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THE GLOBAL MONSOON SYSTEMS

Monsoon rainfall is the life-blood of more than half the world's population, for whom agriculture is the main source of subsistence. Extensive research is being conducted to increase our understanding of monsoon predictability, improve the accuracy of predictions, and refine projections of the impact of man-made climate change on monsoonal systems worldwide. This has the potential to provide significant socio-economic returns by maximizing the benefits of monsoon rainfall and reducing the impact of extreme events such as those witnessed during the northern hemisphere summer monsoon of 2010 in Pakistan, China, and India, and the southern hemisphere summer monsoon of 2011 in Australia.

OVERVIEW

Traditionally, the terminology "monsoon" was used for climate that has an apparent seasonal shift of prevailing winds between winter and summer, notably in tropical Asia, Australia, Africa, and the Indian Ocean. The term also increasingly refers to regions where there is a clear alternation between winter dry and summer rainy seasons. According to this definition, the monsoon region is distributed globally over all tropical continents, and in the tropical oceans in the western North Pacific, eastern North Pacific, and the southern Indian Ocean. Monsoon systems represent the dominant variation in the climate of the tropics with profound local, regional, and global impacts. Figure 1 shows the approximate location of

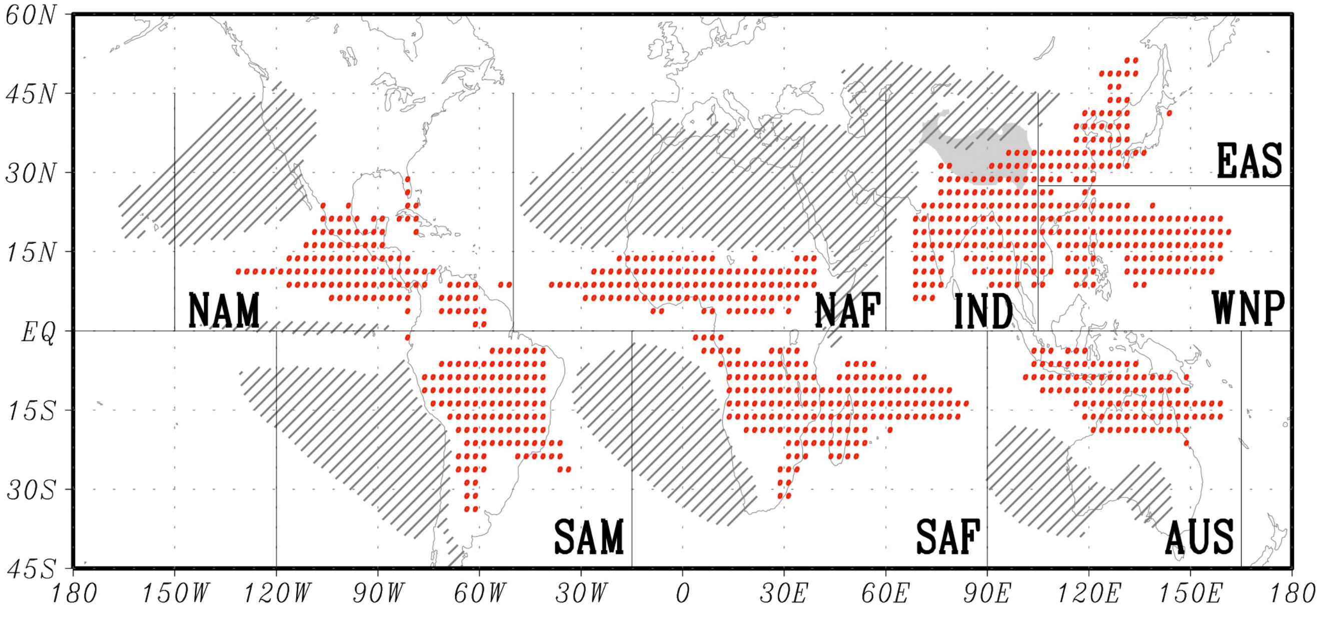


Figure 1: The approximate global monsoon precipitation domain is here defined where the local summer-minus-winter precipitation rate exceeds 2.5 mm/day and the local summer precipitation exceeds 55 % of the annual total (in red). During any individual year, it is possible for the monsoon to affect a broader area than shown here. Summer denotes May through September for the northern hemisphere and November through March for the southern hemisphere. The dry regions, where the local summer precipitation is less than 1 mm/day are hatched, and the 3000m height contour surrounding Tibetan Plateau is shaded. The merged Global Precipitation Climatology Project/Climate Prediction Center Merged Analysis of Precipitation precipitation data were used. These observations are based on rain gauge data over land and satellite data over the oceans. The regional monsoons are the North American monsoon (NAM), North African monsoon (NAF), Indian monsoon (IND), East Asian monsoon (EAS), Western North Pacific monsoon (WNP), South American monsoon (SAM), South African monsoon (SAF), and the Australian monsoon (AUS). This figure kindly provided by Prof. Bin Wang.

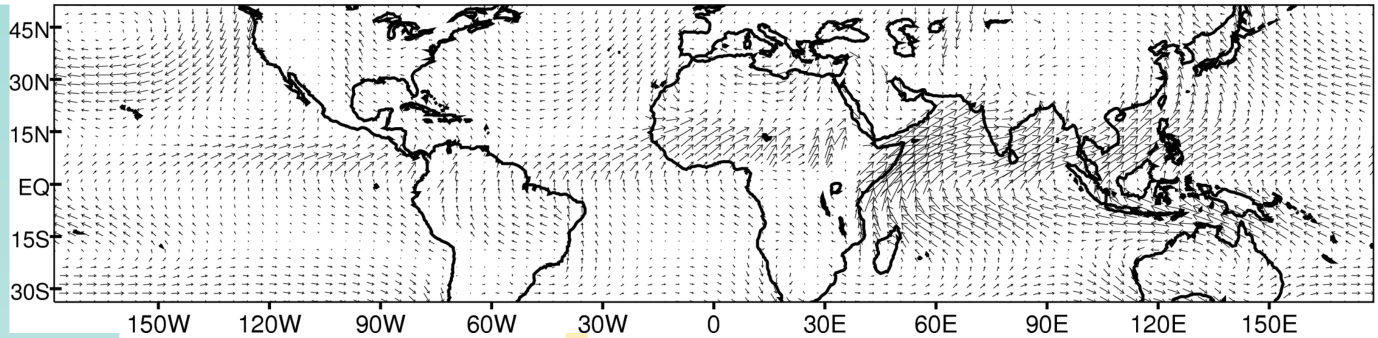


Figure 2: Seasonal change in lower tropospheric wind (925hPa) over the tropical monsoon regions (JJA minus DJF). Note the obvious reversal from north-easterly to south-westerly winds near West Africa and India from northern hemisphere winter to summer in the observations. This data is from the European Centre for Medium-Range Weather Forecasts 40-year Reanalysis project. This figure kindly provided by Dr. Andy Turner.

the monsoons across the globe. Over half of the globe's population, most in developing countries, live under the influence of monsoon-dominated climates. Their culture and lifestyle have evolved around its cyclical nature, and agriculture is still the most common form of land use in most of these regions. The dependency of the agricultural sector on monsoonal rains - particularly in countries with poor infrastructure and increased urbanisation - results in societies that are highly vulnerable to variability in monsoonal characteristics, such as onset and termination dates, total rainfall amounts, and rainfall intensities.

The fundamental driver of all the monsoon systems is solar heating of the land during the spring season that helps to establish a land-sea temperature difference. This contrast, with the land being warmer than the surrounding ocean, triggers a low-level flow of moisture from nearby oceans, and this moisture is rained out during convection over monsoonal regions. As the monsoon season matures during summer, latent heat released by convection high above the land surface helps to pull in additional moisture, maintaining the wet season. Due to the change of seasons the peak solar heating moves equatorward and then into the Southern Hemisphere, thereby heating the adjacent ocean more than the Asian land region. As a consequence the winds reverse direction (Figure 2), and the monsoon rainfall moves to the opposite hemisphere during the Austral summer.

MONSOON VARIABILITY , PREDICTABILITY AND SOCIETAL IMPACTS

Monsoon systems are reliable from year to year as a result of the seasonal heating of the land. Indian monsoon rainfall is especially reliable, with the typical deviation being about 10% of the average, due in part to the presence of the Himalaya/Tibetan Plateau that forces moist air upward, which then condenses out as rainfall. Nonetheless, even relatively small percentage variations, when set against large seasonal rainfall totals, can have a dramatic impact. The dominant driver of Asian-Australian monsoon changes from year to year is El Niño warming and La Niña cooling in the equatorial Pacific Ocean. For example, El Niño during 2002 significantly contributed to the failed monsoon that year, thereby resulting in the largest ever decline in Asian (and worldwide) annual rice production. More recently in 2009, El Niño resulted in a late onset of the monsoon and a patchy progression of the rainy season over India, while in 2010 (a La Niña year) Pakistan and China suffered severe floods. The impacts of El Niño and La Niña on the monsoon are potentially predictable because the sea surface temperature changes associated with them are slow and are themselves predictable to some extent. Even so, seasonal predictions of the Asian-Australian Monsoon remain very difficult, especially over land during the northern hemisphere summer.

Other important influences, which need to be considered for monsoon prediction on yearly time scales, include the Indian Ocean Dipole – a coupled ocean and atmospheric phenomenon over the Indian Ocean, and Atlantic Ocean sea surface temperatures. On longer time scales, monsoon variability may be influenced by large-scale variability in the atmosphere and oceans, such the Pacific Decadal Oscillation which affects sea-surface temperature and circulation over much of the Northern Hemisphere Pacific Ocean.

A prominent feature of the monsoon, and one which is most felt by society, is its variation within a season, known colloquially as active-break cycles. These intraseasonal variations occur with a typical period between active phases of between 20 and 50 days. During the active phase copious rainfall occurs, while during the break phase little or no rainfall occurs. The Indian/Asian monsoon can, in fact, be viewed as a series of active-break cycles, which often originate over the equatorial Indian Ocean that spread polewards over land and eastward over the tropical ocean. Prediction of the intraseasonal rainfall variations is of prime importance as these variations can have dramatic impacts, affecting the timing of crop planting and crop selection, and the management of water resources in the affected regions. The prediction of active-break cycles has been improved in recent years, with skill for up to 20 days in advance using weather forecast models, though many challenges remain.

To reduce the risks and maximize the benefits to society from monsoon variations within a season and from one year to the next, a three-pronged approach is required that includes: a) targeted infrastructure investment programs that help protect people and economies against floods and droughts, b) ongoing investment in research to develop risk management tools for monsoons variations, and c) improved prediction of monsoon variations to underpin investments in the first two areas. It is the latter approach that we focus on now.

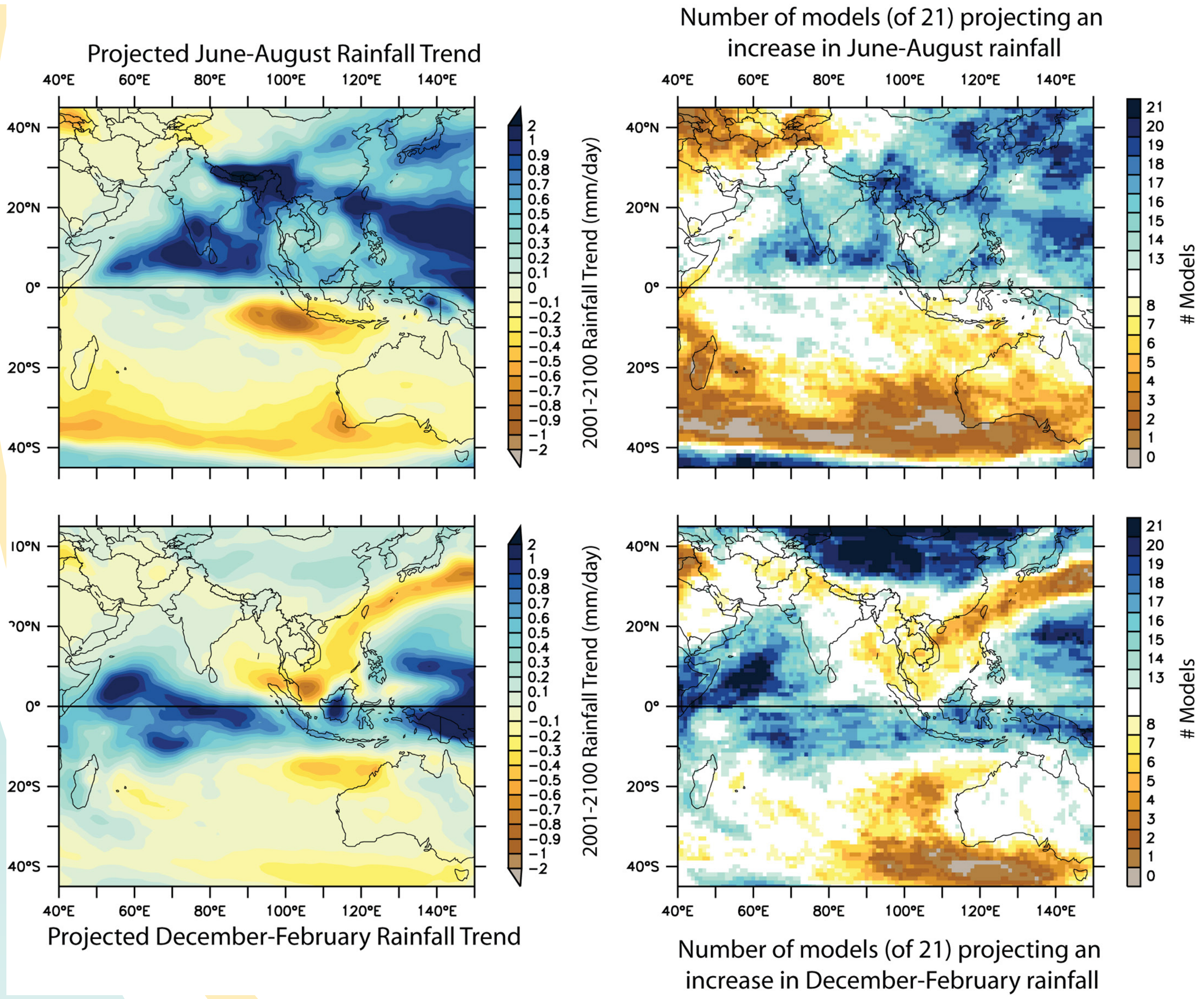
MONSOON MODELING AND CLIMATE CHANGE PROJECTIONS

Over the past few decades we have improved the representation of the monsoon in the numerical models that we use to make weather predictions and that we use to understand longer-term variations, including the possible influence of human-induced climate change. Numerical models, which are typically run on super-computers, are mathematical representations of the atmosphere-sea-land-ice system. Approximately 25 modeling centers worldwide participate in coordinated model experiments to investigate climate change. Because of the diverse complexity of the representation of physical processes among the individual models (e.g., convection, cloud microphysics, land-surface processes, etc.), and due to the scope of forcing that a model may or may not include (e.g., aerosols, ozone, volcanoes, etc.) there is uncertainty in the projections of future climate change by these models. Though scientific challenges remain in the development of improved models and in representing monsoons in numerical models, future climate projections based on the Third Coupled Model Intercomparison Project (CMIP-3) simulations suggest that human-induced climate change will result in increased monsoon precipitation over India, East Asia, and the western Pacific Ocean during June-August. This is seen in the top panels of Figure 3, which show the predicted rainfall trend across all models (left panel), and the number of models that have increased rainfall (right panel). The lower two panels of Figure 3 also indicate increased rainfall over the equatorial regions in December-February during the Southern Hemisphere summer monsoon. Although there is some indication of increased rainfall over Australia, the agreement of these climate change responses among the participating models is not high, and thus we have little confidence that this signal is robust in these simulations. Additionally, most models suggest that average monthly rainfall will become more variable from year to year (not shown), with intensifying extremes of excess and deficient monsoons. It is also suggested that there will be more frequent and more intense rainfall (e.g. →50 mm day^{-1}).

SCIENTIFIC CHALLENGES

Understanding the monsoon involves the study of all aspects of the physical climate system (i.e., atmosphere, ocean, land, and cryosphere), including the role of man-made influences on that system. Of the afore-mentioned physical processes and forcings that give rise to simulation uncertainty, improved convection and aerosol modeling are of primary concern. The goal of producing more reliable models and reducing the uncertainty in their climate change projections is fostered by international field experiments. For example, observational campaigns, such as the World Climate Research Programme sponsored Asian Monsoon Years (AMY 2007-2012) and the GEWEX/CEOP (Global Energy and Water Cycle Experiment/Coordinated Energy and Water Cycle Observations project) have archived both in-situ and satellite data to provide a continuous record of observations that are being used to improve model physics and understand interactions that affect monsoon variability. Additionally, new observational and modeling campaigns, such as DYNAMO (Dynamics of the Madden-Julian Oscillation) and YOTC (Year of Tropical Convection), seek to improve our understanding and representation of tropical convection in our models, including monsoon active-break cycles, to improve medium-range (10-30 days) and seasonal (~90 day) predictions of the monsoon. Furthermore, efforts are underway to improve modeling of aerosols, especially those associated with the Asian Brown Cloud, since they are important for simulating the monsoon because they have a large impact on the radiative heating of the atmosphere and thus can affect the strength of the hydrological cycle. Through the synthesis of modelling and observations the scientific community is poised to make substantial advances in understanding and ultimately predicting monsoons to manage and mitigate adverse impacts on life, property, agriculture, and water resources in a timely and effective manner.

As of 2011, the next phase of climate change model simulations (CMIP-5) is ongoing in support of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, to be published in 2013. Compared to CMIP-3, CMIP-5 is using a wider variety of newer and


Projected June-August Rainfall Trend

Number of models (of 21) projecting an increase in June-August rainfall

Projected December-February Rainfall Trend

Number of models (of 21) projecting an increase in December-February rainfall

Figure 3: Projected change in precipitation amount over the Asian-Australian monsoon region in June-August (top row) and December-February (bottom row) due to human-induced climate change using the Coupled Model Intercomparison Project-3 models. The left panels show the 2001-2100 trend in mm/day (21-model average), and the right panels show the number of models (of 21) that have an increasing trend. The figure is adapted from Christensen et al. (Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA).

more complex models to study past, present, and future climate variability. Additionally, the CMIP-5 simulations will provide more regional-scale information through the use of models that resolve small-scale features, and hopefully they will provide more robust suggestions of how climate change will affect the monsoon.

ACKNOWLEDGEMENT

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