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SPECIAL ISSUE

Monsoons of the World: Addressing Global Challenges in Monsoon Research

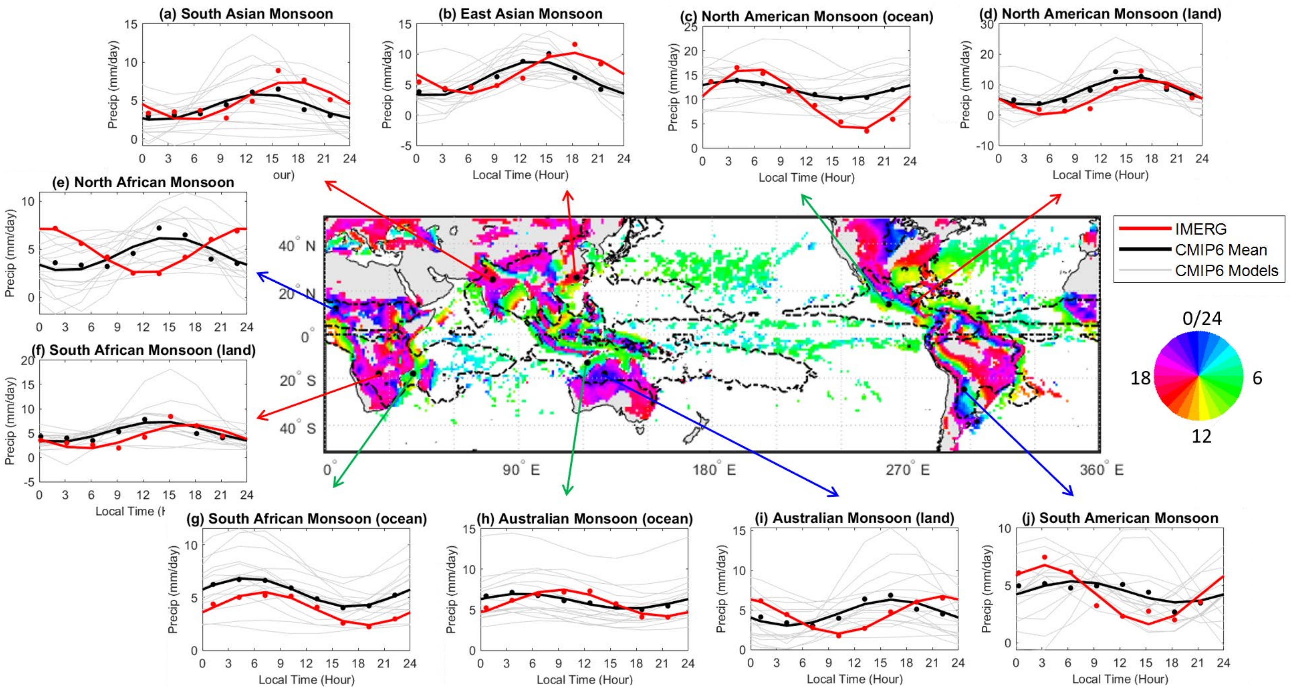

Figure 1 compares the diurnal cycle of precipitation simulated by GCMs that participated in CMIP6 with Integrated Multi-satellitE Retrievals for GPM (IMERG) data for ten selected locations in major monsoon regimes around the world. (Middle) Global diurnal harmonic phase [in local standard time (LST) of maximum precipitation] from IMERG data. The black dashed line indicates the monsoon regions defined from Wang et al. (2011): summer-winter rainfall greater than 2 mm/day and summer rainfall greater than 55% of annual rainfall. Here summer is May-June-July-August-September (MJJAS) in the Northern Hemisphere and November-December-January-February-March (NDJFM) in the Southern Hemisphere and winter is the same months in the other Hemisphere. (a–j) Diurnal cycle (dots) and the first harmonic (lines) of summer monsoon precipitation from IMERG and CMIP6 models at selected locations. The colors of the arrows pointing from the locations represent the different types of diurnal cycle: red represents afternoon peak over land, green represents morning peak over ocean, and blue represents nocturnal peak over land. See Xie et al. on page 8.

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Commentary and News

General

Monsoons Special Content

Commentary: Monsoons as a Cross-Cutting Focus Area for GEWEX and CLIVAR

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Monsoon systems are unique climatic features of our planet. They occur in all continents, with exception of Antarctica, and control the hydroclimate of large tropical areas of the Earth. Billions of people depend on the regularity of the monsoonal rains for agriculture, fresh water supply, energy, and transportation. Moreover, the abundant rainfall produced by summer convective systems over land controls soil moisture and the extent of wetlands and river flows, regulating carbon cycles and creating feedbacks. The alternating dry seasons are also critical in monsoon regions. Unique ecosystems and millions of species have adapted to the monsoon cycle, and so have all communities living in these regions. The dry season is when massive biomass burning occurs in monsoon areas, with impacts on the climate system that are still largely unknown.

While all monsoons are primarily driven by seasonal thermal contrasts between large land masses and surrounding oceans, they exhibit significant variability on daily-to-centennial timescales. For instance, the diurnal cycle of monsoonal precipitation is linked to the buildup of moist static energy and corresponding physical and dynamical mechanisms that enhance cumulus convection and organize mesoscale convective systems. These, in turn, influence soil moisture, leading to important feedbacks that maintain the diurnal cycle of convection throughout the wet season.

Nonetheless, after a monsoon is well established, prolonged periods of suppressed rainfall (or monsoon breaks) are often observed. Conversely, these droughts can alternate with persistent periods of moderate to strong precipitation (or active monsoon periods). The Madden-Julian Oscillation (MJO) appears as the most important tropical mode of intraseasonal variability that influences monsoon systems. Also relevant, the onset and duration of the rainy season, and consequently the total seasonal precipitation, can change from year to year, and the causes for this variability differ in each monsoon domain. The El Niño/Southern Oscillation (ENSO) is considered one of the most relevant coupled modes of interannual variability influencing global monsoon cycles. ENSO teleconnections can alter the basic state of the atmosphere and, consequently, the seasonal cycle of the monsoonal rains, including onset and active and break phases. These effects may depend on the characteristics of ENSO, including where the most pronounced sea surface anomalies occur and the timing when they occur.

Not only ENSO is responsible for large variations in monsoonal cycles on interannual timescales. Temperature anomalies over the Indian Ocean and the tropical Atlantic Ocean have also been recognized as having an impact on global monsoons. Moreover, coupled modes of variability and their respective teleconnections may change over time. Coupled modes with phases varying on decadal-to-multidecadal time scales such as the Pacific Decadal Oscillation, or more generically the Inter-Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation, among others, set the basic state of the atmosphere, modifying patterns of teleconnections that influence monsoon systems.

Observational and theoretical studies point to the undeniable fact that the Earth's climate is changing rapidly and anthropogenic activities have been an important component of this change. Extreme precipitation has been increasing worldwide, which includes monsoon regions. Internal natural coupled modes may either amplify or offset the influence of anthropogenic climate change and regional impacts have yet to be assessed. Adaptation to these extreme conditions will be more challenging for millions of people living in extreme poverty.

Farmers in monsoon regions count on the onset and regularity of the rains for sowing and harvesting. False onsets and prolonged breaks during the wet season may represent large failures in crop production, enhancing the number of undernourished people in at-risk communities who depend on the reliability of the rains for their survival. Conversely, the occurrence of extreme events, such as persistent heavy rains and floods, can disrupt lives, displace large communities from their homes, cause disease and death, and impoverish the most vulnerable. Predicting with accuracy not only the beginning of the rainy season but also how intermittent the rains will be, particularly early in the rainy season, can be critical for a successful crop and can signify economic relief for struggling nations that depend on the monsoon rains.

The capability of humanity to adapt to climate extremes and environmental catastrophes, as well as to reduce risks of famine and extreme poverty, is limited and can be solely achieved by coordinated actions between the science community, society, and decision makers. Climate and Ocean: Variability, Predictability and Change (CLIVAR) research into ocean-atmosphere interactions on multiple spatiotemporal scales aligned with Global Water and Energy cycle Exchanges (GEWEX) activities focusing on land-atmosphere interactions and convective scale processes represent an invaluable contribution to improving predictability of the global monsoons. Moreover, critical progress has been achieved towards a better understanding of monsoons systems at fine and global scales through the CLIVAR-GEWEX cross-cutting foci.

These initiatives have been encouraged through numerous activities carried out by the CLIVAR/GEWEX Monsoons Panel. These include fostering concrete actions to be undertaken in the coming years by international research groups and encouraging the coordination of regional research groups that can establish local priorities with the main goal of advancing understanding and improving predictability of regional monsoon systems.

In the spirit of the joint CLIVAR/GEWEX focus on the monsoons, CLIVAR has published a special issue of *CLIVAR Exchanges* with the theme "India's Monsoon Mission" (*http://www.clivar.org/documents/exchanges-79*). The CLIVAR/GEWEX Monsoons Panel is also closely collaborating with the World Weather Research Programme to organize the 7th International Workshop on the Monsoons (IWM-7), expected to held in India in early 2022.

YESS's First Strategic Action Plan

Carla Gulizia[1] and the YESS Executive Committee
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> *The Young Earth System Scientists (YESS) community strives to help shape the future of Earth system science by fostering international and transdisciplinary leaders of tomorrow who pioneer the development and delivery of research and knowledge, which provide solutions to benefit society, towards a more equitable and sustainable future.*

This is the YESS vision outlined within our recently-developed Strategic Action Plan (SAP, *https://www.yess-community.org/2020/10/19/yess-new-strategic-action-plan/*). To continue to build a strong early career researcher (ECR) community, the SAP's authors intend the text to be a living document, updated by YESS members every few years to propose ways to implement YESS's vision, mission, and plans for up to a decade into the future. The development of the SAP is a product of collective work and joint effort over the last two years. Current and past YESS members, as well as key partners*, were consulted about the role of YESS in the Earth system science community. YESS has now its first SAP, which includes clear strategic objectives and implementation actions.

To understand how YESS could create a virtual environment to support ECR development and success during the current pandemic and in the future, YESS has designed and distributed a survey in which ECRs from all over the world shared the experiences and challenges they have been facing during these difficult times. After a careful analysis of the 197 responses received, the recently-published YESS COVID-19 report (*https://www.yess-community.org/yesscomm_wp/wp-content/uploads/2020/11/REPORT-FINAL-COVID.pdf*) summarizes the common challenges ECRs are facing and made recommendations on how to build a supportive environment that facilitates sustainable development for ECRs in the post-pandemic world. Although the report focuses on ECRs, it is also relevant to the broader scientific community.

To support continuous professional development for ECRs during the pandemic, the YESS Online Events and Science Working Groups remain very active in organizing online activities such as the second edition of the YESS Science Webinar Series (*https://www.yess-community.org/science-webinar-climate-change/*), the YESS and High Impact Weather (HIW) Project webinar series (*https://www.yess-community.org/yess-hiweather-webinar-series/*), and the Webinars for South American ECRs (*https://www.yess-community.org/south-american-webinars/*). The webinars are freely available at *https://www.youtube.com/channel/UCWtMqkIEDiViIWFnzCqeJ1g/featured*.

As we start to implement our latest strategic plans, we are looking forward to further engagement with the GEWEX community's projects and activities.

**We gratefully received constructive comments from the scientific leadership of the WMO, particularly WWRP, the Global Atmospheric Watch (GAW), and the World Climate Research Programme (WCRP). WCRP core projects Stratosphere-troposphere Processes And their Role in Climate (SPARC) and GEWEX also contributed, along with Future Earth, Transdisciplinary Research-Oriented Pedagogy for Improving Climate Studies and Understanding (TROP ISCU), the Pan African University Institute of Water and Energy Sciences (PAUWES), and our honorary members.*

The AGU Hydrology Section Student Subcommittee (H3S) Leads Effort to Bring Justice, Diversity, Equity, and Inclusion (JDEI) to the Hydrology Section

Leila Saberi
AGU H3S Chair

With the support of the American Geophysical Union (AGU) Hydrology Section leadership and the AGU Diversity and Inclusion Advisory Board, the AGU-H3S members set forth a series of goals and action items outlined in a white paper to foster a more Just, Diverse, Equitable, and Inclusive community. We invite you to comment on the white paper, which can be found at *https://z.umn.edu/AGU-H3S-WhitePaper*, and provide feedback on the goals including what changes you would like to see made within the Hydrology Section and the broader AGU. To sustain the effort for years to come, we will be holding biannual meetings for the community to celebrate achievements, discuss progress, and add to the goals through an open forum and online surveys. The first meeting was held as a town hall at the 2020 AGU Fall Meeting and the updated version of the white paper will be published on the AGU-H3S website.

As part of the H3S mission to promote and highlight the success of students and early career hydrologists, we feature cutting edge research conducted by them in a way that is accessible to the broader hydrological and Earth science community. We provide students and early career hydrologists the opportunity to write about their research in a language that is easily understandable to the larger community. To receive more information on how to have your research featured by the AGU-H3S, reach out to us at h3s.agu@gmail.com.

This fall, we teamed up with the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) and organized our fall cyber-seminar series on "Navigating Academic Waters: Essential Skills to Thrive as a Student and Early Career Scientist". Our September cyber-panel was focused on the pervasiveness of impostor syndrome in academia and how to overcome this challenge. A recording of this panel discussion can be found here: *https://z.umn.edu/AGU-H3S-Panel-YouDoBelong*. Follow us on Twitter (@AGU_H3S) to stay up to date with our events.

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Save the Date for the 3rd Pan-GASS Meeting: Understanding and Modeling Atmospheric Processes

Monterey, CA, USA
18–22 October 2021

GASS Travel Awards Competition on Analysis of Global Storm-Resolving Models and ARM Observations for Early Career Researchers

Daniel Klocke[1], Shaocheng Xie[2], Jim Mather[3], Julia Duras[4], Florian Ziemen[4], Xubin Zeng[5], and Peter van Oevelen[6]

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We are happy to announce the 3rd Pan-Global Atmospheric System Studies (GASS) Conference. Please save the dates of 18–22 October 2021 for the next Understanding and Modeling Atmospheric Processes (UMAP) meeting in Monterey, California, USA. The purpose of the conference is to discuss progress in research supporting atmospheric and related model development, coordinate current GASS initiatives, and plan future projects.

As part of this conference, here we announce a data analysis competition for Early Career Researchers (ECRs)–undergraduate or graduate students or scientists who have received their highest degree within the past seven years (up to one year of parental leave time may be added per child, where appropriate). By providing a scientific analysis involving at least one of the two unique data sets listed below, ECRs have the chance to win a travel award to support their attendance at the conference and give an oral presentation about their work.

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program is one of the largest field programs in the world. The ARM data over the past three decades have provided a unique observational basis specifically for understanding aerosol, cloud, radiation, and precipitation-related processes and their interactions and evaluating and improving their representations in climate models, particularly through process-level studies. The ARM data are available at: https://www.arm.gov/data.

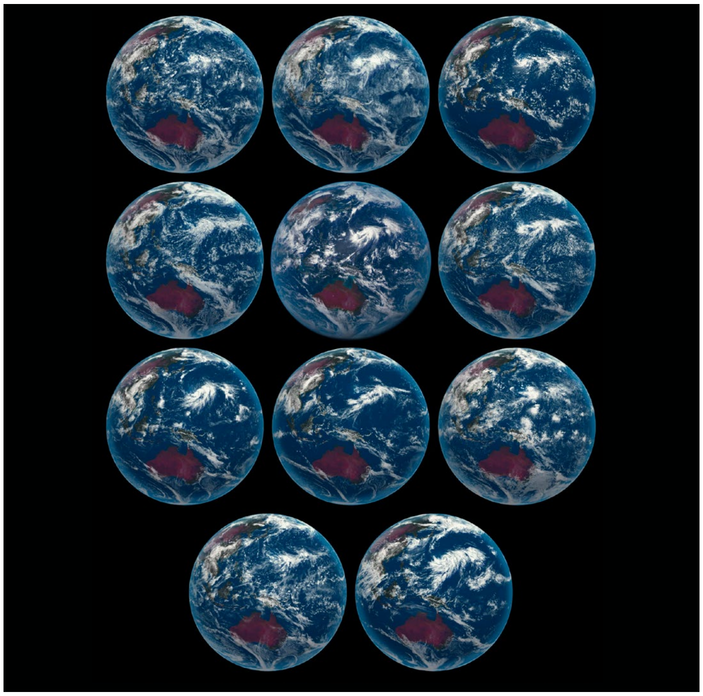

Figure 1. The view of the Earth as seen from space by the Himari-8 satellite (second row center) on the 4th of August 2016 and alternative worlds created by the DYAMOND models 78 hours into the simulation (figure from Stevens et al., 2019[1]).

The DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) Initiative has produced 40 days of simulations from the first of August 2016 by global storm-resolving models with a horizontal grid size < 5km. Now, in the second, currently ongoing phase, participating models, including coupled atmosphere-ocean models at storm- and ocean eddy-resolving resolutions, simulate 40 days starting on the 20th of January 2020, also covering the Elucidating the Role of Clouds-Circulation Coupling in Climate (EUREC4A) field experiment. To share the excitement about the possibilities these models offer, the DYAMOND data and resources for post-processing are available to the community at the German climate computing centre (DKRZ) via the European Union Horizon 2020 Project (ESiWACE2) at: https://www.esiwace.eu/services/dyamond/phase-2.

Submissions to the competition should consist of a single plot accompanied by a one-page description of the analysis and the result, due by 31st May 2021. As data amounts are substantial and data transfer is impractical, if not impossible, for the DYAMOND data, post-processing resources are provided for this competition at DKRZ. We expect one prize for the best analysis involving the DYAMOND models, up to three for analyses using ARM products in either observational or modeling studies, and additional prizes from the World Climate Research Programme (WCRP)/GEWEX and other agencies for any analyses (including those using ARM data or DYAMOND outputs) or modeling by ECRs.

More information about this conference and competitions above will be available shortly on the GEWEX Events website at http://www.gewexevents.org/ and circulated via the GEWEX and other mailing lists.

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[1] Stevens et al., 2019. DYAMOND: The DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains. *Prog. Earth Planet Sci.* **6**, 61. https://doi.org/10.1186/s40645-019-0304-z.

Overview of Rainfall Metrics for the Assessment of Model Simulations of the Monsoons: Current Status and Future Perspectives

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Despite the importance of monsoon systems, weather and climate models struggle to represent the complex interacting processes that comprise them. Forecasting monsoon rainfall on sub-seasonal and seasonal timescales continues to be a challenge and there is also considerable uncertainty as to how monsoon rainfall will change in a future climate.

Countries that depend on monsoon rainfall for their water supplies have often developed bespoke metrics for monitoring rainfall over many decades. These are often regional averages derived from a network of rain gauges (e.g., All-India Rainfall: Parthasarathy et al., 1994). National meteorological services in monsoon-dominated countries usually provide rainfall monitoring alongside their forecasts throughout the monsoon season [e.g., Indian Meteorological Department Pune Southwest Monsoon Monitoring: *http://www.imdpune.gov.in/Seasons/Pre_Monsoon/premonsoon.html*; The East Asian Monsoon Activities Centre: *http://bcc.ncc-cma.net/EAMAC/index.php*; National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center Global Monsoons: *https://www.cpc.ncep.noaa.gov/products/Global_Monsoons/Global-Monsoon.shtml*; Tokyo Climate Centre Asian Monsoon Monitoring: *https://ds.data.jma.go.jp/tcc/tcc/products/clisys/ASIA_TCC/index.html*].

Regular assessments of regional monsoon rainfall simulation in climate models are carried out in conjunction with Coupled Model Intercomparison Project (CMIP) activities (e.g., Gusain et al., 2020; Xin et al., 2020; Moise et al., 2015; Geil et al., 2013; Roehrig et al., 2013). Forecasting centers in monsoon regions also carry out regular assessments of skill on a range of timescales (e.g., Jones et al., 2012; Sahai et al., 2015; Prakash et al., 2016; Joseph et al., 2019; Jain et al., 2019). In many cases, the basic metrics used for rainfall monitoring and evaluation are calculated on seasonal mean timescales and large spatial scales. Standard metrics used for evaluating monsoon rainfall in climate models include:

- Regional, seasonal averages: country-wide, "homogeneous regions" (e.g., Parthasarathy et al., 1995; Das and Akhter, 2019), and district-level;
- Pattern correlation coefficients (PCC), normalized root-mean-square errors (RMSE), threat scores (TS) (e.g., Li et al., 2020);
- Onset, withdrawal, and duration (e.g., Wang and LinHo, 2002; Joseph et al., 2015);
- Seasonal and diurnal cycle (e.g., Wang et al., 2011); amplitude and spatial coverage of global and regional monsoon domains (Wang and Ding, 2008);
- Intra-seasonal modes: boreal summer intra-seasonal oscillation (BSISO) (Lee et al., 2013), the Madden–Julian Oscillation (MJO) (see review in Kim et al., 2018), and active-break cycles [monsoon intra-seasonal oscillation (MISO); e.g., Suhas et al., 2012];
- Interannual standard deviation; and
- Teleconnections with sea surface temperatures (e.g., Roy et al., 2019).

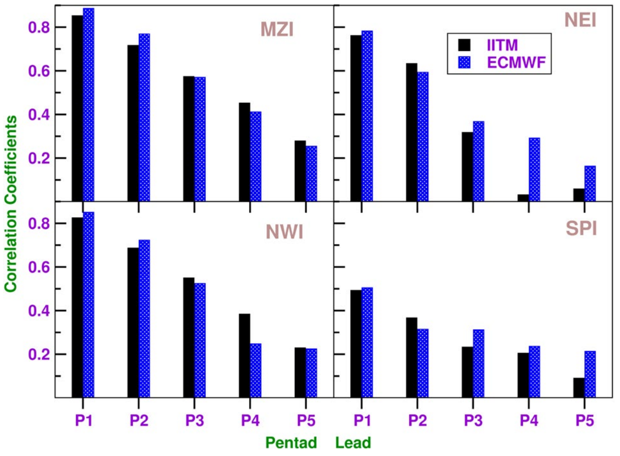
Many such metrics are incorporated in software packages such as the Earth System Model Evaluation Tool (ESMValTool) (Eyring et al., 2016) that are freely available for use by climate modeling groups.

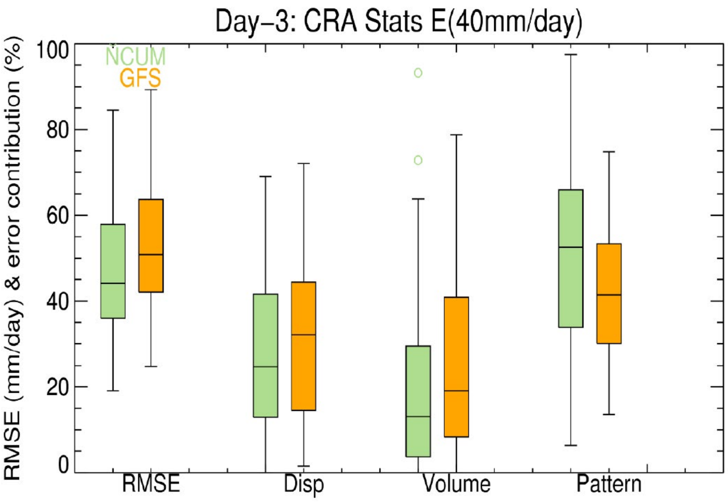
On seasonal timescales, percentage of rainfall departure from long-term seasonal mean rainfall over India and homogeneous regions is taken as one of the primary metrics to assess the skill of the model in predicting the seasonal rainfall by the India Meteorological Department (e.g., Pillai et al., 2018). As rain is one of the most challenging variables to predict, several studies have proposed using different circulation indices as a proxy for monsoon rainfall [e.g., zonal (Webster and Yang, 1992) or meridional (Goswami et al., 1999) wind shear indices].

On intra-seasonal time scales, predicting active and break cycles of monsoon rainfall over India is one of the recent success stories of extended range forecasting (Abhilash et al., 2014). The primary metrics used for evaluating the extended range forecasts are the amount of rainfall over different homogeneous regions of India (e.g., Fig. 1a), as well as MISO indices (MISO1 and MISO2), which are the principal components computed by projecting the multi-model ensemble (MME) forecast and observations onto the extended empirical orthogonal functions (EOFs).

Verification of short- and medium-range precipitation forecasts is carried out using dichotomous, multi-category, continuous, and spatial verification methods (e.g., Sharma et al., 2019). Some of the commonly used metrics are probability of detection (POD), false alarm ratio (FAR), equitable threat score (ETS), and the Peirce skill score (PSS). Additionally, for extreme and rare events, the symmetric external dependency index (SEDI) is used. From among the spatial verification methods, contiguous rain area (CRA) is regularly used at NCMRWF to quantify the precipitation spatial errors. The CRA method allows decomposition of the total error into contributions from errors in pattern, volume, and displacement (e.g., Fig. 1b). Verification of probabilistic quantitative precipitation forecasts is presented using the Brier Score and Brier Skill Score, Relative Operating Characteristic and Reliability Diagrams (e.g., Joseph et al., 2019; Jones et al., 2012).

There is also a need for more complex metrics and diag-





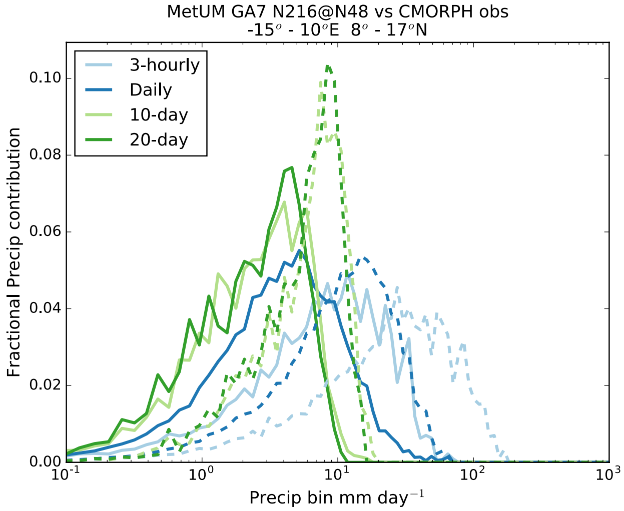


Figure 1. (a) Comparison of correlation skills of Indian Institute of Tropical Meteorology (IITM) MME and a European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble forecast for four homogeneous regions of India (Source: Chattopadhyay et al., 2018). (b) CRA verification: summary of RMSE and the contributions to total error from displacement, volume, and pattern errors in forecast rainfall [National Centre for Medium Range Weather Forecasting (NCMRWF) Unified Model (NCUM) and Global Forecasting System (GFS)] of 40mm/day threshold over eastern India during June to September (JJAS) 2018 (Source: NCMRWF). (c) Analysis of fractional contributions to total mean JJAS rainfall over West Africa from intensities at different timescales in a Met Office Unified Model (MetUM) simulation (solid) compared with CPC MORPHing technique (CMORPH) observations (dashed) (Source: Met Office).

nostics exploring different aspects of monsoon rainfall so that model errors can be traced back to deficiencies in their resolution, complexity, or physical parameterizations. Following the terminology suggested by Pendergrass et al. (2020), some of these may be described as "exploratory" metrics: diagnostics-oriented metrics that "target critical precipitation-related characteristics and processes that are actively being researched but to date lack widely adopted measures for established benchmarking". Examples of such metrics include:

- Monsoon low pressure systems (LPSs) and depressions (e.g., Hurley and Boos, 2015; Hunt et al., 2016; Srivastava et al., 2017)
- Monsoon "burst" events (e.g., Moise et al., 2020)
- Convective vs. large-scale rainfall (e.g., Pathak et al., 2019)
- Rainfall intensity and coherence metrics (e.g., Klingaman et al., 2017; Moron and Robertson, 2020).

Seasonal rainfall amounts include, by definition, all rainy events and may be considered the most comprehensive metric for local rainfall variations. However, this does not necessarily imply that amount is the optimal variable to predict. Decomposing seasonal (or any temporal) aggregation into frequency and intensity, and further decomposing the frequency component by considering (1) the phase of the season with its onset and withdrawal, and (2) the length and number of wet/dry spells, can allow the predictable (vs. the noisy, unpredictable) signal of the season as a whole to be conveyed. A complementary approach is to look at the spatial coherence of rainfall anomalies, assuming that predictable signals must be spatially coherent at a regional scale. A poor-to-moderate predictability may arise due either to the large impact of high intensity and localized events, as for most of India, or to the lack of temporal synchronization of rainy events by sub-seasonal to interannual large-scale modes of variation and the huge control of the diurnal cycle, as in central and western equatorial Africa (Moron and Robertson, 2020; Martin et al., 2017; Fig. 1c). Understanding model errors at this level of detail provides essential information for model developers.

Accurate simulation and forecasting of monsoon precipitation are an ongoing challenge for modeling groups. Monsoons are emergent phenomena whose seasonal total rainfall is a result of modes of variability on a range of time and space scales. The range of modes with their different drivers, and the ability of each to change rainfall amounts and distribution significantly, make achieving the correct climatological distribution of rainfall difficult. Standard metrics for precipitation evaluation do not generally lend themselves to aiding model development. More "exploratory" metrics are now being developed to address this, but there is a need for further development of metrics and diagnostics that target common systematic biases and scale interactions at the process level, to inform parameterization development.

Furthermore, there is a need for high-quality, high-frequency observations with good spatial resolution. Coordinated air, land, and sea field campaigns [e.g., Interaction of Monsoon Precipitation and Convective Organization, Atmosphere, Surface and Sea (INCOMPASS): Turner et al., 2019; African Monsoon Multidisciplinary Analysis (AMMA): Polcher et al., 2011] help to provide local, process-level observations in specific regions, although they are usually time-limited. The continual availability, maintenance, and documentation of good observational data sets for evaluation is essential. Central archives exist [e.g., the Observations for Model Intercomparisons Project (Obs4MIPS); *https://esgf-node.llnl.gov/projects/obs4mips/*] but higher spatial and temporal resolutions and long timeseries are also needed. We also encourage observational experts to publish critical evaluations of such data sets for use by the modeling community so that a reliable benchmark can be established.

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**The full list of references can be found at* https://www.gewex.org/gewex-content/uploads/2020/12/Q42020_Martin_References.pdf.

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Improving the Simulation of Diurnal Precipitation over Monsoon Regimes

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The Challenge

Monsoon precipitation exhibits strong diurnal variations with distinct regional features (Johnson, 2011). In general, it peaks in late afternoon or early evening over land in response to surface solar heating, and in early morning over the adjacent ocean areas caused by more complicated mechanisms including the coupling of radiative-dynamical processes and gravity wave propagation. In addition, a dominant nocturnal peak of precipitation is also found downstream of major mountains like the Rocky Mountains, the Andes, and the Tibetan Plateau associated with the propagation of mesoscale convective systems (MCSs). Daytime maxima in rainfall are often seen over the Bay of Bengal, the South China Sea, and the Gulf of Guinea, likely due to seaward propagation of convection from adjacent coastlines.

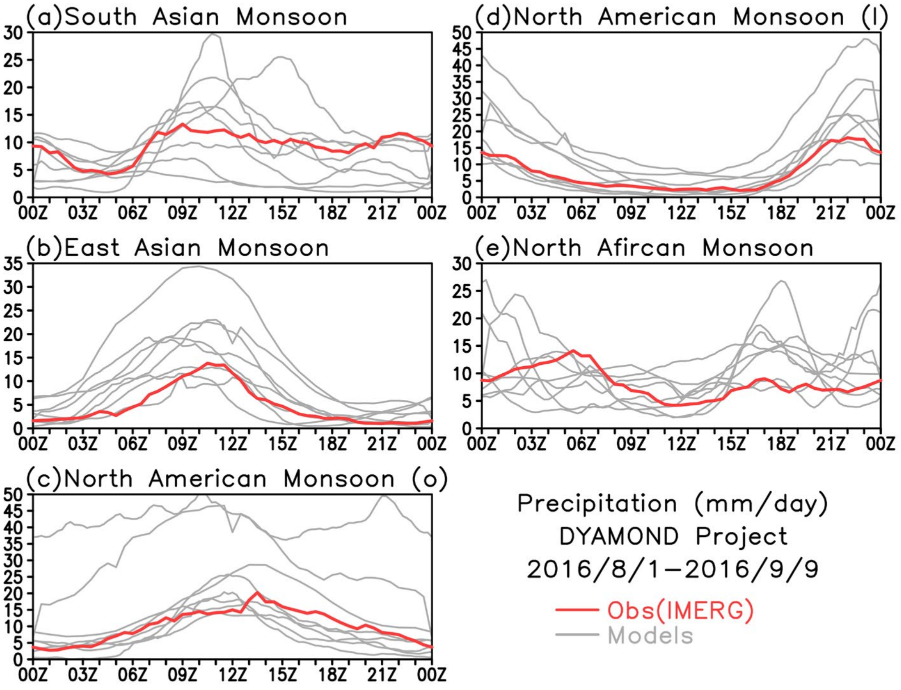

Figure 2. Diurnal cycle of precipitation (mm day^{-1}) at five (a–e) selected monsoon regimes from the DYAMOND project. "(o)" and "(l)" on panel (c) and (d) represent "ocean" and "land" areas. The simulation period is from August 1 to September 9, 2020. The time (x-axis) is in UTC.

The complexity of the underlying physical processes controlling diurnal precipitation variations in the global monsoon system has posed a great challenge for weather and climate models to accurately represent dominant monsoon precipitation behavior (Dai, 2006). Over land, most models tend to rain too early after sunrise with a rainfall maximum around the local noon rather than the observed late afternoon-early evening peak, and they fail to capture the nocturnal peak observed in many regions. Over ocean, many global climate models (GCMs) simulate the precipitation maximum a few hours earlier than the observed early morning peak. These model errors have been persistent across many generations of GCMs despite tremendous efforts made in the community to improve weather and climate modeling over the years.

As an example, Figure 1 (see cover) compares the diurnal cycle of precipitation simulated by GCMs that participated in the sixth phase of the Coupled Model Intercomparison Project (CMIP6) with the Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG) data for ten selected locations in major monsoon regimes around the world. The ten locations represent the three typical features of diurnal cycle observations: an early morning peak over ocean, a late-afternoon to early-evening peak over land, and a nocturnal peak related to propagating convective systems. The long-standing model errors in simulating diurnal cycle precipitation remain in these most recent climate models. Although individual model performance varies, the CMIP6 ensemble mean peaks a few hours too early over both the ocean points and the land points (with a late-afternoon to early-evening peak) and it totally misses the nocturnal peaks at the selected locations in North African Monsoon, Australian Monsoon, and South American Monsoon regimes.

Progress

Problems in simulating the diurnal cycle of precipitation in GCMs are primarily due to shortcomings and deficiencies in representing convection initiation, evolution, and propagation, as well as the interaction between convection and its large-scale atmospheric environment and the underlying land surface. For example, the failure of capturing nighttime convection may be due to the poor treatment of elevated convection initiation in cumulus parameterizations (Xie et al., 2019). It is also highly likely that certain biases in the diurnal cycle arise from errors in how convection onsets respond to the diurnal cycle of the large-scale environment, including dependence on lower free tropospheric water vapor, and mesoscale organization. It has been suggested that the interaction between water vapor in the lower free troposphere and moisture convection, mainly by way of entrainment processes (Holloway and Neelin, 2009), is a primary control on the onset of deep convection.

One way to address the challenge would be to further increase model resolution to a grid spacing such that convective structures can be mostly resolved. This is feasible in the near future through the ongoing developments of global storm-resolving modeling capabilities on exascale computers in several modeling centers. Earlier studies have demonstrated some encouraging improvements in representing the diurnal cycle of precipitation, in particular its amplitude, in simulations with convection explicitly resolved (Dirmeyer et al., 2012; Pearson et al., 2014). However, results are resolution-dependent (Yashiro et al., 2016). In general, models may need to run at a resolution higher than 2 km in order to reasonably capture the phase of the diurnal cycle of precipitation. Figure 2 presents the mean diurnal cycle of precipitation in selected monsoon regimes from a recent global storm-resolving model intercomparison project (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains, DYAMOND, Stevens et al., 2019). The horizontal resolutions for these models are somewhere between 2.5 km to 5 km. The peak hours of the mean diurnal cycle of precipitation from many models are much closer to the observed peak hours and they are superior compared to those in the CMIP6 GCMs. The precipitation magnitudes, however, still vary significantly across the models. Therefore, increasing model resolutions to storm-resolving scales can improve simulations of the diurnal cycle of precipitation in some respects, but not all the biases seen in the low-resolution GCMs can be fully resolved.

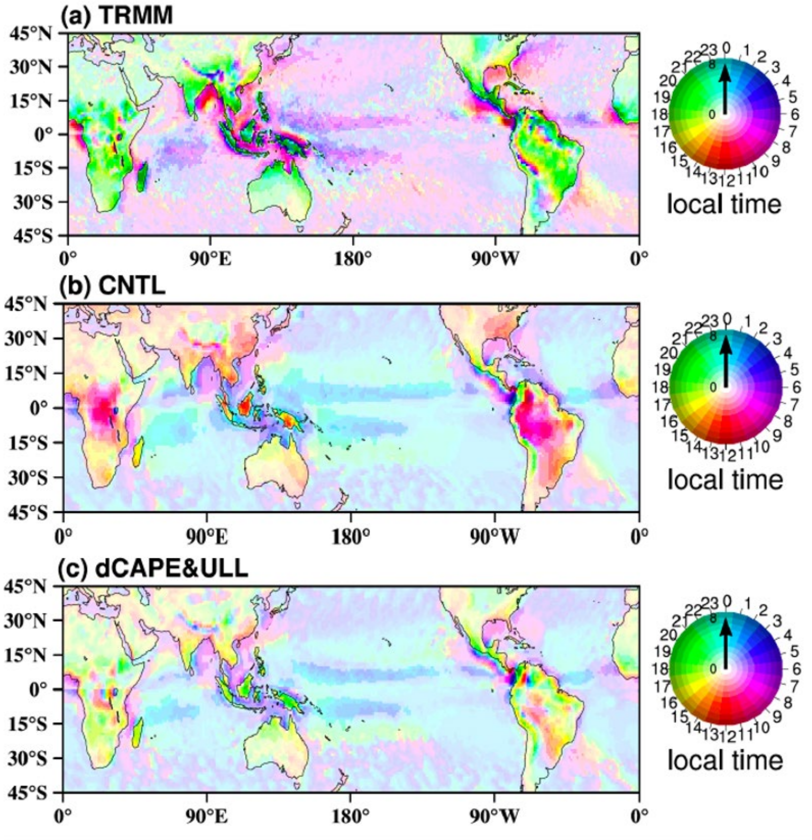

Figure 3. Timing phase (color) and amplitude (color density) of the first diurnal harmonic of total precipitation (mm/day) for summer monsoon systems from ten years of 3-hourly averaged data for (a) the Tropical Rainfall Measuring Mission (TRMM), (b) CNTL, and (c) dCAPE&ULL.

At the same time, improving the representation of cloud and convective processes in GCMs at 25 km to 100 km grid spacing continues to be important not only for better understanding the processes important to the weather and climate phenomena that GCMs attempt to simulate, but also for improving long-term projections of climate changes for which global convection-permitting simulations will not be ready in the foreseeable future. In the past decade, significant efforts have been made to improve the modeling of the diurnal cycle of precipitation. It has been found that model maximum precipitation over land can be delayed from midday to late afternoon through relaxing the unrealistically strong coupling of convection with surface heating, as assumed in many convection parameterizations. This can be done by directly linking convection initiation and closure to large-scale dynamic processes such as vertical velocity and advective cooling and moistening (e.g., Xie and Zhang, 2000; Zhang, 2003; Bechtold et al., 2004) or linking them to sub-cloud lifting processes such as boundary thermals and gust fronts (Rio et al., 2009), as well as making model convection more sensitive to environmental moisture (Bechtold et al., 2008). The nocturnal precipitation peak can be largely captured by allowing air parcels to launch above the planetary boundary layer (PBL) to capture elevated mid-level convection, which often occurs at night above a very stable PBL associated with the passage of mesoscale convective systems (MCSs) or other large-scale disturbances (Lee et al., 2008; Xie et al., 2019). This has been further supported by Tang et al. (2020), which analyzed the diurnal cycle of precipitation represented in CMIP6 models. A common feature found in Tang et al. (2020) in the limited number of models that simulate the nocturnal precipitation peak well is the ability to capture mid-level convection.

Figure 3 provides an example to demonstrate that the diurnal cycle of precipitation could be considerably improved through improving model physics. The figure shows diurnal precipitation over the global monsoon regimes simulated by the U.S. Department of Energy (DOE) Energy Exascale Earth System Model (E3SM) Atmosphere Model version 1 (EAMv1) (Rasch et al. 2019) with and without a new trigger [dynamic convective available potential energy (dCAPE) and unrestricted air parcel launch level (ULL), dCAPE&ULL] proposed by Xie et al. (2019). The dCAPE&ULL trigger introduces a dynamic constraint on the initiation of convection that emulates the collective dynamical effects to prevent convection from being triggered too frequently, as well as allows air parcels to launch above the PBL to capture nocturnal elevated convection. In observation, the diurnal cycle of precipitation typically exhibits a late-evening to midnight peak over tropical lands and an early morning peak around 0500–0700 LST over the oceans. The default model (control forecast, CNTL) fails to capture the late-evening to midnight peak. Instead, it produces maximum precipitation between 1000 LST and 1300 LST over most of the land areas. This problem is largely reduced with the dCAPE&ULL trigger, which simulates the timing of the maximum precipitation between late afternoon and late evening over most of the land, much closer to the observed. It has been found that allowing atmospheric instability above the PBL to be detected is a key for dCAPP&ULL to capture the nocturnal peak in the monsoon regimes. Over the tropical ocean, however, all the simulations show a similar precipitation maximum near midnight to early morning (0001–0300 LST) over the tropical ocean, a few hours earlier than the observations. In addition, the amplitude of the simulated diurnal cycle of precipitation is much weaker than the observed.

Ongoing GEWEX-GASS Effort

Despite this progress, continued efforts from the community are still needed. The GEWEX Global Atmospheric System Studies (GASS) Panel has recently launched a new project that aims to improve the simulation of the diurnal cycle of precipitation in weather and climate models: the GASS Diurnal Cycle of Precipitation (DCP) project (*http://portal.nersc.gov/project/capt/diurnal/*). A hierarchy modeling approach including single-column models (SCMs) and cloud-resolving models (CRMs), large-eddy simulation models (LESs), regional convection permitting models, and GCMs is being used in the multimodel intercomparison study to diagnose and investigate the associated processes and model biases in depth. The research themes include:

- Interaction between convection and water vapor
- Nocturnal convection over land
- Diurnal cycle of convection over ocean
- Convection transition

The goal is to (1) understand what processes control the diurnal variation of precipitation over different climate regimes in observations and models; and (2) identify the deficiencies and missing physics in current GCMs to gain insights for further improving the parameterization of convection in GCMs. The project has attracted more than 20 modeling groups around the world to participate in studies that focus on using different modeling approaches for these research topics.

This is a multi-year research project. The current emphasis is to build up a baseline from multi-year long-term SCM simulations and GCM climate simulations for greater in-depth understanding of model errors using simulations from high-resolution models such as CRMs, LESs, and convection-permitting models. A hindcast approach (Williams et al., 2013; Ma et al., 2015) is also applied to initialize GCMs with modeling center's analysis or reanalysis data for the periods that major field campaigns were conducted so that output from GCMs can be directly compared to the observations. The GASS-DCP project is still open for participation. Please visit *http://portal.nersc.gov/project/capt/diurnal/* or contact xie2@llnl.gov for more details.

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The Monsoons of the Americas

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The rapid warming of the Earth's atmosphere and oceans, combined with internal variability of the climate system, have distinctly modified monsoon systems. The South and North American Monsoon systems (SAM and NAM, respectively) have unique features. Attributing the effect of anthropogenic climate change in SAM and NAM features requires advanced understanding of physical and dynamical processes driving the variability of these systems. We provide some insights on two relevant aspects: the role of moisture sources in the development of the NAM and the importance of decadal-to-multidecadal variability in modulating SAM characteristics and trends.

1. Moisture Sources and the NAM

Much of the recent work regarding the North American Monsoon has focused on the sources of moisture for precipitation. A long-standing debate of monsoonal moisture sources had historically been focused on the relative role of westerly moisture from the Gulf of California vs. the easterly moisture from Gulf of Mexico that arrived to the NAM region after crossing the mountainous region of the Sierra Madre (Schmitz and Mullen, 1996; Adams and Comrie, 1997). However, the importance of terrestrial sources of moisture came to the forefront when water vapor tracers (WVTs) embedded within a general circulation model (GCM) suggested that a very significant amount of monsoonal moisture was terrestrial (Bosilovich et al., 2003). In fact, using the simple Dynamic Recycling Model (DRM), it has been estimated that 40% of monsoonal precipitation could originate from terrestrial sources, compared with approximately 20% coming from the Pacific basins, including the Gulf of California, and about 20% coming from Atlantic basins, including the Gulf of Mexico (Figure 1 and Hu and Dominguez, 2015). A south-to-north-to-south progression of the monsoon indicated that sources from southern Mexico and Central America were critical during the early stages of the NAM, while regions in northern Mexico and the U.S. contributed during the mature phase (Figure 2 and Hu and Dominguez, 2015).

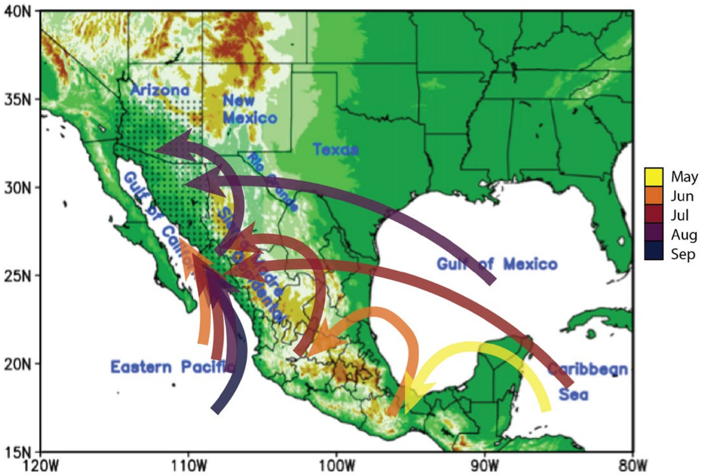

Figure 1. Conceptual diagram of the seasonal progression of moisture sources and the geographical source regions.

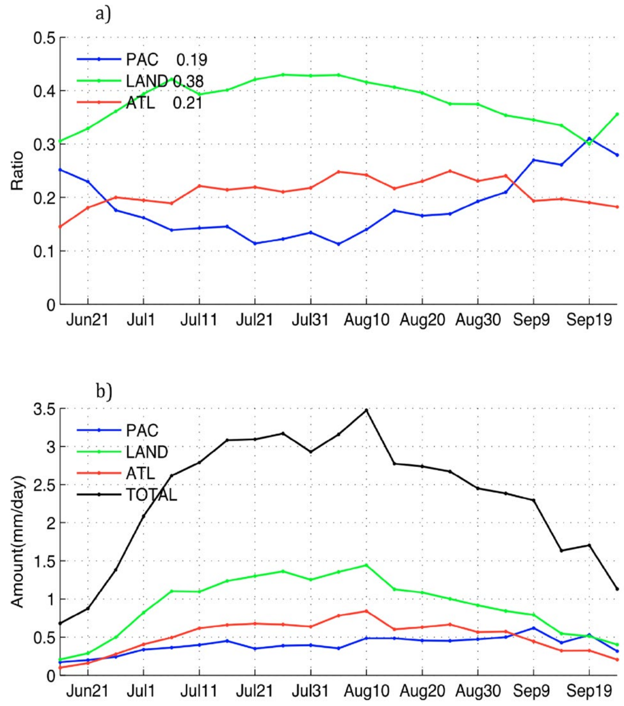

Figure 2. Oceanic and terrestrial contributions to the NAM precipitation throughout the season (from 16 June to 28 September): (a) the ratio contribution from the Pacific Ocean, land area, and the Atlantic Ocean throughout the 21 pentads (the pentads are marked by their starting dates) and (b) the amount contribution from these three regions together with the averaged total amount of precipitation in the NAM region. From Hu and Dominguez, 2015

The DRM used in Hu and Dominguez, 2015 assumed a well-mixed atmosphere. However, more recent work using water vapor tracers embedded within the Weather Research and Forecast (WRF) regional climate model refined these estimates and compared the complex WRF-WVT estimates with those from the simple DRM model (Dominguez et al., 2016). Detailed results suggest that lower-level moisture comes predominantly from the Gulf of California, which is the most important source of precipitation. This water can re-evaporate and contribute to local precipitation through recycling, which is the second largest source. Upper-level moisture from the southeast comes from the Gulf of Mexico and the mountains of the Sierra Madre. Critically, Dominguez et al. (2016; 2020) show that the simple model of Hu and Dominguez (2015) likely underestimates the terrestrial contribution to precipitation, so land evapotranspiration could contribute to nearly half of NAM precipitation.

2. Decadal-to-Multidecadal Variability and the SAM

Historical instrumental records have shown significant upward trends in extreme precipitation (amount, intensity, and

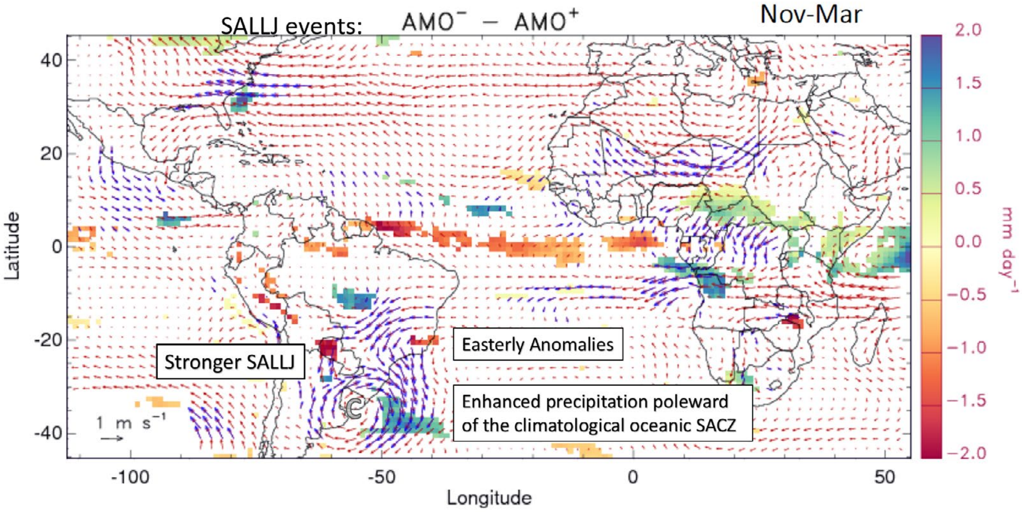

Figure 3. Austral summer (Nov–Mar) differences in mean winds (850-hPa) and precipitation during SALLJ days between negative (1965–1996) and positive (1924–1965) AMO phases. Adapted from Jones and Carvalho (2018).

frequency) in the American monsoon domains (Carvalho, 2019). Moreover, changes in circulation and precipitation patterns have been identified in the SAM (Pascale et al., 2019). However, assessing and attributing the effect of anthropogenic climate change on the SAM is challenging. The sparse, intermittent, and relatively short precipitation records preclude an adequate evaluation of rainfall trends in large tropical regions in the Americas (Carvalho, 2019). An increase in deforestation accompanied by numerous forest fires and intensive land use change have regional and remote impacts on the SAM system that need to be properly assessed (Zilli and Carvalho, 2020). Moreover, multidecadal variability within the climate system may reinforce or offset the effect of anthropogenic climate change in monsoon systems. The Pacific Decadal Oscillation (PDO), or more generally the Interdecadal Pacific Oscillation (IPO), and the Atlantic Multidecadal Oscillation (AMO) are some of the relevant modes of variability affecting the SAM system (e.g., Kayano and Andrioli, 2007; Wang et al., 2012; Grimm et al., 2016; Jones and Carvalho, 2018). Moreover, teleconnections patterns associated with the El Niño-Southern Oscillation (ENSO) also exhibit decadal variability, as, for instance, a dependence on the PDO phase (e.g., Gamelin et al., 2020). Some of these relevant influences are discussed here.

a) The South America Low Level Jet (SALLJ) and the South Atlantic Convergence Zone (SACZ)

The SALLJ on the eastern slopes of the Andes transports large amounts of moisture, controls the spatiotemporal variability of precipitation in southeast South America, and exhibits interannual to multiannual variability (Montini et al., 2019). Jones and Carvalho (2018) have shown that the negative AMO phases are associated with enhanced SALLJ and intensified cyclonic anomalies over the La Plata Basin year round. This pattern accompanies negative precipitation anomalies over the Atlantic Intertropical Convergence Zone. Patterns of precipitation anomalies over the SAM depend on the season. During summer (November–March), AMO-induced changes in circulation appear related to enhanced precipitation anomalies poleward of the climatological oceanic SACZ (Fig. 3).

The SACZ is a relevant component of the SAM with variability on multiple timescales (Carvalho and Cavalcanti, 2016). Recent studies have indicated a poleward shift of the South Atlantic Convergence Zone (SACZ) in the last decades (Zilli et al., 2017; 2019) that appear related to drier (wetter) conditions on the northern (southern) flank of the zone. Decadal changes in circulation associated with the shift of the SACZ are consistent with the enhancement of a cyclonic circulation over La Plata Basin shown in Jones and Carvalho (2018) during SALLJ events. This suggests that AMO may act to either amplify or offset climate change signals, depending on the phase of the oscillation.

b) Climate Change and SAM Variability in Spring and Summer

Understanding the role of ENSO and interdecadal to multidecadal climate oscillations in the SAM circulation and

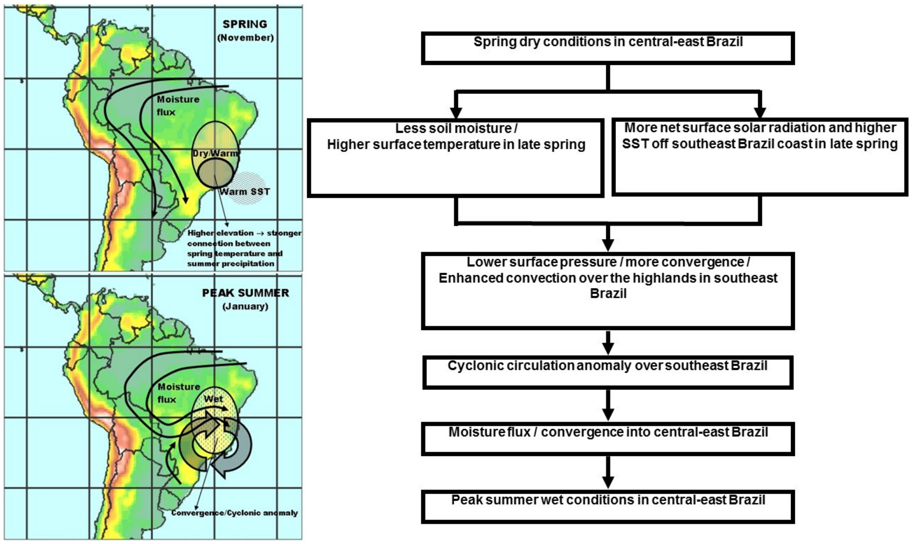

Figure 4. (Left) Schematic evolution from (a) spring dry conditions to (b) peak summer wet conditions in central-east Brazil, through decreasing low-level pressure, convergence, and cyclonic anomaly over southeast Brazil. (Right) Diagram of the pathway through which spring anomalous dry conditions may lead to subsequent peak summer wet conditions in central-east Brazil. The above diagram is also valid for opposite anomalies, starting from spring wet conditions in central-east Brazil (Grimm, Pal, and Giorgi, 2007).

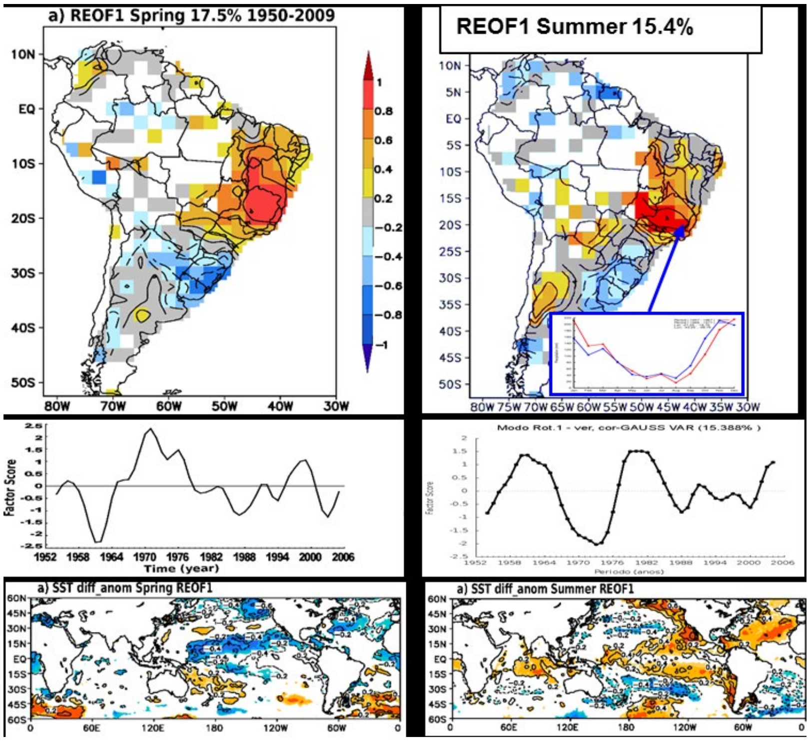

Figure 5. First interdecadal modes of spring and summer precipitation over South America, with factor loadings, factor scores, and associated sea surface temperature (SST) anomalies. The inset displays the annual precipitation cycles for positive and negative phases of these modes, showing that drier springs tend to be followed by wetter summers and vice-versa (Grimm and Saboia, 2015; Grimm et al., 2016).

precipitation patterns is useful and necessary to evaluate the anthropogenic influence in the last century and in future projections of climate change. Coupled Model Intercomparison Project Phase 6 (CMIP6) models indicate that greenhouse gas-induced horizontally differential warming results in "Northern-Hemisphere-warmer than-Southern-Hemisphere" and "land-warmer-than-ocean" patterns, as well as an El Niño–like warming (Wang et al., 2020). The projected future precipitation changes over SAM resemble the anomalies expected for El Niño and respective teleconnections described in previous studies (Grimm, 2003; 2004; 2011; Cai et al., 2020), including influence on extreme events (Grimm and Tedeschi, 2009; Grimm, 2018). Thus, understanding the El Niño teleconnections with SAM is important to assess future projections. The El Niño remote influence prevails in spring whereas regional surface-atmosphere processes dominate during the peak of the summer (Grimm, 2003; Grimm et al., 2007), so that rainfall anomalies tend to be opposite on the early and peak monsoon season in central-east South America (SA) (including SACZ). Therefore, there is little change of annual mean precipitation in the monsoon region, with drier winter and spring and little increase in summer rainfall (Seth et al., 2013; Wang et al., 2020). Mechanisms explaining these relationships are shown in Fig. 4 and discussed in Grimm et al. (2007) and Grimm and Zilli (2009). Moreover, other climate change projection features resemble the El Niño impacts: drier conditions in central-east Amazonia, and wetter conditions in northwestern SA and in southeastern (SE) SA (Seth et al., 2013).

The first interdecadal modes of precipitation in spring and summer mode, which exhibit a dipole feature between central-east SA (including SACZ) and subtropical SE SA, also show an inverse relationship between the spring and summer precipitation, as ENSO (Fig. 5) (Grimm and Saboia, 2015; Grimm et al., 2016). While both modes are associated with the IPO, the signs of the dipole are opposite for spring and summer for a given phase of the IPO. Since the positive phase of the IPO resembles El Niño, the effect is similar to El Niño on central-east SA. The effect on subtropical SE SA may have partly contributed to an increasing rainfall trend from the 1970s to the late 1990s, decreasing afterwards.

The second interdecadal summer precipitation mode (Fig. 6) exhibits largest factor loadings over subtropical SE SA, although anomalies of the same sign extend to the tropical monsoon core region in central SA (Grimm et al., 2016, their Fig. 3b). This mode exhibits strong correlation with the AMO and also shows IPO features of opposite phase. When the mode is in its positive phase, it is associated with positive AMO phase and a weak negative IPO phase. This combination produces low-level divergence over the monsoon region, reducing the monsoon circulation and rainfall, especially in the subtropical region (Grimm et al., 2016), and weakens the low-level jet east of the Andes that transports moisture to SE SA (Grimm et al., 2016, their Figs. 5g-i). This mode has been in positive phase since the late 1990s, partially explaining the weakening of the subtropical SE SA monsoon rainfall in recent decades (Wang et al., 2012). The inversion of the trend in subtropical SE SA from positive in the 1970s to the late 1990s

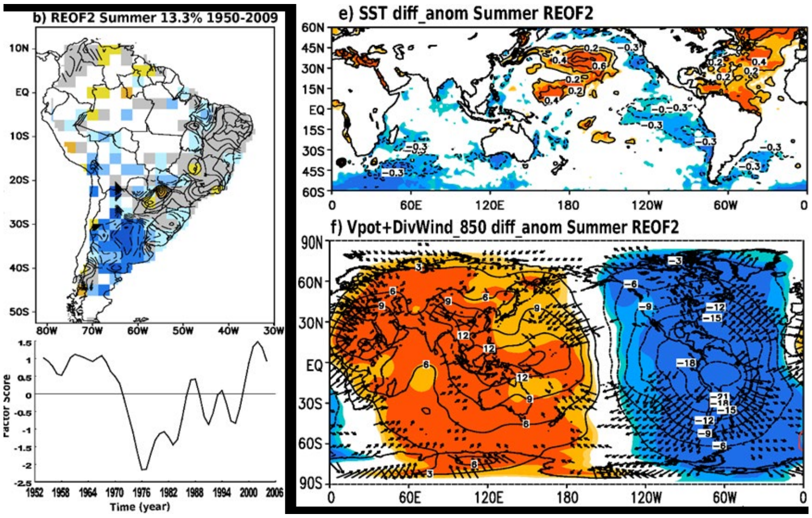

Figure 6. (Left) Factor loadings and factor scores of the second mode of summer rainfall interdecadal variability. (Right) The upper panel displays the anomalous SST patterns associated with this mode, and the lower panel shows the divergent wind at low level (Grimm et al., 2016).

to negative after that is coherent with the changes of phase of IPO and AMO in the late 1990s.

Therefore, interdecadal monsoon variability can affect the anthropogenic climate change signal during certain periods of time. These processes need to be properly investigated to understand future climate projections.

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Multidecadal to Synoptic Scale Extremes within the West African Monsoon System

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**Please see page 20 for a brief tribute to Françoise*

Introduction

In the West African Monsoon (WAM) region, seasonal rainfall is a determinant for many aspects of life, including rain-fed agriculture, pastoralism, and water and disaster management. Variations in the seasonal rainfall amount or in the occurrence of synoptic weather systems can therefore have high-impact consequences on livelihoods, particularly in the Sahel where the vast majority of rain falls within two to four months. At longer timescales, the unprecedented decline of rainfall in the WAM region and its devastating consequences have motivated the scientific community to investigate the mechanics involved in their past and current variability and to attempt to improve future climate projections of these WAM-related events. Below, we summarize key results relevant to West African extremes at different timescales.

Extremes in the Interannual to Multidecadal Timescales

The WAM was marked by a series of anomalously wet years in the first part of the 20th century until the late 1960s, followed by a decline in rainfall with devastating droughts (e.g., in 1972, 1983, and 1984) affecting Sahelian society and economic activity. An upward rainfall trend has been observed since the mid 1980s, but the so-called rainfall recovery (i.e., a return to positive anomalies) only began after the mid-1990s. However, this recovery is marked by less spatial coherence and temporal persistence and an increased interannual variability. This can lead to extremely wet years (e.g., 2020) or extremely dry years (e.g., 2014) (e.g., Lebel and Ali, 2009; Descroix et al., 2015; Zhang et al., 2017; Nicholson et al., 2018).

At interannual timescales, both remote and adjacent sea surface temperature (SST) anomalies appear as major drivers of rainfall variability over the WAM region (e.g., Folland et al., 1986; Rodríguez-Fonseca et al., 2015; Diakhaté et al., 2019). At decadal timescales, Sahelian drought has been attributed to either SST interhemispheric gradients or SST anomalies in individual basins in connection with processes that affect vertical stability and moisture supply. The first mechanism is induced by anthropogenic emissions of reflective aerosols in North America and Europe, which contributed to cooling the northern hemisphere relative to the southern hemisphere and then to shift the zonal mean Inter Tropical Convergence Zone (ITCZ) to the south (Ackerley et al., 2011; Hwang et al., 2013). The second mechanism is linked to warmer tropical SST, due to anthropogenic greenhouse gas (GHG) forcing (e.g., Hagos and Cook, 2008; Giannini et al., 2013). Many studies have attributed the Sahel rainfall recovered in the last

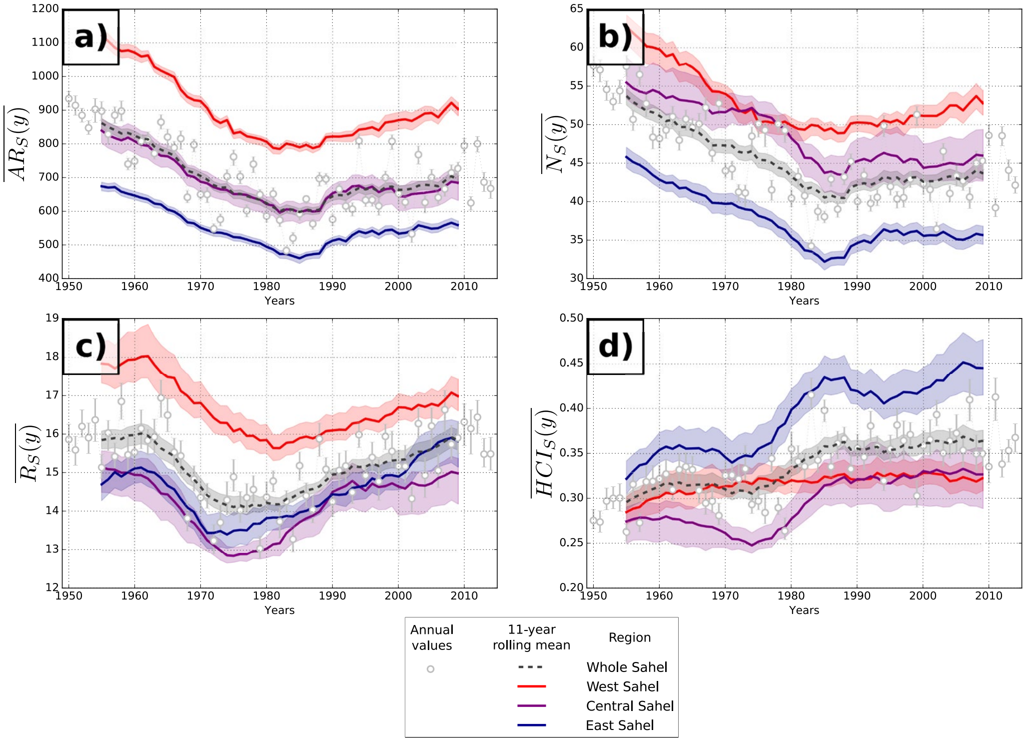

Figure 1. Adapted from Panthou et al., 2018 (Figure 2). Evolution of (a) the mean annual rainfall totals (mm yr $^{-1}$), (b) the mean number of rainy days (d), (c) the mean intensity of rainy days (mm d $^{-1}$), and (d) the mean hydro-climatic intensity (mm d $^{-2}$) over the whole Sahel and sub-domains (West, Central and East Sahel). Error bars (resp. shaded area) delineate 80% confidence intervals for annual values (resp. 11 year rolling mean).

decades to higher levels of GHG in the atmosphere contributing to warming the Sahara (Dong and Sutton, 2015; Evan et al., 2015). However, Earth system models (ESM) are still struggling to reproduce the amplitude of observed decadal variability in the twenty century (e.g., Roehrig, 2013) and to represent the mean climatology (e.g., Monerie et al., 2020; Sow et al., 2020).

Despite similar projections through the third Coupled Model Intercomparison Project (CMIP3), CMIP5, and CMIP6 of a rainfall increase in the central and eastern Sahel and a decrease in rainfall in the westernmost Sahel for the end of the 21st century, large uncertainties remain in the future projected WAM with large inter-model spreads (e.g., Biasutti et al., 2019; Monerie et al., 2020), particularly in the western Sahel.

Extremes in the Seasonal to Intraseasonal Timescales

Wet spells and dry spells within the monsoon season are common phenomena, but they can correspond to extreme drought, flooding, or both in urban and rural areas. While accumulated seasonal rainfall broadly approached normal after the "recovery", extreme dry spells, especially at the beginning and end of the season, are now more prominent (e.g., Salack et al., 2013; Bichet and Diedhiou, 2018). The recovery period has been also associated with an increase in the number of heavy and extreme events, compared to the drought period (e.g., Sanogo et al., 2015; Panthou et al., 2018) and is characterized by a stronger increase of precipitation in the east (e.g., Panthou et al., 2018, Figure 1).

Understanding the mechanisms governing the intraseasonal variability of the WAM has only recently retained attention in the research community. A few modes of variability have notably been identified (e.g., Sultan et al., 2003; Janicot et al., 2009). The Saharan heat low has been identified as a major player in modulating rainfall at intraseasonal timescales, involving an influence of the midlatitudes and the Mediterranean (e.g., Roehrig et al., 2011). Finally, at shorter intraseasonal timescales (around 10 days), precipitable water anomalies have been found to modulate convective activity over West Africa (e.g., Poan et al., 2013). Importantly, a very exhaustive summary of our current understanding of WAM predictability and the mechanisms at stake, including intraseasonal variability, has been provided by *Meteorology of Tropical West Africa: The Forecasters' Handbook* (Parker and Diop, 2016).

The sensitivity of the WAM to SST anomalies (e.g., Lamb, 1978) has stimulated the development of statistical and dynamical seasonal prediction in West Africa since the early 1990s (e.g., Folland et al., 1991) and since 1998 has led to the development of the regional climate outlook forum in the region. There is growing interest in developing subseasonal forecasting systems under the umbrella of the subseasonal-to-seasonal (S2S) project (*http://s2sprediction.net*). Some results, using subseasonal forecast systems, have shown promising skillful forecasts of the WAM, in particular monsoon onset and demise, but forecast of extreme rainfall remains challenging (e.g., Bombardi et al., 2017; Vigaud et al., 2017; Olaniyan et al., 2019). The Real-time Monitoring and forecast of IntraSeasonal Variability over Africa (MISVA) project (*http://isv.sedoo.fr*), which started in 2011 as a joint forecaster-researcher initiative between the Senegal meteorological service (ANACIM) and the French national center for meteorological research (CNRM), is now federating several national meteorological centers across West Africa and the CNRM to monitor intraseasonal variability over the WAM in order to provide more skillful medium-range forecasts of the WAM. It further provided a solid basis for initiatives such as developed in Climate Risk and Early Warning Systems (CREWS) projects.

Extremes in Synoptic Weather Systems

Accumulated seasonal rainfall is the aggregation of synoptic weather systems, which notably includes a major contribution from mesoscale convective systems (MCSs) embedded or not in African easterly waves (AEWs); they bring nearly 80 to 90% of rainfall to the Sahel (e.g., Mathon et al., 2002). An intensification of mesoscale convective systems responsible for extreme rain has been observed over the past decades, which appears to be favored by enhanced meridional gradients of temperature induced by the warming of the Sahara at a higher pace than the mean global warming (Vizy and Cook, 2017; Taylor et al., 2017). The intensification of storms is explained by the intensification of the shallow circulation and the African easterly jet (AEJ), which favor triggering and intensification of MCSs (Taylor et al, 2017).

An example of an intensive convective event occurred in Ouagadougou, Burkina Faso, on 1st September 2009. It was selected as one of The Observing system Research and Predictability Experiment (THORPEX)-Africa (Parsons et al., 2017) case studies and documented in Lafore et al. (2017). This event, with a daily rainfall record of 263 mm, was not isolated as it occurred in the context of a major, long-duration (20 days) wet spell phase, which also led to flooding and grave societal impacts in many other Sahelian countries (e.g., Niger, Senegal, Mauritania, Gambia). During the Ouagadougou event, an exceptional superposition of favorable conditions occurring at different temporal scales, including successive trains of AEWs, favorable SST patterns in the Atlantic and the Mediterranean, and crossing of equatorial Rossby and Kelvin waves, was key to the extreme nature of the event (Figure 2). This result emphasizes the necessity of monitoring and predicting extreme rainfall events in the lens of spatial and temporal multiscale interactions and teleconnections.

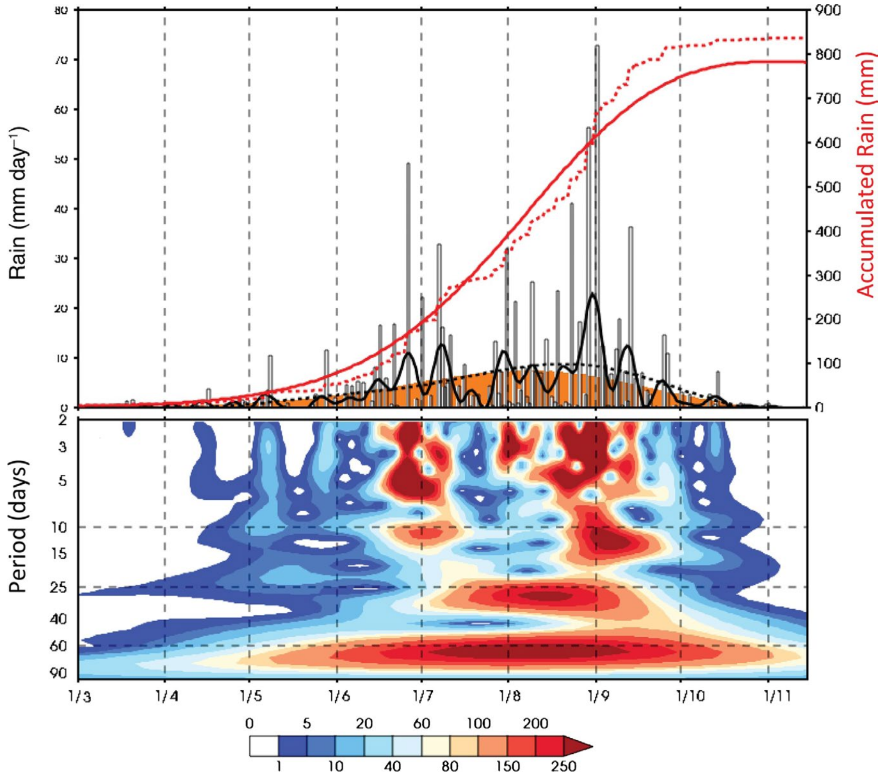

Figure 2. Adapted from Lafore et al., 2017 (Figure 3); (a) Tropical Rainfall Measuring Mission (TRMM) precipitation evolution of the year 2009 (mm/day), averaged over a 1° square around Ouagadougou [12–13°N; 1–2°W] (red square in Fig. 1). Raw daily data are indicated with white bars. The orange shaded area corresponds to the climatological (1998–2013) annual cycle. The 2009 annual cycle is indicated by the dashed black curve and obtained with a 90-day low-pass spectral filter applied in raw precipitation. The intraseasonal scale is emphasized with a solid black curve and obtained with a 10-day low-pass spectral filter. Red curves in Fig. 2a correspond to the accumulated rain (mm) since 1st January for the climatology (solid red line) and the year 2009 (dashed red line). (b) Wavelet analysis of TRMM precipitation averaged over the 1° square around Ouagadougou and 90-day high-pass filtered.

Finally, the strongest MCSs are usually accompanied by extreme winds and lightning, which can lead to loss of property and life (as noted during the monsoon season in operational services). These extreme MCS-related wind gusts are also a major cause of dust emission in the southern Sahel (e.g., Rajot et al., 2001), which poses serious challenges to the aerosol and climate modeling communities.

The research activity on Sahelian heat extremes is still in its infancy (e.g., Guigma et al., 2020), despite the very elevated temperatures prevailing in this region of the world and the strong climatic warming observed there (e.g., Guichard et al., 2017). Indeed, heat waves during the premonsoon period are becoming more intense, mainly as a result of the strong Sahelian warming (Barbier et al., 2018). The Intergovernmental Panel on Climate Change (IPCC)-projected warming in the Sahel (reaching several degrees by the end of the century) raises numerous societal issues related to health and agriculture.

Operational medium range ensemble forecasting has globally improved the prediction of rainfall occurrence (e.g., Matsueda and Nakazawa, 2014; Vogel et al., 2020), but in regard to rainfall amount or extreme rainfall events, "'tropical Africa to the west of the East African highland' stands out as a region of particularly low predictive performance" (Vogel et al., 2020). This is partly related to a misrepresentation of physical processes, including convection, which occurs at small scales and which is currently parameterized in forecast systems. Convection-permitting models have shown more skill in predicting extreme events in the WAM (e.g., Diongue et al., 2002; Beucher et al., 2019), yet their operationalization requires substantial human capacity and infrastructure development. Some global forecasting centers are starting to provide convection-permitting forecasts over Tropical Africa [e.g., UK Met Office, see also the Science for Weather Information and Forecasting Techniques (SWIFT) project, *https://africanswift.org/*]. In the same vein, the severe weather forecast project (*https://www.wmo.int/pages/prog/www/swfdp/*) aims at improving extreme weather forecast, including expanding convection-permitting modeling in West Africa (e.g., Meteo-France convective permitting model, "Arôme", over a portion of West Africa, operational since 2020).

Conclusion

Climate and weather extremes associated with the West African Monsoon correspond to high-impact phenomena and are a source of risk in a region also marked by high socioeconomic vulnerabilities. More importantly, climate change over the decades as well as climatic projections indicate an increase of variability and occurrence of extreme weather events in the West African Monsoon. On the other hand, mechanism-attribution studies of individual extreme events are rare and could become a valuable research area for forecast improvement and climate change attribution.

Forecasts, prediction, and projections in the African monsoon exhibit strong biases partly due to the paucity of available data but also to the misrepresentation of key processes, notably physical processes, and of their interactions with atmospheric dynamics at all scales. Further investigation in process understanding (particularly in the S2S timescales) and process representation in both numerical weather prediction (NWP) and climate models (e.g., convection, radiative processes involving surface properties and states, clouds and aerosols, land-atmosphere interaction) is crucial in order to provide advanced forecasts and projections. On a more practical side, more research and development of climate services and impact-based forecasts and their assessment is needed for decision-making, risk management, and adaptation to climate change in the WAM region.

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The Intersection between Global Monsoons and Regional Hydroclimate Projects

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More than half of the world's population relies on the seasonal rains brought by global monsoons for regional agriculture, water resources, and ecosystem services (WCRP, 2011). However, variations in monsoonal rains can also bring hardship. Too much or too little rain can have devastating impacts on vulnerable communities, with compounding hazards related to water quality. This year alone, intense monsoon rains across southern Asia have affected nearly four million people in Bangladesh, India, Bhutan, Myanmar, and Nepal, destroying homes and submerging entire villages.

Clearly, monsoonal impacts are best tackled at the regional and local scale, with the collaboration of resident stakeholders and scientists. On the other hand, monsoonal understanding and predictability as part of the global climate system must also be addressed through global scientific collaboration. As an example, recent work suggests that the North and South American monsoons are dynamically linked and they have experienced a shorter season in the past few decades through variations of the cross-equatorial flow (Arias et al., 2015). The implications of a shorter North and South American monsoon season in terms of reduced precipitation would be of great importance for area communities. The World Climate Research Programme (WCRP) offers both local and large-scale perspectives. The Climate and Ocean: Variability, Predictability and Change (CLIVAR)/GEWEX Monsoons Panel is devoted to increasing our understanding of monsoons, while the GEWEX Hydroclimatology Panel (GHP) regional hydroclimate projects (RHPs) rely on the local and regional expertise that are directly tied to the affected communities. Here, we will discuss the intersection between the RHPs and monsoons, as depicted in Figure 1. Monsoons are defined as regions where low-level winds shift 180° from summer to winter. However, even if this definition is not strictly met, some areas are still characterized as monsoonal if they exhibit an abrupt increase in rainfall during the summer season (Cook et al., 2013). Red shading in Figure 1 shows monsoonal regions that have been studied within an RHP framework. Some monsoon regions (such as the Australian monsoon) are not included. It is important to highlight that RHPs are multiyear efforts, typically ranging between 4 and 10 years. Several of these efforts have already ended (green ovals), some have morphed into newer projects (blue oval), and some are still prospective RHPs (purple oval).

Monsoon-Focused RHPs of the Past

The Asian monsoon is the largest monsoonal system in the world, affecting an area that is home to more than a billion people. Improved understanding and predictability of the Asian monsoon is critical to this part of the globe. The Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHASRI, 2006–2016), a recently-completed RHP, was a successor to the GEWEX Asian Monsoon Experiment (GAME, 1996–2005). MAHASRI focused on establishing the scientific basis for predicting the Asian monsoon hydroclimate with a focus on the intra-seasonal to seasonal time scale. An important component of MAHASRI was developing warning systems for drought and flood conditions at regional or river-basin scales (Matsumoto et al., 2016). To this end, there were several regionally-targeted projects in Indonesia, Thailand, and Mongolia. There were also efforts to gain greater understanding of local monsoonal impacts in Myanmar, Vietnam, the Philippines, and Indochina. For example, field observations in Vietnam focused on heavy precipitation, and researchers developed a precipitation measurement network in the Indian states of Assam and Meghalaya and in Bangladesh. In terms of socioeconomic impacts, the project targeted applications for rice production and water resource management in the region. It is important to highlight that MAHASRI was part of the Asian Monsoon Year (AMY; Matsumoto et al., 2016, a broader effort that brought together a community of Asian monsoon scientists. The scientific advances made during MAHASRI, including theoretical advances on physical processes and regional impacts, are summarized in the Special Issue on MAHASRI (Matsumoto et al., 2011).

While smaller in extent than its Asian counterpart, the South American monsoon straddles the two largest basins in South America: the Amazon and La Plata River basins. The multi-year Brazil-led international "Large-Scale Biosphere-Atmosphere Experiment in Amazonia" (LBA) focused on the Amazon region. The South American monsoon was not the primary focus of the LBA; the project examined the impacts of land use and climate change on the functioning of the Amazon and the influence of Amazonia on the global climate (see the LBA Special Issue in *Earth Interactions*, Foley et al., 2009). However, the Amazonian hydroclimate is linked to the subtropical and midlatitudes of the La Plata basin (LPB) through atmospheric circulation patterns. The LPB RHP (2007–2012) focused on the second largest basin in South America after the Amazon. The LPB region exceeds the Amazon basin in terms of population density and agricultural, livestock, and socioeconomic activity, so the impacts on society and vice-versa are more direct. The summer hydroclimate of the northern LPB is dominated by the South American monsoon system. Climate and surface hydrology in this region are characterized by variability and trends at different timescales from sub-seasonal to interdecadal and longer (Berbery et al., 2011; Barros et al., 2006). A pronouncedly large trend in land use and land cover change, caused by the expanding production of soy and other crops, poses a challenge to the LPB and LBA regions. This makes it difficult to isolate land use from climate change signals when attributing hydroclimate change. For this reason, both the LBA and LPB efforts have involved a push toward better understanding land-atmosphere interactions in South America and their potential for improved predictability.

The African Monsoon Multidisciplinary Analysis (AMMA) program has been perhaps the largest effort linking African

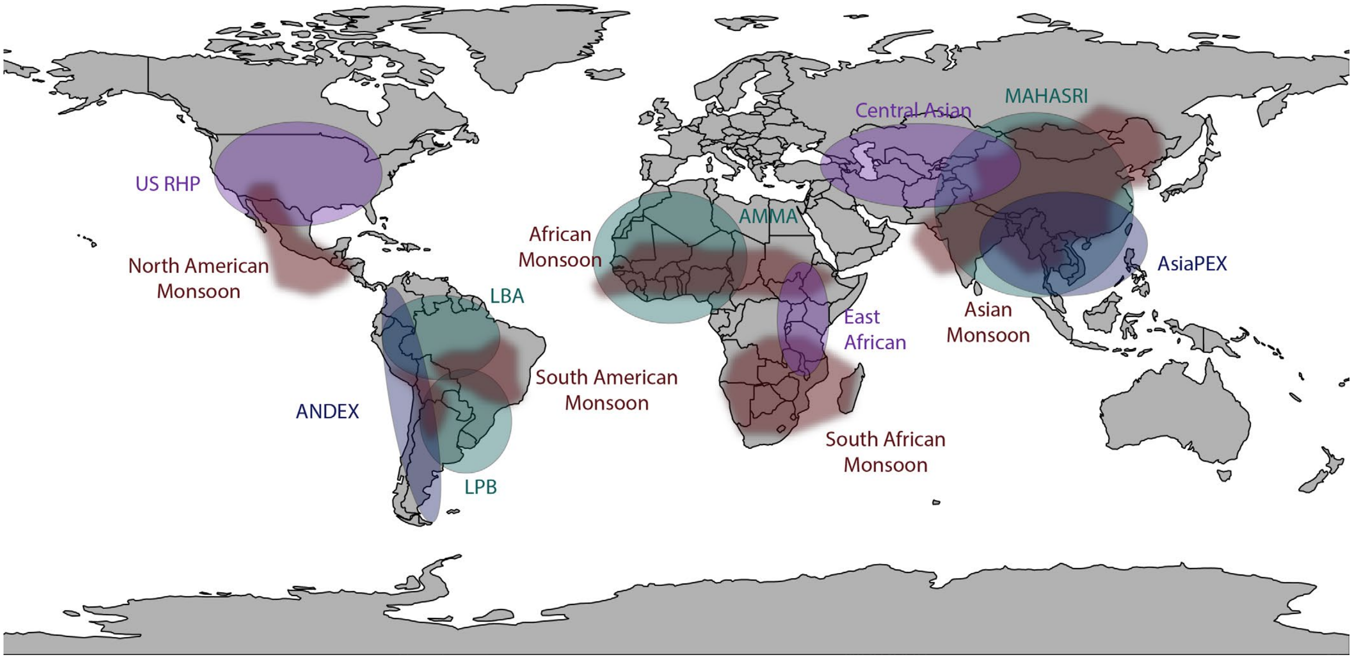

Figure 1. Geographic location of global monsoon regions (dark red shaded areas) that intersect GEWEX's GHP regional hydroclimate projects (RHPs, ovals). Monsoon regions are defined as areas where more than 70% of precipitation falls during the summer season as reported in http://www.clivar.org/clivar-panels/monsoons. *Data from Global Precipitation Climatology Project (GPCP) version 2.5 for 1979–2008 provided by P. Dirmeyer. Green ovals denote RHPs that have ended, blue oval denotes an RHP that has succeeded a previous one, and purple denotes a prospective RHP.*

and European researchers in the study of the African monsoon hydroclimate. It involved a comprehensive field experiment with ocean-land and atmospheric measurements in conjunction with atmospheric and hydrologic numerical modeling at a variety of scales. As such, AMMA made advances toward improved forecasts from weather to climate scales. Some of the most salient achievements of AMMA include a better physical understanding of the African monsoon, better analysis of atmospheric composition in the region, emphasis on land-atmosphere feedbacks, large-scale hydrologic cycle quantification and characterization of hydroclimate variability at different scales. An impressive accomplishment of AMMA was that in addition to the work on hydroclimate processes, it placed special emphasis on applications for food security and agriculture, health, hydrologic impacts, and education (Polcher et al., 2011).

Monsoon-Focused RHPs of the Future

In the coming months, GEWEX and GHP will welcome AsiaPEX as a new RHP. Following in the footsteps of MAHASRI and GAME, AsiaPEX aims to increase our understanding of precipitation over Asia, which is dominated by the Asian monsoon. Its goal is to improve scientific understanding of the Asian hydroclimate and to provide reliable climate projections for people and policymakers. Efforts to provide socially-relevant information drive the focus on precipitation over land. As an example, AsiaPEX has already produced ultra-high resolution climatological rainfall intensity products based on the Tropical Rainfall Measuring Mission (TRMM; Hirose and Okada, 2018). The AsiaPEX kick-off meeting occurred in Sapporo, Japan, in September of 2019.

ANDEX is a proposed RHP focused on the Andes mountains of South America. While the South American monsoon is not located in the Andes, there are important interactions between the cordillera and the monsoonal system of South America. A series of papers has recently been published in *Frontiers in Earth Science* summarizing current knowledge on the hydroclimate of the region (see Espinoza et al., 2020).

The scientific community in the U.S. is beginning to coalesce to form an RHP over the United States (Schneider and van Oevelen, 2020). The region of study would encompass the U.S. North American monsoon region, but its spatial extent will likely extend much further north along the Rockies and east into the U.S. Great Plains. The RHP would tackle fundamental issues related to water resources, water quality, food and energy production, and ecosystem services in the U.S. This project will have a very strong component of high-resolution, convection-permitting modeling at the continental scale. High-resolution modeling will be fundamental in tackling monsoonal precipitation processes. Detailed modeling will go hand-in-hand with surface-to-boundary layer observations in this ambitious continental-scale future RHP.

Two additional RHPs in development are also closely linked to monsoonal systems. We are working to establish a new RHP in Central Asia, and although most areas are not directly affected, there are strong teleconnections between the Asian monsoon and the climate and weather of the central Asian region. Lastly, we are exploring the possibility of a central and east African activity that connects large scale circulation issues with local climate and weather and how that is perturbed by topography as well as human influences.

RHPs are GEWEX and GHP's "boots on the ground", bringing together scientific expertise, local decision makers, and stakeholders. This is not an easy task, as the expectations and priorities of these groups often diverge (Lahsen and Nobre, 2007). However, this is the nature of many hydroclimate problems, and global monsoons are a prime example of this: they affect more than half of the world's population, with vulnerable communities bearing the brunt of the impacts. Yet there are still many questions regarding the underlying physical processes and predictability of monsoonal precipitation. The tension between basic science and societal impacts should be tackled on both ends and this is the task ahead for the CLIVAR/GEWEX Monsoons Panel and GHP.

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Hommage à Françoise Guichard

Members of the CLIVAR/GEWEX Monsoons Panel and International CLIVAR Monsoon Project Office

Shortly before the publication of this special monsoons issue of *GEWEX Quarterly*, Françoise Guichard, member of the Monsoons Panel, passed away on Saturday, 5 December 2020. For her friends around the world, this was the saddest news in a terrible year, as they knew that she was pleased to be home in Concarneau, in her native region of Bretagne (Brittany), France, "with her feet in the water". In the GEWEX and CLIVAR communities, Françoise has been more widely known over recent years as a former Co-Chair of the Monsoons Panel, where she continued to serve as a member, having established a framework for the study of monsoon behavior in different regions under the umbrella of the global monsoon. She was also a member of the Regional Working Group on the African Monsoons, fostering the active coordination of African monsoon research. Françoise is fondly remembered by her current and former colleagues for her pioneering work as part of the African Monsoon Multidisciplinary Analysis (AMMA) program, which reflects the culmination of her scientific interests in the West African monsoon. Françoise, as a senior scientist at Centre National de Recherches Météorologiques (CNRM) with several other affiliations, leaves behind a rich legacy of scientific contributions meticulously documented in publications dating from 1996 to several this year, which this brief tribute cannot do justice. These works span topics on the behavior and structure of tropical clouds, convective modeling during the Tropical Ocean—Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA-COARE), confronting cloud simulations with observational data, as well as significant contributions to weather forecasting and climate projections over West Africa. Her insights into the physical processes governing monsoons are invaluable, and her quest to understand the different monsoon components is unmatched.

As colleagues, we remember her warm and welcoming smile and her engaging yet supportive nature, but above all we remember her as a great human being, generous and open-minded. Her students, colleagues, and our research area at large suffer a great loss without her guidance and contributions. We offer our sincere condolences to her family, friends, and colleagues.