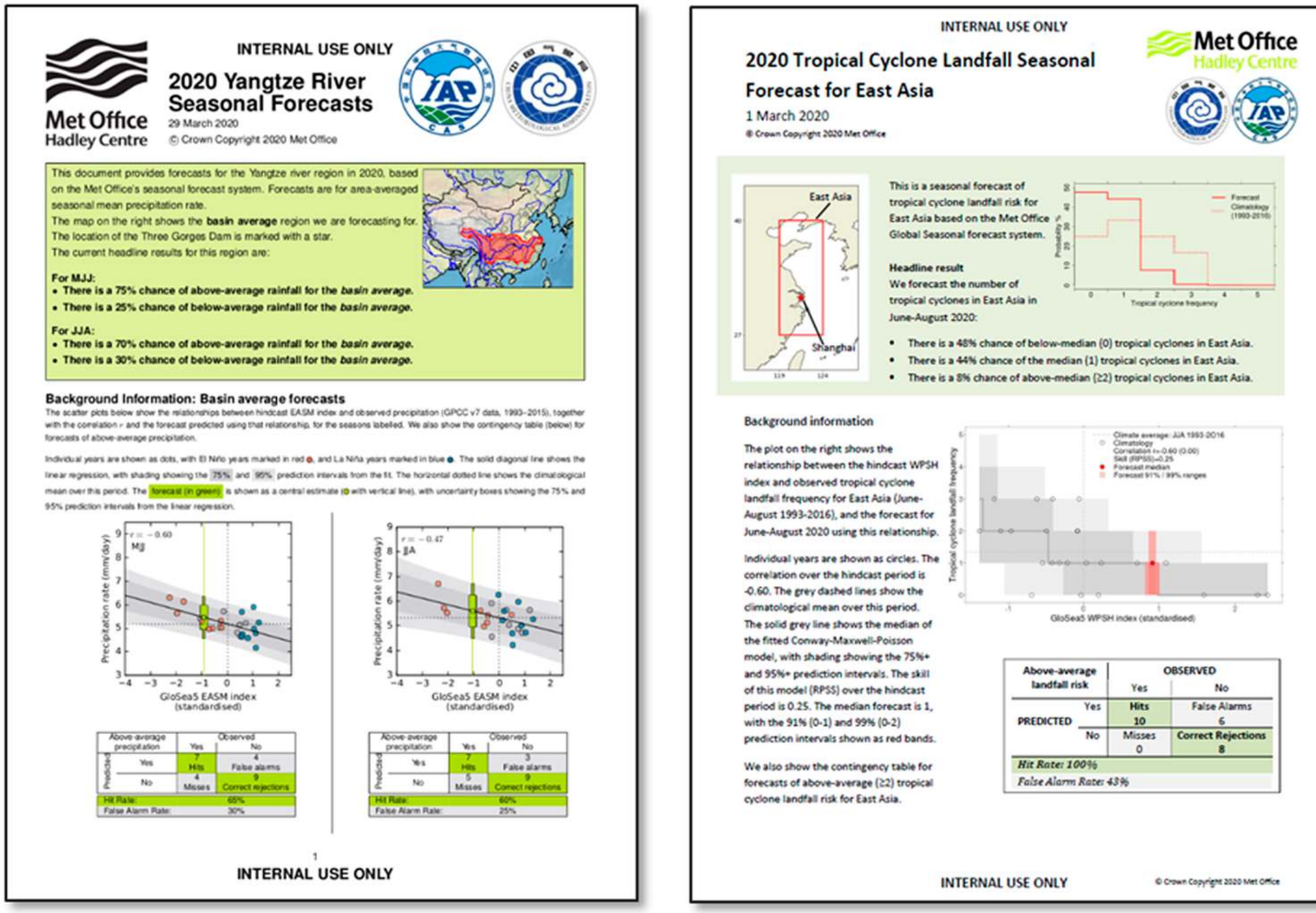


**Fig. 7. Demonstration climate services. Probabilistic forecasts of the (left) Yangtze River valley summer rainfall and (right) tropical cyclone landfall are produced in real time after underpinning research in the CSSP China project has demonstrated that mechanisms and levels of skill make these viable.**

middle and lower reaches," "we managed to reduce water waste losses," "we did good jobs in advance to prevent flood, and avoided agricultural losses," and finally, "we applied pre-flood publicity, flood preparation, material reserves, flood season program … we avoided flood, avoided disaster." Other work focused on the risk of climate change to Chinese megacities Shanghai and Hangzhou (Ke 2014), which the Shanghai Municipal Government considered in its 2017–35 Master Plan and its thirteenth 5-Year Plan, has been extended in CSSP using regional climate models over eastern China to further inform the municipal governments in the Yangtze River delta region (Dong et al. 2020).

Development of climate services brings different players in the climate service chain together, increasing engagement and building trust between providers and users. Users are gaining a better understanding of climate information and how it can or cannot aid their decisions and scientists are gaining a better understanding of how climate information can create societal benefit and how to steer further scientific research for services.

## Summary and lessons learned

The knowledge exchange between Chinese and U.K. scientists involved in this collaborative project is immense. Expertise is increasing dramatically on both sides, as U.K. scientists benefit from Chinese expertise in East Asian climate and Chinese researchers benefit from expertise in European climate and new modeling and prediction capability. Although travel


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restrictions due to the current pandemic have brought face to face meetings to a halt, many dozens of workshops and visiting scientist exchanges over recent years are building lasting collaborations between individual research groups. We find that the most successful visiting scientist exchanges often result from projects that are a few months in length and are clearly defined rather than open-ended. A specific research question and a goal to communicate results via peer reviewed publication are good guidelines for exchange visits. These collaborative networks are a key output from the CSSP between the United Kingdom and China and they are surviving the stress test of purely online collaboration during the current pandemic.

As well as independent scientific review (see acknowledgments), we actively discourage non–peer reviewed reporting of project results wherever possible and focus instead on peer reviewed output in well-established scientific journals to maintain scientific quality and maximize impact. So far, CSSP China has produced over 300 peer reviewed papers in the scientific literature, with examples in journals of the highest quality and examples of awards for outstanding papers.

CSSP has delivered substantial progress in observing, understanding, modeling, and prediction of climate in the United Kingdom and China. The project has delivered important progress in observational climate datasets and is aiding the recovery and use of historical data. The focus on climate dynamics and predictability has improved our understanding and lead to the development of skillful climate services for the summer monsoon and tropical cyclone hazards. Our studies have also uncovered new evidence for climate change in China and the changing frequency and intensity of extremes due to climate change. Our model development work has also documented new climate model capability and continues to assess the benefits of increased complexity and model resolution. Novel climate services are being demonstrated in real time, subject to feedback and codevelopment with users and scientists. Other outstanding issues are now also being brought into scope, such as air pollution in major Chinese cities (e.g., Pei and Yan 2018) which is the subject of additional CSSP research. Interestingly, the most promising new climate services have often emerged from unexpected areas dealing with more fundamental aspects of dynamics and predictability. We also find that seasonal and decadal climate predictions readily yield new services because they provide information on common planning time scales, are frequently updated, and can be issued and assessed with regularity. Although it has been difficult to achieve so far, an important future challenge is to provide quantitative assessment of the reported benefits from our demonstration climate services.

Techniques developed in CSSP have also spawned wider benefits. For example, novel techniques for estimating the current chance of unprecedented events have been applied to both Chinese and U.K. climate and were applied to U.K. government flood risk estimates. The successes of this collaborative partnership are also being replicated for other regions and projects are now running for India, Brazil, Southeast Asia, and South Africa and include research across weather and climate time scales. As climate change unfolds, extreme events increase and populations grow, our sensitivity to climate increases and the work of collaborative projects like the CSSP will become increasingly important.

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## References


Allan, R., and Coauthors, 2016: Towards integrated historical climate research: The example of ACRE (Atmospheric Circulation Reconstructions over the Earth). *Wiley Interdiscip. Rev.: Climate Change*, **7**, 164–174, https://doi.org/10.1002/wcc.379.

Amato, R., H. Steptoe, E. Buonomo, and R. Jones, 2018: High resolution history: Downscaling China's climate from the 20CRv2c reanalysis. *J. Appl. Meteor. Climatol.*, **58**, 2141–2157, https://doi.org/10.1175/JAMC-D-19-0083.1.

Belcher, S., and Coauthors, 2018: Preface to special issue on climate science for service partnership China. *Adv. Atmos. Sci.*, **35**, 897–898, https://doi.org/10.1007/s00376-018-8002-0.

Bett, P. E., and Coauthors, 2018: Seasonal forecasts of the summer 2016 Yangtze River basin rainfall. *Adv. Atmos. Sci.*, **35**, 918–926, https://doi.org/10.1007/s00376-018-7210-y.

——, and Coauthors, 2020: Seasonal rainfall forecasts for the Yangtze River basin in summer 2019 from an improved climate service. *J. Meteor. Res.*, **34**, 904–916, https://doi.org/10.1007/s13351-020-0049-z.

Camp, J., and Coauthors, 2019: The western Pacific subtropical high and tropical cyclone landfall: Seasonal forecasts using the Met Office GloSea5 system. *Quart. J. Roy. Meteor. Soc.*, **145**, 105–116, https://doi.org/10.1002/qj.3407.

Cao, L. J., Z. W. Yan, P. Zhao, Y. N. Zhu, Y. Yu, G. L. Tang, and P. D. Jones, 2017: Climatic warming in China during 1901–2015 based on an extended dataset of instrumental temperature records. *Environ. Res. Lett.*, **12**, 064005, https://doi.org/10.1088/1748-9326/aa68e8.

Carminati, F., B. Candy, W. Bell, and N. Atkinson, 2018: Assessment and assimilation of FY-3 humidity sounders and imager in the UK Met Office global model. *Adv. Atmos. Sci.*, **35**, 942–954, https://doi.org/10.1007/s00376-018-7266-8.

——, X. Xiao, Q. Lu, N. Atkinson, and J. Hocking, 2019: Assessment of the Hyperspectral Infrared Atmospheric Sounder (HIRAS). *Remote Sens.*, **11**, 2950, https://doi.org/10.3390/rs11242950.

——, N. Atkinson, B. Candy, and Q. F. Lu, 2021: Insights into the microwave instruments onboard the Feng-Yun 3D satellite: Data quality and assimilation in the Met Office NWP system. *Adv. Atmos. Sci.*, **38**, 1379–1396, https://doi.org/10.1007/s00376-020-0010-1.

Chen, Y., and Coauthors, 2019: Anthropogenic warming has substantially increased the likelihood of July 2017–like heat waves over central eastern China. *Bull. Amer. Meteor. Soc.*, **100**, S91–S95, https://doi.org/10.1175/BAMS-D-18-0087.1.

Chen, X., and Coauthors, 2020: Emergent constraints on future projections of the western North Pacific subtropical high. *Nat. Commun.*, **11**, 2802, https://doi.org/10.1038/s41467-020-16631-9.

Ciavarella, A., and Coauthors, 2018: Upgrade of the HadGEM3-A based attribution system to high resolution and a new validation framework for probabilistic event attribution. *Wea. Climate Extremes*, **20**, 9–32, https://doi.org/10.1016/j.wace.2018.03.003.

Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis project. *Quart. J. Roy. Meteor. Soc.*, **137**, 1–28, https://doi.org/10.1002/qj.776.

Dong, G., Z. Jiang, Z. Tian, E. Buonomo, L. Sun, and D. Fan, 2020: Projecting changes in mean and extreme precipitation over eastern China during 2041–2060. *Earth Space Sci.*, **7**, e2019EA001024, https://doi.org/10.1029/2019EA001024.

Dunstone, N., and Coauthors, 2020: Skilful interannual climate prediction from two large initialised model ensembles. *Environ. Res. Lett.*, **15**, 094083, https://doi.org/10.1088/1748-9326/ab9f7d.

Furtado, K., and Coauthors, 2018: Cloud microphysical factors affecting simulations of deep convection during the presummer rainy season in southern China. *J. Geophys. Res. Atmos.*, **123**, 10 477–10 505, https://doi.org/10.1029/2017JD028192.

——, P. Field, Y. Luo, T. Zhou, and A. Hill, 2020: The effects of cloud-aerosol interaction complexity on simulations of presummer rainfall over southern China. *Atmos. Chem. Phys.*, **20**, 5093–5110, https://doi.org/10.5194/acp-20-5093-2020.

Geen, R., F. H. Lambert, and G. K. Vallis, 2018: Regime change behaviour during Asian monsoon onset. *J. Climate*, **31**, 3327–3348, https://doi.org/10.1175/JCLI-D-17-0118.1.

——, ——, and ——, 2019: Processes and timescales in onset and withdrawal of "aquaplanet monsoons." *J. Atmos. Sci.*, **76**, 2357–2373, https://doi.org/10.1175/JAS-D-18-0214.1.

——, Geen R., S. Bordoni, D.S. Battisti and K. Hui, 2020: Monsoons, ITCZs, and the concept of the global monsoon. *Rev. Geophys.*, **58**, e2020RG000700, https://doi.org/10.1029/2020RG000700.

Gelaro, R., and Coauthors, 2017: The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), *J. Climate*, **30**, 5419–5454, https://doi.org/10.1175/JCLI-D-16-0758.1.

Golding, N., C. Hewitt, P. Zhang, P. Bett, X. Y. Fang, H. Z. Hu, and S. Nobert, 2017: Improving user engagement and uptake of climate services in China. *Climate Serv.*, **5**, 39–45, https://doi.org/10.1016/j.cliser.2017.03.004.

——, ——, ——, M. Liu, J. Zhang, and P. Bett, 2019: Co-development of a seasonal rainfall forecast service: Supporting flood risk management for the Yangtze River basin. *Climate Risk Manage.*, **23**, 43–49, https://doi.org/10.1016/j.crm.2019.01.002.

Guo, L., N. P. Klingaman, P. L. Vidale, A. G. Turner, M. Demory, and A. Cobb, 2017: Contribution of tropical cyclones to atmospheric moisture transport and rainfall over East Asia. *J. Climate*, **30**, 3853–3865, https://doi.org/10.1175/JCLI-D-16-0308.1.

——, and Coauthors, 2019: Moisture sources for East Asian precipitation: Mean seasonal cycle and interannual variability. *J. Hydrometeor.*, **20**, 657–672, https://doi.org/10.1175/JHM-D-18-0188.1.

Hardiman, S., and Coauthors, 2018: The asymmetric response of Yangtze River basin summer rainfall to El Niño/La Niña. *Environ. Res. Lett.*, **13**, 024015, https://doi.org/10.1088/1748-9326/aaa172.

——, and Coauthors, 2019: The impact of strong El Niño and La Niña events on the North Atlantic. *Geogr. Res. Lett.*, **46**, 2874–2883, https://doi.org/10.1029/2018GL081776.

He C., and W. Zhou, 2020: Different enhancement of the East Asian summer monsoon under global warming and interglacial epochs simulated by CMIP6 models: Role of the subtropical high. *J. Climate*, **33**, 9721–9733, https://doi.org/10.1175/JCLI-D-20-0304.1.

——, Z. Wang, T. Zhou, T. Li, 2019: Enhanced latent heating over the tibetan plateau as a key to the enhanced East Asian summer monsoon circulation under a warming climate. *J Climate*, **32**, 3373–3388, https://doi.org/10.1175/JCLI-D-18-0427.1

Hersbach H., and Coauthors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.*, 146, 1999–2049, https://doi.org/10.1002/qj.3803.

Hewitt, C. D., and Coauthors, 2020a: Making society climate-resilient: International progress under the Global Framework for Climate Services. *Bull. Amer. Meteor. Soc.*, **101**, E237–E252, https://doi.org/10.1175/BAMS-D-18-0211.1.

——, and Coauthors, 2020b: The process and benefits of developing prototype climate services—Examples in China. *J. Meteor. Res.*, **34**, 893–903, https://doi.org/10.1007/s13351-020-0042-6.

Ineson, S., and Coauthors, 2018: Predicting El Niño in 2014 and 2015. *Sci. Rep.*, **8**, 10733, https://doi.org/10.1038/s41598-018-29130-1.

Ke, Q., 2014: Flood risk analysis for metropolitan areas—A case study for Shanghai. Ph.D. thesis, Delft University of Technology, 193 pp., https://doi.org/10.4233/uuid:61986b2d-72de-45e7-8f2a-bd61c725325d.

Khosravi, F., A. Taylor, and Y. L. Siu, 2021: Chinese water managers' long-term climate information needs. *Sci. Total Environ.*, **750**, 141637, https://doi.org/10.1016/j.scitotenv.2020.141637.

Li, C., and Coauthors, 2016: Skillful seasonal prediction of Yangtze River valley summer rainfall. *Environ. Res. Lett.*, **11**, 094002, https://doi.org/10.1088/1748-9326/11/9/094002.

——, and Coauthors, 2018a: Attribution of extreme precipitation in the lower reaches of the Yangtze River during May. *Environ. Res. Lett.*, **13**, 014015, https://doi.org/10.1088/1748-9326/aa9691.



Unauthenticated | Downloaded 08/21/22 10:56 AM UTC

——, and Coauthors, 2018b: Skillful seasonal forecasts of summer surface air temperature in western China by Global Seasonal Forecast System version 5. *Adv. Atmos. Sci.*, **35**, 955–964, https://doi.org/10.1007/s00376-018-7291-7.

Li, P., and Coauthors, 2020: The diurnal cycle of East Asian summer monsoon precipitation simulated by the Met Office Unified Model at convection-permitting scales. *Climate Dyn.*, **55**, 131–151, https://doi.org/10.1007/s00382-018-4368-z.

——, and Coauthors, 2021: Convection-permitting modelling improves simulated precipitation over the Tibetan Plateau. *Quart. J. Roy. Meteor. Soc.*, **147**, 341–362, https://doi.org/10.1002/qj.3921.

Li, Z., Z. W. Yan, Y. N. Zhu, N. Freychet, and S. Tett, 2020: Homogenized daily relative humidity series in China during 1960–2017. *Adv. Atmos. Sci.*, **37**, 318–327, https://doi.org/10.1007/s00376-020-9180-0.

Liu, Y., and Coauthors, 2018: Evaluation and statistical downscaling of East Asian summer monsoon forecasting in BCC and MOHC seasonal prediction systems. *Quart. J. Roy. Meteor. Soc.*, **144**, 2798–2811, https://doi.org/10.1002/qj.3405.

Lockwood, J., and Coauthors, 2019: Skilful seasonal prediction of winter wind speeds in China. *Climate Dyn.*, **53**, 3937–3955, https://doi.org/10.1007/s00382-019-04763-8.

Lott, F. C., and Coauthors, 2020: The effect of human land use change in the Hadley Centre attribution system. *Atmos. Sci. Lett.*, **21**, e972, https://doi.org/10.1002/asl.972.

Lu, B., and Coauthors, 2017: Skilful seasonal predictions of winter precipitation over southeast China. *Environ. Res. Lett.*, **12**, 074021, https://doi.org/10.1088/1748-9326/aa739a.

——, and Coauthors, 2018: An extreme negative Indian Ocean dipole event in 2016: Dynamics and predictability. *Climate Dyn.*, **51**, 89–100, https://doi.org/10.1007/s00382-017-3908-2.

Lu, Y., T. Wu, W. Jie, A. A. Scaife, M. B. Andrews, and J. H. Richter, 2020: Variability of the stratospheric quasi-biennial oscillation and its wave forcing simulated in the Beijing Climate Center Atmospheric General Circulation Model. *J. Atmos. Sci.*, **77**, 149–165, https://doi.org/10.1175/JAS-D-19-0123.1.

Ma, S., and Coauthors, 2017: Detectable anthropogenic shift toward heavy precipitation over eastern China. *J. Climate*, **30**, 1381–1396, https://doi.org/10.1175/JCLI-D-16-0311.1.

Martin, G. M., and Coauthors, 2019: Predictability of South China Sea summer monsoon onset. *Adv. Atmos. Sci.*, **36**, 253–260, https://doi.org/10.1007/s00376-018-8100-z.

Monerie, P., and Coauthors, 2018: A role of the Atlantic Ocean in predicting summer surface air temperature over north East Asia? *Climate Dyn.*, **51**, 473–491, https://doi.org/10.1007/s00382-017-3935-z.

Nie, Y., and Coauthors, 2019: Stratospheric initial conditions provide seasonal predictability of the North Atlantic and Arctic oscillations. *Environ. Res. Lett.*, **14**, 034006, https://doi.org/10.1088/1748-9326/ab0385.

——, and Coauthors, 2020: Enhanced mid-to-late winter predictability of the storm track variability in the North Pacific as a contrast with the North Atlantic. *Environ. Res. Lett.*, **15**, 094037, https://doi.org/10.1088/1748-9326/ab9c4d.

Pei, L., and Z. W. Yan, 2018: Diminishing clear winter skies in Beijing towards a possible future. *Environ. Res. Lett.*, **13**, 124029, https://doi.org/10.1088/1748-9326/aaf032.

Poli, P., and Coauthors, 2016: ERA-20C: An atmospheric reanalysis of the twentieth century, *J. Climate*, **29**, 4083-4097.

Qian, C., and Coauthors, 2018: Human influence on the record-breaking cold event in January of 2016 in eastern China. *Bull. Amer. Meteor. Soc.*, **99**, S118–S122, https://doi.org/10.1175/BAMS-D-17-0095.1.

Ren, H.-L., and Coauthors, 2016: Distinct persistence barriers in two types of ENSO. *Geophys. Res. Lett.*, **43**, 10973–10979, https://doi.org/10.1002/2016GL071015.

——, and Coauthors, 2018: Seasonal predictability of winter ENSO types in operational dynamical model predictions. *Climate Dyn.*, **52**, 3869–3890, https://doi.org/10.1007/s00382-018-4366-1.

Ren, L., and Coauthors, 2020: Anthropogenic influences on the persistent night-time heat wave in summer 2018 over northeast China. *Bull. Amer. Meteor. Soc.*, **101**, S83–S88, https://doi.org/10.1175/BAMS-D-19-0152.1.

Rodríguez, J. M., and Coauthors, 2017: The East Asian atmospheric water cycle and monsoon circulation in the Met Office Unified Model. *J. Geophys. Res. Atmos.*, **122**, 10 246–10 265, https://doi.org/10.1002/2016JD025460.

Scaife, A. A., and Coauthors, 2000: Realistic quasi-biennial oscillations in a simulation of the global climate. *Geophys. Res. Lett.*, **27**, 3481–3484, https://doi.org/10.1029/2000GL011625.

——, and Coauthors, 2017a: Tropical rainfall, Rossby waves and regional winter climate predictions. *Quart. J. Roy. Meteor. Soc.*, **143**, 1–11, https://doi.org/10.1002/qj.2910.

——, and Coauthors, 2017b: Predictability of European winter 2015/2016. *Atmos. Sci. Lett.*, **18**, 38–44, https://doi.org/10.1002/asl.721.

Slivinski, L. C., and Coauthors, 2019: Towards a more reliable historical reanalysis: Improvements to the Twentieth Century Reanalysis system. *Quart. J. Roy. Meteor. Soc.*, **145**, 2876–2908, https://doi.org/10.1002/qj.3598.

Sparrow, S., and Coauthors, 2018: Attributing human influence on the July 2017 Chinese heatwave: The influence of sea-surface temperatures. *Environ. Res. Lett.*, **13**, 114004, https://doi.org/10.1088/1748-9326/aae356.

Stephan, C. C., N. P. Klingaman, and A. G. Turner, 2019: A mechanism for the recently increased interdecadal variability of the Silk Road pattern. *J. Climate*, **32**, 717–736, https://doi.org/10.1175/JCLI-D-18-0405.1.

Thompson, V., and Coauthors, 2019: Risk and dynamics of unprecedented hot months in south East China. *Climate Dyn.*, **52**, 2585–2596, https://doi.org/10.1007/s00382-018-4281-5.

Wang, J., Y. Chen, S. Tett, Z. W. Yan, P. M. Zhai, and J. M. Feng, 2020: Anthropogenically-driven increases in the risks of summertime compound hot extremes. *Nat. Commun.*, **11**, 528, https://doi.org/10.1038/s41467-019-14233-8.

Wang, L., and Coauthors, 2016: Increasing flash droughts over China during the recent global warming hiatus. *Sci. Rep.*, **6**, 30571, https://doi.org/10.1038/srep30571.

Wang, Y., L. Song, C. Hewitt, N. Golding, and Z. Huang, 2020: Improving China's resilience to climate-related risks: The China Framework for Climate Services. *Wea. Climate Soc.*, **12**, 729–744, https://doi.org/10.1175/WCAS-D-19-0121.1.

Wilcox, L. J., N. Dunstone, A. Lewinschal, M. Bollasina, A. M. L. Ekman, and E. J. Highwood, 2019: Mechanisms for a remote response to Asian anthropogenic aerosol in boreal winter. *Atmos. Chem. Phys.*, **19**, 9081–9095, https://doi.org/10.5194/acp-19-9081-2019.

Williamson, F., and Coauthors, 2018: Collating historic weather observations for the East Asian region: Challenges, solutions, and reanalyses. *Adv. Atmos. Sci.*, **35**, 899–904, https://doi.org/10.1007/s00376-017-7259-z.

Wu J. and X.-J. Gao 2013: A gridded daily observation dataset over China region and comparison with the other datasets. *Chinese J. Geophys.*, **56**, 1102–1111, https://doi:10.6038/cjg20130406.

Wu, J., and Coauthors, 2020: Representation and predictability of the East Asia–Pacific teleconnection in the Beijing Climate Center and UK Met Office subseasonal prediction systems. *J. Meteor. Res.*, **34**, 941–964, https://doi.org/10.1007/s13351-020-0040-8.

Wu, T., and Coauthors, 2019: The Beijing Climate Center Climate System Model (BCC-CSM): Main progress from CMIP5 to CMIP6. *Geosci. Model Dev.*, **12**, 1573–1600, https://doi.org/10.5194/gmd-12-1573-2019.

Xiao, C., P. Wu, L. Zhang, and L. Song, 2016: Robust increase in extreme summer rainfall intensity during the past four decades observed in China. *Sci. Rep.*, **6**, 38506, https://doi.org/10.1038/srep38506.

Yan, Z. W., Y. H. Ding, P. M. Zhai, L. C. Song, L. J. Cao, and Z. Li, 2020: Re-assessing climatic warming in China since 1900. *J. Meteor. Res.*, **34**, 243–251, https://doi.org/10.1007/s13351-020-9839-6.

Yang, Q., and Coauthors, 2017: Decadal modulation of precipitation patterns over East China by sea surface temperature anomalies. *J. Climate*, **30**, 7017–7033, https://doi.org/10.1175/JCLI-D-16-0793.1.

——, Z. Ma, P. Wu, N. Klingaman, and L. Zhang, 2019: Interdecadal seesaw of precipitation variability between North China and the southwest United States. *J. Climate*, **32**, 2951–2968, https://doi.org/10.1175/JCLI-D-18-0082.1.


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Yatagai, A., K. Kamiguchi, O. Arakawa, A. Hamada, N. Yasutomi, and A. Kitoh 2012: APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges, *Bull. Amer. Meteor. Soc.*, **93**, 1401–1415.

Yuan, X., and Coauthors, 2019: Anthropogenic shift towards higher risk of flash drought over China. *Nat. Commun.*, **10**, 4661, https://doi.org/10.1038/s41467-019-12692-7.

Zhang, L., P. Wu, and T. Zhou, 2017: Aerosol forcing of extreme summer drought over North China. *Environ. Res. Lett.*, **12**, 034020, https://doi.org/10.1088/1748-9326/aa5fb3.

——, ——, ——, and C. Xiao, 2018: ENSO transition from La Niña to El Niño drives prolonged spring–summer drought over North China. *J. Climate*, **31**, 3509–3523, https://doi.org/10.1175/JCLI-D-17-0440.1.

——, T. Zhou, P. Wu, and X. Chen, 2019: Potential predictability of North China summer drought. *J. Climate*, **32**, 7247–7264, https://doi.org/10.1175/JCLI-D-18-0682.1.

——, and Coauthors, 2020: The late spring drought of 2018 in South China. *Bull. Amer. Meteor. Soc.*, **101**, S59–S64, https://doi.org/10.1175/BAMS-D-19-0202.1.

Zhang, W., and Coauthors, 2020: Anthropogenic influence on 2018 summer persistent heavy rainfall in central western China. *Bull. Amer. Meteor. Soc.*, **101**, S65–S70, https://doi.org/10.1175/BAMS-D-19-0147.1.

Zhang, W., Z. Huang, F. Jiang, M. F. Stuecker, G. Chen, and F.-F. Jin, 2021: Exceptionally persistent Madden-Julian oscillation activity contributes to the extreme 2020 East Asian summer monsoon rainfall. *Geophys. Res. Lett.*, **48**, e2020GL091588, https://doi.org/10.1029/2020GL091588.


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