



THE WATER CYCLE IN A CHANGING CLIMATE

Millions of people across the globe are already affected by natural variability in the water cycle. A multidisciplinary team of experts from the University of East Anglia and the University of Nottingham, led by Timothy Osborn, Professor of Climate Science at the world-renowned Climatic Research Unit, set out the empirical evidence - and argue the need for implementation of measured adaptation mechanisms that take into account uncertainties in the projection of future precipitation patterns.

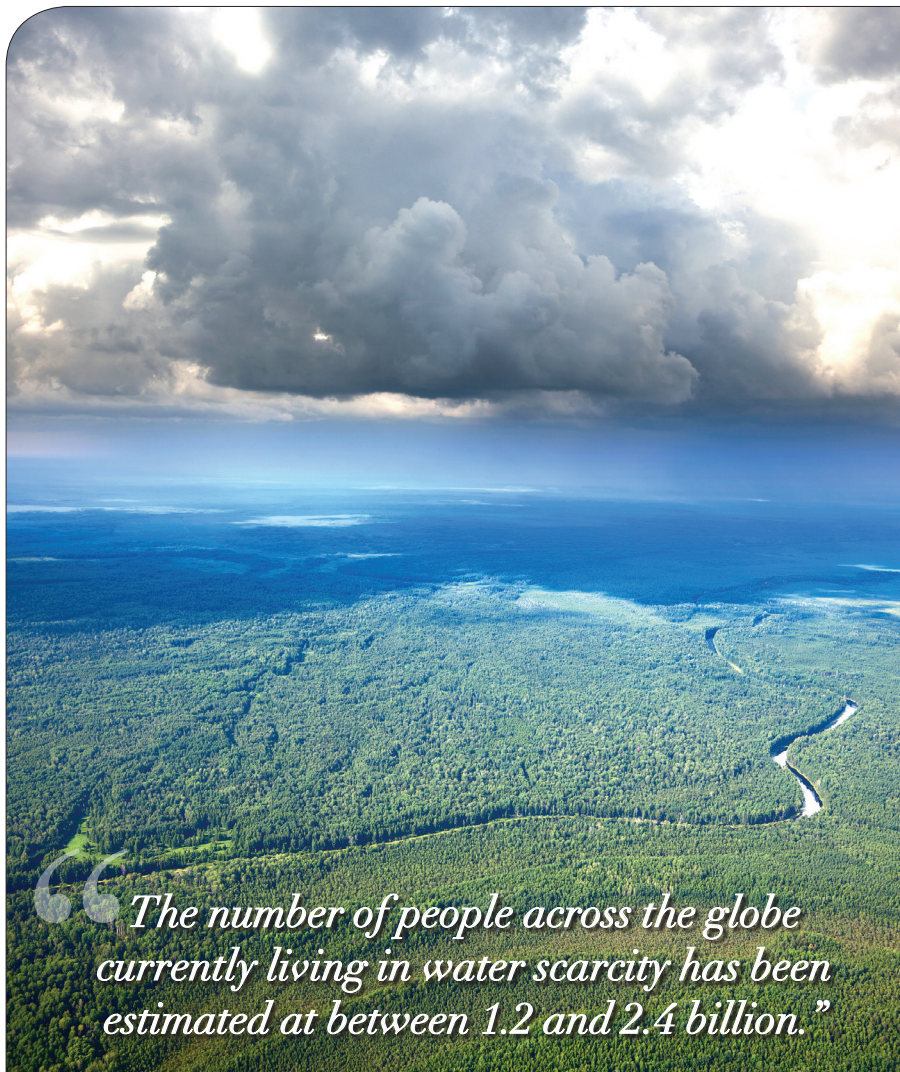
EARTH'S FRESHWATER IS distributed unevenly – spatially, day by day, through the changing seasons, and between dry and wet periods lasting years to decades. Climate change, though still very uncertain in its regional details, will have a tendency to exacerbate this unevenness, drying some already arid regions, wetting some humid regions, enhancing seasonality in many areas, and concentrating rainfall into shorter but more intense spells. As a result, projections of future changes in climate and the hydrological cycle indicate that the population exposed to hydrological risks will increase significantly during the 21st century, though slowing climate change through reductions in greenhouse gas emissions could reduce this risk.

Climate and water: tightly coupled partners

Climate change occurs due to disturbances to the Earth's energy budget, driven particularly by natural and, more recently, human-related variations in greenhouse gases (GHGs) such as CO₂. The response of our climate to such changes is through

a complex mixture of mechanisms in which the hydrological cycle plays a central role – transporting heat energy (through evapotranspiration followed by condensation) from surface to atmosphere and from tropics to poles, affecting absorption and reflection of radiation by the influence of clouds and the water vapour content. Indeed, water vapour is the strongest component of the natural greenhouse effect, yet unlike other GHGs it condenses and rains out of the atmosphere at only moderately low temperatures [Lacis et al., 2010]¹. Thus the amount of water vapour depends strongly on how warm the air is: the atmospheric water vapour concentration is enhanced because CO₂ keeps the atmosphere naturally warm – and increased CO₂ will warm the atmosphere further, allowing increased water vapour to further strengthen the total greenhouse warming effect. This intertwining of the hydrological cycle and the Earth's energy budget means the hydrological cycle is both modified by climate change and interacts with it to shape all aspects of climate change.





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Water in our current climate

Water evaporated from the oceans is carried by the atmosphere away from the subtropics (where evaporation peaks) both equatorward and to the mid latitudes, though also over subtropical land regions during summer monsoons. This transport, combined with the uplift of moist air flows by mountains or over warm land surfaces, and the recycling of water evaporated and transpired from the land surface, determines the complex pattern of land precipitation (Figure 1). It is usually uneconomic to transport water over long distances, so the development

of agriculture, industry and society has been shaped by this distribution of water resources.

The reliability of precipitation is also key, and many regions exhibit large seasonal and interannual variability. Water storage and other adaptations provide some resilience to these large variations, but additional measures and infrastructure may be needed, especially where climate change is expected to alter average rainfall or its variability. The natural infrastructure of geological aquifers plays a key role here, but recent assessments [Gleeson et al., 2012]² have highlighted that many aquifers are being unsustainably exploited, with annual abstractions exceeding the renewable groundwater resources by more than tenfold in some instances (Figure 2).

The number of people across the globe



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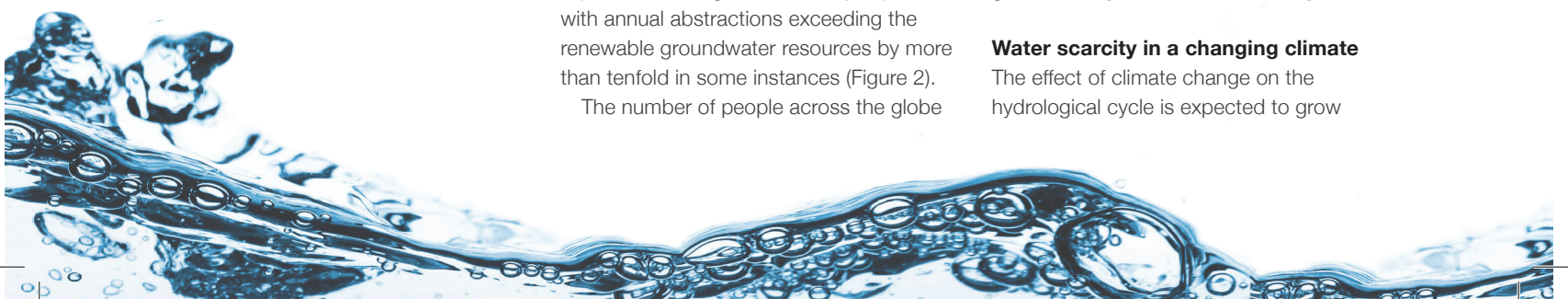
currently living in water scarcity has been estimated at between 1.2 and 2.4 billion (Gosling and Arnell, 2013)³, with the wide range arising because the measure of scarcity differs between studies. Figure 2 shows regions of high Water Stress Index.

Natural climate variability

Despite the high profile given to climate change driven by increasing GHGs, it is the natural and mostly unpredictable variations in our weather and climate which will dominate the hydrological cycle in the coming decade or two. This is especially the case when considering local scales, where rainfall variability is large compared with the expected climate change signal [Hawkins and Sutton, 2011]⁴. Nevertheless, the underlying climate change signal is expected to grow and may be felt most where it alters the frequency of extreme events such as droughts and floods. There is indeed some evidence for increased precipitation extremes in recent decades, though not in all regions and our observing networks are not sufficient to provide a global picture [Hegerl et al., 2014]⁵. Natural variability, especially related to the El Niño–Southern Oscillation (ENSO) phenomenon, has so far prevented the identification of any clear trend in drought occurrence at the global scale [Trenberth et al., 2014]⁶.

Water scarcity in a changing climate

The effect of climate change on the hydrological cycle is expected to grow



as we look further ahead, with increased precipitation projected at mid to high latitudes and drying on the poleward side (e.g. the Mediterranean) of the already dry subtropical regions. Changes in the equatorial and monsoon regions are very uncertain, with some climate models projecting drying in some regions and other models projecting increased precipitation, and vice versa elsewhere. This uncertainty should not be equated with an assumption of little change: on the contrary the changes in precipitation could be very large, perhaps leading to changes in average streamflow of more than $\pm 30\%$. But there is more to consider than simply changes in average climate. The vertical gradient, up through the troposphere, is expected to weaken in temperature but strengthen in water vapour, especially in the tropics. The former may stabilise the atmosphere and make convection less frequent, while the latter would intensify convection when it does occur [Hegerl et al., 2014]⁵. This combination of less frequent but more intense rainfall is a robust prediction of how the hydrological cycle will change, and coupled with increased potential evapotranspiration (PET) resulting from warmer temperatures, may lead to widespread decreases in soil moisture during the growing season and thus an increased risk of agricultural drought [Jiménez Cisneros et al., 2014]⁷.

Over the past decade, assessments of how water scarcity might change under different socio-economic pathways and emissions scenarios have increased in number, and they have become more comprehensive by coupling multiple climate models and hydrological models. There is considerable uncertainty in the regional patterns of change (Figure 3), but nevertheless strong scientific agreement that increasing GHG emissions will adversely affect water security at the global-scale and especially in most dry subtropical regions due to an

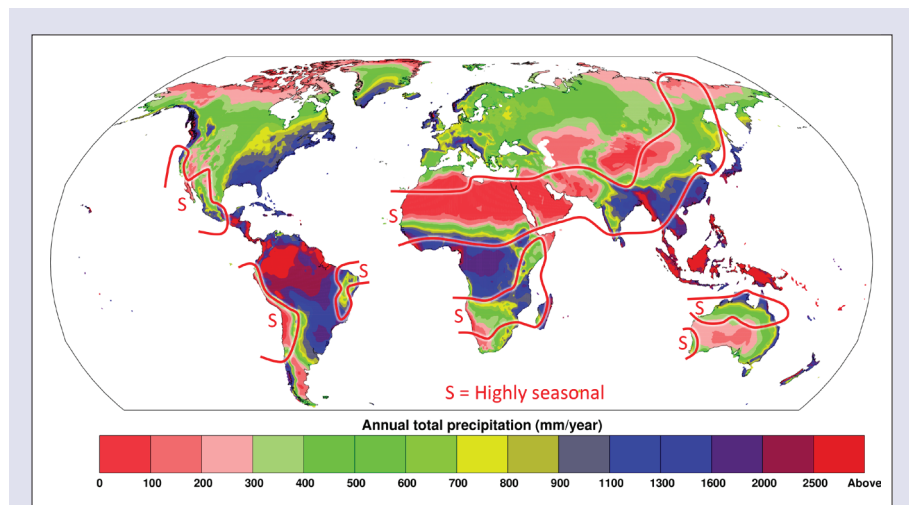


Figure 1. Climatology of annual total precipitation, also highlighting areas where precipitation is highly seasonal (defined here as regions where half the annual total falls in three months or less).

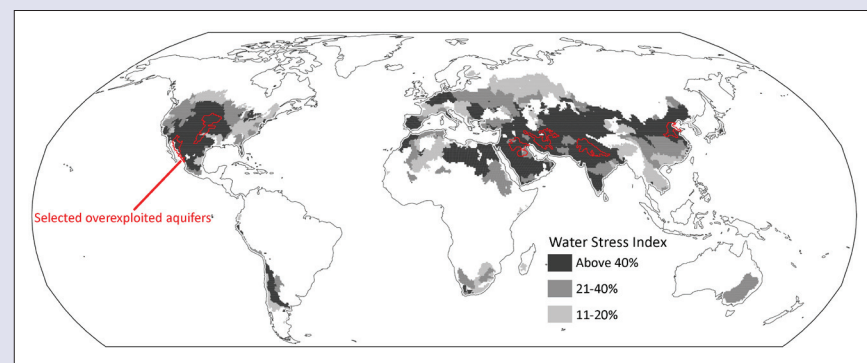


Figure 2. Areas of present-day water stress (grey shading) and six aquifers where groundwater resources are under particular pressure (red outlines). Water Stress Index is the percentage of total water resource that is being withdrawn for human use, estimated using population in year 2000 (11-20% light grey; 21-40% medium grey; above 40% dark grey)³. Highlighted aquifers all have annual abstractions between 8 and 54 times the renewable groundwater resource.

increase in variability of precipitation and surface runoff [Gerten et al., 2013⁸; Arnell et al., 2013⁹]. Schewe et al. (2014)¹⁰ estimated that about 8% of the global population would see a severe reduction in water resources with even a relatively modest global warming of 1 °C above present day, rising to 14% at 2°C and 17% at 3°C.

Change in groundwater recharge and storage will reflect the regional interplay

of future precipitation, runoff and PET. Simulations using the latest climate projections [Collins et al., 2013]¹¹ indicate recharge and storage volume increases in the northern mid-to-high-latitudes but a mixed pattern of decreases and limited increases in lower latitudes. Although increases are projected in parts of agriculturally-intensive eastern China and India, climate projections for these areas are very uncertain and groundwater withdrawal already greatly exceeds recharge in some significant aquifers (Figure 2) such as the North China Plain and Upper



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Ganges (Gleeson et al., 2012)². It might appear beneficial to increase groundwater withdrawals in response to increases in river flow variability under climate change but this is only sustainable where groundwater withdrawals remain well below groundwater recharge (Kundzewicz and Döll, 2009)¹². Moreover, groundwater would not offset declines in surface freshwater availability in regions where groundwater recharge decreases due to climate change. Portmann et al. (2013)¹³ predict that for each degree of global temperature rise, an additional 4% of the global land area would experience at least 30% decrease in groundwater resources.

A more variable future?

Assessments with multiple climate and hydrological models indicate that fluvial flood hazard could increase over about half of the globe by the end of the century but there is high variability at the catchment scale and the *magnitude* of projected changes varies strongly between climate models (Dankers et al., 2014^{14.1}; Hirabayashi et al., 2013^{14.2}; Arnell and Gosling, 2014^{14.3}). The *direction* of change is more certain, however, for increases in flood frequency in Southeast Asia, Peninsular India, eastern Africa and the northern half of the Andes (Hirabayashi et al., 2013)^{14.2}. Approximately 600 million people currently live in flood-prone areas, yet few studies have incorporated data on

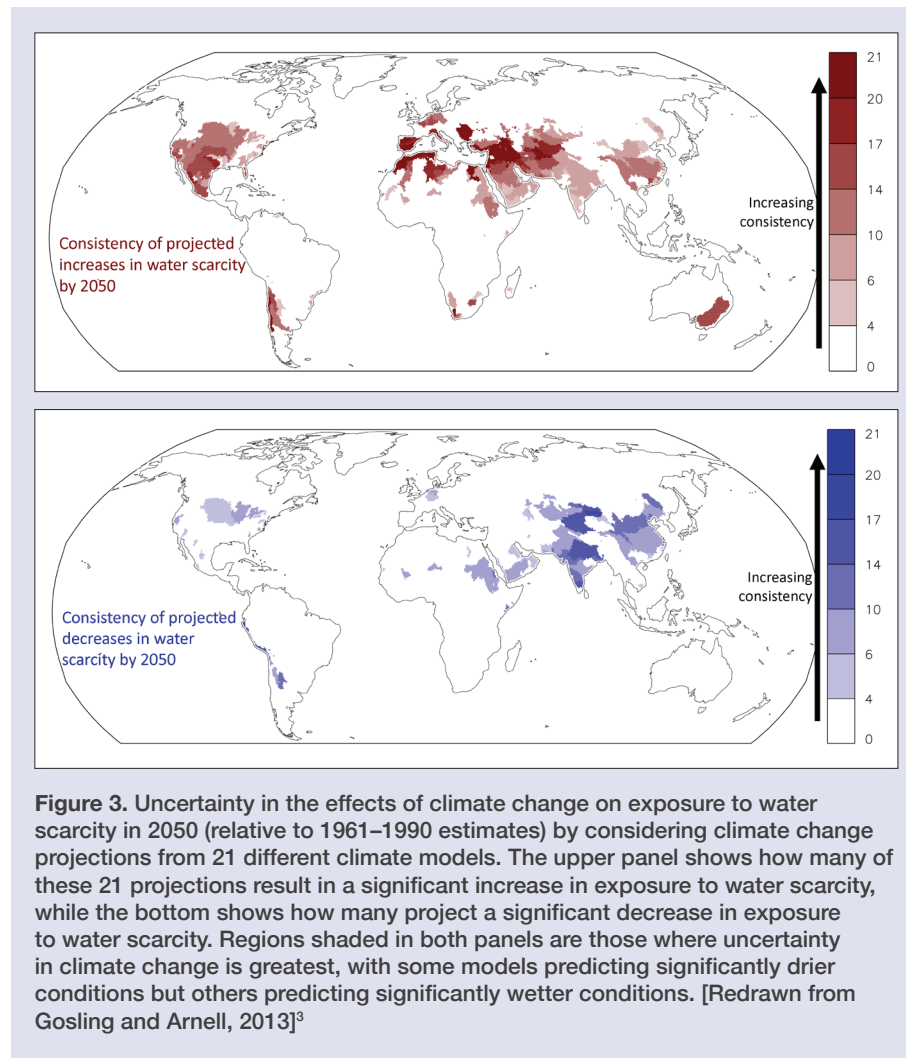


Figure 3. Uncertainty in the effects of climate change on exposure to water scarcity in 2050 (relative to 1961–1990 estimates) by considering climate change projections from 21 different climate models. The upper panel shows how many of these 21 projections result in a significant increase in exposure to water scarcity, while the bottom shows how many project a significant decrease in exposure to water scarcity. Regions shaded in both panels are those where uncertainty in climate change is greatest, with some models predicting significantly drier conditions but others predicting significantly wetter conditions. [Redrawn from Gosling and Arnell, 2013]³

flood-prone populations and infrastructure to quantify global-scale fluvial flood risk. An initial assessment (Arnell and Gosling, 2014)^{14.3} suggests that by 2050 between 31 and 450 million people may experience an increase in exposure to flood hazard, with the large range reflecting our uncertainty in future precipitation changes.

Closing remarks

Millions of people across the globe are already affected by natural variability in the water cycle. In some regions, an increasing population and climate change will combine to exacerbate issues such as water scarcity and flood risk. This points towards a need for the implementation of measured adaptation mechanisms that take into account uncertainties in the projections of future precipitation patterns. While climate change presents opportunities for

some regions (e.g. lowering water scarcity), such opportunities may only be realised if infrastructure is in place to manage water resources appropriately.



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Acknowledgements

Preparation of this paper was supported by the EU HELIX project (603864), the Belmont Forum SAHEWS project (NERC NE/L008785/1) and a NERC Impact Accelerator Award.

Author contributions

All authors contributed to the writing of the paper.

About University of East Anglia

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