Climate for Development in South Asia (ClimDev-SAsia)

An inventory of cooperative programmes and sources of climate risk information to support robust adaptation

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Photo: Barbara Adolph

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EXECUTIVE SUMMARY

The livelihoods and well-being of the poor in South Asia are already vulnerable to climate variability because of high dependency on natural resources and high exposure to climate-mediated hazards such as floods, droughts, landslides, famine and epidemics. In the absence of significant mitigation and adaptation measures, human-induced climate change is expected to multiply these risks and undermine development goals.

The overall objective of this scoping study is to gather evidence of existing cooperation amongst the suppliers and users of climate risk information in South Asia, and to identify opportunities for strengthening future data demand and coordination for climate change adaptation and development planning. The present review adds to earlier assessments completed by the Global Climate Observing System (GCOS) and the International Development Research Centre (IDRC).

There is widespread recognition of the need to improve climate observation networks and data availability, particularly in mountainous, island and coastal regions. Significant benefits could accrue through improved harmonization and exchange of hydro-meteorological data between riparian states, most notably for water resource and flood management. Evidence of cooperative activity already exists in the form of coordinated research and data collection programmes; multi-institutional collaborations to develop capacities in climate science and technology; forums for sharing experience about water, land and ecosystem management; infrastructure and institutional arrangements to improve hazard forecasting and management; strategic initiatives to address long-term risks posed by climate variability and change; and efforts to improve public awareness and knowledge exchange.

However, there remains significant uncertainty about the future evolution of tropical sea surface temperature anomalies and how these might interact with the South Asian monsoon system. Land use modifications across the sub-continent and biomass burning are also affecting the regional climate in complex ways. Therefore, ***a widely acknowledged research priority is to facilitate a step change in the understanding and representation of the South Asian monsoon to improve climate prediction over seasonal to decadal time-scales***.

In the meantime, progress on adaptation can still be made via "low regret" actions that yield societal benefits now and in the future regardless of the climate outlook. Such measures include hazard zoning and early warning systems for fluvial, glacial and tidal hazards. Likewise, by rejuvenating traditional rain and groundwater harvesting systems, managing water demand, and increasing water efficiency in agriculture. Changes in crop cultivar and soil moisture conservation could also improve yields and reduce vulnerability to protracted drought and flood episodes. Therefore, ***a second priority should be to develop capacities for adaptation options appraisal and decision-making under uncertainty via multi-national training and networking workshops***.

In addition to standard suites of meteorological and hydrological data, other less obvious sources of local information are needed to support adaptation (e.g., accurate soil and geological maps to estimate artificial recharge potential, human development indicators to predict vulnerability, inventories of infrastructure condition and installed capacities to schedule maintenance and upgrading). National- to regional-level data are needed on water transfers, crop yields and flood affected areas to build more reliable hazard forecasting and planning systems. Therefore, ***a third priority should be to support initiatives that build the multi-tiered evidence base of transboundary socio-economic and environmental "hot spots" and hence the case for collective action on adaptation.***

Against this background, two case studies are used to illustrate potential benefits from international data-sharing and harmonization of modelling efforts. First, the closer integration of satellite-derived precipitation and snow cover products with hydrological modelling to improve the accuracy and lead-times of flood forecasts in transboundary river systems. Second, the development of a regional capability in seasonal forecasting to better prepare partner organisations for variability in water supplies, staple crop yields, monsoon flooding, and weather-related epidemics.

Other options for enhancing regional cooperation and adaptive capacity include financial instruments to spread the risk associated with imperfect seasonal forecasts, development of field techniques and guidance to enhance groundwater recharge, or for ameliorating the affects of saline intrusion. Again, such measures would be beneficial regardless of the climate outlook.

None of the above recommendations will realise their full potential unless there are strong two-way interactions between the suppliers and users of climate risk information, i.e., an emphasis on “end-to-end forecasting”. Therefore, ***in addition to strengthening capacity within government and development agencies, comparable effort should be invested at other levels, including participation by vulnerable communities and farmers***.

Given the range of opportunities and wide spectrum of activities already underway, it is recommended that DFID and counterparts host a consultation workshop to determine where greatest value might be added. An existing forum such as the South Asia Water Initiative (SAWI) or multi-lateral organisation such as the International Centre for Integrated Mountain Development (ICIMOD) would be well-placed to facilitate such discussions.

1. INTRODUCTION

1.1 The challenge

The livelihoods and well-being of the poor in South Asia are already vulnerable to climate variability because of high dependency on natural resources and high exposure to climate-mediated hazards such as floods, droughts, landslides, famine and epidemics.

Human-induced climate change is expected to multiply these risks. Nonetheless, successful integration of climate risk information within disaster risk reduction, development and adaptation programmes is not guaranteed. This outcome depends on several factors, not least: access to high-quality meteorological data to characterise present climate variability; credible climate change scenarios at the spatial and temporal scales needed to support decision-making; technical capacity to interpret trends, undertake impacts assessment, options appraisal, and adaptation planning; institutional and sectoral governance structures in place to identify then deliver “climate-compatible” development programmes and projects.

Climate change impacts transcend national boundaries so there are potential benefits from information sharing and coordination of adaptation responses amongst neighbours (Box 1). Furthermore, a regional approach can help to avoid duplication of effort, pool capacities and spread costs, as well as to meet internal social, economic and environmental needs.

Box 1 – The rationale for regional cooperation (on flood and drought management)

South Asia faces flood disaster on a regular basis. This problem crosses international borders and as the regional hydrology is affected by climatic change, the nature of the problem has become complex. Past approaches focused on altering of stock and flow of water using embankments and reservoirs, but are insufficient. The structural solutions are inadequate to address the problems because they require collaboration... Mirza (2003: vii)

...the ability of populations to adapt to floods, droughts and climatic variability is heavily influenced by the degree to which people, finance, goods, services and information can move across local and national borders. The factors governing these flows are a critical area for policy research both within countries and at the global level. If global climatic change occurs abruptly, as some predict it may, the importance of migration and local to global flows of information, finance, goods and services to local adaptive capacities – and, indeed, to the very survival of local populations – raises critical humanitarian issues that extend beyond the provision of relief... Moench and Dixit (2004:vii)

*...systematic climate observation programmes in South and Southwest Asia are, at present, inadequate to permit reliable assessment, quantification and prediction of climatic conditions and their impacts...*WMO (2005: 9)

It is widely recognized that floods in the HKH region cannot be eliminated or totally controlled and that efforts should therefore be directed towards reducing flood vulnerability and mitigating flood impact through improved flood management. At the level of an international river basin effective flood management calls for meaningful co-operation of the riparian countries... HKH-HYCOS (2009:7)

1.2 Project objectives

The overall objective of this study is to build on the lessons learnt and evidence gathered by earlier scoping exercises, and begin to shape a plan of action for strengthening the demand, delivery, and use of climate risk information in adaptation and development planning for South Asia. This information could help to guide regional initiatives, stakeholders and development partners as they seek to harmonize climate observation and modelling, by identifying key knowledge gaps, selecting entry points, and prioritising future activities.

The specific goals of this report are to:

- Compile an inventory of available climate risk information, cooperative programmes, and strategies for addressing climate risks at regional-scales.

- Provide an update on studies of climate variability and change that have emerged since the publication of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (FAR).
- Compile an inventory of adaptation responses to realised and/or anticipated climate risks across South Asia, focusing on activities at national- to regional-scales.
- Propose case studies for exploring the practical value and limitations of climate risk information for adaptation planning at regional scales.
- Suggest how these studies might incentivise regional cooperation, and exploit opportunities offered by information technologies that transcend national boundaries.

The analysis is backed by a detailed but far from exhaustive bibliography. For ease of cross-reference to post IPCC research and inventories, literature has been grouped by region-wide and national activities. In order to frame the literature search "South Asia" was defined as Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka.

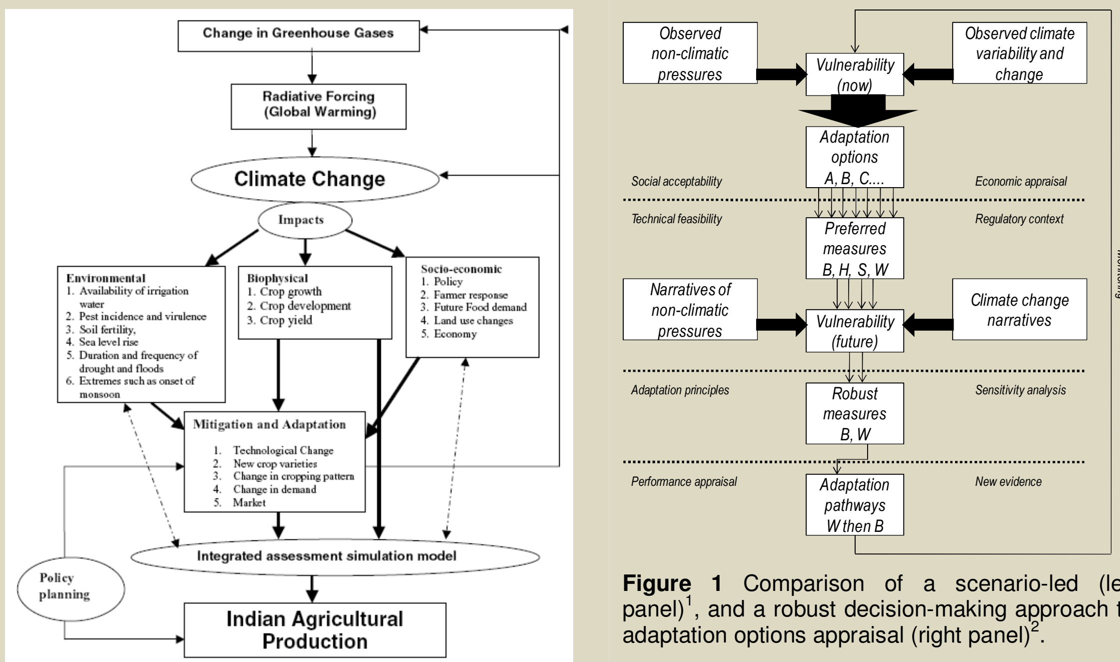

Figure 1 Comparison of a scenario-led (left panel)[1], and a robust decision-making approach to adaptation options appraisal (right panel)[2].

1.3 Conceptual framework

Keeping the above in mind, it is important to recognise that there are many different ways in which climate risk information can be used for adaptation and development planning[3]. However, the over-arching conceptual framework strongly determines the types of information that are required and the ways in which data are deployed (Figure 1, above). For example, scenario-led (so-called "top down") methods place much greater emphasis on climate model output and high-resolution, downscaled scenarios (Figure 1, left panel).

[1] Mall, R.K., Gupta, A., Singh, R., Singh, R.S. and Rathore, L.S. 2006. Water resources and climate change: An Indian perspective. *Current Science*, **90**, 1610-1626.

[2] Wilby, R.L. and Dessai, S. 2009. Robust adaptation to climate change. *Weather*, submitted.

[3] Wilby, R.L., Troni, J., Biot, Y., Tedd, L., Hewitson, B.C., Smith, D.G. and Sutton, R.T. 2009. A review of climate risk information for adaptation and development planning. *International Journal of Climatology*, **29**, 1193-1215.

Conversely, vulnerability assessment (“bottom up”) approaches depend more on knowledge of coping thresholds and changing exposure to extreme weather events at the level of individuals, households and communities. Robust decision-making methods, by definition, arrive at low regret adaptation options that are largely independent of climate model projections, although final selection may refer to climate change “narratives” to describe the direction of climate change (Figure 1, right panel).

Whilst the weight attached to climate model projections may depend on the preferred conceptual framework, routine monitoring and reporting of environmental change is required by all approaches to evaluate performance and to trigger decisions at critical junctures along the adaptation pathway. Previous reviews of capabilities undertaken by the Global Climate Observing System (GCOS) have already highlighted the most urgent needs for climate information in relation to climate policies, national activities, and sustainable development of the countries of South and Southwest Asia (Box 2). Above all, the Regional Action Plan stresses the importance of improving coordination and improving data management, data exchange and data availability within the region[4].

Box 2 – Priority projects identified by the 2005 GCOS Regional Action Plan

1. Enabling improved regional assessments of climate change by strengthening GCOS Global Surface Network (GSN) and Global Upper Air Network (GUAN) monitoring activities.
2. Establishing Global Atmosphere Watch (GAW) aerosol monitoring within the region.
3. An Indian Ocean observing system for climate: The CLIVAR/GOOS Indian Ocean Panel Report on Plans for Sustained Observations for Climate.
4. Enhancing the availability and use of hydrological data in South and Southwest Asia.
5. Monitoring glaciers for water resources in South and Southwest Asia.
6. Fluxnet for South and Southwest Asia (for systematic monitoring of fluxes of carbon dioxide and other gases between the surface of the Earth and the atmosphere).
7. Needed improvements in database management and data rescue for climate assessment.
8. Building regional capacity for satellite applications for climate and national development.
9. Enhancement of regional climate modelling capacity in South and Southwest Asia.

Other obstacles have been identified such as “market atrophy”, or *negligible demand coupled with inadequate supply of climate services for development decisions*. A major lesson learnt from the ClimDev-Africa programme is the importance of funding demand-led initiatives that strengthen the use of climate risk information for decision-making, by improving analytical capacity, knowledge management and dissemination activities[5]. Mainstreaming climate risk management in development efforts also requires improvement in the usability of climate information and sharing of best practice[6].

[4] World Meteorological Organisation (WMO), 2005. *GCOS Regional Action Plan for South and Southwest Asia.* Global Environment Facility and United Nations Development Programme, 97pp.

[5] African Union Commission (AUC), Economic Commission for Africa, and African Development Bank, 2008. *Climate for development in Africa: Framework programme document*, October 2008, 61pp.

[6] Agrawala, S. and van Aalst, M. 2008. Adapting development cooperation to adapt to climate change. *Climate Policy*, **8**, 183-193.

2. CLIMATE MONITORING

2.1 Climate observation capabilities

GCOS was established in 1992 in order to secure the data necessary for climate system monitoring, climate change detection and response monitoring, development of national economies, and research. Progress towards achieving these objectives has recently been reviewed with respect to 21 high-level and cross-cutting actions (Box 3). Most notably the overall decline of the global meteorological network witnessed during the 1990s has been halted or reversed, but observational coverage remains sparse and uneven across South Asia (see Annex 1). For example, glaciological research and monitoring programmes in the Himalayas have tended to be piece-meal, uncoordinated and short-lived. Efforts to sustain a long-term glacier monitoring network are clearly hampered by political tensions and regional conflicts, but there has also been inadequate funding by national governments, and failure of external organizations to sustain support[7]. The technical and logistical challenges of instrumenting such remote, high altitude and harsh environments are also significant factors.

Box 3 Progress on the implementation of the Global Observing System for Climate[8]

- The increasing profile of climate change has reinforced world-wide awareness of the importance of an effective Global Climate Observing System.
- Developed Countries have improved many of their climate observation capabilities, but national reports suggest little progress in ensuring long-term continuity for several important observing systems.
- Developing Countries have made only limited progress in filling gaps in their *in situ* observing networks, with some evidence of decline in some regions, and capacity building support remains small in relation to needs.
- Both operational and research networks and systems, established principally for other purposes, are increasingly responsive to climate needs including the need for timely data exchange.
- Space agencies have improved both mission continuity and observational capability, and are increasingly meeting the identified needs for data reprocessing, product generation, and access.
- The Global Climate Observing System has progressed significantly over the last five years, but still falls short of meeting all the climate information needs of the UNFCCC and broader user communities.

2.2 Regional cooperation

There is a long history of bilateral agreements for water allocation and management within the region. For example, the Kosi Treaty (1954) and Gandak Treaty (1959) both involve India and Nepal for the purpose of flood control, irrigation and hydroelectric power generation. The Indus Basin Treaty (1960) between India and Pakistan, and the Ganges Treaty (1996) between India and Bangladesh are about sharing the water resources of these transboundary rivers.

Other arrangements are in place to exchange near real-time meteorological and hydrological data for flood control. For example, China and India have had a data sharing agreement for the Yarlungzambo/Brahmaputra River since 2002. Likewise there are data sharing

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[7] Rees, G. 2008. *A review of current knowledge on Himalayan and Andean glacier melting*. Centre for Ecology and Hydrology, Wallingford, 25pp.

[8] World Meteorological Organisation (WMO), 2009. Progress report on the implementation of the Global Observing System for Climate in support of the UNFCCC 2004-2008. GCOS Secretariat GCOS-129, 105pp.

arrangements between India and Nepal, Bhutan and India, Bangladesh and India, Pakistan and India, and between Bagladesh and Nepal, all for the purpose of securing upstream data for downstream flood forecasting and warning systems. The arrangement may be limited to the flood season, or involve provision of monitoring equipment and training by one riparian state to another.

Growing concern about regional climate change impacts is prompting new types of collective action across South Asia. Evidence of cooperative programmes for climate monitoring was compiled through consultation with donor organisations, key stakeholder groups and researchers. To date, 33 activities involving more than one national agency have been identified (Annex 2). The list is unlikely to be exhaustive but does provide a sample from which to distil several recurrent themes. The main types of activity include:

- Networks of scientists to ***coordinate research and data collection*** (e.g., Asia-Clic; Consultative Group on International Agricultural Research [CGIAR]; Coordinated Regional Downscaling Experiment [CORDEX]; Flow Regimes from International Experimental and Network Data [FRIEND]; Monsoon Himalayan Precipitation Experiment [MOHPREX]).
- Bi-lateral and multi-institutional collaborations to ***develop capacities*** in science and technology (e.g., Center for Space Technology Education in Asia Pacific [CSSTEAP]; EU-India Cooperation in Science and Technology; South Asian Association for Regional Cooperation [SAARC]; UK-India “science bridges initiative”).
- Consortia that share experience and tools for common ***water, land and ecosystem management*** issues (e.g., Delta Research and Global Observation Network [DRAGON]; WWF’s Himalayan Glaciers and Rivers Project).
- Infrastructure and institutional cooperation to improve ***hazard forecasting and management*** (e.g., Early Warning and Environmental Monitoring Program [EROS]; Hindu Kush Himalayan Hydrological Cycle Observing System [HKH-HYCOS]; Regional Integrated Multi-hazard Warning System [RIMES]).
- Strategic regional initiatives addressing ***long-term risks*** posed by climate variability and change (e.g., HighNoon; South Asia Water Initiative [SAWI]; EU-WATCH; WWF’s Living Ganga Programme).
- Public ***awareness raising*** and knowledge exchange (e.g., Third Pole Project [3PP]).

International donors and agencies have been supporting these cooperative ventures through financing (e.g., Asian Development Bank, DFID, USAID, World Bank), coordinating (e.g., GCOS, UNDP), policy analysis (e.g., International Centre for Integrated Mountain Development [ICIMOD]) and convening (e.g., International Research Institute for Climate and Society [IRI]) roles.

Despite all the above arrangements there is still scope for improved data gathering and further development of pro-poor climate services. Satellite data are already being used to monitor regional changes in the cryosphere (such as glacier area, terminus position, melt-water lakes) and glacial hazards at remote sites. However, cutting-edge research is demonstrating how remotely sensed precipitation data, when combined with flood-forecasting systems, could also increase lead-times and thereby improve hazard management. Indeed, remotely sensed rainfall data may be particularly appealing in situations where riparian nations do not yet have treaties for sharing real-time data[9].

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[9] Hossain, F., Katiyar, N., Wolf, A. and Hong, Y. 2007. The emerging role of satellite rainfall data in improving the hydro-political situation of flood monitoring in the under-developed regions of the world. *Natural Hazards*, **43**, 199-210.

Similarly, improved knowledge of the forces exerted on the region's climatology by sea surface temperatures in the Tropical and Indian Oceans could yield long-range forecasts of water availability, yields of major agricultural commodities, and even human health indices. Better understanding of topographic controls on monsoon rainfall distributions and regional aerosol affects on temperature could help to explain past and projected climate changes. Integrated river basin modelling could be used to investigate the sensitivity of water resource allocations (under bi-lateral treaties) to plausible socio-economic and climate changes. The opportunities afforded by such information technologies will be revisited later in the form of case studies.

2.3 Regional climate trends

The following paragraphs synthesize evidence of climatic trends published since IPCC FAR (based on the inventory in Annex 3). South Asia is clearly an extremely heterogeneous region that encompasses marked variations in topography, a vast land mass juxtaposed with strong influences from the Indian Ocean, Bay of Bengal and Arabian Sea, and incorporating a range of island, delta, desert and plateau environments. Therefore, great care must be taken when generalising about changes in often relatively sparse and short-lived meteorological records. Furthermore, trend analyses should always keep in mind possible confounding factors such as the influence of urbanisation or land surface modifications on temperature and rainfall records[10].

With the above caveats in mind, *in situ* meteorological records for the region show increasing temperatures in all seasons (although there are exceptions, such as small decreasing trends in the northwest and western Himalaya regions of India[11]). Maximum temperatures appear to be increasing more than minimum temperatures with a resultant widening of the diurnal temperature range. For example, across India as a whole mean maximum and mean minimum temperatures increased by ~0.9 and ~0.1°C respectively over the last century. The warming was generally stronger in winter than summer, greater at higher than lower elevation sites, and greatest in the south of the sub-continent. Higher annual temperatures have resulted in less precipitation as snowfall.

Seasonal and annual precipitation records exhibit considerable inter-annual and inter-decadal variability with few examples of spatially homogeneous, long-term trends (Figure 2). [Local increases and decreases can always be found at individual meteorological stations particularly in records of just a few decades]. Monsoon rainfall totals are strongly correlated with sea surface temperatures (SSTs) in the tropics, such that El Niño Southern Oscillation (ENSO) episodes are typically associated with persistent drought across much of the sub-continent. However, there is evidence that the strength of the correlation has weakened in recent decades[12]. Likewise, the positive correlation between above average winter precipitation totals in the Karakoram and Himalayas and the strength of the North Atlantic Oscillation (NAO) index has also weakened. Across South Asia there has been a tendency towards more frequent small to large rainfall daily rainfall events, and increased intensity of large rainfalls. Records beginning in the nineteenth century suggest that the frequency of tropical cyclones in the Bay of Bengal has increased, most notably during November[13].

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[10] Adel, M.M. 2002. Man-made climatic changes in the Ganges basin. *International Journal of Climatology*, **22**, 993-1016.

[11] Ganguly, N.D. and Iyer, K.N. 2009. Long-term variations of surface air temperature during summer in India. *International Journal of Climatology*, **29**, 735-746.

[12] Bhutiyani, M.R., Kale, V.S. and Pawar, N.J. 2009. Climate change and the precipitation variations in the north-western Himalaya: 1866-2006. *International Journal of Climatology*, **early view online**.

[13] Singh, O.P. 2007. Long-term trends in the frequency of severe cyclones of Bay of Bengal: Observations and simulations. *Mausam*, **58**, 59-66.

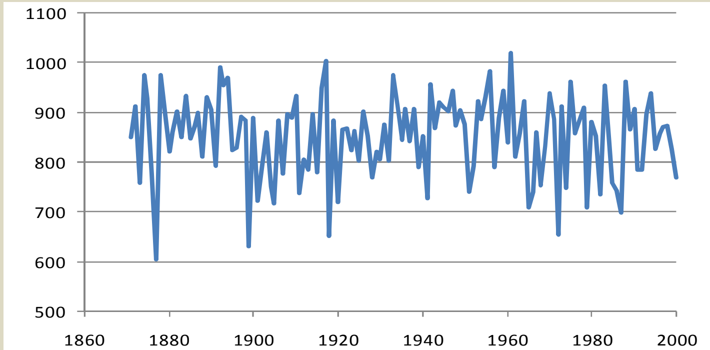

Figure 2 The All India Monsoon Rainfall Index. Source: http://www.iges.org/india/allindia.html

Rising air temperatures and seasonal precipitation variability are being reflected by dramatic changes in the region's glaciers[14]. The terminuses of glaciers have been retreating in the majority of cases, at rates exceeding 50 m/yr in some valleys[15]. [Even where there are unusually high concentrations of *surging* glaciers this is attributed to high-latitude warming affecting snow and glacier thermal regimes, or to intense, short-term melting episodes[16]]. Wasting of snow and ice has led to the shrinkage of glacier area, growth of supra- and pro-glacial lakes, and increased risk of glacial lake outburst floods (GLOFs). The permafrost lower limit has risen by as much as 300m since the 1970s on southern aspect slopes in Nepal[17]. Hill districts have also witnessed an upward trend in fatalities due to landslides that is partly explained by variations in the monsoon precipitation index over the same period[18].

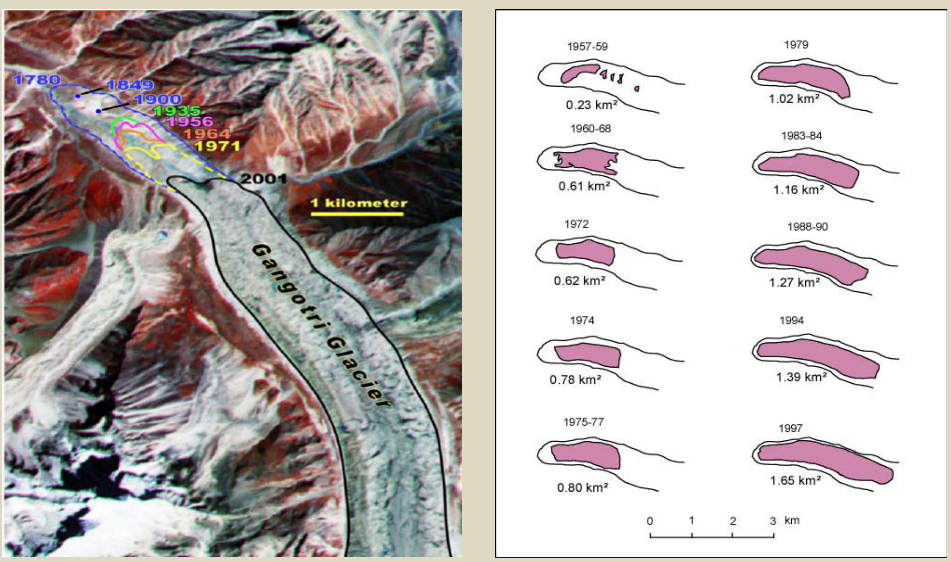

Figure 3 Left: retreat of the Gangotri Glacier (Garhwal Himalayas) snout during the last 220 years. Source: Jeff Kargel, (USGS). Right: growth of Tsho Rolpa from the late 1950s to 1997. Source: WWF (2005).

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[14] Ibid 7.

[15] Kulkarni, A.V., Rathore, B.P., Mahajan, S. and Mathur, P. 2005. Alarming retreat of Parbati glacier, Beas basin, Himachal Pradesh. *Current Science*, **88**, 1844-1850.

[16] Hewitt, K. 2007. Tributary glacier surges: an exceptional concentration at Panmah Glacier, Karakoram Himalaya. *Journal of Glaciology*, **53**, 181-188.

[17] Fukui, K., Fujii, Y., Ageta, Y. and Asahi, K. 2007. Changes in the lower limit of mountain permafrost between 1973 and 2004 in the Khumbu Himal, Nepal Himalayas. *Global and Planetary Change*, **55**, 251-256.

[18] Petley, D.N., Hearn, G.J., Hart, A., Rosser, N.J., Dunning, S.A., Oven, K. and Mitchell, W.A. 2007. Trends in landslide occurrence in Nepal. *Natural Hazards*, **43**, 23-44.

3. REGIONAL CLIMATE CHANGE PROJECTIONS

3.1 Resumé of IPCC FAR

This section provides a concise overview of the main findings of the IPCC with regard to climate change projections for South Asia, and any significant research findings since.

Working Group I of the IPCC FAR concluded that *warming of the climate system is unequivocal* and, that *most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to observed increases in anthropogenic greenhouse gas concentrations*. Furthermore, human influences are now discernible at continental scales in temperature and wind records. An IPCC Technical Paper on Water further asserted that *observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences on human societies and ecosystems*[19].

Regional climate change projections for South Asia suggest more rapid warming than the global average, with fewer very cold days, more precipitation in summer, and more frequent extreme rainfalls associated with tropical cyclones (Box 4). The average of the IPCC ensemble of Ocean Atmosphere General Circulation Models (OA/GCMs) shows a significant increase in mean monsoon (June to September) precipitation and possible extension of the monsoon period. Extreme wet and dry monsoons are expected to intensify[20].

However, there is considerable variation amongst the precipitation projections of individual GCMs. This means that any regional climate change scenarios are also highly contingent upon the choice of host climate model and regional climate model (RCM) used to perform the downscaling. For example, PRECIS simulations under scenarios of increased greenhouse gas concentrations indicate marked increases in both rainfall and temperature by the end of the 21st century (Figure 4); conversely experiments using RegCM3 suggest overall suppression of summer precipitation, a delay in monsoon onset, and an increase in the occurrence of monsoon break periods[21].

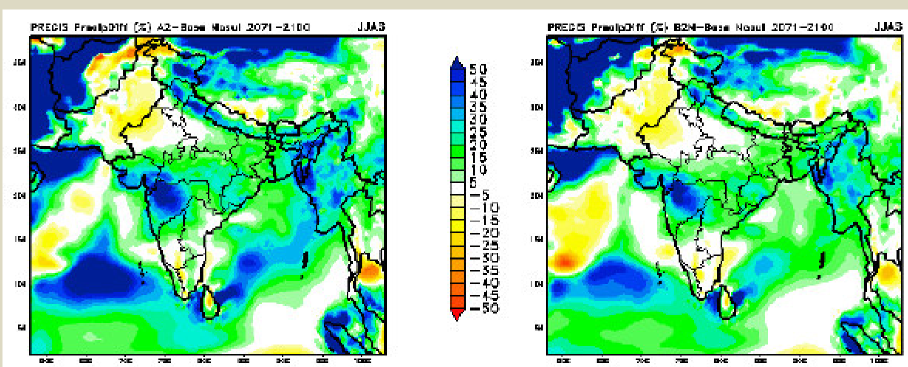

Figure 4 PRECIS model projections of changes in summer monsoon rainfall by the 2080s, under SRES A2 and B2 emissions scenarios[22].

[19] Bates, B.C., Kundzewicz, Z.W. Wu, S. and Palutikof, J.P. (Eds.) 2008: *Climate Change and Water*. Technical Paper VI of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp. Available at: http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf

[20] Kripalani, R.H., Oh, J.H., Kulkarni, A., Sabade, S.S. and Chaudhari, H.S. 2007. South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4. *Theoretical and Applied Climatology*, **90**, 133-159.

[21] Ashfaq, M., Shi, Y., Tung, W.W., Trapp, R.J., Gao, X.J., Pal, J.S. and Diffenbaugh, N.S. 2009. Suppression of south Asian summer monsoon precipitation in the 21st century. *Geophysical Research Letters*, **36**, L01704.

[22] Kumar, K.R., Sahai, A.K., Kumar, K.K., Patwardhan, S.K., Mishra, P.K., Revadekar, J.V., Kamala, K. and Pant, G.B. 2006. High-resolution climate change scenarios for India for the 21st century. *Current Science*, **90**, 334-345.

Box 4 – Summary of IPCC climate change projections for Asia[23]

Warming is *likely* to be well above the global mean in central Asia, the Tibetan Plateau and northern Asia, above the global mean in eastern Asia and South Asia, and similar to the global mean in Southeast Asia. Precipitation in boreal winter is *very likely* to increase in northern Asia and the Tibetan Plateau, and *likely* to increase in eastern Asia and the southern parts of Southeast Asia. Precipitation in summer is *likely* to increase in northern Asia, East Asia, South Asia and most of Southeast Asia, but is *likely* to decrease in central Asia. It is *very likely* that heat waves/hot spells in summer will be of longer duration, more intense and more frequent in East Asia. Fewer very cold days are *very likely* in East Asia and South Asia. There is *very likely* to be an increase in the frequency of intense precipitation events in parts of South Asia, and in East Asia. Extreme rainfall and winds associated with tropical cyclones are *likely* to increase in East Asia, Southeast Asia and South Asia.

Whilst there is broad agreement amongst Ocean Atmosphere General Circulation Models (OA/GCMs) concerning the above climate changes some important uncertainties remain. Most significantly there is a lack of consensus amongst models about the future behaviour of ENSO, and how this might translate into regional changes to the southwest monsoon and tropical cyclones. This is reflected in the uncertainty of the sign of the precipitation change over large parts of South Asia in summer (indicated by the white areas in Figure 5 bottom row, rightmost panel).

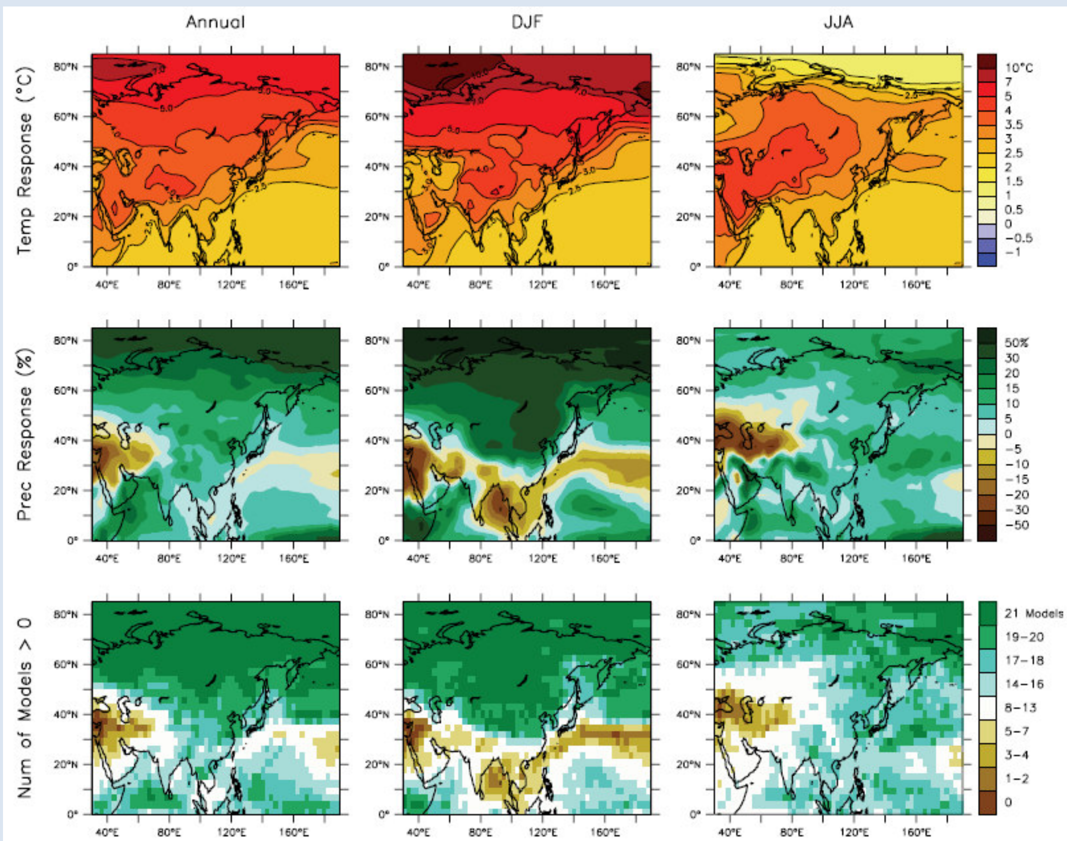

Figure 5 Projected temperature and precipitation changes over Asia under A1B emissions. Top row: Annual mean, winter (December to February) and summer (June to August) temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation. Source: IPCC FAR Figure 11.9

[23] Christensen, J.H., Hewitson, B., Busuioc, A., et al. 2007. Regional Climate Projections. *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., Quin, D., Manning, M., et al (eds.), Cambridge University Press, Cambridge.

3.2 Developments since IPCC FAR

As noted above, climate models simulate the behaviour of the South Asian monsoon with varying outcomes to greenhouse gas forcing. This is partly due to incomplete understanding and representation of evolving ocean temperature anomalies, and partly because of the complex topography and coastline of the region which are not resolved well by GCMs[24]. Even in the absence of greenhouse gas forcing, the strength of the ENSO-monsoon teleconnection is known to vary widely across interdecadal timescales so there is always the possibility that individual projections lie within the range of natural variability[25].

Rigorous scrutiny of the GCMs underpinning the IPCC FAR revealed that just six of the 18 models were found to have a *reasonably realistic representation of monsoon precipitation climatology*[26]. Of these six GCMs only four exhibit a robust ENSO-monsoon correlation, including the known inverse relationship between ENSO and rainfall variations over India. These four models correctly simulate the timing and location of SST and atmospheric heating anomalies in the equatorial Pacific and associated changes to the equatorial Walker circulation during El Nino events. Under doubled CO_2 concentrations these "best" models show increases in both the mean monsoon rainfall over the Indian subcontinent (by 5%-25%) and in its inter-annual variability (5%-10%). The strength of the correlation with ENSO remains unchanged when compared with runs for the 20th century.

Another comprehensive assessment reviewed 79 OA/GCMs simulations from 12 different climate models and 6 different emission scenarios to ascertain whether any consensus can be reached about predicted changes in the main features of ENSO and the monsoon climates of South Asia[27]. Although most models project La Nina-like anomalies and thus an intensification of the summer monsoon precipitation in India by the end of the 21st century, the response is barely distinguishable from natural climate variability. Substantial warming in the eastern tropical Pacific was the most prominent climate change signal to be found in the ensemble pointing to a change in the background state of ENSO. Overall, however, large model uncertainty still exists with respect to the future behaviour of the South Asian monsoon (see Box 4).

Other studies address individual components of regional climate forcing. For example, an analysis of CMIP3 climate models (used by the IPCC FAR) assessed the climatology, multi-decadal trend, and response of global monsoon precipitation to volcanic aerosols over the second half of the twentieth century[28]. The study concluded that overall the multi-model ensemble simulates the climatology of the global monsoon precipitation and circulation, but there are significant biases on the windward side of narrow mountain chains (such as the western coast of India). Model runs that included volcanic aerosol forcing better reproduced observed trends in the land monsoon index since the 1950s. Another climate model sensitivity analysis showed that changes in surface albedo and roughness due to forest conversion or desertification could lead to a decrease in Indian summer rainfall[29].

[24] Pal, J.S., Giorgi, F., Bi, X., et al. 2007. RegCM3 and RegCNET: Regional climate modeling for the developing world. *Bulletin of the American Meteorological Society* **88**: 1395–1409.

[25] Turner, A.G., Inness, P.A. and Slingo, J.M. 2007. The effect of doubled CO2 and model basic state biases on the monsoon-ENSO system. I: Mean response and interannual variability. *Quarterly Journal of the Royal Meteorological Society*, **133**, 1143-1157.

[26] Annamalai, H., Hamilton, K. and Sperber, K.R. 2007. The South Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations. *Journal of Climate*, **20**, 1071-1092.

[27] Paeth, H., Scholten, A., Friederichs, P. and Hense, A. 2008. Uncertainties in climate change prediction: El-Nino-Southern Oscillation and monsoons. *Global and Planetary Change*, **60**, 265-288.

[28] Kim, H.J., Wang, B. and Ding, Q.H. 2008. The global monsoon variability simulated by CMIP3 coupled climate models. *Journal of Climate*, **21**, 5271-5294.

[29] Knopf, B., Zickfeld, K., Flechsig, M. and Petoukhov, V. 2008. Sensitivity of the Indian monsoon to human activities. *Advances in Atmospheric Sciences*, **25**, 932-945.

One study focused on the role played by ocean temperature variations in the observed weakening of global monsoon precipitation over the land during the second half of the twentieth century. Experiments with the NCAR Community Atmosphere Model, version 2 (CAM2) model suggest that the decreasing tendency was mainly caused by the warming trend over the central-eastern Pacific and the western tropical Indian Ocean. Discrepancies between the model and observed ocean monsoon precipitation were attributed to uncertainties in the satellite data and deficiencies in the representation of atmosphere-ocean feedbacks in the Asian-Australian monsoon system[30].

A raft of experiments are exploring the extent to which aerosols produced by biomass burning (so-called "brown clouds") can also affect the region's energy balance, monsoon rainfall and temperatures (Figure 6). Some conclude that anomalous aerosol loading in late spring leads to large-scale variations in the monsoon evolution. Excessive aerosols in May lead to reduced cloud amount and precipitation, increased surface shortwave radiation, and land surface warming[31]. Analysis of tropospheric temperatures from satellite measurements in the pre-monsoon season show a warming of 2.7℃ over the Himalayan-Gangetic region during the period 1979-2007, raising the possibility that aerosol solar heating has strengthened the land-sea gradient and thereby affected monsoon onset[32]. Other research shows that black carbon aerosols increase lower-atmosphere heating over South Asia and reduce the amount of surface radiation during the dry season. Consequent weakening of the latitudinal SST gradient leads to modelled increases in precipitation in spring (March to May) over northern India and the Tibetan Plateau and to decreased precipitation in summer over parts of India, Bangladesh, Burma and Thailand[33].

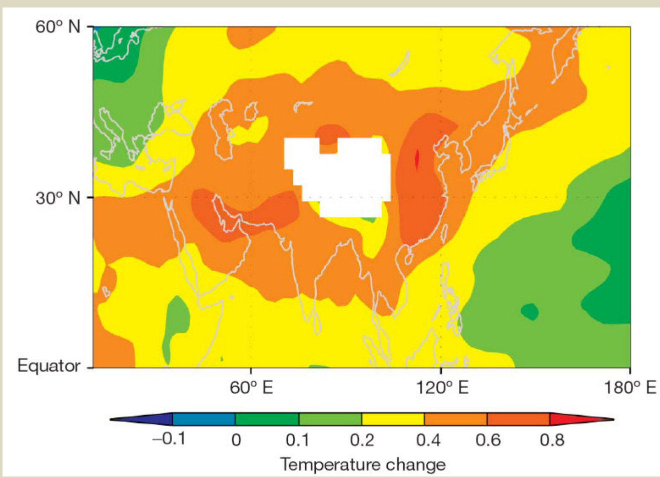

Figure 6 Modelled temperature change over Asia due to atmospheric brown cloud solar heating at ~3km level[34]. The change is estimated from a 50-year average of climate model experiment minus control. The standard error of the mean difference is 0.05° K.

The issue of climate model resolution continues to figure prominently in the literature. For example, a study of the ensemble predictions of the NCEP Climate Forecast System (CFS) indicated that the model successfully simulates key features of the Asian summer monsoon including the climatology and inter-annual variability of major precipitation centres and

[30] Zhou, T.J., Yu, R.C., Li, H.M. and Wang, B. 2008. Ocean forcing to changes in global monsoon precipitation over the recent half-century. *Journal of Climate*, **21**, 3833-3852.

[31] Bollasina, M., Nigam, S. and Lau, K.M. 2008. Absorbing aerosols and summer monsoon evolution over South Asia: An observational portrayal. *Journal of Climate*, **21**, 3221-3239.

[32] Gautam, R., Hsu, N.C., Lau, K.M., Tsay, S.C. and Kafatos, M. 2009. Enhanced pre-monsoon warming over the Himalayan-Gangetic region from 1979 to 2007. *Geophysical Research Letters*, **36**, L07704.

[33] Meehl, G.A., Arblaster, J.M. and Collins, W.D. 2008. Effects of black carbon aerosols on the Indian monsoon. *Journal of Climate*, **21**, 2869-2882.

[34] Ramanathan, V., Ramana, M.V., Roberts, G., Kim, D., Corrigan, C., Chung, C. and Winker, D. 2007. Warming trends in Asia amplified by brown cloud solar absorption. *Nature*, **448**, 575-579.

atmospheric circulation systems[35]. However, the model was more skilful at reproducing the onset of the monsoon than the retreat, and the seasonality of rainfall was better represented in Southeast Asia than South Asia. A higher resolution version of the model better captured the climatology and variability of the monsoon thanks in part to improved simulations of precipitation near the Tibetan Plateau and over the tropical Indian Ocean.

There is ongoing interest within some sections of the climate science community to conduct "hyper-matrix" (i.e., large inter-comparison) studies based on the results from different permutations of climate forcing scenario, GCM, initial conditions, downscaling method, and region[36]. Inter-comparison studies such as CORDEX are motivated by the desire to better characterise the uncertainties affecting regional climate change. This may be a scientifically tractable proposition, but the likelihood of *reducing* uncertainty in the climate risk information supplied to decision-makers still seems a remote prospect. Nonetheless, proposed regional climate downscaling experiments for a domain covering West Asia could, in due course, increase the availability of high resolution (~25km) climate change scenarios for development and adaptation planners in South Asia (Figure 7).

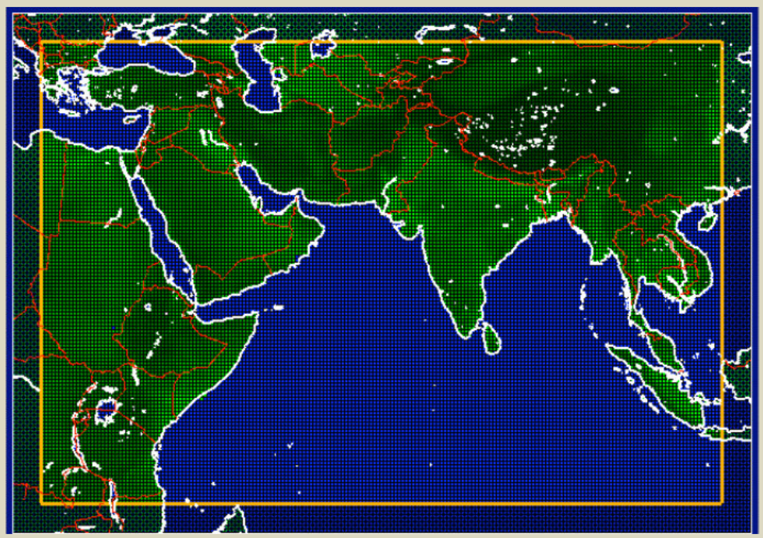

Figure 7 The West Asia domain of CORDEX.
Source: http://wcrp.ipsl.jussieu.fr/RCD_Projects/CORDEX/CORDEX.html

Statistically downscaled climate scenarios are also becoming more widely available for South Asia thanks to online resources and public domain downscaling software. For example, a portal supported by the Climate Systems Analysis Group (CSAG) at the University of Cape Town[37] now offers daily and monthly rainfall and temperature indices for meteorological stations in Bangladesh (7 sites), India (72), Nepal (11), Pakistan (20) and Sri Lanka (2). Downscaled scenarios are currently available for 7 GCMs under SRES A2 emissions, for a control period (1961-2000) and for the 2080s. Other downscaling tools such as the Statistical DownScaling Model (SDSM)[38] enable greater flexibility in terms of site and scenario choice but there is much more onus on the user to prepare the required meteorological data for calibration, and the GCM predictors needed for downscaling future

[35] Yang, S., Zhang, Z.Q., Kousky, V.E., Higgins, R.W., Yoo, S.H., Liang, J.Y. and Fan, Y. 2008. Simulations and seasonal prediction of the Asian summer monsoon in the NCEP Climate Forecast System. *Journal of Climate*, **21**, 3755-3775.
[36] Giorgi, F., Diffenbaugh, N.S., Gao, X.J., Coppola, E., Dash, S.K., Frumento, O., Rauscher, S.A., Remedio, A., Seidou Sanda, I., Steiner, A., Sylla, B. and Zakey, A.S. 2008. The regional climate change hyper-matrix framework. *Eos*, **89**, 445-446.
[37] http://data.csag.uct.ac.za/
[38] https://co-public.lboro.ac.uk/cocwd/SDSM/

daily time series. The World Bank's *Climate Change Data Portal*[39] provides access to a more comprehensive package of climate risk information including: country-level summaries of historic and projected climate change; high-level summaries of key sector vulnerabilities and anticipated climate change impacts; priority adaptation initiatives; as well as links to supporting documentation and guidance.

Finally, a few climate modelling centres are exploring the feasibility of decadal forecasting of global (and some regional) mean temperatures from information about the heat content of the upper ocean[40,41]. This skill arises from the persistence and predictability of ocean temperatures over multi-year timescales and reinforces the case for ocean monitoring, such as the array of ARGO floats, which provide data streams for decadal forecasting systems. Despite significant technical advances in decadal forecasting capability, these products will remain of limited value to policy-makers and planners until credible forecasts of regional climate anomalies become available. Work in this area has only just begun. For example, Figure 8 shows a prototype forecast of regional precipitation anomalies out to 2017 based on the UK Met Office's Decadal Climate Prediction System (DePreSys). The plot shows the difference between model runs with and without ocean temperature information. Although the ocean temperature forcing yields coherent positive anomalies over the Indian subcontinent, more research is needed to determine whether the signals are robust. [A later forecast also shows increased annual mean precipitation over South Asia by the 2020s that persists or increases further by the 2030s in more than 66% of the members in the climate model ensemble[42]]. In addition, further consideration is needed as to how best to apply the information in an adaptation planning context.

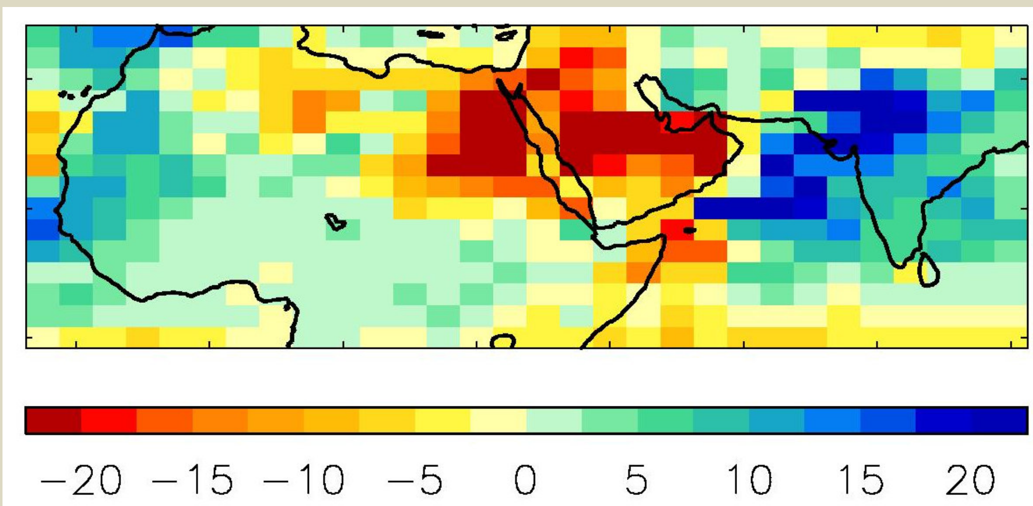

Figure 8 Precipitation anomalies for 2007-2017 as a percentage of the 1979-2001 mean. This prototype forecast was based on information on upper ocean heat content up to March 2007. Source: Met Office

[39] http://sdwebx.worldbank.org/climateportal/
[40] Smith, D.M., Cusack, S., Colman, A.W., Folland, C.K., Harris, G.R. and Murphy, J.M. 2007. Improved surface temperature prediction for the coming decade from a global climate model. *Science*, **317**, 796-799.
[41] Keenlyside, N.S., Latif, M., Jungclaus, J., Kornblueh, L. and Roeckner, E. 2008. Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature*, **453**, 84-88.
[42] Brookshaw, A. and Graham, R. 2008. Predicted changes in precipitation by 2030. UK Met Office, Exeter, 41pp.

4. IMPACTS AND ADAPTATION RESPONSES

4.1 Summary of anticipated impacts

South Asia is already the most disaster prone region of the world and supports in excess of 1.3 billion people. This means that a huge population would be exposed to any changes in the frequency of extreme weather events like floods and droughts. According to previous reviews of regional climate change impacts the most vulnerable sectors are water resources, agriculture, biodiversity/conservation, and human health[43,44,45].

In short, climate-driven changes in water quantity, quality and biology will affect the performance and operation of existing water infrastructure – including hydropower, structural flood defences, drainage, and irrigation systems – plus water management practices[46]. These impacts will be exacerbated by non-climatic pressures arising from population and economic growth, as well as by trends towards greater urbanisation[47], agricultural intensification and extensification[48]. There is evidence that variability in the timing and strength of the monsoon are already affecting hydropower and production of staple crops in the region[49,50].

However, perhaps the greatest concern is that long-term wastage of the region's snow and ice stores (the "water towers" of the continent) will have a profound impact on water security[51]. Mountain communities also face increased risks associated with GLOFs, thawing permafrost, slope instability, soil erosion and associated impacts on rural infrastructure.

Coastal and island communities are threatened by water scarcity (due to physical shortage and/or saline intrusion) as well as by the combined effects of sea level rise, changes in the frequency and severity of cyclones, and associated fluvial flooding and tidal surges. The incidence of water related and waterborne diseases is expected to increase and the distribution of vector borne diseases may change (in terms of the timing and new zones of infection).

Mountain and marine ecosystems are losing 'climate space' thanks to rising air and ocean temperatures, or being directly degraded in the case of coral bleaching episodes or flooding and erosion of coastal habitats.

Two critical hotspots stand out as a consequence of multiple climate and non-climatic risk factors juxtaposed with highly vulnerable populations[52]:

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[43] Cruz, R.V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li and N. Huu Ninh, 2007: Asia. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (Eds.), Cambridge University Press, Cambridge, UK, 469-506.

[44] Kelkar, U. and Bhadwal, S. 2007. *South Asian regional study on climate change impacts and adaptation: Implications for human development*. United Nations Development Programme, Occasional Paper, 2007/27, 47pp.

[45] United Nations Framework Convention on Climate Change (UNFCCC), 2007. *Report on the Asian regional workshop on adaptation*. FCCC/SBI/2007/13, Bonn, 16pp.

[46] Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., et al. 2007. Freshwater resources and their management. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, pp 173-210.

[47] Revi, A. 2008. Climate change risk: an adaptation and mitigation agenda for Indian cities. *Environment and Urbanization*, **20**, 207-229.

[48] Rockström, J., Lannerstad, M. and Falkenmark, M. 2007. Assessing the water challenge of a new green revolution in developing countries. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 6253–6260.

[49] Asada, H. and Matsumoto, J. 2009. Effects of rainfall variation on rice production in the Ganges-Brahmaputra Basin. *Climate Research*, **38**, 249-260.

[50] Wassmann, R., Jagadish, S.V.K., Sumfleth, K., Pathak, H., Howell, G., Ismail, A., Serraj, R., Redona, E., Singh, R.K. and Heuer, S. 2009. Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. *Advances in Agronomy*, **102**, 91-

[51] Viviroli, D., Dürr, H.H., Messerli, B., Meybeck, M. and Weingartner, R. 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*, **43**, W07477.

[52] International Development Research Centre (IDRC), 2008. *From research to capacity, policy and action*. Report from the Adaptation Team to IDRC, 122pp.

- The Eastern Ganga basin (including parts of India, Nepal and Bangladesh) which is susceptible to glacial melt and flooding as well as drought due to delayed onset or weakening of the monsoon;
- The densely populated mega-deltas of the Indus, Ganga-Brahmaputra and Cauvey rivers which are susceptible to flooding, sea level rise, saline intrusion and wetland degradation.

Although *quantitative* assessments of the above impacts are increasingly available – thanks to more widespread access to regional climate change scenarios – most studies, to date, rest on the projections of just one or two climate models. Relatively few consider the wider range of plausible impacts that could arise when uncertainties in climate model structure and parameterization, emissions pathway, downscaling technique, impacts model structure and parameterization are acknowledged. Furthermore, many studies provide information on impacts in the latter half of the 21st century rather than the next few decades. Not surprisingly, there are very few practical examples of scenario-led adaptation decision-making. Given large uncertainty, decision-makers prefer adaptation responses that are "low regret" or "robust"[53] because, regardless of the climate outlook, such measures are likely to be beneficial now and in the future.

Within the framework described by Figure 1, it appears that climate model scenarios provide a persuasive case for the *need to act*, but less help with *how to act*. This assertion is supported by the following review of adaptation responses to climate variability and change across South Asia because there is little reference to climate change scenarios. However, the question still remains as to what information is most urgently needed to support these activities and what further opportunities could be realised through improved data sharing and cooperation? These needs are assessed using evidence of current adaptation in practice.

4.2 Adaptation responses

Annex 4 provides an inventory of surveyed measures to address climate variability and change impacts on the water and agriculture sectors of South Asia. As with the table of multi-agency activities (Annex 2) it is unlikely that the list is exhaustive, not least because practical cases will seldom penetrate the peer reviewed scientific literature.

Other exercises have drawn together examples of adaptation efforts from throughout the developing world[54] but, as far as the author is aware, no such table has been compiled specifically for South Asia. However, there was a recent review of climate change adaptation activities in order to identify knowledge, gaps on adaptation and research opportunities[55]. The consultations revealed that *most adaptation in South Asia is occurring through autonomous processes at the individual, household or community level*. Table 1 provides a summary of adaptation measures and accompanying information needs captured by the present survey – most occur at district, national or regional levels. More detailed project descriptions are available by country in Annex 4.

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[53] Lempert, R., Nakicenovic, N., Sarewitz, D. and Schlesinger, M. 2004. Characterizing climate-change uncertainties for decision-makers. *Climatic Change*, **65**, 1-9.

[54] World Resources Institute (WRI), 2007. *Weathering the Storm: Options for Framing Adaptation and Development.* Washington, pp57.

[55] International Development Research Centre (IDRC), 2008. *From research to capacity, policy and action: Full report of the South Asia Team*. Report from the Adaptation Team to IDRC, 46pp.

Table 1 Examples of climate adaptations and information needs in South Asia

Adaptation measure	Information needs	Locations
Disaster risk reduction		
Hazard zoning and "hot spot" mapping	Inventories of landslide, flood, drought, cyclone occurrence and impacts at district level; human development indicators	Region
Relief payments	Dense network of rain gauges to calculate meteorological drought indices; household surveys of resource access	India, Sri Lanka
Seasonal outlooks for preparedness planning	Seasonal climate forecast model; sea surface temperatures; remotely sensed snow cover; in situ snow depths; ENSO indices; monthly rainfall-runoff; crop yields; epidemiology	Region
Flood risk management		
Early warning systems for fluvial, glacial and tidal hazards	Real-time meteorology and water-level telemetry; rainfall and tidal surge forecasts; remotely sensed snow, ice and lake areas; rainfall-runoff model	Bangladesh, Bhutan
Structural and non-structural flood controls	Inventories of pumps, drainage and defence works; land use maps for hazard zoning; post disaster plan; climate change allowances for structures; floodplain elevations	Bangladesh, Bhutan, India
Artificial draining of pro-glacial lakes	Satellite surveys of lake areas and glacier velocities; inventories of lake properties and infrastructure at risk; local hydro-meteorology	Nepal
Water management		
Traditional rain and groundwater harvesting, and storage systems	Inventories of system properties including condition, reliable yield, economics, ownership; soil and geological maps of areas suitable for enhanced groundwater recharge; water quality monitoring; evidence of deep-well impacts	Afghanistan, Bhutan, Maldives, Pakistan
Long-range reservoir inflow forecasts	Seasonal climate forecast model; sea surface temperatures; remotely sensed snow cover; in situ snow depths; ENSO indices; multi-decadal rainfall-runoff series	Nepal, Pakistan
Water demand reduction and efficiency measures	Integrated climate and river basin water monitoring; data on existing systems' water use efficiency; metering and survey effectiveness of demand management	Region
Agricultural activities		
Crop selection, timing of sowing and irrigation scheduling	Long-range forecasts of monsoon onset; seasonal drought and famine forecast model; satellite surveys of soil moisture status; biophysical models of crop yield	Region
Crop vulnerability assessment	Maps of land capability under present and future climate limits for existing and new cultivars; regional climate projections and meteorology for crop modelling; multi-decadal crop yields	Region
Soil moisture conservation	Satellite monitoring of vegetation cover; meteorological data to support tactical grazing decisions	India

From the selected adaptation measures listed in Table 1 it is evident that several categories of data are being employed at <u>household- to national-levels</u>:

- ***Meteorological, hydrological and water quality*** data at river basin scales for calibrating and updating real-time flood forecasting systems, for ground-truthing satellite products; for estimating the reliable yield of aquifers, or for predicting inter-annual variations in crop yields.
- ***Soil, crop, vegetation and geological data*** for predicting landscape instability, potential for artificial recharge of groundwater, or biophysical crop modelling.

- ***Remote sensing and in situ surveys*** of natural hazards and landscape features to support risk assessments of GLOFs, landslides and infra-structure damages; high resolution topographic surveys of floodplain levels and shoreline changes.

- ***Satellite monitoring*** of precipitation, snow cover, soil moisture and vegetation greenness for water resources, irrigation and agriculture management.

- ***Socio-economic indicators*** at community- and household-levels for assessing and mapping vulnerability to hazards; water use data to refine demand management strategies; epidemiological data for public health forecasting; surveys to more effectively target post-disaster relief.

- ***Inventories of infrastructure*** condition and installed capacities of flood pumps, retention ponds, embankments, and drainage systems; likewise for traditional water harvesting and storage infrastructure to extend and prioritise refurbishment programmes.

Additional types of information and modelling capability needed to support adaptation at national to regional-levels include:

- ***Telemetry to transmit real-time rainfall and river flow data*** at upstream sites to regional flood forecasting centres.

- ***Basin wide water balance and transfers*** to enable integrated water resource management and planning for transboundary (national) resources.

- ***Sea surface temperatures and teleconnection indices*** to enable seasonal forecasting of snow cover, water resources, flood affected areas, monsoon onset and strength, crop yields and epidemics.

- ***Impact metrics*** (such as crop yields or drought indices) aggregated to district, state, national and regional scales to enable development, calibration and verification of seasonal forecast systems (see Figure 9).

The next section sets out two preliminary case studies for exploring ways in which information technologies and modelling might contribute to improved regional cooperation on adaptation. The first outlines the potential for extended lead times in flood forecasting by using satellite estimates of precipitation in headwaters. The second considers the feasibility of a region-wide seasonal forecasting system to support water planning and agriculture.

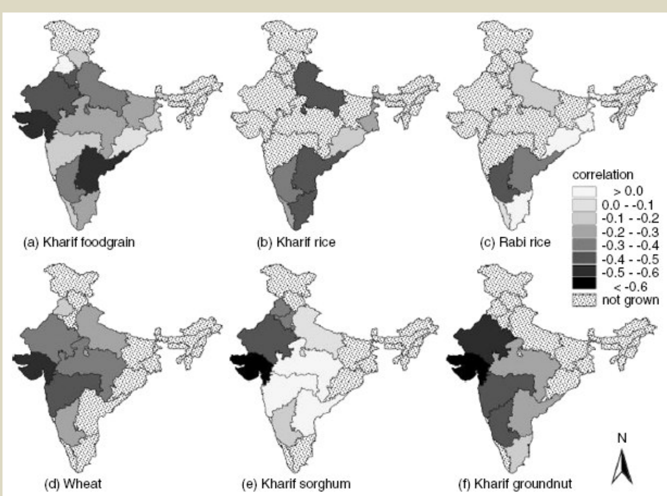

Figure 9 Correlation between summer (June–August) NINO3 SST anomalies and state-level production of different crops. The maps show the potential seasonal predictability of yields for each crop as well as the states in which forecast skill might be greatest. Source: Kumar et al. (2004)

5. CASE STUDY 1: EXTENDING LEAD-TIMES FOR FLOOD FORECASTING

Historically the most significant constraints to integrated flood management in South Asia have been more social and political than technical[56]. Bangladesh is particularly vulnerable because only 7% of the river basin area that contributes to the flows of the Ganges-Brahmaputra-Meghna (GBM) lies within the country, and 80% of the annual precipitation falls in just four months (June to September). Extreme floods in 1987, 1988 and 1998 inundated as much as 70% of country[57]. Yet this situation could worsen under climate change with the prospect of region-wide increases to mean monsoon rainfall, more intense local storms, and rising sea levels (see Box 4).

It is also recognised that structural methods of managing flood risk (e.g., upstream storage, sluice gates and embankments) are only part of the solution. Increasingly, non-structural methods (e.g., flood forecasting, insurance and land zoning) are being considered as ways of avoiding flood hazards and strengthening coping strategies. For example, the Flood Forecasting and Warning Center (FFWC) of the Bangladesh Water Development Board (BWDB) operates 30 gauging stations where 24, 48 and 72 hour forecasts are issued every day[58]. Under the bilateral arrangement with India, Bangladesh receives rainfall and water level information from several stations upstream in India. When the time taken to trigger then transmit hydrometric data from India is taken into account, the flood lead time may be only 24-30 hours for central Bangladesh and just four hours for areas near the border[59].

Several steps could be taken to improve the reliability and lead times of flood forecasts not just in Bangladesh but for all riparian states in the Hindu Kush Himalaya[60]. First, establish an integrated system for real-time data exchange amongst all parties within the GBM basin (i.e., Bangladesh, Bhutan, India, Nepal and Tibet). Second, instigate systematic transmission of water levels during the entire monsoon season (May to October). Third, share ownership and development of an integrated flood simulation model for the GBM basin. Fourth, survey the river channel cross-sections used for hydrodynamic simulation before the monsoon each year. Fifth, when upgrading and extending the hydrometric network, standardize technologies for measurement and transmission of hydrometric data. Sixth, build the region's institutional capacity and professional expertise in operational flood forecasting.

In addition to the above elements (which will feature within HKH-HYCOS) there may also be scope to extend flood forecast horizons and supplement terrestrial stations with information from numerical weather prediction models and satellite observations. For example, a prediction scheme based on NCEP-NCAR re-analysis products yielded skilful 20-day hindcasts of river discharge in the Brahmaputra and Ganges[61]. A recent appraisal of both technologies concluded that the accuracy of daily rainfall estimates from satellite observations and short-range numerical model forecasts are complimentary because satellites show greater skill in summer and models in winter[62].

The Tropical Rainfall Measuring Mission (TRMM) is satellite-based radar that measures precipitation (Figure 10). The TRMM data products are freely available and being used to

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[56] Mirza, M.M.Q., Dixit, A. and Nishat, A. 2003. Special issue on flood problems and management in South Asia: Preface. *Natural Hazards*, **28**, vii-ix.
[57] Mirza, M.M.Q. 2003. Three recent extreme floods in Bangladesh: A hydro-meteorological analysis. *Natural Hazards*, **28**, 35-64
[58] Chowdhury, M.R. and Ward, M.N. 2007. Seasonal flooding in Bangladesh – variability and predictability. *Hydrological Processes*, **21**, 335-347.
[59] Ahmad, Q.K. and Ahmed, A.U. 2003. Regional cooperation in flood management in the Ganges-Brahmaputra-Meghna region: Bangladesh perspective. *Natural Hazards*, **28**, 181-198.
[60] International Centre for Integrated Mountain Development (ICIMOD), 2009. *The Hindu Kush Himalayan Hydrological Cycle Observing System (HKH-HYCOS).* Draft Full Project Document, Kathmandu, Nepal, 109pp.
[61] Webster, P.J. and Hoyos, C. 2004. Prediction of monsoon rainfall and river discharge on 15-30 day time scales. *Bulletin of the American Meteorological Society*, **85**, 1745-1765.
[62] Ebert, E.E., Janowiak, J.E. and Kidd, C. 2007. Comparison of near-real-time estimate from satellite observations and numerical models. *Bulletin of the American Meteorological Society*, **88**, 47-64.

investigate the structure of monsoon rainfall systems around the Himalayas[63], as well as diurnal, seasonal[64] and orographic[65] controls on precipitation intensities. Other satellite "proxies" for rainfall have also been analysed. For example, an evaluation of hybrid infrared and microwave satellite precipitation algorithms over India and Sri Lanka showed accuracies to within 25% of observed precipitation for nearly half of the stations tested[66].

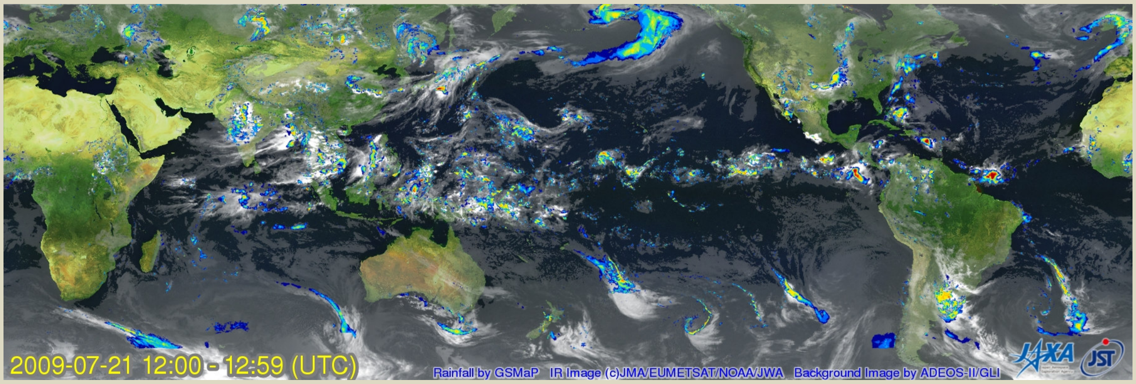

Figure 10 An example satellite image from the Global Rainfall Map Source: http://sharaku.eorc.jaxa.jp/GSMaP/

Prototype satellite-hydrological modelling systems demonstrate that remotely sensed precipitation and snow cover in headwaters can yield accurate daily flow predictions in the upper Indus[67] (Figure 11) and long-lead flood forecasts in the lower Brahmaputra[68]. Therefore, it is proposed that these technologies are further integrated and tested with a view to developing shared operational systems for longer-lead flood forecasts. This objective would also be supported by advances in numerical weather prediction and downscaling.

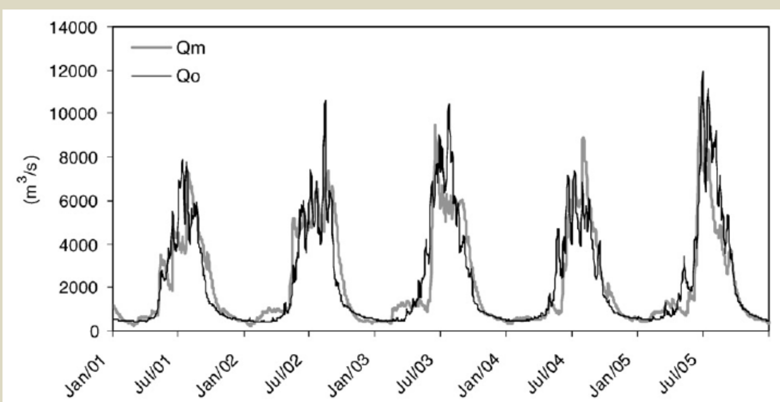

Figure 11 Observed (Qo) and modelled (Qm) runoff at Besham Qila, Upper Indus based on remotely sensed (TRMM) snow cover and precipitation data.

Source: Immerzeel et al. (2009)

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[63] Bhatt, B.C. and Nakamura, K. 2005. Characteristics of monsoon rainfall around the Himalayas revealed by TRMM precipitation radar. *Monthly Weather Review*, **133**, 149-165.

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6. CASE STUDY 2: SEASONAL FORECASTING FORUM

Adapting better to *present* climate variability is regarded by some as the first step towards addressing the greater development and scientific challenges posed by climate change[69]. This strategy for reducing vulnerability is appealing when considering the deep uncertainty in regional climate change projections for South Asia (see section 3). Furthermore, there is convincing evidence that seasonal forecasting offers valuable information for managing the effects of inter-annual climate variability on society, especially in the agricultural sector.

Seasonal climate predictability is made possible because slowly varying SSTs and land surface properties (such as the area covered by snow and ice) imprint themselves on overlying atmosphere circulation patterns for several months, or even years to come. The technique rests on the premise that relationships between the ocean forcing and remote climatic response (teleconnection) is stable in time. In practice, the strength (and sometimes even the sign) of the teleconnection varies between decades[70] meaning that forecasting systems should be regularly reviewed and re-calibrated.

There are broadly two methods of seasonal forecasting: statistical, and dynamical. Statistical techniques have been in use since the late nineteenth century and were first applied to predictions of Indian monsoon rainfall[71]. Statistical methods typically rely on relationships between large-scale/slowly-varying predictor(s) and subsequent regional-scale climate response(s). These empirical relationships might be expressed using a transfer function (such as a regression equation) or by clustering observations under similar forcing. For example, different ENSO phases have historically determined the yields of staple crops in India (Figure 12)[72]. Under warm phases (El Niño) the average drop in rice production (*Kharif season*) was 3.4 million tonnes (or 7%) during the period 1950-1999, and the value of total food grain production falls by as much as $2183 million.

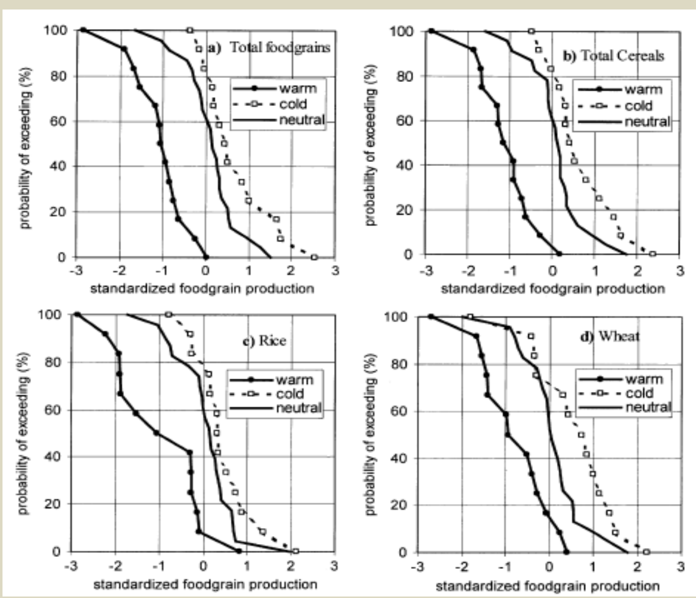

Figure 12 Cumulative frequency distributions of standardized food grain production in India during warm, cold and neutral ENSO phases: (a) total foodgrains; (b) total cereals; (c) rice; (d) wheat.

Source: Selvaraju (2003)

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[69] Washington, R., Harrison, M., Conway, D., Black, E., Challinor, A., Grimes, D., Jones, R., Morse, A., Kay, G. and Todd, M. 2006. African climate change: taking the shorter route. *Bulletin of the American Meteorological Society*, **87**, 1355-1366.

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Dynamical seasonal forecasting systems incorporate the same ocean-atmosphere processes as standard coupled Ocean-Atmosphere General Circulation Models (OA/GCMs) and daily weather forecasting models but at spatial resolutions between the two. The models are normally run with multiple sets of initial SSTs to produce ensembles of forecasts one to six months ahead. Multi-model ensemble prediction systems combine information from many different models to produce probabilistic forecasts. For example, the probabilistic forecast issued by IRI in June 2009 suggests a 40% probability of below normal precipitation across parts of India this summer (July-August-September 2009) (Figure 13).

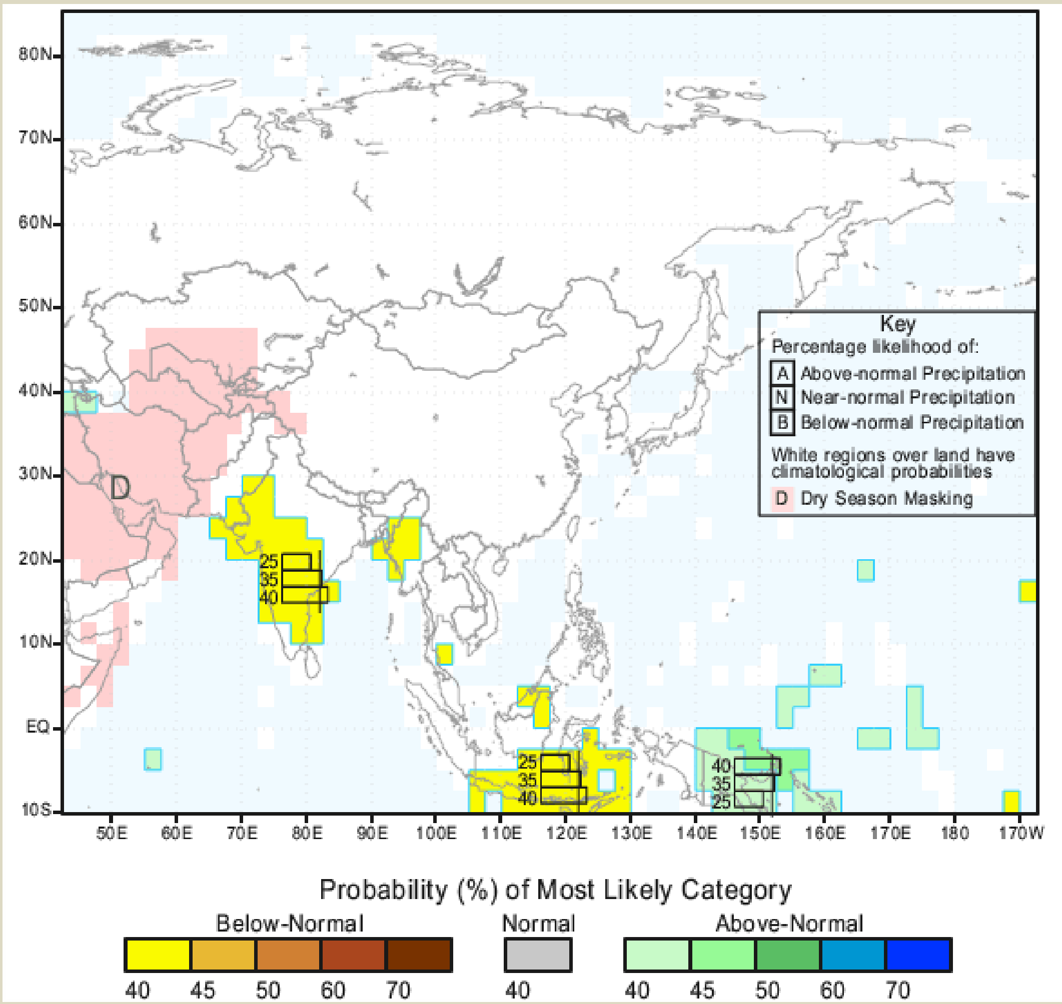
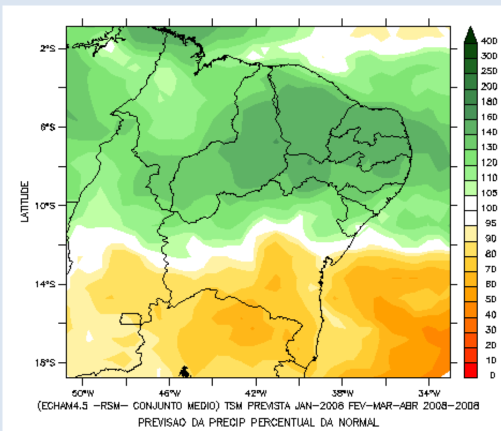


Figure 13 International Research Institute for Climate and Society (IRI) probability forecast for precipitation for July-August-September 2009, issued in June 2009. Source: http://iri.columbia.edu/climate/forecast/net_asmt/

Seasonal climate forecasts combined with real-time monitoring can help plan agricultural activities (e.g., crop planting, fertilizer and pesticide application, irrigation scheduling, etc.), wildfire, rangeland, reservoir and hydro-power management, or provide alerts for extreme events, disease control, and civil construction. Seasonal outlooks are more likely to be translated into action when disseminated at appropriate scales and in forms that are meaningful to users (i.e., salience), the technical quality of the information is perceived to be valid (i.e., credibility), and the system genuinely has the interests of users in mind (i.e., legitimacy)[73,74]. These expectations have been addressed by the seasonal forecast system developed by the Ceará State Foundation for Meteorology and Water Resources (FUNCEME), in partnership with the National Institute for Space Research (INPE), for Nordeste Brazil (Box 5). Their system and protocols for end-to-end forecasting (i.e., strong stakeholder engagement) provide a useful model for others to follow.

Box 5 - Seasonal rainfall forecasts for the State of Ceará, Brazil

Each year FUNCEME issues forecasts for the rainy season following an established format. The process begins in November with a review of Tropical SST anomalies. These are carried forward as boundary conditions for dynamical forecasts of rainfall anomalies in January-February-March. Developments of the SST fields along with forecasts from several dynamical models are then reviewed at a December/January workshop attended by a panel of experts and users. The forecasts are published at the end of the workshop.



Central to the FUNCEME methodology is the nesting of two regional models (RSM and RAMS) within ECHAM5 AO/GCM outputs generated by IRI[75]. An ensemble of ten members is generated for a period of 6 months based on December OA/GCM forecasts. This enables downscaling of probabilistic rainfall forecasts for the State of Ceará (Figure 14). FUNCEME continues to monitor ocean and atmosphere conditions and releases forecasts to end-users via a public-domain web-site (http://www.funceme.br).

Figure 14 Forecast of February-March-April rainfall anomalies (% normal) based on SSTs in January 2008, downscaled from ECHAM4.5 by RSM.

As far as the author is aware no such integrated system currently exists for South Asia. However, there are plenty of examples of forecast applications across the region including seasonal outlooks for drought and reservoir inflows (Afghanistan and Pakistan)[76], flood affected areas (Bangladesh)[77], crop yields and probabilities of crop failure (India)[78], low flows (Nepal)[79], malaria epidemics[80] and staple crop yields (Sri Lanka)[81]. All these models derive their skill from teleconnections to the tropical Pacific (ENSO). Hence, there is considerable scope for centralizing the forecasting effort and issuing region-wide outlooks of commodities, natural resources and human health indicators.

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7. CONCLUDING REMARKS

At the time of writing, India was being gripped by severe drought triggered by a 26% deficit in monsoon rainfall (Figure 15), but compounded by the legacy of unsustainable groundwater exploitation particularly in the "food bowl" states of Punjab, Haryana and Rajasthan[82]. This extreme event provides a stark reminder of the importance of a balanced approach to development and adaptation that addresses risks posed by the interplay of both climatic *and* non-climatic drivers.

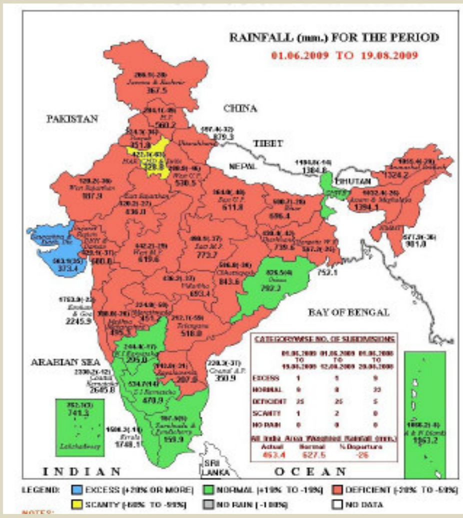

Figure 15 Rainfall anomalies for sub-divisions during the period 1 June to 19 August 2009. Source: Indian Meteorological Department

http://www.imd.gov.in/section/nhac/dynamic/pressrelease.pdf

Keeping the above point in mind, this report has brought together inventories of climate change science and cooperative programmes in South Asia. The information frames the wider context, and helps to identify opportunities for improved data gathering, exchange and uptake in adaptation and development planning across the region. Flood- and seasonal-forecasting case studies illustrate how advances in information technologies and integrated modelling could improve preparedness for extreme events affecting riparian countries. Both are "low regret" in the sense that they potentially yield benefits regardless of the climate change outlook. However, the prospect for evolving these information sources depends on parallel developments in supporting infrastructure and professional expertise (Box 6).

Box 6 – Overall assessment of remote sensing

Considerable capability to receive, process, and apply satellite remote sensing data is already in place in South and Southwest Asia, but there are substantial variations in reception and processing facilities and expertise between different nations. The application of satellite technologies to the observation and exchange of data on the climate system must, therefore, continue to be encouraged and facilitated. Needs exist to improve infrastructure in many countries, facilitate users' access to satellite data and products, expand the retrieval and validation of satellite-derived parameters and enhance satellite data processing and applications capabilities. Capacity building and investment initiatives need to be undertaken in response to these needs, taking advantage of regional and other training institutions to further develop national and regional capabilities in data pre-processing, product retrievals, and application of satellite products.

Meteorological and Oceanographic Satellite Data Centre (MOSDAC)
Center for Space Technology Education in Asia Pacific (CSSTEAP)

[82] http://timesofindia.indiatimes.com/news/india/Driving-water-under-ground/articleshow/4917122.cms

Despite the multi-faceted, contextual issues that can either enhance or constrain prospects for data sharing and cooperation amongst the information provider and user communities of South Asia, two priority actions emerged from consultations:

- ***Step change understanding and representation of the South Asian monsoon to improve climate prediction over seasonal to decadal time-scales***. This is a key objective of the Asian Monsoon Years (AMY) project which is a major initiative under the WCRP International Monsoon Study (2007-2012). However, there is an enduring need for enhanced climate science capacity in the region that could be serviced through partnerships with the UK. Furthermore, the *Changing Water Cycle* theme envisaged by the UK Research Council's *Living With Environmental Change* programme could provide an opportunity to deepen understanding of the drivers of climate variability and change, and for testing models at a process level using a wide range of observations. Research could also target the variables needed for impact assessment at the specific space and time-scales used by decision-makers.
- ***Regional training workshops to strengthen networks and build capacity in climate downscaling, impacts modelling, and decision-making under uncertainty***. Notwithstanding acknowledged limitations of scenario-led approaches to adaptation (section 1.3), there is merit in raising levels of discernment amongst climate information users at all levels so that the most appropriate products are applied to local development and adaptation planning. This includes wider recognition of alternative frameworks leading to measures that are low regret, or reversible, incorporate safety margins, employ 'soft' solutions, are flexible and mindful of actions being taken by others to either mitigate or adapt to climate change[83]. Region-wide understanding and networking could be further strengthened through judicious choice of training materials, and by multi-national participation.

Further options for enhancing regional cooperation and adaptive capacity are listed in Box 7 and explained in more detail in Annexes 5 to 8. The proposed measures include financial instruments to spread the risk associated with imperfect forecasts, development of field techniques and guidance to enhance groundwater recharge, or to ameliorate the affects of saline intrusion. Again, such measures would be beneficial regardless of the climate outlook.

Box 7 – Summary of options for strengthening regional cooperation and adaptive capacity

1. Coordinated international research programme to improve physical understanding and predictability of the South Asian monsoon over seasonal to decadal time-scales (see Annex 5).
2. Feasibility assessment of insuring small-holders against "false alarms" or "missed opportunity" seasonal forecasts (see Annex 6).
3. Extended flood-forecast lead-times through improved integration of numerical rainfall prediction and satellite observations with flood forecast models (see Annex 7).
4. Techniques for rehabilitating soils and aquifers that have been or are being affected by saline intrusion (see Annex 8).
5. Regional training workshops to strengthen networks and build capacity in climate downscaling, impacts modelling, and decision-making under uncertainty.
6. Assessing dam safety and sustainability of hydropower production under climate change.
7. Developing tools for transboundary (state and international) water allocation, including for environmental flows.
8. Development of technologies for achieving "zero runoff" through improved effluent recycling and enhanced groundwater recharge.

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[83] Hallegatte, S. 2009. Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19**, 240-247.

None of the above steps will realise their full potential unless there are strong two-way interactions between the suppliers and users of climate risk information, i.e., end-to-end forecasting. Therefore, in addition to strengthening capacity within government and development agencies, comparable effort should be invested at other levels, including vulnerable communities and farmers. For example, recent work in Africa suggests that participatory workshops can play a positive role in the provision of effective climate services to farmers[84]. However, workshop effectiveness must be assessed in the context of local dynamics of power and information flow, as well as the sustainability of participation beyond individual seasons. It is further assumed that users of forecasts have the means to react and are not hindered by lack of land, labour, credit, fertilizer or institutional factors.

Given that there are already several programmes in place with some of the above objectives in mind (e.g., AMY, HKH-HYCOS, SAARC, and SAWI) a key task will be to determine where DFID and counterparts might add greatest value. Therefore, it is recommended that the next step should be to convene a regional workshop that brings together donors, government ministries, NGO's, researchers and representatives of vulnerable communities to discuss the content of this report and to develop a coordinated plan of action. An existing forum such as SAWI or multi-lateral organisation such as ICIMOD would be well-placed to facilitate such discussions. However, to ensure that any plan is proportionate, a prerequisite should be confirmation of the available resources.

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Annex 1 Global Surface Network (GSN) stations in South Asia (1 January 2005). According to GCOS, the GSN is comprised of stations that provide good geographic coverage and have long histories and historical databases. They are considered the minimum required for characterizing global climate. These networks represent a stable and, ideally, sustainable underpinning for national networks operating on finer temporal and spatial scales.

Index	Station name	Lat/Lon	Elevation (m)
AFGHANISTAN			
40930	NORTH-SALANG	35 19N 69 01E	3,366
INDIA			
42027	SRINAGAR	34 05N 74 50E	1,587
42083	SHIMLA	31 06N 77 10E	2,202
42165	BIKANER	28 00N 73 18E	224
42182	NEW DELHI /SAFDARJUNG	28 35N 77 12E	216
42295	DARJEELING	27 03N 88 16E	2,128
42410	GAUHATI 2	06 06N 91 35E	54
42515	CHERRAPUNJI	25 15N 91 44E	1,313
42539	DEESA	24 12N 72 12E	136
42587	DALTONGANJ	24 03N 84 04E	221
42671	SAGAR	23 51N 78 45E	551
42731	DWARKA	22 22N 69 05E	11
42779	PENDRA ROAD	22 46N 81 54E	625
43041	JAGDALPUR	19 05N 82 02E	553
43063	POONA	18 32N 73 51E	559
43128	HYDERABAD AIRPORT	17 27N 78 28E	545
43279	MADRAS /MINAMBAKKAM	13 00N 80 11E	16
43295	BANGALORE	12 58N 77 35E	921
43333	PORT BLAIR	11 40N 92 43E	79
43339	KODAIKANAL	10 14N 77 28E	2,343
43363	PAMBAN	09 16N 79 18E	11
43369	MINICOY	08 18N 73 09E	2
MALDIVES			
43555	MALE 04	12N 73 32E	2
NEPAL			
44454	KATHMANDU AIRPORT	27 42N 85 22E	1,337
PAKISTAN			
41560	PARACHINAR	33 52N 70 05E	1,726
41620	ZHOB	31 21N 69 28E	1,407
41640	LAHORE CITY	31 33N 74 20E	215
41712	DAL BANDIN	28 53N 64 24E	850
41759	PASNI	25 16N 63 29E	6
41765	HYDER ABAD	25 23N 68 25E	30
SRI LANKA			
43473	NUWARA ELIYA	06 58N 80 46E	
43497	HAMBANTOTA	06 07N 81 08E	20
MALDIVES			
43599	GAN	00 41S 73 09E	2

Annex 2 Cooperative weather monitoring and climate change programmes in South Asia. Projects shown in *italics* are completed.

Programme/lead	**Activities**	**Partners**	**Sources**
Asia-CliC	Coordinates cryosphere research in Asia through: regional workshops and conferences; development and rescue of cryosphere data sets; cooperation on a snow-cover data archive. Proceedings of the 1st Asia-CliC Symposium: http://www.jamstec.go.jp/iorgc/sympo/asiaclic2006/1st_Asia_CliC_Symposium.pdf	WCRP regional initiative, scientists from over a dozen Asian countries	http://www.wmo.ch/pages/prog/wcrp/AP_CLIC.html
Asian Development Bank (ADB)	Financing regional cooperation through technical assistance grants and projects loans	Various	http://www.adb.org/SouthAsia/default.asp
Asian Monsoon Years (AMY)	A coordinated observational and modelling effort to improve Asian monsoon prediction for societal benefits through: 1) better understanding of multi-scale ocean-atmosphere-land-biosphere interactions, over diurnal, intra-seasonal to inter-annual time-scales, and role of aerosol-cloud-water cycle interactions in the Asian monsoon system; 2) improved physical representations of these interactions in coupled climate models, and data assimilation of the ocean-atmosphere-land system in the Asian monsoon region; 3) assessment of the predictability of the Asian monsoon on intra-seasonal and seasonal time scales, and the roles of land initialization in continental seasonal rainfall prediction; and 4) better understanding of how human activities in the monsoon Asia region interact with monsoon and its related environment.	GEWEX, WCRP, CLIVAR	http://www.wcrp-amy.org
BRAHMATWINN	Improving capacity to carry out harmonised integrated water resources management (IWRM) in mountain river systems like the Brahmaputra and to transfer IWRM expertise, approaches and tools, based on studies carried out in the Upper Danube River Basin in Europe, and the Upper Brahmaputra River Basin in South Asia.	ICIMOD, scientific partners in Bhutan, India, China, as well as various European groups under EU FP6	http://www.icimod.org/?page=141
Center for Space Technology Education in Asia Pacific (CSSTEAP)	The CSSTEAP vision is: Human resource development in the Asia-Pacific region in applying space science and technology for sustainable development of the region, achieved through academic excellence thereby enabling all learners to reach their individual potential.	Under the aegis of the United Nations a regional centre operates in India	http://www.cssteap.org/
Consultative Group on International Agricultural Research (CGIAR)	An alliance of scientists and policy-makers addressing sustainable production (crops, livestock, fisheries, forests and natural resources); enhancing national capacities (through joint research, policy support, training, and knowledge-sharing); germplasm improvement (for priority crops, livestock, trees and fish); germplasm collection (including holding in public trust the world's larggest seed collections in 11 genebanks); policy (fostering research on policies that have a major impact on agriculture, food, health, spread of new technologies and the management and conservation of natural resources)	15 international research centres including: the International Water Management Institute (IWMI), Sri Lanka; the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India.	http://www.cgiar.org/centers/index.html

Coordinated Regional Downscaling Experiment (CORDEX)	Provide a quality-controlled data set of regional climate downscaling (RCD) information for the recent historical past and coming century, covering the majority of populated land regions on the globe. This data set will sample uncertainties in regional climate change associated with (i) varying Global Climate Model (GCM) simulations (ii) varying greenhouse gas emission scenarios (iii) uncertainties related to natural variability and (iv) uncertainties due to different downscaling methods. CORDEX downscaling will be based on the latest set of GCM climate scenarios and predictions produced within the Fifth Coupled Model Intercomparison Project (CMIP5).	WMO, WCRP, Regional Climate Downscaling research community, national climate modelling centres and agencies	http://wcrp.ipsl.jussieu.fr/RCD_Projects/CORDEX/CORDEX.html
Delta Research And Global Observation Network (DRAGON)	Improving management outcomes for massive deltaic coastal systems like that of the Ganges by comparing the ecological, hydrological, geological, and biogeochemical processes of large deltaic systems across the globe. The scientific framework aims to compare integrate, and ultimately predict the effects of key drivers and management practices in these large ecosystems	USGS	http://deltas.usgs.gov/default.aspx?info=home
Early Warning and Environmental Monitoring Program (EROS)	Provision of timely and analytical early warning and vulnerability information to strengthen the abilities of countries and regional organizations to manage risk of food insecurity. Products include daily rainfall estimates for Central and Southeast Asia	USGS, USAID	http://earlywarning.usgs.gov/SEasia/
EU-India Cooperation in Science and Technology	Range of projects addressing sustainable development, global change and ecosystems including: development of an Assessment System to Evaluate the Ecological Status of Rivers in the Hindu Kush-Himalayan Region (ASSESS-HKH); Global Change in Mountain Regions: An Integrated Assessment of Causes and Consequences (GLOCHAMORE); Strategy and methodology for improved integrated water resource management (STRIVER); Twinning European and South Asian river basins to enhance capacity and implement adaptive integrated water resources management approaches (BRAHMATWINN)	Various Indian organisations participating in EU FP6	http://www.delind.ec.europa.eu/en/stcoop/fp6_ind.pdf
Expert Team on Climate Change Detection and Indices (ETCCDI)	Production of time series of daily temperature and precipitation extremes for 116 stations by the Expert Team on Climate Change Detection, Monitoring and Indices	WMO/CLIVAR,13 national meteorological agencies across central and southern Asia	http://cccma.seos.uvic.ca/ETCCDMI/data.shtml
Famine Early Warning Systems Network (FEWS-NET)	USAID-funded activity that collaborates with international, regional and national partners to provide timely and rigorous early warning and vulnerability information on emerging and evolving food security issues		http://www.fews.net/Pages/default.aspx?l=en
Flow Regimes from International Experimental and Network Data	The FRIEND Hindu Kush – Himalayan project developed a strategy for a Regional Hydrological Data Centre to share data from across the region, the creation of two Focal Nodal Agencies in Nepal and Pakistan, the development of prototype integrated water resource management software	UNESCO International Hydrological Programme (IHP)	http://typo38.unesco.org/en/worldwide/ihp-asia-and-pacific.html

(FRIEND)	for estimating dry season flows in Nepal and the Indian State of Himachal Pradesh, and a range of training activities which have helped develop the hydrological capacity of the region.		
From Risk to Resilience	Various activities including assessing the costs and benefits of proactive disaster risk reduction for vulnerable communities in Pakistan, India, and Nepal; developing and documenting methods for community risk assessment and adaptation and implementing livelihood resilience pilots and research in regions vulnerable to extreme climatic variability and change	Institute for Social and Environmental Transition (ISET), ProVention Consortium, IDRC	http://www.i-s-e-t.org/
Global Climate Observing System (GCOS)	Regional action plan for South and Southwest Asia based on discussions held at the seventh GCOS workshop in New Delhi, October 2004. Participating countries were: Afghanistan, Bahrain, Bangladesh, Bhutan, India, Iran, Iraq, Kuwait, Maldives, Nepal, Oman, Pakistan, Qatar, Saudi Arabia, Sri Lanka, United Arab Emirates, and Yemen.	WMO, UNEP, GEF, UNDP	http://www.wmo.int/pages/prog/gcos/documents/GCOS_SSWA_RAP_FINALDRAFT_Sept2005.pdf
Global Land Ice Measurement from Space (GLIMS)	An inventory of the majority of the world's 160,000 glaciers	60 institutions worldwide	http://nsidc.org/glims/
HighNoon	Assessing the impact of Himalayan glaciers retreat and possible changes of the Indian summer monsoon on the spatial and temporal distribution of water resources in Northern India and providing recommendations for appropriate and efficient response strategies that strengthen the cause for adaptation to hydrological extreme events.	EU FP7	http://www.eu-highnoon.org/nl/25222858-Home.html
Himalayan Glaciers and Rivers Project	Builds on glacial research in the Indian and Nepali Himalayas and on the Tibetan Plateau and links to ongoing freshwater and species programme work in the Ganga Basin of India, including the Climate Witness approach in the Sundarbans. In Nepal, the project implements adaptation measures in Gokyo lake, which is partially fed by Ngozumpa glacier. It supports the High Altitude Wetlands project in Ladakh, India through a Climate Witness project component.	WWF	http://www.panda.org/what_we_do/where_we_work/project/projects/index.cfm?uProjectID=9S0814
Hindu Kush Himalayan Hydrological Cycle Observing System (HKH-HYCOS)	The project goal will be to establish an efficient and operational flood information system based on real-time data and information on a regional level involving Bangladesh, Bhutan, China, India, Nepal and Pakistan.	WMO, ICIMOD, National Meteorological and Hydrological Agencies, USAID/OFDA, DANIDA	http://www.whycos.org/rubrique.php3?id_rubrique=35
Indo-UK programme on climate change impacts and adaptation-phase II	Five projects linking water and agriculture in river basins; development of high-resolution climate change scenarios for India; state-level vulnerability and adaptation assessment Madhya Pradesh; state-level vulnerability assessment and adaptation strategies Orissa; and the socio-economic impact of climate extremes	DECC; IIT,Delhi; Indian Institute of Tropical Meteorology, Pune; Madhya Pradesh-Development Alternatives, New Delhi;	http://www.hindu.com/2009/05/12/stories/2009051252601100.htm

		Orissa-Winrock International India; IIM, Ahmedabad	
International Centre for Integrated Mountain Development (ICIMOD)	Projects include protecting water and other natural resources under extreme weather conditions and other pressures; developing crop varieties that are adapted to harsh climates; identifying policy and institutional innovations that enable countries and communities to cope with these conditions. See: http://news.bbc.co.uk/1/hi/sci/tech/8109389.stm	Partnership of regional countries, partner institutions, and donors	http://www.icimod.org/ http://books.icimod.org/index.php/search/publication/549
International Research Institute for Climate and Society (IRI)	Outlook forums involving scientists and representatives of university and government forecasting organizations, national meteorological services and international forecasting centers. At each meeting, the climate scientists fashion seasonal forecasts for their regions.		Seasonal mean forecasts: http://portal.iri.columbia.edu/portal/server.pt?open=512&objID=944&PageID=0&cached=true&mode=2
Living Ganga Programme	Developing vulnerability assessment indices for identified areas in the Ganga basin; integrating vulnerability assessment processes into project components for developing adaptation strategies; implementing site specific adaptation pilots; sharing knowledge of field adaptation strategies and best practices.	WWF, HSBC, IWMI, the Indian Institute of Technology, Local Governments for Sustainability (ICLEI), Ecofriends, various industry associations, central and state government institutions	http://www.wwfindia.org/about_wwf/what_we_do/environment_development/wwf_hsbc_partner/
Monsoon Himalayan Precipitation Experiment (MOHPREX)	*Radiosondes launched from two sites on the southern flanks of the Himalaya in Nepal to improve understanding of the diurnal cycle of precipitation, evolution of the atmosphere during the monsoon onset, regional-scale variability of weather, and coupling of monsoon and hydrological cycle at altitude.*	*Intense field campaign June 2001 supported by NSF, the Nepal Department of Hydrology and Meteorology*	*Barros and Lang (2003)*
ProVention	Five thematic priorities for research: mainstreaming risk reduction, risk analysis and application, reducing risks in recovery, risk transfer and private sector investment, expanding risk research and learning	Coalition of international bodies, governments, private sector and civil society led by World Bank	http://www.proventionconsortium.org/?pageid=1
Regional Cooperation in Flood Forecasting and Information exchange	Application of NOAA Satellite Rainfall Estimation (SRE) in the Hindu Kush-Himalayan Region – Phase II. Project objectives include to: validate and improve Rainfall Estimates (RFE) provided by NOAA; implementation of SRE to flood forecasting; people-centered, end-to-end forecast system operational in pilot basins; capacity building of ICIMOD and partner countries in SRE techniques.	ICIMOD, USAID-OFDA, USGS, NOAA	http://www.icimod.org/?page=156
Regional Integrated	Establishing a regional network of multi-hazard observing stations; exchange	Facilitated by the Asian	http://www.ga.gov.au/image_cache/GA1

Multi-hazard Warning System (RIMES)	of real-time data; provision of tsunami watch to national warning centers; capacity building of early warning professionals	Disaster Preparedness Center (ADPC)	2454.pdf
Snow and Glacier Aspects of Water Resource Management in the Himalayas (SAGARMATHA)	*To assess the seasonal and long-term water resources in snow and glacier-fed rivers originating in the Hindu-Kush Himalayan region and to determine strategies or coping with impacts of climate-change-induced deglaciation on the livelihood of people in the region.*	*Knowledge Acquisition and Research programme of DFID*	*http://www.dfid-kar-water.net/projects/files/R7980.html*
South Asia Water Initiative (SAWI)	Cooperative management of shared waters that drain from the Greater Himalayas, which will in turn promote poverty reduction, low carbon growth and regional stability. The Alliance is currently designing a project to integrate climate change and river models, and use this information to explore the impacts (and possible interventions) for livelihoods, poverty, food production, migration	7 countries - Afghanistan, Bangladesh, Bhutan, China, India, Nepal and Pakistan. Multi-donor trust administered by the World Bank on behalf of DFID and AusAID	http://huwu.org/climatechange/projectsearch/proj_details.asp?projID=182&ck=sU7CF7pftNaNIG5
South Asian Association for Regional Cooperation (SAARC)	The SAARC Disaster Management Centre (SDMC) was established at the National Institute of Disaster Management in New Delhi. SDMC provides policy advice and facilitates capacity building services including strategic learning, research, training, system development and information exchange for effective disaster risk reduction and management in South Asia.	Member Countries - Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka	http://saarc-sdmc.nic.in/index.asp http://www.saarc-sec.org/?t=2.6
Third Pole Project (3PP)	Building the capacity of local media in Himalayan region and in downstream countries to understand the complex issues of climate change and its impacts via training, online tutoring, digital media tools, and other methods such as disseminating the work of leading scientists	Chinadialogue, Internews, International Center for Communication Development, EJN	http://www.internews.org/flyers/FlyerEJN_3PP_200807.pdf
UK-India Education and Research Initiative (UKIERI)	A major award was made for a project on Climate Change Science for India. This work is intended to improve capability to forecast India's climate in the coming decades by linking India's knowledge of the monsoon with the UK's expertise in climate prediction.	University of Reading, Indian Institute of Tropical Meteorology, Pune	http://www.ukieri.org/
United States Department of State's South Asia Regional Environment Office (REO)	*Drought assessment and mitigation in southwest Asia focuses primarily on parts of Afghanistan, Pakistan and western India. The Project analyzes hydro-meteorological and human factors involved, conducts reviews of existing drought coping and management experiences in the region and identifies knowledge gaps.*	*Pakistan Agricultural Research Council, Pakistan Meteorological Department, Central Arid Zone Research Institute*	*http://www.iwmi.cgiar.org/droughtassessment/index.asp*
United Nations Development Programme (UNDP)	National Adaptation Programmes of Action (NAPAs) plus supporting projects including: Comprehensive Disaster Risk Reduction Programme (CDRRP) (Afghanistan); Reducing Climate Change-induced Risks and Vulnerabilities from Glacial Lake Outburst Floods in the Punakha-Wangdi and Chamkhar Valleys (Bhutan); Comprehensive Disaster Management Programme	Various	http://www.undp.org/asia/environment.shtml

	(Bangladesh); Atoll Ecosystem-based Conservation Project in Baa Atoll (Maldives); Disaster Risk Reduction at the National Level (Nepal); National Environmental Information Management System (NEIMS) (Pakistan)		
WATCH	Brings together hydrological, water resources and climate communities to analyse, quantify and predict the components of the current and future global water cycles and related water resources states; evaluate their uncertainties and clarify the overall vulnerability of global water resources related to the main societal and economic sectors.	EU FP6 project Coordinated by the Centre for Ecology and Hydrology (CEH) and Wageningen UR	http://www.eu-watch.org/nl/25222705-Home.html
Western Orissa Rural Livelihoods Project (WORLP)	Contributes to reducing poverty by promoting livelihoods initiatives for the poorest by involving all sections of rural society across caste, class, gender and other divides. WORLP focuses on building, and working with, people's existing strengths and resources by informing, enabling, initiating and empowering appropriate choices for long-term well being.	Government of Orissa Watershed Development Mission, DFID	http://www.worlp.com/ s
World Food Programme	Vulnerability analysis and mapping, early warning systems, emergency needs assessments, and weather-based insurance which have been recognised as key adaptation instruments in the Bali Action Plan. An example project involved digging 227 water wells and rehabilitating 652 reservoirs throughout Afghanistan – all in exchange for food	Community level assistance	http://www.wfp.org/content/building-resilience-climate-changes

Annex 3 Catalogue of observed climate trends for regions of South Asia

Regions	Variables	Periods	Trends	Sources
Afghanistan	Satellite images of glacier positions in Wakhan Pamir	1976-2003	28/30 glacier terminus positions have retreated, the most rapid at an average rate of 36 m/yr; disconnection of tributary glaciers from main trunk; increased are and number of proglacial lakes	Haritashya et al. (2009)
Bangladesh	Annual and monthly rainfall totals, monthly maximum and minimum temperatures at five stations	1960s+	No trend in annual rainfall totals, significant decrease during monsoon at two stations, increase during dry season at several stations; increased maximum temperatures; decrease in minimum	Ali et al. (2007)
	Meteorological records for the Ganges basin prior to and following the upstream water diversion by the Farakka Barrage	1968-1996	Increased heating and cooling degree days, higher (lower) summer (winter) mean temperatures, increased maximum relative humidity, fewer heavy rainfalls following the loss of Ganges wetlands	Adel (2002)
	Monthly temperature and precipitation from the CRU TS 2.1 gridded data set for the Brahmaputra basin	1901-2002	No clear trend in precipitation, 6 out of the 10 warmest years occurred since 1995; ENSO not correlated with monsoon rainfall	Immerzeel (2008)
	Frequencies of storms and depressions forming in the Bay of Bengal	1974-1999	Reduced frequency of storms	Alam et al. (2003)
Bhutan	Inventory of variations in glacier lakes based on photographs, satellite imagery, maps and observation	1950s-	In northern region there has been growth of supraglacial ponds on some debris-covered glaciers, and expansion of proglacial lakes as glaciers shrink	Ageta et al. (2000), Komori (2008), Karma et al. (2003)
Himalayas	High-resolution snow accumulation record from Dauopu (central Himalayas)	Last 295 years	The monsoon weakened in 18th century and strengthened throughout much of 19th and early 20th century, and then weakened again from the early 1920s to the present	Duan et al. (2004)
	Monthly precipitation totals, monthly maximum and minimum air temperature, monthly mean temperature, monthly winter snow depth for stations in northwest Himalayas	1866-2006	No trend in winter precipitation but significant decrease in monsoon precipitation; significant increasing trend in annual temperature (and reduced snowfall amounts) particularly in winter; significant increase in diurnal temperature range with maximum increasing most; weakened influence of NAO (winter) and ENSO (summer) on precipitation since late 1960s	Bhutiyani et al. (2009; 2007)

	Daily discharge and annual maximum flood for rivers in the northwest (Beas, Chenab, Ravi and Satluj)	1922-2004	Statistically significant decrease in average annual and monsoon discharge and insignificant increase in winter and spring discharge, despite increasing temperatures during all three seasons; decreasing discharge during winter and monsoon seasons in the post-1990 period, despite rising temperatures and average monsoon precipitation indicates decreasing contribution of glaciers to the discharge and their gradual disappearance; increasing frequency of high-magnitude flood events	Bhutiyani et al. (2008)
	Field surveys and remotely sensed glacier extent, mass balance and seasonal snow cover for 466 glaciers in Chenab, Parbati and Baspa basins	1962-2001	Overall reduction in glacier area of 21%, average stream runoff of the Baspa basin has increased by 75% in December	Kulkarni (2007); Kulkarni et al. (2007)
India	Extreme daily precipitation indices	1910-2000	Moderate increase in measures related to the total annual rainfall, frequency of small to large daily events, and intensity of large rainfall events	Roy & Balling (2004; 2009)
	Annual and monsoon rainfall in the Himalayas based on analysis of the 30 stations	1901-1980	Increasing totals to 1965, a decline thereafter	Basistha et al. (2009)
	All India monsoon (June-September) rainfall index	1881-1998	Coherence in the strength of the Indian monsoon and East Asia monsoon	Kripalani and Kulkarni (2001)
	Monthly rainfall for five major regions and combinations of region, including all India	1871-2003	Unstable relationship between ENSO and drought; marked weakening of correlation in recent years	Kane (2006)
	Monthly temperature anomalies in summer (March to June) for seven homogeneous regions	1901-2003	Small decreasing trend in the northwest and western Himalaya regions and a small increasing trend in the other five regions	Ganguly and Iyer (2009)
	Seasonal and annual mean, maximum and minimum temperature series at 125 stations distributed over the whole of India	Check	Annual mean, mean maximum and mean minimum temperatures increased at the rate of 0.42, 0.92 and 0.09°C century^{-1} respectively. On a regional basis, stations of southern and western India warmed by 1.06 and 0.36°C century^{-1} respectively, while stations of the north Indian plains cooled by 0.38°C century^{-1}. Seasonal mean temperatures increased by 0.94°C century^{-1} for the post-monsoon season and by 1.1°C century^{-1} for the winter season.	Arora et al. (2005)
	Seasonal and annual maximum, minimum, mean, range, and extreme temperatures for nine river basins in northwest and central India	Check	Of the nine river basins studied, seven showed a warming trend, whereas two showed a cooling trend. The Narmada and Sabarmati river basins	Singh et al. (2008)

			showed the maximum warming and cooling, respectively. Most basins in the study area show increasing trend in T-range, H-max and L-min. Seasonal analysis shows that the greatest changes in T-max and T-mean were observed in the post-monsoon season, while T-min experienced the greatest change in the monsoon season	
	Monthly grass reference evapotranspiration estimated from meteorological data at 133 selected stations	1971-2002	Significant decreasing trend all over India caused by a significant increase in relative humidity and a consistent significant decrease in wind speed throughout the country	Bandyopadhyay et al. (2009)
	Field survey and remote sensing of Parbati glacier terminus, Himachal Pradesh	1990-2001	Glacier has retreated by 578 m; high rate explained by 90% of glacier located below the snowline at the end of the ablation season (~5200 m)	Kurkani et al. (2005)
India/ Sri Lanka	Grid area-average rainfall anomalies	1856-2004	Persistent droughts in the 1850s-1860s, 1870s, 1890s, 1930s and 1950s linked to tropical SSTs	Herweijer and Seager (2008)
Maldives	Daily, monthly, annual, maximum daily precipitation total at Hulhulé (Malé International Airport)	1975-2005	No significant long term trends	MEEW (2006)
	Annual mean sea surface temperatures (SSTs); mean tidal level (MTL)	1988-1998	Annual mean SST trends at Hulhulé and Gan are 0.2±℃ and 1.1 to 1.6℃/decade respectively; rates of MTL change are: +8.5, 7.6, and 5.8 mm/yr during the post-monsoon (October-December), pre-monsoon (March-May) and southwest monsoon (June-September) seasons respectively.	Singh et al (2001); Khan and Quadir (2002)
Nepal	Maps of glacier surface areas Sagarmatha national park	Late 1950s to early 1990s	Overall 4.9% decrease in glacier area (but subject to possible cartographic errors; some larger, higher altitude, south facing glaciers increased in area	Salerno et al. (2008)
	Terminus elevations and mass balance of glaciers in Hidden Valley, Mukut Himal	1974-1994	Retreat of glaciers by 30-60m, Rikha Samba glacier lost 13% of total mass	Fujita et al. (1997)
	Ground temperature measurement and seismic reflection soundings of permafrost lower limits southern-aspect slopes	1973-2004	Permafrost lower limit has risen 100-300m in response to warming of 0.2 to 0.4℃; the rise in permafrost limit exceeds that of the Tibetan Plateau	Fukui et al. (2007)
	Monthly mean maximum and minimum temperatures for 49 stations	1971-1994	No significant trend in minimum temperatures at the majority of sites; significant rise in maximum temperatures, more rapid in the Middle Mountain and Himalayan region than southern plains	Shrestha et al. (1999)

	Monthly meteorological and hydrological records for the Kosi Basin	1947-1993	Localised increases in temperature and precipitation; localised decrease in streamflow particularly during low flow months	Sharma et al. (2000)
	Monthly, annual and seasonal precipitation totals for 78 stations	1948-1994	Significant variability on annual and decadal time scales but no distinct long-term trends; all-Nepal record correlates well with precipitation from northern India, and with the SOI series during the monsoon period	Shrestha et al. (2000)
	Standardized precipitation anomalies	1987-1996	Positive correlation between monsoon rainfall and the Southern Oscillation Index, but composite analysis shows no positive anomalies over Nepal	Ichiyanagi et al. (2007)
	Inventory of landslide fatalities	1978-2005	High level of inter-annual variability but overall trend is upward; strong correlation with Hill districts monsoon precipitation index; rise in fatalities also explained by rural road building	Petley et al. (2007)
Pakistan	Seasonal mean, maximum and minimum temperature series at seven stations in the Upper Indus Basin, compared with records from neighbouring regions	1961-2000	Winter mean and maximum temperature show significant increases while mean and minimum summer temperatures show consistent decline. Increase in diurnal temperature range is consistently observed in all seasons and in the annual dataset (as in the case of much of the Indian subcontinent).	Fowler and Archer (2006);
	Annual, winter (October to March) and summer (April to June) precipitation totals at 17 stations in Upper Indus Basin	1893-1999	No long term trend, but a significant in winter, summer and annual totals at several stations from 1961-1999. Significant positive (negative) correlations between winter (summer) NAO and winter (summer) precipitation in the Karakoram	Archer and Fowler (2004)
	CRU TS 2.1 gridded climatology for Upper Indus	1972-2002	Clear warming trend in all seasons, with the strongest trend in winter and the weakest in summer; annual warming rate is greater at higher (5000m) than lower (2000m) elevations; winter snow cover reducing by 2.2% yr^{-1} at 5000m	Immerzeel et al. (2009)
	Monthly gridded precipitation anomalies	1936-1995	Above (below) normal winter snow depth over European Russia and corresponding below (above) normal snow depth over central Siberia is associated with reduced (increased) summer monsoon rainfall over southern and western India and eastern Pakistan	Ye and Bao (2001)

	Documented glacier surges in the Karakoram	1860s-	34 surges involving 23 glaciers, with increased frequency since 1985 linked to high-altitude warming affecting snow and glacier thermal regimes, or intense, short-term melting episodes	Hewitt (2005; 2007)
South Asia	Indices of daily temperature and precipitation extremes	1961-2000	Warming of minimum and maximum temperatures, slight indication of disproportionate increases in precipitation extremes	Tank et al. (2006)
	Aerosol concentrations, soot amount and solar fluxes over the Indian Ocean	2000-2003	Atmospheric brown clouds (resulting from biomass burning and fossil fuel consumption) enhanced lower atmospheric solar heating by about 50%, suggesting that brown clouds contribute as much as the 1950s+ increase in anthropogenic greenhouse gases to regional lower atmospheric warming trends	Ramanathan et al. (2007)
Sri Lanka	Tropical cyclone frequency and intensity in the Bay of Bengal during May, October and November	1877-2005	Significant increase in frequency during the intense cyclonic months, most notably in November	Singh (2007)
	Monthly rainfall for 15 stations	1869-2000	Significant changes in southwest-monsoon-related precipitation at five stations, with three stations showing enhanced rainfall, two stations a decrease in rainfall with time, and one station experienced a decrease of both first and second inter-monsoon rainfall over time. The stations showing loss of rainfall are confined to higher elevation areas and those exhibiting enhanced rainfall are located in the lowlands in the southwestern sector.	Malmgren et al. (2003)

Annex 4 Examples of measures to address climate variability and change impacts on water and agriculture sectors in South Asia

Regions	Measures	Data and modelling needs	Sources
Afghanistan	Famine Early Warning Systems Network (FEWS-NET)	Remotely sensed river networks, and irrigated and un-irrigated lands in mountainous areas; estimates of seasonal actual evapotranspiration for irrigated areas based on the Normalized Difference Vegetation Index (NDVI).	Krasnozhon and Zurmati (1992), Senay et al. (2007)
Afghanistan/ Pakistan	Prioritizing karez (qanat) systems for re-vitalization	Inventories of karez condition, length, water output, irrigated area; information on karez ownership, degree of community dependence on the source, cultural/ religious/historical value, maintenance costs, scope for introducing water conservation technologies	Hussein et al. (2008)
	Potential for seasonal forecasts of drought from ENSO phase	November-April anomalies of precipitation over central and southwest Asia, combined with sea surface temperature (SST) anomalies over the tropical Pacific	Barlow et al. (2002)
Asia	Change crop varieties and/or timing of agricultural activities	CO_2 concentrations, local daily temperature, soil moisture deficit, salinity, and atmospheric vapour pressure deficit; biophysical models of crop yields	Luo and Lin (1999)
	Spatial and temporal vulnerability ("hot spot") assessment of rice production systems to stress from heat, drought and/or salinity	Maps of rain-fed rice and precipitation anomalies, maps of regions where current temperatures are already approaching critical levels during susceptible stages of the rice plant, maps of rice growing areas on mega-deltas threatened by sea level rise	Wassmann et al. (2009)
Bangladesh	Fluvial flood forecasting and warning system; 20-day flow forecasts	Real-time rainfall-runoff data from upstream areas within the Ganges-Brahmaputra-Meghna catchment; National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data	Ahmad and Ahmed (2003); Webster and Hoyos (2004)
	Combination of structural and non-structural flood control measures for Dhaka City	Data on the condition and installed capacity of drainage network, retention ponds, pumps; information to raise awareness of drain maintenance issues and flood preparedness; surveys of land suitable for flood retention and zoning	Faisal et al. (2003)
	Seasonal forecast of flooded affected area; forecasts of flows in the Ganges with lead-time of one year	El Nino-Southern Oscillation and Indian Ocean SST indices, standardized deviation of seasonal (June to September) rainfall over Bangladesh, and upstream in the Ganges-Brahmaputra-Meghna river system, homogeneous flood affected area (FFA) time series; daily discharge measurements, remotely sensed precipitation and snow cover	Chowdhury (2003), Chowdhury & Ward (2007), Jian et al. (2009) Kamal-Heikman et al. (2007), Whitaker et al. (2001)
	Private transfers (gifts) to those affected by	Household surveys	Mozumder et al. (2009)

	massive flooding		
	Change crop varieties and/or timing of agricultural activities	CO_2 concentrations, local daily temperature, soil moisture deficit, salinity, and atmospheric vapour pressure deficit; biophysical models of crop yields	Karim et al. (1996), Faisal and Parveen (2004)
Bhutan	Conservation of natural resources (water and forests)	Forest cover surveys, river and lake water levels	Uddin et al. (2007)
	Warning systems for Glacier Lake Outburst Floods (GLOFs), flash floods; hazard zoning; rain water harvesting	Networks of early warning systems; national data base on flood and landslide prone areas close to settlements; telemetered synoptic stations, data assimilation system, and limited area weather model for forecasting flash floods; surveys of glacial lake depths and channel slopes to assist artificial draining and hazard zoning; soil properties and surface water fluxes to identify areas suitable for water harvesting	NEC (2007)
	Detecting potentially dangerous glacial lakes	Repeat space-borne optical data to monitor expansion of glacial lake areas	Fujita et al. (2008), Komori (2008)
India	Prediction of monsoon rainfall on 15-30 day and seasonal timescales; probabilistic forecasts of (groundnut) crop failure; foodgrain production forecasts; community based preparedness planning, drought monitoring and early warning systems	Estimates of rainfall from the Geostationary Operational Environmental Satellite (GOES) Precipitation Index (GPI) product, NCEP–NCAR reanalysis data; annual national production of foodgrains, state-, and sub-divisional level crop yields; ENSO and Indian Ocean SST indices; monthly NDVI, soil moisture and surface temperature	Webster and Hoyos (2004), Selvaraju (2003), Prabhakar and Shaw (2008), Prasad et al. (2007), Challinor et al. (2005a;b), Kumar et al. (2004), Nayagam et al. (2008)
	District level analysis to determine areas of rice production that are most vulnerable to rainfall variation	Multi-decadal records of rice production and cultivated area at state and district level; gridded monthly rainfall totals; flood affected area; district-level mapping of composite biophysical, social and technological indicators of adaptive capacity	Asada and Matsumoto (2009), O'Brien et al. (2004)
	Soil moisture conservation techniques increase forage yield	NDVI to estimate green vegetation and range management; ground monitoring of short-term environmental (seasonal) conditions, include support for tactical grazing decision-making, statutory reporting, range monitoring, and production forecasting.	Tewari and Ayra (2005), Mishra et al (2002)
	Mainstreaming climate change risk assessment , adaptation and mitigation measures into existing institutional structures and natural hazards programmes	Maps of climate vulnerability at district level; risk assessment considered as part of urban renewal plans	Revi (2008)
	Integrated framework for local level, water planning and management	Data on existing systems' water use efficiency, effectiveness of demand management, and conservation; real-time water balance information for early flood and drought warning; infiltration and groundwater properties to identify zones for artificial recharge	Gosain et al. (2006)

	Water demand reduction and management measures	National climate monitoring programme, river basin characteristics, water availability and demands in water scarce regions (now and projected), improved coordination and exchange of data, Hydrological Information System for collection, processing, storage and dissemination; remote sensing and field survey to update the database	Kumar et al. (2005)
	Resource accessibility vulnerability index	Questionnaire survey of respondents from villages, local NGOs, members of local (*Zilla Parishad*) and *mandal* level government administrations; socio-economic determinants of access to resources in the wake of tropical cyclones	Bosher et al. (2007)
	Changes in sowing date and genotype selection, high intensity irrigation to buffer against dry years	CO_2 concentrations, local daily temperature, soil moisture deficit, salinity, and atmospheric vapour pressure deficit; biophysical models of crop yields	Attri and Rathore (2003), Mall et al. (2004), Pathak and Wassmann (2008), Challinor et al. (2007)
Maldives	Vulnerability assessment of atoll reef islands to sea level rise and cyclone impacts; revegetation of beach ridges, shoreline nourishment and protection	High resolution topographic surveys of reef islands, mean sea level (datum); spatial variation of water levels during extreme events, including observations of wave runup, water table behaviour, and ponding of water in island interiors; surveys of sediment production and transport, lithification and coastal vegetation; satellite sensing of waterline and shoreline changes; spatial variations in wave energy due to monsoon	Woodroffe (2008), Kench et al. (2009)
	Rainwater harvesting, desalination, bottled water import, development of *kulhis* (freshwater ponds); artificial recharging of aquifers to reduce saltwater intrusion and storm surge flooding; underground community rainwater tanks	Water quality monitoring and groundwater assessment; water balance modelling to assess groundwater recharge and sustainable yields; basic information on rainfall, vegetation cover, porosity and permeability of soils, tidal movements, groundwater abstractions	Ibrahim et al. (????)
Nepal	Artificial draining of glacial lakes, raised awareness of upstream hazards, warning systems and contingency planning	Regional hydrological database and inventory of lake size, dam stability, information about communities and infrastructure downstream to identify lakes posing greatest risks	Chalise et al. (2005), Kattelmann (2003)
	Detecting glacier motion and potentially dangerous glacial lakes	Repeat space-borne optical data to monitor spatial-temporal variations in glacier velocities and glacial lake areas	Bolch et al. (2008), Kääb (2005)
	Potential seasonal prediction of below normal flows due to El Niño	Mean monthly streamflow for Karnali, Narayani and Koshi basins, ENSO indices	Shrestha and Kostaschuk (2004)
Pakistan	Seasonal forecasts of runoff and reservoir inflows	Seasonal precipitation and runoff totals; satellite snow cover observations to predict seasonal runoff	Archer & Fowler (2008), Dey et al. (1983), Makhdoom and Solomon (1986)
	Long-term water balance and resource	Vertical spatio-temporal distribution of total annual precipitation based	Winiger et al. (2005)

	estimate for the Indus irrigation scheme	on *in situ* measurements of meteorology and snow depth, combined with remotely sensed snow cover	
	Monitoring systems to assist water and drought management, more efficient irrigation water conveyance and scheduling, encourage traditional water spreading to recharge aquifers, local water storage tanks	Drought monitoring and impact assessment, quantitative evidence of impacts of deep tube-well technology on traditional methods such as the drying of karezes	Ahmad et al. (2004)
Sri Lanka	Seasonal forecasts of rainfall, stream flow, coconut and rice production; forecasts of high and low risk years for future malaria epidemics	Monthly sea surface temperatures, rainfall totals, stream flow, national coconut and rice yields	Chandimala and Zubair (2007); Zubair (2002; 2003); Peiris et al. (2008), Zubair et al. (2008); Bouma and vanderKaay (1996)
	District level drought relief payments	Dense network of rain gauges to calculate meteorological drought indices	Lyon et al. (2009)
	Mapping hazards and risk hot spots	Data for administrative divisions on monthly climatology, river flow and (land slide, flood, drought, cyclone) hazards; population, socio-economic, infrastructure, food security, and human development indicators	Zubair et al. (2006)
	Improved water efficiency, reduced cropped areas, earlier planting, shorter duration crops, relocating paddy production (to cooler central highlands)	Monthly rainfall, reference evapotranspiration and paddy irrigation requirements in the wet season (*Maha*); climate model projections; household-level data to analyze long-term climate impacts on farm profitability using Ricardian models	De Silva et al. (2007), Kurukulasuriya and Ajwad (2007), Seo et al. (2005)
	Sensitivity testing of food security and environmental quality to changed cropped area and irrigation depth	Global land surface climate data set; annual mean temperature and precipitation changes from GCMs; basin scale water allocation and field scale models	Droogers (2004), Droogers and Aerts (2005)
	Hardier tea clones to resist drought, pests, diseases; improved shade and soil management; expand multi-cropping	Yield components of tea (shoot population density, shoot weight, and shoot extension rate), CO_2 concentrations, local daily temperature, soil moisture deficit, and atmospheric vapour pressure deficit; empirical models of crop yields	Wijeratne (1996)

Annex 5 Improving operational seasonal forecasts of the South Asian monsoon

1. Principal Objective

To improve the skill of seasonal and intra-seasonal forecasts of the South Asian monsoon to improve planning for droughts and flooding at national and district scales.

2. Rationale

The South Asian summer monsoon is the lifeline of the subcontinent. For example, most regions of India receive more than 80% of their annual rainfall during the South West Monsoon season (June-September). Agriculture over large tracts of the region is still largely rain-fed; river systems and water reservoirs are dependent on this rainfall; hydro-electric power generation is primarily dependent on this rainfall. Hence, failure of the monsoon can have significant impacts on agriculture and industrial output of the region. Therefore, a seasonal forecast system with a high degree of accuracy and sufficient lead time (about 2 months) at the scale of the sub-continent would help Governments to formulate plans for water conservation, power generation, relief payments, commodity imports, etc.

Intra-seasonal forecasts that provide outlooks of active/break spells of the monsoon can be of great help as farmers can fine tune their sowing and irrigation patterns. Reservoir operations can also be managed in a better fashion.

Short range forecasts will be useful for flood control, reservoir operations and disaster management and mitigation.

Potential Benefits

– Formulating plans for the coming monsoon season and beyond. If a drought is forecast, then plans can be made for water allocation, reservoir operations can be optimized and water conserved for coming seasons.

– Alert government to augment food grain stocks if necessary.

– Assist local authorities to implement contingency plans for drought and flooding.

– Assist farmers to select the correct crop and crop varieties and also modify farming strategies to mitigate abnormal variations.

3. Technical Approach

Both numerical and statistical methods are proposed:

– At the scale of the South Asian region, numerical models and statistical models would be used for predicting seasonal rainfall with lead-times of 2-3 months.

– At smaller spatial scales, statistical downscaling techniques would be used to generate higher resolution, short-range forecasts.

Proposed methodology

Regional scale seasonal forecasts

Seasonal prediction of monsoons is still a major challenge for weather/climate forecasting. Both statistical and dynamical (numerical modelling) approaches have significant shortcomings. Seasonal forecasts using numerical models are still largely experimental. Analysis of hindcasts made by various agencies has shown that skill has not reached acceptable levels. An evaluation of DEMETER (a European seasonal prediction inter-comparison project) showed that for some seasons, seasonal forecasts models do not even get the sign of anomaly correct (Gadgil et al., 2005).

One of the major limitations could be less than satisfactory initial conditions both for ocean and atmosphere in coupled model seasonal forecasts. The atmosphere has an upper limit of about 15 days for skilful forecasts. Hence longer scale predictions can only obtained by co-evolution of atmosphere and oceans. While oceanic data is generally hard to measure, sub-surface data is even more difficult to obtain. Sub-surface data of the oceans can have a significant impact in improving initial conditions of the oceans and thus in the evolution of oceanic surface conditions. The oceanic surface conditions affect the atmosphere above.

With the recent deployment of ARGO floats (which drift below the surface for up to 15 days and then surface to relay these conditions) subsurface data can be obtained in near real time. The assimilation of these data using techniques such as Ensemble Kalman filtering could significantly improve initial conditions and longer scale forecasts (Krishnamurti et al., 2007)

Another technique could be the use of the super-ensemble method. Using this method, seasonal forecasts from multiple forecasting agencies can be combined such that the obtained super-ensemble has greater skill than any one of its constituents (Chakraborty and Krishnamurti, 2006).

Some agencies such as the India Meteorological Department (IMD) have been using statistical techniques for seasonal forecasting. These are essentially regression-based methods with long range atmospheric and oceanic predictors from various parts of the world. The efficacy of such techniques has been in doubt for some time (Gadgil et al 2005), however, recent statistical techniques such as Empirical Intrinsic mode techniques and machine learning based techniques such as Relevance Vector Machines (RVM) in combination with Bayesian techniques have shown promise for improving statistical forecasts at regional scales (Tripathi and Govindraju, 2008). It would be highly worthwhile to further research these techniques with emphasis on improving the quality of predictors. The work of Tripathi and Govindarjau (2008) used only Sea Surface Temperatures (SST) with large lead times to predict all India summer monsoon rainfall. Other predictors which have significant association with summer rainfall could be used for this purpose.

Predictions on intra-seasonal and local scales

Intra-seasonal variations such as active/break spells of rainfall within the monsoon season can have significant impacts on various activities. For example, extended break spells would imply increased requirement of water (both surface and sub-surface) for irrigation purposes. Also knowledge of an impending active/break period could help farmers to plan the use of water, fertiliser, pesticides, etc.

Intra-seasonal forecasts are still in their infancy and most use statistical techniques. One useful technique which shows potential in foretelling impending active-break periods is that of Roundy and Schreck (2009). This involves reconstruction of filtered Outgoing Long-wave Radiation (OLR) and its forecast. The method appears to have been skillful in predicting the long dry spells during June 2009 and July-August 2009.

Webster and Hoyos (2004) propose the use of a Bayesian scheme based on ten predictors for forecasting pentad rainfall with 30 days lead. Their method involves use of wavelet banding and linear regression. Over large regions such as Central India, their method shows considerable skill. However, over the scale of a province such as Orissa and Rajasthan, the skill is poorer.

Numerical models have also shown some potential for improved forecasting thanks to the assimilation of sub-surface oceanic data (Krishnamurti et al., 2007). For example, the correlation between observed and predicted all-India rainfall on the intra-seasonal scale improved from 0.38 to 0.60 with assimilation of ARGO data.

It is generally assumed that seasonal scale forecasts at scales of a district or smaller are likely to have lower skill than regional forecasts. For this purpose one can either use statistical techniques to obtain seasonal forecasts or downscaling techniques can be applied to larger scale forecasts (either via statistical or numerical models). For example, Kumar et al. (2007) used large scale indices such as the ENSO and EQUINOO monsoon teleconnection to predict rainfall over Orissa with some degree of success. This approach could be pursued further to improve seasonal scale forecasts for meteorological sub-divisions and smaller scales. Similarly, Zhou et al. (2007) developed a multi-model ensemble technique to downscale GCM rainfall forecasts. They recommend use of atmospheric circulation features (which are predicted more robustly) rather than precipitation itself for the downscaling. However, the skill of such downscaled forecasts is currently modest.

At shorter time scales (3-5 days) high resolution regional models can be used to generate forecasts at the scale of districts. For example, Krishnamurti et al. (2009) report improved forecast skill for monsoon rainfall using a combination of super-ensemble and downscaling techniques applied to GCM forecasts.

Webster et al. (2007) discuss rainfall and flood forecasts for Bangladesh involving a three-tiered approach. This begins with coarse scale long lead forecasts (essentially from coupled models) followed by empirical models on the intra-seasonal scale and numerical model forecasts for shorter scales. Since their interest was on forecasting floods originating from the Ganga-Bhramaputra basin, they suggest coupling these forecasts to hydrological models. Subbiah et al. (2007) also discuss similar techniques with emphasis on hazard warning, management and mitigation.

4. Information needs

Software to implement techniques such as Ensemble Kalman Filtering; downscaling and super-ensemble techniques may need to be developed.

Climatic Data

Climatic data such as SSTs, rainfall, atmospheric parameters (such as airflows), temperature, etc. Initial conditions are required for conducting seasonal forecasts with numerical models. Seasonal and intra-seasonal forecasts for downscaling to finer spatial scales.

5. Potential partners

South Asian Region

1) Indian Institute of Science, Bangalore, India; (2) National Atmospheric Research Laboratory, Tirupati; (3) India Meteorological Department, Long Range Forecast Unit, Pune, India; (4) Indian Institute of Tropical Meteorology, Pune, India; (5) Climate Risk Management Division, Asia Disaster Preparedness Centre, Asia Institute of Technology, Bangkok, Thailand; (6) SAARC Meteorological Research Centre, Dhaka, Bangladesh; (7) International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal; (8) Chinese Academy of Meteorological Sciences, Beijing, China; (9) Satellite Applications Centre, Ahmedabad, India; (10) National Centre for Medium Range Weather Forecasting, NOIDA, India.

Outside South Asia

(1) Met Office, UK; (2) University of Reading, Reading, UK; (3) Dept of Meteorology, Florida State University, Tallahasse, USA; (4) Meteorological Research Institute, Japanese Meteorological Agency, Japan; (5) Dept of Geography, Tokyo Metropolitan University, Tokyo (possible link to the Mahasri project which involves prediction of monsoons); (6) Asia Pacific Climate Centre (APCC), Busan Korea; (7) Frontier Research Center for Global Change, Yokohama, Japan; (8) International Research Institute for Climate and Society, Columbia University, New York; (9) Climate Prediction Centre, NOAA, USA; (10) ECMWF, Reading, UK; (11) Meteo France, France (12) LMD, France.

6. Estimated resources

Time: 5 years

Cost: Variable, based on types of forecasts generated. Forecasts with numerical models would be expensive. Statistical techniques would be less expensive. In the pilot phase, forecasts from existing prediction centres could be used and this could involve substantial cost savings.

7. Other information

Studies have shown that seasonal prediction of the South Asian monsoon is an exceedingly tough problem (Gadgil et al., 2005). For example, IMD's statistical technique has never predicted a drought. Variability at smaller scales is even more challenging and this makes seasonal forecasting at district scales even more difficult. These factors may have significant impact in developing a successful seasonal forecasting technique for the region’s monsoons.

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Annex 6 Insuring operational seasonal forecasts

1. Principal objective

To assess the feasibility of insuring operational seasonal forecasts to reduce agricultural vulnerability in South Asia.

2. Background

Climate variability poses a serious challenge to agriculture in South Asia, being predominantly driven by the monsoon rainfall. Smallholder farmers (typically defined as holding land of around 1 to 2 acres, or 0.4 to 0.8 ha), constitute a significant section of population in the region. The vulnerability of such farmers to crop failure is very high. With increasing skill in seasonal rainfall forecasts, use of operational forecasts with innovative insurance instruments could play a significant role in reducing vulnerabilities. When contracts are appropriately designed, important synergies between forecasts, insurance, and effective input use, may be achieved. Used together, these tools potentially overcome barriers preventing the use of imperfect information in crop production (Carriquiry and Osgood, 2008).

Potential benefits

By linking insurance to seasonal operational forecasts, rather than to reduction in crop yield, the financial uncertainties of a farmer will be reduced significantly. If an insured seasonal forecast indicates, for example, that a drought is likely to hit a particular area, the farmer will be in a position to take adaptive measures, such as changing the crop or altering the economic activity during the season.

3. Technical approach

Proposed methodology

i. Selection of three or four pilot case studies based on vulnerability to climate variability, in different hydro-climatic zones of South Asia.

Vulnerability to climate variability may be assessed by socio-economic surveys of the regions. Previous studies and willingness of the insurance companies to participate will also play a critical role in selection of the case studies. In India, for example, the insurance sector recently opened up for private participation and there is enthusiasm on the part of private companies to enter the agriculture sector.

ii. Development/ use of probabilistic seasonal monsoon rainfall forecasts for the case studies. Forecasts are based on relationships with sea surface temperatures and teleconnections to large scale climate phenomena such as El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

Several regions in South Asia are known to be influenced by these large scale climate phenomena. With an increased skill in the forecasts of such phenomena, use of teleconnections will likely provide improved rainfall forecasts at seasonal scales with sufficient lead times (see Annex 5).

iii. Development of disaggregation models to provide intra-seasonal forecasts that are updated in real-time with latest available information and data.

Availability of soil moisture during critical growth stages of crops is important for ensuring maximum crop yield. Seasonal rainfall forecasts, therefore, need to be disaggregated into smaller time periods (such as ten days), for use in the crop yield models. This is achieved by stochastic disaggregation techniques. The intra-seasonal forecasts may be updated as data become available in real-time. In arriving at the intra-seasonal forecasts, it would be necessary to ensure that disaggregation would give the phase of intra-seasonal variations correctly. This will need additional research, as current disaggregation techniques may give the statistics of variability correctly but not reproduce the phase of active-break spells which would be important to the farmers for crop management.

iv. Use of crop yield models incorporating soil moisture stress

Crop models that simulate yield response to soil moisture stress across time during a crop season are useful in assessing vulnerability. Previously published models may be tested in the pilot studies. A given sequence of disaggregated rainfall hindcasts may be used in simulating yields for various crops, to help generate the insurance contracts.

v. Assessment of vulnerabilities for various levels of forecast failures

With decisions based on the seasonal forecast (e.g., the type of crop to be planted), modelled yield and loss of income may be assessed for various levels of failures of the forecasts. Such information, along with the economic status of a farmer could be used in vulnerability assessment.

vi. Development of insurance instruments in consultation with farmer associations for acceptability

With the vulnerability information from above (v), appropriate instruments could be developed to protect the farmer against loss of income due to poor forecasts. The farmers would need to be educated on participation in the insurance based probabilistic forecasts. It is envisaged that training programmes would be necessary to help educate the farmers.

vii. Testing for one monsoon season with real-time data

The methodology would be tested with a sample set of farmers in all the pilot case studies for one monsoon season.

Successful experiments available in other regions provide a useful starting point for the project (e.g., Southern Africa, discussed in Osgood et al. [2008]).

Pilot site(s) Three or four agricultural districts in different regions of South Asia (e.g., Andhra Pradesh, Karnataka, Nepal, Sri Lanka, etc), based on vulnerability and hydro-climatic conditions.

4. Information needs

Climatic data

Sea Surface Temperatures (SSTs) and teleconnection indices for seasonal outlooks; daily rainfall, wind speed, relative humidity, evaporation rates, solar radiation for crop modelling.

Non-climatic data

Soil maps, crop characteristics (such as crop factors, yield factors, crop period and intra-season growth stages), hydrologic data (including available groundwater resources), socio-economic data pertaining to farmers, market data.

5. Potential partners

South Asia region

(1) Indian Institute of Science (IISc), Bangalore, India; (2) International Crops Research Institute for Semi-Arid Tropics (ICRISAT), Hyderabad, India; (3) Institute for Social and Economic Change (ISEC), Bangalore, India; (4) International Water Management Institute (IWMI), Colombo, Sri Lanka; (5) ICICI Lombard Insurance, India; (6) local NGOs working with farmers.

Outside South Asia

(1) International Research Institute for Climate and Society, Columbia, US; and (2) Asian Institute of Technology, Bangkok, Thailand.

6. Estimated resources

Time: Three years

Cost: £375,000

7. Other information

(a) Even with the best of numerical models and model ensembles (such as EUROSIP - consisting of ECMWF, Meteo-France and UK Met Office), the forecast for current year's (2009) monsoon, even on the scale of all-India average was inaccurate at a lead time of 1-2 months (starting April/May). On smaller scales, the errors could be even larger. These limitations should be kept in mind when developing insurance instruments. (b) A concept workshop would be needed to formulate a detailed research proposal. (c) Lack of enthusiasm from farmers to participate in the insurance could be a constraint. (d) Drawing up contracts may require involvement of legal experts as consultants to the project.

8. Supporting materials

Key publications

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www.card.iastate.edu (accessed 25 Aug 2009).

Annex 7 Integrating precipitation forecasts with real-time flood forecasting models

1. Principal objective

To assess the science and information needs for real-time flood forecasting.

2. Background

The Ganga-Brahmaputra-Meghana (GBM) system, the Kosi, and the Mahanadi are particularly flood prone, and cause frequent flooding in Bangladesh, Nepal and India. The Brahamputra is the fourth largest river in the world in terms of annual discharge, and is susceptible to catastrophic flooding with major impacts. With increasing human settlement in floodplains, vulnerability to flooding is expected to increase. Early warning systems that integrate real-time flood forecasts with sufficient lead times can help to reduce the vulnerability.

Rationale

Real-time flood forecasts cannot rely only on observed precipitation. Forecasted rainfall is an essential input to hydrologic models that provide flood forecasts, as the gains in lead time can be achieved only by including precipitation information ahead of its occurrence. However, errors in rainfall prediction can be an important source of uncertainty. The reliability of precipitation forecasts that drive the hydrologic models are often unsatisfactory, as uncertainty in Quantitative Precipitation Forecasts (QPFs) is considerable at the scales of interest for hydrological purposes (Diomede et al., 2008). The ensemble approach uses multiple precipitation scenarios generated from Numerical Weather Prediction (NWP) models, addresses this uncertainty to a certain extent, but the hydrologic model used may introduce its own sources of uncertainties that also propagate through the forecasts. Another means of obtaining precipitation forecasts is through satellite estimates of precipitation. An increasing number of satellite-based rainfall products are now available in near-real time that may be used in conjunction with hydrologic models to provide flood forecasts.

In the context of South Asia, the questions that need to be addressed are similar to those posed by Volkert (2000) for the Alpine Region, namely: (a) what is the spatial extent and temporal duration of severe precipitation events; (b) how predictable are such events using operational NWP models; and (c) what spatial and temporal data resolution can be realistically expected by hydrologists?

With the satellite estimates of precipitation, a major source of uncertainty is due to the scale mismatch. Most real-time and quasi-global satellite products are currently available at spatial scales ranging from 0.25° to 0.5° and are considered too coarse for dynamic hydrologic modelling of basin-scale flood events (Harris et al., 2007).

Furthermore, hydrologic models that produce flood forecasts and early warnings need other information beyond precipitation forecasts. These data include, but are not limited to, land use patterns, soil cover, antecedent soil moisture, catchment characteristics, flood plain zoning, channel characteristics, structural measures for flood control, etc. With many rivers in South Asia being trans-boundary, sharing such data amongst riparian countries becomes a critical necessity. It is thus essential to assess both the science needs and the information/data needs in the context of South Asia to reduce flood vulnerabilities in the region.

Potential benefits

Identification of science needs should trigger further research, and the data/information needs will open up paths for generating and sharing such data and information.

3. Technical approach

Proposed methodology

I. Two or three case studies could be chosen based on flooding history and vulnerability. Sub-catchments of the Kosi in India-Nepal and the Brahmaputra in Nepal-India-Bangladesh are potential candidates for the study. The science and information needs would be collated with respect to these pilot case studies, but will be presented in a form applicable in general to any river basin in the region. High resolution NWP models may be required to generate rainfall forecasts for each of the sub-catchments. For larger basins longer-lead forecasts would be required as flooding at lower levels would be an integral of rainfall over the upper parts of the river.

II. A suite of hydrologic models appropriate for generating flood hydrographs would be selected consistent with the spatial scales of precipitation forecasts from the NWP models and satellite estimates. These may be drawn from the set of HEC-HMS, MIKE11, Variable Infiltration Capacity (VIC), Conceptual Models, topographic index based model (abbreviated TOPMODEL), etc. Use of multiple model configurations would help to characterise uncertainties due to hydrologic model structures and parameters.

III. For the Lower Brahmaputra basin, it has already been shown that interannual rainfall variability is low and is a weak predictor of monsoon discharge volumes (Heikman et al., 2007). Significant correlations between spring snow cover and monsoon season discharge is seen in the basin, indicating its potential as a predictive tool. This aspect should be studied further and also for the other pilot case studies and should be explored for use in flood forecasting, with an appropriate model, that predicts runoff due to snow-melt.

IV. Precipitation forecasts would be obtained both from NWP models and from satellite estimates. Typical time resolution of such forecasts would be from a few hours to one day, depending on the data availability and importance to the case study. An ensemble precipitation forecast with uncertainties quantified in terms of spread/probabilities would be used in the hydrologic models to generate an ensemble of flood forecasts. Validation would be with respect to the recent significant floods observed in each case study basin.

V. By assembling prototype suites of hydrologic models, different precipitation forecasts and representative case studies, the science and information/data needs for a fully operational system would be better understood. Discussions with custodians of data and stakeholders for information-exchange would be necessary to achieve this objective.

4. Information needs

Climatic data

Gauge rainfall, satellite estimates of precipitation

Non-climatic data

Land use patterns, catchment characteristics, satellite images showing snow cover.

5. Potential partners

South Asia region

(1) Indian Institute of Science, Bangalore, India; (2) National Institute of Hydrology, Roorkee, India; (3) Indian Space Research Organisation (ISRO), India.

Outside South Asia

International Centre for Integrated Mountain Development (ICIMOD), Nepal.

6. Estimated resources

Time: Three years

Cost: £375,000

7. Other information

(a) The Global Precipitation Measurement (GPM) mission to be launched by NASA in 2012 provides an enormous opportunity for South Asian countries to improve their flood prediction capabilities. It is necessary that the hydrologic tools, data and other information are geared up to integrate real-time data to provide flood forecasts. The project proposed here would help prepare the way.

(b) Studies have shown that rainfall could be significantly underestimated over regions of high orography such as the Himalayas (Qi and Yunfei, 2007). This would need to be addressed especially for flood forecasting which needs quantitative estimates. Ground truth over these regions is also challenging.

8. Supporting materials

Key publications

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NCEP: http://www.cpc.ncep.noaa.gov/products/global_precip/html/web.shtml (accessed 28 Aug 2009)

Annex 8 Rehabilitation of soils and aquifers affected by saline intrusion

1. Principal objective

To review existing approaches and anticipated information needs to support rehabilitation of soils and aquifers affected by saline intrusion in South Asia

2. Background

Salinity in the coastal areas of south Asian countries of India, Sri Lanka, Bangladesh, Maldives (and China) is a major concern. For example, India has a very long coast line and large river deltas, which are fertile and the land is extensively used for agricultural crops such as rice. Several river systems drain through the coastal regions and have diverse ecosystems (e.g., mangroves). Further, large mega cities exist along the coast (for example in India, Mumbai, Chennai, Kolkata, etc), which depend extensively on groundwater resources from the aquifers for drinking water and other uses. The following list outlines some of the causes of saltwater intrusion and associated affects on soil and water resources:

I. Damages to water resources (for drinking and irrigation) and soil have been caused by sea water waves due to cyclonic storms and tsunamis. Several forms of land damage have been reported, namely: a) crop destruction by waves, salt poisoning, and uprooting; b) de-surfacing of landscape as a result of erosion and sedimentation; c) deposition of salt sediment; d) trash and debris accumulation; e) salt infiltration; and f) fertility depletion. Groundwater resources are affected during such events due to flooding of open/dug wells and bore wells with surface sea water and also salt-water intrusion into the aquifers.

II. In several river basins in the coastal areas of the south Asia, rice is cultivated both in the monsoon and dry season. However, water use in the upper reaches has increased over the years and during the dry season, river flows are so low that salt water intrudes into the lower river reaches, producing brackish water conditions that are unsuitable for rice growth. Diversion of upstream flows for dry season irrigation also threatens to exacerbate salt water intrusion to productive lands.

III. Groundwater is extensively pumped for water consumption in urban areas leading to saline ingress into the aquifers. This is further exacerbated below major cities (e.g., Hong Kong, Mumbai) by reduced groundwater flows towards the sea due to development of deep underground infrastructure (e.g., deep building foundations).

IV. Rising sea levels are causing salt water to flow into some of the rivers, and aquifers threatening dependent ecosystems and farmlands.

V. Expansion of salinity inland is also caused by changing land use practices such as growth of shrimp farming. As a means for increasing income some farmers have adopted the practice of allowing saline water onto rice fields for aquaculture.

3. Technical approaches for rehabilitation of soils and aquifers

Soil reclamation:

I. For leaching/surface flushing of salts an adequate drainage system is a critical component of the overall reclamation process as this network will transport soluble salts from the field. It is necessary to obtain data on soil characteristics, surface drainage, and sub-surface drainage conditions. *Currently data are available at regional scale, yet farm level assessment is necessary.*

II. Reclamation of saline-sodic and sodic soils is often more problematic. Comprehensive soil chemical testing is required prior to any intervention to ascertain the nature of the problem for selected soils in critical regions. *Field and laboratory analyses* should include an assessment of the exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), electrical conductivity (EC) and pH. Rates of gypsum or phosphogypsum necessary to allow effective displacement of sodium from the exchange complex need to be estimated on the basis of these assessments.

III. A challenge for the future will be the optimal utilisation of any additional flows in river systems to arrest environmental degradation by salinity control and extension of irrigation facilities. Diversion, distribution and management of this additional flow will require major interventions like barrages on the critical rivers along with water control structures and distribution canals. *An assessment should be undertaken of potential surplus flows in river systems available for this task.*

IV. Addition of organic matter materials will assist in accelerating the reclamation process for saline-sodic and sodic soils as well as improving the supply of nutrients to the developing crop. The growing of green manure crops and their subsequent incorporation into the soil will assist in improving soil properties. There are a range of crops that could be used as green manures. *Mapping of regions for taking up these activities are required. Remote sensing methods can play an important role in mapping such areas.*

V. Crops and varieties that tolerate high salt levels may form an intermediate strategy in the reclamation of salt-affected soils. There are a number of salt-tolerant rice genotypes. The use of these salt-tolerant genotypes should be viewed as an intermediate step in the reclamation of saline soils, to be combined with normal leaching/ flushing. *Studies should be carried out for assessing the integration of these approaches in the current farm practices.*

Reclamation of aquifers:

VI. Intrusion of sea water is a threat from excess pumping, and can cause ingress of salinity particularly in locations where the aquifers are highly permeable. Water quality data during rainy and dry season in these areas have to be analysed at the village or watershed scale to identify problem areas related to excess pumping. *Studies using density dependent groundwater flow models are required for simulating different pumping rates and pumping schedules that can keep the water salinity within acceptable limits*.

VII. Areas with groundwater aquifers vulnerable to sea level rise should be mapped. Following Don et al. (2006) integrated surface and groundwater models can be used to *identify and map vulnerable groundwater*.

VIII. Few studies have coupled climate change scenarios with hydrological models to study the effects of climate change on coastal fresh groundwater resources. *The investigation of the relationship between climate change and loss of fresh groundwater resources is important for understanding the characteristics of the different coastal water stressed regions under selected climate change scenarios.*

IX. Modelling of the groundwater flow regime in coastal mega cities is required to assess impacts of underground infrastructural projects and groundwater utilization on subsurface drainage towards the sea and associated effects of sea water intrusion on the aquifers supporting these cities.

X. Permanent monitoring sites should be set up to undertake a comprehensive assessment of soil chemical, physical and biological properties. Such monitoring sites (e.g. Karnataka (west coast), Tamil Nadu/ Andhra Pradesh (East Coast), Sri Lanka, Bangladesh) should be selected in each of the affected countries. These monitoring sites would then be routinely sampled in order to assess the efficacy of rehabilitation over the years.

4. Information needs

Climatic data

Climatic data such as rainfall, atmospheric parameters such as wind, temperature, solar radiation etc are required for hydrological model simulations.

Non-climatic data

Groundwater levels, pumping patterns, land use and land cover, soil data, water quality parameters in groundwater are needed for simulating groundwater flow and salt water intrusion models.

5. Potential partners

South Asia region

(1) National Institute of Technology, Surathkal, Karnataka, India; (2) Indian Institute of Science, Bangalore, India; (3) Anna University, Chennai, India; (4) Indian Institute of Technology, Mumbai; (5) Indian Institute of Technology, Chennai.

Outside South Asia (possible partners)

(1) Tohuku University, Japan; (2) Institute of Low Land Technology, Saga, Japan; (3) University of Oklahoma, Norman, USA; (4) International Rice Research Institute, Philippines; (5) International Institute for Land Reclamation and Improvement, Wageningen University, The Netherlands

6. Estimated resources

Time: 5 years

Cost: The cost would vary depending on the work packages selected and on the scale of the study including data collection. An approximate figure may be £500,000.

7. Other information

A regional workshop involving participants from countries in south Asia (India, Bangladesh, Sri Lanka, Maldives and China) addressing the problems being faced on salinity of soils and aquifers along with mitigation measures should to be conducted to review the present status and approaches to salinization.

8. Supporting materials

Key publications

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