Developing Hydro–Climatic Services For Water Security

Report of Scientific Workshop 29 Nov–1 Dec 2016

April 2017

INDIA-UK
Water Centre
भारत-यूके
जल केन्द्र

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India-UK Water Centre
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The India-UK Water Centre promotes cooperation and collaboration between the complementary priorities of NERC-MoES water security research.

भारत-यूके जल केंद्र, एनईआरसी-एमओईएस जल सुरक्षा अनुसंधान की मानार्थ प्राथमिकताओं के बीच सहयोग और सहकार्यता को प्रोत्साहित करता है।

Front cover image: River Ganga

Contents

Executive Summary

This report represents an overview of the participation, activities and conclusions at a joint India-UK science workshop held at IITM in Pune 29th November–1st December 2016 and convened by the India-UK Water Centre co-coordinators Dr A.K. Sahai (Indian Institute of Tropical Meteorology, Pune, India) India and Dr Harry Dixon (Centre for Ecology & Hydrology, Wallingford, UK). It outlines the structure, participation, presentation and discussion sessions undertaken during the course of the workshop. The report is intended for the workshop participants, India-UK Water Centre members and stakeholders.

Figure 1: Participants at the IUKWC Workshop, 1 December 2016, Pune, India.

1. Workshop Conveners

The Workshop was convened by the India-UK Water Centre (IUKWC) and led by the co-coordinators:

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Indian Institute of Tropical Meteorology (IITM)
Dr. Homi Bhabha Road
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The Workshop was held at the Indian Institute of Tropical Meteorology, Pune 29th November – 1st December 2016.

2. Workshop Aims

The India-UK Water Centre is based around five key cross-sectoral themes and aims to deliver a portfolio of activities across these themes. For its inaugural activity the IUKWC secretariat decided to host a workshop on the first of its five themes: Developing hydro-climate services to support water security.

The workshop aimed to bring together scientists and practitioners to explore the scientific challenges involved in the production, translation, distribution and use of climate information and tools to inform decision making in the Indian and UK water sectors. The workshop addressed the following issues:

- What are the key areas of water management in India and the UK, where new climate services are needed to inform future planning and adaptation?
- How can climate change projections be used by the hydrological community for decision making?
- What are the key gaps in our understanding of hydro-climatological systems which need to be filled in order to develop new tools and information products for the water community?
- What hydrological data is needed / available at local-regional scales to develop appropriate hydro-climatic information services?
- What other communities could benefit from enhanced hydrological climate service?

Figure 2: Official workshop opening and lamp-lighting ceremony. Seated L-R: Dr Harry Dixon (IUKWC Co-coordinator, CEH), Prof V.K. Gaur (Distinguished Scientist, CMMACS), Prof Alan Jenkins (CEH), Dr Atul K Sahai (IUKWC Co-coordinator, IITM)

3. Workshop Participants

An Open Call for participants was hosted on the IUKWC website open to members of the Open Network of India-UK Water Scientists (http://www.iukwc.org/open-network) and delegates were selected based on:

- applicant expertise relevant to the workshop theme;
- motivation for attending the workshop;
- expected contribution to the workshop;
- potential benefit to the applicant in attending;
- organisational balance.

Around sixty delegates (14 from UK and 46 from India) attended the workshop representing a broad variety of Indian and UK organizations involved in scientific and social research in the water security sector. Delegates included representatives of the Government of India and UK, numerous Indian Institutes for Technology and Science, research centers and universities in the UK and India and Non-Government Organizations. A full list of delegates can be found below in Table 1; further details about participants' interests and contact information can be found on the Open Network of India-UK Water Scientists.

Table 1. List of Delegates

	Name	Institution
		UK
1	Bharucha, Dr Zareen	Global Sustainability Institute, Anglia Ruskin University, Cambridge
2	Bhave, Dr Ajay	University of Leeds
3	Dixon, Dr Harry	Centre for Ecology & Hydrology, Wallingford
4	Gadian, Dr Alan	National Centre for Atmospheric Sciences, University of Leeds
5	Jenkins, Prof. Alan	Centre for Ecology & Hydrology, Wallingford
6	Jobson, Ms. Anita	Centre for Ecology & Hydrology, Wallingford
7	Kasiviswanathan, Dr KS	Heriot Watt University, Edinburgh
8	Lumbroso, Dr Darren	HR Wallingford
9	McKenzie, Mr Andrew	British Geological Survey, Wallingford
10	Momblanch, Dr Andrea	Cranfield University
11	Orr, Dr Andrew	British Antarctic Survey, Cambridge
12	Prudhomme, Prof. Christel	Centre for Ecology & Hydrology, Wallingford
13	Tsarouchi, Dr Gina	HR Wallingford
14	Widmann, Dr Martin	University of Birmingham
		INDIA
15	Abhilash, Dr S	Cochin University of Science and Technology
16	Anoop C K, Dr	Viswajyothi College of Engineering and Technology, Kerala
17	Apparusu, Dr Suman	Change Planet Partners Climate Innovation Foundation, Hyderabad, Kolkata
18	Bhatla, Prof. Rajeev	Banaras Hindu University, Varanasi
19	Chakraborty, Dr Surajit	Indian Institute of Social Welfare and Business Management
20	Chattopadhyay, Dr Rajib	Indian Institute of Tropical Meteorology, Pune
21	Das, Dr Ashok Kumar	India Meteorological Department, Pune
22	Deshpande, Dr Nayana	Indian Institute of Tropical Meteorology, Pune

23	Gaur, Prof. V. K.	CSIR Centre for Mathematical Modelling and Computer Simulation, Bangalore
24	Ghosh, Dr Subimal	Indian Institute of Technology, Bombay
25	Haldar, Sh. S.K.	Narmada & Tapi Basin Organization, Gandhinagar
26	Halder, Dr Subhadeep	Indian Institute of Tropical Meteorology, Pune
27	Indu J, Dr	Indian Institute of Technology, Bombay
28	Jain, Dr Sharad K	National Institute of Hydrology, Roorkee
29	Joseph, Dr Susmitha	Indian Institute of Tropical Meteorology, Pune
30	Joshi, Ms. Priya	Indian Institute of Tropical Meteorology, Pune
31	Kar, Dr Sarat C	National Centre for Medium Range Weather Forecasting, Noida
32	Krishnaswamy, Dr Jagdish	Ashoka Trust for Research in Ecology and the Environment, Bangalore
33	Kumar, Dr Pankaj	Indian Institute of Science Education and Research, Bhopal
34	Kumar, Shri. Sunil	National Water Academy, Central Water Commission, Pune
35	Lobo, Crispino	Watershed Organization Trust, Pune
36	Mandal, Raju	Indian Institute of Tropical Meteorology, Pune
37	Mani, Dr Pankaj	National Institute of Hydrology , Patna
38	Maulik, Dr Dipanjana	Government of West Bengal, Kolkata
39	Mitra, Dr Ashis K	National Centre for Medium Range Weather Forecasting, Noida
40	Mondal, Dr Arpita	Indian Institute of Technology, Bombay
41	Mrudula G	CSIR - National Aerospace Laboratories, Bangalore
42	Muddu, Prof. Sekhar	Indian Institute of Science, Bangalore
43	Mukhopadhyay, Dr B.	Indian Meteorology Dept, Pune
44	Mujumdar, Prof. P.	Dept. of Civil Engineering; IISC, Bangalore
45	Mujumdar, Dr Milind	Indian Institute of Tropical Meteorology, Pune
46	Pandey, Prof. Prem Chand	Indian Institute of Technology, Bhubaneswar
47	Patil, Dr S.N.	North Maharashtra University, Jalgaon
48	Priya P, Dr	Indian Institute of Tropical Meteorology, Pune
49	Puttaiah, Dr Shivaraju Harikaranahalli	Jagadguru Sri Shivarathreeswara University, Mysuru
50	Rai, Dr Shailendra	University of Allahabad
51	Ray, Dr Sujata	Indian Institute of Science Education and Research, Kolkata
52	Revadekar, Dr Jayashree	Indian Institute of Tropical Meteorology, Pune
53	Sahai, Dr A.K.	Indian Institute of Tropical Meteorology, Pune
54	Saravanan K, Dr	VIT University, Chennai
55	Sen, Dr Sumit	Indian Institute of Technology, Roorkee
56	Singh, Dr Riddhi	Indian Institute of Technology, Hyderabad
57	Sivakumar, Dr	Central Ground Water Board, Chennai
58	Soundhara Raja Pandian R	Anna University, Chennai
59	Sridhar, Dr SGD	University of Madras, Chennai
60	Srivastava, Dr Prashant	Banaras Hindu University, Varanasi
61	Tripathi, Prof. Sachchida	Indian Institute of Technology, Kanpur
62	Varikoden, Dr.Hamza	Indian Institute of Tropical Meteorology, Pune

4. Workshop Structure

The workshop, being the inaugural workshop of the India UK Water Centre, also officially launched the Centre. This involved an introductory session outlining the background of recent collaboration between NERC and MoES in water science and the goals of the Centre. The conveners explained that the workshop aimed to explore opportunities for future collaboration in hydro-climatic services amongst UK and Indian scientists with the objective of promoting future research ideas and partnerships. The needs of key stakeholders were also intended to be considered with a view of identifying ways of enhancing links between India-UK science and current/potential end-users of hydro-climatic services.

With this perspective the workshop was structured around the six key themes, reflected through the following presentation sessions conducted the first two days:

I. Hydro-climate science and services – the global agenda;
II. Using climate information to inform water management – Recent experiences from the UK and India;
III. Improving understanding of spatial and temporal variability in Indian hydrology;
IV. Improving understanding of climate process for hydrology;
V. Future water resource availability and management;
VI. Climate services for disaster risk reduction.

Each topic included four to five presentations, followed by an interactive question & answer session. The workshop also provided an opportunity for experts to present their research in the form of posters. In all 36 presentations and 24 posters on varying themes were successfully delivered in these sessions. A full outline of the workshop Agenda and details of presentations and posters can be found in Annex B. Copies of presentations will available online at www.iukwc.org.

Figure 3: Left: Workshop in progress; Right: Prof. Sharad K Jain presenting.

Figure 4: Left: Dr Andrea Momblanch presenting; Right: Poster sessions.

The third day of the workshop was dedicated to discussion sessions. These sessions were in the form of break-out discussions where the participants were divided into small groups led by a nominated facilitator. The focus of these sessions was mainly on the following topics:

A. **Knowledge gaps in science and data needs**: Groups debated on the key areas of need and ideas for how to take them forward in the water security, hydrology and climate services sector.
B. **Improving Stakeholder Engagement and Science Capacity**: The groups debated on how to improve working with end users/stakeholders/policy makers (research translation, problem /solution driven research) along with ideas for how to develop improved joint UK-India scientific capacity in the area of hydro-climatic services (e.g. training/sharing capabilities).

A summary of break-out group discussions can be found in Annex C.

Figure 5: Breakout discussion groups

For recreation, and to acclimatize the delegates to India and its culture, a cultural programme was organized on the second day of the workshop. The event included an audio-visual narrative about the different regions of India and dance performances by artists depicting various Indian states and their respective culture and traditions.

Figure 6: Cultural dance programme

5. Workshop Conclusions and Outputs

The workshop presentations and discussions covered a wide range of technical topics, considerations of studies applying science on the ground and included cross - sectoral discussions looking at translating science to user communities.

5.1. Key themes arising

Two of the key aims of the workshop were to identify the key gaps in our understanding of hydro-climatological systems which need to be filled in order to develop new tools and information products for the water community and to understand what hydrological data is needed to develop appropriate hydro-climatic information services? Participants identified the following key areas (further details can be found in Annex C):

- Hydrology/Water Balance;
- Need for interdisciplinary approach between differing scientific areas as well as between scienceand social science;
- Precipitation forecasting;
- Physcial process understanding and role of this in models;
- Role of groundwater in hydro-climatic services;
- Standardise data, data assimilation and data sources;
- Role of Land Use and Land Use Change (LULUC);
- Food-Energy-Water Nexus and its quantification;
- Communicating uncertainty;
- Regional Climate modelling.

A key theme arising from the workshop was that in considering hydro-climatic services the development of the science base should not take place in isolation, there is a compelling need consider and engage with the users of those services—whether they be stakeholders or policy makers. There is a need to understand how the research informs hydro-climatic services translated and communicated to those who need to understand and use it. Participants identified the following areas for focus (further detail can be found in Annex C):

- Defining and understanding who are the stakeholders and users;
- Co-design and joint delivery of projects;
- Sharing of data and outputs;
- Engagement with end users to facilitate decision support;
- Improving trust in science;
- Funding support for engagement with users and stakeholder and not just funding for research.

5.2. Conclusions from the workshop

The workshop provided a valuable forum to bring together scientists from a range of disciplines with a number of stakeholders to showcase recent knowledge in the field of hydro-climatic services for water security and discuss future needs and opportunities to advance the science and delivery. An accompany Policy Brief summarizing the key thematic points arising from the workshop can be found at www.iukwc.org

5.3. Participant feedback

At the conclusion of the Workshop a feedback form was circulated to participants who were asked to provide comment on:

- the Workshop content;
- the meeting venue and organisation;
- networking opportunities; and
- provide an overall score out of 10 for the workshop.

42% of participants returned the form, with anonymous responses. Participants feedback positively on the content of the workshop (including the inclusion of breakout discussion sessions); the mix of participants (researchers/stakeholders and differing scientific backgrounds) and the time dedicated to networking opportunities (poster sessions, refreshment breaks, lunches and dinners). They reported that possible changes to enhance the workshop might have been to have slightly fewer talks per session and/or shorter sessions; the inclusion of more talks from stakeholders was also mentioned as a possible means of enhancing the workshop, and also perhaps opportunities for training sessions.

Logistical organisation and delivery of any workshop are of high importance to participants' enjoyment and participants at this workshop were on the whole complementary about the meeting space and hospitality provided.

A key goal of the India-UK Water Centre is to provide a platform for bringing together users, researchers and stakeholders in water science, it was thus pleasing to note that 95% of those completing the feedback form stated that they had made new contacts as a result of the workshop with potential opportunities for future collaboration with the new contacts. Participants identified ways in which joint UK-India capacity in the area of hydro-climatic services could be taken forward (See also Annex C) and these included provision of continued opportunities for **linkages between disciplines and between researchers and users/stakeholders**. Methods to facilitate the continued and increased linkages included, further events such as **workshops, exchanges and training** opportunities in various aspects of hydro-climatic services such as flood forecasting, modelling, downscaling etc.

Overall participants scored the workshop on average 9/10.

6. Annexes

ANNEX A: Workshop agenda

Day 1 – Tuesday 29 November

Time	Agenda item
09:00 – 09:30	**Arrival and Registration** Refreshments - Tea / coffee
09:30 – 11:00	**Welcome Addresses and Launch of the IUKWC** • Welcome and introduction to the IUKWC *Dr Atul Sahai (IUKWC Coordinator, IITM)* • Introduction to the IUKWC aims and functions *Dr Harry Dixon (IUKWC Coordinator, CEH)* • Research Needs and Opportunities for India – UK Water Science *Prof. Alan Jenkins (Deputy Director, CEH)* • Building resilience to water stress - A joint endeavor *Prof. Vinod K. Gaur (Distinguished Scientist, CMMACS, Bangalore)*
11:00 – 11:30	High Tea
11:30 – 13:00	**Session 1: Introduction to the Workshop and Keynote Presentations** • Introduction to the workshop aims and agenda *Dr Harry Dixon (CEH)* **Format: 4* 15' talks + 3' questions** • Hydromet forecasts and projections: Some recent applications *Prof. Pradeep Mujumdar (IISc Bangalore)* • Hydro-meteorological inputs for hydrological studies *Dr Sharad K. Jain (NIH, Roorkee)* • A new initiative of MoES towards developing Hydrological Information System for flood warning *Dr S. C. Kar (NCMRWF, MoES, Govt. of India)* • Existing Indian flood forecasting methodology *Shri. Sunil Kumar (National Water Academy, Pune)*
13:00 – 14:00	Lunch
14:00 – 15:30	**Session 2: Hydro-Climate Science and Services – the Global Agenda** Chair: *Prof. Alan Jenkins (CEH)* **Format: 3* 25' talks + questions** • WMO Global Framework for Climate Services *Dr Rupa Kumar Kolli (WMO)* • Extended Range Prediction Activities of IITM *Dr A K Sahai (IITM, Pune)* • UK Met Office Weather and Climate Science for Service Partnership Programme *Dr Chris Hewitt (Met Office)*
15:30 – 16:15	Refreshments
16:15 – 17:45	**Session 3: Using climate information to inform water management – Recent experiences from the UK and India** Chair: *Dr S K Srivastava (National Water Academy)*

	Format: 5* 15’ talks + 3' questions • Qualitative and quantitative RDM for water resources adaptation decision-making under uncertainty *Dr Ajay Bhave (University of Leeds)* • EDgE: a prototype climate service for the water sector in Europe *Prof. Christel Prudhomme (CEH)* • Past and present evolution of Himalayan glaciers: a regional climate model study *Dr Pankaj Kumar (IISER Bhopal)* • Water security in the long durée: Insights for developing hydro-climatic services *Dr Zareen Bharucha (Anglian Ruskin University)* • Incorporating climate change impacts in estimating maximum flood level at a project site *Dr Pankaj Mani (National Institute of Hydrology, Roorkee)*
17:45	Wrap-up of Day 1 *(Harry Dixon)*
18:00 – 19:00	Poster Session with refreshments
19:00 – 21:00	Workshop Dinner at IITM

Day 2 – Wednesday 30 November

Time	Agenda item
08:30 – 09:00	Arrival Refreshments
09:00	Welcome to Day 2 *(Atul Sahai)*
09:00 – 10:30	**Session 4: Improving understanding of spatial and temporal variability in Indian hydrology** Chair: *Prof. V. K. Gaur (CMMACS, Bangalore)* **Format: 5* 15’ talks + 3' questions** • Operational Hydro-meteorological Services in IMD *Dr A. K. Das (Hydromet Division, India Meteorological Department)* • Assessing WRF model experiments of precipitation in the Indian-Himalaya *Dr Andrew Orr (British Antarctic Survey)* • Modeling hydrological changes using multiscale remote sensing in India *Prof. Sekhar Muddu (IISc Bangalore)* • Highlights on the use of climate services for hydrological modelling in the Indian Himalayas *Dr Andrea Momblanch (Cranfield University)* • On the frequency of 2015 monsoon season drought in the Indo-Gangetic plain *Prof. Vimal Mishra (IIT Gandhinagar)*
10:30 – 11:30	Poster Session with refreshments
11:30 – 13:00	**Session 5: Improving understanding of climate process for hydrology** Chair: *Dr R. Krishnan (IITM)* **Format: 5* 15’ talks + 3' questions** • The challenge of providing defensible downscaled and bias-corrected climate simulations *Dr Martin Widmann (U of Birmingham)*

	• Coupling of aerosol-land-cloud-rainfall system over Gangetic Plains: Observations and modelling analysis *Prof. Sachi Tripathi (IIT Kanpur)* • LSM-RTM Coupling for Microwave Tb Assimilation over India *Dr Indu J (IIT Bombay)* • Space Technology Applications in Water Resource Management *Dr Ravi Prakash Singh (National Remote Sensing Centre)* • Rainfall information from NCMRWF Unified Numerical Modeling System *Dr Ashis K. Mitra (NCMRWF, MoES, Govt. of India)*
13:00 – 14:00	Lunch
14:00 – 15:30	**Session 6: Future water resource availability and management** Chair: *Dr B. Mukhopadhyay (IMD)* **Format: 5* 15’ talks + 3' questions** • Satellites for Hydrology *Prof. P. C. Pandey (IIT Bhubaneswar)* • Interconnecting field level services and researchers for effective hydro-climatic services *Dr Dipanjana Maulik (Dept. of Environment, Govt. of West Bengal)* • WRF-PDM: Prototype for discharge prediction in ungauged basin *Dr Prashant Srivastava (Institute of Environment and Sustainable Development, BHU)* • Understanding migration of arsenic in the aquifer of North Bengal plain using numerical modelling: A case study of English Bazar Block, Malda District, West Bengal, India *Dr Surajit Chakraborty (Dept. of Environment Management, IISWBM, Kolkata)* • Water security in Tamilnadu *Dr Navaraj Perumalsa (Annai Fathima College of Arts and Science)*
15:30 – 16:30	Poster Session with refreshments
16:30 – 18:00	**Session 7: Climate services for disaster risk reduction** Chair: *Prof. Pradeep Mujumdar (IISc Bangalore)* **Format: 5* 15’ talks + 3' questions** • Hydrologic extremes under Climate Change: Non-stationarity and Uncertainty *Prof. Arpita Mondal (IIT Bombay)* • An overview of the effectiveness of early warning systems and risk assessments for weather-related hazards in South Asia *Dr Darren Lumbroso (HR Wallingford)* • Making Smallholder Farming Climate Resilient *Dr Crispino Lobo (WOTR, Pune)* • Changes in Convective Rainfall in future climates over Western Europe *Dr Alan Gadian (NCAS Leeds)* • Floods research in the UK: potential application in India *Dr Nick Reynard (CEH)*
18:00	Wrap-up of Day 2 (*Dr Atul Sahai*)
18:00 – 19:15	Cultural Programme
19:15 – 21:15	Dinner at IITM hosted by the Director, IITM, Pune

Day 3 – Thursday 1 December

Time	Agenda item
08:30 – 09:00	Arrival Refreshments
09:00	Welcome to Day 3 (*Dr Harry Dixon*)
09:00 – 10:30	**Session 8: Breakout Topic A – Gaps in the Science** **Format: Breakout groups of around 10-15 people discuss:** • knowledge gaps in the science and data needs. Groups should identify the key areas of need and ideas for how to take them forward.
10:30 – 11:00	Refreshments
11:00 – 12:30	**Session 9: Breakout Topic A – Improving Stakeholder Engagement and Science Capacity** **Format: Breakout groups of around 10-15 people discuss either:** • how to improve working with end users/stakeholders/policy makers (research translation, problem /solution driven research) or; • Ideas for how to develop improved joint UK-India scientific capacity in the area of hydro-climatic services (e.g. training/sharing capabilities).
12:30 – 13:30	Lunch
13:30 – 15:00	**Session 10: Feedback from Breakout Groups** Chair: *Dr Harry Dixon (CEH)* **Format: 10' talks + questions from each breakout group** Presenters: Rapporteurs from groups
15:00 – 15:30	Refreshments - Tea / coffee
15:30 – 16:00	**Session 11: Conclusions** Chair: *Dr Atul Sahai (IITM)* **Format: Short presentations giving conclusions from the workshop and next steps**
16:00	Close of Meeting

ANNEX B: Abstracts

Copies of presentations, where authorized by speaker, will be made available on the IUKWC website www.iukwc.org

Day 1 – Tuesday 29 November

Session 1: Introduction to the workshop and keynote presentations

Introduction to the workshop aims and agenda : *Dr Harry Dixon (CEH)*

Hydromet forecasts and projections: Some recent applications

Prof. Pradeep Mujumdar *(IISc Bangalore)*

The presentation discusses the applications of 1)Medium Range Weather Forecasts for Irrigation Water Management, 2) Climate Change Projections for Developing Adaptive Responses - Water Resources Systems and 3) Near-Real-Time Forecasts for Urban Floods . The main conclusions include: Medium range weather forecasts are useful in updating irrigation schedules; especially useful in increasing water use efficiencies; It is possible to derive adaptive policies for hydropower generation, flood control and irrigation water supply as a response to climate change; Real-time rainfall forecasts are useful in integrated urban flood management

Hydro-meteorological inputs for hydrological studies

Dr Sharad K. Jain *(NIH, Roorkee)*

The presentation discusses major uses of hydro–met data including: Hydrologic modelling and Water Resources Assessment, Improve understanding of hydrologic processes, Management of Hydrologic extremes: Flood and drought forecasts, Warning of cloudbursts, Trend analysis and study impacts of climate change and Assessment of Environmental water requirements. The key questions that need to focus in future research include: Is the precipitation intensity changing with time. If yes, where and attributions? Changes in ET, Relative Humidity? What are the uncertainties in observed estimates? What are the impacts on components of the hydrologic cycle at various scales? and More research and observations are required to understand occurrence of cloudburst events and their prediction.

A new initiative of MoES towards developing Hydrological Information System for flood warning

Dr S. C. Kar *(NCMRWF, MoES, Govt. of India)*

The main causes of floods are intense and/or long-lasting precipitation, snow/ice melt, a combination of these causes, dam break (e.g., glacial lakes), or by a local intense storm. Floods are affected by various characteristics of precipitation, such as intensity, duration, amount, timing, and phase (rain or snow). The work of flood forecasting and warning in India is entrusted with the Central Water Commission (CWC) of Ministry of Water Resources (MoWR). The activity of flood forecasting by CWC comprises of level forecasting and inflow forecasting. The Hydromet Division of IMD at New Delhi provides meteorological support for flood warning and flood control operations to CWC through its Flood Meteorological Offices. While the MoES through IMD provides weather forecasts at various space and time scales and CWC issues warnings/advisories on floods, many instances of extreme rainfall having potential of causing floods and flooding events are missed causing loss to economy and life. This is mainly due to the model limitation of capturing the actual magnitude of rainfall, its spatial and temporal distribution. Moreover, the meteorological forecasts are not readily usable by various stake holders such as CWC. Therefore, there is an urgent need to improve and customize meteorological forecasts specifically for floods. For developing an efficient system for improving meteorological supports for flood forecasting in India, a coordinated action plan with MoES (IMD, IITM, NCMRWF), and various stake holders (such as CWC, academic institutes) is required. MoES has recently initiated a new program with the objectives: (i) To develop a meteorological support system for flood warning and forecasting and (ii) Monitoring and understanding 3-dimensional features of water cycle and its change over India.

Existing Indian flood forecasting methodology

Shri. Sunil Kumar *(National Water Academy, Pune)*

All major ancient civilizations were developed in the river valleys because river served as source of water, food, transportation and protection to the mankind. On contrary, nowadays even a small, slow-flowing stream or gentle river could cause severe damage to the people and their businesses by flooding. With the changing patterns of rainfall and global climate, floods are matter of greater concern nowadays as it has enhanced damage potentials. Not only river plains are vulnerable to riverine or fluvial flooding but also places far away from the river are prone to surface water or pluvial flooding due to heavy rainfall. Central Water Commission is the national agency for flood forecasting and it has established 151 Level Forecasting Stations and 48 Inflow Forecasting Stations on all major rivers across the country (Water & Related Statistics 2015, CWC). Flood forecasting system is based on gauge-to-gauge correlation involving two measuring stations named as Base Station (upstream) and Forecast Station (downstream). At both these stations, measurements of water level/discharge have been taken from long time and a correlation has been established between them. Using this correlation, flood forecast for Forecast Station is issued once the water level/discharge is measured at Base Station. CWC issues flood forecast bulletin which provide information in respect of various predefined categories of floods namely low, moderate, high and unprecedented in yellow, pink, orange and red colour coding respectively. These forecasts issued by CWC are over 90% accurate. However it has many limitations such as low lead time, it gives only level/inflow forecasts, no information about extent, depth and duration of flood in flood plain, no correlation with rainfall, limited coverage, no pluvial flood forecast etc.

Session 2: Hydro-climate science and services – the global agenda

Chair: *Prof. Alan Jenkins (CEH)*

WMO Global Framework for Climate Services

Dr Rupa Kumar Kolli *(WMO)*

Abstract: The Global Framework for Climate Services (GFCS) aims to enable better management of the risks of climate variability and change and adaptation to climate change at all levels, through development and incorporation of science-based climate information and prediction into planning, policy and practice. The presentation discusses the various components, governance, strategy and activities under GFCS.

Extended range prediction activities of IITM

Dr A K Sahai *(IITM, Pune)*

Of late, there have been some efforts by various research groups to predict the monsoon and topical weather on extended range time scale. The extended range forecasting (forecasts between 7 and 30 days) fills the gap between medium-range weather forecasting and seasonal forecasting. It is often considered a difficult time range for weather forecasting, since the time scale is sufficiently long so that much of the memory of the atmospheric initial conditions is lost, and it is probably too short so that the variability of the ocean is not large enough, which makes it difficult to beat persistence. Since the Madden Julian Oscillation (MJO) is the most important mode of tropical intra-seasonal variability with potentially important influences on the monsoon activity in the Asian regions, the capability of statistical or numerical models in capturing MJO signal is very crucial in capturing the active/break cycle of monsoon.

UK Met Office Weather and Climate Science for Service Partnership Programme

Dr Chris Hewitt *(Met Office)*

The presentation discusses the key principles of the Weather and Climate Science for Service Partnership (WCSSP) in addressing global challenges and its activities South Africa, Asia and China. Further, the priority focus areas of Climate services at the UK Met Office are discussed along with the User engagement initiatives under WMO.

Session 3: Using climate information to inform water management – Recent experiences from the UK and India **Chair:** ***Dr S K Srivastava (National Water Academy)***
Qualitative and quantitative RDM for water resources adaptation decision-making under uncertainty **Dr Ajay Bhave** *(University of Leeds)* We apply qualitative and quantitative robust decision making approaches in the Cauvery River Basin. Using plausible future climatic and socio-economic conditions we develop WEAP scenarios, and evaluate adaptation options and pathways. Agricultural demand options are most robust, while adaptation pathways demonstrate variable value depending on timing and sequencing of options.
EDgE: a prototype climate service for the water sector in Europe **Prof. Christel Prudhomme** *(CEH)* The EDgE project 'End-to-end Demonstrator for Improved decision making in the water sector for Europe' (1.6mE) will develop a prototype tool box to deliver seasonal forecasts and climate change projections to the water sector. Using modelling (for both climate and hydrological impact) EDgE will produce terrestrial Essential Climate Variables (tECVs) specific to the water sector for past, current and future time horizons. In so doing it will contribute to the efforts of Climate-ADAPT and the WMO Global Framework for Climate Services (GFCS), among others. EDgE will also deliver new Sectoral Climate Impact Indicators (SCIIs) co-designed with users from the European water sector community. EDgE involves 6 other international organizations: the Environment Agency of England, The Helmholtz Centre for Environmental Research UFZ (Germany), the Norwegian Water Resources and Energy Directorate (Norway), Cetaqua (Spain), the Mediterranean Network of Basin Organisations MENBO (Spain) and the Climate Partnership Ltd (USA)
Past and present evolution of Himalayan glaciers: a regional climate model study **Dr Pankaj Kumar** *(IISER Bhopal)* The presentation discusses the simulation of glacier climate interaction over South Asia. The study reports that over the highly complex and data sparse region, the simulated mass balance largely agrees with observations including the positive Karakoram anomaly. REMO glacier simulates the glacier-climate interaction reasonably well; it has clear potential to be used for future climate assessments.
Water security in the long durée: Insights for developing hydro-climatic services **Dr Zareen Bharucha** *(Anglian Ruskin University)* This presentation summarizes recent research on the complex socioeconomic terrain influencing water security in rainfed agricultural landscapes in India, using data gathered from interviews with rainfed farmers, policy makers, civil society activists and other stakeholders. I use this data to generate insights to inform the development of new hydro-climatic services which cater to long-term resilience.
Incorporating climate change impacts in estimating maximum flood level at a project site **Dr Pankaj Mani** *(National Institute of Hydrology, Roorkee)* The adaptation of climate change effect in the hydrological design of flood protection measures are a major challenge for water resources planners and engineers. The wide range of possible estimates of climate change effects, rainfall intensity and duration, are of great interest for hydrological design. The general prediction from climate change research indicates comparatively more vigorous hydrological cycle with increased precipitation and evaporation rates leading to effect the water availability and runoff and thus flood characteristics. The potential effects on discharge extremes that determine the design of water management regulations and structures are of much concern. On the other hand, with the growing population, the development activities in the floodplain are increasing, resulting into the increased vulnerability to flood hazards. The basic hydrological design parameters for majority of flood protection measures are either the peak flood discharge and level, flow velocity and extent of

flooding. These parameters must be computed with the computed hydrological estimates under projected climate change scenario. In this paper, safe-grade elevation is estimated for an important project site lying in north India.

Day 2 – Wednesday 30 November

Session 4: Improving understanding of spatial and temporal variability in Indian hydrology

Chair: *Prof. V. K. Gaur (CMMACS, Bangalore)*

Operational hydro-meteorological services in IMD

Dr A. K. Das (Hydromet Division, India Meteorological Department)

The mandates of IMD for operational Hydro-meteorological services are in the field of Real time Rainfall Monitoring, Flood Meteorological Services and Design Storm Studies.

Real time Rainfall Monitoring: Based on real time daily rainfall data, weekly, monthly, seasonal and annual district wise, subdivision wise and state wise rainfall distribution summaries are prepared and sent to various authorities & uploaded on IMD website. Flood Meteorological Service: Flood Forecasting is joint responsibility of India Meteorological Department (IMD) and Central Water Commission (CWC). IMD's contribution in flood warning through Flood Meteorological Offices (FMOs) is mainly in the form of sub-basin-wise Qualitative and Quantitative Precipitation Forecast (QPF) issued to Flood Forecasting Divisions (FFDs) of CWC which is used by them in the formulation of flood warning/forecast. Designing Storm Studies: Designing of storm studies is conducted to evaluate design storm estimates (rainfall magnitude and time distribution) for various river catchments/ projects in the country, for use as main input for design engineers in estimating design flood for hydraulic structures, irrigation projects, dams etc. on various rivers.

Assessing WRF model experiments of precipitation in the Indian-Himalaya

Dr Andrew Orr (British Antarctic Survey)

This study examines the impact of different physical parameterisations on the representation of precipitation in the Beas-Sutlej basin of north-west India, as simulated by the Weather Research and Forecasting (WRF) model at 5 km grid spacing. The model results are evaluated by comparison with both remote-sensing and in-situ measurements.

Modeling hydrological changes using multiscale remote sensing in India

Prof. Sekhar Muddu *(IISc Bangalore)*

The presentation discusses: Water Budget components from RS, ET estimation from Energy Balance method & India product at 5 km grid resolution, Soil moisture estimation from remote sensing & mapping crop-water stress regions, Groundwater budget & Baseflow modelling: Hydrology outlook and framework for addressing climate change impacts on groundwater.

Highlights on the use of climate services for hydrological modelling in the Indian Himalayas

Dr Andrea Momblanch *(Cranfield University)*

The presentation will show the results of a systematic review on hydrological studies in Himalayan river basins published between 2010 and 2016. The limitations of climate services regarding the temporal-spatial resolution and bias of meteorological variables, snow and ice processes, and land use changes are identified. From these findings, the key research gaps to improve the use of climate services for hydrological modelling in the Indian Himalayas are highlighted.

Understanding land atmosphere interactions for Indian monsoon

Dr Subimal Ghosh *(IIT Bombay)*

Weakening of Indian summer monsoon rainfall (ISMR) is traditionally linked with large-scale perturbations and circulations. However, the impacts of local changes in land use and land cover (LULC) on ISMR have yet to be explored. Here, we analysed this topic using the regional Weather Research and Forecasting model with European Center for Medium range Weather Forecast (ECMWF) reanalysis data for the years 2000–2010 as a boundary condition and with LULC data from 1987 and 2005. The differences in LULC between 1987 and 2005 showed deforestation with conversion of forest land to crop land, though the magnitude of such conversion is uncertain because of the coarse resolution of satellite images and use of differential sources and methods for data extraction. We performed a sensitivity analysis to understand the impacts of large-scale deforestation in India on monsoon precipitation and found such impacts are similar to the observed changes in terms of spatial patterns and magnitude. We found that deforestation results in weakening of the ISMR because of the decrease in evapotranspiration and subsequent decrease in the recycled component of precipitation.

Session 5: Improving understanding of climate process for hydrology

Chair: *Dr R. Krishnan (IITM)*

The challenge of providing defensible downscaled and bias-corrected climate simulations

Dr Martin Widmann *(U of Birmingham)*

Downscaling and bias correction of climate model output are crucial elements when providing regional climate scenarios and hydrological projections. Although such methods are routinely used, it is not well understood under which conditions they actually yield plausible projections on which defensible impact studies and climate change adaptation decisions can be based. This presentation will review validation results and discuss the key challenges in the field of downscaling and bias correction.

Coupling of aerosol-land-cloud-rainfall system over Gangetic Plains: observations and modelling analysis

Prof. Sachida Tripathi *(IIT Kanpur)*

We quantified the spatial and temporal aspects of the urban heat island (UHI) effect for Kanpur, a major city in the humid subtropical monsoon climate of the Gangetic basin. Fixed station measurements are used to investigate the diurnality and inter-seasonality in the urban-rural differences in surface temperature (UHIs) and air temperature (UHIc) separately. The extent of the night-time UHIc and UHIs's spatial variations are investigated through mobile campaigns and satellite remote sensing respectively. Night-time UHIc dominates during both pre-monsoon (maximum of 3.6°C) and monsoon (maximum of 2.0°C). However, the diurnality in UHIs is different, with higher daytime values during pre-monsoon, but very little diurnality during the monsoon. We found that the night-time UHIs is mainly associated with the differences in urban-rural incoming longwave radiative flux (r2 = 0.33 during pre-monsoon; 0.65 during monsoon), which, in turn, causes a difference in the outgoing longwave radiative flux. This difference may modulate the night-time UHIc as suggested by strong correlations (r2 = 0.68 for pre-monsoon; 0.50 for monsoon). A combination of in-situ, remotely sensed, and model simulation data were used to show that the inter-seasonality in UHIs, and, to a lesser extent, the UHIc, may be related to the change in the land use of the rural site between pre-monsoon and monsoon. This study suggests that the degree of coupling of UHIs and UHIc may be a strong function of the land use and land cover (Chakraborty, Tripathi et al., BLM, 2016, provisionally accepted).

LSM-RTM coupling for microwave Tb assimilation over India

Dr Indu J *(IIT Bombay)*

The microwave radiometers on-board satellites are responsible for creating indirect estimates of soil moisture using the relationship between observed microwave brightness temperature (Tb) which is emitted by the earth's surface and the soil moisture content. Numerous studies have examined the possibility of assimilating the satellite derived soil moisture products for improving the LSM initial states. In this regard, there are two questions at stake: a) Whether satellite observed Tb circumvents the need for processing soil moisture retrievals and (b) questions regarding the relationship between the assimilation of Tb observations and the Radiative Transfer Model (RTM). Studies have tried to improve soil moisture prediction by assimilating microwave Tb to the LSM (Tian et al., 2010; Jia et al., 2013), which requires the LSM coupled to a forward radiative transfer model to convert the forecast state to the observation state during the assimilation stage. In this method, one of the crucial factors affecting the prediction skills of LSM, is the forward RTM used as the observation operator. Few studies have addressed this issue of global calibration of RTM (De Lannoy et. al., 2013). Literature presents RTMs to simulate the microwave Tb over varying surface conditions (Dobson et al., 1985; Weng et al., 2001; Drusch et al., 2001; Chen et al., 2003; Shi et al., 2005; Wigneron et al., 2007). Very few studies have examined the feasibility of the CMEM RTM over India to simulate brightness temperature (Tb). In the present study, the sensitivity of CMEM with two parameterization schemes as is conducted, by using the soil moisture from the assimilation experiment to simulate 10.7 GHz brightness temperature at an incidence of 550, which is compared with the actual AMSR-E Tb. The study is conducted to check the variation in Tb simulation with change in parameterization rather than to simulate accurate AMSR-E Tb. The community microwave emission model (CMEM) developed by the ECMWF was used as a forecast operator for the present study over India. Results of Tb simulation are presented for two parameterization schemes over India in this study.

Applications of geo-spatial technology for groundwater resource management

Dr Ravi Prakash Singh *(National Remote Sensing Centre)*

The hydro-geomorphology is an integrated study of lithology, geomorphology, fractures, lineaments, soil, land use, drainage, slope and their linkages with hydrological processes in spatial dimensions (Sidle and Onda, 2004). Hydro-geomorphological units play a significant role in ground water occurrence in any area (Jaiswal et al., 2003; Surrete et al., 2008; Yeh et al., 2008). Ground water resources depend upon hydro-geomorphological nature of landforms and lineament distribution with respect to the permeable nature of subsurface, percolation and run off status of the area.). Integrated studies using conventional surveys along with satellite image data interpretation techniques and geographical information systems (GIS) technology are useful, not only to increase the accuracy of results, but also to reduce the biasness on any single theme. The ground water potential of an area is dependent upon the intrinsic characters of the rock and soil. Overall lithology (physical characteristics of the rock, size and sorting of the grains in the soil) play a significant role in determining the hydrogeology and have a great influence over groundwater occurrence in the study area. The drainage system is strictly dependent on the slope, the nature of bedrock and on the regional and local fracture pattern. In hilly and rocky terrain, GIS based models such as Digital Elevation Model (DEM) and Digital Surface Terrain Model (DSTM) are extremely valuable in understanding slope, aspect curvature, flow accumulation, stream ordering etc (Kumar et al., 1997). Steeper slope have higher runoff and less percolation time, whereas low runoff zone allows more time for water to be in contact with the surface and allows higher infiltration into the subsurface, thereby increasing the recharge of ground water in different geomorphic units.

Rainfall information from NCMRWF Unified Numerical Modeling System

Dr Ashish K. Mitra *(NCMRWF, MoES, Govt. of India)*

Information and proper management of water availability contribute to sustainable development and economic growth for any region. Prior information on rainfall and associated river waters is highly sought after information in the field of water management. Current generation of weather and climate simulation models of the Earth system is able to provide estimates of rainfall in advance for different time and spatial scales. India and broadly south Asia is heavily dependent of rainfall from monsoon climate pattern of Earth. Simulation and prediction of South Asian monsoon rainfall by Numerical Models is a challenging scientific task for world modelling community. NCMRWF is working closely with UK Met office and other partners in India and abroad to further develop the global/regional modelling system for reliable prediction of rainfall for India and neighbouring regions. NCMRWF carries out research on data assimilation, model development, uncertainty estimation, and coupling of ocean and land-surface components to make it a complete modelling system. The aim is to continuously improve the unified modelling system to be realistic across a scale from days-to-season. The use of probabilistic forecast from the ensemble prediction system from a global 45-member simulation will take care of the uncertainty in quantitative terms. Use of high volume of satellite data and use of bigger super computers are continuously helping in improving the skill of the model increasing the model resolution, using more data and use of improved physical processes in model.

Session 6: Future water resource availability and management **Chair:** ***Dr B. Mukhopadhyay (IMD)***
Satellites for hydrology **Prof. P. C. Pandey** *(IIT Bhubaneswar)* The global climate change, the increasing population and intensified human activities lead to changes in the global hydrological cycle including spatial and temporal distribution and the total amount of water resources. In addition, scaling the point observation to large area will include errors. With the rapid development in remote sensing, it is possible to obtain some critical components of the hydrological cycle such as soil moisture, precipitation, salinity and total water storage etc. By a proper combination of *in situ* observations, model and satellites, useful information about terrestrial hydrology can be studied. The imaging and satellite altimetry can give surface part of hydrology but new technological marvel GRACE (Gravity Recovery and Climate Experiment) and SMOS can provide earth's mass distribution, Soil Moisture and Ocean Salinity. GRACE can give time series of gravity field from which total water storage (TWS) and their variations can be studied. Already GRACE has been successfully used for monitoring the ice mass balance of Greenland ice and found to be declining. For terrestrial hydrology, GRACE can give integrated water storage, i.e. surface water, soil, ground water and snow pack, There is an urgent need for harnessing this powerful technology for terrestrial hydrology applications.
Interconnecting field level services and researchers for effective hydro-climatic services **Dr Dipanjana Maulik** *(Dept. of Environment, Govt. of West Bengal)* Interpreting information from the researcher's desk to the farmers at the field or to the sluice gate operators at discharge outlet is not an easy task. It requires regular interaction by the interpreter at both ends. Navigating among the scientific wisdom or among skills and experiences of the users, feed backs and demands of different actors is a fascinating journey. However this requires continuous up gradation of scientific knowledge as well as regular field level appraisal of the system. The scopes of hydro-climatic services are understandably broader than that of water services. Establishment of efficient hydro-climatic services would be successful only when the user groups not only start using the information products but also start sending feedback. Climate change is inducing more uncertainties and climate projections as well as real time forecasting are becoming more difficult work. Improving the reliability of the system as well as expanding the information exchange systems is need of the day. The accuracy can be improved by repeated field level trials. However, this may require change of mind set at both ends. The researchers are required to pay attention to the feed backs received while district or block level actors are required to send regular feedbacks. Uncertainty in predictions should be minimized as real life applications involve use of taxpayers money and many other complex socio technical impacts.
WRF-PDM: Prototype for discharge prediction in ungauged basin **Dr Prashant Srivastava** *(Institute of Environment and Sustainable Development, BHU)* Hydro-meteorological variables such as precipitation and evapotranspiration (ET) are the most important variables for discharge prediction. However, it is not always possible to obtain these from ground-based measurements, particularly in ungauged catchments. The mesoscale Weather Research & Forecasting model (WRF) can be used for prediction of hydro-meteorological variables. However, hydro-meteorologists would like to know how well the downscaled global data products compare with ground-based measurements and whether it is possible to use the downscaled data for ungauged catchments. In this study, the hydro-meteorological variables are downscaled using the WRF model from the European Centre for Medium Range Weather Forecasts (ECMWF) ERA interim reanalysis global datasets and subsequently used for ET estimation. The analysis of the downscaled weather variables and precipitation are compared against the ground-based datasets, which indicates that they are in agreement for the whole monitoring period as well as during the seasons, except precipitation whose performance is poorer in comparison with onserved rainfall. After performance assessment, the WRF estimated precipitation and ET are used as input for the Probability Distributed Model (PDM) for discharge prediction. The input data and model parameter sensitivity analysis and uncertainty estimation are also taken into account for the PDM calibration and prediction following the Generalised Likelihood Uncertainty Estimation (GLUE) approach. The overall analysis suggests that the uncertainty estimates in the predicted discharge using the WRF meteorological derived ET have comparable performance to the ground-based observed datasets and are promising for discharge prediction in the absence of ground-based measurements.

Understanding migration of arsenic in the aquifer of North Bengal plain using numerical modelling: A case study of English Bazar Block, Malda District, West Bengal, India

Dr Surajit Chakraborty *(Dept. of Environment Management, IISWBM, Kolkata)*

In this paper numerical simulations of regional-scale groundwater flow of North Bengal Plain have been carried out with special emphasis on the arsenic-rich alluvium filled gap between the Rajmahal hills on the west and the Garo hills on the east. Groundwater flow in the north Bengal Basin is complicated to conceptualize, even without considering extensive anthropogenic impacts. Therefore, only the features that are thought to have significant control on the groundwater flow have been incorporated and a simple model has been designed. The horizontal conductivity and bulk anisotropy are the primary factors that control the regional groundwater flow. Other factors, such as boundary conditions and vertical discretisation, have little effect on the flow system. Therefore, in the present study the ‘base case’ model has been set up with the large-scale bulk properties of the aquifer system as horizontal hydraulic conductivity (Kh) = 3 x 10-4 m/s; vertical hydraulic conductivity (Kv) = 1 x 10-7 m/s and anisotropy (Kh/Kv) = 3,000. The modelling study was undertaken for the entire North Bengal Plain with special emphasis on English Bazar block of Malda district, West Bengal. English Bazar block is bounded by latitude 24○50’N to 25○05’N and longitude 88○E to 88○10’E with a total area of 265.5 km^2.

Changing monsoon and mid-latitude circulation interactions over the Western Himalayas and possible links to occurrences of extreme precipitation

Ms. Priya P. *(IITM, Pune)*

Historical rainfall records reveal that the frequency and intensity of extreme precipitation events, during the summer monsoon (June to September) season, have significantly risen over the Western Himalayas (WH) and adjoining upper Indus basin since 1950s. Using multiple datasets, the present study investigates the possible coincidences between an increasing trend of precipitation extremes over WH and changes in background flow climatology. The present findings suggest that the combined effects of a weakened southwest monsoon circulation, increased activity of transient upper-air westerly troughs over the WH region, enhanced moisture supply by southerly winds from the Arabian Sea into the Indus basin have likely provided favourable conditions for an increased frequency of certain types of extreme precipitation events over the WH region in recent decades.

Session 7: Climate services for disaster risk reduction

Chair: ***Prof. Pradeep Mujumdar (IISc Bangalore)***

Hydrologic extremes under climate change: Non-stationarity and uncertainty

Dr Arpita Mondal (IIT Bombay)

Assessment and evaluation of environmental risk is a major challenge faced by the society. In particular, hydrologic extremes such as floods and droughts affect people’s lives and properties. While such extremes are difficult to understand due to their complexity and rarity, their impact is reportedly increasing as the environment changes and population and industrialization grows, exposing more human settlements to natural hazards. Changes in hydrologic extremes can be caused by rapid modifications in land-use/land-cover, human interventions and climate change. Such changes imply that the past can no longer be used as a guide to the future and has led to the belief that ‘stationarity is dead’. In particular, climate change is believed to possibly increase the frequency and magnitude of extreme events. Indeed, the risk of both floods and droughts are reported to be increasing under climate change projections in the twenty-first century. Increasing number of studies in hydrologic literature therefore use future forcing-based scenarios to replace the assumption of stationarity in order to assess future hydrologic risk. While human-induced climate change has reportedly led to intensification of extreme temperature or precipitation events for the present as well as the future, only low to medium confidence exists in the projections of floods and droughts, owing to modeling limitations and lack of good quality records at local or regional scales. Moreover, understanding and attributing observed changes in hydro-climatic extremes to anthropogenic climate change is particularly difficult due to large natural variability and poor simulation of human-induced signals by the climate models challenging at regional scales. This study first discusses specific limitations of a future forcing-scenario based hydrologic projection typically obtained from General Circulation Model (GCM) simulations. These model simulations are commonly used in conjunction with downscaling models and/or rainfall/runoff models to address scale and physical processes mismatch with hydrologic variables of interest.

An overview of the effectiveness of early warning systems and risk assessments for weather-related hazards in South Asia

Dr Darren Lumbroso *(HR Wallingford)*

Low-income countries are significantly more vulnerable than high-income countries to the risks posed by natural hazards. This presentation aims to discuss the findings of research into stakeholders' perceptions of the overall effectiveness of early warnings and risk assessments for weather-related hazards (i.e. cyclones, floods, droughts and landslides), for humanitarian and development purposes in low-income countries in Africa, the Caribbean and South Asia. New findings are derived from a survey and consultations with some 400 practitioners, scientists, researchers and decision-makers in the regions. Our findings, which were based upon the collated results of a literature review, stakeholder interviews together with other reviews and surveys, show that although there would appear to have been some progress in improving early warning and risk assessments for weather-related hazards, it is highly variable across the three regions. The findings are inconsistent with the self-reporting of progress against the Hyogo Framework for Action, which in many cases give a more positive view of their status. Significantly, more work is required to produce robust, reliable and accessible information to reduce vulnerability and manage risks, and this should concentrate on understanding aspects of vulnerability, effective risk communication and community-level actions, as well as some well-focused improvements in technical, and underpinning scientific aspects of early warning systems and risk assessments

Making smallholder farming climate resilient

Dr Crispino Lobo *(WOTR, Pune)*

Climate change is accompanied by increasing weather uncertainty. Farmers, especially smallholder farmers, need advance warning of emergent weather conditions at a local level. Mobile telecommunication systems are increasingly cost-effective and an efficient way of delivering weather-based agro-advisories to farmers at a large scale. Agrometeorological services facilitate flexible, weather-based agriculture planning and help build evidence and capacities of communities, technical and developmental agencies to plan and implement climate-adaptive responses. The relevance and innovativeness of multi-institutional collaboration lies in the institutional, technical and pedagogical strategy adopted which offers important lessons on how agrometeorological services can be organized to make smallholder farming climate-resilient on a larger scale.

Changes in convective rainfall in future climates over western Europe

Dr Alan Gadian (*NCAS Leeds*)

The WISER project analyses changes in extreme weather events in a future climate, using a weather research model (WRF). Climate models have insufficient resolution to properly simulate small meso-scale precipitation events which are critical in understanding climate change. Use of the weather model at ~ 3km is specifically designed to resolve convection permitting processes.

Integration of excess rainfall run-off into Aquifer Management Plans

Dr Sivakumar *(CGWB, Chennai)*

The presentation aims to discuss the systematic approach adopted by CGWB for delineation of aquifers, preparation of aquifer management plans with the ultimate objective of participatory ground water management

Poster abstracts

Name of the participant; Poster title
Role of Integrated Water Resource Management (IWRM) System in water security at urban scenario **Dr Shivaraju H.P.** The World Health Organization reports that for the first time ever, the majority of the world's population lives in urban areas, and this proportion continues to grow with projections of 70 % by 2050. The present study reveals a comprehensive analysis on the concept of water security from the prospects of integrated water resource management (IWRM) in resolving the existing water crisis at Mysore City, India as a special reference. The research addresses the importance of IWRM in assessment and management of hazardous events and risks associated with physical, hydraulic, and water quality integrities in water transmission and distribution system, from the perspective of water resource conservation and pollution remediation. The study indicated that water security, which impacts on socio-economic and environmental conditions, has increased significantly in recent years across the city. It identified several hazardous events in the water supply systems and also explored a water safety planning framework with reference to IWRM approaches for sustainable governance. It recommends the assessment and possible utilization of portfolio of water sources such as municipal wastewater effectively for sustainable conservation of available water resources. Utilization of portfolio of water sources brings urban water security and management more sustainable with respect to water conservation, utility, and micro-climate change. It could be concluded that an IWRM approach to urban water security brings a good governance and sustainably water conservation and management in urban areas.
Impact of climate change on water resources in Kiliyar sub-basin of Palar river basin, Tamilnadu, India **Dr S.G.D. Sridhar** The study area has a total geographical area of 919km^2, which encompasses 335 villages. The impact of water resources due to climate change are on water bodies including tanks and rivers. In the study area, the size of tanks were compared for the year 1916 and 1972 and found that 18 tanks are diminished or vanished. In the study area, the river course changes and are compared for the year 1916 and 1972. The change of river course is due to heavy rainfall and climate change and as a consequence water level fluctuation is noticed. The water spread area is decreased year by year and is very significant during the year 1988 to 2014. Diminishing of water bodies and changes of river course will lead to hurtle in water management for agricultural and drinking purposes. Land use maps for the years 1998, 2008 and 2014 were prepared by visual interpretation from the respective years of IRS ID, P6 LISS III and LISS IV Mx data. The study also identifies groundwater potential zones and favourable recharge zone for further development of water resources.
Monsoon forecast impact assessment approach for Indian agriculture **Ms. Suman Apparusu** This abstract seeks to delineate a high-level idea to assessing the monsoon forecasting impact on the agriculture sector in India drawing on the GAEZ assessment approach at the global agro ecological zone level. The global GAEZ approach uses 7 climate variables in arriving at the production and yield gap planning global outputs. The suggested idea is to potentially adapt the global approach to suit Indian context by using the probabilistic monsoon-relevant climate variables /seasonal forecasts and by applying the approach at the Indian sub-national level (15-20 agro ecological zones) to arrive at production and yield gaps for key crops grown in 2 agri-crop seasons, Kharif and Rabi. If the suggested approach stands feasible, we believe the policy makers and the sector, at large, stand to benefit in terms of better window into the production and yield outputs and gaps and thereby initiate necessary plan/correction measures to support the control of food inflationary pressures on the Indian economy.

Importance of land surface initialization for hydrological forecasts: An assessment based on CFSv2 and observations

Dr Subhadeep Halder

When initial soil moisture is perturbed among ensemble members of retrospective forecasts made with the operational Coupled Forecast System (CFSv2) global forecast model, immediately surface latent and sensible fluxes are affected much more strongly, systematically and over a greater area of the continents than conventional land-atmosphere coupling metrics suggest. Flux perturbations are likewise transmitted to the atmospheric boundary layer more formidably than climatology-based metrics would indicate. Impacts extend over nearly all ice-free land areas of the globe and are not just limited to the traditional land-atmosphere coupling hot spots. A consequence of this high sensitivity is that significant positive impacts of realistic land surface initialization on the skill of near surface temperature and humidity forecasts are also immediate and nearly universal during boreal spring and summer (the period investigated) and persist for at least three days over most land areas. We conclude that land surface initialization may be more broadly important for weather forecasts and forecasts of hydrological extreme events such as floods than previously realized, as focus historically has been on sub seasonal-to-seasonal time scales. This study attempts to bridge the gap between climate studies with their associated coupling assessments and weather forecast time scales. Furthermore, errors in land surface initialization and shortcomings in the parameterization of atmospheric processes sensitive to surface fluxes may have greater consequences than previously recognized, the latter exemplified by the lack of impact on precipitation forecasts even though the simulation of boundary layer development is shown to be greatly improved with realistic soil moisture initialization. Implications of accurate land surface initialization for hydrological forecasts shall be discussed.

Southern Indian Ocean SST as a modulator for the progression of Indian summer monsoon

Dr Shailendra Rai

Many of the previous studies show that the Indian Ocean Sea Surface Temperature (SST) play an important role in tropical climate variability. The Indian Ocean Dipole (IOD) is one of the most dominant modes of climate variability in the tropical Indian Ocean, and its mechanisms and climatic impacts have been investigated extensively. There is another important climate mode in the Southern Indian Ocean (SIO) called the Indian Ocean subtropical dipole (IOSD), with mature phase locked to the austral summer, has also been documented by researchers. The influence of the IOSD on the Africa rainfall has been explored by many studies and also shows by many authors that the IOSD affects the South China Sea summer monsoon onset and it can be considered as one of the main factors for the prediction of the rainfall in China. There are only few studies related to influence of the SIO on the Indian monsoon rainfall and is at initial stage. The present study explores the possibility of SIO SST as modulator for the early phase of Indian summer monsoon and its possible physical mechanism. The Empirical Orthogonal Function (EOF) analysis has been applied on the seasonal SST anomalies over the SIO region (30°E–120°E, 60°S–Eq.) averaged in December–January–February (DJF) and March–April–May (MAM) seasons during the time domain 1952–1982 and 1983–2013. We wish to see the effect of developing and dying phase of IOSD on Indian summer monsoon and therefore both the DJF and MAM seasons were considered.

Indian summer monsoon simulation using RegCM-4.3 during different phases of monsoon

Dr R. Bhatla

The climate model faces considerable difficulties in simulating the rainfall characteristics of the South-West summer monsoon. In this study, the dynamical downscaling of European Centre for Medium Range Weather Forecasts (ECMWF) Era interim EIN15 is performed for simulation of Indian summer monsoon (ISM) through the Regional Climate Model version 4.3 (RegCM-4.3) over the South-Asia Co-ordinated Regional Climate Downscaling Experiment (CORDEX) domain. The complexity of model simulation over a particular terrain are influenced by many factors such as the complex topography, coastal boundary and lack of unbiased initial and lateral boundary conditions. In order to overcome some of the limitations, the RegCM-4.3 is employed in this study for simulating the rainfall characteristics over the complex topographical conditions. For reliable simulation of rainfall, implementation of numerous initial and time dependent lateral boundary conditions are provided in RegCM-4.3. The model is simulated over the South-Asia CORDEX domain with specific horizontal grid resolution of 50km. The analysis is provided for 30 years for climatological simulation of rainfall, outgoing longwave radiation (olr), mean sea level pressure (mslp) and wind with different vertical levels over the selected region. The dependency of model simulation with the forcing of EIN15 initial and lateral boundary conditions are used to understand the impact of simulated rainfall characteristics during the different phases of summer monsoon rainfall. The results show that the activity of initial conditions of zonal wind circulation speed causes an increase in the uncertainty of the model output over the region under investigation.

Ensemble-based data-driven models for river flow forecasting

Mr. Soundhara Raja Pandian. R

Reliable and accurate river flow forecast helps planning and managing water resources effectively. River flow forecasts/or predictions made by all types of modelling approaches depend on available data and contain uncertainty, since complex hydrologic processes cannot be perfectly represented in mathematical forms. Therefore, the quantification of uncertainty in forecasting/prediction is crucial. To date, the uncertainty originated from model inputs and parameters has been well investigated, however a very limited number of studies have dealt with the assessment of the uncertainty originated from model structure. In this paper, an ensemble based Genetic Programming (EGP) approach was employed to forecast river flows and to quantify the uncertainty in forecasting. A bootstrap based sampling technique, which samples different combinations of input-output patterns from the pool of the dataset with replacement, was applied to develop an ensemble of GP models. The resulting models¬¬ were used to construct the prediction uncertainty interval (PUI) of forecasting. The application of the EGP was demonstrated through a case study in the Bow River Basin, Alberta, Canada, in one-step ahead flow forecasting. The importance of taking account of the structure uncertainty was illustrated by comparing the EGP with an ensemble based artificial neural network (EANN) model, in which the model structure was assumed deterministic. The results show that the EGP and the EANN perform equivalently in terms of reproducing observations; whereas the EGP overall outperforms the EANN in reducing uncertainty, especially in high flow domain

Isotope hydrology

Dr CK Anoop

As rightly mentioned by many researchers and practically everyone in the world, water is the most abundant substance on earth, the principal constituent of all living things and a major force shaping the surface of earth. It is also a key factor in air conditioning of the earth for human existence and in influencing the progress of the civilization. Hydrology which treats all phases of earth's water is a subject of great importance to people and their environment. It deals with the scientific study of water, its occurrence, and movement through the earth atmosphere system. The importance of hydro climatic services for the improvement of health, the production of food, and the support of industry is vital in the rapidly developing world of today. The political and social context of developing hydro climatic service has always been important and will remain so in the future. Advanced research has contributed to a better understanding of the subject of hydro climatic services and new concepts of resource management have been evolved. The aim of research in various aspects of hydrology is to provide sufficient breadth and depth of understanding in each sub section of hydro climatic services.

An investigation of trends and variability of rainfall in Shillong City

Dr Kamal Kumar Tanti

This study aims to investigate and analyse the trends and variability of rainfall in Shillong and its nearby areas, located in Meghalaya hills of North-east India; which is geographically a neighbouring area to the wettest places of the Earth, i.e., Cherrapunji and Mawsynram. The analysis of variability and trends to annual, seasonal, monthly and daily rainfall was carried out, using the data collected from the IMD station at Shillong; thereby attempting to highlight whether rainfall in Shillong area has been increasing or decreasing over the years. Rainfall variability coefficient is utilized to compare the current rainfall trend of the area with its past rainfall trends. The present study also aims to analyse the frequency of occurrence of extreme rainfall events over the region. These studies will help us to establish a correlation between the current rainfall trend and climate change scenario of the study area.

Increasing civil society capacity to generate and disseminate hydro-climate data and services

Dr Jagdish Krishnaswany

River flood events have devastating consequences for health, livelihoods & economic development in India. The discussed project "Hydrologic and carbon services in the Western Ghats: Response of forests and agro-ecosystems to extreme rainfall events" is focused on the role of extreme rainfall events in the generation of floods in a region of India that has some of the largest short-term rainfall intensities. The methods used were capable of identifying changing dynamics directly from meteorological and hydrological time-series from both existing government stations & new experimental systems. Both field and numerical techniques were used so that change can be observed to reduce uncertainties. The underpinning mantra being that change is rarely easy to see in observations of environmental systems. Robust experimental designs and sophisticated sensors and numerical tools are needed to identify these changes. We also used the field experience from experimental catchments in the Western Ghats to train a diverse set of trainees from diverse academic, government and civil society backgrounds in field hydrology and hydro-climatic data processing. The poster describes the methods and approaches we used (field training, web-based approaches and workshops) to develop the capacity of civil society to generate primary hydro-climatic data and use secondary and primary hydro-climatic data to measure and monitor changes in water resources at local to regional scales.

Impacts of ENSO and IOD on the Indian rainfall

Dr Sumit Sen

Water is vital to life. India is an agriculture based economy more than 50% of the population dependents on the agriculture. More than 60% of agricultural land is rainfed. The main source of water is summer monsoon rainfall as 78% of total annual rainfall occurs in the monsoon period. Though the summer monsoon rainfall varies on inter-annual basis, the variation in the summer monsoon is modulated by two phenomena El Nino Southern Oscillation (ENSO) and recently discovered Indian Ocean Dipole (IOD). For the study we used IITM area weighted rainfall data series, Aphrodite's gridded rainfall and TRMM rainfall data with ENSO and IOD indices data. Specific objectives were to study (i) the impact of ENSO and IOD on the Indian rainfall, (ii) temporal as well as spatial variation of rainfall due to ENSO and IOD, and (iii) Impact of ENSO and IOD on magnitude and intensity of extreme rain events (EREs). Obtained results were broadly agrees with the previous studies. It was found that ENSO is negatively correlated with monsoon rainfall in India, while IOD is not significant at 90% significance level for the IITM data (1876-2005).

Development of water balance model for climate impact assessment

Dr Saravanan K

Water balance model is usually estimating the change in storage over a catchment. Water balance model is simply used the water balance components as equation based on hydrological concepts. The application of Water balance model is carried out in ungauged catchments by relating water balance components with physical characteristics of catchments is possible. It is usually used the monthly water balance components in long term duration. Some components are negligible due to physiographical and hydrological features of catchments. The disadvantage of water balance model is a difficult to obtain the reliable results over the semi-arid and arid catchments. It is very complex work process and needs to be done by qualified experts. It requires considerable time and resources. Moreover, model is develop over a catchment by using water balance components such as Precipitation, Infiltration, Evapo transpiration, Surface Runoff, Groundwater/Base flow, Soil moisture, Interception, Depression storage etc.

Identifying critical climate and land use change thresholds for watersheds using the bottom-up modelling paradigm: case studies from India and the US

Dr Riddhi Singh

Quantifying the availability of freshwater resources in the future is essential for managing water resources for an increasingly water intensive world. A major challenge in this regard are the large uncertainties in projections of climate and land use change that translate into large uncertainties in estimates of future water availability. In several parts of the globe, climate model projections do not even agree on the nature of climate (precipitation) change. One way for water managers to plan for an uncertain future is to assess how vulnerable a watershed is to environmental change. If a watershed is identified as more vulnerable, it will call for a highly risk averse planning and vice-versa. Here, we provide a framework to quantify watershed's vulnerability to environmental change despite large uncertainties in future projections of these changes. There are two main features of this framework. First, it enables a flexible user-driven definition of vulnerability. Second, it identifies unacceptable climate and land use combinations, i.e., those environmental changes that are likely to cause a watershed to transition to a vulnerable regime. We apply this framework to watersheds across the US, and also to a case study in India. We identify critical thresholds of climate change for watersheds in both case studies. We show that these critical thresholds vary significantly across watersheds and thus, can serve as indicators of watershed vulnerability to environmental change. The proposed framework can be applied independently of future projections of change drivers, and can use varying definitions of vulnerability.

Cosmic-ray soil moisture probe at IITM Pune

Dr Milind Mujumdar

The Hydrometeorology Research Unit (HMRU) at the Centre for Climate Change Research (CCCR), IITM was recently formed for the coordinated development and implementation of observational and modeling challenges involving climate scientists and hydrologists. It is proposed to develop and promote the observational national network for continuous monitoring of water balance components (e.g., soil moisture, evapotranspiration, runoff etc.). This collaborative observational program is a segment of Natural Environment Research Council (NERC) and UK and Ministry of Earth Sciences (MoES), Government of India i.e. “NERC-MoES”. A network of field-scale soil moisture monitoring stations across India (COSMOS-India) is being developed under the NERC-MoES program using cosmic-ray soil moisture sensors (CRS). The Centre for Ecology and Hydrology, UK (CEH; cosmos.ceh.ac.uk) is working in partnership with IISc Bangalore, IIT Kanpur, IITM Pune, UAS Dharwad and NIH Roorkee to develop the COSMOS-India network, and to deliver high temporal frequency observations of soil moisture at the intermediate spatial scale in near real-time. Data from this national observational network are being telemetered over the mobile communications network to be made available in near-real time.

Changing monsoon and mid-latitude circulation interactions over the Western Himalayas and possible links to occurrences of extreme precipitation

Ms. P. Priya

Historical rainfall records reveal that the frequency and intensity of extreme precipitation events, during the summer monsoon (June to September) season, have significantly risen over the Western Himalayas (WH) and adjoining upper Indus basin since 1950s. Using multiple datasets, the present study investigates the possible coincidences between an increasing trend of precipitation extremes over WH and changes in background flow climatology. The present findings suggest that the combined effects of a weakened southwest monsoon circulation, increased activity of transient upper-air westerly troughs over the WH region, enhanced moisture supply by southerly winds from the Arabian Sea into the Indus basin have likely provided favorable conditions for an increased frequency of certain types of extreme precipitation events over the WH region in recent decades.

Surface water stress and its probable impact on ground water resource in a changing climate scenario: A study based on CMIP5 models

Dr Rajib Chattopadhyay

Depletion of ground water resources over Indian region is a cause of concern for long term policy makers. The same fact could be aggravated due to stress in the surface sources of ground water. Considering precipitation, evapotranspiration and surface runoff as major stress factors affected by climate change, a study is made based on two CMIP5 models is made to understand the impact on ground water resources in coming century in RCP8.5 scenario runs.

Building resilience to climate change for groundwater resources in India

Dr Sujata Ray

Groundwater, a critical water resource in both India and the UK, is currently threatened by potential changes in climate as well as heavy abstraction. The case for building resilience and optimizing water resources has never been stronger. Yet, this process is impeded by large uncertainties associated with potential groundwater response. Water accumulates in aquifers through natural recharge, but this process is often inadequate when huge quantities of water are drawn out for daily use. As a result, the water level in individual aquifers is falling at an alarming rate – thereby posing a serious threat to the continued availability of groundwater for domestic, commercial or agricultural purposes. Here, we report results of an aquifer recharge project in which runoff is collected and injected into the alluvial aquifer continuously at a very fast rate for a period of the year. The process includes two stages. First, the turbidity of runoff water is filtered and decontaminated. Subsequently, the treated and decontaminated water is injected through two sets of pipes pushed down into the aquifer. The technology functions with the principle of siphon by the help of atmospheric pressure forming a recharge cone in the aquifer, without any constant supply of energy. It is observed from the observation wells that water level of the aquifer has, in an average, increased by 0.3 m at a radial distance of 1km from recharge shaft, after a period of 36 months since the inception of artificial recharge by this technology.

Extreme rainfall events in the northeast regions of India during recent decades

Dr Hamza Varikoden

Indian summer monsoon has always important to northeast India because of their high dependency of natural water sources for their agriculture and circadian activities. Floods and flash floods associated with extreme rain events are a major hydrological disaster in the northeast region (Goswami et al 2010). The cause of floods may be due to topographic features of the region as well as the frequency of occurrence of high intensity rain events. In the present work, we tried to explore the major characteristics of the extreme rain events over the northeast India. The work has been carried out using TRMM 3B42 and NCEP-NCAR reanalysis products. The data sets having different spatial resolutions with daily temporal resolution. The climatological rainfall during the southwest monsoon period is more in the northeast regions and in some regions the climatological rainfall exceeds 15 mm day-1. The second maximum zone is in the windward side of the Western Ghats. In the present analysis, we explore the properties of the extreme events over the northeast India (88E-93E & 24N-27.5N). We chose the extreme rainfall events if the rainfall is exceeding 35 mm day-1 over the above box and we identified 32 such events from the 16 year period from 2000 to 2015. These extreme events are mostly isolated over northeast location and the extremity is not spreading much to the entire foot Himalayas range and therefore the events are not organised but more local nature. The events are more seen during the month of July followed by June. The trend of yearly rainfall in different intensities are found increasing. However, for different intensity bins, the rainfall shows a decreasing trend for the rain intensity bins <5 and 35-50 mm day-1 categories and all other categories the rainfall showed an increasing trend especially for the 50- 60 mm day-1 bin. In the case of rainy days, for lower rain intensity bins, it shows a decreasing trend and for upper bins it shows an increasing trend. The mechanisms for these events and their temporal changes is need to be explored.

Sensitivity analysis of potential evapotranspiration to climate parameters

Dr Nayana Deshpande

The study analyses the changes in the monthly Potential Evapotranspiration (PET) using Penman-Monteith method of estimation. Daily data on meteorological parameters such as Temperature, Relative Humidity, Net Radiation, wind speed and Atmospheric Pressure have been obtained from NCEP-NCAR website for the period 1951-2015. Seasonal climatology and temporal changes of these parameters have been discussed. Extent of Association between input and output parameter is tested here. Sensitivity analysis of PET to changes in meteorological variables is carried out by varying one variable at a time. The order of sensitivity noticed is relative humidity>net radiation> temperature. Increasing trend in PET in peninsular India may be explained by the decrease in relative Humidity and increase in temperature. Sensitivity coefficient shows seasonal variations.

Skill evaluation of extended range forecast on sub-divisional scale over India

Dr Susmitha Joseph

Extended range prediction (ERP) of 1-3 weeks in advance supplements seasonal forecasts. Different skill measures have been used to evaluate the usefulness as well as the accuracy of both pentad lead deterministic and probabilistic rainfall forecast.

Coupling a land surface model with a crop growth model to improve ET flux estimations in the Upper Ganges basin, India.

Gina Tsarouchi

Land-Surface Models (LSMs) are tools that represent energy and water flux exchanges between land and the atmosphere. Although much progress has been made in adding detailed physical processes into these models, there is much room left for improved estimates of evapotranspiration fluxes, by including a more reasonable and accurate representation of crop dynamics. Recent studies suggest a strong land-surface–atmosphere coupling over India and since this is one of the most intensively cultivated areas in the world, the strong impact of crops on the evaporative flux cannot be neglected. In this study we dynamically couple the LSM JULES with the crop growth model InfoCrop. JULES in its current version (v3.4) does not simulate crop growth. Instead, it treats crops as natural grass, while using prescribed vegetation parameters. Such simplification might lead to modelling errors. Therefore we developed a coupled modelling scheme that simulates dynamically crop development and parametrized it for the two main crops of the study area, wheat and rice. This setup is used to examine the impact of inter-seasonal land cover changes in

evapotranspiration fluxes of the Upper Ganges River basin (India). The sensitivity of JULES with regard to the dynamics of the vegetation cover is evaluated. Our results show that the model is sensitive to the changes introduced after coupling it with the crop model. Evapotranspiration fluxes, which are significantly different between the original and the coupled model, are giving an approximation of the magnitude of error to be expected in LSMs that do not include dynamic crop growth. For the wet season, in the original model, the monthly Mean Error ranges from 7.5 to 24.4 mm month−1, depending on different precipitation forcing. For the same season, in the coupled model, the monthly Mean Error's range is reduced to 5.4– 11.6 mm month−1. For the dry season, in the original model, the monthly Mean Error ranges from 10 to 17 mm month−1, depending on different precipitation forcing. For the same season, in the coupled model, the monthly Mean Error's range is reduced to 2.2–3.4 mm month−1. The new modelling scheme, by offering increased accuracy of evapotranspiration estimations, is an important step towards a better understanding of the two-way crops–atmosphere interactions.
Characterizing groundwater droughts in the UK **Dr Andrew McKenzie** Drought and water scarcity (D&WS) are significant threats to livelihoods and wellbeing in many countries, including the United Kingdom (UK). Based on an analysis of information from a wide range of sectors (hydrometeorological, environmental, agricultural, regulatory, social and cultural), the presented project will characterize and quantify the history of drought and water scarcity (D&WS) since the late 19th century and will produce the first systematic account (UK Drought Inventory) of droughts in the UK. The Inventory forms the basis of a novel joint hydro-meteorological and socio-economic analysis of the drivers of drought and their impacts, with a focus on a search for characteristic systems interactions. The enhanced systems-based understanding is expected to improve decision-making for future drought management and planning, including more informed and thus effective public discourse related to D&WS.
Groundwater and hydro-climatic information. **Dr Andrew McKenzie** BGS has used its long term datasets of groundwater level data to develop understanding and predictive tools that are used to inform decision makers in how aquifer systems will respond to extreme events. Examples of their use, and limitations, during both flood and drought episodes are presented.
Land-use change may exacerbate climate change impacts on water resources in the Ganges basin **Gina Tsarouchi** We quantify how land-use and climate change future projections affect the hydrology of the Upper Ganges. Significant differences arise under future scenarios. In a water resources context, we discuss whether future demand thresholds will be exceeded.

ANNEX C: Summary of breakout group discussion sessions

Participants divided into four groups and discussion were facilitated by a member of the group;
Group 1: S.C. Kar;
Group 2: Jagdish Krishnaswamy;
Group 3: Christel Prudhomme;
Group 4: Andrew McKenzie.

Session 8: Knowledge gaps in the science and data needs

Category	Group responses
Hydrology/Water Balance	**Group 1:** Methodology for water budget at decision-relevant-scale (sub basin) and uncertainty estimate
	Group 3: Water consumption data. Is it monitored? If so where is the data- Access
	Group 4: Hydrology (data quality / access) soil maps- variable, parameterise; radar data calibration, satellite processes
Interdisciplinary science-social science	**Group 2:** Need for interdisciplinary approach to knowledge generation within and between natural and social science. IUKWC could foster approaches to knowledge generation.
	Group 3: Interaction between physical science and water demand /use sciences
Precipitation forecasting	**Group 1:** Prediction of extreme rainfall events and incorporation of the same in hydrology models
	Group 3: Improved precipitation simulation; post processing for flood forecast; monsoon process/forecasting; high elevation precipitation/snowfall
Physical process understanding and role in models	**Group 3:** Atmosphere- land- groundwater interaction understanding • Vegetation role in hydrology • Soil moisture feedback • Recharge/groundwater feedback small and large scale processes

	Group 4: Land surface processes • ALL India, Land use and land use change • Role of JULES? Assimilation needs more initialization Physical understanding of monsoon process (land surface process) and replication in global models: • Variability in all timescales. • Problems: sea surface temperature correction • Where is the boundary between hydro-climate and climate modelling? • Monsoon mission lacks hydrology Lack of fine scale understanding of mountain meteorology/hydrology • Supersites (climatic zones?); cloud bursts, • TRMM/GPM validate (Data dissemination) Ice- volume - melting: • Poorly characterized; • Lack of monitoring • Snow process in JULES
Groundwater role	**Group 1:** Estimation of ground water storage in fractured / non-homogenous aquifer system. How much can we extract?
	Group 3: Sub-surface/surface/groundwater monitoring: • higher spatial density; • continuous monitoring; • coupled with water quality; • low cost monitoring (empowerment, engagement, water management)
Standardised data/data assimilation/data sources	**Group 2**: • Standardized baseline data and different scales e.g. LULUC, soil, hydrogeology. • Open access to all. Compare performance of models. Improve if we can decrease uncertainty due to different datasets at different scale. • Better integration between modelling and instrumented catchment data • Better data assimilation routines that synthesis spot measurements with multiscale data (e.g. remote sensing)
	Group 3: Consolidation of existing data sources:

	• common procedures/quality control; • win:win situations, • sharing data; • network gap identification; • local/regional/state/national collaboration; • academic & government agencies & NGOs sharing. Satellite /Airborne information: • land use, vegetation; rainfall; soil? How to use citizen data/stakeholder data need incorporation into mainstream science, crowd sourcing.
Role of LULUC	**Group 1:** Impact of LULUC on the water budget/hydrology (surface and ground) and their feedback to climate
Nexus	**Group 1:** Quantify food-water-energy nexus using empirical data and develop model prototype for the coupled system
Communication	**Group 2:** How to communicate uncertainty without hampering ability to make decisions
RCM	**Group 4:** Regional climate modelling – downscale and bias correction (at all scales, weather-climate) • MOS, PPM, cloud burst • Extreme events, convection, opt (ical?imum?) resolution topographic process • Opt(ical?itmum?) combination of dynamic modelling and statistical post -processing

Session 9: a) How to improve working with end users/stakeholders/policy makers

Categories	Group responses
Co-Design, Joint projects	**Group 1:** Involve the stakeholders from the very beginning in developing hydro-climatic services
	Group 2: Process; MS groups (across scale), utility, co-creation, TEK (Converging different needs)
	Group 3: Joint problem solving for India • Short term scientific missions in India • Studentships hosted in UK (6 months min) • Share resources e.g. monitoring by India staff

	• Validation of results • workshops/networking/webinars
	Group 4: Demonstration Projects? (review Reports) (Trade Offs) Climate change impact on: • Hydropower (season to year) (Link to supersites?) • Groundwater • Public supply • Flood risk • Water quality
Sharing data and outputs	**Group 1**: Sharing of experiences of hydro climatic service among: • Different states; UK
	Group 3: Share tools and data access community models cloud saas systems for software modelling protocols and shared outputs • Output dissemination • All outputs including research reports • Data easy access
	Group 4: Document/disseminate skill/reliability of precipitation at basin scale (short/medium/seasonal) -agro climate zone; dissemination via 130 agriculture universities Hydrologist, CWC state, agriculture, health, etc
End user engagement/decision support	**Group 2:** Decision Support: accessibility, risk assessment, visualization, capacity & literacy (including uncertainty), TEK.
	Group 4: Hydro climate services: Seasonal forecast (exist); Better link to end user; Modelling skill (trust- big issue; skill and economic benefit etc. • Hydrological outlook India • Monsoon timing/phase for farmers and water managers
Defining stakeholders/users	**Group 2**: Who: defining groups; priorities; power differences
Trust in Science	Group 4: Global issue: lack of trust of hydro- climate community Vs Agriculture/Health • Limit in processing interpretation • What does WOTR and NGOs use?
Funding	**Group 3:** Research funding matched UK/India; timing critical; limit bureaucracy

Session 9: b) Ideas for how to develop improved joint UK-India scientific capacity in the area of hydro-climatic services.

Categories	Group responses
Links	**Group 2:** Collaborators: different disciplines with different interests/needs/knowledge/capacity. Enablers: Inclusiveness and Transparency • Platform- showcase work; interaction; opportunities; marketplace • Funding • Frequent interaction Community building: • expanded; • targeted; • key outcomes; • awards; • needs assessment; • ambassadors; E • CRS; • MOOCs (virtual workshop, webinar)
	Group 3: More links between researchers and grass roots • via training education/capacity building. • Simplified but contextual message • government agencies/policy makers/stakeholders: • Mapping • Secondment/internships • Understanding stakeholder goals and intentions • Simplify language • Workshops/networks follow-up/ web forums (Active) Acknowledge stakeholders (e.g. data) and involve them in interpretation/publications Demand-driven research calls
Next generation	**Group 3:** Advertise environment science at schools/universities to get bright students
Funds	**Group 3:** More money in environmental science
Training	**Group 1:**

	• Training on flood forecasting:
	    ○ current methods,
	    ○ advanced methods for scientists and other stakeholders;
	• Training on region specific disaster preparedness;
	• Training on statistical techniques for downscaling and bias correction; .
	• Training on derivation of hydrological parameters from various satellite sensors;
	• Development of fully instrumented watershed and management centre (pref. in Eastern region)

	Group 2: Challenges: inter-disciplinarily, country-specific challenges
	Group 4: Training + Capacity building • JULES crop modelling for agro climate • Downscaling (WRF) tools , methods and validation (other funding for WRF) • Use/understanding of ensemble probabilistic forecasts (80-100 mmber ensembles, 10km by 2018) • statisticians

Back cover image: River Ganga

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