GEWEX NEWS

GEWEX is a Core Project of WCRP on Global Energy and Water Exchanges

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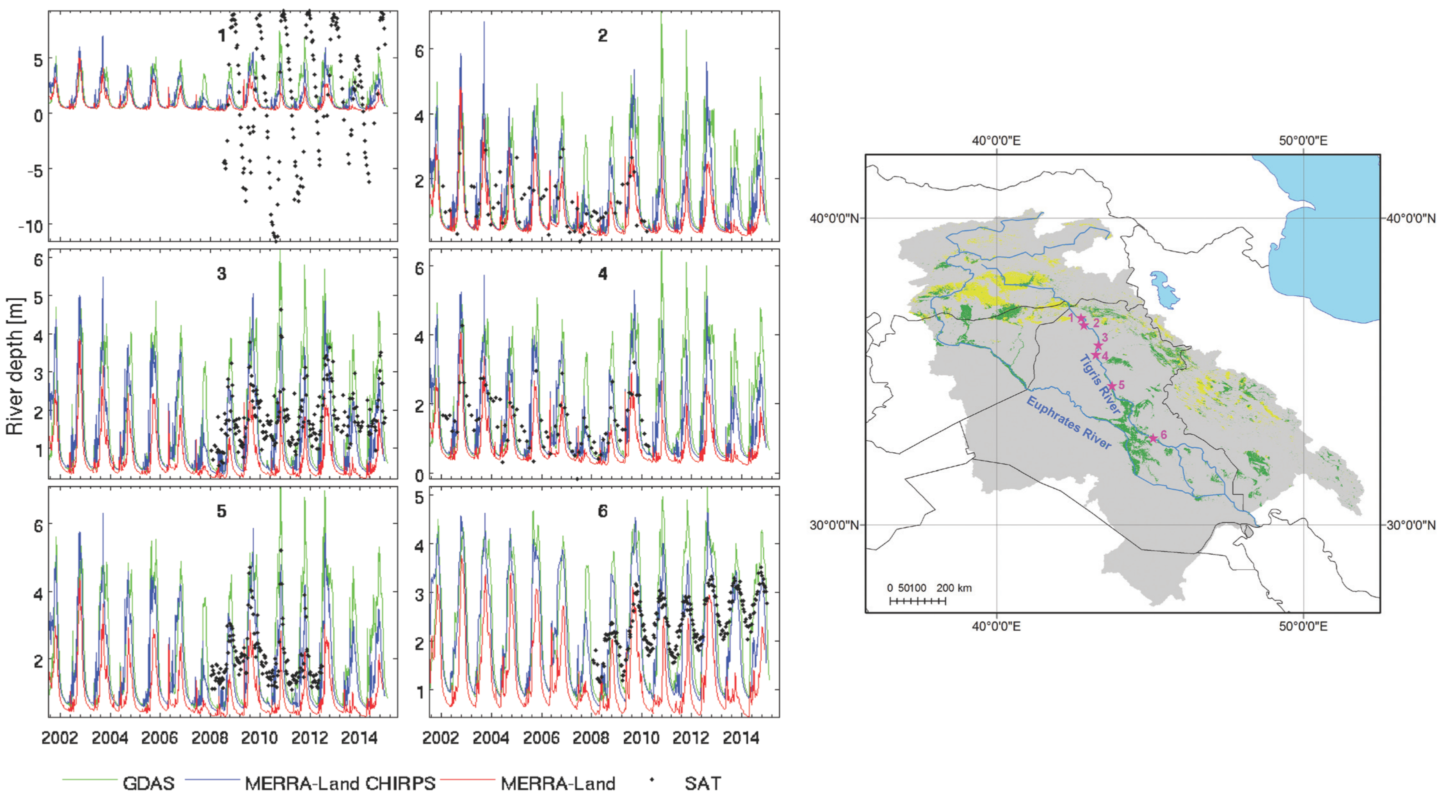
Forecasting for Africa and the Middle East (FAME) Project to Develop a Seasonal Water Deficit Forecasting System



Simulated and satellite-based water levels at six locations along the Tigris River as shown in the map on the right. Radar altimetry data were bias corrected, matching water level simulations. The yellow and green colors on the map represent rainfed and irrigated agriculture, respectively, as reported in the Global Map of Rainfed and Irrigated Paddy Croplands (GRIPC; Salmon et al., 2015). Reservoir operation at the Mosul Dam results in a high amplitude and shifted water level fluctuation when compared to the naturalized regime, as simulated by the Hydrologic Modeling and Analysis Platform (HyMAP) at Location 1. The model shows some skill at other locations, but altered reservoir outflows still impact water levels downstream of the dam. Radar altimetry data at Location 6 show a positive trend in annual minimum water levels not detected by the model. The observed regime is probably due to recent changes in the Tharthar Lake water flow operation. *See article by A. Getirana et al. on page 8.*

Also Inside

Commentary

New Plans for Water Cycle Science and Related GEWEX Activities

Peter van Oevelen
Director, International GEWEX Project Office

In October, GEWEX and the European Space Agency (ESA) held a very successful conference on Earth Observation for Water Cycle Science in Frascati, Italy. Special emphasis was placed on new science avenues and observational requirements for water cycle science. Two important Earth observation activities being planned in Europe and the U.S. were presented. In Europe, ESA is planning the follow-on to its 4th Earth Observation Envelope Programme, which represents the main driver for science and innovation in ESA Earth observation activities. The Programme currently covers the preparation and implementation of the Earth Explorers, development of future technologies, mission operations and exploitation activities in terms of science and applications, providing an end-to-end approach for the early preparation of future missions to the exploitation activities hand-to-hand with the user and scientific community. For more information, see: *http://www.esa.int/Our_Activities/Space_Engineering_Technology/About_the_Earth_Observation_Envelope_Programme_EOEP*.

In the U.S., the National Academy of Science is initiating its 2017 Decadal Survey to "consider developments in the full enterprise of space-based Earth observations, including new non-governmental providers of Earth observations, the availability of smaller platforms and the increasing emphasis on operational affordability." The survey includes the Earth and environmental monitoring programs at the National Oceanic and Atmospheric Administration and U.S. Geological Survey, and will pay particular attention to these agencies' operational responsibilities for continuous observations and delivery of application products to the public. For more information, see: *http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_166359*.

One of the primary conclusions of the ESA-GEWEX Conference was that, although past single or limited parameter Earth observational missions have proven their usefulness, they are most likely not the best way forward in tackling climate change issues. This is especially true of challenges related to the water cycle. There is general concurrence that new observational systems should add on to existing systems by maximizing synergy and minimizing duplicity, while ensuring that the system has redundancy (e.g., a constellation-type approach similar to the A-Train). It is always exciting to think about the possibilities of new spaceborne observational missions and what is planned in this regard in the next two years.

In this newsletter, there are many articles on new GEWEX activities, several of which are focused on Africa and climate change. One of these is the GEWEX Process Evaluation Study (GEWEX-PROES, on page 4), which will take advantage of existing data sets to advance process understanding and representation in models, both through new efforts and in collaboration with existing groups and activities. Another new GEWEX focus area is the anthropogenic influences on the global water cycle as a part of the World Climate Research Programme (WCRP) Water Availability Grand Challenge. The article on page 6 reviews the various aspects of this topic and how they will be addressed within GEWEX, mostly by the GEWEX Hydroclimatology Panel (GHP) and the Global Land Atmosphere System Studies Panel (GLASS). An interesting article by Augusto Getirana, an early career scientist working at the National Aeronautics and Space Administration's Goddard Space Flight Center, is "Forecasting Water Availability in Data Sparse and Heavily Managed Catchments in Africa and the Middle East" on page 8. The report on the "First HyCRISTAL Workshop—Integrating Hydroclimate Science into Policy Decisions for Climate-Resilient Infrastructure and Livelihoods in East Africa" (page 23) has strong scientific connections to Getirana's article. GEWEX and HyCRISTAL are connected through the new GHP Regional Hydroclimate Project (RHP) in central Africa called the Hydrology of the Lake Victoria Basin (HyVic) Study. The article on page 11 focuses on the Sahel in northern Africa and explores the effect of global climate on the character of precipitation in this region.

To conclude, I would like to highlight an issue that has arisen often over the past several years: how do we as scientists deal with meetings and experiments that take place in regions of the world that have ideologies and policies that are at odds with our own? Often the initial response is that such efforts are easier to abandon than support, as continuing them implies tacit encouragement for policies that we do not endorse. In general I do not agree with that assessment, as firstly we are not a political organization and discontinuing our collaboration in these regions will only further increase their isolation. Secondly, doing so would not advance either our own or their scientific interests. In addition, I believe that a continued dialogue and presence may improve understanding of the ideological differences on both sides. Of course, this is only valid when those ideologies and policies do not hamper or interfere with our safety. If there are any concerns of this nature within the GEWEX community, I would like to hear them, and will address them in a confidential manner. Being part of a global collaborative effort such as WCRP and GEWEX means that we deal with a lot of cross-cultural interactions. It also means finding common ground and shared goals, which can be both a challenge and a boon as we gain new insights and opportunities. The latter is of particular importance in the education of new scientists in all regions of the world, and will help to increase our ability, both in human resources and other capacities, to tackle the global climate change challenge.

Recent News of Interest

NEWS WEB Climatology Data Set Version 1.0 Released by NASA GES DISC

The NASA Goddard Space Flight Center Hydrological Sciences Laboratory and Goddard Earth Sciences Data and Information Services Center (GES DISC) are pleased to announce the release of the NASA Energy and Water Cycle Study (NEWS) Climatology of the 1st Decade of the 21st Century Data Set, available from: *http://disc.sci.gsfc.nasa.gov/uui/#/search/NEWS*.

This data set summarizes the original observation-based mean fluxes of Water and Energy Budget (WEB) components during the first decade of the 21st century for each continent and ocean basin. These data are summarized on both monthly and annual scales, as well as means over all oceans, all continents, and the globe. A careful accounting of uncertainty in the estimates is included. Also, the data set includes optimized versions of all component fluxes that simultaneously satisfy energy and water cycle balance constraints.

More information is available at: *http://disc.sci.gsfc.nasa.gov/datareleases/news-web-climatology-data-set-version-1.0-released-by-nasa-ges-disc.*

Contents

GEWEX Scientists Elected to National Academy of Engineering

The National Academy of Engineering membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature," and to the "pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education."

Graeme L. Stephens, Director of the Center for Climate Sciences at the Jet Propulsion Laboratory in Pasadena, California, was chosen for his elucidation of the Earth's cloud system and radiation balance.

Eric F. Wood, Susan Dod Brown Professor of Civil and Environmental Engineering at Princeton University in Princeton, New Jersey was chosen for his development of land surface models and use of remote sensing for hydrologic modeling and prediction.

Siegfried Schubert, NASA Research Scientist and GEWEX SSG Member, Has Retired

On behalf of the GEWEX community, we thank Dr. Schubert for all the work he has done to support GEWEX as a member of the Scientific Steering Group and his contributions towards the formation of a global drought information system. Dr. Schubert led the group on subseasonal to decadal climate at NASA's Global Modeling and Assimilation Office before he retired.

Joint GASS/WWRP/THORPEX MJO Task Force Paper on MJO Highlighted in *Eos*

The GEWEX Atmospheric System Study (GASS) Panel and WCRP World Weather Research Program (WWRP)/THORPEX MJO Task Force (MJOTF) paper on challenges in predicting and simulating the Madden-Julian Oscillation (MJO) was selected for highlight in the American Geophysical Union's *Eos* magazine. Shortcomings in representing the MJO indicate a lack of understanding when it comes to the fundamental physics of the atmospheric circulation pattern. Read more at *https://eos.org/research-spotlights/circulation-models-cannot-simulate-organized-tropical-convection.*

Student Involvement at the 2015 AGU Fall Meeting

Natasha T. Krell[1] and Tim H.M. van Emmerik[2]
On behalf of the Young Hydrologic Society

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The American Geophysical Union (AGU) Fall Meeting presents myriad opportunities for students and early career scientists to network and advance their research. In the last few years, AGU has increased its student activities to meet demand and promote student leadership.

A Student and Early Career Scientist Conference will take place on the Sunday before the Fall Meeting. This preconference event for students features two tracks—an interdisciplinary science track and a career guidance and professional track. Both will provide ample opportunities to network and connect with peers, as well as facilitate discussions on broadening equality and participation in academia.

This year there are three pop-up talk sessions on: (1) innovations, challenges and future directions in hydrology; (2) social dimensions of geoscience; and (3) interactive demonstrations in Earth sciences. Pop-up talks are 5-minute presentations on a variety of topics not typically covered in posters or oral presentations, and are given by students and early career scientists. For location and times, see *http://fallmeeting.agu.org/2015/students/student-pop-talks/*.

This year, the AGU Meeting offers a mentoring program for undergraduates. If you missed the application deadline, or are a graduate student wanting additional guidance, sign up for the AGU Career Center E-Newsletter, which offers support and opportunities, such as information on Career Advice Workshops during the Fall Meeting.

At the student lounge in the Moscone South Poster Hall, you can meet your Student Representative and learn about impromptu activities. Stop by at 5:30 PM during the conference and pick up menus and walking maps to join other students for dinner.

Hydrologist Bingo is designed to stimulate interaction between young hydrologists and established researchers. Pick up bingo cards at the mixer or at the student lounge. The game will last throughout the conference. Attend the The Consortium for the Advancement of Hydrologic Science Inc. (CUAHSI) mixer on Tuesday from 6-8 PM at Jillian's to complete your card. There will be prizes.

Bottom-up initiatives such as the Young Hydrologic Society and the AGU Hydrology Student Subcommittee aim to involve, connect and empower students and early career scientists. The Hydrology Section Student Subcommittee will host a meeting on Wednesday morning to seek feedback and future representatives; stay updated through Twitter at @AGU_H3S.

The GEWEX Process Evaluation Study: GEWEX-PROES

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Progress in realistically simulating the energy and water cycles in weather and climate models has been slower than desirable. Climate models submitted to the Coupled Model Intercomparison Project Phase-5 (CMIP-5), while more comprehensive than their predecessors, have shown little to no improvement in their biases in simulating key features of the climate system. As a result, uncertainties in global climate and hydrological sensitivities, and in the simulation of regional climate change, have not been reduced significantly.

Such thwarted progress is starkly contrasted against significant advances made in observing the energy and water cycle over the last decade. The advent of spaceborne active remote sensors on the National Aeronautics and Space Administration's (NASA) Tropical Rainfall Measuring Mission (TRMM), Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and CloudSat missions, as well as the recent Global Precipitation Measurement (GPM) Mission and the soon-to-be-launched European Space Agency (ESA) EarthCARE missions, all contribute to a significant increase in our ability to observe clouds and precipitation.

GEWEX-coordinated cloud, precipitation and other data sets, as exemplified by the International Satellite Cloud Climatology Project (ISCCP) and the Global Precipitation Climatology Project (GPCP), have strongly contributed to our growth in knowledge. They have also been accompanied by more reliable estimates of radiative budgets at the top of the atmosphere and improved estimates of surface balances. New measurements, such as those taken by the ESA Soil Moisture and Ocean Salinity (SMOS) mission, and NASA and partners' Soil Moisture Active Passive (SMAP) and Gravity Recovery and Climate Experiment (GRACE) missions, significantly extend our ability to estimate the volume of water storage, including water changes over land, water mass changes over oceans and mass changes of ice sheets. New activities within GEWEX to obtain reliable estimates of the turbulent surface exchanges of energy and water are also underway.

Concurrent with the improvement of our measurement capabilities, the climate system has experienced substantial variability, driven by both natural processes and anthropogenic influences. This variability has been observed at unprecedented detail and at scales ranging from the mesoscale to the synoptic on decadal and climate timescales. In addition to the well-known changes in global mean temperature, we are now beginning to observe global patterns in the change of precipitation, radiation and clouds, which provide another opportunity to understand the processes involved in energy and water exchanges, and to assess our capabilities in correctly simulating them.

It is time to make use of these opportunities to significantly advance our understanding of key energy and water cycle processes at a wide range of space and time scales, and to provide a more insightful evaluation of the representation of these processes within models. This will require new ways of both analyzing the observations and diagnosing model behavior. The keys to success will be in skillfully combining different data sets and exploring relationships between them, as well as in the ability of models to reproduce those relationships correctly.

GEWEX Process Evaluation Study (GEWEX-PROES)

In response to this challenge, a new GEWEX-wide activity, the GEWEX Process Evaluation Study, will take advantage of the opportunities that the combination of many of the existing data sets provide. The goal of GEWEX-PROES is to advance process understanding and representation in models, both through new efforts and in collaboration with already existing key groups and activities. Broadly, the goals are to:

1. provide a better understanding of the mechanisms involved in energy and water exchanges on Earth;
2. diagnose the sources of major model shortcomings; and
3. use the knowledge gained in new treatments of energy and water exchange processes in models.

GEWEX, through its decades of experience in producing global data sets, diagnosing model performance and executing comprehensive process studies, is well positioned to take on the challenge of optimally exploiting these developments.

A strong connectivity to other efforts also lies at the very heart of GEWEX-PROES and must become one of its main strengths. To avoid duplication of labor, it is important to consult the wider community when designing the implementation of GEWEX-PROES. Particularly strong connections beyond GEWEX include, but are not limited to the following:

- the World Climate Research Programme (WCRP) Grand Challenge on Clouds, Circulation and Climate Sensitivity and Grand Challenge on Water Availability;
- CMIP and the Cloud Feedback Model Intercomparison Project (CFMIP);
- Observations for Model Intercomparison Projects (obs4MIPs);
- Analysis for Model Intercomparison Projects (ana4MIPs);
- the World Meteorological Organization (WMO) and WCRP Working Group on Numerical Experimentation (WGNE);
- the WCRP Working Group on Seasonal to Interannual Prediction (WGSIP);
- the WCRP Working Group on Coupled Modeling (WGCM);
- the WCRP Data advisory Council (WDAC);
- the WCRP Modeling Advisory Council (WMAC);
- WCRP Climate and Cryosphere (CliC) Project; and
- WCRP Stratospheric Processes and their Role in Climate (SPARC) Project.

We are looking forward to a strong consultation process with the wider community to design GEWEX-PROES as a valuable addition to our common goal to better understand and predict climate system behavior.

Scope and Structure of GEWEX-PROES

PROES is proposed around specific projects, each constructing an infrastructure that will include three main components, all of which aim to enable the global, regional and local analysis of key processes focused on energy and water exchanges. The first component is the collection and provision of data sets at a time and space resolution that allows for given process evaluation at a range of time scales for both the real world and in models. The second component focuses on developing, applying and serving diagnostic tools that enable the process evaluation. Finally, the third component will focus on the design, execution and analysis of model simulations. All three components plan to take advantage of and strongly collaborate with existing efforts and to add value to them through additional rather than duplicative work.

Proposed Activities for GEWEX-PROES

Four GEWEX-PROES activities are currently in different phases of development and include: (i) an upper tropospheric clouds and convection process study; (ii) a radiation kernels study; (iii) an ice sheet surface mass and energy balance study; and (iv) a mid-latitude storms study. More details about these activities, their goals and how they are to be implemented will be forthcoming in future GEWEX newsletters.

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Anthropogenic Influences on the Global Water Cycle—Challenges for the GEWEX Community

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Water and energy are fundamental for life on Earth. Freshwater is a major pressure point for society owing to increasing demand and the vagaries of climate. The role of human activities in modifying and controlling the continental water cycle has been recognized by the World Climate Research Programme (WCRP) as one of its Grand Challenges and also underlies the GEWEX Science Questions. To better understand the mechanisms behind this challenge, the GEWEX Hydroclimatology Panel (GHP) and the GEWEX Global Land/Atmosphere System Study (GLASS) Panel have begun the joint effort presented here.

Water Security in the 21st Century

Water security is widely recognized as one of the major challenges for human society in the 21st century. Water resources are limited in many of the populous areas of the world and water scarcity is likely to increase in the coming decades as population increases and climate change alters rainfall and evaporation. Sir John Beddington (until recently the Chief Scientific Advisor to the UK Government) identified a "perfect storm" of global events where the world will need to produce 50% more food and energy, together with 30% more freshwater, by 2030, while at the same time adapting to a changing climate and reducing greenhouse gas emissions (Beddington 2009). These pressures are set in a context of unprecedented human impacts on the Earth system. Man's activities are changing the land surface, river flows and groundwater storage, with largely unknown feedbacks to the climate system. There is thus a social and scientific imperative to understand and predict the impacts of anthropogenic influences on the water cycle.

Water Consumption Representation

Globally, man uses only a small fraction (about 3%) of freshwater runoff. However, in the more populated regions of the world, this proportion can be much larger; for example, in India, 40% of potential water resources are used, and in certain basins, much more. In fact, it has been estimated that in India nonrenewable extraction of water is 68 km^3 per year (Wada et al., 2010). In California and the midwestern United States, the Mediterranean, Pakistan, India and China, water is being extracted at a faster rate than it is replenished, leading to the rapid reduction of groundwater levels and decreasing river flows. We know that 80-90% of the world's consumptive use of water is for irrigation, and that the enhanced evaporation induced by irrigation can feed back on the atmosphere at local and mesoscales (although the impact on regional and global climates is uncertain). There are also indications that the reduced freshwater discharge from continents can affect processes in certain oceans or coastal regions. Still, there is no strategy for systematically monitoring these manmade interventions within the global water cycle or for including them in the models we use to predict climate variability and change.

Land-Surface Component in Models

The land-surface component of our climate and Earth system models has improved considerably over the last two decades. Representations of physically realistic runoff generation and river routing are now the norm within most climate models. These representations, however, still describe the "natural" system and there have only been sporadic attempts at the inclusion of anthropogenic influences on evaporation, water storage, runoff generation and flow. Few of these additions have found their way into the routine versions of climate models. In addition to the land surface models (LSMs), recent decades have seen the development of stand-alone global hydrology models (GHMs). These have been developed by the hydrological community and tend to have a very different structure; they are typically simpler and focus on representing water resources, rather than the full range of land surface processes. They may also make some use of local calibration; however, calibrated models need to be used with caution in climate scenarios where flow regimes may be radically different. Many of the GHMs have a more explicit representation of man-made features, such as dams, water extraction and diversions. Currently both LSMs and GHMs are imperfect and incomplete and simulations rarely match available hydrological observations (e.g., Haddeland et al., 2011).

Water Resource Management

The issue of water resource management can be divided into two interdependent elements—water demand and water supply (and allocation) (Nazemi and Wheater, 2015a). Global water demand is dominated by agriculture, which accounts for approximately 90% of total global water consumption and 70% of all water withdrawals from surface and groundwater. Other demands, such as domestic and industrial use and energy-related requirements, are smaller but increasing, and often are of major local importance. There is considerable regional variation in domestic and industrial use of water, which is a constraint on development in many high population regions of the world. Crop irrigation is primarily a consumptive water use while the non-irrigative demands often return water to the system, although these uses will impact the timing and quality of the resulting river flows.

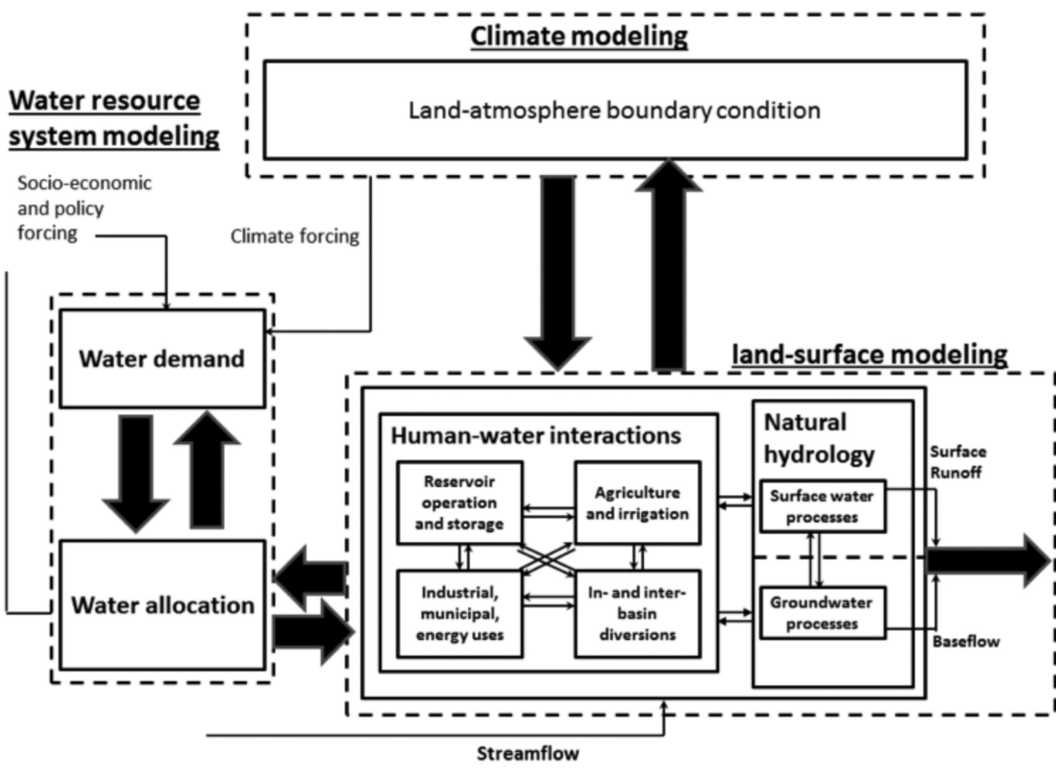
Irrigated areas have been included in a large number of offline LSMs and GHMs (Nazemi and Wheater, 2015a, Table 1) and a smaller number of online simulations (mostly regional models), but with very different levels of complexity. The simplest irrigation algorithms allow evaporation at a potential rate and keep the soil layer topped up with water at the expense of water conservation. More complex representations use published estimates of water requirements for crops and information on the irrigation techniques used and their efficiency. Very few algorithms link water demand to water constraints and ensure water conservation. Projecting forward requires an estimation of future agricultural development, and thus needs to be conditioned by socio-economic and technological factors. These factors can be included using integrated assessment models; however, the current state-of-the-art versions of these models poorly represent the water constraints on agricultural development.

While surface water is the primary supplier of irrigation water, nearly 40% is derived from groundwater. It is essential, therefore, when considering supply constraints, that both surface water reservoirs and groundwater be included in land surface descriptions. Reservoirs can be represented within the routing algorithms of large-scale models but, unlike natural lakes, their dynamics will be controlled by downstream demand and management decisions (further complicated by the multi-functional nature of many reservoirs). Regionally, interbasin transfers may also need to be considered, and local management decisions (as well as infrastructural constraints) will determine their nature and extent.

In principle, a physical 3-dimensional gridded groundwater model can be linked to climate models, but computational constraints (and detailed knowledge of global aquifer properties) limit this approach to a few regional examples. Simpler approaches, such as a conceptual linear groundwater reservoir (parameterized using local topography and lithology), have been proposed and implemented in a small number of regional instances. Groundwater recharge is often a fine balance between rainfall and evaporation, although in semi-arid regions lateral redistribution of surface water may determine recharge, and is imperfectly modeled in LSMs. Overlaid on this physical description is the need for estimates of groundwater withdrawals.

The simplest allocation schemes assume grid-based demands can be supplied within the model grid cell. There is a need to parameterize grid-to-grid transfer and rules for water allocation (complicated by the multiple and conflicting demands on reservoirs; for example, flood prevention in the winter and supply in the summer). In principle, local operating rules could be applied, but an alternative approach is to find release scenarios, which minimize the costs and use economic theories to derive the most likely allocation strategies.

Major gaps remain in representing water resource management in LSMs. The first is to fully couple the various components to provide water and energy conservation (often violated in irrigation and groundwater algorithms) and provide true water constraints on agricultural use (for example, as proposed by Nazemi and Wheater, 2015b, in the figure below). The second is the problem of scale. Much water resource management takes place at finer resolution than current GCM grids. Future global or regional models with finer grids will have an increased need for a representation of these processes as they matter for spatial contrasts and establish resolved land surface



A fully coupled framework for inclusion of water resources management in a typical land surface model grid.

structures. This will bring difficulties of increasing complexity, computational burden and data requirements. Thirdly, many current algorithms require local knowledge and parameterization. How algorithms developed for offline analyses can be generalized and used in coupled models and how this might be used in future scenarios is a complex issue. Finally, we need to address the considerable uncertainties in our estimations of the components of the global water cycle in our current models. To these must also be added the uncertainties in demand, reservoir operation and groundwater withdrawals.

The need to include water management in the coupled climate and Earth system models to provide a realistic assessment of the current and future terrestrial water cycle is clearly urgent. To advance, we need high performance computing, improved data sources (for example, remote sensing) and improved data sharing, calibration algorithms and continued improvements in process representation and parameter identification. It is clear that with limited resources the various communities need to increasingly share algorithms, data and experience to ensure the development of the best models for the future.

New GHP/GLASS Crosscut to Include Water Management in Models

In order to address these issues, GHP and GLASS are creating a crosscutting project focused on the inclusion of water management in large-scale models. This project will be launched with a workshop in late 2016 at the Ebro River Basin in Spain. The location was chosen because it is within the area of the GEWEX Regional Hydroclimate Project (RHP) called the Hydrological Cycle in the Mediterranean Experiment (HyMeX). The Elbro River Basin has lost two-thirds of its discharge in the past 50 years due to irrigated agriculture in the catchment. Plans for the new GEWEX crosscutting project include: (1) defining a program of research that addresses the four key gaps identified above; (2) developing a coherent action plan that integrates the current rather disparate activities in this area; and (3) linking modeling development to regional case studies through the RHP projects.

References

Beddington J., 2009. Food, energy, water and the climate: A perfect storm of global events? In-conference presentation given to the Sustainable Development UK Annual Conference, QEII Conference Centre, London, March 19, 2009. See *http://www.bis.gov.uk/assets/goscience/docs/p/perfect-storm-paper.pdf.*

Haddeland, I., et al., 2011. Multimodel Estimate of the Terrestrial Global Water Balance: Setup and First Results. *J. Hydrometeorol.*, 12, 869–884, doi: 10.1175/2011JHM1324.1.

Nazemi, A., and H.S. Wheater, 2015a. On inclusion of water resource management in Earth system models–Part 1: Problem definition and representation of water demand. *Hydrol. Earth Syst. Sci.*, 19, 33–61.

Nazemi, A., and H.S. Wheater, 2015b. On inclusion of water resource management in Earth system models–Part 2: Representation of water supply and allocation and opportunities for improved modeling, *Hydrol. Earth Syst. Sci.*, 19, 63-90.

Wada, Y., L.P.H. Van Beek, Ch.M. Van Kempen, J.W.T.M. Reckman, S. Vasak, M.F.P. Bierkens, 2010. Global depletion of groundwater resources. *Geophys. Res. Lett.*, 37, L20402, doi:10.1029/2010GL044571.

Forecasting Water Availability in Data Sparse and Heavily Managed Catchments in Africa and the Middle East

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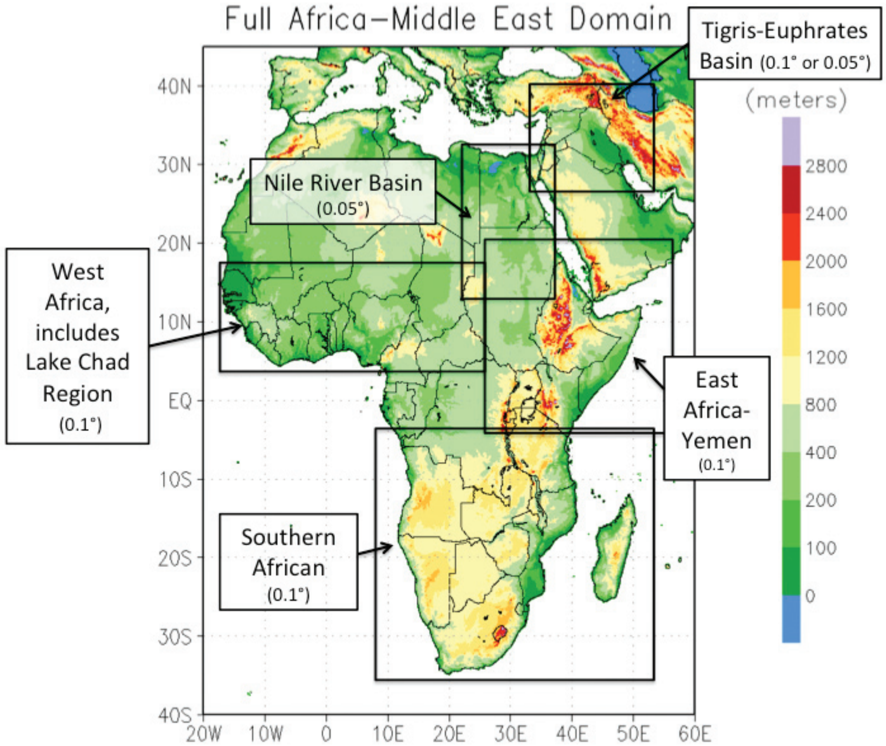
The National Aeronautics and Space Administration's (NASA) Hydrological Sciences Laboratory and its partners initiated the Forecasting for Africa and the Middle East (FAME) Project earlier this year to develop a seasonal water deficit forecasting system that is relevant to U.S. Agency for International Development (USAID) and U.S. Army Corps of Engineers (USACE) activities in the Middle East and Africa. FAME is based upon existing NASA and National Oceanic and Atmospheric Administration (NOAA) Earth science capabilities and has two discrete goals: (1) align with the current focus of the NASA-USAID Famine Early Warning Systems Network (FEWS NET) collaboration to predict water supply deficits related to agricultural drought and food security; and (2) describe water supply and water supply anomalies in the regions of interest through a suite of indicators. FAME will rely on remotely sensed data and the NASA Land Information System-based (LIS: Kumar et al., 2006) FEWS NET Land Data Assimilation System (FLDAS; *http://ldas.gsfc.nasa.gov/fldas/*) to understand the physical processes and to conceptualize, calibrate and evaluate models. After the model evaluations are completed, satellite-based soil moisture and terrestrial water storage data assimilation and meteorological seasonal forecasts will be used to augment FLDAS.

The Tigris-Euphrates River Basin

Among FAME's regions of interest (see figure on next page), the Tigris-Euphrates River Basin (TERB), with its headwaters in the mountains of Turkey, northern Iraq and Iran, has a high level of anthropogenic activities and scarce data availability. The river system flows from the cool, relatively humid mountain areas into the broad, arid plains of Syria and Iraq, where precipitation is less than 150 mm/year. In these regions, the rivers are in water deficit due to both natural evaporation and anthropogenic withdrawals for irrigation and other uses (Beaumont, 1998). The Tigris-Euphrates River flow reflects the seasonality of both precipitation and snowmelt. Both rivers are characterized by strong springtime peaks—April for the Tigris and May for the Euphrates—and relatively low flow through the summer and autumn months. Diversion systems for irrigation, interannual variability and a paucity of publicly



FAME's regions of interest.

available discharge data in the headwaters region has led to uncertainty in estimates of total river flow. Typical estimates for natural discharge are on the order of 950-1100 m^3/s for the Euphrates and 1600 m^3/s for the Tigris (Kolars, 1994).

Given the prominence of anthropogenic regulation in the TERB, modeling efforts that represent the flow of water from the atmosphere to and through the land surface, should take into consideration, at least at a conceptual level, both the structure of the regulated flow system, as well as the dynamics of the human systems that regulate the flow through it. Seven on-river reservoirs with dams operate with irrigation, flood management and hydropower production objectives. In addition, smaller dams provide irrigation and flood management to specific communities. A network of 27,000 km of irrigation canals can be filled by manipulation of on-river barrages that raise river levels to divert water into canals. Off-river storage is also utilized for flood management, both in canals and natural ponds and depressions. A prime example of this is Lake Tharthar, which can receive water from the Tigris via a flood escape channel, and divert water either to the Euphrates or back to the Tigris, and store a volume equivalent to two years of Tigris flows. Finally, a massive outfall drain or "third river" was constructed between the Tigris and the Euphrates that collects drainage waters from north of Baghdad to the Persian Gulf, exiting via a siphon underneath the Euphrates and into the Shat-al Arab Canal and the Persian Gulf (World Bank, 2006). Each one of these engineered structures represents a location where naturalized runoff and routing simulations may inadequately represent in situ conditions at any given time.

Validation Data Availability

Even though the TERB region has undergone significant human-induced hydrological changes, recent ground-based observations of streamflow are not publicly available. The Global Runoff Data Centre (GRDC: *http://www.bafg.de/GRDC/EN/Home/homepage_node.html*) has significantly improved streamflow data access in the past years; however, most of the time series in the Middle East end in the 1980s. In this sense, hydrologists depend upon remote sensing data to understand physical processes, and to conceptualize, calibrate and evaluate models.

Numerous spatially distributed satellite data sets are available for evaluation of water budget variables: (1) terrestrial water storage derived from the Gravity Recovery and Climate Experiment (GRACE; Tapley et al., 2004); (2) soil moisture through the European Space Agency's (ESA) Climate Change Initiative (CCI) merged active and passive microwave data set (Liu et al., 2011), NOAA's Soil Moisture Operational Product System (SMOPS; Zhan et al., 2011) and NASA's Soil Moisture Active Passive (SMAP: Entekhabi et al., 2010) Mission; and (3) evapotranspiration through the Atmosphere-Land Exchange Inverse (ALEXI; Anderson et al., 2011) modeling scheme and the U.S. Geophysical Survey's (USGS) Simplified Surface Energy Balance (SSEB; Savoca et al., 2013) approach.

Surface water dynamic variables can also be evaluated through radar altimetry (RA) data. Although publicly available data sets cover main water bodies worldwide, only reservoir and lake levels are available within TERB. Collaborative work with partners at the Laboratoire d'Etudes en Géophysique et

Océanographie Spatiales (LEGOS) allowed RA data acquisition at six locations along the Tigris River. These data were derived from Jason-2 and Envisat missions, and have been used to better understand the river dynamics.

Modeling Framework

The NASA Land Information System (LIS) has been used in the first modeling experiments over the Middle East and Northern Africa region, providing modeling and computational capabilities to merge observations and model forecasts to generate spatially and temporally coherent estimates of land surface conditions. These analyses are of critical importance to applications such as agricultural production, water resources management and prediction of flood, drought, weather and climate. LIS includes several community land-surface models (LSMs) and supports their application at varying spatial and temporal scales over regional, continental and global domains. Other subsystems available in LIS include data assimilation, uncertainty estimation and optimization, in addition to the Hydrological Modeling and Analysis Platform (HyMAP; Getirana et al., 2012) river routing scheme. In order to support terrestrial water storage data assimilation in upcoming modeling experiments, FLDAS LSMs require a prognostic water table. In this sense, two LSMs are being used within the FAME framework: the Catchment LSM (CLSM; Koster et al., 2000) Fortuna 2.5 Version and the Noah LSM multi-physics option (Noah-MP; Niu et al., 2011). For comparison reasons, other models included in LIS will be run.

Experiments will be designed considering meteorological forcing data sets, such as NASA's Modern Era-Retrospective Analysis for Research and Applications (MERRA)-Land (Reichle et al., 2011) and NOAA's Global Data Assimilation System (GDAS; Derber et al., 1991). Impacts of improved precipitation data sets (e.g., USGS Climate Hazards Group InfraRed Precipitation with Station, CHIRPS; Funk et al., 2014) will also be evaluated. Combining different LSMs and meteorological forcing data sets will allow the identification of the most suitable combination for the ensemble.

Preliminary Results

As a first attempt in modeling the basin, three experiments were performed using Noah LSM version 3.3 (this version does not include a prognostic water table) and HyMAP at a 0.1-degree spatial resolution forced with GDAS, MERRA-Land only, and MERRA-Land + CHIRPS for the period 2000–2014. The first runs indicate a non-negligible difference between precipitation rates at the basin scale, averaging 277 mm/year, 193 mm/year and 237 mm/year, respectively. The total runoff (surface runoff + baseflow) generated in these experiments are 84 mm/year, 47 mm/year and 22 mm/year. These results show how sensitive the total runoff (surface runoff + base flow) generation is to different forcing data sets. It is worth noting that incremental evapotranspiration from irrigated areas and reservoirs are not considered in this balance. This means that simulated runoff rates can be lower in a modeling system where anthropogenic activities are taken into account.

Also, discrepancies between the forcing data sets have a non-negligible impact on the river dynamics. Reservoir operation at the Mosul Dam results in a high amplitude and shifted water level fluctuation when compared to the naturalized regime, as simulated by HyMAP at Location 1 (see figure on cover). The model shows some skill at other locations, but altered reservoir outflows still impact water levels downstream of the dam. In particular, radar altimetry data at Location 6 show a positive trend in annual minimum water levels not detected by the model. The observed regime is probably due to recent changes in water flow operations at Tharthar Lake and in agricultural areas southeast of Baghdad.

Prospects

The expected outcome of FAME is a seasonal water deficit forecasting system to support USAID and USACE activities in Africa and the Middle East. However, lack of data and knowledge of anthropogenic activities add to the limitations for more precisely simulating the water balance in these regions. Undoubtedly, anthropogenic activities have a major impact on most river systems worldwide, and incorporating them in Earth system modeling platforms is the next step towards an improved representation of physical processes. In particular, dams, irrigation and canals affect river flow regime, evapotranspiration and soil moisture, directly impacting the hydrological cycle, atmosphere, biosphere and, ultimately, the regional climate. FAME will address modeling limitations.

A NASA call for participation in a land model intercomparison is expected in the near future in order to evaluate a larger range of LSM parameterizations. In terms of GEWEX activities, FAME's tasks and outcomes would support Global Land/Atmosphere System Study (GLASS) Panel activities, and seeking crosscutting model and observational data set support for this region could give back to the GEWEX community in data sparse regions, such as the ones highlighted (e.g., TERB) in the project. Finally, we hope that the GEWEX network of scientists will share their expertise in different modeling approaches, data availability and personal experience to further our understanding of water and energy exchanges in the Middle East and North Africa region.

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The authors thank Jean-Francois Creteaux of the Centre National d'Etudes Spatiales (CNES) Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS) for providing Jason-2 and Envisat radar altimetry data over the Tigris River.

References

Anderson, M.C., W.P. Kusta, J.M. Norman, C.R. Hain, J.R. Mecikalski, L. Schultz, M.P. Gonzalez-Dugo, C. Cammalleri, G. d'Urso, A. Pimstein and F. Gao, 2011. Mapping daily evapotranspiration at field to continental scales using geostationary and polar orbiting satellite imagery. *Hydrol. Earth Syst. Sci.*, 15, 223–239, doi:10.5194/hess-15-223-201.

Beaumont, P., 1998. Restructuring of water usage in the Tigris-Euphrates Basin: The impact of modern water management policies. *Transformations of Middle Eastern Natural Environments: Legacies and Lessons*, Coppock and Miller (Eds.), Yale University, 168-186.

Derber, J.C., D.F. Parrish and S.J. Lord, 1991. The new global operational analysis system at the National Meteorological Center. *Weather Forecasting*, 6, 538–547.

Entekhabi et al., 2010. The Soil Moisture Active Passive (SMAP) mission–*Proceedings of the IEEE*, 98, 704-716.

Funk, C.C., P.J. Peterson, M.F. Landsfeld, D.H. Pedreros, J.P. Verdin, J.D. Rowland, B.E. Romero, G.J. Husak, J.C. Michaelsen and A.P. Verdin, 2014. A quasi-global precipitation time series for drought monitoring: U.S. Geological Survey Data Series 832, 4 p.. *http://dx.doi.org/10.3133/ds832*.

Getirana, A.C.V., A. Boone, D. Yamazaki, B. Decharme, F. Papa and N. Mognard, 2012. The Hydrological Modeling and Analysis Platform (HyMAP): Evaluation in the Amazon basin. *J. Hydrometeorol.* 13, 1641–1665, doi: 10.1175/JHM-D-12-021.1.

Kolars, J., 1994. Problems of international river management: The case of the Euphrates. *International Waters of the Middle East—from Euphrates–Tigris to Nile.* Oxford University Press, London, 44-94.

Koster, R.D., M.J. Suarez, A. Ducharne, M. Stieglitz and P. Kumar, 2000. A catchment based approach to modeling land surface processes in a general circulation model: 1. Model structure, *J. Geophys. Res. Atmos*., 105, 24809–24822, doi:10.1029/2000JD900327.

Kumar, S.V., C.D. Peters-Lidard, Y. Tian, J. Geiger, P.R. Houser, S. Olden, L. Lighty, J.L. Eastman, P. Dirmeyer, B. Doty, J. Adams, E.F. Wood and J. Sheffield, 2006. LIS – An interoperable framework for high resolution land surface modeling. *Environ. Modell. Softw*., 21, pp 1402-1415.

Liu, Y., R. Parinussa, W. Dorigo, R. De Jeu, W. Wagner, A. Van Dijk, M. McCabe and J. Evans, 2011. Developing an improved soil moisture dataset by blending passive and active microwave satellite-based retrievals. *Hydrol. Earth Syst. Sci.*, 15, 425-436.

Niu, G.-Y., Z.-L. Yang, K.E. Mitchell, F. Chen, M.B. Ek, M. Barlage, L. Longuevergne, A. Kumar, K. Manning, D. Niyogi, E. Rosero, M. Tewari and Y. Xia, 2011. The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *J. Geophys. Res*., doi:10.1029/2010JD015139.

Reichle, R.H., R.D. Koster, G.J.M. De Lannoy, B.A. Forman, Q. Liu, S.P.P. Mahanama, and A.Touré, 2011. Assessment and Enhancement of MERRA Land Surface Hydrology Estimates. *J. Clim.*, 24, 6322–6338. doi: *http://dx.doi.org/10.1175/JCLI-D-10-05033.1*

Salmon, J. M., M.A. Friedl, S. Frolking, D. Wisser, and E.M. Douglas, 2015. "Global rain-fed, irrigated, and paddy croplands: A new high resolution map derived from remote sensing, crop inventories and climate data." *Int. J. Appl. Earth Obs. and Geoinf.*, 38: 321-334

Savoca, M.E., G.B. Senay, M.A. Maupin, J.F. Kenny and C.A. Perry, 2013. Actual evapotranspiration modeling using the operational Simplified Surface Energy Balance (SSEBop) approach: U.S. Geological Survey Scientific Investigations Report 2013-5126, 16 p., *http://pubs.usgs.gov/sir/2013/5126*.

Tapley, B., S. Bettadpur, J.C. Reis, P.F. Thompson and M.M. Watkins, 2004. GRACE measurements of mass variability in the earth system. *Science*, 305(5683), 503–505, doi:10.1126/science.1099192.

World Bank, 2006. Iraq: Country Water Resources Assistance Strategy: Addressing Major Threats to People's Livelihoods. Report No. 36287-IQ. Water, Environment, Social and Rural Development Department, Middle East and North Africa Region.

Zhan et al., 2011. Soil Moisture Operational Product System (SMOPS) algorithm theoretical basis document Version 3.0. *http://www.ospo.noaa.gov/Products/land/smops/figures/SMOPS_ATBD_v3.0.pdf.*

The Recent Partial Recovery in Sahel Rainfall: A Fingerprint of Greenhouse Gases Forcing?

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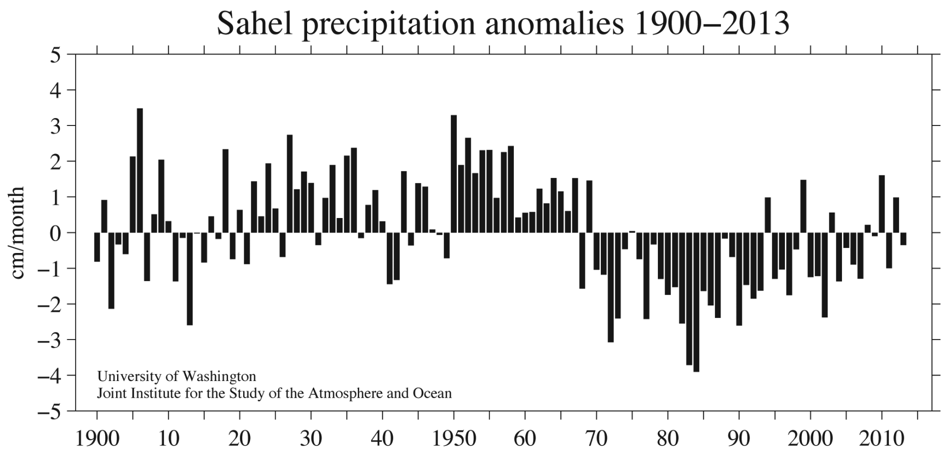
In the present context of climate transition under the influence of anthropogenic forcings, a critical issue is proper attribution of climate anomalies, in order to avoid misinterpretations leading to possible maladaptations. Over the last 60 years, the monsoon region of the Sahel has been coping with some of the most severe climate variability in the world, including two decades of persistent excessive rainfall in the 1950s–1960s, followed by two decades of rainfall deficits (see figure on page 12). Recently, there has been a partial recovery with annual rainfall amounts fluctuating around the long-term mean, more evident over the central Sahel than over the western Sahel (Lebel and Ali, 2009). The current period is also characterized by a deficit of rainy days with a rise in extreme rainfall occurrences, indicating the intensification of the hydrological cycle (Giannini et al., 2013; Panthou et al., 2014). This climate is drier in the sense of persistent dry spells compared to the 1950s–1960s, while at the same time there is an increased probability of floods.

While projections of future climate over the Sahel in Coupled Model Intercomparison Project Phase 5 (CMIP5) runs are quite uncertain in terms of rainfall regime (Biasutti, 2013), they are qualitatively consistent with this recent evolution: they show that at the end of the 21st century under the highest greenhouse gases (GHG) emission scenario, RCP8.5, a zonal rainfall anomaly dipole with more summer precipitation over the central Sahel (especially in August-September), and less summer precipitation (especially in June-July) over the west-



June–October averages over 20-10N, 20W-10E. NOAA/NCDC Global Historical Climatology Network data.

ern Sahel (Biasutti, 2013), is accompanied by an increase in the number of extreme rainfall days (Vizy et al., 2013).

Various studies have noted the importance of global sea surface temperature (SST) variability, land surface and GHG and aerosol concentrations, and how they may impact monsoon precipitation. Based on multi-model experiments including the latest CMIP5 results, a consensus is emerging on the drying effect of global SST, and the opposing positive effect of increasing GHG concentration (e.g., Haarsma et al., 2005; Held et al., 2005; Hoerling et al., 2006; Cook and Vizy, 2006; Caminade and Terray, 2010; Giannini, 2010; Biasutti, 2013; Bony and al., 2013; Gaetani et al., 2015).

Uncertainty in Climate Models Sensitivity to SST and GHG Forcings Over the Sahel

Recently, Dong and Sutton (2015) suggested that higher atmospheric concentrations of GHG and the direct increase in atmospheric temperature were primarily responsible for the Sahel rainfall recovery. Using the Hadley Centre Global Environment Model Version 3-A (HadGEM3-A), they simulated epochal climate changes for the period 1964–2011 under different idealized conditions and investigated the individual roles of global SST, GHG and atmospheric aerosol concentrations in driving the recent recovery of the monsoonal precipitation in the Sahel. They suggest that the direct influence of higher levels of GHG in the atmosphere is the main cause of Sahel rainfall recovery, with an additional role for changes in anthropogenic aerosol precursor emissions. They also found that recent changes in SSTs, although substantial, did not appear to have a significant impact on the recovery, and that rainfall is likely to be sustained or amplified in the near term.

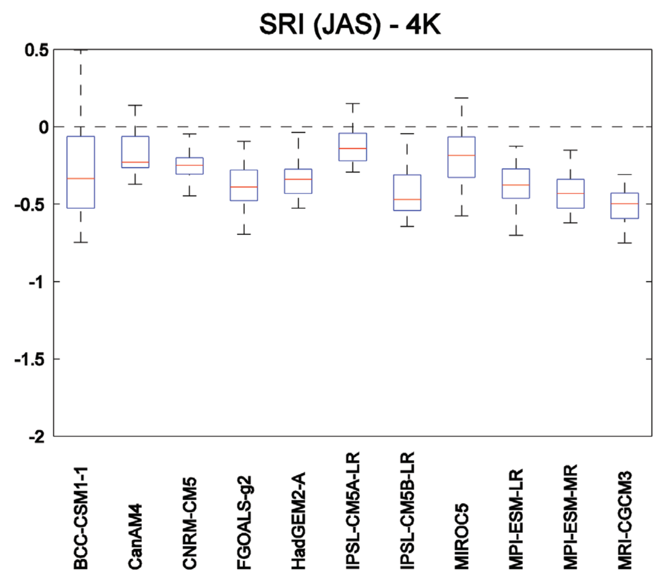
By using only one model, it is not possible to evaluate the robustness of the results. Giannini (2015) showed how the HadGEM2-A underperforms in reproducing the effect of historical SST on Sahel rainfall compared to the ensemble of the other models available in CMIP5. Multiple data sets of numerical experiments were also analyzed and extracted from the recently available CMIP5 archive (Taylor et al., 2012) that simulate idealized conditions that are more or less similar to the ones used by Dong and Sutton (2015). The behaviors of 11 models were compared, including the HadGEM2-A (Table 1), and these were run in the atmosphere-only configuration. The monsoonal season from July to September (JAS) also analyzed.

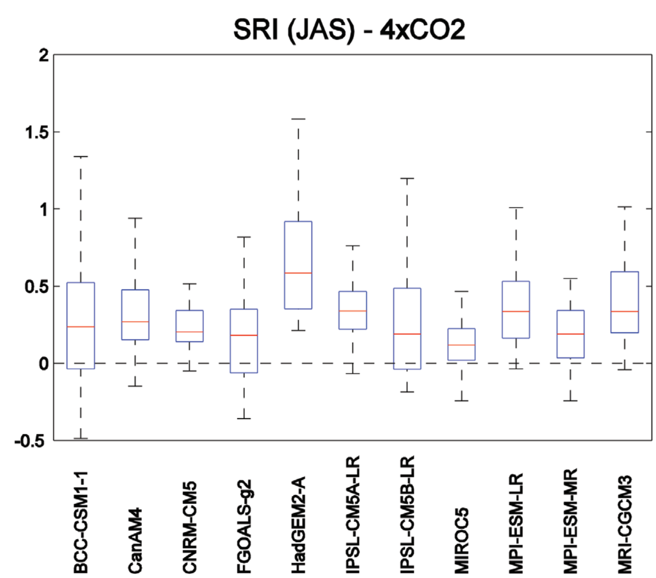
First, the simulations of the 11 CMIP5 models (Table 1) forced by the observed global SST over the period 1979-2008 (control simulations, CTL) were analyzed. The long-term trends of Sahelian precipitation are affected by global SST variability, mainly through the differential heating in the Northern

Table 1. Models analyzed. CMIP5 model information and outputs are available through the Earth System Grid Federation Archive at: *http://cmip-pcmdi.llnl.gov/cmip5*.

Modeling Center	Model	Resolution Lat./Long.
Beijing Climate Center, China Meteorological Administration	BCC-CSM1-1	T42 (~2.8°)
Canadian Centre for Climate Modeling and Analysis	CanAM4	T42 (~2.8°)
Centre National de Recherches Météorologiques/Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	CNRM-CM5	T127 (~1.4°)
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	FGOALS-g2	3.0° x 2.8°
Met Office Hadley Centre	HadGEM2-A	1.25° x 1.875°
Institut Pierre-Simon Laplace	IPSL-CM5A-LR	1.875° x 3.75
	IPSL-CM5B-LR	1.875° x 3.75
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	T127 (~1.4°)
Max Planck Institute for Meteorology	MPI-ESM-LR	T73 (~1.9°)
	MPI-ESM-MR	T73 (~1.9°)
Meteorological Research Institute	MRI-GCCM3	T159 (~1.125°)

Hemisphere and the Tropics (Mohino et al., 2011; Giannini et al., 2013), and by the GHG radiative warming of the land surface, which is particularly important at the regional scale (Giannini, 2010; Gaetani et al., 2015). The sensitivity of the Sahelian rainfall was then compared to the differential heating of global SST to the response to land surface warming over North Africa. Indexes were defined for Sahelian rainfall (SRI), North Atlantic minus Global Tropical SST differential heating (NAT), and surface air temperature for North Africa (SAT). The SRI sensitivity to the changes in NAT and SAT shows that the HadGEM2-A is less sensitive to the SST differential heating and surface air temperature, with SRI versus





Box plot of the SRI changes in the idealized sensitivity experiments relative to CTL (Δ = (Exp – CTL) / |CTL|). In each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the most extreme data points.

Table 2. Sensitivity of the Sahelian precipitation to global warming in the 4K and 4xCO_2 experiments.

Model	4K	4xCO_2	Ratio
BCC-CtSM1-1	-0.0678	0.5754	8.49
CanAM4	-0.0951	1.2682	13.34
CNRM-CM5	-0.2428	1.9412	8.00
FGOALS-g2	-0.1642	0.5282	3.22
HadGEM2-A	-0.0898	2.1713	24.18
IPSL-CM5A-LR	-0.0591	1.5311	25.91
IPSL-CM5B-LR	-0.0929	0.4781	5.15
MIROC5	-0.2001	0.9134	4.56
MPI-ESM-LR	-0.1937	1.8522	9.56
MPI-ESM-MR	-0.2552	1.0659	4.18
MRI-CGCM3	-0.1395	1.3075	9.37

A Global Warming (GW) index is computed by averaging the surface air temperature in the band [50°S-70N], and the sensitivity is estimated through the ratio between the SRI response and the GWs in the idealized experiments compared to control simulations (CTL). Third column: ratio of the two sensitivity coefficients (4xCO_2/4K).

NAT being particularly weak. HadGEM2-A shows SAT to be three times more important than NAT, whereas all other models show NAT to be six to as much as 80 times more important than SAT (not shown). This suggests a specific high sensitivity of the Sahelian precipitation to the regional-versus-global thermal forcing in HadGEM2-A compared to the other models, which might favor the regional scale GHG radiative heating impact compared to the global scale SST heating impact.

Second, the response of the same models to changes in SST and GHG forcings was studied by analyzing two idealized experiments aiming at emphasizing the responses through the simulation of extreme conditions, one with a 4K homogeneous increase in global SST, and the other having a fourfold increase in atmospheric CO_2 concentration. By analyzing the SRI responses, it appears that the HadGEM2-A response to 4K SST is in line with most of the model ensemble, while in the 4xCO_2 experiment, the HadGEM2-A shows the strongest response compared to the other models (see figure on left). The SRI sensitivity summarized in Table 2 in the 4K experiment is in the range -0.26 to -0.06 mm/day/K, with the HadGEM2-A response close to the lower limit (-0.09 mm/day/K). On the other hand, in the 4xCO_2 experiment, the sensitivity is in the range 0.48–2.17 mm/day/K, and the HadGEM2-A is at the upper limit, showing the strongest response compared to the other models (figure on left). HadGEM2-A also has the second highest ratio of relative sensitivity of 4xCO_2/4K, well above the other models (third column of Table 2).

Possible Contribution of Internal Variability

Another issue that should be considered is the range of atmospheric-only internal variability and its possible contribution to the recent Sahel rainfall recovery. In an Atmospheric Model Intercomparison Project (AMIP)-type simulation ensemble that is different from the repeating SST-forced experiments of Dong and Sutton, five members of the IPSL-CM5A-LR model predicted a Sahel rainfall recovery from the 1980s–2000s but with large internal variability, ranging from +6% to +21% (Figure 3b of Roehrig et al.). Other 100-year simulations of the same IPSL model forced by either the 1955–1965 or the 1975–1985 mean SST global pattern show a high variation of the 10-year running means of Sahel rainfall along each of the 100-year periods, close to 20% between the highest and the lowest running means (F. Hourdin, personal communication). That means that decadal scale variability (at least for 10-year sequences) due to the atmosphere alone is high over the Sahel and might be responsible for a significant part of the recent Sahel rainfall recovery.

The Need for a Process-Based Assessment: Example of the Saharan Heat Low

To better understand the diversity of West African monsoon sensitivity in climate models, it is necessary to address some of the key processes in play. In summer, the Saharan heat low (SHL), combined with the high-pressure southward, produces a low-level pressure gradient that controls the West African monsoon. The warmer the Sahara is, the stronger the thermal depression becomes and the more intense the monsoon flow leading to enhanced convection over the central and eastern Sahel and weaker convection over the western Sahel (Lavaysse et al., 2010). In this context, Cook and Vizy (2015) show by using three reanalysis products that the recent recovery in Sahel rainfall is concomitant with the increase of Sahara surface temperature that is 2-4 times greater than that of the tropical-mean temperature. It is accompanied by a strengthening of both the Saharan heat low and the African easterly jet. This amplified warming, confined to the lower troposphere, seems to be due to large increases in both downward and upward longwave radiation. The contribution of atmospheric carbon dioxide increase and water vapor increase in this warming is probable. However uncertainties in the surface heat balance remain large in reanalysis products due to the sparse ground-based observations over the desert and to poor representation of the radiative properties of aerosols and of the surface reflectivity in this arid region. Evan et al. (2015) also addressed the origins of the recent recovery from the Sahel drought, showing that the temperature increase in the SHL over the last 30 years was forced by anomalous nighttime longwave heating of the surface by water vapor. They identified a Saharan water vapor–temperature feedback associated with an increase in the low-level water vapor convergence within the SHL as SHL temperatures rise. The structure of the drought recovery is consistent with a warming SHL and is evidence of a fundamental, but not exclusive, role of the SHL in the recent increase in Sahelian monsoon rainfall.

Regarding climate simulations, Biasutti et al. (2009) highlighted the role of SHL with a better understanding of the source of discrepancy in CMIP3 Sahel rainfall projections. Lavaysse et al. (2015) showed that despite a large variability in CMIP5 AMIP simulations over the last 30 years within a set of 15 climate models, the warming trend in SHL is observed in the models' ensemble mean. These climate models represent the West African monsoon interactions with SHL pulsations quite differently; however, some of them are able to simulate an accurate rainfall-SHL regression pattern, or a zonal rainfall anomaly pattern, with more precipitation over the Central Sahel and less precipitation over the western Sahel associated with the long-term SHL increase. Projections of future climate over the Sahel in CMIP5 runs are qualitatively consistent with this recent evolution and this zonal dipole is associated with a continuing increase of temperature in the SHL (Monerie et al., 2012). James et al. (2015) explained the simulated drying over the western Sahel by anomalous subsidence at 400 hPa, possibly associated with the SHL warming that may be responsible for increases in dry convection with potential feedbacks on the monsoon and the African easterly jet. However, they questioned the accuracy of this modeled circulation mode, as it is not clear in reanalysis products what different mechanisms are used for drying in the western Sahel.

Addressing the possible role of GHG increases in the recent recovery in Sahel rainfall requires more process-based assessments on ensembles of both historical simulations and future climate projections. This will help reduce uncertainties over this region and provide well-founded expert judgements of the trustworthiness of climate model projections to decision-makers, which is one of the objectives of the new African Monsoon Multidisciplinary Analysis (AMMA)-2050 Project (Department for International Development-Natural Environment Research Council Future Climate For Africa project 2015–2019). However, there are still weaknesses in our understanding of atmospheric processes in this region. Data from recent short-term AMMA field campaigns, as well as other affiliated campaigns over West Africa and the surrounding oceans, are potentially valuable resources. Moreover, the maintenance of long-term monitoring of the hydrological cycle over West Africa is critical to detect possible trends and attribute their causes.

References

Biasutti, M., A.H. Sobel and S.J. Camargo, 2009. The role of the Sahara heat low in summertime Sahel rainfall variability and change in the CMIP3 models. *J. Clim.*, 22, 5755-5770.

Biasutti, M., 2013. Forced Sahel rainfall trends in the CMIP5 archive. *J. Geophys. Res. Atmos.*, 118, 1613–1623.

Bony, S., G. Bellon, D. Klocke, S. Sherwood, S. Fermepin and S. Denvil, 2013. Robust direct effect of carbon dioxide on tropical circulation and regional precipitation. *Nat. Geosci.*, 6, 447–451.

Caminade, C., and L. Terray, 2010. Twentieth century Sahel rainfall variability as simulated by the ARPEGE AGCM, and future changes. *Clim. Dynam.,* 35, 75–94.

Cook, K.H., and E.K. Vizy, 2006. Coupled model simulations of the West African monsoon system: Twentieth- and twenty-first-century simulations. *J. Clim.*, 19, 3681–3703.

Cook, K.H., and E.K. Vizy, 2015. Detection and analysis of an amplified warming of the Sahara desert. *J. Clim.*, 28, 6560-6580.

Dong, B., and R. Sutton, 2015. Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall. *Nat. Clim. Change*, 5, 757-760.

Evan, A.T., C. Flamant, C. Lavaysse, C. Kocha and A. Saci, 2015. Water vapor-forced greenhouse warming over the Sahara desert and the recent recovery from the Sahelian drought. *J. Clim.*, 28, 108-123.

Gaetani, M., C. Flamant, S. Bastin, S. Janicot, C. Lavaysse, F. Hourdin, P. Braconnot and S. Bony, 2015. Climate Dynamics West African Monsoon dynamics and precipitation: The competition between global SST warming and CO_2 increase in CMIP5 idealized simulations. *Clim. Dynam.*, in revision.

Giannini, A., 2010. Mechanisms of climate change in the semiarid African Sahel: The local view. *J. Clim.*, 23, 743–756.

Giannini, A., S. Salack, T. Lodoun, A. Ali, A.T. Gaye and O. Ndiaye, 2013. A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environ. Res. Lett.*, 8, 024010.

Giannini, A., 2015. Climate change comes to the Sahel. *Nat. Clim. Change*, 5, 720–721.

Haarsma, R.J., F.M. Selten, S.L. Weber and M. Kliphuis, 2005. Sahel rainfall variability and response to greenhouse warming. *Geophys. Res. Lett.*, 32, 1–4.

Held, I.M., T.L. Delworth, J. Lu, K.L. Findell and T.R. Knutson, 2005. Simulation of Sahel drought in the 20th and 21st centuries. *Proc. Natl. Acad. Sci. U.S.A.*, 102, 17891–17896.

Hoerling, M., J. Hurrell, J. Eischeid and A. Phillips, 2006. Detection and attribution of twentieth-century northern and southern African rainfall change. *J. Clim.*, 19, 3989–4008.

James, R., R. Washington and R. Jones, 2015. Process-based assessment of an ensemble of climate projections for West Africa. *J. Geophys. Res.*, 120, 1221-1238.

Lavaysse, C., C. Flamant and S. Janicot, 2010. Regional-scale convection patterns during strong and weak phases of the Saharan heat low. *Atmos. Sci. Lett.*, 11, 255-264.

Lavaysse, C., C. Flamant, A. Evan, S. Janicot and M. Gaetani, 2015. Recent climatological trend of the Saharan heat low and its impact on the West African climate. *Clim. Dynam.*, doi:10.1007/s00382-015-2847-z.

Lebel, T. and A. Ali, 2009. Recent trends in the Central and Western Sahel rainfall regime (1990-2007). *J. Hydrol.*, 375, 52-64.

Mohino, E., S. Janicot and J. Bader, 2011. Sahel rainfall and decadal to multidecadal sea surface temperature variability. *Clim. Dynam.*, 37, 419–440.

Monerie, P.-H., B. Fontaine and P. Roucou, 2012. Expected future changes in the African monsoon between 2030 and 2070 using some CMIP3 and CMIP5 models under a medium-low RCP scenario. *J. Geophys. Res.*, 117, doi:10.1029/2012JD017510.

Panthou, G., T. Vischel and T. Lebel, 2014. Recent trends in the regime of extreme rainfall in the Central Sahel. *Int. J. Climatol.*, 34, 3998-4006.

Roehrig, R., D. Bouniol and F. Guichard, 2013. The present and future of West African monsoon: A process-oriented assessment of CMIP5 simulations along the AMMA transect. *J. Clim.*, 26, 6471–6505.

Taylor, K.E., R.J. Stouffer and G.A. Meehl, 2012. An overview of CMIP5 and the experiment design. *Bull. Am. Meteor. Soc.*, 93, 485–498.

Vizy, E.K., K.H. Cook, J. Crétat and N. Neupane, 2013. Projections of a wetter Sahel in the twenty-first century from global and regional models. *J. Clim.*, 26, 4664-4687.

Meeting/Workshop Reports

Workshop on Uncertainties at 183 GHz

Paris, France
29-30 June 2015

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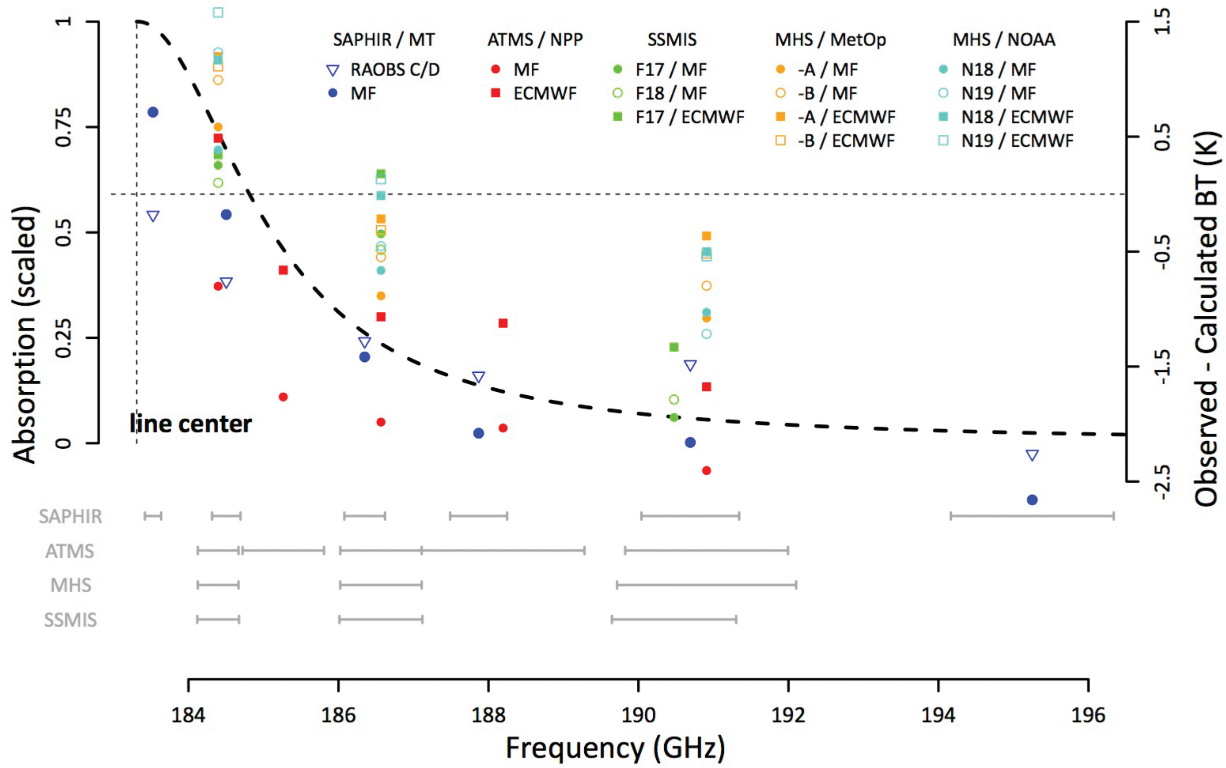
Thirty-eight scientists from 19 institutes attended the Workshop to discuss the uncertainties of radiometric observations at 183 GHz. These observations are among the most important sources of humidity information for global and regional analyses, weather forecasts and climate monitoring. A sound characterization of their absolute calibration is important for their effective use in models. Recent cross-comparisons between the existing microwave sounders, Sondeur Atmospheric du Profil d'Humidité Intertropical par Radiométrie (SAPHIR, on Megha-Tropiques), the Advanced Technology Microwave Sounder (ATMS; on Suomi-National Polar-orbiting Partnership missions), the Special Sensor Microwave Imager/Sounder [SSMIS, on Defense Meteorological Satellite Program (DMSP)-F17 and F18)] and the Microwave Humidity Sounder (MHS on MetOp-A and B and National Oceanic and Atmospheric Administration-18 and -19), show a very good consistency among them, well within the radiometric noises of the instruments. However, when the measurements are simulated in a numerical weather prediction (NWP) system, or compared to radiative transfer model (RTM) calculations that use radiosonde (RAOBS) profiles of temperature and humidity, a channel-dependent bias, which increases from the center to the wings of the 183 GHz line, is observed. The figure on page 16 clearly shows this pattern.

The workshop was organized around three main objectives: (1) describe the biases and separate those that are common to all approaches from those that may have resulted from a particular methodology; (2) identify and, where possible, quantify uncertainty in every component of the comparison; and (3) where possible, begin the process of attribution of the biases, which may in due course lead to their elimination. To address these ambitious goals, experts in many different aspects of the problem were assembled. This included specialists in RAOBS calibration, NWP models and data assimilation, instrument biases and radiative transfer models (both the models themselves and the underlying spectroscopy). Comparisons were also undertaken with other techniques for sensing humidity information, such as the Global Navigation Satellite Systems (GNSS), Differential Absorption Lidar (DIAL), Raman Lidar, and infrared (IR) radiances.



Observed minus calculated brightness temperature (BT) using either radiosonde measurements [RAOBS from the Cooperative Indian Ocean Experiment on Intraseasonal Variability (CINDY)/Dynamics of the Madden-Julian Oscillation (DYNAMO)/ARM Madden-Julian Oscillation (MJO) Investigation Experiment (AMIE) field campaign, Northern Hemisphere winter 2011–2012, triangles] or Météo-France NWP models (MF, circles) or European Centre for Medium-Range Weather Forecasts (ECMWF, squares). Each color refers to a specific sensor, displayed in the legend, and the horizontal grey bars indicate the width of the band passes. All the calculated BTs have been done with the RTTOV [Radiative Transfer for the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder] model.

In Situ Observations of Tropospheric Water Vapor

The first session focused on the limits and merits of in situ observations of tropospheric water vapor, including uncertainties in the measurements from RAOBS, GNSS receivers and Lidar systems (Raman and DIAL), as well as the meteorological closure when comparing two measurements (e.g., co-location effects, uncertainties from calibration). An emphasis was also placed on the Global Observing System for Climate (GCOS) Reference Upper-Air Network (GRUAN) and on the Gap Analysis for Integrated Atmospheric Essential Climate Variable Climate Monitoring (GAIA-CLIM, Horizon 2020) Project.

It appears that uncertainties in relative humidity measurements by radisosondes arise mainly from the calibration procedures, the calibration corrections, time lags due to low temperatures and (for some probes) the solar radiation heating of the sensor. After correction of all known biases, verified by comparisons with frost point hygrometer (FPH) measurements, the most recent World Meteorological Organization intercomparison campaign showed good agreement between most operational sondes up until the mid-to-upper troposphere. In the lower-to-mid troposphere, there is robust agreement and evidence that sonde biases could at most be 2–5% with somewhat broader random uncertainties on individual ascent profiles. GNSS estimations of the atmospheric precipitable water (PW, estimated from delays induced by absorption by water vapor and by the dry gases) have a mean uncertainty of about 2% (less than 1.0 mm), while a recent analysis of the upper-air sounding network deployed during the CINDY/DYNAMO/AMIE field campaign has revealed an unclear, and statistically significant, dry bias of about 2.0 mm at moist conditions. Finally, DIAL systems (self-calibrating) and Raman Lidars (calibrated using a profile of the inelastic scattering coefficient) provide data under cloud-free atmospheres or until the laser beam reaches optically thick clouds. Both systems have a typical accuracy below 5% in the troposphere, estimated from several intercomparison campaigns. Therefore, in situ errors could only explain biases near the 183.31 GHz center line, whereas the biases are more significant towards the wings.

Calibration of Spaceborne Observations

The second session overviewed the status of spaceborne observations and homogenization of procedures between 183 GHz sensors. The calibration status of the current 183.31 GHz channels was discussed along the lines of the comparisons performed by the Global Precipitation Mission (GPM) Intercalibration (XCAL) Working Group. Calibration maneuvers were performed on the GPM Microwave Imager (GMI) in order to develop corrections for magnetic-induced biases, cross-track biases and updates to the pre-launch spill-over corrections, as well as to verify the channel polarizations. The resulting calibration of GMI shows very consistent results between similar channels of MHS, ATMS and SAPHIR, with values within 1K for all channels with no detectable temporal trend. It was emphasized during the discussions that the recording and availability of digital data and metadata of spectral response functions (SRF) and antenna patterns are strongly encouraged for future instruments. The SRF are often averaged over the pass bands and assumed to have a hat shape when unknown. Attention was also raised concerning the possible impact of sideband asymmetry and on the right methodology to handle double-side bands channels.

Radiactive Transfer Models in Microwave and Infrared Domains

Session three focused on the state-of-the-art in RTMs in the microwave (MW) and IR domains, as well as the current issues in the estimation of the spectroscopic parameters. Intercomparison exercises of MW RTMs (fast models and line-by-line models) have revealed small differences mainly attributed to the differences in spectroscopy and continua and not to the RTMs themselves. It was noted that the impact of the ozone line (0.2-0.3 K, around 184 GHz) is too small to explain the pattern of the bias. A parallel between IR and MW regions was done thanks to results obtained with the Infrared Atmospheric Sounding Interferometer (IASI) in channels located in the water vapor band (6.3 μm), and sensitivity studies showed similar behavior to what is observed in the analogous MW channels. The same qualitative behavior is observed irrespective of the atmospheric state used in the simulations (i.e., either RAOBS or NWP data). However, it was emphasized that this does not necessarily mean that the same mechanisms were underlying.

Estimation of Spectroscopic Parameters

The estimation of spectroscopic parameters led to lively discussions. The main contributions to the molecular absorption in the MW region of the spectrum are from water vapor, oxygen and nitrogen, with some minor contributions from ozone and nitrous oxide. Line parameters (line position and strength, the air-broadened half-width, the self-broadened half-width, the temperature exponent of the width and the pressure shift) may be obtained from laboratory experiments or from theoretical calculations and collated in databases such as the widely used High Resolution Transmission (HITRAN) compilation. It was noted that estimated uncertainties on the foreign (±3%) and self-broadened (±15%) half-widths, on the temperature exponent (maximum of 15%) and the pressure shift (maximum of 20%) and the uncertainties of the dry air absorption and related wings of neighboring water lines are too small to explain the bias. Finally, it was underscored that recent laboratory studies have resulted in unambiguous detection of water vapor dimer absorption in the millimeter-wave range and to the development of a model to describe such absorption. While the inclusion of dimer absorption can result in small-scale spectral variation of 0.5 to 1K in up-looking millimeter-wave spectra, it is not accounted for in the current version of continuum models [MlawerTobin_CloughKneizysDavies (MT_CKD) or Liebe-based model]. The impact of accounting for dimer absorption on RT modeling has yet to be evaluated. There was therefore a clear recommendation to encourage stronger coordination between instrument and calibration experts and RT modelers, to arrange a dedicated "183 GHz" session during spectroscopy meetings (such as HITRAN) and to perform new laboratory measurements and explore new line shape parameterizations.

Biases from Inversion Techniques

The last session focused on the possible biases that could arise from inversion techniques, whether for a geophysical retrieval or within a NWP data assimilation system. For ATMS, the comparison of Temperature Data Records (TDR, calibrated antenna temperatures) and Sensor Data Records (SDR, brightness temperature after applying a beam efficiency and scan position dependent bias correction) for channels 18 to 22 (the 183.31 GHz channels) shows the same behavior as reported previously, meaning that the TDR to SRD conversion is not responsible for the 183 GHz bias. Nevertheless, the conversion seems to introduce some dependence to the viewing angle, which requires further investigation.

Data Assimilation Within NWP Systems

Discussions regarding data assimilation within NWP systems were oriented towards cloud detection. Nowadays, Variational Bias Correction (VarBC) techniques have been developed to adaptively estimate a bias correction for each of the assimilated observations. RAOBS are generally not bias corrected with VarBC in order to anchor the system and the final humidity analysis, which explains the consistency between the bias observed using RAOBS and NWP fields. In fact, the cloud detection process is the main issue in comparisons between 183 GHz observations and a reference. The observed bias in the 183 GHz channels is consistent with a cloud detection that is missing some cloud-affected scenes, even though it is difficult to screen all clouds. The all-sky first guess departures from ECMWF is the only comparison which attempts to take into account the effects of cloud and precipitation in RTM. These biases can be compared to those computed using clear-sky RTM and cloud-screening, suggesting that 0.4 K of bias in the ±7 GHz channel can be explained by residual cloud effects. However, this is not enough to explain all of the bias.

The workshop report is available to download at: *http://megha-tropiques.ipsl.polytechnique.fr/available-documents/meeting-workshop/index.html*. Presentations are available from a password protected ftp site, hosted by the Institut Pierre Simon Laplace. The password may be obtained by contacting Hélène Brogniez at *helene.brogniez@latmos.ipsl.fr*.

Alpine Summer School on Land-Atmosphere Interactions

Valsavarenche, Valle d'Aosta, Italy
22 June–1 July 2015

Course Directors:
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Land-atmosphere interactions describe the coupled exchanges of momentum, heat, moisture and carbon between the land surface and the overlying atmosphere. These feedbacks are regulated through the interface of the planetary boundary layer, in which intense turbulence occurs. Land-atmosphere interactions are important sources of seasonal climate predictability in several parts of the world. Soil moisture and vegetation are key parameters influencing land-atmosphere interactions in the climate system by modifying the moisture and carbon fluxes, surface energy, and boundary conditions in the boundary layer. Because soil moisture and turbulence (boundary layer and moist convection) organize on many different temporal and spatial scales, the study of land-atmosphere interactions has been notoriously difficult. The study of land-atmosphere interactions encompasses a wide range of disciplines from soil science, surface hydrology, hydrometeorology, plant physiology, turbulence, convection and atmosphere circulation. As such, there is no single type of land-atmosphere interaction but a wide variety of cases embedded within the larger-scale general circulation.

Correctly modeling and measuring the feedbacks between the land surface and the atmosphere is key for improved hydrological, weather and climate forecasts, especially on subseasonal-to-seasonal and interannual time scales. In particular, extreme hydrological events over continents (floods and droughts) are strongly modulated by land-atmosphere interactions. The field of land-atmosphere interactions encompasses many areas such as boundary layer turbulence, convection, surface fluxes and ecophysiology.

The summer school is organized annually by the Italian National Council of Research's (CNR) Institute of Atmospheric Sciences and Climate (ISAC) and the French National Centre for Scientific Research (CNRS). The overall objective is to cover a wide range of topics—within a coherent and comprehensible framework—in order to help young researchers (Ph.D. students in particular) better understand the science behind the interactions occurring between the different elements of the land and atmosphere systems.

The theme of this year's summer school was "fundamental processes in geophysical fluid dynamics and the climate system." Fifty students out of a record 180 applicants attended the school, which focused on providing young researchers an up-to-date training program with a quantitative approach outlining physical principles and the mathematical basis of land-atmosphere interactions. Some of the most highly regarded researchers in the field were present, both teaching and interacting with the students. Sponsors of the school included the U.S. National Science Foundation, GEWEX and the European Geophysical Union. The program and presentations are available at *http://www.to.isac.cnr.it/aosta/index.html.*

Participants of the Alpine Summer School on Land-Atmosphere Interactions.

ECMWF Seminar on Physical Processes in Present and Future Large-Scale Models

ECMWF, Reading, UK
1–4 September 2015

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More than 80 scientists from around the world attended the Annual European Centre for Medium-Range Weather Forecasts (ECMWF) Seminar on the topic of "Physical processes in present and future large-scale models." Both early career scientists and experts benefited from the diverse range of presentations on the modeling of physical processes from leading scientists at ECMWF and internationally. Special emphasis was placed on the representation of physical processes in a modeling environment where resolution keeps increasing and where processes related to convection and orography are partially resolved. The link between large-scale variables and sub-grid scale processes is a key aspect of parameterizations, and the understanding of associated processes is increased through use of observations and high-resolution model simulations. The seminar was organized into sessions on radiation, convection, clouds, gravity waves, boundary layer, land surface processes, physics in data assimilation and uncertainty in verification. Each session covered fundamental aspects, process representation in large-scale models and evaluation.

The primary objective of radiative transfer schemes is to provide accurate broadband fluxes, which are then used to compute heating of the atmosphere and the surface. But these schemes must strike a balance between accuracy and computational efficiency, probably more so than any other physical parameterization in an atmospheric model. For example, it was shown that current codes are very accurate, but too expensive to run at full temporal and spatial resolution. In addition, the number of spectral intervals used in some schemes can be reduced as a trade-off for including phenomena that are the source of significant biases, such as 3-dimensional cloud effects and longwave scattering. The development of efficient codes to deal with high resolution on massively parallel computer architectures and accelerator hardware is an active area of research. Despite all of the progress in recent years, there are still considerable uncertainties in the Earth's radiation in global models (e.g., the Coupled Model Intercomparison Project Phase 5, CMIP5). This uncertainty is dominated by the input from clouds, aerosols and precipitation.

Convection is one of the processes that is already partially resolved in limited-area models, and will be increasingly resolved in future global models as more and more operational centers move towards nonhydrostatic model forecasts. Joint work done at ECMWF and Deutscher Wetterdienst (DWD) has established a scaling law for the convective mass flux over the range for which resolved convective motions are supposed to occur (10 km to 500 m), and preliminary work using this law at a 5 km equivalent spatial resolution is very promising in terms of precipitation and wind scores in both the tropics and extratropics. As an even longer term prospective, some operational centers are testing sub-kilometric regional scale simulations as test beds. Using a 100-m resolution nested model, it was shown that kilometric spatial resolution grids can lead to an underestimate of convective error growth rate. All of this work should help address the so-called "grey zone" issues, which are being increasingly faced in operational numerical weather prediction. Finally, recent work with super-parameterization was presented, and the improved representation of the Madden-Julian Oscillation (MJO) was highlighted. Currently, this approach is still deemed to be too expensive for operational applications, but with ever-increasing computing power, this method holds promise.

The representation of clouds in large-scale models varies considerably among both weather forecast and global climate models, and it is a significant source of uncertainty owing to the myriad feedbacks with other atmospheric processes. For example, relatively small changes in cloud radiative effects can result in significant feedbacks with substantial repercussions for the large-scale radiation balance. The presentations emphasized that both the representation of subgrid heterogeneity and microphysics require a unified approach involving dynamical, boundary layer and convective processes. Even though operational models are approaching cloud-resolving scales, there is still the need for subgrid representations at resolutions below 10 km. There is also a renewed emphasis on improving microphysical processes. Historically, the main scheme advances consisted of adding more hydrometeorology categories into the microphysical schemes; however, recently there has been a move towards adding more predictive information to the existing categories. Such schemes were shown to offer certain improvements while being computationally less expensive than the aforementioned schemes.

Gravity waves act as the restoring force in a stable stratified medium and are a prominent feature of the atmosphere affecting both the troposphere and the stratosphere through momentum transport and deposition. Their impact was demonstrated both from observational and modeling perspectives. As it turns out, most operational centers currently use conceptually similar gravity wave drag plus flow blocking schemes, but there is a need to improve such schemes. For example, the resolution of global models is now sufficient for resolving the propagation of certain gravity waves; however, the various sources and associated processes are not as well represented. It is expected that, in the future, schemes will be better constrained by observations and results from high-resolution models. For example, recent field campaigns have sought to better understand the vertical propagation of the wave energy generated by mountains in certain "hot spots" into the middle atmosphere.

The sessions on the boundary layer and land surface illustrated the interactive nature of the processes, and it has become increasingly evident that the land surface is a potentially important source of predictability on numerical weather prediction timescales. There are strong feedbacks between precipitation and evaporation, and between turbulent heat transport in the atmosphere and heat transfer in the soil and snow. The drag exerted by the surface on the atmosphere also has a strong impact on the atmosphere; however, the partitioning of the land surface drag between the orographic and boundary layer components differs considerably based on recent model intercomparison project results. There are even significant differences in the surface stress diurnal cycle among operational models. Large-scale circulations are sensitive to these parameterizations on forecast spatial and temporal scales; thus the need for improving the basic underpinning of such schemes was recommended. In terms of surface turbulent fluxes, research on extremes has shown that a dry anomaly in the soil is a necessary (but not sufficient) condition for a heat wave, and that there is predictability on the sub-seasonal timescale which is probably not fully exploited yet by state-of-the-art models. Another aspect of the boundary layer is the simulation of low clouds, which has strong implications for forecasting at all time ranges, and particularly for climate change. The difficulty is that such clouds interact strongly with small-scale turbulence, which is unresolved in current numerical weather prediction models. The subtropical stratocumulus-to-cumulus transition over subtropical oceans was highlighted as an area where improvements are needed in global models. Finally, the challenges of describing the processes that occur in the Arctic, specifically in the Arctic boundary layers, and their importance for the interaction with the surface were highlighted. The main challenges are surface heterogeneity, cloud radiative interactions and the frequently strong stably stratified boundary layer. These issues are being addressed, in part, by international boundary layer-surface model intercomparison projects, such as the GEWEX-sponsored GEWEX Atmospheric Boundary Layer Study (GABLS) Project that uses recent field campaign data.

The Seminar concluded with sessions on data assimilation, uncertainty and verification. There is an obvious synergy between verification and assimilation, because model errors can often be isolated through the systematic confrontation of the model with observations in the data assimilation system. This is increasingly the case with modern satellite observations that are sensitive to hydrometeors. Examples were shown of systematic errors that have an impact on the feedbacks relevant for El Niño forecasts. Talks were given on the estimation and representation of model error in ensemble systems and the modeling of meteorological processes in the transport of tracers. Finally, the application of linear models in 4-dimensional variational data assimilation was presented. The physical processes were shown to be important, but the limitations were illustrated too. For very high resolution, it may be necessary to consider alternative data assimilation techniques.

Erland Källén, the ECMWF Director of Research, closed the Seminar by noting that remarkable progress has been made in the modeling of the physical processes in the atmosphere and that exciting prospects for the coming years were offered at the meeting. Presentations and summaries are available at: *http://www.ecmwf.int/en/annual-seminar-2015*.

HyMeX Midterm Program Review and Perspectives—Report of the 9th HyMeX Workshop

Mykonos, Greece
21–25 September 2015

Philippe Drobinski[1], Véronique Ducrocq[2], Vassiliki Kotroni[3], Kostas Lagouvardos[3] and HyMeX Session Coordinators*

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The Hydrological Cycle in the Mediterranean Experiment (HyMeX; Drobinski et al., 2014) is a 10-year (2010–2020) GEWEX Hydroclimatology Panel (GHP) Regional Hydroclimate Project (RHP). Its objectives are to: (i) improve the understanding of the water cycle, with emphasis on extreme events, by monitoring and modeling the Mediterranean coupled system (atmosphere-land-ocean), its variability (from the event scale to the seasonal and interannual scales) and characteristics over one decade in the context of global change; and (ii) evaluate societal and economical vulnerability, and adaptation capacity to extreme meteorological and climate events.

The HyMeX 10-year Long Observation Period (LOP) began in 2010 and includes hydrometeorological and oceanic measurements from operational national weather and hydrological services, research hydrometeorological and oceanic observatories, and satellite (Drobinski et al., 2014) and social impact data (Llasat et al., 2013). The 2010–2015 Enhanced Observation Period (EOP) was primarily dedicated to the hydrological monitoring of flash floods (Braud et al., 2014). Two Special Observation Periods (SOPs) were organized in late 2012 and early 2013 with instrumentation deployment dedicated to heavy precipitation and flash floods (Ducrocq et al., 2014; Ferreti et al., 2014; Jansà et al., 2014; Bousquet et al., 2015; Davolio et al., 2015; Defer et al., 2015; Doerenbecher et al., 2015) and strong air-sea interaction and dense water formation (Estournel et al., in revision; Doerenbecher et al., 2015), respectively. Dedicated science teams were set up to organize and coordinate research activities in HyMeX (e.g., on water vapor, lightning, microphysics, flash floods, regional climate modeling, vulnerabilities), combining collected data and numerical modeling in the various Earth components at different time and space scales. For regional climate modeling, HyMeX has a joint initiative with the Mediterranean Coordinated Regional Climate Downscaling Experiment (Med-CORDEX, Ruti et al., 2015).

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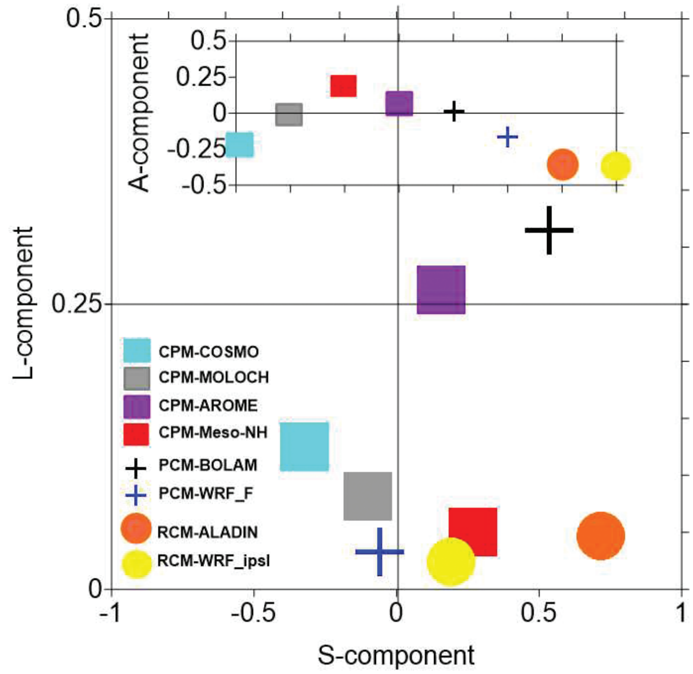
5-Year Review of HyMeX Achievements

More than 130 scientists from 11 countries participated in the 9th HyMeX Workshop to review the progress of HyMeX and define the remaining 5 years of the Project. With regard to the GEWEX Grand Challenges, HyMeX studies have led to significant progress in understanding the formation of heavy precipitating systems, notably over the Mediterranean Sea and the plains. Heavy rainfall in the coastal regions can have strong impacts in southeastern France and northern Italy, and show the key role of mountain ranges and islands. HyMeX field campaign observations have helped to design, improve and evaluate new tools and methods of forecasting heavy precipitation and flash floods (e.g., convection-permitting data assimilation and ensemble prediction systems). The figure on this page shows the seamless analysis of a heavy precipitation event in IOP-12, which extended from Spain to Italy during SOP-1. Numerical model simulations are compared with explicit Convection-Permitting Models (CPMs), Parameterized Convection Models (PCMs), or Regional Climate Models (RCMs). Heavy precipitation is characterized in a more bottoms-up approach with respect to the affected population and economic sectors in Spain, France, Italy and Greece. Studies in southern France investigated the evolution of urban management policies with respect to floods and model mobility/transportation. The evolution of heavy precipitating systems with climate change has also been investigated. In relation to the GEWEX crosscutting activity on subdaily precipitation extremes, observations and regional climate, HyMeX simulations show that the number and intensity of precipitation episodes across all of the Mediterranean increase by a few percent per degree of global warming.

Water management issues related to droughts, heat waves and other impacts have been addressed at several spatial scales (e.g., catchment scale in Morocco and Spain, and large scale for the entire Mediterranean region). The figure on page 22 shows how large yearly precipitation anomalies are "remembered" for 1-2 years into the future by the groundwater table, which suggests that the water table has more memory than soil moisture. These activities were covered in part in the GEWEX Land-Atmosphere System Studies (GLASS) Panel, where the network management of dams in North Africa was modeled,



Structure (S), Amplitude (A), Location (L) for the 24-hour (11 October 2012, 0600 UTC to 12 October 2012, 0600 UTC) mean precipitation simulation over northwestern Mediterranean (heavy precipitation event of IOP-12 that extended from Spain to Italy). The colored markers refer to the models (CPMs, PCMs, RCMs). The diagnostics are shown with respect to the CPMs ensemble mean upscaled to a coarser model resolution (approximately 20 km). Source: S. Khodayar, KIT, Germany.

allowing for the estimation of the impact of dams on water resources and their evolution in climate change constrained by offer/demand equilibrium. These studies showed the role of groundwater memory in precipitation deficit and its impact on hydrological droughts. Other studies analyzed the strong interlink between precipitation deficits, vegetation phenology and soil moisture variability on heat waves, droughts and wildfires. Soil dryness can contribute to the severity of heatwaves by up to 40%. Abundance or scarcity in vegetation can respectively mitigate or otherwise increase the severity of heatwaves by about 10%. Assimilation of vegetation characteristics (e.g., Leaf Area Index, Normalized Difference Vegetation In-

Participants at the 9th HyMeX Workshop.

dex) showed significant improvement on drought forecasting. Droughts were also characterized by indices defined in a bottoms-up approach of the Ebro River Basin scale. New climate projections confirm longer dry periods and more frequent heat waves in the Mediterranean with global warming.

The new knowledge related to the Mediterranean water cycle produced in the first 5 years of HyMeX has lead to the publication of more than 260 articles in international peer-reviewed journals and four special issues. About 400 researchers from 20 countries, as well as more than 110 Masters students, 70 PhD students and 20 post-docs have worked or are still working on HyMeX projects. In addition, HyMeX has contributed to the organization of four summer schools on severe weather and integrated water and society studies.

Planning for the Next 5 Years

Plans for HyMeX include more object-oriented studies with scale continuums (i.e., dense water formation and ocean circulation, Mediterranean cyclones, heavy precipitation systems, flash floods) and integrated transdisciplinary studies (e.g., water resources; droughts and impacts; water cycle and renewable energy resources; flash floods and social vulnerabilities and integrated forecasting of heavy precipitation, flash-floods and impacts). These studies will support a water cycle related regional climate assessment in 2020. HyMeX studies will benefit from the European Space Agency Water Cycle Observation Multi-mission Strategy (WACMOS)-MED Project to produce a new integrated satellite database of the Mediterranean water cycle over a multi-decadal period. Finally, discussions at the Workshop identified several strategic actions to be supported in the upcoming years, including field campaigns in the eastern Mediterranean focused on aerosols, water vapor feedbacks on precipitation and associated hydrology, and the documentation of Levantine intermediate waters of the Mediterranean Sea. These also include MED-CORDEX-2 preparation and organization and support for a flash floods and social impacts information and analysis platform. Securing data collection over the 10-year period and the outreach of the HyMeX research results are also of high priority.

References

Bousquet, O., et al., 2015. Multiple-frequency radar observations collected in southern France during the field phase of the hydrometeorological cycle in the Mediterranean experiment (HyMeX). *Bull. Am. Meteor. Soc.,* 96, 267–282.

Braud, I., et al., 2014. Multi-scale hydrometeorological observation and modeling for flash-flood understanding. *Hydrol. Earth Syst. Sci.*, 18, 3733-3761.

Davolio, S., et al., 2015. The role of the Italian scientific community in the first HyMeX SOP: An outstanding multidisciplinary experience. *Met. Zeit.*, in press.

Defer, E., et al., 2015. An overview of the lightning and atmospheric electricity observations collected in Southern France during the HYdrological cycle in Mediterranean EXperiment (HyMeX), Special Observation Period-1. *Atmos. Meas. Tech.*, 8, 649-669.

Doerenbecher, A., et al., 2015. Low atmosphere drifting balloons: Platforms for environment monitoring and forecast improvement. *Bull. Am. Meteor. Soc.*, in revision.

Drobinski, P., et al., 2014. HyMeX, a 10-year multidisciplinary program on the Mediterranean water cycle. *Bull. Am. Meteor. Soc.*, 95, 1063-1082.

Ducrocq, V., et al., 2014. HyMeX-SOP1, the field campaign dedicated to heavy precipitation and flash flooding in northwestern Mediterranean. *Bull. Am. Meteor. Soc.*, 95, 1083-1100.

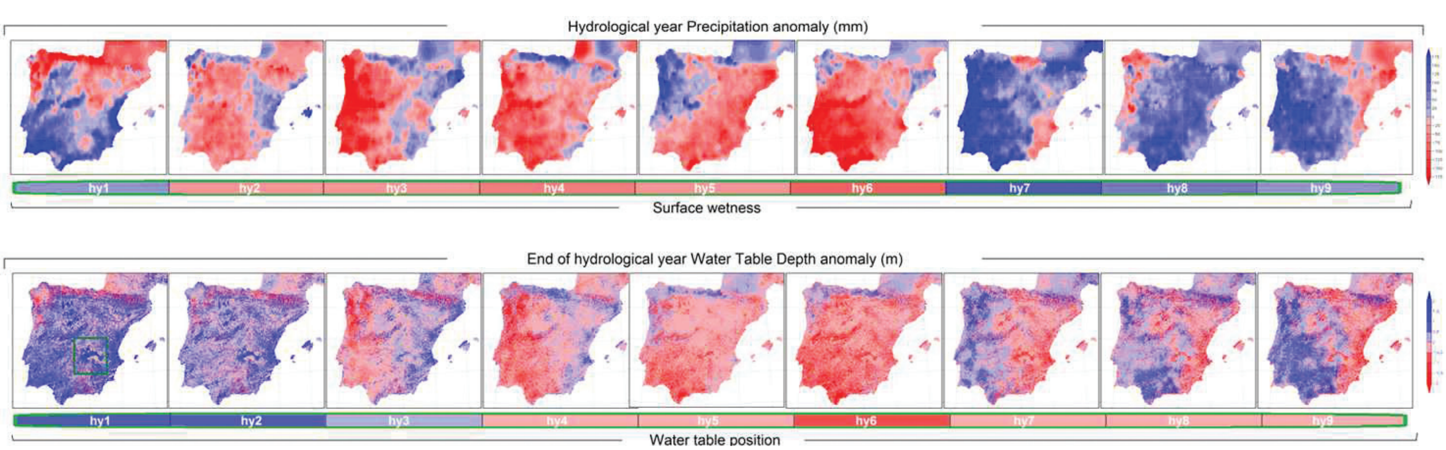
Estournel, C., et al., 2015. HyMeX-SOP2, the field campaign dedicated to dense water formation in the northwestern Mediterranean. *Oceanography*, in revision.

Ferretti, R., et al., 2014. Overview of the first HyMeX Special Observation Period over Italy: Observations and model results. *Hydrol. Earth Syst. Sci.*, 18, 1953-1977.

Jansà, A., J. Campins, M.A. Picornell, J.A. Guijarro, 2014. Heavy rain and strong wind events over Spain during HyMeX SOP1. *Tethys*, 11, 25-38.

Llasat, M.C., et al., 2013. Towards a database on societal impact of Mediterranean floods within the framework of the HyMeX project. *Nat. Hazards Earth Syst. Sci.*, 13, 1337-1350.

Ruti, P.M., et al., 2015. MED-CORDEX initiative for Mediterranean climate studies. *Bull. Am. Meteor. Soc.*, in press.



Yearly anomalies of soil moisture (first row) and water table depth (second row) calculated by the LEAFHYDRO model. Source: Alberto Martínez de la Torre and Gonzalo Míguez Macho.

First HyCRISTAL Workshop—Integrating Hydroclimate Science into Policy Decisions for Climate-Resilient Infrastructure and Livelihoods in East Africa

Kampala, Uganda
22–24 September 2015

John Marsham[1,2], David Rowell[3], Barbara Evans[1], Rosalind Cornforth[4], Fred Semazzi[5], Rob Wilby[6], Jackson Efitre[7], Kamazima Lwiza[8] and Richard Ogutu-Ohwayo[9]

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HyCRISTAL is a four-year project to develop an understanding of climate change and its impacts in East Africa and to work with the region's decision makers to provide a future that is more resilient to climate change. The HyCRISTAL Team and 29 partners from six countries attended the Workshop, which was opened by the Hon. Flavia Munaaba Nabugere, the Acting Minister for Water and Environment in the Cabinet of the Government of the Republic of Uganda, and closed by the Rt. Hon. Dr. Ruhakana Rugunda, the Prime Minister of the Republic of Uganda. Both delegates stressed the importance of the work for East Africa and their support for the project.

HyCRISTAL is part of the Future Climate for Africa (FCFA) Programme (*http://www.futureclimateafrica.org*), funded by the UK Department for International Development (DfID) and the UK Natural Environment Research Council (NERC). FCFA aims to develop both climate science for Africa and its use for decision making on a 5-40 year timescale. HyCRISTAL, which is supported by GEWEX, will work with the Lake Victoria Basin-Hydroclimate to Nowcasting Early Warning Systems (LVB-HyNEWS) Consortium, which consists of three components: the World Climate Research Programme (WCRP)/GEWEX Regional Hydroclimatology Project (RHP) Hydrology of the Lake Victoria Basin (HyVic) Study; the WMO Severe Weather Nowcasting Demonstration Project (LVB-SWNDP); and the East African Community (EAC) Nowcasting Early Warning Systems (NEWS) Project, which addresses weather and safety on Lake Victoria. LVB-HyNEWS is governed by EAC, the Lake Victoria Basin Commission and the National Meteorological and Hydrological Centres of the five EAC states, with the African Ministerial Conference on Meteorology (AMCOMET) as an observer.

East Africa has one of the world's fastest growing populations, and is experiencing rapid urbanization. Environmental problems include land degradation, pollution, over fishing and declining water resources, resulting in changing livelihoods. Climate change adds to these problems by increasing the vulnerability of the poorest. The impact of climate change on water resources, such as rainfall, lakes, rivers and groundwater, will be critical in East Africa, but projections of the future water cycle are highly uncertain. Climate projections show a warming trend in East Africa, but changes in rainfall are uncertain (Lyon and Dewitt, 2012; Shongwe et al., 2011; Rowell et al., 2015). The East African long rains have been observed to be decreasing in some areas, but Coupled Model Intercomparison Project (CMIP) models tend to predict an increase, although with some disagreement on the size and substantial disagreement on magnitude.

HyCRISTAL will work with users to characterize model projections for decision-relevant metrics of climate change in East Africa on a 5-40 year time-scale and will address the roles of aerosols, lake hydrology, urbanization and land-use in regional climate change. HyCRISTAL will also develop our un-

Left: Delegates and the Hon. Flavia Munaaba Nabugere, Acting Minister for Water and Environment, at the first HyCRISTAL workshop in Kampala. Right: Hon. Nabugere addresses the workshop.

derstanding of the reliability of projections for East Africa by determining the mechanisms that drive the changes in model projections, evaluating models and understanding recent decadal climate variability. The representation of convection is a key source of error in simulations of African climate (Marsham et al., 2013). HyCRISTAL will use new convection-permitting simulations from the Met Office-led Improving Model Processes for African Climate (IMPALA) FCFA Project to better understand the implications for projections.

HyCRISTAL will address the impacts of climate change for two key settings in East Africa: rapidly growing urban centers and their water supply and sanitation systems, and rural communities reliant on agriculture and fisheries. This requires underpinning work on climate impacts on lakes and lake ecosystems, groundwater and agriculture, as well as understanding vulnerabilities, decision-making governance structures and institutional influence. This work will feed into two key pilot studies using climate information for decision making for the 5-40 year time-scale in these two key contexts, and potentially additional smaller pilots as the project develops. The development impact and legacy of HyCRISTAL will be evaluated using frameworks such as that of Brooks et al. (2011) and the adaptation indicators of the Pilot Programme on Climate Resilience (PPCR) and Adaptation Fund (2011).

The HyCRISTAL consortium consists of the University of Leeds (*http://www.wateratleeds.org*); the African Centre for Technology Studies; the British Geological Survey; the Centre for Ecology and Hydrology (UK); Evidence for Development; Jomo Kenyatta University; Loughborough University; the Met Office (UK); the National Centre for Atmospheric Science (UK); the National Fisheries Resources Research Institute (Uganda); North Carolina State University; Practical Action; Stony Brook University; the Tanzanian Meteorological Agency; the Ugandan National Meteorological Authority; the Ugandan Ministry of Water Resources; the University of Connecticut; Makerere University; Maseno University; Walker Institute; and the University of Reading (Africa Climate Exchange).

References

Adaptation Fund, 2011. Project level results framework and baseline guidance document. Ethics and Finance Committee. 4th Meeting, Bonn, Germany.

Brooks, N., et al., 2011. Tracking adaptation and measuring development. IIED Climate Change Working Paper No. 1.

Lyon, B. and D.G. DeWitt, 2012. A recent and abrupt decline in East African long rains. *Geophys. Res. Lett.*, 39, L02702, doi:10.1029/2011GL050337.

Marsham, J.H., et al., 2013. The role of moist convection in the West African monsoon system - Insights from continental-scale convection-permitting simulations. *Geophys. Res. Lett.*, 40, 1843-1849, doi: 10.1002/grl.50347.

Rowell, D.P., B.B.B. Booth, S.E. Nicholson, and P. Good, 2015. Reconciling past and future rainfall trends over East Africa. *J. Clim.*, in press. doi: 10.1175/JCLI-D-15-0140.1.

Shongwe, M.E., et al., 2011. Projected Changes in mean and extreme precipitation in Africa under global warming. Part II: East Africa. *J. Clim.*, 24, 3718-3733, doi: 10.1175/2010JCLI2883.1.

GEWEX/WCRP Calendar

For the complete Calendar, see: http://www.gewex.org/

16–19 November—GEWEX Hydroclimatology Panel Meeting—Entebbe, Uganda

30 November–1 December—3rd Session of WCRP Working Group on Regional Climate—Norwich, UK

2 December 2015—Second Annual OzEWEX Workshop—Broadbeach, Queensland, Australia

14–16 December 2015—AGU Fall Meeting—San Francisco, CA, USA

10–14 January 2016—96th AMS Meeting—New Orleans, LA, USA

25–29 January 2016—GEWEX SSG-28 Meeting—Zürich, Switzerland

15–19 February 2016—Conference on Understanding Clouds and Precipitation Through Highly Resolved Process Modeling and Observations—Berlin, Germany

16–19 February 2016—SPARC Workshop on Stratospheric Change and its Role in Climate Predicition—Berlin Germany

2–4 March 2016—Global Climate Observations: The Road to the Future—Amsterdam, The Netherlands

2–4 March 2016—International Scientific Conference on MAHASRI—Tokyo, Japan

29 March–1 April 2016—Austin International Conference on Soil Modeling—Austin, TX, USA

5–15 April 2016—WWRP/WCRP/Bolin Centre School on Polar Prediction—Abisko Scientific Research Station, Sweden

17–22 April 2016—EGU General Assembly—Vienna, Austria

25–30 April 2016—31st Meeting of the Working Group on Numerical Experimentation (WGNE)—CSIR, South Africa

26–29 April 2016—14th BSRN Scientific Review and Workshop—Canberra, Australia

9–13 May 2016—2016 ESA Living Planet Symposium—Prague, Czech Republic

10–13 May 2016—Conference on Earth Observation and Cryosphere Science—Frascati, Italy

17–20 May 2016—CORDEX 2016: International Conference on Regional Climate Change—Stockholm, Sweden

30 July–7 August—41st COSPAR Scientific Assembly—Instabul, Turkey

16–18 September 2016—CLIVAR Early Career Scientists Symposium—Qingdao, China

16–23 September 2016—CLIVAR Open Science Conference—Qingdao, China

13–17 February 2017—International Symposium on Cryospheric Processes, Climate Drivers and Global Connections—Wellington, New Zealand