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CLIMATE TRENDS AND IMPACTS IN CHINA

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This background paper was prepared as an input to a series on Climate Risk Management and Adaptation in China (CLIMA). Each of the papers in the CLIMA series outlines a framework for managing risks posed by present-day climate variability, extreme weather events, and future climate change to an individual sector in China, including transportation, urban water utilities, and forestry.

The paper was written by Chris Sall (Consultant, World Bank; Affiliated Researcher, Center for International Environment and Resource Policy, the Fletcher School, Tufts University) under the guidance of team leaders Paul Procee (Lead Urban Specialist, World Bank) and Carter Brandon (Lead Economist, Sustainable Development, World Bank), with contributions by Yu Rong (Consultant, World Bank). The paper benefited greatly from critical review and comments by Rosina Bierbaum (World Bank Fellow on Climate Change Adaptation), Abed Khalil (Water and Climate Risk Management Specialist, World Bank), and Mike MacCracken (Chief Scientist for Climate Change Programs, Climate Institute). Vivian Argueta-Bernal (Consultant, World Bank) and Zuzana Staton-Geddes (Operations Analyst, World Bank) coordinated the editing and publication process. Anne Himmelfarb edited the final draft. Huang Dafei (Climate Change Specialist, World Bank) and Zhang Lijun (Operations Assistant, World Bank) reviewed and edited the Chinese translation.

About the East Asia and Pacific Sustainable Development Discussion Paper Series

Sustainable development issues are an integral part of the development challenge in the East Asia and Pacific (EAP) region. The World Bank's Sustainable Development Strategy for the region provides the conceptual framework for setting priorities, strengthening the policy and institutional frameworks for sustainable development, and addressing key environmental, social, and rural development challenges through projects, programs, policy dialogue, nonlending services, and partnerships. The EAP Sustainable Development Discussion Paper series provides a forum for discussion of good practices and policy issues within the development community and with client countries.

EAP Sustainable Development Discussion Papers carry the names of the authors and should be cited accordingly. The findings, interpretations, and

ABSTRACT

This discussion paper summarizes observed and projected trends in extreme weather events, present-day climate variability, and future climate change and their impacts on China's different regions. Findings are presented from China's *National Assessment Report on Climate Change* (2007) and Second National Assessment Report on Climate Change (2011) as well as other studies by Chinese and international experts. In addition to reviewing the physical climate science, the paper also looks at trends in economic damages in China from weather-related hazards. The paper serves as background for a series of discussion papers on climate risk management and adaptation in China.

The growing body of scientific evidence shows that China's climate is indeed changing, especially when climate is viewed at the regional level. Temperatures are rising, precipitation regimes are changing, and shifts have occurred in the distribution of extreme weather events. The effects of extreme weather events, present-day climate variability, and future climate change cut across many different sectors of China's economy. China's government estimates that direct economic losses from extreme weather events cost the country 1–3 percent of gross domestic product each year. As China's economy continues to grow, its exposure to weather-related hazards is expected to heighten, especially without policies to limit building in hazardous areas such as floodplains and alleviate non-climate pressures such as overuse of freshwater resources. Effective risk management policies and investments are crucial to reducing the sensitivity and increasing the resilience of the country to extreme weather, climate variability, and long-term climate change.

ABBREVIATIONS

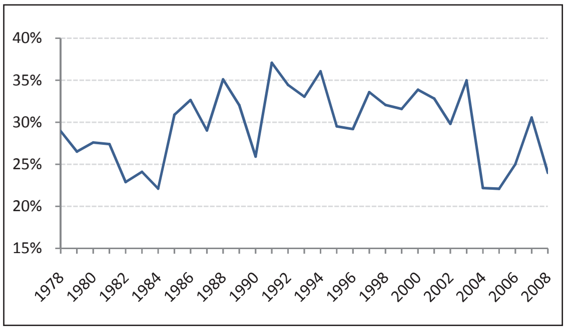
CLIMA	Climate Risk Management and Adaptation in China
cm	centimeter
EAP	East Asia and Pacific
GCM	general circulation model or global climate model
GDP	gross domestic product
ha	hectare
IPCC	International Panel on Climate Change
km	kilometer
km^2	square kilometer
m	meter
m^3	cubic meter
mm	millimeter
OECD	Organisation for Economic Co-operation and Development
NARCC	National Assessment Report on Climate Change

INTRODUCTION

Covering more than 9.6 million km^2, China is a vast country with a diverse climate. The country's weather system is dominated by monsoons, which bring cold, dry air down from Siberia during the winters and warm, moist air up from the Indian subcontinent and South China Sea during the summers. Parts of China along the southeastern coast receive around 2,000 mm of rainfall annually, while much of the arid Northwest receives less than 25 mm. During the summers, temperatures in Chongqing routinely reach more than 35˚C, while temperatures during the winters in Heilongjiang can dip below -40˚C.

As a result of its large territory and diverse conditions, China is exposed to a wide array of weather-related hazards, such as typhoons, heat waves, severe cold, floods, and drought. China's government estimates that direct economic losses from extreme weather events cost the country 1–3 percent of gross domestic product (GDP) each year (see Xinhua 2010). Among the reported losses, damages from droughts and flooding have averaged 284 billion yuan since 2006 (MWR 2006–2010; Xinhua 2012). Since 1978, about one-quarter to one-third of the country's farmland has experienced reduced yields each year due to floods, droughts, wind, hail, typhoons, cold spells, freezes, and snow (figure 1).

Figure 1: Percent of planted cropland in China affected by weather disasters, 1978-2008



Sources: NBS 1996a, 1996b-2009b, 2007c-2011c, 2009d, 2010e; NBS and MEP 2005-2011; MWR 2006-2010; Xinhua 2012.

Notes: "Affected" area refers to the area of planted land were crop yields have declined by at least 10 percent

The goal of China's government is to cut direct economic losses from weather disasters in half by 2020,[1] yet this will be no easy feat. China is a rapidly urbanizing middle-income country with a huge economy and a quickly expanding stock of valuable assets such as buildings, roads, and other infrastructure. Without policies such as restrictive zoning codes and higher insurance premiums that discourage settlement and economic activities in the most hazardous areas, social and economic forces will continue to drive up its levels of exposure. At the same time, projected changes in China's climate may also increase exposure. The current scientific research in China projects that evaporation and drought will increase across the North, Northeast, and Northwest; flooding is expected to increase for the middle and lower reaches of the Yangtze and Pearl River basins; a higher portion of rainfall is projected to come from shorter, intense storms in some regions; the melting of glaciers in the Southwest and Northwest will affect river flows downstream; heat waves will become more common; and storm surges, tidal floods, and rising seas will threaten a larger area of coastal lands.

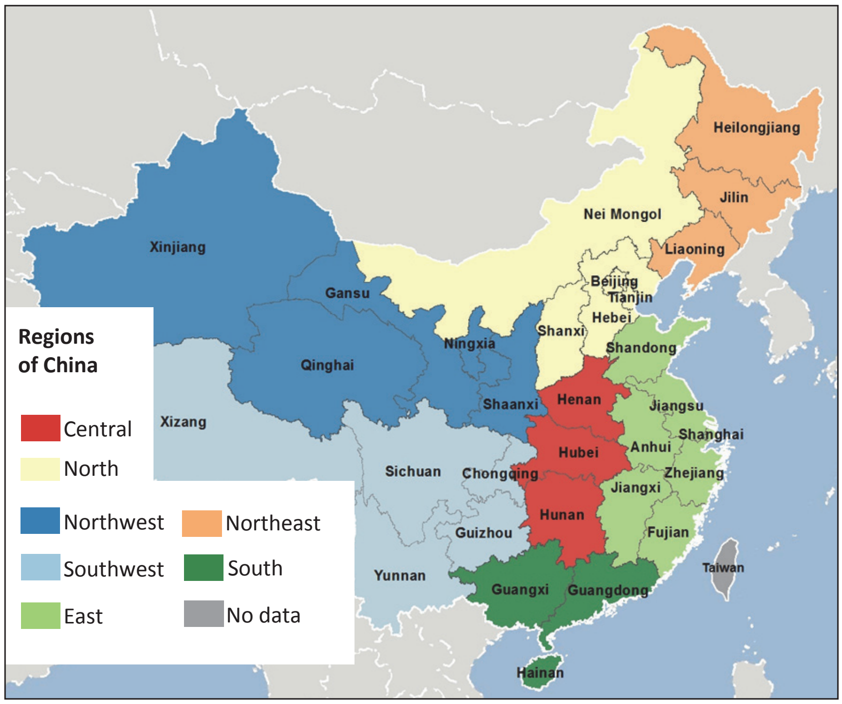
Though less dramatic than extreme weather events, long-term changes in average climate conditions also present risks. Available research suggests that productivity gains in agriculture and forestry from longer growing seasons, CO_2 fertilization, and an expanded area of potentially arable land may be reversed at higher levels of warming as greater evapotranspiration and water demand from plants leads to more drying and relative declines in vegetative growth. In the southwest and northwest provinces, high levels of warming by midcentury could also lead to shortages of freshwater from melting glaciers and mountain snows. Even in regions where annual precipitation is expected to increase, such as the North, Northeast, and Northwest, it is unlikely that water stress will be alleviated, as absolute demand by industries, agriculture, and cities continues to rise.

This discussion paper summarizes observed and projected trends in extreme weather events, present-day climate variability, and future climate change and their impacts on China's different regions. This summary is intended to serve as background for a series of discussion papers on climate risk management in adaptation in China. Research findings presented in the paper are drawn from an extensive review of China's *National Assessment Report on Climate Change* (NARCC 2007) and *Second National Assessment Report on Climate Change* (NARCC 2011) as well as other studies by Chinese and international experts. Trends are summarized for average and extreme temperatures, precipitation, runoff and water availability, droughts, floods, typhoons, and sea-level rise. In addition to reviewing the climate science, the paper also looks at trends in economic damages from weather-related hazards.

[1] The goal is stated in CMA (2010).

Unless otherwise indicated, the regions referred to in this paper are defined according to the groupings in China's Second National Assessment Report (NARCC 2011), illustrated below (map 1).

Map 1: Regions of China, as Defined by the Second National Climate Change Assessment Report



Source: Based on NARCC 2011

Notes: The regions correspond to those in China's national statistical yearbooks

1. Temperatures, Including Extreme Heat and Cold

Measurements from weather monitoring stations across China show that temperatures increased an average of 1.4˚C between 1951 and 2009 (NCCAR 2011). Winter days and nights have warmed the fastest, especially since the mid-1980s; the number of days with temperatures below freezing has decreased; and the coldest days are now milder (by about 2.5˚C compared to 1951). By contrast, warming during the summers has been more gradual (NCCAR 2011; Zhou and Ren 2010).

Changes in temperature have varied markedly between regions. The most pronounced warming has occurred in the far North and high on the Tibetan Plateau, where average temperatures in some areas have increased several times faster than the rate for the nation overall (Liu and Chen 2000). Meanwhile, small parts of Yunnan, Guizhou, and Sichuan provinces in the Southwest either saw no discernible temperature change or became slightly cooler over the past 60 years (NARCC 2011).[2] Urbanization has also played a significant, though not fully understood, role in warming. The heat island effect from expanding cities may account for 40 percent of the warming recorded by China's network of monitoring stations over the past 50 years (NARCC 2011).

The number of extremely hot days experienced each year has increased on the whole for China (Zhou and Ren 2010; Zhang and Qian 2008). For the nation, the number of days each year with extremely high temperatures increased at a rate of about four days per decade from 1965 to 2008 (Zhou and Ren 2010).[3] Regionally, however, there were pronounced differences. Parts of the interior Northwest experienced the largest increase in the number of extremely hot days, while slight decreases in the number of hot days were seen for parts of the South, Southwest, and East (Zhang and Qian 2008; Zhou and Ren 2010). No clear trend was observed in the number or temperature of hot days for the Yangtze River basin (Gong, Pan, and Wang 2004; Zhang and Qian 2008). Furthermore, while there is no clear evidence that heat waves (periods of more than six extremely hot days in a row) have grown more frequent on a national scale, the number of days each year with record-breaking temperatures has increased (Zhou and Ren 2010). Extremely hot temperatures have been associated with increased public health problems in large Chinese cities. In July 2006, for example, a heat wave struck Chongqing. With temperatures in the city reaching as high as 44.5˚C, an additional 20,000 cases of heat stroke were recorded (NARCC 2011). The elderly are especially vulnerable to such extreme heat (Kan et al. 2007).

Not surprisingly, while extremely hot days have become more frequent, the number of extremely cold days has decreased (Zhang and Qian 2008; Zhou and Ren 2010; Qian 2011; Gong et al. 2012). On the whole, the number of extremely cold days experienced

[2] The reason for this lack of measurable warming in parts of the Southwest is not yet clear (Chen, Liu, and Ma 2002). Possible causes suggested by previous research include reduced solar radiation due to backscatter and cloudiness from human-emitted aerosols in the lower atmosphere. See Li et al. (1995), for example.

[3] Days with extremely high temperatures are defined as days for which the highest temperature exceeds a relative threshold far above what is considered normal. Zhou and Ren (2010), for example, define this threshold as 90 percent of the highest daily temperature recorded between 1970 and 2000 for a given monitoring station.

each year decreased at a rate of seven days per decade for the nation between 1956 and 2008. Over these 52 years, the lowest temperature of the coldest days rose by about 3˚C (Zhou and Ren 2010; see also Qian 2011).[4] Similarly, the number of frost days (with low temperatures below freezing) has also decreased. On average, nationwide there were 10 fewer frost days annually in 1990 than in 1960 (Zhai and Pan 2003). The decrease in the number of cold days was most pronounced for parts of the North and Northeast (Zhang and Qian 2008).

The observed warming in recent decades has benefited farmers in the northern provinces by lengthening the growing season—allowing for earlier planting and later harvesting—and by expanding the area in which crops such as rice can grow. Warmer springs have contributed to accelerated and more vigorous growth of forests and grasslands in the North and Northwest (see Zhang forthcoming; Sall and Brandon forthcoming). Yet despite warmer temperatures and fewer days with freezing temperatures, the area of cropland reportedly affected by cold snaps and freezing temperatures has actually increased for every region except the Northeast (where no statistically significant change was observed). This observed increase in exposure was driven almost entirely by the expanding area of crops being planted.[5] Furthermore, milder winters have also led to worse outbreaks of pests (Piao et al. 2010), and while the number of heating days has declined, energy savings from this decrease have been offset by population growth, housing construction, changes in heating methods, and increased demand for air conditioning and other electrical appliances.

According to the Intergovernmental Panel on Climate Change (IPCC), average surface temperatures are projected to rise another 1˚C to 5˚C globally by 2100 (Meehl et al. 2007), depending on the sensitivity of the climate to increased atmospheric concentrations of greenhouse gases, the ambitiousness of the world's countries to reduce emissions, and other uncertain factors. Drawing on results obtained from 22 global climate models used in the IPCC's Fourth Assessment Report (Solomon et al. 2007), China's Second National Climate Change Assessment Report (2011) projects an increase in average annual temperatures of 2.5˚C to 4.6˚C for the nation by the end of this century. Warming is projected to continue to be the greatest for the North, Northwest, Northeast, and Tibetan Plateau. In Xinjiang, for example, middle-of-the-road projections of annual temperatures show 2.5°C to 3.3°C of warming by the 2050s and 3.3°C to 4.8°C of warming by the 2080s (see figure 2).[6] Most of the additional increase in average temperatures will come

[4] An extremely cold day is defined by Zhou and Ren (2010) as a day for which the daily low temperature is within 10 percent of the coldest daily temperature recorded for a given monitoring station between 1970 and 2000. As with extreme high temperatures, the way "extremely cold days" are defined and calculated can influence results (see Zhang and Qian 2008).

[5] The rates of increase in planted area by region are far greater than the rates for area affected by cold spells and freezing temperatures, with the exception of the eastern provinces, where the planted area has actually decreased, while the area affected by cold snaps and freezes has increased. Results are from author's calculations using statistics for reported area of cropland affected by cold spells and freezing temperatures by the provinces for 1978 to 2007 (NBS 2009). Note that the observed increase could also be due to improved reporting over the years. Also note that the definitions of regions in the underlying statistical yearbook differ from those used in the *Second National Assessment Report on Climate Change*.

[6] The projections for average annual temperatures in Xinjiang reported here refer to the 20th and 80th percentiles of results from 16 GCMs reviewed in the IPCC Fourth Assessment Report. See figure 2 for data sources.

from warmer nights (higher lows) (NARCC 2011; Li and Zhou 2010), though the results of some finer-scale regional models project that summers could warm even faster than winters toward the end of this century (Gao, Shi, and Giorgi 2010, 2011; Yang et al. 2010). Hotter temperatures during the summer months could cause greater drying and exacerbate water shortages (Piao et al. 2010).

With additional warming, it is also "very likely" (that is, there is a 9 in 10 chance) that the intensity, frequency, and length of heat waves will increase globally (Meehl et al. 2007; Seneviratne et al. 2012).[7] In China, the number of hot days per year with average temperatures above 35°C is expected to increase from 4 to around 20 by the end of the century (NARCC 2011). The number of consecutive hot days is also projected to increase (Yang et al. 2010). Meanwhile, a decrease in the number of cold nights and days over most of the world's land areas is "virtually certain" (Seneviratne et al. 2012).

Available research shows that additional warming will have far-reaching and complex effects on the health of China's agriculture, ecosystems, and people (NARCC 2011). The area of arable land in northern China will continue to grow; however, productivity gains from higher temperatures could be undone by the consequent increases in evaporation and demand for water (NARCC 2011). Some studies indicate that at higher levels of warming (above 3°C), net primary productivity (biomass growth in plants) will decrease by more than 40 percent for much of the country (Wu et al. 2007). Such warming is expected to have profound negative impacts on the functioning of ecosystems—from the alpine tundra of the Tibetan Plateau to the wetlands of the central provinces to the coral reefs along the southern coast—and to increase the risk of irreversible species loss (see Fischlin et al. 2007; Wu and Lü 2009; Ramsar-CBD 2007; Xiao et al. 2011; NARCC 2011). Warming also affects people's health. Health effects associated with higher temperatures include higher bacterial and fungal content in surface waters, higher survival rates for waterborne pathogens, greater disease transmission, and host susceptibility (Harvell et al. 2002; Bates et al. 2008). Research shows that as winter weather continues to grow warmer, schistosomiasis could spread to provinces farther north (Zhou et al. 2010; Zhou et al. 2008). Higher concentrations of microbes and other temperature-dependent pollutants in rivers and reservoirs will in turn require greater investment in water treatment facilities and processes. There is also evidence that warming is elevating ground-level concentrations of ozone and smog in cities (Murray et al. 2012). A rapidly urbanizing and aging population will only amplify health problems related to extreme heat. A recent review commissioned by the World Bank provides additional insight into the dangers that high levels of warming are expected to have for China and other countries (see box 1).

[7] Statements about the likelihood of changes presented in this paper follow the standard language set out in Mastrandrea et al. (2010) for the characterization of uncertainty. Outcomes that are "virtually certain" are assigned a 99–100 percent probability of occurring; "very likely" outcomes are assigned a 90–100 percent probability; "likely" outcomes a 66–100 percent probability; "unlikely" outcomes a 0–33 percent probability; "very unlikely" outcomes a 0–10 percent probability; and "exceptionally unlikely" outcomes a 0–1 percent probability. Outcomes that are "about as likely as not" are assigned a 33–66 percent probability. Where this paper does not use the IPCC language set out by Mastrandrea et al. (2010), no statement of likelihood is intended. In these cases, changes are said to be "projected" or "may" or "could" occur. This paper is meant to be a literature review. It does not set out to make an independent scientific assessment of the potential likelihood of observed and projected events, trends, or other outcomes.

Box 1: Why a 4°C Warmer World Must Be Avoided

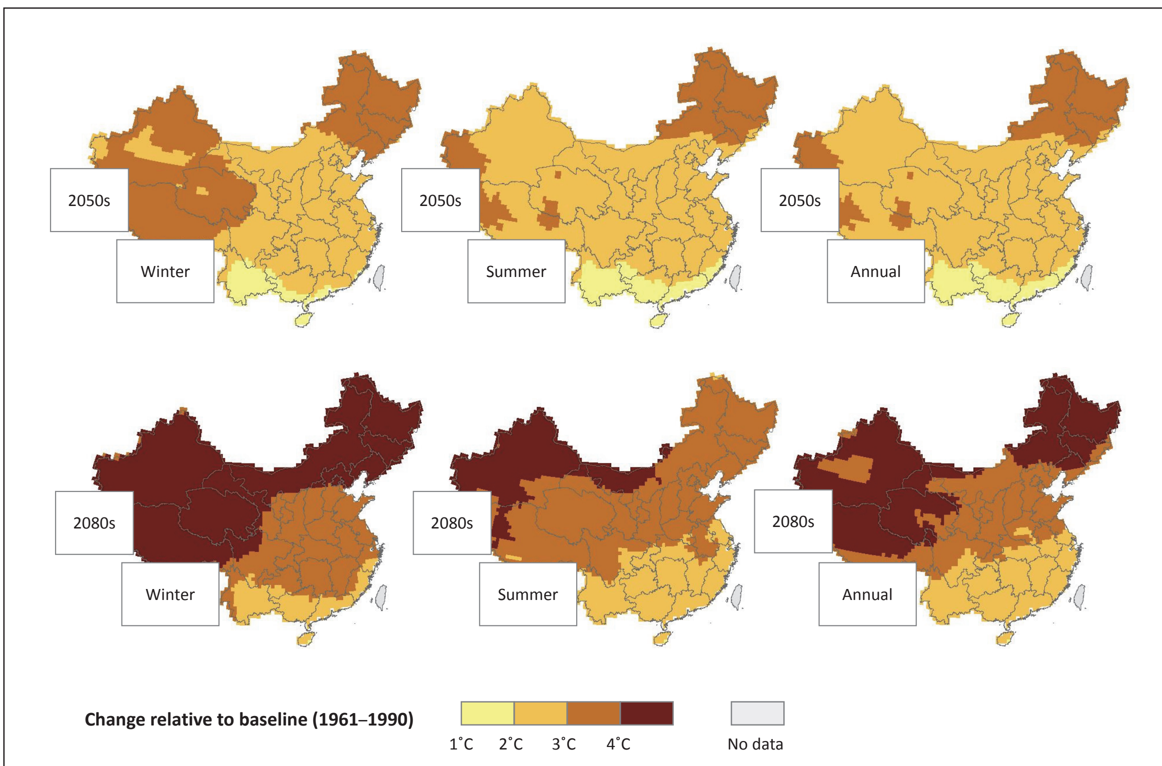
The current level of ambition to reduce greenhouse gas emissions reflected in the Copenhagen and Cancun pledges will put the world on a path for warming of more than 3°C. If pledges are not met, then there is a 40 percent chance of more than 4°C warming by the end of this century. Turn Down the Heat (2012), a report for the World Bank by the Potsdam Institute for Climate Research and Climate Analytics, finds that 4°C of warming is likely to take us into a world of wide-ranging and dangerous risks.

One of the greatest dangers of a 4°C warmer world is the increased likelihood of crossing nonlinear tipping points, thus bringing about abrupt changes in climatological, hydrological, and ecological systems. Examples of abrupt changes include the breaking up of the West Antarctic ice sheet, the dieback of the Amazon rainforests, the disintegration of corals, and large-scale crop failures.

Nonlinear changes in natural systems will likely have cascading impacts on human development at the national and regional scale. Regional crop failures, for example, could cause spikes in food prices, cutting into wages for poorer households especially, and putting a drag on GDP growth. As has been the case with warming observed so far, developing countries are likely to be affected most by such impacts.

The ability of society to cope with large, abrupt changes is limited. As the Potsdam Institute study concludes, "given that uncertainty remains about the full nature and scale of impacts, there is also no certainty that adaptation to a 4°C world is possible. A 4°C world is likely to be one in which communities, cities, and countries would experience severe disruptions, damage, and dislocation, with many of these risks spread unequally" (Potsdam Institute 2012, xviii).

Figure 2: Projected changes in average seasonal temperatures, 2050s and 2080s



Source: Author, using data from Climate Wizard, The Nature Conservancy (accessed July 2013), http://www.climatewizard.org/.

Note: The figure shows changes in average temperatures for 2041–2070 and 2061–2090 under a "middle-of-the-road" emissions scenario (SRES A1B) compared to average temperatures in the 1961–1990 baseline climate. The temperature changes shown in the figure are those projected by the "middle" model of an ensemble of 16 global climate models (GCMs). GCM results have been downscaled to a spatial resolution of 0.5° x 0.5°.

2. Precipitation and Water Resources

Annual precipitation did not exhibit a significant change over the last half of the 20th century for the nation as a whole (NARCC 2011; Zhai et al. 2005; Ren et al. 2008; Piao et al. 2010). Yet these overall trends mask significant regional and seasonal variation. Precipitation has declined for much of the northeastern part of the country (including the Yellow, Liao, and Hai River basins) and increased for the Yangtze River basin and northwestern China (NARCC 2011; Zhai et al. 2005; Ren et al. 2008; Piao et al. 2010; Shen 2010).[8] These changes may be associated with the Pacific Decadal Oscillation or a shift in the East Asian summer monsoon system, which delivered less moisture to northeastern China and brought more to the southern part of the country (NARCC 2011; Ma and Ren 2007; Zhai et al. 2005; Ren et al. 2008). The number of rainy days each year has decreased everywhere except in parts of western China (Zhai, Wang, and Li 2007; Zhai et al. 2005). This decrease has been offset by a slight but statistically significant increase in the frequency and intensity of extreme precipitation events, especially in south and southwest China (Wang and Qian 2009; Zhai, Wang, and Li 2007; Zhai et al. 2005). Seasonally, winter precipitation has increased in Tibet and parts of south China, but decreased over most of north China and the Sichuan basin. Spring precipitation has increased in the Southwest and South and decreased over most of northern China and the mid to upper Yellow River basin. Summer rainfall has increased for the Yangtze River basin and decreased for the Yellow River basin and most of northern China. These trends in spring and summer rainfall are especially important because 50–70 percent of the country's annual precipitation usually comes during the summer, and spring and summer are the prime growing seasons (Zhai et al. 2005).

Together with warmer temperatures, changes in precipitation observed in the northern river basins have affected water resources (NARCC 2011; Wang and Zhang 2011). In such dry regions, surface water availability is particularly sensitive to changes in the volume, timing, and intensity of precipitation. Rainfall is concentrated during just a few months, and year-to-year variability tends to be greater (Kundzewicz et al. 2007). Since 1950, annual flow volumes measured at gauging stations in mid to lower reaches of the Yellow River have declined by 21–39 percent, while flows in the Hai River basin have diminished by 24–65 percent (NARCC 2011). By contrast, there were no significant long-term trends observed for runoff in the Huai, Yantgze, and Pearl Rivers (Zhang et al. 2007).

Water availability is also highly sensitive to nonclimate pressures such as land use patterns and the rising demand for water. Nationwide, consumptive water use in China has increased from 481 billion m^3 in 1987 to 590 billion m^3 in 2011 (see box 2). Water use has increased most dramatically in regions such as the North China Plain, where irrigated agriculture has expanded by nearly 8 million hectares over the past 30 years (Li 2010). In fact, there is evidence that demand for water had an even larger effect

[8] Piao Shilong and his coauthors argue that these regional trends "appear to fall within the bounds of normal decadal variability of rainfall" (Piao. et al. 2010, 44).

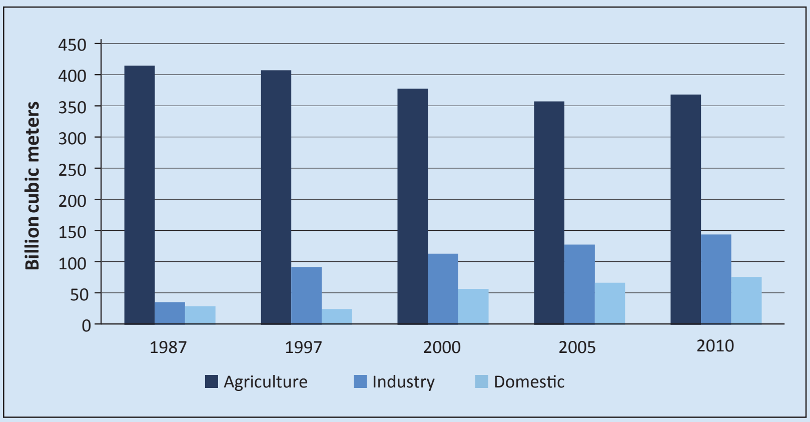
than the climate in reducing river runoff in the northern basins during the late 20th century. In the mid to lower section of the Yellow River basin, for example, water use by agriculture, industry, and cities accounted for about 60 percent of the observed change in flow volumes between 1970 and 2000 (NARCC 2011).

Box 2: Water Demand and Scarcity in China

China is a water-scarce country. Nationwide, per capita freshwater resources are 2,310 m^3 (NBS 2011c), which is about one-quarter the world average. In the dry regions of the North and Northeast, freshwater resources are only 785 m^3 per person, about 200 m^3 less than the international threshold for "severe" water stress, below which there is a high likelihood of frequent shortages and supply disruptions (see UNDP 2006).

Agriculture continues to be the biggest user of water, followed by industry and households, as illustrated in figure B2.1. In 2010, the agricultural sector consumed 370 billion m^3 of water; industry consumed 145 billion m^3, and households in urban areas used 77 billion m^3.

Figure B2.1: Water Withdrawals in China by Sector, 1987-2010



Source: World Bank data, http://data.worldbank.org (accessed September 2012); NBS 2012c

There is strong evidence that the continued growth of agriculture and industry, coupled with the lifestyles of an increasingly affluent population, will increase demand for water in the coming decades (Rosegrant, Cai, and Cline 2002; Alcamo, Henrichs, and Rösch 2000; Alcamo et al. 2003; Alcamo, Flörke, and Märker 2007; 2030 Water Resources Group 2009; Hubacekand Sun 2005; Xionget al. 2010). In a reference case scenario, total withdrawals of surface water and groundwater could reach nearly 820 billion m^3 by 2030 (2030 Water Resources Group 2009),[9] an increase of 35 percent over 2010 (NBS 2011c). In a continuation of current trends, water use by industries and households in cities is projected to grow the fastest. Agricultural water use is projected to decline as more efficient irrigation technologies are introduced and the composition of China's economic activity gradually shifts toward higher-value-added sectors, though it will continue to account for the largest bulk of water withdrawals (Rosengrant, Cai, and Cline 2002).

These results indicate that the growth in demand for China's scarce resources will continue to exacerbate water stress, even in the absence of climate change. Even under a balanced growth scenario in which local governments give higher priority to environmental protection, Xiong Wei et al. (2010) project that by 2050, all of the major basins currently experiencing severe water stress will face even greater shortages. Baseline projections from the Organisation for Economic Co-operation and Development (OECD) for global water stress by 2050 also show that stress for all major basins is expected to increase, with the Yellow, Hai, and Liao basins remaining under the greatest pressure (OECD 2012).

[9] This business-as-usual projection of China's water resource requirements by the 2030 Water Resources Group (2009) assumes that existing policy regimes remain in place and that current levels of efficiency hold. It is roughly consistent with earlier projections of China's water needs in 2025, based on more sophisticated global modeling of water supply and demand by Alcamo, Henrichs, and Rösch (2000); Alcamo et al. (2003); Alcamo, Flörke, and Märker 2007; and Rosegrant, Cai, and Cline (2002).

How precipitation patterns in China will change over the next decades is not wellestablished (NARCC 2011). Examining the results from 18 global climate models included in the IPCC's Fourth Assessment Report, Li and Zhou (2010) found that by mid-century (2040–2059) annual precipitation was generally expected to increase for most of China under a middle-of-the-road emissions scenario (the A1B scenario), with the largest increases expected for parts of the Southwest and the mid to lower reaches of the Yangtze River. However, the models show little agreement, and the resulting trends are statistically weaker than the background variation or "noise" for all of China except parts of western Sichuan, Tibet, and the Northeast. The downscaled results from a subset of seven global models in the larger ensemble evaluated by Li and Zhou (presented in figure 3) illustrate this lack of agreement, particularly in the South and Southwest.

By comparison with the coarse-resolution global models, the finer-scale regional climate model (RegCM3) considered by the *Second National Assessment Report on Climate Change* is better at representing the effects of the country's varied topography (NARCC 2011). The results of the underlying study cited by the assessment report (Gao, Shi, and Giorgi 2010, 2011) and other studies using the same model (Gao et al. 2012a, 2012b) are illustrated in figure 4. In this illustration, the RegCM3 regional model is driven by two separate global models (MIROC3.2 and FvGCM) under two separate emissions scenarios (A1B and A2). Like the global models, the regional models show an increase in precipitation from winter snows and rain across the North and Northwest. This may be due to milder temperatures, a northward tracking of mid-latitude storms, and more moisture being transported to these dry regions (Meehl et al. 2007). In contrast with the global models, however, the regional models reflect a decrease in summer rainfall of around 4 percent nationwide in both a middle- and high-emissions scenario. The greatest difference is in southwestern China; an average decrease of 6–7 percent is expected during the summers for Tibet and Yunnan.

Projected changes in precipitation will continue to influence future water availability. Overall, by late century, surface runoff is projected to decrease in the North and Northeast, as the effects of drying associated with warmer temperatures outweigh the effects of projected increases in rainfall. Runoff in the central, southern, and southwestern provinces, meanwhile, is projected to increase along with heavier rains in the summers (NARCC 2011). Yet the size and even the direction of change in surface water availability are still highly uncertain. Projections are highly sensitive to future emissions scenarios and to biases in the underlying results of the global climate models that are fed into the hydrological models (Piao et al. 2010). One study, for example, projected that by 2030, summer runoff in the Liao River basin could decrease by 7 percent in a low-emissions (B2) scenario or increase by 21 percent in a middle-emissions (A1B) scenario; runoff in the Hai River basin could decrease by 8 percent in a low-emissions scenario or increase by 10 percent in a middle-emissions scenario (Wang et al. 2012).[10]

[10] Results are based on modeling done by Wang et al. (2012) using a VIC hydrological model and PRECIS climate model to analyze trends from 2021 to 2050.

Even if annual precipitation increases in the water-stressed parts of the North, Northeast, and Northwest, it is unlikely that shortages will be alleviated if upward trajectory in the demand for water is not curbed (NARCC 2011). In a "normal" (wetter) climate scenario, water shortages in the Beijing-Tianjin-Tangshan region are still projected to reach 5 billion m^3 per year by 2030, shortages in the Hai-Luan basin could reach 57 billion m^3, shortages in the Yellow River basin could reach 36 billion m^3, and shortages in the Huai River basin could hit 19 billion m^3. In this scenario, the effects of baseline growth in population and economic activity account for 71–83 percent of the shortfalls (Wang and Zhang 2011).

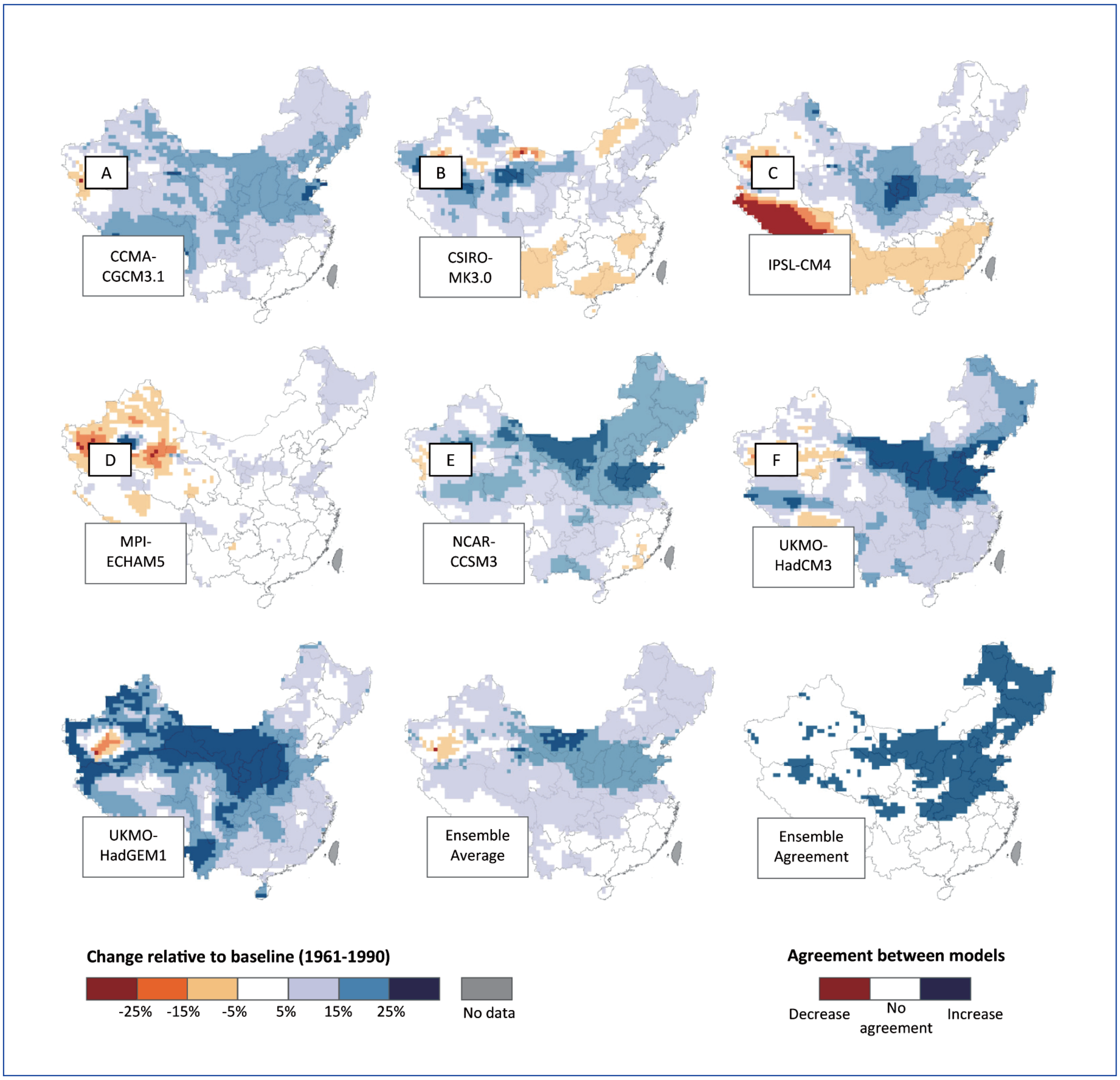
Along with rising demand for water, interannual variability in rainfall and the proportion of rainfall from short, intense storms is also projected to increase (Gao et al. 2012a, 2012b; Shi et al. 2010; NARCC 2011). More than three-quarters of the additional precipitation expected for the Northeast and the Yellow and Huai River basins is projected to come from days of heavy rain. As a result, the timing of flows would be less predictable, and runoff would be more difficult to capture and store. Such "lumpy" hydrology would also lead to higher concentrations of nonpoint source pollutants in surface waters, reducing the quality of water at intake points for water utilities.

In the Southwest and Northwest, the availability of freshwater will also be influenced by the accelerated melting of China's glaciers. China has more than 46,000 glaciers in the Himalaya, Nyainqêntanglha, Kunlun, Karakoram, and Tianshan mountain ranges (Wang and Liu 2001; Li et al. 2008). These glaciers provide a crucial supply for hundreds of millions of users in China and downstream countries (Erikkson et al. 2009; Xu et al. 2009). For example, meltwater accounts for 30–80 percent of water supply in the Tarim basin in the Northwest (NARCC 2011). More than 80 percent of China's glaciers have begun to retreat more quickly in recent decades (Yao et al. 2004), which has increased water supply in the short term. While higher temperatures are expected to increase the flow of glacial meltwater in the near term (and cause flooding), by mid to late century, the reduced size of glaciers, and the water they store, could cause shortages downstream (Eriksson et al. 2009; Xu et al. 2009). China's previous National Climate Change Assessment Report estimated that for a rise in average surface temperatures of 1.9–2.3°C, glacier coverage in the Northwest will shrink by 27 percent (NARCC 2007); by 2100, it is projected that glacier ice volumes could be 45 percent smaller (cited in Ni 2011). The rapid melting of glaciers and reduced snowmelt in alpine areas of the Southwest and Northwest is also associated with landslides, debris flows, flashfloods, and shifts in vegetation types dependent on meltwater. Taken together, the altered water balance, the loss of alpine wetlands, the destruction of permafrost, and the degradation of rangelands observed in parts of the Southwest and Northwest have profound implications for the agricultural and pastoral livelihoods of rural people (Sall and Brandon forthcoming; Xu et al. 2009; Erikkson et al. 2009).

Changes in seasonal precipitation along with temperature and potential evapotranspiration will play a pivotal role in the advance or retreat of deserts in arid and semi-arid parts of northern and northwestern China. Between the mid-1950s and the end of the 1990s, more desert area in China was revegetated than new desert was created (Wang et al. 2008). While there is substantial debate as to whether climate change or local resource use has had a greater influence in reversing desertification (Wang et al. 2008, 2009; Chen and Tang 2005; Su et al. 2006), it is clear that the climate has played at least some role. Since the 1980s spring precipitation has increased, wind erosion has lessened, and vegetation has anchored sand dunes in Northern and Northwestern China (Wang et al. 2008). Whether these trends will continue in the immediate future is unclear. In the longer term, researchers project that deserts in western and eastern China may begin to expand, while desertification in central China may be reversed.[11] Because the results of the global climate models (general circulation models, or GCMs) driving these projections are themselves driven by projected changes in precipitation, they suffer from the same uncertainty as the models mentioned above. Results should be interpreted with caution, especially because the models do not take into account changing land use patterns, population growth, or government policies that can improve or degrade vegetative cover in areas susceptible to desertification.

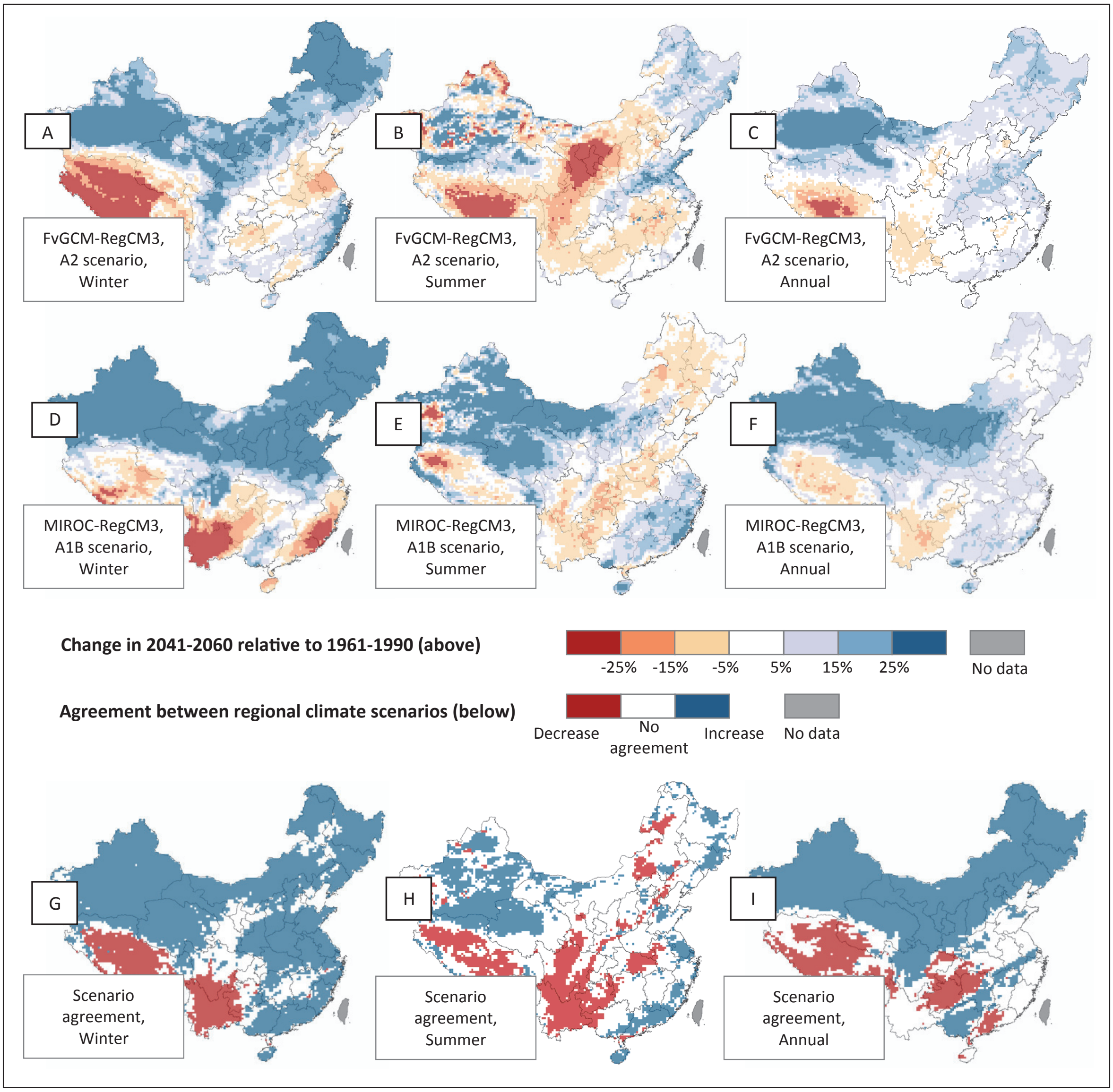
[11] Results are for the 2040s, as modeled by the ECHAM4 and HadCM3 global climate models under the IPCC SRES A1F1, A2a, A2b, A2c, B2a, and B2b scenarios. The parts of western China where desertification is generally expected to increase include the Taklimakan, Gurbantunggut, Kumutage, and Caldam deserts; the parts of eastern China where desertification is generally expected increase include the Horqin, Otindag, and Hulunbeir deserts. The parts of central China where desertification is generally expected to decrease include the BodainJaran, Tengger, Mu Us, and Hobq deserts (Wang et al. 2009).

Figure 3: Projected change in annual precipitation for 2041-2060 compared to baseline climate (1961-1990), as represented by seven downscaled global climate models



Notes and sources: created with data from global climate models included in the IPCC Fourth Assessment Report: CCMA-CGCM3.1(T47) (Flato 2005); CSIRO-MK3.0 (Gordon et al. 2002); IPSL-CM4 (Hourdinet al. 2006); MPI_ECHAM5 (Roeckneret al. 2003); NCAR-CCSM3 (Collins et al. 2004); UKMO-HadCM3 (Pope et al. 2000); and UKMO-HadGEM1 (Martin et al. 2004). Data were downscaled to resolution of 30 arc minutes using ClimGen statistical method (Osborn 2009), and obtained from the CCAFS GCM Data Portal (http://www.ccafs-climate.org/).

Figure 4: Projected changes in seasonal precipitation for the 2080s (2071-2100) compared to baseline climate in 1970s (1961-1990), under twodynamic regional climate model scenarios



Sources: FvGCM-RegCM3 results for high emissions scenario (A2), based on Gao X.J. et al. (2010 and 2011); MIROC-RegCM3results from Gao X.J. et al. (2012a and 2012b); data for both scenarios obtained from China Regional Climate Change Projection Data site (http://www.climatechange-data.cn/).

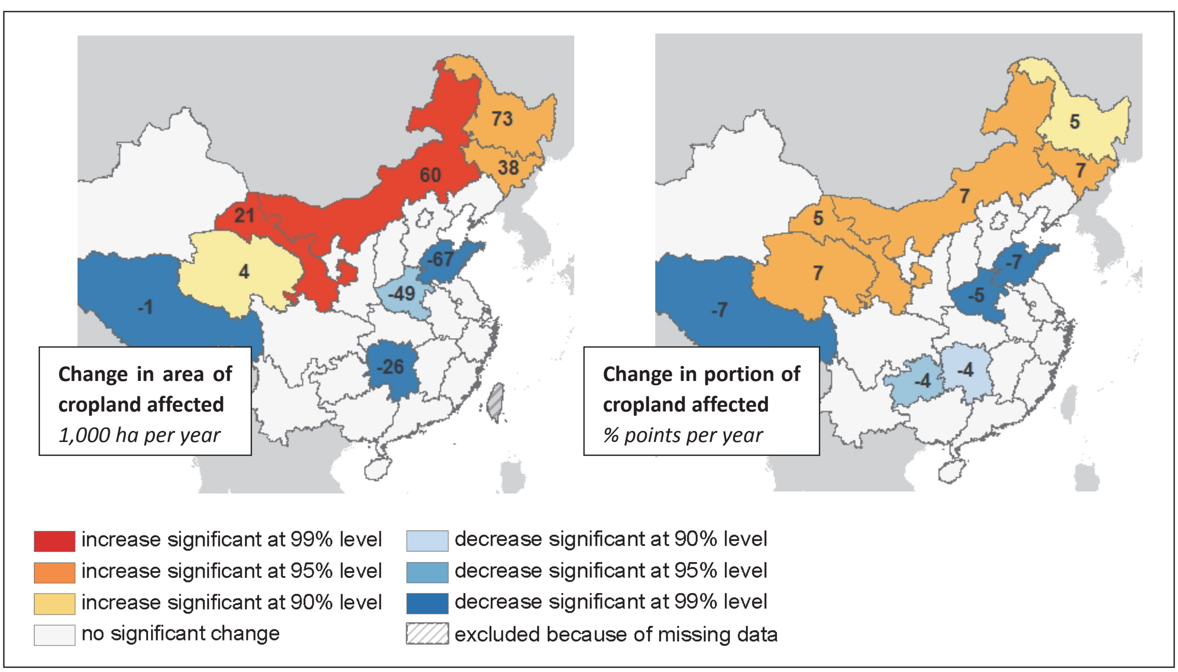
3. Drought

On average, droughts affected 25 million hectares each year from 1977 to 2008 (NBS 1996a, 1996b–2009b, 2007c–2011c, 2009d, 2010e). Direct economic losses from drought between 2006 and 2011 were particularly severe, averaging 115 billion yuan at 2011 prices (MWR 2006–2010; Xinhua 2012).

As precipitation and soil moisture in the Song, Liao, and Hai River basins has declined, data collected from China's network of weather monitoring stations reveal that the area affected by drought in these regions has expanded (Ma and Ren 2007; Zou, Ren, and Zhang 2010; Qian, Shan, and Zhu 2011; see also Zhai and Zou 2005). The exposure of the agricultural sector to drought in the provinces that form these water-stressed regions has also increased (see figure 5). The observed increase in exposure is due primarily to the fact that a larger area of land has been brought under cultivation.[12] There is no evidence that the intensity of drought has worsened (Qian 2011).

Beyond the dry lands of China's north, in recent years Yunnan, Guizhou, Guangxi, and Sichuan Provinces have also experienced a spate of bad droughts. The drought that hit the Southwest in the winter of 2009–2010, for instance, caused direct losses of 82.2 billion yuan in Yunnan and Guizhou (about 8 percent of their combined GDP in 2009), and left 23.3 million people and 16.3 million head of livestock facing severe water shortages (MWR 2010).

Figure 5: Trends in Exposure of Cropland to Drought, 1978-2009



Sources: Author, based on NBS 1996a, 1996b-2009b, 2007c-2011c, 2009d, 2010e

Notes: Tianjin and Hebei have been merged, as has Sichuan and Chongqing, for consistency across entire the timeframe. ha= hectare.

[12] Results are from author's calculations using sources cited for figure 5. Note that the increase could also reflect improved reporting in disaster losses over the years.

Droughts have ripple effects that proliferate across a range of sectors in China's entire economy, including the power sector. China uses about 120 billion m^3 of freshwater (20 percent of the country's total water use) every year for mining, processing, and burning coal (Han 2010; Dai and Cheng 2008). China's abundant coal reserves are located in some of the country's most water-poor areas, such as Inner Mongolia. Greater exposure to droughts in the coal mining belt thus adds to existing bottlenecks in the supply of coal for power production and industry. Even in the water-rich South, droughts have had a direct and significant impact on power production. The drought that hit southern China in the winter and spring of 2011, for example, lowered water levels in reservoirs and forced dam operators to cut back on electricity generation by as much as 48 percent in some provinces at a time when electricity demand from manufacturers in coastal areas was spiking (see He 2011; Wang T. 2011; Wang W. Z. 2011; Schneider 2011a, 2011b).

Droughts also amplify the risk of other extreme events such as forest fires. In Chongqing, for example, wildfires rarely occur during the summer monsoons. In the summer of 2006, however, Chongqing battled 158 separate incidents of forest fires, as the province was experiencing a one-in-100-year drought (Zhao et al 2009; see also Zhang forthcoming). The heightened risk of forest fire is especially severe in the years following severe storms because blown-down trees and other organic debris increase the amount of available fuel. Such changes in disturbance regimes affect the functioning of forest ecosystems and lead to reduced ecosystem services such as soil erosion control and flood regulation (Sall and Brandon forthcoming). The adverse effects of greater exposure to drought and fire on forests are especially evident for plantation forests, which lack diverse groups of species and show low levels of resilience. With additional warming and drying expected for parts of the Northeast, the spring and autumn fire seasons will grow longer, and fire danger is projected to rise (Tian et al. 2011; Cheng and Yan 2007).[13]

The incidence of drought is projected to increase in the North and Northeast (NARCC 2011). Using the RegCM3 regional climate model, Li Xinzhou and Liu Xiaodong (2012) project that warming and the northward shift of vegetation zones will lead to greater water demand from plants and worsening droughts in the Northwest, and the area affected by severe drought in this region will begin to trend upward by the 2040s.[14] By the end of the century, exposure to drought will grow increasingly significant. Similarly, McKinsey & Company (Woetzel et al. 2009) project that agricultural drought could worsen for most of the Northeast by the 2040s as warming becomes more pronounced and precipitation during the critical spring months decreases.[15] With warmer and drier

[13] In the United States, researchers have estimated that 1°C of warming is associated with a 200–400 percent increase in fire danger for the western states (NRC 2011).

[14] The upward trend is projected for low-(B1), medium- (A1B), and high- (A2) emission scenarios.

[15] Projections are based on the results of the PRECIS regional climate model, run under a high- (A2) emissions scenario.

conditions projected by the regional climate models for parts of the South, drought could also worsen in that region, especially during the dry winter months (NARCC 2011). By contrast, Zhao et al. (2011) project that the drying effect of increased evapotranspiration from crops in Tibet over the next 40 years will likely be outweighed by precipitation increases projected by the PRECIS model, and there will be fewer droughts. Note that these projections for drought are highly uncertain, and that there are large discrepancies in the results of the different GCMs used in the IPCC's Fourth Assessment Report to project changes in soil moisture associated with drought (Wang 2005; Seneviratne et al. 2010; see also IPCC 2012).

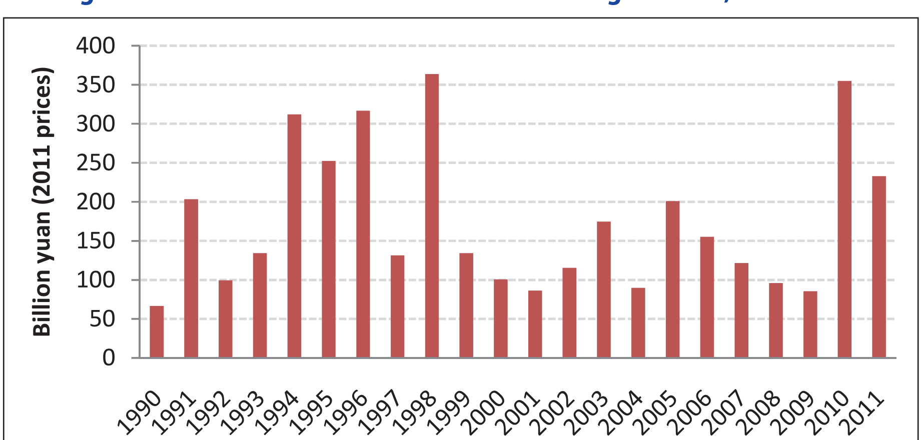
4. Floods

Floods affected about 10 million hectares each year between 1977 and 2008 (NBS 1996a, 1996b–2009b, 2007c–2011c, 2009d, 2010e). Since 1990, they have caused direct economic losses of 174 billion yuan annually (figure 6). These losses include damages to agriculture, forestry, aquaculture, transportation, water utilities, and other sectors.

Since 1978, the area of farmland inundated by floods in the upper Yangtze River basin, Tibetan Plateau, and parts of the Southhas shown a significant upward trend (figure 7).[16] Evidence suggests that variability in the climate contributed at least in part to this trend. Since the 1950s, there has been a slight but statistically significant increase in the observed frequency and intensity of heavy precipitation events for the Pearl River basinand parts of the upper Yangtze River basin (Chen, Chen, and Ren 2010). As days of extreme precipitation increased for the middle and lower reaches of the Yangtze, the share of intense storms in total precipitation also went up (NARCC 2011). With more rainfall from severe storms during the spring and summer, flooding events have been more frequent along the Yangtze since the 1970s (Renet al. 2008; Zhaiet al. 2005; NARCC 2007).

Intense rainfall, flooding, and other water-related hazards are particularly damaging to infrastructure assets. Erosion from such hazards shortens the life-span of road and rail networks and causes sudden drops in service levels (Ollivier forthcoming). Disruptions of transportation services in cities are exacerbated by poor drainage systems, many of which are inadequate to deal with current weather risks let alone with even more frequent or severe flooding events (Ollivier forthcoming; Jensen forthcoming). Floods and mudflows also have adverse impacts on hydropower reservoirs. As China's stock of infrastructure assets continues to grow at a rapid pace, greater exposure to floods and other water-related hazards could lead to higher life-cycle costs and more expensive investments.

Figure 6: Direct Economic Losses from Flooding in China, 1990-2011



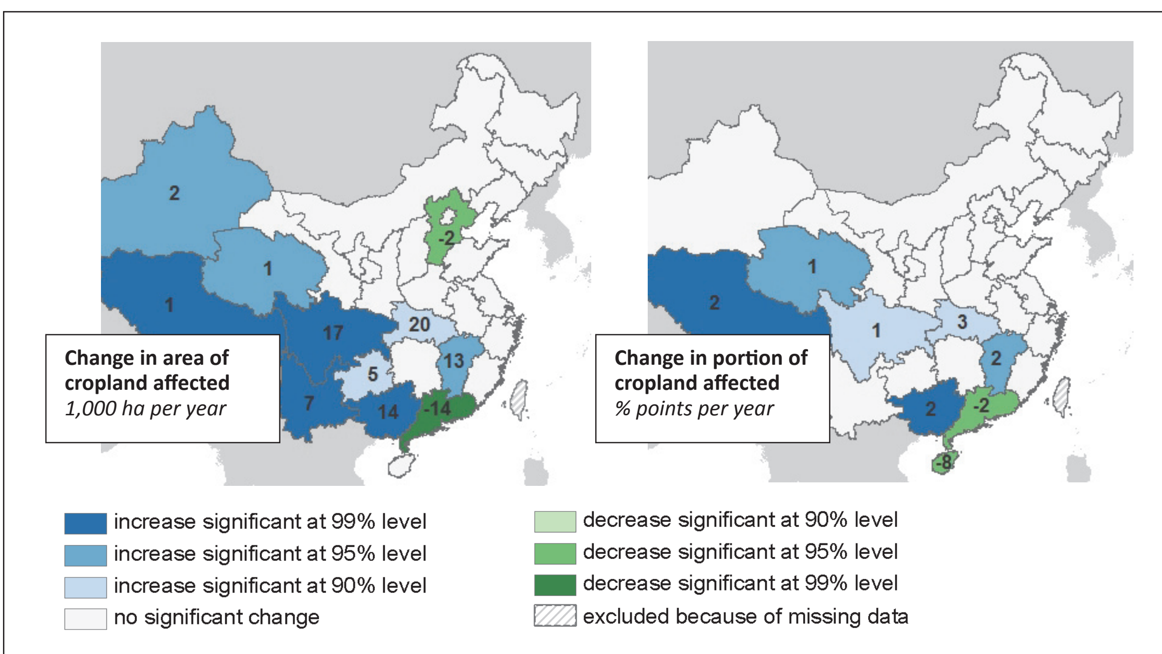
Sources: NBS 1996a; MWR 2006-2010; Xinhua 2012

[16] Results are from author's calculations using sources cited for figure 7. Note that the increase could also reflect improved reporting in disaster losses over the years.

With a doubling of preindustrial atmospheric concentrations of CO_2 by 2070, the number of rainy days in southern China is not expected to increase much, but precipitation is, meaning that more of southern China's precipitation will likely come from shorter, more intense storms (NARCC 2007). Under a high-emissions scenario (A2) and a RegCM3 regional model, it is projected that there will be a 10–50 percent increase in the number of days of heavy rain (days with more than 20 mm of rainfall) annually for the mid to lower Yangtze and the Pearl River basins by the 2080s (NARCC 2011). Similar results are obtained from the PRECIS regional model for a low-emissions scenario (B2) (Zhang et al. 2006). Along with increases in summer runoff for the central, southern, and eastern provinces, this increase in days of heavy rain could signal more flooding. Fujian, Jiangxi, Guizhou, Sichuan, and Yunnan Provinces are at greatest risk (NCCAR 2007; Zhai et al. 2009).

That said, floods are far from being purely "natural" disasters and are determined by a myriad of other nonclimate factorssuch as upstream land use and erosion, the construction of dams and other infrastructure in river channels, the health of water-retaining ecosystems such as forests and wetlands, and encroachment on floodplains. Because of the intricate link between floods and future societal choices, it is unclear how exactly the risk of flooding for China's different regions will be altered by projected shifts in precipitation patterns.

Figure 7: Trends in Exposure of Cropland to Flooding, 1978-2009



Sources: Author, based on NBS 1996a, 1996b-2009b, 2007c-2011c, 2009d, 2010e

Notes: Tianjin and Hebei have been merged, as have Sichuan and Chongqing, for consistency across the entire timeframe. ha= hectare.

5. Tropical Cyclones

Both the frequency of tropical cyclones affecting China and the rainfall brought by these storms have decreased over the past 50 years. Yet their destructive force has grown, as indicated by higher maximum wind speeds and lower barometric pressure in storm centers (NARCC 2011; Ren et al. 2006; Lei, Xu, and Ren 2009). The number of residents affected by tropical cyclones and storm surges has increased, as more people have migrated from the interior provinces to the coastal areas in the East and South. As a result of rapid economic development, economic losses caused by tropical storms of the same intensity have also shown a significant upward trend (NARCC 2007). Direct economic losses from tropical cyclones averaged 0.38 percent of China's GDP for the years from 1983 to 2006. Although Guangdong is hit most frequently by tropical cyclones, Zhejiang typically experiences the heaviest losses. Together, four provinces (Zhejiang, Fujian, Guangdong, and Hainan) account for nearly two-thirds of total damages from tropical cyclones suffered in China each year (Zhang, Wu, and Liu 2009). Table 1 presents information on the 10 costliest tropical cyclones in China between 1983 and 2006.

The IPCC's assessment is that globally, tropical cyclone wind speeds will "likely" increase, while the frequency of tropical cyclones will "likely" decrease or show no change (IPCC 2012). Many researchers agree that future warming is likely to lead to greater storm intensities and destructive potential (Emanuel 2005; Emanuel, Sundararajan, and Williams 2008; Tracy, Trumbull, and Loh 2006). Others, however, claim that typhoons affecting China will likely become more frequent but less powerful (see Zhao and Jiang 2010). According to analysis done for the World Bank of potential damages from typhoon winds under four different climate scenarios, annual losses in Fujian and Guangdong Provinces are expected to increase 1 billion to 2 billion yuan over 2011 levels by the end of this century (2081–2100), assuming that today's level of development in those provinces remains constant and the value of assets exposed to storms does not increase (Katz and Kaheil 2012). Increased wind damage in these provinces is primarily the result of more typhoons making landfall each year. A slight increase in wind speeds for the strongest typhoons is expected for Hainan and Zhejiang. By comparison, taking into account higher levels of development (and thus greater exposure of assets to storms), Mendelsohn et al. (2012) estimate that economic losses from tropical cyclones in East Asia will grow by more than a factor of three between 1981–2000 and 2081–2100, even in the absence of climate change.

Table 1: China's Ten CostliestTropical Cyclones, 1983-2006

Name and number	Year	Areasworst affected	Direct Losses (Billion RMB)
Herb (No. 9608)	1996	Fujian, Taiwan	90.05
Winnie (No. 9711)	1997	Zhejiang	59.70
Bilis (No. 0604)	2006	Fujian, Zhejiang	42.80
Sally (No. 9615)	1996	Guangdong	30.16
Fred (No. 9417)	1994	Zhejiang	29.50
Rananim (No. 0414)	2004	Zhejiang	26.34
Saomai (No. 0608)	2006	Fujian, Zhejiang	24.15
Utor (No. 0104)	2001	Guangdong	23.81
Matsa (No. 0509)	2005	Zhejiang	22.74
Tim (No. 9406)	1994	Fujian, Guangdong	22.03

Source: Zhang Q. et al 2009
Notes: Year 2010 prices.

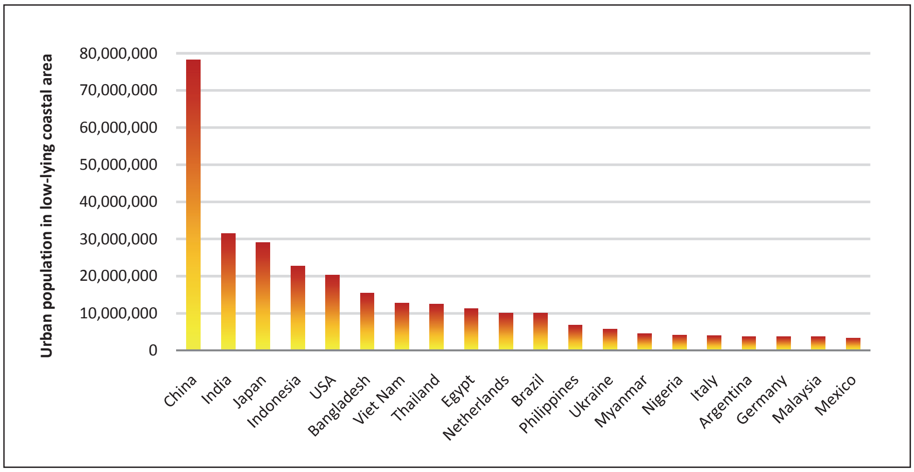
6. Sea-level Rise

China's coastal areas account for only 16.8 percent of the country's total territory and contribute 72.5 percent of the national GDP (Chen 1997; NBS 2000c). Low-lying coastal zones are the most economically developed areas of China. They are also the most heavily populated; an estimated 80 million people live in coastalcities exposed to sea-level rise and storm surges (figure 8).

China's coastal sea level has increased at an average rate of 2.5 mm per year during the past 50 years, higher than the global average of 1–2 mm per year. Local rates of sea-level changes vary considerably, and have been much higher in coastal cities that are sinking due to the weight of construction and overwithdrawals of groundwater. By 2005, more than 90 Chinese cities were affected by land subsidence. Central parts of Shanghai have sunk by more than 2 m since the 1920s. Direct and indirect losses attributed to land subsidence in Shanghai from the 1950s to the early 2000s totaled 290 billion yuan. Losses have also been substantial in Tianjin, parts of which have subsided by more than 3 m since the 1920s (Li et al. 2004; Xu et al. 2008; Yin, Zhang, and Li 2006).

China's State Oceanic Administration projects that by the end of the 2030s, sea level along China's southern and eastern coasts will have risen 8–13 cm over 2010 levels (SOA 2010). Rising seas and increased exposure to storm surges and tidal flooding present a significant risk to coastal infrastructure. The *Second National Assessment Report on Climate Change* projects that by 2030 standards for seawall construction will require heights 40 percent above current standards to project against one-in-100-year events. If seawalls are not elevated above today's standards, then by the 2080s, around 18,000 km^2 of land in China's heavily populated deltas could be inundated by higher seas (NARCC 2011). With additional sea-level rise, saltwater will continue to intrude on groundwater resources in coastal areas, putting greater pressure on the supply of freshwater and potentially requiring investment in more expensive solutions such as desalination (Jensen forthcoming). Additional sea-level rise may also compromise the operational and environmental safety of nuclear power plants constructed in coastal areas. "Green" infrastructure such as coastal mangroves, wetlands, coral reefs, and sand dunes can help reduce the need for higher and more expensive hard defenses. Internationally, there is growing evidence that protecting natural ecosystems is a cost-effective solution for reducing climate risks (Sall and Brandon forthcoming; World Bank 2009).

Figure 8: Vulnerability of Population to Sea-level Rise and Storm Surges, Top 20 Countries



Source: McGranahan, Balk, and Anderson 2007

Note: A "low-lying coastal area" is defined as "the contiguous area along the coast that is less than 10 meters above sea level."

7. Conclusions

The growing body of scientific evidence shows that China's climate is indeed changing, especially when climate is viewed at the regional level. Temperatures are rising, precipitation regimes are changing, and shifts have occurred in the distribution of extreme weather events. Changes vary remarkably from one region to the next, but the effects of more frequent extreme weather events and other long-term changes cut across the whole of China's economy.

One of the biggest knowledge gaps facing both scientists and policy makers is how the impacts of climate change will be amplified or moderated by China's future development. While the unpredictability of distant trends in China's economy and society adds to the uncertainty of climate change, it also points to the important role of government action. Effective policies and investments to manage risks are imperative for reducing the sensitivity and increasing the resilience of the country to climate change. The other papers in the series pick up on this challenge by providing a framework for assessing risks and choosing appropriate policies and investments for specific sectors.

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