IPC 12

12th International Precipitation Conference

June 19-21, 2019

Irvine, California

IPC12 2019

12th International Precipitation Conference 2019
and the Soroosh Sorooshian Hydrometeorology Symposium

June 19 - 21, 2019
Beckman Conference Center, Irvine, California
Pre-Conference Workshops: June 18, 2019 (UCI)

University of California, Irvine

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and the Soroosh Sorooshian Hydrometeorology Symposium

University of California, Irvine
The Beckman Center of the National Academies of Sciences and Engineering

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Welcome

Welcome to IPC12 and the Soroosh Sorooshian Hydrometeorology Symposium

Precipitation research stands at the intersection of atmospheric, hydrologic, and climate sciences and demands dedicated attention in view of the tremendous implications for water availability and the impact of extremes for the safety, economy, and sustainability of many regions around the globe. The International Precipitation Conference (IPC) started in 1986 (IPC1 in Caracas, Venezuela as a Chapman Conference) dedicated to bringing together hydrologists, atmospheric scientists and mathematicians to understand the space-time structure of rainfall at multiple scales for the purpose of modeling, downscaling regional and climate models and incorporating stochastic parameterizations into numerical weather prediction models. Since then, 11 IPCs followed, organized every 2-3 years around the world, attracting a large community of hydrologists, physical/atmospheric scientists, climate scientists, and mathematicians/statisticians and advancing precipitation research and applications.

The past 4 IPCs were held abroad (IPC11 in 2013 in the Netherlands; IPC10 in 2010 in Portugal; IPC9 in 2007 in France; and IPC8 in 2004 in Canada). The 12th IPC brings the community back to the U.S, with an impressive participation of colleagues from all over the world and involvement of a large number of early career scientists (graduate students, post-docs and junior scientists), to take a stock of accomplishments, define challenges and opportunities, and draft directions for future research. IPC12 focuses on three main themes: (1) estimation of precipitation from multiple sensors; (2) water cycle dynamics and predictive modeling at local to global scales; and (3) hydrologic impacts of precipitation extremes and anticipated change. IPC12 also leads a new era of precipitation research with the “big data revolution,” that is, with the unprecedented explosion of earth observations from space and model outputs from the development of community climate, hydrologic and earth system models, calling for new research on data-model integration for improved understanding and prediction.

A special feature of IPC12 is the “Soroosh Sorooshian Hydrometeorology Symposium” to honor the pioneering career of Professor Soroosh Sorooshian in advancing hydrometeorology research and applications, providing community leadership, and mentoring a cadre of colleagues over the past four decades. As the founder of the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California Irvine, he has built global capacity for monitoring, forecasting and mitigation of hydrologic disasters through the development of precipitation products, leveraging and extending the benefits of space and weather agencies' technological resources into applications that assist hydrologists and water resource managers worldwide with equitable access to relevant information. A trademark of CHRS is the PERSIANN product used worldwide for hydrologic prediction and water resources applications.

We received more than 150 abstracts from diverse corners of the world and from academia, agencies and the private sector, and have put together an exciting three-day program with oral and poster presentations, leaving also time for discussion, interaction and opportunities to foster new collaborations. Four short courses are offered the day before the Conference (June 18) on diverse topics of precipitation research and applications, especially geared toward hands-on experience of junior scientists.

There are several people who have contributed their expertise, talent and time to the success of IPC12. Special thanks go to the IPC12 organizing committee for putting together the sessions and the technical program. The local organizing committee helped with the many organizational tasks of the conference and the local events. Alyssa Sanchez, John Seaman, and Jerry Martinez handled the travel arrangements of participants and Shelly Nazarenus helped with the Beckman Center and registration logistics. Lawrence Vulis created and maintained the IPC12 web site and handled hundreds of emails from participants and travel support requests. Clement Guilloteau put together the initial copy of abstracts and Beth Riley and Jonathan K. Cohen compiled, edited and produced the IPC12 conference proceedings volume. Alejandro Tejedor designed the cover of the proceedings. Phu Nguyen, Diane Hohnbaum and Amir AghaKouchak helped with the organization of the Soroosh Sorooshian Hydrometeorology Symposium.

The generous support by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the University of California, Irvine (UCI) is graciously acknowledged. Without their support this conference would not have been possible.

We welcome all of you to the beautiful setting of Irvine in Southern California and we look forward to an exciting IPC12.

Regards,

Efi Foufoula-Georgiou
University of California, Irvine

On behalf of the IPC12 Organizing Committee

IPC12 Organizing Committee

Efi Foufoula-Georgiou, University of California Irvine
Amir AghaKouchak, University of California Irvine
Kuo-lin Hsu, University of California Irvine
Antonio Busalacchi, University Corporation for Atmospheric Research
Christa Peters-Lidard, NASA, Goddard Space Flight Center
Taikan Oki, University of Tokyo
Qingyun Duan, Beijing Normal University
Remko Uijlenhoet, Wageningen University
William Logan, International Center for Integrated Water Resources Management
David Feldman, University of California Irvine
Ana Barros, Duke University
Vincenzo Levizzani, NRC Italy, Institute of Atmospheric Sciences and Climate
Joseph Turk, NASA, Jet Propulsion Laboratory
Hoshin Gupta, University of Arizona
Witold Krajewski, University of Iowa
Terri Hogue, Colorado School of Mines
Clement Guilloteau, University of California Irvine
Alejandro Tejedor, University of California Irvine

Local Organizing Committee

Efi Foufoula-Georgiou, University of California Irvine
Amir AghaKouchak, University of California Irvine
Phu Nguyen, University of California Irvine
Diane Hohnbaum, University of California Irvine
Lawrence Vulis, University of California Irvine

Sponsors

The organizing committee gratefully acknowledges the support of the following sponsors: the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the University of California, Irvine (UCI), the Linked Institutions for Future Earth (LIFE) NSF project, and the Center for Hydrometeorology and Remote Sensing (CHRS).

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12th International Precipitation Conference (IPC12) and the Soroosh Sorooshian Hydrometeorology Symposium

The Beckman Center of the National Academies of Sciences and Engineering
100 Academy Way, Irvine, CA 92617

University of California Irvine
June 19 - 21, 2019 (Beckman Center)
Pre-Conference Workshops: June 18, 2019 (UCI)

Tuesday June 18, 2019 - Pre-Conference Workshops

Pre-Conference Workshops will be held in Colloquia Room (Engineering Hall, Room 2430) on UCI Campus. Google Maps link: https://goo.gl/maps/3h34LFLXX122H5Zv7

8:30-9:00am	Working Breakfast – Introductions and Scope of Workshops **Amir AghaKouchak (UCI)**
9:00-11:00am	Quantitative Precipitation Estimation (QPE): observations from radar, gauges and satellites for flood prediction **Pierre Kirstetter (NOAA)**
11:00-11:30am	Coffee Break and Group Discussions
11:30-12:30pm	CHRS PERSIANN: algorithms, data products and applications **Kuolin Hsu & Phu Nguyen (UCI)**
12:30-1:30pm	Working Lunch – Upcoming Tutorial Opportunities
1:30-3:30pm	Hands-on workshop on Extreme Value Analysis **Amir AghaKouchak (UCI), Charlotte Love (UCI) & Mojtaba Sadegh (BSU)**
3:30-4:00pm	Coffee Break and Group Discussions
4:00-6:00pm	A deep dive into the configuration and features of the National Water Model **David Gochis (NCAR)**
6:00pm	Dinner on your own

WEDNESDAY JUNE 19, 2019

8:00-9:00 am	Registration and Breakfast
9:00-9:15 am	Opening Remarks and Welcome **Efi Foufoula-Georgiou**

Session 1: Remote Sensing of Precipitation
Moderator: Taikan Oki

9:15-9:45am (**invited)**	NASA's Studies of Earth's Water Cycle **Jack Kaye, Gail Skrofonick-Jackson, Jared Entin, Bradley Doorn**
9:45-10:00am	Research Highlights from the International Precipitation Working Group (IPWG) **Viviana Maggioni, Philippe Chambon, Ziad Haddad, Dong-Bin Shin, Vincenzo Levizzani, Ralph Ferraro**
10:00-10:15am	IMERG V06: The Role of IR Precipitation **Jackson Tan, George Huffman, David Bolvin, Eric Nelkin**
10:15-10:30am	Questions and Group Discussion
10:30-11:00am	Coffee Break and Research Introductions

Session 2: Hydrologic Applications
Moderator: Witold Krajewski

11:00-11:30am **(invited)**	Strange Floods: The Upper Tail of Flood Peaks in the US **Jim Smith, Mary Lynn Baeck**
11:30-11:45am	Insight into the Changing Characteristics of Global Snow Droughts **Laurie Huning, Amir AghaKouchak**
11:45am-12pm	Forecast Verification Applications at the Australian Bureau of Meteorology **Thomas Pagano**
12:00-12:15pm	Data Driven Distributionally Robust Modeling of Extremes **Bita Analui, Kuolin Hsu, Soroosh Sorooshian**
12:15-12:30pm	Questions and Group Discussion
12:30-1:30pm	Working Lunch – Subgroup Discussion on the Conference Themes

Session 3: Water Cycle Dynamics
Moderator: Joseph Turk

1:30-2:00pm **(invited)**	Atmospheric Rivers: Recent Developments in Science and Applications **Marty Ralph**
2:00-2:15pm	Process-oriented Diagnostics Framework and Stochastic Process Models for Precipitation **J. David Neelin, Yi-Hung Kuo, Fiaz Ahmed, Cristian Martinez-Villalobos, Xianan Jiang, Eric Maloney, Allison Wing, Andrew Gettelman, Yi Ming, John Krasting**
2:15-2:30pm	Convective/stratiform classification from passive microwave imagers: Implications for improved precipitation retrieval and understanding of the water and energy cycles **Svetla Hristova-Veleva, Eun-Kyoung Seo, Ziad Haddad, Sahra Kacimi, Ousmane Sy, Jeffrey Steward**
2:30-2:45pm	Ensemble-based Simultaneous State and Parameter Estimation for Hydrological Modeling and Beyond **Fuqing Zhang**
2:45-3:00pm	Questions and Group Discussion
3:00-3:30pm	Coffee Break and Research Introductions

Session 4: Hydrologic Applications
Moderator: Amir AghaKouchak

3:30-4:00pm **(invited)**	The Role of Satellite-Based Precipitation in Monitoring and Predicting Drought for the Famine Early Warning Systems Network (FEWS NET) **Christa Peters-Lidard, Amy McNally, Chris Funk, Shraddhanand Shukla, Kristi Arsenault, Pete Peterson, Jossy Jacob, Augusto Getirana, Abheera Hazra, Greg Husak**
4:00-4:15pm	The Importance of Precipitation Information for the Water-Energy-Food (W-E-F) Nexus Sustainability **Richard Lawford**
4:15-4:30pm	Spatiotemporal Analysis of Compound Hot and Dry Years Across the United States **Mojtaba Sadegh, Mohammad Reza Alizadeh**
4:30-4:45pm	Embracing Uncertainty: A Risk-based Approach to Incorporation of Future Projections of Extreme Rainfall into Engineering Design **Ali Nazemi, Uttam Puri Goswami**

4:45-5:00pm	Questions and Group Discussion
5:00-7:30pm	Reception and Poster Session Presentations
7:30pm	Transportation to Hotels

THURSDAY JUNE 20, 2019
The Soroosh Sorooshian Hydrometeorology Symposium

8:00-9:00am	Registration and Breakfast

Session 5: Soroosh Sorooshian Tribute
Moderator: Efi Foufoula-Georgiou

9:00-9:30am **(invited)**	Contributions of Professor Soroosh Sorooshian to Four Decades of Advances in Hydrometeorology **Steven Burges**
9:30-9:45am	Automatic model calibration of numerical weather prediction models to improve short range precipitation forecasting **Qingyun Duan**
9:45-10:00am	Today's Earth - A Global Monitoring System of Hydrological Cycles based on Earth Observation from Satellites and a Terrestrial Modeling System **Taikan Oki, Kenshi Hibino, Kei Yoshimura, Hyungjun Kim, Dai Yamazaki, Akira Takeshima, Misako Kachi, Riko Oki, Kosuke Yamamoto, Yuta Ishitsuka**
10:00-10:15am	Regional Implication of Extremes for Water Demand in Food and Energy Systems **Ghassem Asrar, Mohamad Hejazi, Sean Turner, Yiyun Cui**
10:15-10:30am	Utilizing Remote Sensing and in situ Observations for Improved Quantification of Hydrologic Partitioning in Post-fire Watersheds in the Western U.S. **Terri S. Hogue**
10:30-11:00am	Coffee Break and Research Introductions

Session 6: Remote Sensing of Precipitation
Moderator: Remko Uijlenhoet

11:00-11:30am **(invited)**	Earth's Water Reservoirs in a Changing Climate **Graeme Stephens**
11:30-11:45am	Insights on Precipitation Estimation and Hydrologic Simulations in Cold Mountainous Basins Using Diverse Remote Sensing Observations **Ali Behrangi**
11:45am-12pm	Recent Developments of Satellite Precipitation Products and Data Systems at UCI CHRS **Phu Nguyen, Kuolin Hsu, Dan Braithwaite, Soroosh Sorooshian**
12:00-12:15pm	A Look at Typhoons Using Satellite-based Precipitation from NASA and NOAA **Jessica Sutton, Kathryn Lanyon, Venkat Lakshmi**
12:15-12:30pm	Questions and Group Discussion
12:30-1:30pm	Working Lunch – Subgroup Discussion on the Conference Themes

Session 7: Water Cycle Dynamics
Moderator: Christa Peters-Lidard

1:30-2:00pm **(invited)**	Land Water, Energy and Carbon Cycles Coupling Diagnosed From Remotely Sensed Global Observations **Dara Entekhabi**
2:00-2:15pm	Integrated Satellite-based Data Assimilation Systems for Monitoring and Predicting Water Cycle **Toshio Koike, Mohamed Rasmy, Hiroyuki Tsutsui, Katsunori Tamakawa, Rie Seto, Yohei Sawada**
2:15-2:30pm	It's Raining Bits: Trends in the Information Content of Daily Rainfall Persistence Across the U.S. **Allison Goodwell, Praveen Kumar**
2:30-2:45pm	On the Role of Montane Forests as Gatekeepers of Clouds and Precipitation in the Tropical Andes **Ana Barros**
2:45-3:00pm	Questions and Group Discussion
3:00-3:30pm	Coffee Break and Research Introductions

Session 8: Hydrologic Applications
Moderator: Terri Hogue

3:30-4:00pm **(invited)**	Human and Climate Impacts on Hydrologic Change in an Agricultural Landscape **Kristie Franz, David Dziubanski**
4:00-4:15pm	Hydrologic Investigations of Propagation of Errors in Rainfall to Hydrographs **Ganesh Ghimire, Witold Krajewski, Radoslaw Goska**
4:15-4:30pm	The Continued Importance of Global Climate Processes Monitoring: A GEWEX Perspective on Precipitation **Peter J. van Oevelen**
4:30-5:00pm	**Perspectives in Hydrometeorology and A Life in Science** **Soroosh Sorooshian**
5:00-6:00pm	Poster Session Presentations
6:30-8:00pm	**Conference Dinner and the Soroosh Sorooshian Hydrometeorology Symposium** **Moderator: Antonio Busalacchi**
8:00pm	Transportation to Hotels

FRIDAY JUNE 21, 2019

8:00-9:00am	Registration and Breakfast

Session 9: Remote Sensing of Precipitation
Moderator: Vincenzo Levizzani

9:00-9:30am **(invited)**	GPM Mission Status and NASA Decadal Survey Activities Related to Precipitation **Scott Braun**
9:30-9:45am	Atmospheric River Precipitation Characteristics Revealed by NASA GPM Ground Validation Observations in Complex Terrain **Stephanie Wingo, Walter Petersen**
9:45-10:00am	Evaluating the Skill of GPM-IMERG Satellite Precipitation Estimation Over the Mountains of Central Chile **Yazmina Rojas, Justin Minder**
10:00-10:15am	Enhancing GPM Constellation Retrievals Over Land With Dynamic Surface Information **Sarah Ringerud, Christa Peters-Lidard, Yalei You, S. Joe Munchak**

10:15-10:30am Questions and Group Discussion

10:30-11:00am Coffee Break and Research Introductions

Session 10: Hydrologic Applications
Moderator: Ana Barros

11:00-11:15am The Challenge and Opportunity of Global Hydrology: Integrating Multi-source Observations for Multi-scale Hydrology Study
Yang Hong, Jonathan Gourley

11:15-11:30am Study of Global River Basins for Hydrological Extremes Using Satellite Data and Model Outputs
Venkataraman Lakshmi, John Bolten

11:30-11:45am Remotely Sensed Data Assimilation for Extreme Events
Hamid Moradkhani

11:45-12:00pm Hydrological Cycle in the Heihe River Basin and Its Implication for Water Resource Management in Endorheic Basins
Xin Li

12:00-12:15pm North American Land Data Assimilation System Version 2.5: Real-time Evaluation, Operational Implementation, and Drought Monitoring at NCEP
Youlong Xia, Jack Kain, Jesse Meng, Helin Wei, Mike Ek, David Mocko, Christa Peters-Lidard, L. Gwen Chen, Muthuvel Chelliah

12:15-12:30pm Questions and Group Discussion

12:30-1:30pm Working Lunch – Subgroup Discussions on the Conference Themes

Session 11: Remote Sensing of Precipitation
Moderator: Sara Ringerud

1:30-2:00pm **(invited)** IMPACTS: A NASA Earth-Venture Suborbital-3 airborne Field Campaign to Investigate U.S. East Coast Snowstorms and Improve Remote Sensing of Snow
Lynn McMurdie, Gerald Heymsfield, Scott Braun, John Yorks

2:00-2:15pm Evaluating the Streamflow Simulation Capability of PERSIANN-CDR Daily Rainfall Products in Two River Basins on the Tibetan Plateau
Tiantian Yang, Xiaomang Liu

2:15-2:30pm	Opportunistic Sensing of Rainfall Using Microwave Links from Cellular Communication Networks in Africa and Asia **Thomas Van Leth, Aart Overeem, Jenny Prosser, Daniele Tricarico, Hidde Leijnse, Remko Uijlenhoet**
2:30-2:45pm	When Radar Calibration by in-situ Networks Becomes Misleading **Ioulia Tchiguirinskaia, Abdellah Ichiba, Igor Paz, Auguste Gires, Elektra Skouri-Plakali, Daniel Schertzer**
2:45-3:00pm	Questions and Group Discussion
3-3:30pm	Coffee Break and Research Introductions

Session 12: Remote Sensing of Precipitation
Moderator: Pierre Kirstetter

3:30-3:45pm	What on Earth is the Space/Time Structure of Rainfall Uncertainty? **Christian Kummerow, Alfonso Jimenez Alcazar, Francisco Tapiador**
3:45-4:00pm	Multi-Satellite Global Satellite Mapping of Precipitation - Design and Products **Tomoo Ushio, Tomoaki Mega, Takuji Kubota**
4:00-4:15pm	Validation of Second Generation Pole-to-Pole CMORPH **Robert Joyce, Pingping Xie, Shaorong Wu, Bert Katz**
4:15-4:30pm	Questions and Group Discussion
4:30-4:45pm	Closing Remarks and Plans for IPC13
5:00pm	Transportation to Hotels

Poster Presentations

Poster Session 1, Wednesday June 19, 2019

5:00-7:30pm

1.01 Cell-tracking for analysis of simulated Alpine thunderstorms
Timothy Raupach, Andrey Martynov, Luca Nisi, Yannick Barton, Alessandro Hering, Olivia Martius

1.02 A Random Forest-based Algorithm to Downscale Precipitation for Hyper-Resolution Hydrology
Yiwen Mei, Viviana Maggioni, Paul Houser, Yuan Xue

1.03 Statistical Characterization of Annual and Seasonal Daily Precipitation Extremes in Central Arizona
Giuseppe Mascaro

1.04 An evaluation of rainfall characteristics associated with hydro-disaster occurrences in the Lake Kyoga basin, using PERSIANN-CDR data
Jamiat Nanteza

1.05 Extreme Heat Events in a Semi-Arid Region Heighten Soil Respiration
Hassan Anjileli, Laurie S. Huning, Amir AghaKouchak, Hamed Moftakhari, Hamid Norouzi

1.06 Changing Characteristics of Aridity over Pakistan in the Twentieth Century
Kamal Ahmed, Nadeem Nawaz, Shamsuddin Shahid

1.07 High-resolution characterization of rainfall patterns during heavy precipitation events in the eastern Mediterranean
Moshe Armon, Francesco Marra, Yehouda Enzel, Efrat Morin

1.08 Regional extreme analysis from radar-based estimates
Edouard Goudenhoofdt, Laurent Delobbe, Patrick Willems

1.09 On the suitability of clustering techniques to classify meteorological drought
Arash Modaresi Rad, Mojtaba Sadegh, Davar Khalili

1.10 Extreme value analysis based on satellite multi-sensor precipitation products
Enrico Zorzetto, Marco Marani

1.11 Explore Forecast skill of HRRR on extreme events across CONUS
Haowen Yue, Mekonnen Gebremichael

1.12 Hydrometeorological extremes and their impacts in Kerala
Shadananan Nair Krishnapillai

1.13 Impact of the data assimilation of airborne cloud-profiling radar data on the prediction of heavy-precipitation events
Mary Borderies, Olivier Caumont, Julien Delanoe, Veronique Ducrocq, Nadia Fourrie, Pascal Marquet

1.14 Extreme rainfall from multiple event types and the Metastatistical Extreme Value distribution
Arianna Miniussi, Gabriele Villarini, Marco Marani

1.15 Spatial analysis of sub-daily rainfall time structure variability
Marek Kaspar, Vojtech Bliznak, Filip Hulec, Miloslav Muller

1.16 Extreme rainfall in spatial precipitation clusters: observations and a simple stochastic prototype
Fiaz Ahmed, J. David Neelin

1.17 Why daily precipitation intensities tend to follow Gamma distributions — theory and applications
Cristian Martinez-Villalobos, J. David Neelin, Angeline G. Pendergrass

1.18 The importance of warm rain processes in orographic enhancement of precipitation during atmospheric river conditions
Joseph Zagrodnik, Lynn McMurdie

1.19 Climate Projections and Drought: A Study of the Colorado River Basin
Noe Santos, Thomas Piechota, Sajjad Ahmad

1.20 Evaluation of precipitation extremes with respect to the size of the affected area
Miloslav Muller, Blanka Gvozdikova, Marek Kaa¡par, Petr Zacharov

1.21 Space-time Structure of Subseasonal Indian Monsoon Droughts
Venugopal V., Pritam Borah, Jai Sukhatme, B. N. Goswami

1.22 A Contribution-weighted Rainrate View of Indian Monsoon Extremes
Vaibhav Bathri, Venugopal V.

1.23 Applying the adjusted CFSR to predict Rainfall data
Mohamed Mokhtar, Abdin Salih, Adil Elkhider, Salih Hamid

1.24 Forest fires impact and processes of desertification analysis with remote sensing data in semi arid lands in Algeria
Ahmed Zegrar, Nadjla Bentekhici

1.25 Polarimetric Radar Observations over the Tropical Oceans
Steven Rutledge, V Chandrasekar

1.26 Evaluation of Ground-Based Precipitation with Satellite-Based Model Observations over West Africa
Samuel Akande, Olajomoke Jejelola

1.27 The NCEP's Climatology-Calibrated Precipitation Analysis (CCPA) Product and Its Applications
Yan Luo, Ying Lin, Jason Levit, Yuejian Zhu, Dingchen Hou

1.28 Detecting Convective Class to Enhance PMW Satellite Precipitation Estimates
Veljko Petkovic, Marko Orescanin, Pierre Kirstetter, Christian Kummerow, Ralph Ferraro

1.29 Error Modeling of Passive Microwave Precipitation Products over Complex Terrain
Yagmur Derin, Emmanouil Anagnostou, Ehsan Bhuiyan, Marios Anagnostou, John Kalogiros

1.30 Intercomparison of radar rainfall nowcasting techniques for the Netherlands
Ruben Imhoff, Claudia Brauer, Aart Overeem, Albrecht Weerts, Remko Uijlenhoet

1.31 Estimating raindrop size distributions using microwave link measurements
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1.65 Looking behind the curtain of advanced snowpack estimation in the Sierra Nevada, CA
Kayden Haleakala, Steve Margulis, Mekonnen Gebremichael

1.66 Life Cycle of Vertical Scale Invariance Structure of Wind and Moisture Fields during Cold Air Intrusions with Implications for the Predictability of Orographic Precipitation Extremes in the Andes
Masih Eghdami, Ana Barros

1.67 Multi-sensor and Modeling Assessment of Vegetation and Precipitation Changes Influenced by ENSO Events in Saudi Arabia
Hesham El-Askary, Wenzhao Li, Mohamed Qurban, Mohammad H. Makkawi Ashri, Thomas Piechota

1.68 Satellite-based Estimates of Groundwater Depletion in Basin of Sinai Peninsula, Red Sea, East Coast and Western Desert and Delta in Egypt
Jet Li, Wenzhao Li, Thomas Piechota, Hesham El-Askary

1.69 Estimating Tropical Cyclone Precipitation Risk in North America from Observations and Models
Laiyin Zhu

1.70 Impact of Climate Variability on Ecohydrology of Upper Alaknanda Basin Western Himalaya, India
Bindhy Wasini, Pandey Suman, Saurabh Abhay, Shankar Prasad

1.71 Stationarity considerations in stochastic-dynamic hydrometeorological models
Alin-Andrei Carsteanu, Cesar Aguilar Flores

1.72 Evaluating fire-induced hydrologic responses with a dynamic vegetation model
Lauren Lowman, Ana Barros

1.73 Simulating Precipitation Using a Climate-Informed k-NN Algorithm
Saman Armal, Naresh Devineni, Nir Krakauer, Reza Khanbilvardi

Poster Session 2, Thursday June 20, 2019

5:00-6:00pm

2.01 Rainfall and Flood Frequency Analysis using Stochastic Storm Transposition and Precipitation Remote Sensing
Daniel Wright, Guo Yo

2.02 The Simplified Metastatistical Extreme Value formulation (S-MEV): modeling extreme precipitation emerging from multiple synoptic conditions
Francesco Marra, Davide Zoccatelli, Moshe Armon, Efrat Morin

2.03 Exploring the relationship between cyclone-related precipitation and stability
Katherine Towey, James Booth, Catherine Nau

2.04 Spatial extreme precipitation modeling using satellite information and Bayesian hierarchical models
Mohammad Faridzad, Tiantian Yang, Kuolin Hsu, Soroosh Sorooshian

2.05 Analysis of changes in precipitation characteristics over the contiguous USA in recent decades
Iman Mallakpour, Mojtaba Sadeghi, Hamidreza Mosaffa, Mojtaba Sadegh, Amir AghaKouchak

2.06 Atmospheric River-CONNECT (ARC): Lifecycle AR detection with machine learning
Eric Shearer, Phu Nguyen, Soroosh Sorooshian, Kuo-lin Hsu, Scott Sellars, Brian Kawzenuk

2.07 DiPMaC: Disaggregation Preserving Marginals and Correlations
Simon Michael Papalexiou, Yannis Markonis, Federico Lombardo, Amir AghaKouchak, Efi Foufoula-Georgiou

2.08 Studying Extreme Land Surface Temperature Records of the Hottest Place on Earth
Marzi Azarderakhsh, Amir AghaKouchak, Satya Prakash

2.09 An Advanced Deep Learning framework for Near-real-time Precipitation Estimation from New Generation of Geostationary Multispectral Satellite Imageries - Application of the conditional Generative Adversarial Networks (cGANs)
Negin Hayatbini, Bailey Kong, Kuolin Hsu, Phu Nguyen, Soroosh Sorooshian

2.10 A review of global precipitation datasets: data sources, estimation, and intercomparisons
Chiyuan Miao

2.11 The ongoing challenge of retrieving the fine-scale spatial and temporal variability of precipitation from Satellite
Clement Guilloteau, Efi Foufoula-Georgiou

2.12 Probabilistic Quantitative Precipitation Estimation
Pierre Kirstetter, Shruti Upadhyaya, Micheal Simpson

2.13 The role of X-band radars in rainfall estimation for urban and complex terrain applications
Chandra V Chandrasekar

2.14 Precipitation Estimation from Remotely Sensed Information Using Deep Neural Networks
Mojtaba Sadeghi, Ata Akbari Asanjan, Phu Dinh Nguyen, Mohammad Faridzad, Kuolin Hsu, Soroosh Sorooshian

2.15 On the Evaluation of Micro Rain Radar: A comparative study with Disdrometers and S-band Polarimetric Radar.
Elisa Adirosi, Luca Baldini, and Ali Tokay

2.16 Application of Recurrent Neural Networks in spatiotemporal precipitation forecasts
Ata Akbari Asanjan, Tiantian Yang, Kuolin Hsu, Soroosh Sorooshian

2.17 Translating the Physics of Snowfall to Radar-Based Validation of GPM
Walter Petersen, Claire Pettersen, Pierre Kirstetter, Dmitri Moisseev, Annakaisa von Lerber, Mark Kulie, David Marks, Ali Tokay, David Wolff, Hudak David

2.18 Comparison of precipitation estimates using a GPM-constellation retrieval scheme
Chris Kidd, Sarah Ringerud, Toshihisa Matsui

2.19 Towards Consistency between the Near-Surface and Vertical Precipitation Structure in the GPM Precipitation Constellation Data Record
Francis J Turk, Nobuyuki Utsumi, Ziad S Haddad, Pierre Kirstetter

2.20 Identifying Cloud Types from New Generation of Geostationary Satellite Multispectral Images for Precipitation Estimation using Deep Learning Techniques
Vesta Afzali Gorooh, Phu Nguyen, Kuo-lin Hsu, Soroosh Sorooshian

2.21 25th Anniversary of a scaling law for the raindrop size distribution
Remko Uijlenhoet

2.22 Constraining the deconvolution of oversampled satellite microwave observations to enhance the spatial resolution of rain estimates
Ziad Haddad

2.23 Regime-Dependent Differences in Active Satellite Rainfall Products
Ethan Nelson, Matthew Lebsock

2.24 A millennial-scale perspective on modern precipitation trends, mean and variance in the Levant based on reconstructed precipitation of the past 4500 years
Efrat Morin, Tamar Ryb, Ittai Gavrieli, Yehouda Enzel

2.25 From scalar to vector multifractal precipitation modelling
Daniel Schertzer, Ioulia Tchiguirinskaia

2.26 Estimates of Accumulated Rainfall of Mei-Yu Front in Taiwan using GSMaP Measurements
Nan Ching Yeh, Yao-Chung Chuang, Hsin-Shuo Peng, Kuo-Lin Hsu

2.27 Future responses of the intertropical convergence zone under global warming
Antonios Mamalakis, James Randerson, Jin-Yi Yu, Michael Pritchard, Gudrun Magnusdottir, Padhraic Smyth, Paul Levine, Efi Foufoula-Georgiou

2.28 Improvement of Winter Climate Forecasts for the Great Lakes Region with a Coupled Climate Forecast System-Lake model
Jiming Jin, Zhemin Lv, Shaobo Zhang, Yihua Wu, Michael Ek

2.29 Impacts of fuel moisture and fuel treatment on wildland fire behavior
Tirtha Banerjee, Rod Linn

2.30 CloudSat Based Assessment of GMI and ATMS Snowfall Observation Capabilities
Daniele Casella, Andrea Camplani, Anna Cinzia Marra, Paolo Sanò, Jean-François Rysman, Mark Kulie, Lisa Milani, Giulia Panegrossi

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Oral Sessions

Session 1: Remote Sensing of Precipitation

NASA's Studies of Earth's Water Cycle

Jack Kaye,[†] Gail Skrofonick-Jackson, Jared Entin, Bradley Doorn

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The US National Aeronautics and Space Administration (NASA) maintains a vigorous program that studies the Earth's water cycle using satellites, aircraft, surface-based measurement, and computational modeling. Many of the reservoirs and fluxes that are critical to the water cycle are regularly observed from NASA's fleet of orbiting satellites, including elements of the terrestrial water cycle, such as precipitation, soil moisture, atmospheric moisture, snow properties, ground water change, as well as related distributions of ice and ocean properties (including salinity). Aircraft campaigns provide additional insight, both in terms of focused process knowledge and calibration/validation support for satellite missions. Models are used to test hypotheses, produce integrated data sets (e.g., through data assimilation and reanalysis), and prediction for future evolution of the global water cycle. These activities are carried out in the interdisciplinary perspective of Earth System Science, so that relationships between the water cycle and other Earth system components (e.g., the global carbon cycle) can be examined. NASA's Applied Science program helps serve as the flexible bridge to make the connection between NASA's satellite and research programs and the many current and potential users who can use NASA-provided information to improve the products and services that they provide to end users. NASA's water-related programs are carried out in close cooperation with our interagency and international partners (both research and operational) and the global user community. The Earth Science Technology Office develops new technologies that can enable new, improved, and or less costly observations for the future.

Keywords: Water cycle, satellite, remote sensing, airborne science, precipitation, soil moisture, snow

Research Highlights from the International Precipitation Working Group (IPWG)

Viviana Maggioni[1†], Philippe Chambon[2], Ziad Haddad[3], Dong-Bin Shin[4], Vincenzo Levizzani[5], Ralph Ferraro[6]

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The International Precipitation Working Group (IPWG) is a permanent International Science Working Group (ISWG) of the Coordination Group for Meteorological Satellites (CGMS), co-sponsored by CGMS and the World Meteorological Organization (WMO). IPWG provides a forum for the international scientific community to address issues and challenges related to satellite-based precipitation retrievals. Through partnerships and biennial meetings, the group promotes the exchange of scientific and operational information between the producers of precipitation measurements, the research community, and the user community. Specifically, IPWG furthers the refinement of current estimation techniques and the development of new methodologies for improved global precipitation measurements, together with the validation of the derived precipitation products with ground-based precipitation measurements. IPWG promotes international partnerships, provides recommendations to the CGMS, and supports upcoming precipitation-oriented missions. This presentation will highlight some of the latest research findings from the IPWG working groups.

IMERG V06: The Role of IR Precipitation

Jackson Tan[1†], George Huffman[2], David Bolvin[3], Eric Nelkin[3]

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The Integrated Multi-satellitE Retrievals for GPM (IMERG) product, computed by the NASA Global Precipitation Measurement (GPM) mission science team, merges intercalibrated observations from an international constellation of satellites to provide precipitation estimates on a 0.1° 0.1° grid every half-hour globally. IMERG is used in a wide range of operational and research applications, from modeling floods and landslides to improving extreme weather predictions to understanding global precipitation patterns. The latest version, IMERG V06, is a retrospective processing of IMERG to create a homogeneous record starting from 1998 and extend the coverage to the poles, replacing the widely used TRMM Multisatellite Precipitation Analysis datasets.

One key component of IMERG is the PERSIANN-CCS algorithm, which provides IR precipitation estimates for the Kalman filter to the morphing scheme. This presentation will discuss the role of IR precipitation in IMERG V06, which has increased importance in the TRMM era due to fewer passive microwave sensors. On top of being an input to the Kalman filter, IR precipitation estimates are also mobilized in V06 to fill in gaps that emerged due to a revised processing approach and the sparse constellation in the early TRMM era. Furthermore, quality control measures are implemented in V06 to mitigate potential data issues. These improvements are part of the continuing development of IMERG to produce high-resolution estimates of precipitation across the TRMM and GPM eras, enabling applications such as revealing the diurnal cycle globally, which will be demonstrated in closing.

Keywords: GPM, IMERG, PERSIANN-CCS, IR precipitation, Kalman filter, V06, TRMM

Session 2: Hydrologic Applications

Strange Floods: The Upper Tail of Flood Peaks in the U.S.

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The strangest flood in U.S. history is arguably the June 14, 1903, Heppner, Oregon, flood. Strange floods and the storms that produce them will be examined through analyses of records from more than 8,000 stream gauging stations in the U.S. and through hydrometeorological analyses of the storms that produce the most extreme floods. Close examination of several events, including the 1903 Heppner flood, a monsoon thunderstorm flood in the canyons of Utah in 2015, and the Great Mississippi River flood of 1927, will also be used to assess the nature of extreme floods.

Insight into the Changing Characteristics of Global Snow Droughts

Laurie Huning[†], Amir AghaKouchak

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Seasonal snowpack provides freshwater for domestic, municipal, and agricultural uses and supports a variety of ecosystems and industries across the globe. However, a framework for characterizing snow drought conditions does not currently exist. Snow droughts, which are manifested as low or below-average snow water equivalent (SWE), can therefore stress a number of sectors, including water resources, hydropower generation, tourism, and economics, across the globe. We present a framework for characterizing snow drought conditions and provide insight into how they are changing in both space and time across various regions around the world. In particular, we characterize the changing nature of snow drought severity, duration, intensity, and extent from regional to global scales at sub-seasonal to seasonal time scales.

Forecast Verification Applications at the Australian Bureau of Meteorology

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The Australian Bureau of Meteorology produces a suite of automated objective and expert-enhanced hydrometeorological forecasts. These are used to inform flood warnings and other environmental prediction applications. The Bureau has been interested in automation of forecast production, while retaining the value added by meteorologists, which has been supported by a large body of forecast verification work. The organization has also greatly expanded its real-time verification activities.

Many national hydrometeorological services produce ensemble Numerical Weather Predictions. However, most countries' public forecasts include a probability of precipitation (PoP), a deterministic forecast total, a weather icon, and/or a text narrative (e.g., "A shower or two, thunderstorms likely"). Australia is unusual in that its public forecasts are derived from expert-enhanced probabilistic national grids. These include PoP as well as 50%, 25%, and 10% chance of exceeding a given rainfall amount. Users can also access products related to the % chance of getting more than a given threshold, e.g., 10 mm. The "first cut" of the official forecast is based on an Optimal Consensus Forecast (OCF) that is bias-adjusted using recent station observations.

This talk will present some of the various ways that the Bureau verifies its hydrometeorological forecasts. This includes scorecards that evaluate the performance of OCF versus Official forecasts. Forecasters use interactive dashboards for map-based and time-series views of recent performance. Automated systems calculate daily, weekly, monthly, and annual performance metrics. In case of extreme conditions (e.g., extreme weather, an extreme forecast error, or a large difference in skill between OCF and Official), push alerts with custom reports are emailed to key stakeholders. There are challenges presenting the information to non-technical audience, and the Bureau has explored a variety of options, which will be discussed.

Keywords: Forecast verification, accuracy, performance, operational forecasting

Data-driven Distributionally Robust Modeling of Extremes

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In the context of extreme value modeling, we study how numerical estimations can be robustified against inaccurate assumptions about the true underlying probability model. These types of problems have been studied in various fields where natural stochastic processes are incorporated into the model as uncertain parameters. We employ the Kantorovich metric in order to construct an ambiguity neighborhood around our baseline model $\hat{P}$. The baseline is simply assumption-free and is derived from the observed historical phenomena. The purpose of this study is to shed light on the risks associated with extreme events for which a true probability model does not exist. We choose Average Value at Risk (AV@R) as a coherent risk measure to avoid deriving wrong conclusions about the risks beyond one single statistic. Our case studies are extreme (i.e., annual maxima) precipitation observations from 20 basins across the Western and Eastern United States.

Session 3: Water Cycle Dynamics

Process-oriented Diagnostics Framework and Stochastic Process Models for Precipitation

J. David Neelin[1†], Yi-Hung Kuo[1], Fiaz Ahmed[1], Cristian Martinez-Villalobos[1], Xianan Jiang[2], Eric Maloney[3], Allison Wing[4], Andrew Gettelman[5], Yi Ming[5], John Krasting[5]

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Process-oriented diagnostics (PODs) aim to help to constrain climate and weather model parameterizations by confronting the models with statistics directly involved in the physical processes being represented, while providing physical understanding of the processes. This presentation consists of two parts. 1) A brief overview of a framework for PODs being developed by NOAA's Model Diagnostics Task Force (MDTF). Several MDTF diagnostics package contributions are related to precipitation, including PODs for warm-rain micro-physical processes, tropical and extratropical cyclones, diurnal precipitation cycle, lake-effect snow, deep convective transition, and the Madden Julian oscillation. 2) An example of taking a particular POD for convective precipitation and using it to inform a process model to enhance understanding of the physical underpinnings. If a given model behaves poorly—for instance, in the expected precipitation as a function of water vapor and temperature, or in moisture distribution between dry and precipitating regimes, or between weakly and strongly precipitating regimes, or in the propensity to produce large precipitation clusters, or in the precipitation probability distribution—the question remains of which among the series of connected processes is most in need of revision. Stochastic process models based on simplifications of the full climate model equations can aid in understanding some of the connections between underlying physics and the precipitation statistics. Here, a set of properties exhibited by the models and observations is shown to arise from relatively simple postulates. Analogs to some of the error types exhibited in certain models are demonstrated as a means of generating hypotheses. Pathways to making such comparisons ever more quantitative are outlined.

Keywords: Process-oriented diagnostics, stochastic model

Convective/Stratiform Classification from Passive Microwave Imagers: Implications for Improved Precipitation Retrievals, for Developing the Climatology of Precipitation Types, and for Better Understanding of the Water and Energy Cycles

Svetla Hristova-Veleva[1], Eun-Kyoung Seo[2], Ziad Haddad[1], Sahra Kacimi[1], Ousmane Sy[1], Jeffrey Steward[3]

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Currently there are differences in precipitation trends, as determined from radar and radiometer estimates (Henderson et al., 2017 and 2018), with implications for understanding the Water and Energy Cycles. Henderson et al. traced these differences to issues related to the radiometer retrieval by the GPROF Bayesian algorithm, which did not properly account for the convective and stratiform fractions within the satellite FOV.

Acknowledging the importance of identifying the dominant precipitation type in a given satellite FOV, we developed an algorithm that provides rain detection and classification based on passive microwave observations alone: PMW_CLASS (Hristova-Veleva et al., 2018). This algorithm is being used as the initial step in KGPM precipitation retrieval to help select the most appropriate retrieval database to be used for a particular observation, selecting from a couple of different databases designed to represent the characteristics of different precipitation types. Our goal is to increase the estimation's accuracy and to decrease its uncertainty. This presentation will describe the algorithm and present the results of its validation. Furthermore, we will discuss the proposed use of the algorithm to obtain a global climatology of oceanic precipitation.

Currently precipitation type classification over the global oceans is provided only by space-based radars such the GPM's DPR and NASA's CloudSat. Although they are considered the gold standard, today only two of these radars are flying in space. This factor, in addition to the very narrow radar swaths, severely limits our ability to obtain a global climatology. PMW_CLASS will allow such precipitation classification based on the multitude of conically-scanning radiometers flying today (GMI, AMSR2, the SSMISs), thus greatly expanding our ability to develop a climatology of these two types of precipitation and to study their geographical variability and trends on a number of spatio-temporal scales.

Keywords: Convective, stratiform, convective/stratiform classification, precipitation estimation, radiometer retrievals, precipitation types

Ensemble-based Simultaneous State and Parameter Estimation for Hydrological Modeling and Beyond

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Among Professor Sorooshian's myriad contributions, he and his colleagues are the first to propose the use of the ensemble Kalman filter for dual state-parameter hydrological models (Moradkhani, Sorooshian et al. 2005, Advances in Water Resources). This approach not only allows simultaneous state and parameter estimation but also can be used to quantify various sources of uncertainties in hydrological modeling systems, including uncertainties in both physical processes and model representations as well as in observations. Here I will present an extension of this framework for simultaneous state and parameter estimation and uncertainty quantification of a local watershed in central Pennsylvania that is part of an NSF-sponsored Critical Zone Observatory, using a fully coupled hydrology and land surface model (FLUX-PIHM). Also presented will be the further expansion and applications of the ensemble-based simultaneous state and parameter estimation framework to a broad range of geoscience and environmental processes, which include but are not limited to atmospheric boundary layer processes and air-sea interactions, carbon cycle data assimilation, ice stream modeling, and uncertainty quantification, as well as paleoclimate reanalysis and observation impacts and targeting.

Keywords: Ensemble Kalman filter, coupled hydrology and land surface modeling, parameter estimation, uncertainty quantification

Session 4: Hydrologic Applications

The Role of Satellite-Based Precipitation in Monitoring and Predicting Drought for the Famine Early Warning Systems Network (FEWS NET)

Christa Peters-Lidard[1†], Amy McNally[2], Chris Funk[3], Shraddhanand Shukla[4], Kristi Arsenault[5], Pete Peterson[4], Jossy Jacob[6], Augusto Getirana[2], Abheera Hazra[2], Greg Husak[4]

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Since 1985, the U.S. Agency for International Development's Famine Early Warning Systems Network (FEWS NET) has been providing evidence-based guidance for effective humanitarian relief efforts. FEWS NET depends on a Drought Early Warning System (DEWS) to help understand, monitor, model, and predict food insecurity. One component of this DEWS is the FEWS NET Land Data Assimilation System (FLDAS; McNally et al., 2017). FLDAS uses remotely sensed precipitation and reanalysis inputs to drive land surface hydrologic models, with the goal to produce a global archive of historic hydroclimate conditions as well as routine updates for monitoring current events (1982-present). Key to the accuracy of FLDAS is the remotely sensed precipitation inputs from the USGS and UCSB Climate Hazards Group InfraRed Precipitation with Station (CHIRPS; Funk et al., 2015) daily rainfall dataset, and MERRA-2, which contains global, hourly atmospheric forcing fields that can be used to temporally disaggregate the daily CHIRPS.

CHIRPS is a 30+ year quasi-global rainfall dataset spanning 50°S-50°N starting in 1981 to near-present. The CHIRPS algorithm 1) is built around a 0.05° climatology that incorporates satellite information to represent sparsely gauged locations; 2) incorporates daily, pentadal, and monthly 1981-present 0.05° Cold Cloud Duration (CCD)-based precipitation estimates; 4) blends station data to produce a preliminary information product with a latency of about 2 days and a final product with an average latency of about 3 weeks; and 4) uses a novel blending procedure incorporating the spatial correlation structure of CCD-estimates to assign interpolation weights. We will describe the performance of CHIRPS and FLDAS for historical drought assessment, monitoring, and forecasting via bias-correction and spatial disaggregation (BCSD)-based downscaling of subseasonal to seasonal precipitation forecasts.

The Importance of Precipitation Information for Water-Energy-Food (W-E-F) Nexus Sustainability

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Food security is generally assured when water, energy, and arable land are abundant, but it becomes vulnerable when shortages occur in these essential resources. The W-E-F Nexus concept applies to an integrated approach to managing the three sectors (water, energy, and food). It is anticipated that this approach will lead to improved resource efficiencies and food security, and to more coherent resource and environmental policies. Data and information on water availability is critical to the Nexus planning and decision making processes. Precipitation is one of the most critical drivers for all resources within the W-E-F Nexus. Furthermore, spatial and temporal precipitation distribution strongly influences the W-E-F Nexus elements and their interactions. Given the links between precipitation and the W-E-F Nexus, one would expect that many of the effects of climate variability and change on the Nexus would be transmitted through changes in precipitation. This presentation provides a general introduction to precipitation and climate's influence on the three sectors and their interactions. It will also discuss the important aspects of precipitation data (in terms of resolutions, frequencies of occurrence, amounts, intensities, and lag times, and for precipitation forecasts with different time horizons) needed for data and information systems serving the Nexus. The possibility will also be considered that the W-E-F Nexus could be a gateway to assessments of the Sustainable Development Goals' needs for precipitation data.

Keywords: Precipitation, water-energy-food nexus, information system

Spatiotemporal Analysis of Compound Hot and Dry Years Across the United States

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In the face of a warming climate, severe climate events (droughts, heat waves, floods, etc.) are increasing in terms of frequency, magnitude, severity, and spatial extent. Moreover, climatic extremes often occur simultaneously (e.g., droughts and heatwaves) or successively (e.g., extreme precipitation after wildfire), which can escalate their adverse societal impacts. These extremes are referred to as compound events. In this study, we evaluate the frequency of dry and hot years in a multivariate framework using copulas. We show that there is a statistically significant correlation between total annual precipitation and mean annual temperature across the United States, and analyze temporal trends in both variables. We then derive univariate and bivariate return period levels for excess heat and precipitation deficits. By comparing the number of observed 25-, 50-, and 100-year events in three quarter-century periods (1943-1967, 1968-1992, 1993-2017), we show that while a majority of U.S. climate divisions observe an increasing trend in numbers of hot years, the precipitation deficit doesn't portray a significant trend. However, the compound hot and dry years are increasing in number across the U.S., at a rate that surpasses that of the hot years. Hence, compound events are growing increasingly frequent. Moreover, we show that the spatial extent of compound hot and dry years is also growing at a rate that surpasses the spatial growth of hot and dry years analyzed individually. Spatial correlation analysis, through Moran's I, further confirms that the spatial extent of compound hot and dry years has been increasing in recent years.

Keywords: Drought, excess heat, compound events, copulas, global warming

Embracing Uncertainty: A Risk-based Approach to Incorporating Future Projections of Extreme Rainfall into Engineering Design

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Intensity-Duration-Frequency (IDF) curves summarize the characteristics of historical extreme rainfall events under a range of durations and return periods. Despite multiple limitations, IDF curves are still the main engineering tool for designing storm water management systems worldwide, particularly at urban scales. However, application of historical IDF curves implies that the future characteristics of extreme rainfall remain unchanged, an assumption that raises major questions considering climate change's unfolding effects. The engineering community, however, often hesitates to use future projections of rainfall extremes due to the uncertainties in future concentration pathways, GCM projections, and downscaling techniques. Here, it is shown that uncertainty is an integral part of the IDF curves, even under historical conditions, due to the parametric uncertainty in fitted extreme distributions. Considering multiple Canadian case studies, we argue that in many circumstances, the uncertainty in historical IDF curves is in fact larger than the uncertainty in multi-model ensemble projections of rainfall extremes under future conditions. Accordingly, we suggest a risk-based approach to embrace, rather than to ignore, uncertainty in IDF curves and on which to base engineering design under future conditions.

Keywords: Rainfall extremes, IDF curves, future projections, engineering design, risk-based approach

Session 5:   Soroosh Sorooshian Tribute

Contributions by Professor Soroosh Sorooshian to Four Decades of Advances in Hydrometeorology

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I start with identifying some of the basic tools of hydrology and meteorology that were in use at the start of Professor Sorooshian's career and trace his exceptional contributions to advancing the field of hydrometeorology with time that reflect evolving computing capability and observation systems. Emphasis is placed on the inventive nature of research and on his contributions with colleagues to test and develop model calibration techniques that are at the heart of modern hydrology research and practice. The need for improved measurements of precipitation inputs to models for all aspects of hydrology and water resource engineering is addressed with attention to his work with colleagues on the derivation of precipitation fields from observations made by modern Earth-orbiting satellites.

Automatic Model Calibration of Numerical Weather Prediction Models to Improve Short-range Precipitation Forecasting

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Automatic model calibration refers to the process in which a dynamical model's parameters are tuned using mathematical optimization methods to minimize the aggregated difference between model predictions and corresponding observations. Thus far, this approach has not been widely practiced in numerical weather predictions because of difficulties related to model complexities, such as high dimensionalities of model parameters and model outputs, and the extraordinary demand for computational resources. This talk introduces a platform called Uncertainty Quantification Python Laboratory (UQ-PyL) to perform automatic calibration of a numerical weather prediction model as the WRF model. The key functions of UQ-PyL include design of experiment (DoE), uncertainty analysis, global sensitivity analysis, surrogate modeling, and multi-objective optimization. Those functions will be demonstrated using the WRF model with a case study involving short-range precipitation forecasting in the Greater Beijing region. We found that automatic model calibration can improve the WRF model's predictive skill significantly according to numerous skill metrics.

Keywords: Numerical weather predictions, UQ-PyL, uncertainty analysis, global sensitivity analysis, multi-objective optimization

Today's Earth: A Global Monitoring System of Hydrological Cycles Based on Earth Observation from Satellites and a Terrestrial Modeling System

Taikan Oki[1†], Kenshi Hibino[2], Kei Yoshimura[3], Hyungjun Kim[3], Dai Yamazaki[3], Akira Takeshima[4], Misako Kachi[5], Riko Oki[5], Kosuke Yamamoto[5], Yuta Ishitsuka[5]

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Today's Earth (TE) is a global monitoring system of hydrological cycles at JAXA/EORC. Various water-related quantities at the land surface, such as river discharge, snow depth, soil moisture, and flood area fraction, are obtained from terrestrial modeling systems utilizing reanalysis dataset, JRA-55, and satellite derived data; rainfall from the Global Satellite Mapping of Precipitation (GSMaP) and solar radiation from Aqua and Terra MODIS are provided by the JASMES system. The terrestrial modeling system simulates energy and water balances over global land surface using MATSIRO (Minimal Advanced Treatments of Surface Interaction and Runoff) (Takata et al., 2003) version 5 (MATSIRO5; Nitta et al., 2014) and calculates river-oriented quantities, such as discharge and flood area fraction, by the CaMa-Flood global hydrodynamic model (Yamazaki et al., 2011).

Validation studies on the TE were performed for in-situ observations of snow depth, soil moisture, and river discharge, and it was found that TE can estimate these quantities with comparable or better accuracies than standard satellite estimates from GCOM-W/AMSR-2. Soil moisture was well estimated using remotely-sensed precipitation data (GSMaP) compared to precipitation forcing from reanalysis or solar radiation from the MODIS dataset in terms of error indices of root mean square error, bias, and mean absolute error; however, GSMaP did not estimate snow depth and daily river discharge well.

In addition to the global model, the TE developer group is currently developing a regional version of the system at 1km resolution around the Japan area, and also will introduce an example of ensemble flash flood hindcasting using high-resolution TE for a severe flash flood event that occurred in September 2015.

Keywords: LDAS, satellite precipitation product, real-time forecasting

Regional Implication of Extremes for Water Demand in Food and Energy Systems

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Supply and demand for water from all available sources are affected by extreme environmental conditions, especially under projected warmer environmental conditions. Such effects already are being observed in major food-producing regions of the world, which have greater needs for water for energy. Providing solution-based approaches for efficient and effective management and use of available water resources, based on a holistic assessment of these interrelated systems (i.e., food, energy, water), together with available economically feasible technologies (irrigation, genomics/genetics, innovative agronomic practices), can benefit decisions and investments in systems that are more sustainable and resilient to perturbations caused by extreme environmental conditions. We will present a summary of several model-based studies that identify major food-producing regions of the world superimposed with current and future water resource conditions to illustrate the need for such a holistic approach for analysis/assessment of these systems. We will highlight some key observations/data and modeling needs for this purpose.

Keywords: Extremes, water-energy-food, human-Earth systems interactions

Utilizing Remote Sensing and In Situ Observations for Improved Quantification of Hydrologic Partitioning in Post-fire Watersheds in the Western U.S.

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The number of wildfires in the western United States is increasing annually, on average costing billions of dollars a year in suppression efforts and causing an increase in flood events destructive to both life and infrastructure. The greatest increases in fire frequency in the U.S. are being observed in mid-elevation forests, including the northern Rockies, Sierra Nevada, southern Cascades, and western Coast Ranges in Northern California and southern Oregon. This marked change is strongly correlated with climate change impacts, including warmer springs and longer dry seasons, commonly occurring with reduced winter precipitation rates and earlier spring snowmelt. In addition to the immediate impacts on watershed processes— floods, debris flows, and degradation of water quality—post-fire watersheds can exhibit longer-term changes in water yield. There are some disparities in post-fire water yield behavior, owing to the transient nature of climate patterns, variations in basin geomorphology, and vegetation recovery patterns. This presentation will provide an overview of recent work on the use of remote sensing and in situ observations to better quantify hydrologic partitioning in Western watersheds after fire, including short- and long-term changes in annual water yield and recovery trajectories. Results will ultimately provide water managers with new tools and information to improve mitigation and treatment efforts as well as plan for long-term water supply changes in the arid West.

Keywords: Wildfires

Session 6: Remote Sensing of Precipitation

Earth's Water Reservoirs in a Changing Climate

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The talk will review progress toward understanding Earth's water reservoirs and the interactions between. Discussion of this progress is developed around interpretation of observations from the latest technologies used in Earth Observations. The focus will be mostly global, and put into the context of global mean sea level rise (GMSL). A particular emphasis is on the interactions between the various reservoirs and how these interactions not only impact GMSL but also Earth's hydrological cycle.

Insights into Precipitation Estimation and Hydrologic Simulations in Cold Mountainous Basins Using Diverse Remote-sensing Observations

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Uncertainties in quantifying precipitation over cold mountainous regions have been large, partly due to the sparseness of in situ data, snow on the ground, orographic enhancement, and several complicating processes affecting remote-sensing techniques. These uncertainties must be reduced to improve hydrologic simulation of water resources, water and energy budget analyses, understanding of physical processes, and assessment of reanalyses and climate models. This presentation summarizes our recent studies over mountainous regions in the western United States and Tibetan Plateau, where we utilize new remote-sensing observations to gain additional insights into precipitation amounts and distribution. These new resources include the NASA Airborne Snow Observatory (ASO), Gravity Recovery and Climate Experiment (GRACE), Cloud-Sat Cloud Profiling Radar (CPR), and the global precipitation measurement (GPM) mission. Furthermore, we show how uncertainties in precipitation estimation and other forcing data (such as temperature) can impact simulation of the key hydrologic variables (e.g., runoff and snow water equivalent) and partitioning between rainfall and snowfall. The presentation also discusses uncertainties that are related to point versus areal measurement and challenges in calculating proper correction factors to mitigate the gauge-undercatch problem in cold regions.

Keywords: Precipitation, remote sensing, mountain, snow

Recent Developments of Satellite Precipitation Products and Data Systems at UCI CHRS

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Precipitation measurements with high spatiotemporal resolution are a vital input for hydrometeorological and water resources studies; decision-making in disaster management; and weather, climate, and hydrological forecasting. Over the past two decades, Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) products, including PERSIANN, PERSIANN-CCS and PERSIANN-CDR, have been produced and incorporated in a wide range of studies and applications.

While algorithms that exclusively use satellite infrared data as input are attractive owing to their rich spatiotemporal resolution and near-instantaneous availability, their sole reliance on cloud-top brightness temperature (T_b) readings causes over-predictions in wet regions and under-predictions in dry regions—this is especially evident over the Western Contiguous United States (CONUS). We introduce a new algorithm, the Precipitation Estimations from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) Dynamic-Infrared Rain rate model (PDIR), which utilizes climatological data to construct a dynamic (e.g. laterally shifting) T_b-rain rate relationship that better estimates precipitation totals and distributions, notably over the Western CONUS. Validation of PDIR over the Western CONUS shows its high degree of skill, notably at the annual scale, where it is superior to other satellite-based products. Analysis of two extreme landfalling atmospheric rivers show that PDIR is superior to other existing satellite precipitation products in detecting heavy rainfall and possesses the potential to be effective in real-time monitoring of extreme storms. This research suggests that IR-based algorithms will soon contain the spatiotemporal richness and near-instantaneous availability needed for rapid natural hazards response while retaining sufficient skill to be suitable for hydrologic and water resources applications.

This presentation also introduces the recently developed data and information systems by CHRS including the integrated system for satellite precipitation and information (RainSphere); the real-time high-resolution satellite and crowdsourced rainfall observations for hydrologic and natural disaster management applications (iRain); and the on-demand data processing system for CHRS's satellite precipitation products (DataPortal).

A Look at Typhoons Using Satellite-based Precipitation from NASA and NOAA

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Extreme weather events entail associated economic and human costs due to the inability to predict them and the devastation that accompanies them. A typhoon is an extreme weather event that causes devastation for many Asian-Pacific countries around the Pacific Ocean. Typhoons are known for causing heavy precipitation, very strong winds, and storm surges. These effects then lead to flooding, heavy runoff, and landslides, which often result in water contamination, heavy sedimentation, and building collapse. With climate change, the occurrence, strength, and duration of typhoons are changing, and it is generally acknowledged that typhoons are becoming stronger. The need to better understand these typhoon events in order to predict the outcomes that many Asia-Pacific countries will face is of the utmost importance. Our approach to better understanding typhoons and their associated precipitation was to estimate the precipitation during a subset of typhoon events. We compared daily precipitation estimates during 29 typhoon events in the western North Pacific from 2000 to 2018 using two widely used and understood datasets: NASA's Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR). Bias and root mean square error varied based on typhoon and spatial extent (five different ones) used for analysis. The bias for all typhoons at the smallest spatial extent (1°x 1°) ranged from 0.33 mm to 2.05 mm. The bias for all typhoons at the largest spatial extent (90° x 40°) ranged from -4.25 mm to 20.72 mm. While variation existed between PERSIANN and TRMM TMPA estimates, TRMM TMPA consistently estimated higher precipitation across typhoons and spatial extents.

Keywords: Typhoon, precipitation, TRMM, PERSIANN

Session 7: Water Cycle Dynamics

Land Water, Energy, and Carbon Cycle Coupling Diagnosed from Remotely Sensed Global Observations

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The Soil Moisture Active Passive (SMAP) satellite mission is the first NASA satellite project designed primarily for land hydrologic applications. The mission was launched on January 31, 2015 and its science data acquisition is continuing. In this presentation results on the use of data in three long-standing hydrologic science goals are presented. These include: 1) observation-based mapping of the link between the water, energy and carbon cycles, aka soil moisture control one evapotranspiration, 2) closing the water budget on the landscape using satellite observations and without reliance on landsurface models, and 3) detecting shifts in hydrologic regimes such as transitions between water-limited and energy-limited evapotranspiration and drainage-dominated landscape water loss.

Integrated Satellite-based Data Assimilation Systems for Monitoring and Predicting Water Cycles

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By making maximum use of the information derived from brightness temperatures at different frequencies and polarizations observed by satellite-based passive microwave remote sensing, various types of data assimilation systems are developed for monitoring and predicting water in atmosphere, land surface, and vegetation. The Land Data Assimilation System coupled with Atmospheric model (LDAS-A) couples a satellite-based land data assimilation with an atmospheric model to physically introduce land surface heterogeneities into a land-atmosphere coupled model. The LDAS-A can clearly identify the vertical structure of atmospheric heating processes in the Tibetan Plateau. The Coupled Atmosphere and Land Data Assimilation System (CALDAS) merges the land surface information obtained ranging from the lower frequencies (6.9GHz) to the higher frequency (89 GHz) to assimilate soil moisture, vertically integrated cloud water content over land, and heat and moisture within clouds simultaneously. The CALDAS can assimilate cloud signals, produce very accurate cloud and precipitation distributions, and form a consistent atmospheric field around the cloud. Furthermore, it can demonstrate improvement of heavy rain prediction with the high accuracy of the events' location and rainfall intensity. Microwave is sensitive to water included in surface soil and terrestrial vegetation. Satellite-based microwave remote sensing effectively assimilates surface soil moisture and vegetation biomass, which are simulated by an ecohydrological model. Based on these advantages, the Coupled Land and Vegetation Data Assimilation System (CLVDAS) can calibrate both hydrological and ecological parameters of the model as a first step, and then provide better estimates of surface soil moisture, root-zone soil moisture, and leaf area index (LAI) sequentially using a genetic particle filter. The CLVDAS shows the high performance of the agricultural drought monitoring and predictions in northeastern Brazil.

Keywords: Data assimilation, microwave remote sensing, water cycle

It's Raining Bits: Trends in the Information Content of Daily Rainfall Persistence Across the U.S.

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The sequencing, or persistence, of daily rainfall has implications for streamflow, soil moisture, and vegetation. Due to these influences that are relevant to water availability and ecosystem health, it is important to identify trends over time in various aspects of rainfall occurrence and predictability. We use an information theoretic perspective to address regional and seasonal characteristics and trends in daily rainfall patterns, where rainfall is considered as a binary variable. We use the CPC gridded gauge-based dataset of daily rainfall in the continental U.S, and use information measures to quantify rainfall uncertainty, predictability in the form of information gained from the knowledge of lagged states, and associated dominant time scales of information content between 1 and 20 days. We find that the predictability given the knowledge of two time-lagged histories is highest in the western U.S., but the relative influence of a longer lagged history over a one-day lagged history is highest in the East. These characteristics of predictability and persistence, along with associated time scales, vary seasonally and regionally, and constitute an information-based climatology that can be compared with traditional metrics. An analysis of annual and seasonal trends from 1948 to 2018 also shows varying regional characteristics, particularly increasing and decreasing information content in the West and East, respectively. Trends also show seasonal patterns, and differences between non-extreme versus moderate to extreme event magnitudes. This study introduces information theory and information partitioning to obtain a new perspective on spatial and temporal rainfall patterns, and has broader potential to connect changes in climate and weather to patterns and predictability of other environmental factors.

Keywords: Information theory, rainfall persistence, gridded rainfall

On the Role of Montane Forests as Cloud and Precipitation Gatekeepers in the Tropical Andes

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The foothills and mid-elevation (<1,500 M, FME) slopes of the eastern Andes provide multiple hydrometeorological services beyond the physical connectivity between the Amazon foreland basin and the High Mountain Andes and the Altiplano. Precipitation measurements on the altitudinal envelope show that the highest precipitation amounts are observed at the higher elevation edge of the FME belt between 1,000 and 1, 500 m, and modeling experiments suggest that tropical forests on the FME play a critical role governing orographic moist convergence and convective activity in the FME belt, which in turn determine orographic precipitation and freshwater resources at high elevations and, through the hydrologic process chain, determine the runoff and transport of materials in fluxes from the Andes to the Amazon. The hydrometeorological functionality of the FME belt is therefore key to long-term regional sustainability. Recent research reveals that significant macroscale changes in forest cover are taking place along the FME in the Andes. These changes are attributed primarily to land-use change and anthropogenic activities. However, the nonlinear feedbacks of these changes on regional weather and climate, and the potential long-term impacts of cutting off ecological and water cycle connectivity on the macroscale Andes-Amazon system remain largely unknown.

Data suggest that similar processes are taking place elsewhere along the foothills of the world's mountains beyond the tropics and well into the mid-latitudes. In this presentation, we explore the notion of eco-hydro-meteorological mutualism and its implications for Environmental Wellness at regional scales.

Session 8: Hydrologic Applications

Human and Climate Impacts on Hydrologic Change in an Agricultural Landscape

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Through land use modifications and more intense precipitation events, human activities and changing climate are jointly impacting hydrologic system behavior. Adding to this complex interaction is the recognition that hydrologic and human systems are coupled and co-evolutionary, such that the hydrologic system affects the human system's behavior and response as well as vice versa. Quantifying these two factors' relative impacts is necessary for understanding hydrologic change and may allow for more robust planning under future extremes. Using a social-hydrologic modeling system that combines a rainfall-runoff module with an agent-based model (ABM), the impact of climate and human decision-making on streamflow is examined for a typical U.S. Midwest watershed. The rainfall-runoff module relates land cover change to hydrologic response through the use of the curve number method. The ABM simulates farmer agents that manage the majority of the land in the watershed and whose land use decisions are influenced by economic, social, and environmental factors. A government agent aims to reduce downstream flooding through a subsidy program that pays farmers to implement conservation practices that reduce runoff, similar to the Conservation Reserve Program. Two future climate scenarios are simulated, and the impacts of climate and agent decisions on peak streamflow are quantified. Under both RCP 4.5 and RCP 8.5 scenarios, the government agent increases the number of conservation contracts due to increasing flooding. Along with decreased yields under a wetter climate, these increases lead farmer agents to implement more conservation land over time. As a result, the average 95th percentile discharge decreases by 5-6% compared to simulations with constant land use. The human influence on peak discharges is more significant in the 2018-2065 period and lessens in the latter half of the century, when climate is found to account for 60-90% of the changes in flow.

Keywords: Precipitation extremes, flooding, agent-based modeling

Hydrologic Investigations of Propagation of Errors in Rainfall to Hydrographs

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In this study, the authors explore the rainfall characteristics that are most important for skillful streamflow predictions. They perform comprehensive hydrologic investigations of radar rainfall characteristics, such as rainfall resolutions, radar range visibility, statistical characterization, wind turbine effect, and basin-wide rainfall volume bias, among others. Since the true areal rainfall is unknown, the authors work with two independently constructed radar rainfall products called multi-radar multi-sensor (MRMS) (1 km2 by 1 hour) and Iowa Flood Center (IFC) (0.35 km2 by 5 minutes). The authors use a distributed hydrologic model called the Hillslope-Link Model (HLM) for the domain of Iowa. They evaluate the model performance at some 140 USGS stations, which regularly monitor streamflow in Iowa. Through spatial and temporal rainfall aggregation experiments, the authors show that the impact of inter-resolutions' variability is significant typically for smaller basin sizes, while it starts to vanish for basin sizes of around 1000 km2, considering the scale of basins where we monitor stream flows. Other rainfall characteristics that the authors explored do not reveal strong relationships between rainfall characteristics and hydrograph errors between the two products. As a result, the authors explored the similarities between the two products. They matched the basin-wide rainfall volume between the two products on an hourly basis to make them similar. Consequently, the performance measures show similar results as MRMS after equalization of rainfall volume. The authors conclude that the basin-wide rainfall volume bias outweighs other characteristics in explaining the errors in hydrologic predictions, provided that the two products have similar spatial structures. The authors believe that the findings reported in this study are flexible in the sense that they can guide rainfall estimation requirements obtained from other sources.

Keywords: Rainfall error propagation, Hillslope-Link Model, rainfall resolutions, basin-wide rainfall volume bias

The Continued Importance of Global Climate Processes Monitoring: A GEWEX Perspective on Precipitation

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In the early 1990s, when GEWEX was established, one of the main objectives was to improve our estimates of the global water and energy budget. Part of that mission was to support the development of new Earth observation missions as well as the continuation of existing ones. This goal has led to the current culmination of observations from space that we might speak of as a "golden age." However, now 30 years later, the landscape is changing, and with that the view on how to continue Earth observations in the future. The proliferation of various types of available Earth observations and the exponential increase of data involved, among other factors, requires a thoughtful consideration of how to effectively continue these global observations. Precipitation is a key element in the observation and modeling of Earth's processes and as such is a critical element in showcasing future prospects and challenges.

Keywords: Earth observation, GEWEX, precipitation, global

Session 9: Remote Sensing of Precipitation

GPM Mission Status and NASA Decadal Survey Activities Related to Precipitation

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The Global Precipitation Measurement (GPM) mission celebrated 5 years in orbit on February 27, 2019. This presentation will focus on current mission status and recent algorithm developments, particularly the reprocessing of the IMERG multi-satellite precipitation product to cover the TRMM and GPM eras from 2000 onward. Plans for the next version of GPM algorithms, along with other GPM project activities, will also be described. Looking beyond GPM, this presentation will also describe a new study to address recommendations from the 2017 Earth Science Decadal Survey Report, released in January 2018. The report included recommendations for NASA to augment the Program of Record (PoR, which includes GPM) with five designated observables; the two most relevant to the precipitation community are Aerosols (A) and Clouds, Convection, and Precipitation (CCP). Beginning in late 2018, NASA funded an intra-NASA-center study, with university and community participation, to define a combined A-CCP observing system, including identification of science goals and objectives, desired geophysical variables, and desired observing system capabilities. The study is exploring architecture designs that would deliver on desired observing-system capabilities, with consideration of a single-platform system, constellations of small satellites, and hybrid approaches.

Keywords: GPM, decadal survey

Atmospheric River Precipitation Characteristics Revealed by NASA GPM Ground Validation Observations in Complex Terrain

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One major component of NASA's Global Precipitation Measurement (GPM) mission is Ground Validation (GV). A series of field campaigns were conducted to support this effort, including the Olympic Mountains Experiment (OLYMPEX) over the 2015-16 winter in complex coastal terrain. During OLYMPEX, several atmospheric river events were observed using the full complement of GPM's GV platforms. Measurements captured the orographic enhancement of unblocked warm sector moist flow at various temporal and spatial scales, including data from precipitation gauges and disdrometers; soundings; ground-based radars at S-, C-, X-, Ku-, K-, and Ka-bands; the GPM Microwave Imager (GMI, 10-183 GHz) and Dual-frequency Precipitation Radar (DPR, 13.6/35.5 GHz) onboard the Core Observatory; and a suite of remote-sensing and in situ sensors deployed on three separate aircraft. This presentation will discuss integrative analyses of the OLYMPEX atmospheric river events, focusing on coastal and topographic impacts on precipitation signatures, variability, and evolution. A tool developed for GPM GV, the System for Integrating Multi-platform data to Build the Atmospheric column (SIMBA), has been applied to generate fused data products containing concomitant ground- and space-based observations. These column-centric products permit efficient multi-platform investigations of the precipitation vertical profile. Bulk characteristics and variabilities are assessed for insight into how precipitation processes and spaceborne observations are affected by oceanic, coastal, and mountainous geography. Particular attention is granted to long-duration ground-based radar data, including a detailed composite analysis of multi-wavelength observations, such as dual-frequency ratios, at S-, Ku-, and Ka-bands. Results establish context for continuing evaluation of the airborne measurements, which include in-cloud microphysical probes and dropsonde data as well as analog sensors to GPM's payload.

Keywords: GPM, ground validation, field campaigns, multi-sensor observations

Evaluating the Skill of GPM-IMERG Satellite Precipitation Estimation Over the Mountains of Central Chile

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Satellite data provide vital information for those places lacking precipitation observations from ground-based sensors, especially over oceans, mountainous regions, or developing countries. This is the case over much of South America, including Chile, which is a long and narrow country with complex topography that lacks long-term precipitation records, high-elevation data, and operational radars. We investigate the skill of the Global Precipitation Measurement (GPM) products using the Integrated Multi-SatellitE Retrievals for GPM (IMERG: version 5.2) quantitative precipitation estimation (QPE). We use the "late run" with 0.1° horizontal resolution and 30-minute temporal resolution.

These data are evaluated against observations from two field campaigns that took place near 36°S: the Chilean Coastal Orographic Precipitation Experiment (CCOPE; winter 2015) and The Chilean Orographic and Mesoscale Precipitation Study (ChOMPS; winter 2016). Both campaigns deployed precipitation gauges, disdrometers, and vertically profiling Micro Rain Radar (MRR). CCOPE collected observations across a coastal mountain range. ChOMPS collected observations along a transect from the coast into the Andes mountain range.

For each campaign, we classified 30-min rainfall periods into microphysical regimes based on the presence or absence of a well-defined melting layer in the MRR data. Rain was classified as "ice-initiated rain" or "warm rain." Gauge data was used to evaluate performance of IMERG QPE overall and for these two regimes. We found that the GPM-IMERG exhibits orographic enhancement of precipitation, but that this enhancement is greatly underestimated, by about 40%. In contrast, the coastal precipitation is well represented, with differences of 10%. The ability of IMERG to reproduce rain events decreases with increasing rain intensities. Additionally, IMERG performance during ice-initiated periods is substantially better than during warm periods.

Enhancing GPM Constellation Retrievals Over Land with Dynamic Surface Information

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Accurate, physically-based precipitation retrieval over global land surfaces is an important goal of the NASA Global Precipitation Measurement Mission (GPM). This is a difficult problem for the passive microwave constellation, as the signal over radiometrically warm land surfaces in the microwave frequencies means that the measurements used are indirect, and typically require inferring some type of relationship between an observed scattering signal and precipitation at the surface. GPM, with collocated radiometer and dual-frequency radar, along with a constellation of partner radiometers, is an excellent tool for tackling this problem and improving global retrievals. In the years following the launch of the GPM core satellite, physically-based passive microwave retrieval of precipitation over land continues to be challenging. This work demonstrates that the operational GPM passive microwave algorithm, the Goddard Profiling Alogorithm (GPROF), tends to overestimate precipitation at the low (< 5 mm/hr) end, and to underestimate at the high end (> 10 mm/hr) of the distribution over land. Retrieval sensitivities to dynamic surface conditions are explored using instantaneous retrievals of surface emissivity and associated soil and vegetation characteristics. The retrieval is then enhanced with dynamic, retrieved information from a GPM-derived optimal estimation emissivity retrieval. The retrieved parameters describing surface and background characteristics replace current static or ancillary GPROF information, including emissivity, water vapor, vegetation, and snow cover. Modest retrieval improvements are observed, and importantly, the enhancements with retrieved parameters move the retrieval away from dependence on ancillary datasets and lead to improved physical consistency.

Keywords: Precipitation, algorithm, passive microwave, GPM, land surface

Session 10: Hydrologic Applications

The Challenge and Opportunity of Global Hydrology: Integrating Multi-source Observations for Multi-scale Hydrology Study

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The global water cycle is driven by a multiplicity of complex processes and interactions between and within the Earth's atmosphere, lands, oceans, and biological systems over a wide range of space and time scales. As the time and space scales change, new levels of complexity and interactions are introduced, and such multi-scale nonlinearity can hardly be explained by simply upscaling or downscaling methods. Hydrologic sciences have been making a concerted effort to extend the range and scale of observations and to couple cross-disciplinary models for improved predictions and better societal benefits. This presentation briefly overviews the progress, challenges, and opportunities of integrating multi-source (in situ, remote sensing, analysis) observation techniques for global and regional water studies, with particular focus on flowing research. A CONUS and Global Hydrometeorological Extreme Mapping and Prediction System (HyXtreme-MaP), initially built on the Coupled Routing and Excess STorage (CREST) distributed hydrological model, is driven by real-time quasi-global TRMM/GPM satellites and by the U.S. Multi-Radar Multi-Sensor (MRMS) radar network with dual-polarimetric upgrade to simulate streamflow, actual ET, soil moisture, and other hydrologic variables at 0.05 degree resolution quasi-globally (http://flash.ou.edu/global) and at 250-meter 2.5-mintue resolution over the Continental United States (CONUS: http://flash.ou.edu). Multifaceted and collaborative by design, this end-to-end research framework aims to not only integrate data, models, and applications but also bring people together (i.e., NOAA, NASA, university researchers, and end-users). This presentation will review the progresses, challenges, and opportunities of such a HyXTREME-MaP System used to monitor global floods and droughts, and to predict flash floods over the CONUS.

Study of Global River Basins for Hydrological Extremes Using Satellite Data and Model Outputs

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Most of the world's large river basins have few observations of the variables of the hydrological cycle, with the exception of stream gauges at a few locations and at the basin outlet, along with sparsely distributed rain gauges. In this presentation, we use observations from publicly available satellite sensors and output from global land surface models to study the water cycle in these river basins. With populations greater than a billion people, some of these rivers (e.g., the Ganga-Brahmaputra, the Yangtze, the Nile, and the Mekong) are the economic engines of the countries they influence, yet thorough assessment of their variability in regard to water resource availability is still lacking. We are specifically interested in the hydrological extremes: floods and droughts that impact societies. We use soil moisture (0-2m) and surface runoff from the NASA Global Land Data Assimilation System (GLDAS), evapotranspiration, and Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS), rainfall from the Tropical Rainfall Measuring Mission (TRMM), and total water storage anomaly from the Gravity Recovery and Climate Experiment (GRACE) to examine variability among individual water balance components. To this end, understanding the extremes of inter-annual and intra-seasonal variability and the spatial variability of the water balance components in the world's major river basins will help decision makers to plan for improved management of water resources for the future.

Keywords: Droughts and floods, satellite data, hydrological cycle

Remotely Sensed Data Assimilation for Extreme Events

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Tropical storms and hurricanes in the Southeast United States have become more frequent and intense over the past decades, mainly due to the effects of climate change. They often produce torrential rains that may result in deadly and destructive floods depending on orographic, geomorphologic and hydrologic characteristics of the region. Hydrological models, irrespective of their types, most often do not provide accurate and reliable estimates of such floods as the model prognostic variables (e.g., soil moisture and streamflow) are subject to large uncertainties stemming from hydrometeorological forcing, model parameters, boundary or initial condition and model structure. However, data assimilation can be used as an effective and reliable method to integrate the hydrometeorological observations from in-situ and remotely sensed measurements into hydrological models for enhancing their forecasting skills while accounting for the associated uncertainties. Also, the availability of remotely sensed soil moisture data in conjunction with data assimilation can provide means to improve upon the prediction of extreme events. Although, these products are promoting a wide range of global and continental land-atmosphere studies, their coarse spatial resolutions impede their use in regional and local studies that require a finer resolution data. Therefore, we present a machine learning approach for downscaling satellite soil moisture product at 1-km resolution and then we propose a framework to demonstrate the benefit of assimilating such a high-resolution soil moisture product into a hyper-resolution hydrological model, here the WRF-Hydro model. As a prototype study we implement our approach over a region in the Southeast Texas where heavy rainfall from Hurricane Harvey caused deadly flooding.

Hydrological Cycle in the Heihe River Basin and Its Implication for Water Resource Management in Endorheic Basins

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Endorheic basins around the world are suffering from water and ecosystem crisis. To pursue sustainable development, quantifying the hydrological cycle is fundamentally important. However, knowledge gaps exist in how climate change and human activities influence the hydrological cycle in endorheic basins. We used an integrated eco-hydrological model, in combination with systematic observations, to analyze the hydrological cycle in the Heihe River Basin, a typical endorheic basin in an arid region of China. The water budget was closed for different landscapes, river channel sections, and irrigation districts of the basin from 2001 to 2012. The results showed that climate warming, which has led to greater precipitation, snowmelt, glacier melt, and runoff, is a favorable factor in alleviating water scarcity. Human activities, including ecological water diversion, cropland expansion, and groundwater overexploitation, have both positive and negative effects. The natural oasis ecosystem has been restored considerably, but the overuse of water in midstream and the use of environmental flow for agriculture in downstream have exacerbated the water stress, resulting in unfavorable changes in surface-ground water interactions and raising concerns regarding how to fairly allocate water resources. Our results suggest that water resource management in the region should be adjusted to adapt to a changing hydrological cycle, and that cropland area must be reduced and the abstraction of groundwater be controlled. To foster long-term benefits, water conflicts should be handled from a broad socioeconomic perspective. The findings can provide useful information on endorheic basins to policy makers and stakeholders around the world.

Keywords: Hydrological cycle, cryospheric change, endorheic basin, arid region

North American Land Data Assimilation System Version 2.5: Real-time Evaluation, Operational Implementation, and Drought Monitoring at NCEP

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The NLDAS has a long, successful history of producing 1) surface meteorological forcing, and 2) land surface datasets from land-surface models (LSMs) to provide soil moisture, snow cover, surface evaporation, and runoff/streamflow products, among other quantities. Since Phase 2 of NLDAS (NLDAS-2) was implemented in the NCEP product suite in August 2014, these products have been widely used for drought monitoring and water resources management purposes. However, this operational system has a 3.5-4 day time lag, which hampers its applications for real-time operational tasks, such as the weekly U.S. drought monitor and initializing land states in NWP models. To close this time lag, the NCEP/EMC NLDAS team worked with its collaborators for the last two years to integrate CPC daily gauge precipitation, EMC hourly stage IV radar-based national precipitation analyses, and fields from both the NAMv4 reanalysis and forecast to upgrade the current operational NLDAS system to an actual real-time NLDAS system with zero time lag. The upgraded NLDAS-2.5 is expected to be operationally implemented in near future. The resulting zero-lag, real-time status of NLDAS-2.5 products will positively benefit the NLDAS Drought Monitor, which is updated daily in support of national operational drought monitoring and prediction tasks. Real-time NLDAS-2.5 drought products will result in better timeliness for depictions of drought extent and severity over CONUS. This presentation summarizes the evaluation of the upgraded fully real-time NLDAS-2.5 system, including its design and infrastructure changes from NLDAS-2, product distribution, and assessment of water and energy fluxes, and state variables, as well as its impacts when compared with NLDAS-2 drought persistence results. In particular, using the current operational NLDAS drought-monitor indicators as a benchmark, we evaluate the impact of real-time surface meteorological forcing, including NAMv4 forecast products, on drought indicators.

Keywords: Ops NLDAS, real-time NLDAS, drought monitoring, evaluation

Session 11: Remote Sensing of Precipitation

IMPACTS: A NASA Earth-Venture Suborbital-3 Airborne Field Campaign to Investigate U.S. East Coast Snowstorms and Improve Remote Sensing of Snow

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Northeastern U.S. snowstorms impact large populations in major urban corridors, and cause major disruptions to transportation, commerce, and public safety. Snowfall within these storms is frequently organized in multi-scale banded structures that are poorly understood and poorly predicted by current numerical forecast models. Despite this problem, no major study of East Coast snowstorms has taken place in over 30 years. To address these needs, the NASA Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) Earth-Venture Suborbital-3 (EVS-3) field campaign will take place during the winters of 2020 – 2022 to sample a range of East Coast snowstorms using airborne remote-sensing and in situ instrumentation. The ER-2 aircraft will fly at high altitudes and carry a suite of remote-sensing instruments, including cloud and precipitation radars, lidar, and passive microwave radiometers to simulate satellite-borne instrumentation. The P-3 aircraft will fly within clouds and sample environmental quantities with a turbulent air motion measurement system and a vertically profiling dropsonde system, and microphysical characteristics using several microphysical probes. These airborne measurements will be supplemented with ground-based measurements from rawinsondes launched from mobile sounding systems and at National Weather Service stations, ground-based radars stationed over Long Island, and the New York State mesonet ground network. With this suite of instrumentation, IMPACTS will provide observations critical to understanding the dynamical and thermodynamical mechanisms of snowband formation, organization, and evolution. IMPACTS will also examine how the microphysical characteristics and likely growth mechanisms of snow particles vary across snowbands and apply this understanding to improve remote sensing and modeling of snowfall.

Keywords: Snowbands, field campaign, remote sensing, radar, microphysics

Evaluating the Streamflow Simulation Capability of PERSIANN-CDR Daily Rainfall Products in Two River Basins on the Tibetan Plateau

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On the Tibetan Plateau, limited ground-based rainfall information owing to a harsh environment has entailed great challenges to hydrological studies. Satellite-based rainfall products, which allow better coverage than both radar network and rain gauges on the Tibetan Plateau, can be suitable alternatives for studies investigating hydrological processes and climate change. This study uses a newly developed daily satellite-based precipitation product, termed Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR), as a hydrologic model input to simulate streamflow in the upper Yellow and Yangtze River Basin on the Tibetan Plateau. The results show that the simulated streamflows using PERSIANN-CDR precipitation and the Global Land Data Assimilation System (GLDAS) precipitation are closer to observations than that using limited gauge-based precipitation interpolation in the upper Yangtze River Basin. The simulated streamflow using gauge-based precipitation is higher than the streamflow observation during the wet season. In the upper Yellow River Basin, gauge-based precipitation, GLDAS precipitation, and PERSIANN-CDR precipitation have similar good performance in simulating streamflow. The evaluation of streamflow simulation capability in this study partly indicates that PERSIANN-CDR rainfall product has good potential to be a reliable dataset and an alternative information source of a limited gauge network for conducting long-term hydrological and climate studies on the Tibetan Plateau.

Keywords: PERSIANN-CDR, remote sensing precipitation, streamflow simulation, Tibetan Plateau

Opportunistic Sensing of Rainfall Using Microwave Links from Cellular Communication Networks in Africa and Asia

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Microwave backhaul links from cellular communication networks provide a valuable "opportunistic" source of high-resolution space–time rainfall information, complementing traditional in situ measurement devices (rain gauges, disdrometers) and remote sensors (weather radars, satellites). Over the past decade, a growing community of researchers, in close collaboration with cellular communication companies, has developed retrieval algorithms to convert raw microwave link signals, stored operationally by their network management systems, to hydrometeorologically useful rainfall estimates. Operational meteorological and hydrological services as well as private consulting firms are showing an increased interest in using this complementary source of rainfall information to improve the products and services they provide to end users from different sectors, from water management and weather prediction to agriculture and traffic control. The greatest potential of these opportunistic environmental sensors lies in those geographical areas over the Earth's land surface where the densities of traditional rainfall measurement devices are low: mountainous and urban areas and the developing world. We present several examples of high-resolution rainfall monitoring over countries in Africa and Asia, both for densely populated urban areas and for rural areas. We also discuss some of the challenges and opportunities regarding continental-scale rainfall monitoring using microwave links from cellular communication networks.

Keywords: Opportunistic sensing, microwave links

When Radar Calibration by In Situ Networks Becomes Misleading

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We have detailed tests between data of our polarimetric X-band radar and those of the C-band radar of Météo-France of Trappes, based on different algorithms, using single and/or double polarization. These studies demonstrate that adjustments of radar measurements on in situ network data do not necessarily play a positive role. Considering that precipitation fields are extremely variable over a wide range of space-time scales, we use the Universal Multifractal (UM) framework to confront the highly non-Gaussian statistics of space-time structures of precipitation measured by radars with the sparse information captured by in situ measurement networks. A criterion for compatibility among these measures is based on the intersection theorem between two multifractal fields. More specifically, we first evaluate the fractal dimension of the in situ network (C0), as well as the UM parameters of the precipitation measured by the radar, more precisely the codimension of the mean intermittency (C1) and the index of multifractality (α). We then show that that conditioning by an in situ network could be rather counterproductive for rainfall events when $C1/(\alpha -1)$ is smaller than the co-dimension of the fractal in situ network C0. Indeed, in this case the in situ network only introduces a bias in the rainfall estimates instead of refining them.

Keywords: Radar, calibration, adjustment, in situ network, polarimetry, biases

Session 12: Remote Sensing of Precipitation

What on Earth Is the Space/Time Structure of Rainfall Uncertainty?

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Satellite precipitation programs often emphasize the need for validating products. This has resulted in a long list of validation campaigns and efforts dating back to the earliest VIS/IR products and can be categorized as those that: (1) compare in situ precipitation rates or accumulations to the equivalent satellite product for a specific mission or sensor, (2) compare in situ precipitation rates or accumulations to satellite products intended for specific applications (e.g., hydrology), or (3) compare specific properties of the precipitation measured on the ground to equivalent satellite-derived (or sometimes assumed) properties. When these studies are viewed not as individual efforts or campaigns but in their totality, it becomes fairly obvious that satellite products have very different validation statistics in different regions and time periods. That is, satellite products have a large dependence on the atmospheric state, which is rarely considered in these validation efforts. This is the direct result of the under-constrained nature of cloud and precipitation retrievals. With validation results depending on the atmospheric state, it therefore becomes next to impossible to provide any meaningful assessment about the quality of satellite products anywhere except where previous validation studies have been performed. While developing a general framework, this paper focuses on predicting the statistical performance of a single product, the 1° daily rainfall accumulation from the IMERG product, for locations that may not have any in situ observations. While this initial attempt stops short of providing full global uncertainty estimates, the paper does offer a proof of concept that outlines two potential methods for achieving robust and quantitative uncertainty estimates for 1° daily rainfall anywhere on Earth.

Keywords: Satellite precipitation, uncertainty

Multi-Satellite Global Satellite Mapping of Precipitation—Design and Products

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Estimation of the global distribution of precipitation with high accuracy and resolution has long been one of the major scientific goals. To produce global precipitation maps is important for modeling the water cycle, maintaining the ecosystem environment, predicting agricultural production, and improving precision in weather forecasts and flood warnings, among other tasks. GSMaP (Global Satellite Mapping of Precipitation) is a project aiming to: (1) produce a high-precision and high-resolution global precipitation map using satellite-borne microwave radiometer data, (2) develop reliable microwave radiometer algorithms, and (3) establish precipitation map techniques using multi-satellite data for GPM. The GSMaP_MVK system, short for Global Satellite Mapping of Precipitation using Moving Vector and Kalman filter, uses a Kalman filter model to estimate precipitation rates at each 0.1 degree with 1-hour resolution on a global basis. One example of the GSMaP_MVK is shown in Figure 1 in the paper. The input data sets are precipitation rates retrieved from the microwave radiometers and infrared images to compute the moving vector fields. Based on the moving vector fields calculated from successive IR images, precipitation fields are propagated and refined on the Kalman filter model, which uses the relationship between infrared brightness temperature and surface precipitation rate. This Kalman filter–based method shows better performance than the moving vector–only method, and the GSMaP_MVK system shows a comparable score compared with other high-resolution precipitation systems. In addition to the GSMaP_MVK product, a gauge-adjusted GSMaP_MVK product has been developed and opened to the public recently. This presentation begins by providing an overview of the GSMaP algorithms, particularly GSMaP_MVK and GSMaP_Gauge, and then shows some evaluation results comparing radar-rain gauge networks around Japan's main island.

Keywords: Precipitation, satellite, GSMaP

Validation of Second-generation Pole-to-Pole CMORPH

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The 2nd generation CMORPH (CMORPH2) is developed to produce satellite-derived 30-minute precipitation estimates on a 0.05° lat/lon grid over the entire globe, pole-to-pole. CMORPH2 is built on the Kalman filter-based CMORPH algorithm of Joyce and Xie (2011). Inputs to the system include rainfall and frozen precipitation rate retrievals from passive microwave (PMW) measurements aboard all available low-Earth orbit (LEO) satellites, infrared (IR) observations of geostationary (GEO) and LEO platforms, and model precipitation forecasts from the NCEP operational global forecast system (GFS). Inputs from the various sources are inter-calibrated to ensure quantitative consistencies in representing precipitation events of different intensities through PDF calibration against collocated precipitation retrievals from the NASA GPM GMI PMW sensors. The inter-calibrated precipitation estimates are then propagated from their respective observation times to target analysis time, using motion vectors initially derived separately from IR-based precipitation and GFS precipitation fields, then 2D-VAR combined to form global analyzed fields of precipitation motion vectors. Propagated precipitation estimates are finally integrated through the Kalman filter framework. In addition, fraction of frozen precipitation is computed using the algorithm of Sims and Liu (2015). CMORPH2 has been reprocessed for a period from May 1, 2017, to present and updated on a quasi-real-time basis. CMORPH2 estimates are compared against CPC daily gauge analysis, Stage IV radar precipitation over CONUS, Multi-Radar/Multi-Sensor (MRMS), and numerical model forecasts to quantify improvements against first-generation CMORPH. Special attention will focus on CMORPH2 over high-latitude regions beyond the 60N/60S restriction of first-generation CMORPH. At the IPC12, performance of CMORPH2 concerning the quantification of both precipitation detection and amount will be discussed.

Keywords: CMORPH, satellite, precipitation, retrievals

Poster Sessions

Poster Session 1

1.01 Cell-tracking for Analysis of Simulated Alpine Thunderstorms

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In the warmer months in Switzerland, thunderstorms occur often and can produce significant damage. Climate change will likely affect the frequency and severity of thunderstorms, but the exact nature of the expected changes remains elusive. To help reduce the uncertainty on future thunderstorm changes, we investigate a technique that uses cell-tracking of simulated thunderstorms to compare current to future thunderstorm properties.

We produced convection-resolving simulations for Switzerland using the Advanced Research Weather Research and Forecasting (WRF) weather model. We used the well-established thunderstorm tracker TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting) to process simulated radar reflectivity fields and produce statistics on storm cells. The advantage of this object-based approach is that instead of comparing individual storm occurrences, which may not exactly align between simulations, we can compare overall thunderstorm properties.

We compared current climate model output to an independent set of storm observations characterized by the MeteoSwiss-developed Thunderstorms Radar Tracker (TRT). TRT was designed specifically for the high-resolution Swiss radar network and handles radar data issues caused by mountainous terrain. It is in operational use, and its data archive has been used for a hail climatology in Switzerland. The TRT dataset forms a reliable storm reference.

In this work we show that the simulation properties compare well to the TRT observations. We then compare the current-climate scenario to a simulated future-climate scenario, as an initial investigation into how storm properties may change in Switzerland with significant warming. Our study differs from previous applications of TITAN to WRF simulations in that we study thunderstorms in the complex topography of the Alps, compare current to future climate simulations, and test the technique's reliability using independently derived thunderstorm properties.

Keywords: Thunderstorms, anticipated change, heavy precipitation, simulations

1.02 A Random Forest-based Algorithm to Downscale Precipitation for Hyper-resolution Hydrology

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Developing a predictive capability for terrestrial hydrology across landscapes, with water, energy, and nutrients as the drivers of these dynamic systems, faces the challenge of scaling meter-scale process understanding to practical modeling scales. Hyper-resolution hydrological modeling can provide a framework for addressing science questions that we are not able to answer using coarse modeling scales. This work focuses on introducing a Random Forest downscaling technique for precipitation. Precipitation data from the NASA Modern-Era Retrospective analysis for Research and Applications – Version 2 (MERRA2), available at 50km resolution, have been downscaled to a 1km regular grid over the High Mountain Asia domain. Results are encouraging, showing good agreement between the downscaled dataset and ground- and satellite-based observations. The Coupled Routing and Excess STorage model soil-vegetation-atmosphere-snow (CREST-SVAS) is then forced with the downscaled precipitation in a Nepalese basin to produce streamflow simulations. Hydrologic models commonly simulate and predict extreme events triggered by precipitation at coarser resolutions. This work demonstrates the level of detail that a hydrological model forced with 1km precipitation can capture with respect to the original resolution re-analysis precipitation product.

Keywords: Downscaling, hydrologic model

1.03 Statistical Characterization of Annual and Seasonal Daily Precipitation Extremes in Central Arizona

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This study characterizes daily precipitation extremes in Central Arizona by applying the Generalized Pareto Distribution (GPD) to the peak-over-threshold series of 240 gauges. Analyses are conducted at annual scale and in the summer (July-September) and winter (November-March) seasons. The suitability of the GPD hypothesis is first evaluated and its parameters estimated through recent methods that account for the bias due to rounding effects and short sample size. It is found that the distribution of daily rainfall extremes: (1) is heavy-tailed (i.e., GPD shape parameter $\kappa > 0$) during the summer season, dominated by convective monsoonal thunderstorms; (2) is exponential (a special case of GPD with $\kappa = 0$) in winter when extremes are mainly caused by cold fronts transported by westerly flow; and (3) exhibits a mixed behavior at annual scale, with lighter upper tails than those found in summer. The spatial variability of the GPD parameters was also explored, finding a relatively strong control of elevation on the scale parameter and the absence of any clear effect of location or orography on the shape parameter. Results of this work are useful for improving statistical modeling of daily rainfall extremes at high spatial resolution and provide diagnostic tools for assessing climate models' ability to simulate extreme events.

Keywords: Rainfall extremes, peak-over-threshold analysis, generalized pareto distribution, seasonal extremes, annual extremes, spatial variability

1.04 An Evaluation of Rainfall Characteristics Associated with Hydro-disaster Occurrences in the Lake Kyoga Basin, Using PERSIANN-CDR Data

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Climate-induced hydro disasters have become more frequent in Uganda, especially within the Lake Kyoga basin. The mountainous areas of the basin have experienced a number of landslides that have killed over 300 people within the last 10 years. This study examines the variability of daily rainfall (using PERSIANN-CDR data) within the basin over the period 1985-2017. The study also examines the characteristics of the rainfall events that triggered significant landslides of 2010 and 2012 within the basin. Results show that the peak daily rainfall and the mean seasonal rainfall have declined by about 0.22 mm/day and 6.2 mm/season, respectively, within the March April May (MAM) season in the mountainous parts of the basin. There is significant variability in the 5-day seasonal rainfall totals across the years over the basin. Extreme rainfall (over 20 mm) events frequently occur within the mountainous areas of the basin, although their incidence has declined with time across the basin. It is evident that landslides in the region result from a combined effect of accumulated rainfall over a number of days. The mountainous regions receive rainfall frequently within a given year; hence, the soils are mostly moist. The results show that 3-4 consecutive days of rainfall greater than 10 mm would further intensify existing moisture conditions and would likely trigger a landslide. These results provide an initial basis for using PERSIANN-CDR data for formulating early warnings of landslide risks in Uganda.

Keywords: Landslides, Kyoga Basin, Uganda

Extreme Heat Events in a Semi-Arid Region Heighten Soil Respiration

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The terrestrial biosphere, particularly drylands, plays a crucial role in the carbon cycle. Extreme events such as heatwaves are considered to be key players in the terrestrial biosphere. Heatwave frequency and severity have risen substantially in the past decades, and are projected to continue to intensify in the future. A key question remains unclear: How do changes in extreme heatwaves affect the carbon cycle? Soil respiration is the second-largest contributor to the carbon cycle, and heatwaves' impacts on soil respiration have not been fully understood. We examine the response of soil respiration to heatwaves during wet and dry conditions in a semi-arid region using high-frequency observations and a probabilistic framework. We conclude that during heatwaves, soil respiration rates increase significantly, by 12%, relative to those observed in non-heatwave conditions. However, soil moisture is the key component dominating soil respiration response dynamics, when heatwaves impact soil respiration in a semi-arid area.

Keywords: Heatwates, soil respiration, soil moisture, semi-arid region, probabilistic model

1.06 Changing Characteristics of Aridity Over Pakistan in the 20th Century

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The changing characteristics of aridity due to climate change have gained interest through the assessment of precipitation and potential evapotranspiration over a larger spatiotemporal scale. This study's objective is to evaluate the changing characteristics of aridity using the gauge-based gridded precipitation and potential evapotranspiration obtained from the Global Precipitation Climatology Centre (GPCC) and Climatic Research Unit (CRU) of East Anglia University. The UNESCO aridity index was used to characterize the aridity for the period 1901-2016 over Pakistan's diverse climate. Sen's Slope and a modified version of the Mann Kendall trend test were used to estimate the rate of change and significance of trends, respectively. The study's results indicated that around 60% of the area is characterized by the arid climate, which is concentrated in southern parts of the country. The spatial patterns of aridity trends showed a strong influence of precipitation occurrence (monsoon and western disturbances) over the changing characteristics of aridity. The increasing trends in aridity were noticed in the southeastern regions, where precipitation is low during Kharif seasons, while decreasing trends occurred in Rabi season where precipitation is high during western disturbances. The spatial patterns of aridity changes showed that a larger area is transformed from an arid to a semi-arid climate annually and during Kharif season, while a small area changes from an arid to a hyper-arid region in Rabi season. Most of the significant changes were recorded from the years 1971 to 1980. It is expected that the study's findings will shed light on the changing characteristics of aridity over Pakistan.

Keywords: UNESCO aridity index, climate change, precipitation, potential evapotranspiration, modified Mann-Kendall trend, Pakistan

1.07 High-resolution Characterization of Rainfall Patterns During Heavy Precipitation Events in the Eastern Mediterranean

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Resulting in flash floods and tied to water availability in the eastern Mediterranean (EM), heavy precipitation events (HPE) are a major phenomenon in the region. The formation of HPEs requires unique atmospheric conditions that cause distinct rainfall patterns. Analyses of rainfall patterns during HPEs traditionally utilize various indices, rain-gauge IDF-curves, high-resolution meteorological simulation of case studies, or coarser resolution climatological simulations. However, these are insufficient to characterize spatiotemporal rainfall patterns in HPEs. To do so, and to evaluate the ability to simulate HPEs using a weather model, we (1) identified HPEs in the EM using a uniquely long weather radar record, and (2) simulated the same HPEs using a convection-permitting numerical weather model (WRF). Then we jointly analyzed rainfall patterns derived from both modelled rainfall and radar and evaluated the ability to simulate observed patterns. A pixel-based (1km2) identification of HPEs from the radar record yielded 41 events that were later modeled. Simulated rainfall patterns are in good agreement with the radar data, showing the same rain field structure, but having a positive bias. EM HPEs are centered near the coastline; however, short-duration, high rain-rates also are found in the region's desert areas. The studied HPEs consist of small (<10km decorrelation distance) and intense rain-cells, oriented WSW-ENE, covering a small portion of the region at each moment. However, given enough time, frequent arrival of rain-cells accounts for the accumulation of high rainfall depths over an increasingly wider area. The methodology and analyses we used, of high-resolution, event-based simulations, are highly valuable in representing the specifics of rainfall patterns during HPEs and allow the investigation of the causative meteorological ingredients for HPEs. Thus, this approach will be further used in our future research to study and simulate rainfall patterns under a changing climate.

Keywords: Heavy precipitation events, weather radar, WRF, high-resolution weather model, rainfall patterns, eastern Mediterranean

1.08 Regional Extreme Analysis from Radar-based Estimates

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Long rain gauge time series are typically used to analyse local extreme rainfall. This study evaluates the potential of rainfall estimates at 1km resolution from a single weather radar. Extremes are fitted to an exponential distribution using regression in Q-Q plots with a sample size that minimizes the mean squared error.

Compared to automatic rain gauges over a 12-year period, a basic radar estimation exhibits unrealistically high extremes for 1h accumulations and systematic underestimation for 24h accumulations. These issues are mitigated by a careful processing of the radar data and a gauge bias correction, respectively. The remaining differences are caused by radar signal attenuation, spatial and temporal sampling, gauge underestimations, and other radar errors. Nonetheless, most of the radar models are within the gauge models' confidence interval, which remains large due to the short study period.

A regional frequency analysis for 1h accumulations is performed at the locations of four reference gauges with 40 years of records. Independent radar extremes in a 20km neighborhood are selected using two different assumptions on the decorrelation distance. For the two closest stations from the radar, the gauge models match the radar models, a relationship which has a significantly reduced confidence interval due to its large sample size. For one station, radar-based extremes are significantly higher than extremes measured by the reference gauge, but closer to those of the automatic gauge during the same period. The models exhibit only slight variations related to topography.

This new method will be extended to averaged precipitation over areas with different sizes.

Keywords: Extremes, radar, regional

1.09 On the Suitability of Clustering Techniques to Classify Meteorological Drought

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Time series clustering of rain-gauge stations has been widely adopted for representing spatio-temporal meteorological drought similarity. Meteorological drought is a result of accumulated precipitation deficiencies over time and space, and it defines drought onset. In the case of meteorological droughts, the standardized precipitation index (SPI) has been extensively studied in many areas. Clustering time series of drought utilizing different data mining approaches have been frequently used in the literature; however, none addresses the appropriateness of clustered rain-gauge stations with respect to spatio-temporal changes in time series. We address the suitability dilemma by finding the most homogenous clusters of meteorological drought time series and analyzing their temporal behavior over a long time period. Given that trend and seasonality are common features of time series, a seasonal classification is performed utilizing a box plot, where a hydrological year is divided into a wet and a dry season. The significance of autocorrelation in precipitation data is assessed and inappropriate stations are removed, as well as those with significant trends identified by the Mann-Kendall test. Several attributes of rain-gauge time series were used to identify similarity, and to reduce the dimension, a self-organizing map (SOM) was used. The K-means and hierarchical clustering algorithms were applied to the outputs of SOM or the best matching units to find cluster boundaries. Cluster validation techniques were also used to identify the optimum number of clusters and the best method for clustering. According to the results, even at the highest achieved homogeneity, all time scales represented non-coherent clusters, whereby at least one rain-gauge station had different SPI time series behavior compared to other cluster members. This indicates high spatio-temporal variability of meteorological drought at the watershed scale.

Keywords: Meteorological drought, clustering, self-organizing map, rain-gauge, SPI

1.10 Extreme Value Analysis Based on Satellite Multi-sensor Precipitation Products

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Analyzing the frequency of rainfall extremes from satellite multi-sensor precipitation products poses two significant challenges: on one hand, optimally use the information contained in the short and possibly inhomogeneous time series available, and on the other hand, quantify how the bias and uncertainty characterizing the satellite quantitative precipitation estimates (QPEs) propagates to the extreme value quantiles to be estimated. Addressing and evaluating the impacts of these two issues requires extensive information at the ground level, such as that provided by radars or dense networks of rain gauges. These requirements often lead to the exclusion from extreme value rainfall studies of vast areas globally characterized by poor rain gauge density. Here we present a novel statistical technique that 1) downscales the probability distribution of daily rainfall from the grid cell of satellite rainfall products to the point scale, and 2) uses this information to model the frequency distribution of extreme daily rainfall at the point. The first result allows the evaluation of satellite-derived rainfall statistics in areas with only sparse rain-gauge measurements. The study of extreme daily rainfall frequency is carried out by connecting the downscaled properties of the rainfall field to the cumulative distribution of annual maxima, which is modeled using the Metastatistical Extreme Value distribution (MEVD). MEVD provides a connection between the bulk of the probability distribution of QPEs and the distribution of annual maximum rainfall extremes at a point. The approach presented here is tested and applied to a 19-year-long dataset from the Tropical Rainfall Measuring Mission (TRMM) over the continental United States, where available ground observations are used for independent validation of the method. However, the technique is general and can be applied to different gridded precipitation products.

Keywords: Extreme events, precipitation downscaling, remote sensing of precipitation

1.11 Exploring HRRR Forecast Skill on Extreme Events Across CONUS

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The National Water Model (NWM), launched in August 2016, is the cornerstone of NOAA's new effort to establish an integrated water information system for the entire United States. High-Resolution Rapid Refresh (HRRR), which has a spatial resolution of 3 km and a temporal resolution of 1 hour, is utilized as the forcing input of NWM for short-range forecast configuration. This paper investigates the forecast skill of downscaled HRRR QPF on extreme events throughout the entire United States. Currently, six recent extreme events caused by different weather systems are selected for forecast verification. We apply both temporal and spatial analysis to the selected extreme events. Various error metrics, such as normalized RMSE, bias ratio, correlation coefficient, and coefficient of variation, are utilized to characterize the forecast skill of HRRR QPF from a 1-hour to an 18-hour lead time. Various weather systems and watersheds with different domain sizes and locations are chosen to comprehensively explore the error properties of HRRR. Overestimation of precipitation is observed in most cases, especially at short lead times, while underestimation of precipitation is found at longer lead times. It is highlighted that the error characteristic is quite complicated, and may vary by locations, domain properties, and weather systems. More recent cases should be examined in the future to fully understand the forecast skill of HRRR products.

Keywords: HRRR, extreme events, forecast verification, NWM, CONUS

1.12 Hydrometeorological Extremes and Their Impacts in Kerala

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Climate change and its impacts are evident in the State of Kerala in India. In August 2018, abnormally heavy monsoon rains led to the worst flooding in a century, killing around 500 people and thousands of livestock, displacing one million people, and damaging 50,000 houses, roads, and other types of infrastructure. Estimated losses amounted to more than $3 billion. Seasonal rainfall was 42% above normal, and rainfall during August 1-19 was 164% above normal. Around 414 mm of rainfall occurred during August 15-17, which led to severe flooding. Steep slopes and destruction of wetlands added to its severity. All 39 major dams had reached their full reservoir level by the end of July, and were incapable of absorbing the torrential volumes in August. After flooding, surface water bodies, especially rivers, dried up quickly because of abnormal landslides and sedimentation. Around 8 to 10% of all reservoirs were already filled with sand because of deforestation and urbanization. As a result of the loss of surface soil and failures caused by the northeast monsoon, groundwater level in the state fell by 3 meters, and the state experienced a serious water crisis in the beginning of 2019. Destruction of check dams and erosion and deepening of rivers allowed fast flow of groundwater toward the sea. Decreases in runoff now permit salinity intrusion far inland. The state was not prepared to cope with the unexpected situation, and flooding initiated several socioeconomic problems, such as shortage of reliable water, escalating prices of food and water, conflicts over allocations, the spread of contagious diseases, and the requirement for large investments to rebuild infrastructure and rehabilitate the displaced population. This study analyzes the hydrometeorological extremes in Kerala during 2018, trends in extremes, and their impacts on different facets of life. Results show an increasing trend in extremes in the near future. Guidelines for developing a better climate policy and adaptation strategy have been provided.

Keywords: Extremes, Kerala, flood, socioeconomic, policy, adaptation

1.13 Impact of Data Assimilation of Airborne Cloud-profiling Radar Data on Predicting Heavy Precipitation Events

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The French Falcon aircraft has made numerous flights in clouds during the intensive observation periods of the HyMeX first special observation period (SOP1), which were dedicated to studying heavy precipitation events (HPEs). Among other research instruments, the aircraft was carrying the RASTA W-band cloud radar (Delanoë et al., 2013), which provided vertical profiles of reflectivity and wind along the flight track. These observations provided microphysical and dynamical information that is potentially useful for the numerical prediction of HPEs.

The presentation will show to which extent the assimilation of airborne reflectivity and/or wind observations collected during SOP1 may improve the analyses and forecasts of a storm-scale numerical weather prediction system. The AROME-WMED model (Fourrié et al., 2015) and its three-dimensional variational (3DVar) data assimilation (DA) system are used to this end. The 1D+3DVar data assimilation method of Caumont et al. (2010) is adapted to assimilate vertical profiles of reflectivity, using the reflectivity observation operator of Borderies et al. (2018). The vertical profiles of retrieved horizontal wind are directly assimilated in the 3DVar DA system. The impact on AROME-WMED analyses and forecasts is evaluated through the use of both research and operational data, and both case studies and the whole SOP1. Both the joint and separate assimilation of reflectivity and wind data are considered.

Keywords: Heavy precipitation events, Doppler cloud radar, data assimilation, storm-scale NWP models

1.14 Extreme Rainfall from Multiple Event Types and the Metastatistical Extreme Value Distribution

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The estimation of extreme precipitation's frequency of occurrence is central in hydrology. The traditional applied Extreme Value Theory (EVT) is based on the use of yearly maxima or few values/year over a high threshold, making limited use of the available information in inferring the probability distribution of extreme values. Furthermore, the traditional EVT cannot handle non-stationarity and interannual variability, due to its underlying assumptions. A new approach to extremes has been introduced to overcome these limitations: the Metastatistical Extreme Value distribution (MEVD). It relaxes some hypotheses at the basis of the classical EVT, makes full use of the observations, and lends itself to describing extremes in the presence of interannual variability and a changing climate. Moreover, its formulation allows for the explicit inclusion of different distributions to potentially represent different rainfall-generating mechanisms or coexisting regimes. We analyze synthetic and observed series of daily rainfall using the MEVD and compare its estimation uncertainty to that of the Generalized Extreme Value (GEV) distribution, which is grounded in the traditional EVT. Furthermore, we expand the MEVD formulation to account for mixtures of distributions representing different storm types (e.g., stratiform, convective, and tropical storms). Here we focus on the metropolitan areas of Houston, Charlotte, and Miami, exposed to relatively high likelihood of tropical cyclones (TCs) and subject to heavy rainfall events. When applied to long historical series of daily rainfall records, the MEVD outperforms the GEV distribution due to its capability of accurately describing rainfall interannual variability, its reduced assumptions, and its better use of the observations. For TC-related rainfall, we find that using mixed distributions reduces the estimation errors at some locations and for high quantiles compared to the GEV distribution and the MEVD with a single component.

Keywords: Extreme value theory, Metastatistical Extreme Value Distribution, tropical cyclones, mixed distributions

1.15 Spatial Analysis of Sub-daily Rainfall Time Structure Variability

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High sub-daily precipitation totals play an important role in flash flood formation, which can be influenced mainly by the course of precipitation intensity in very small catchments (less than 10 km^2). Therefore, water management should deal with not only site-specific design precipitation depths but also with design storm hyetographs. However, since precipitation episodes in a catchment usually differ significantly in terms of their time structure, they can hardly be represented by a single design storm hyetograph. This fact motivated our research on the time structure of heavy rains in a typical central European region (Czechia). The input dataset consists of 10-year radar-derived precipitation series adjusted by daily measurements from rain gauges with a time resolution of 10 min and a spatial resolution of 1 km. We focus on the 6-hour intensity course and distinguish 6 main variants of heavy rains by the k-means cluster analysis of reference episodes using 3 indexes quantifying the concentration of precipitation in time as similarity measures. The variants correspond to simple shapes of the intensity course (i.e., longer-lasting steady rains and short torrential rains) and to episodes comprising two well-marked intensity maxima. Each variant is represented by the synthetic storm hyetograph. Instead of assigning a single typical hyetograph to the site, we evaluate the site-specific probability of occurrence of individual variants of heavy rains by the regional frequency analysis. Thus, every selected small catchment can be characterized for the given return period of totals by both the design precipitation depth and variants' frequency distribution. The analysis reveals the frequency's dependence on topography (e.g., increase in the percentage of long-lasting steady rains with altitude), which becomes more significant for longer return periods.

Keywords: Rainfall intensity, weather radar, synthetic storm hyetograph, regional frequency analysis, design precipitation depth

1.16 Extreme Rainfall in Spatial Precipitation Clusters: Observations and a Simple Stochastic Prototype

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Precipitation clusters—spatially contiguous areas of rainfall—can be characterized by their size (cluster area) and the total precipitation they contain (cluster power). Remote sensing observations suggest that the probability distribution functions (PDFs) of both cluster size and power possess a long power law range (with slope -3/2) and an exponential cutoff at some large value. This cutoff determines the probabilities of large, organized, precipitating, extreme events, so it is important to understand what controls its value. Any changes to the cutoff's position on the PDFs mark changes to the occurrence probability of extreme events. Climate model simulations suggest that the cutoff does indeed shift to greater values—implying increases in the frequency of extreme events—in the event of global warming. We present a two-dimensional stochastic model of moisture to generate the statistics of precipitation clusters. The model is equipped with key elements of tropical convective dynamics and a stochastic component, but despite its simplicity is capable of generating precipitation clusters with statistics very similar to those observed. We find that feedbacks between precipitation and circulation, and lateral mixing processes are important to this model's cluster distributions. The cutoff is sensitive to multiple model parameters, strongly suggesting that the cutoff is an emergent property of the system. This sensitivity is qualitatively captured by the average number of nearest neighbors that a precipitating point can spawn in a given time interval. This particular metric, inspired by analogies between mechanisms of convective organization and a stochastic branching process, is also posited to explain the robustness of power law slope (-3/2), seen in climate models and observations. The neighbor probability metric has potential use in climate model diagnosis and helps explain the apparent observed limits on the size of tropical precipitating systems.

Keywords: Precipitation extremes, stochastic models, convective organization

1.17 Why Daily Precipitation Intensities Tend to Follow Gamma Distributions—Theory and Applications

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The probability density function (PDF) of daily precipitation impacts a wide range of applications. In most regions this PDF decays slowly with size at first, approximately as a power law with exponent between 0 and -1, and then more sharply, for values larger than a characteristic cutoff scale. This cutoff is important because it limits the probability of extreme daily precipitation occurrences in current climate. Daily precipitation PDFs are usually represented using Gamma or similar distributions; here we present a theory of how daily precipitation distributions get their shape. Processes shaping daily precipitation PDFs can be separated into non-precipitating and precipitating regime effects, the former partially controlling how many times in a day it rains, and the latter set by single-storm accumulations (the total precipitation from storm onset to termination). Using available theory for precipitation accumulation PDFs—which follow a sharper power law range (exponent <-1) with a physically derived cutoff for large sizes—analytical expressions for daily precipitation PDF power law exponent and cutoff are calculated as a function of key physical parameters. Precipitating and non-precipitating regime processes both contribute to reducing the power-law range exponent for the daily precipitation PDF relative to the fundamental exponent set by accumulations. The daily precipitation distribution cutoff is set by the precipitating regime and scales with moisture availability, with important consequences for future distribution shifts under global warming. These results help inform a simple set of metrics for model evaluation of daily precipitation PDFs and their future change, and the understanding of which physical factors can contribute to model bias in representing these distributions.

Keywords: Stochastic modeling, precipitation extremes, global warming, daily precipitation, theory, probability distribution

1.18 The Importance of Warm Rain Processes in Orographic Enhancement of Precipitation During Atmospheric River Conditions

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When warm, moist flow present in warm sectors of midlatitude cyclones encounters coastal mountain ranges, the processes producing their clouds and precipitation are modified, leading to considerable enhancement of precipitation on the windward slopes and precipitation spillover to the lee side. Surface, radar, and aircraft observations collected on the Olympic Peninsula, located in the northwest corner of Washington State, during the 2015-16 Olympic Mountains Experiment (OLYMPEX) field campaign and realistic, high-resolution WRF model runs provide complementary perspectives on the dynamic and microphysical processes associated with terrain-modified precipitation distribution. During environmental conditions characteristic of warm sectors of midlatitude cyclones, such as moist-neutral conditions, high values of integrated vapor transport, and low-level southwesterly flow, the upstream side of the Olympic Mountains experienced broad ascent and minimal descent over small-scale ridges. Significant quantities of cloud liquid water were produced over the coastal foothills and lower windward slopes, allowing additional time to generate precipitation-sized hydrometeors on the lower-windward slopes. Enhancement in the ice layer occurred directly over the barrier, where the ice particles were further advected downstream by cross-barrier winds and spilled over into the lee. Although climatologically the observed precipitation enhancement over the windward slopes is only a factor of two or less, during these warm sector periods, the observed rain rates were as much as five times larger on the windward slopes compared to the observed rates on the coast, with small to medium drops contributing up to half of the total amount of precipitation. These observations and modeling results point to the importance of warm rain processes of autoconversion and self-collection in contributing to precipitation enhancement during warm atmospheric river-like conditions.

Keywords: Orographic precipitation, atmospheric rivers, precipitation processes, field campaign

1.19 Climate Projections and Drought: A Study of the Colorado River Basin

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The Colorado River Basin has experienced the driest 19-year period (2000-2018) in over 100 years of historical record keeping. While the Colorado River reservoir system began the current drought at near 100% capacity, reservoir storage has fallen to just above 50% during the drought. Even though federal and state water agencies have worked together to mitigate the drought's impact and have collaboratively sponsored conservation programs and drought contingency plans, the 19 years of observed data raise the question of whether the most recent climate projections would have been able to project the current drought's severity.

This study analyzes observations and downscaled ensemble projections (e.g., temperature, precipitation, streamflow) from the CMIP3 and CMIP5 archive in the Colorado River Basin. Furthermore, a sub-ensemble of CMIP3/CMIP5 projections, developed using a teleconnection replication verification technique developed by the author, will be compared to the ensemble record to assist in further validating the technique as a usable process to increase skill in ensemble projections. This study's results will help to better inform water resource managers about climate ensembles' ability to project hydroclimatic variability, extreme drought conditions, and the appearance of decadal drought periods.

Keywords: Colorado River, drought, climate change, teleconnections

1.20 Evaluation of Precipitation Extremes with Respect to the Size of the Affected Area

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To assess past and possible future changes in precipitation extremes correctly, attention must be paid to the evaluation metric's design. As precipitation events' hydrologic impacts correspond with both precipitation intensity and the size of the affected area, both of these features should be combined when evaluating precipitation extremes. We present the concept of the weather extremity index (WEI), which we successfully employed in evaluating precipitation events at various spatial scales from individual Czech river basins of less than 10,000 km2 up to the whole area of central Europe (almost 600,000 km2). Moreover, it enables us to compare precipitation events even of different durations. Precipitation totals accumulated at rain gauge stations from one hour up to five days are first transformed into respective return period values, which are then interpolated in space. Within a given region, the WEI equals the maximum product of the mean logarithm of the return periods and the radius of the area in which the mean logarithm of return periods is calculated. Comparison with simple metrics (maximum precipitation total at one station, mean precipitation total within the whole area) demonstrates that the WEI successfully reduces rating of intense precipitation events affecting only a limited area, as well as of moderate precipitation events equally affecting the whole study area. Maximum values of the WEI correspond quite well with maximum warm-half-year floods in the respective river basins.

Keywords: Extreme precipitation events, return period, evaluation of precipitation extremes

1.21 Space-time Structure of Subseasonal Indian Monsoon Droughts

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The forecast of Indian monsoon droughts has conventionally been predicated on the development of well-defined warm anomalies in the equatorial Pacific. Using daily rainfall observations, we show that, in fact, all droughts over the past century can be classified into two categories with distinct subseasonal space-time characteristics/subseasonal evolutionary patterns and external oceanic markers. In the first category, associated with an El Niño that extends to the central Pacific, rainfall deficit intensifies gradually from mid-June, and progresses from the foothills of the Himalayas in the north to peninsular India in the south. The second category of droughts shows a dramatic decline in rainfall over 20 days in mid-August, with widespread deficits originating in the central plains. In terms of potential oceanic teleconnections, a feature that stands out in the latter case is a coherent cold anomaly in the north Atlantic. These classification and evolution characteristics have important implications for drought predictability, especially in the absence of any telltale equatorial Pacific signatures.

Keywords: Droughts, monsoon, precipitation

1.22 A Contribution-weighted Rainrate View of Indian Monsoon Extremes

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Extreme rain events have been conventionally analyzed on the basis of their frequency of occurrence above a prescribed threshold or based on a percentile. Noting rain's high spatio-temporal variability, we segregate important rain events during a season by defining contribution-weighted rainrates. This results in two quantities: the average or "effective" rainrate and "snapshots" in time that contribute to a given fraction of total rainfall accumulation. We use this approach to study extreme rainfall events over the Indian region which have been reported to show a secular change over the past few decades. Firstly, we find that even though rainrate and frequency are mathematically constrained, their behavior differs, with the latter resembling total accumulation. Secondly, while the Indian monsoon rainrates corresponding to extreme rainfall show secular trends since the 1950s, the frequency (fraction of time) shows a robust half-cycle over the past century. Finally, we will discuss the implications of these findings in the context of the changes in the Indian monsoon rainfall.

Keywords: Extreme rainfall, contribution-weighted rainrates

1.23 Applying the Adjusted CFSR to Predict Rainfall Data

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As rainfall is arguably regarded as the most driver and input for the hydrologic mod- elling, therefore estimating or measuring the rainfall is the main challenging factor for scientists. The extreme rainfall events or consecutive heavy rain day over the Blue Nile River Basin (BNRB) led to the substantial increases in streamflow extremes, which are the main causes of frequent floods in the Basin. Data scarcity has been regarded as a huge problem in modeling the water resources of the BNRB. The main objective of this paper is to develop methodology for obtaining basin meteorological and hydrological data for the Blue Nile sub-basins. The paper merge a wide range of gauge and reanalysis rainfall datasets, correcting for distribution biases allowing for reliable rainfall. However, in data- scarce regions such as in a transboundary basin, remote sensing data could be a valuable option for meteorological estimation when ground rainfall stations are not available. As well as the remote sensing data can use to fill gaps in the ground rainfall stations. The historical rainfall data for all Blue Nile sub-basins were downloaded in a daily basis for the period 1980-2010 from the Global Weather Data for the National Centers of the En- vironmental Prediction. These data were adjusted/calibrated with the actual measured rainfall from near gauge stations for the period 1993-1999 by using a weighting factor depending on the distance between satellite node, by using inverse equation and the dis- tances between the middle of sub-basins and the first and second nearest measured rainfall stations respectively, the calibrated satellite rainfall data have been found. The selection of the boundary coordinates is used for each sub-basin to set the nearest rainfall satellite station in the middle of each sub-basin and, this is done by using the global weather and Google earth capability. Results show that using the adjusted CFSR rainfall data can be utilized to provides a daily runoff flow.

Keywords: CFSR, Rainfall, Blue Nile River Basin

1.24 Forest Fire Impacts and Desertification Processes with Remote Sensing Data in Semi-arid Lands in Algeria

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The forest in steppe presents ecological diversity, and observed unfavorable climatic conditions in forest fire zones and impact; we note deterioration of the physical environment, and particularly, of natural forest. This deterioration of forests provokes an environmental unbalance which provokes a process of deterioration which, when advanced to the ultimate state, is desertification. Elsewhere, where climatic conditions are favorable, fire is an ecological agent that becomes an integral part of ecosystem evolution. The regeneration of plants is influenced greatly by the fire regime (season, intensity, interval), which leads to the recuperation of vegetation in meadow fires. In this survey we used data from the ALSAT and LANDSAT satellites to detect zones with risk of forest fire and their impact on the natural forests in the Tlemcen region. A thematic detailed analysis of forests well attended ecosystems some processing on the satellite data, we allowed to identify and classifying the forests in their opinion components flowers. We also identified the ampleness of fire in this zone, and studied parameters such as the slope, the proximity to the road, the nature of vegetation, and forest formations with the goal to identify the zones at risk of forest fire. A crossing of diaper of information in a SIG according to a very determined logic allowed us to classify the zones according to degree of fire risk in a middle arid forest zone, which does not encourage regeneration, while on the other hand permitting the influx of steppe, which encourages desertification.

Keywords: Remote sensing, SIG, forest fires, ecosystem, degradation, desertification, semi-arid lands

1.25 Polarimetric Radar Observations Over the Tropical Oceans

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Colorado State University has developed a new C-band polarimetric radar, SEA-POL, specifically built to afford easy deployment on global-class ships within the U.S. UN-OLS fleet. SEA-POL is the first ship-based weather radar deployed by the U.S. Since its construction and testing was finished in spring 2017, SEA-POL has made two deployments to the tropics. First, SEA-POL deployed to the SPURS-2 cruise to the eastern tropical Pacific during October-November 2017, sailing on the R/V Roger Revelle. During SPURS-2, SEA-POL collected high-quality rainfall information to map the location of freshwater lenses formed on the ocean's surface. Oceanographers then made measurements within the lenses to determine the lenses' impact on stabilizing the upper ocean and analyzing the times required to mix out the stability via wind. Polarimetric-based rain estimates were used, which are superior to previous Z-R based estimates. During August-October 2018, SEA-POL deployed on the R/V Thomas G. Thompson to the western Pacific as part of the PISTON (Propagation of Intraseasonal Oscillations) field campaign. The intent was to study rainbands associated with the BSISO (Boreal Summer Intraseasonal Oscillation). However, typhoons were very active during PISTON, allowing SEA-POL to collect data on outer rainbands of several passing typhoons. Data were also obtained in close proximity to the Japanese research ship R/V Mira, which also carries a C-band polarimetric radar. Ship-based Dual-Doppler observations will also be discussed, which are extremely rare over the oceans. SEA-POL is thus a valuable new asset for the U.S. research community.

Keywords: Radar, rainfall estimation, polarimetric radar, ship radar

1.26 Evaluation of Ground-Based Precipitation with Satellite-Based Model Observations Over West Africa

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Precipitation and clouds are sensible weather elements that are essential to forecasting in the tropics. Despite rain's importance for human activities, techniques in forecasting day-to-day tropical rainfall events has not been explored extensively. With the atmospheric and tuning constants over West Africa ranging from 0.3 to 1.2 and 0.4 to 0.7, respectively, the average aerosol retention over West Africa is 30%. Thus, the study examined more statistical climate model analyses from experimental ground-based measurements of precipitation data with satellite observations/model simulations over West Africa (20°W-20°E, 4-20°N). Monthly and annual cloud cover data were obtained from the International Satellite Cloud Climatology Project (ISCCP), European Centre for Medium-Range Weather Forecasts (ECMWF), and local stations. The Tropical Rainfall Measuring Mission (TRMM), European Centre for Medium Range Weather Forecasting (ECMWF), and Tropical Application of Meteorology Using Satellite Data and Ground-Based Observations (TAMSAT) were used for precipitation simulations. Results obtained indicated that the satellite-based data have great difficulties representing the diurnal cycle of winds and clouds, leading to associated errors in radiation. Typical errors from the satellite datasets had a larger degree of variability than the ground-based measurements. The degree of variability in precipitation estimates also varied by region, with significant differences in both seasonal and annual estimates (b 1.01; R2 0.5). The reliability of precipitation datasets is limited mainly by the number and spatial coverage of surface stations, the satellite algorithms, and the data assimilation models. The inconsistencies described limit the products' capability for climate monitoring, attribution, and model validation.

Keywords: Simulations, monitoring, variations, measurements

1.27 The NCEP's Climatology-Calibrated Precipitation Analysis (CCPA) Product and Its Applications

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Through extensive collaboration efforts, the NCEP Environmental Modeling Center has developed Climatology-Calibrated Precipitation Analysis (CCPA) products at high temporal and spatial resolutions for precipitation verification, calibration, and downscaling. This primary 6-hourly analysis product utilizes linear regression and spatial and temporal downscaling techniques. It is generated by combining two widely used datasets, taking advantage of the higher reliability of the NCEP CPC Unified Global Daily Gauge Analysis and the higher temporal and spatial resolution of the NCEP EMC Stage IV multi-sensor quantitative precipitation estimations. CCPA was first implemented in operations at the National Centers for Environmental Prediction Central Operations in July 2010 and experienced three upgrades afterwards. The product is available to users at six basic grids over the CONUS with 1-, 3-, and 6-hour accumulations from 2002 to present. At EMC CCPA provides a proxy of truth for the bias correction and statistical downscaling of precipitation forecasts from the NCEP GFS Ensemble Forecast System (GEFS) and Short-Range Ensemble Forecast System (SREF) products, and precipitation verification in evaluating the performance of various forecast systems. In recent years, CCPA application is also expanded to the National Blender Models (NBM) projects led by MDL, which apply CCPA as the best analysis for precipitation forecast calibration. Driven by users' needs and feedback, CCPA will be continuously improved and expanded. To support the NBM projects, an upgrade to CCPAv5 is planned for further development. The CCPA domain will be expanded to cover CONUS-adjacent ocean areas by merging 8km/30min CMORPH and gauge quality-controlled 1km/1hour Multi-Radar Multi-Sensor (MRMS) data. This presentation will provide an overview of the CCPA methodology, applications, and future plans, as well as some preliminary results from recent development.

1.28 Detecting Convective Class to Enhance PMW Satellite Precipitation Estimates

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A decades-long effort in observing precipitation from space has led to satisfying the accuracy of satellite Passive Microwave (PMW) large-scale precipitation products. However, due to a limited ability to relate observed radiometric signatures to precipitation type (convective and stratiform) and associated precipitation rate variability, PMW retrievals are prone to large systematic errors at instantaneous scales. The present study explores the use of deep learning approaches in extracting the information content from PMW observation vectors to help identify precipitation types. A deep learning neural network model is developed to retrieve the convective type in precipitating systems from PMW observations. Global Precipitation Measurement mission PMW Imager (GMI) observations are used for model development and verification. The model reduces precipitation rate biases associated with convective and stratiform precipitation in the GPM operational algorithm by a factor of two while preserving the correlation with reference precipitation rates, and is insensitive to surface type variability. Based on comparisons against currently used convective schemes, it is concluded that the neural network approach has the potential to address regime-specific PMW satellite precipitation biases affecting operations.

Keywords: Passive Microwave Precipitation, machine learning, satellite precipitation retrievals, convective precipitation

1.29 Error Modeling of Passive Microwave Precipitation Products Over Complex Terrain

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Difficulties in representing high rainfall variability over mountainous areas using ground-based sensors are an ongoing problem in hydrometeorological applications. These difficulties highlight the need to use satellite-based precipitation products (SPP) because of their ability to represent the space-time variability of rainfall with quasi-global coverage. The rational and effective use of SPP requires a thorough understanding of their individual sensor error characteristics and uncertainties. Identifying the strengths and weaknesses of the passive microwave (PMW) retrievals associated with each sensor is crucial to gaining this understanding. Evaluating PMW retrievals is challenging since it requires reference datasets with high temporal and spatial resolution. The use of short-range dual-polarization X-band radar over complex terrain gives the advantage of multiparameter measurements near ground that carry significant information. To retrieve rainfall and microphysical estimates from X-band radar, we used an in-house set of algorithms (SCOP-ME). High-quality and high-resolution rainfall fields were derived over six study regions: Northeast Italian Alps, North Carolina, Olympic Mountains, Southern tip of Vancouver Island, Rocky Mountains Colorado, and Swiss Alps. The benchmark rainfall dataset (bias-adjusted high-resolution 4D rainfall variability) for each site is obtained by evaluating the error characteristics of SCOP-ME retrieval against in situ observations. The evaluation of PMW products over orographic terrain will allow development of a PMW rainfall machine learning error model. Specifically, the nonparametric tree-based quantile regression forests (QRF) model is used by applying the idea of quantile regression from econometrics to develop a nonparametric error correction model for the PMW retrievals over complex terrain. The ensembles will be generated using the QRF model and will be validated based on independent matchups of PMW/GR data.

Keywords: Remote sensing, satellite-based precipitation, passive microwave sensor, dual polarization X-band radar, complex terrain, error model, machine learning

1.30 Intercomparison of Radar Rainfall Nowcasting Techniques for the Netherlands

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Accurate and timely hydrological forecasts highly depend on their meteorological input. Current numerical weather predictions (NWP) do not have sufficiently high spatial and temporal resolutions for adequate use for short lead times (<6 hours) in fast-responding lowland and polder catchments. Radar nowcasting seems to be a solution, and an increasing number of nowcasting algorithms is becoming available. However, best practices for the use and choice of these algorithms within operational forecasting systems are not yet available. In this study, we performed an analysis in time over 12 catchments in the Netherlands, using state-of-the-art nowcasting algorithms (e.g., pySTEPS), benchmarking systems (RainyMotion), and the local NWP (HARMONIE). We focused on the rainfall predictability of different nowcasting algorithms and the choice for simple advection, or deterministic or probabilistic nowcasting. We quantified this as a function of lead time, rainfall type, initial conditions, catchment size, and catchment location with regard to the radar rainfall estimates.

Keywords: Nowcasting, radar, rainfall, hydrology

1.31 Estimating Raindrop Size Distributions Using Microwave Link Measurements

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We present a novel method of using two or three collocated microwave link instruments to estimate the three parameters of a gamma raindrop size distribution (DSD) model. This allows path-average DSD measurements over a path length of several kilometers as opposed to the point measurements of conventional disdrometers. Our model is validated in a round-trip manner using simulated DSD fields as well as five laser disdrometers installed along a path. Different potential link combinations of frequency and polarization are investigated. We also present preliminary results from this method's application to an experimental setup of collocated microwave links measuring at 26 GHz and 38 GHz along a 2.2 km path. Simulations show that a DSD retrieval on the basis of microwave links can be highly accurate. We found that a triple-link retrieval provides no added benefit over a dual-link retrieval. In practice, the retrieval's accuracy and success are highly dependent on the base power level stability.

Keywords: Microwave links, drop size distribution

1.32 Bias Adjustment of Satellite-based Precipitation Over Thailand

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This study contributes to the assessment and bias adjustment of PERSIANN-CCS over Thailand. PERSIANN-CCS is an hourly product with 0.04 x 0.04 degrees with 1-hour latency. Compared to the Thai Meteorological Department rain gauge data (TMD), the product depicts spatial distribution well, with a hit rate of 67%, bias ratio of 0.89, and false alarm rate of 23% in 2017, and underestimation in monthly and annual rainfall, especially in Thailand's east coast river basin and the southern regions. The bias adjustment was carried out to improve the product's amount and spatial distribution using observed daily rainfall data. First, quantile mapping was applied to adjust the data from 400 automatic rain gauges over Thailand. The adjusted observed rainfall data was used to adjust the bias of PERSIANN-CCS using the spatial bias adjustment. After the adjustment procedure, the false alarm rate is decreased significantly, with an improvement in the correlation coefficient from 0.48 to 0.57 and in RMSE from 16 mm/day to 13.2 mm/day. For the monthly rainfall during May to October, the correlation coefficients were improved from 0.06 – 0.49 to 0.49 – 0.79, and the RMSE was decreased from 164 mm/month to 113 mm/month. The adjusted products are input for the operational flood forecasting system and contribute to flood warning, especially in areas with limited rain gauge and radar coverage.

Keywords: Satellite-based precipitation, bias adjustment, PERSIANN-CCS, Thailand

1.33 Radar Remote Sensing of Rain/Snow in High Mountains: Melting Layer Climatology in the French Alps

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Complex terrain's influence on atmospheric flow patterns causes high spatio-temporal variability of precipitation in high-mountainous regions, which complicates quantitative precipitation estimation (QPE) using both raingauge and radar networks. Radar remote sensing presents the dilemma of beam blockage, limiting the view for a valley-based radar and the occurrence of melting layer (ML), thereby altering the precipitation phase below radar altitude for mountaintop radar. A unique observation system—composed of a Météo France X-band MOUC radar (dualpol) atop Mt. Moucherotte (1912 m), an X-band XPORT radar (dualpol), a K-band MRR (micro rain radar, Doppler, vertically pointing), and in situ sensors (rain gauges, disdrometers), the latter three operated by IGE in the valley (210 m)—has been operational in the French Alps (Grenoble) since 2016. Two radar systems just 11 km apart with an altitude gradient of 1700 m provide us an opportunity to study precipitation characteristics at both mesoscale (MOUC) and high-resolution local scale within the valley (XPORT, MRR). We developed automated algorithms for detecting and characterizing ML using high elevation angles (15°, 25° and 45°) of XPORT measurements and the MRR data. It allows the detection of the ML, vertical profiles of hydrometeors' polarimetric parameters (Zh, Zv, Zdr and ρhv) from XPORT, and vertical profiles of hydrometeors' apparent fall velocities from MRR. These vertical profiles characterize ML by the peaks and inflection points (boundaries of ML). This study addresses 42 significant rainfall events (>=5mm) in the valley. Typical signatures of the various profiles are evidenced, supporting some speculations about the micro-physical processes at work. The information content of the ML dataset is analyzed using various statistical techniques (correlation matrix, multi regression, PCA). We also study the influence of rainfall intensity and the 0°C isotherm altitude on ML and the added value of Zdr and ρhv peaks.

Keywords: Radar remote sensing, hydrometeorology, melting layer, precipitation

1.34 Merging Multi-source Precipitation Products or Their Simulated Hydrological Flows to Improve Streamflow Simulation

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Satellite and reanalysis precipitation products are widely utilized for streamflow simulation, which is one critical hydrological application, especially for ungauged regions. This study investigates possible ways to improve streamflow simulation by merging multi-source precipitation products or by directly merging streamflow simulated with different precipitation products. Two satellite-based precipitation products, Tropical Rainfall Measuring Mission 3B42 Version 7 (TRMM) and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR), and one reanalysis precipitation product, National Centers for Environment Prediction Climate Forecast System Reanalysis (NCEP), are selected. The Bayesian model averaging (BMA) method is used to merge multi-source precipitation estimates and streamflow simulations. The results show that in this case, merging multi-source precipitation products made little difference to improving streamflow simulation. Merging multi-source streamflow simulations using the BMA generally achieved better performance on streamflow simulation, indicating that merging multi-source streamflow simulation is more efficient than merging multi-source precipitation products.

Keywords: Satellite precipitation, merging method, hydrological modeling, streamflow simulation

1.35 Rainfall Variability and Trends Over East Africa

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The ARC v2, CHIRPS v2, and TARCAT v3 satellite rainfall products are exploited to study the spatial and temporal variability of East Africa (EA) rainfall between 1981 and 2017 through the time series of selected rainfall indices from the Expert Team on Climate Change Detection and Indices (ETCCDI). The indexes' total rainfall amount (PRCPTOT), Simple Daily Intensity (SDII), number of precipitating days (R1), number of consecutive dry and wet days (CDD and CWD), and number of very heavy precipitating days (R20) are analyzed to characterize the rainfall over the region. The work focuses on rainfall variability, particularly on the recent ENSO episode (2015-2016) analyzed in connection with previous episodes (1982-83 and 1997-98), and on the identification of significant rainfall trend patterns. Trends are extracted regardless of the single satellite product through the Mann-Kendall technique, considering the time series of the ensemble mean of the three satellite products and the corresponding time series of the standard deviations used as error bars associated with the ensemble mean time series. The trend rate variability stemming from the multiplicity of the products also is evaluated. Indications on rainfall trends are extracted at annual and seasonal scales, and the regions that more frequently exhibit statistically significant trends are located in eastern Kenya, Somalia at the border with western Ethiopia, northern Tanzania, and limited areas of South Sudan. At the seasonal scale, increasing trends are identified for the October-November-December PRCPTOT, SDII, and R20 indices over eastern EA, with the exception of central Kenya, where positive trends with limited areas of significance stand out for R1 and CWD, also at the yearly scale. In March-April-May, a rainfall decline is detected only through R1 and CWD, in particular over the eastern EA region, whereas PRCPTOT, even though associated with negative trends, does not present high confidence areas.

Keywords: East Africa, satellite rainfall measurement, trend analysis

1.36 Improving Quantitative Precipitation Estimation in Complex Terrain Over the San Francisco Bay Area Using Gap-filling Radar Network

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The San Francisco Bay Area is covered by two operational S-band WSR-88D: KMUX and KDAX. However, at low elevation angles the KDAX radar beams are partially blocked by the mountainous terrain, whereas the KMUX radar is deployed at an elevation of over 1000 m, which can easily overshoot precipitation during the winter storm season in Northern California. As a result, these two radars are not sufficient to provide detailed precipitation information for quantitative hydrometeorological applications. NOAA is building the Advanced Quantitative Precipitation Information (AQPI) system to improve monitoring and forecasting of precipitation and coastal flooding in the San Francisco Bay Area. As part of the AQPI program, high-frequency (i.e., C and X band) high-resolution gap-filling radars are being deployed over the Bay Area to improve precipitation observations and investigate the detailed precipitation microphysics over such complex terrain. To date, two X-band radars have already been deployed and have collected a substantial set of precipitation measurements that contribute to the development of local radar rainfall algorithms. This paper presents the preliminary design of a real-time rainfall system for the gap-filling AQPI radars, as well as a strategy to integrate the AQPI and WSR-88D radar data for improved precipitation estimation over the Bay Area. In addition, the polarimetric radar rainfall algorithms are detailed. Case studies during the 2018-2019 winter storm season are presented. The high-resolution rainfall products are evaluated through cross-comparison with surface rain gauge measurements. Results show that the products generated by the AQPI radar rainfall system have better performance than the operational products currently available in this domain.

Keywords: AQPI, gap-filling radar, Bay Area, complex terrain, QPE

1.37 One-year Evaluation of Fuzzy Logic Non-Meteorological Echo Removal for Two C-band Radars

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Since January 2017, the Royal Netherlands Meteorological Institute (KNMI) has operated two new dual-polarization C-band weather radars in Simultaneous Transmission And Reception (STAR; i.e., horizontally and vertically polarized pulses are transmitted simultaneously) mode. Data from these radars are composited to obtain operational 2-D rainfall products for the Netherlands. These products are extensively used, for example, for nowcasting, water management, and climatological purposes.

Despite the application of Doppler filtering, remaining ground echoes due to anomalous propagation still pose a problem. Moreover, remaining sea echoes can be abundant. These issues call for additional filtering algorithms.

The polarimetric radars offer new opportunities for ground clutter removal. Here we explore the effectiveness of the open-source wradlib fuzzy logic classification, extended with the depolarization ratio and clutter phase alignment. Optimal weights and threshold are determined, employing a 4-h calibration dataset from one radar near the coast. These are applied to a full year of volumetric data from the two radars in this temperate climate.

The verification focuses on the presence of remaining ground echoes by mapping the number of exceedances of radar reflectivity factors for given thresholds. Moreover, accumulated rainfall maps are obtained to detect radar pixels with unrealistically large rainfall depths. The results are contrasted to those for which no further filtering has been applied. Verification against rain gauge data reveals that only a little precipitation is removed. Despite the fuzzy logic algorithm's removing many non-meteorological echoes, compositing data from both radars in logarithmic space (as opposed to linearly averaging reflectivities) remains necessary to reduce non-meteorological echoes to an acceptable level.

Keywords: Ground-based radar, clutter, dual-pol

1.38 Validation of Global Precipitation and Evapotranspiration Datasets from a Water and Energy Balance Perspective

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Global precipitation (P) and evapotranspiration (E) datasets are widely used for long-term hydrologic, climate, and land use studies. However, these datasets are generally validated separately using ground-based measurements. In this study, we evaluate the combined ability of global precipitation and evapotranspiration datasets to capture catchments' long-term water and energy balance. We use a recently developed validation framework based on the Budyko hypothesis. The framework characterizes the combined error in P and E datasets at long-term time scales using a root mean square error (RMSE)-based error metric. We apply the framework to 63 different combinations of P (10 products) and E (six products) datasets at a global scale (4730 catchments). The precipitation products considered are satellite-based (TRMM 3B42RT, CMORPH, PERSIANN-CCS, GPM), gauge-based (CPC, CRU, GPCC), and combined (TRMM 3B43, PERSIANN-CDR, CHIRPS) datasets. The evapotranspiration products considered are remote sensing-based (GLEAM v3.1a, AVHRR, MODIS), land surface model-based (LandFlux-Eval), reanalysis-based (LandFlux-Eval), and merged (LandFlux-Eval). The 4730 global catchments are based on the HydroBASINS level-5 catchment classification, with an average area of approximately 28,500 km2. Preliminary results from selected catchments in the continental United States show that the combination of TRMM 3B42RT (precipitation) and GLEAM (evapotranspiration) datasets performs best among the remote sensing datasets in representing catchments' long-term water and energy balance.

Keywords: Global validation of remote sensing data, Budyko hypothesis

1.39 Systematic Biases Associated with Cloud Types in Satellite Precipitation Estimations

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Two along-track (level 2) satellite precipitation retrievals by the Global Precipitation Measurement (GPM) Microwave Imager and Ku-band Precipitation Radar (DPR-Ku) and two multi-satellite precipitation products, Global Satellite Mapping of Precipitation (GSMaP) and Integrated Multi-satellitE Retrievals for GPM (IMERG), are compared for different cloud types during the warm season over the western North Pacific region. A MTSAT-based cloud-type product is reclassified and validated against CloudSat observations. The results suggest that the biases in the precipitation measurements are systematically associated with cloud types. The best agreements of passive microwave (PMW) products and infrared-based (IR) products with satellite radar-based estimates are found for a relatively weak precipitation range for mid-low clouds (except over land) and high clouds, while similar agreement is found for heavier precipitation ranges for deep convection, regardless of surface type. PMW and IR products considerably underestimate precipitation from mid-low clouds over land by over almost the entire intensity range. The IR-based precipitation estimates for deep convective clouds considerably overestimate the intensity for both weak precipitation and cases where precipitation was not detected by the DPR-Ku algorithm. The findings reveal that the products' bias characteristics depend on the associated cloud types, which suggests the need for considering cloud type information to improve satellite-based precipitation estimates.

Utsumi, N. and H. Kim (2018) Warm Season Satellite Precipitation Biases for Different Cloud Types Over Western North Pacific, IEEE Geoscience and Remote Sensing Letters, 10.1109/LGRS.2018.2815590

Keywords: Cloud types, systematic bias, error estimation, cloud classification

1.40 Improving Overland Precipitation Retrieval with Brightness Temperature Temporal Variation

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The primary signal used in all current passive microwave precipitation retrieval algorithms over land is the depression of the instantaneous brightness temperature (TB) caused by ice scattering. This study presents a new methodology to retrieve instantaneous precipitation rates over land by using TB temporal variation (ΔTB). Results show that ΔTB correlates more strongly with precipitation rate than the instantaneous TB. At high frequencies (89-183), the underlying reason is that ΔTB largely eliminates the negative influences from snow-covered land, which frequently are misidentified as precipitation. Another reason is that ΔTB is less affected by environmental variation (e.g., temperature, water vapor). At low frequencies (e.g., 19 GHz), the correlation primarily reflects surface emissivity variation due to precipitation impact. As a proof-of-concept, we exploit high-frequency microwave observations from eight polar-orbiting satellites and low-frequency observations from five polar-orbiting satellites. High-frequency results show that the correlation with precipitation rate improved to -0.6 by using over the Rocky Mountains and north of 45°N, while the correlation is only -0.1 by using TB. Additionally, the retrieved precipitation rate over snow-covered regions by only using ΔTB at 89 GHz agrees well with the ground radar observations, which opens new opportunities to retrieve precipitation in high latitudes for sensors with the highest frequency at 89 GHz. Low-frequency results over the Southern Great Plains show that ΔTB at 19 GHz is better correlated with the precipitation rate than TB itself at 19 GHz. The retrieved instantaneous precipitation rate over the Southern Great Plains from ΔTB at 19 GHz reasonably agrees with the surface radar observations. Future work seeks to combine the ice scattering signal at high frequencies with this surface emissivity variation signal at low frequencies to achieve an optimal retrieval performance.

1.41 Radar Data Quality Control Using a Random Forest Model Based on Polarimetric Observations and GOES-16 Data

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Although radar polarimetric capability has improved data quality control (QC) to remove non-precipitation (NP) echoes, the clutter caused by wind turbine and anomalous propagation is still challenging due to their difficult-to-distinguish features from those of precipitation (P). These false echoes with high reflectivity values may exacerbate the accuracy of hydrological applications. To resolve this problem, we propose a novel radar QC approach based on a random forest (RF) classifier using dual-polarimetric observations and GOES-16 multi-channel products. The unique features of the RF model, different bootstrap samples for each tree in the RF, and random feature selections can increase the diversity of possibilities, thus enabling ensemble predictions to overcome the limitations caused by fixed thresholds and limited training samples. The authors evaluate the model performance developed in this study for NEXRAD radar data quality control. The model is trained by using clear cases (> 400 volume scans) of P and NP, observed mainly in April and July in 2017. For the model structures, it is found that: (1) incorporating multi-scale local variability (or texture) estimates of dual-polarimetric variables can improve classification accuracy while capturing scale-dependent properties of P echoes, and (2) GOES-16 multi-channel products can help remove false echoes which are not discriminated by radar variables alone. We demonstrate our classification model's efficiency using several cases (ranging from distinct to complicated rain/no-rain events) and long-term comparisons (from 1 April to 31 October) with existing QC approaches (e.g., used in NOAA's Multi Radar Multi Sensor products).

Keywords: NEXRAD, polarimetric observations, GOES-16, quality control, random forest

1.42 Using Vertical Rain Profile Information to Improve Satellite-based Sub-hourly Surface Rain Estimates

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Quantifying time-averaged rain rate, or rain accumulation, on sub-hourly time scale is essential for various application studies requiring rain estimates. This study proposes a new idea to estimate sub-hourly time-averaged surface rain rate based on the instantaneous vertical rain profile observed from LEO satellites. Instantaneous rain estimates from the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) are compared with 1-minute surface rain gauges in North America and the Kwajalein atoll for the warm seasons of 2005–2014. Time-lagged correlation analysis between PR rain rates at various height levels and surface rain gauge data shows that the peak of the correlations tends to be delayed for PR rain at higher levels up to around 6 km altitude. PR estimates for low- to middle-height levels have better correlations with time-delayed surface gauge data than the PR's estimated surface rain rate product. This implies that rain estimates for lower to middle heights may have skill to estimate the eventual surface rain rate that occurs 1–30 minutes later. Therefore, this study averages the vertical profiles of TRMM/PR instantaneous rain estimates between the surface and various heights above the surface to represent time-averaged surface rain rate. It was shown that vertically-averaged PR estimates up to middle heights (4.5 km) exhibit better skill, compared to the PR estimated instantaneous surface rain product, to represent sub-hourly (30 minutes) time-averaged surface rain rates. These findings highlight the merit of additional consideration of vertical rain profiles, not only instantaneous surface rain rates, to improve sub-hourly surface estimates of satellite-based rain products.

Reference: Nobuyuki Utsumi; Hyungjun Kim; F. Joseph Turk; Ziad S. Haddad (2019), Improving satellite-based sub-hourly surface rain estimates using vertical rain profile in- formation, Journal of Hydrometeorology (Accepted).

Keywords: Precipitation, rain, vertical profile, LEO satellite

1.43 Investigating Weather Radar Quantitative Estimations for a Record Precipitation Event in Turkey

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Weather radars are the most advanced devices for quantitative precipitation estimation (QPE) with high temporal and spatial resolution. However, they suffer from many error factors, such as beam blockage and attenuation, and hence generally underestimate precipitation. This study examines a heavy rainfall event (a record of precipitation in Turkey measured at Ovacik village on 17 December 2018, 24-hour total precipitation is 490.8 mm). Among Marshall-Palmer, NSSL, and R-KDP radar rainfall estimators employed in Antalya radar, the best estimator (R-KDP) estimated rainfall to be 49.5 mm. According to a Visibility Analysis Tool developed by the Turkish State Meteorological Service (TSMS), one of the reasons why radar estimation deviated dramatically from the ground truth is that the first three radar beams employed in the radar task were subject to beam blockage due to the mountainous areas. Hence, the minimum visible elevation angle was 3 degrees and the minimum visibility height was 3000 m above MSL in Ovacik village. When a neighboring location which is 6 km northwest of Ovacik is considered, it is seen that there is no beam blocking, and total radar rainfall was estimated as 327 mm during the same period. Although this result confirms that a heavy rainfall occurred in the region, radar underestimates rain due to another error source, such as attenuation. By means of statistical improvement techniques and radar quality index (RQI), radar precipitation is improved, and this study also gives these techniques.

Keywords: Weather radars, beam blockage, attenuation, QPE, RQI

1.44 Dense Crowdsourced Rainfall Observations from Personal Weather Stations: Proposed Real-time Quality Control Methodology

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Personal weather stations are owned and maintained by weather enthusiasts who are interested in monitoring the weather in their surroundings. Their measurements are often visualized and shared on online weather platforms. These platforms thereby make it possible to collect large-scale in situ rainfall observations in (near) real time, which are far denser than typical rain gauge networks operated by weather institutes. The expected errors from these often low-cost devices are significant. This study identifies four error types that this data source is prone to, and proposes a quality control (QC) methodology that is able to identify these errors in real time without the need for auxiliary observations. This QC is designed using the first year of a two-year dataset of crowdsourced rainfall observations from Netatmo weather stations in the Amsterdam metropolitan area with typical interval lengths of 5 min. Then, the QC is applied on the second year of that dataset as well as on a national scale. Excluding all observations in the Amsterdam metropolitan area rainfall dataset that were flagged by the QC increased the accuracy of hourly rainfall observations significantly: The resulting Pearson correlation increased above 0.8 with a coefficient of variation 2.9, while maintaining 88% of the original number of observations. The QC is also shown to be successfully applicable on a nationwide scale, with a good match with the rainfall product constructed from gauge-adjusted radar operated by the Royal Netherlands Meteorological Institute.

Keywords: Quality control, rainfall, crowdsourcing, rain gauges

1.45 Hydrologic Evaluation of Polarimetric Quantitative Precipitation Estimates Over Iowa

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The Iowa Flood Center (IFC) provides state-wide streamflow predictions based on a distributed hydrologic model, Hillslope Link Model (HLM), mainly forced by real-time radar-based precipitation estimates. This in-house forcing product is a composite of seven NEXRAD radars covering Iowa, with time and space resolutions of five minutes and approximately 0.5 km. The IFC's current quantitative precipitation estimation (QPE) algorithm is based on a conventional relationship between reflectivity (Z) and rain rate (R), with data quality control using polarimetric observations. The IFC composite QPE product has demonstrated challenges that might affect IFC's streamflow prediction: (1) relative biases among different radars that occasionally lead to a noticeable border at the overlapping areas, and (2) inconsistent rainfall estimation and its seasonal variation in a region covered by one of the radars (e.g., KFSD in Sioux Falls, Iowa) caused by partial beam blockage effects. As an effort to resolve these challenges, the IFC has implemented and tested polarimetric QPE algorithms that are less sensitive to the effects from radar miscalibration, partial beam blockage, and the variability of raindrop size distributions. In this study, we use a set of QPE algorithms including R(Z), R(Kdp), R(Z, Zdr), and R(A) and assess their performance and reliability using ground reference data (e.g., rain gauges) over a long period. We also run the HLM using the generated QPE products and discuss space- and time-dependent similarities and differences in the propagation of their errors into streamflow prediction.

Keywords: Precipitation, weather radar, QPE, hydrology

1.46 The Role of Free Tropospheric Moisture for Convective Onset from Radio Occultation vs Climate Models

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There is a wide disparity among convective precipitation as represented by various climate models, owing to poor understanding of parameterized physical processes. Assessing improvements to the modeled precipitation is inhibited by a lack of observations of the moisture state around convection. Previous work has suggested the importance of lower free-tropospheric moisture to convective onset by examining the precipitation-buoyancy relation using radiosonde data. Such relationships provide a new constraint for convective parameterizations. To estimate buoyancy (conditional instability), the vertical moisture distribution is needed. Using Global Navigation Satellite System (GNSS) signals, satellite radio occultation (RO) offers the desired moisture profile with high-frequency and near-global coverage compared with traditional site-specific radiosondes. In this study, we expand the previous analysis by compiling the precipitation-buoyancy relation using the COSMIC RO data to assess the relative importance of moisture in different layers to convective onset. The resulting precipitation conditioned on plume buoyancy estimated with deep-inflow mixing shows a sharp pickup as buoyancy increases, and exhibits little quantitative variation across climate regimes. The relative contributions of water vapor vs temperature to buoyancy variations in the high precipitation regime are quantified, and are compared with the analytic approximations to the plume buoyancy that are useful for understanding dominant physical processes. In addition, sensitivity to various assumptions relevant to model parameterizations is tested, including the impacts of condensate removal by precipitation on the buoyancy sensitivity to freezing processes. We apply the same analyses to the output from climate models as offline diagnostics, testing the extent to which COSMIC RO data provide more precise constraints on convective parameterizations for the interaction with free tropospheric moisture.

Keywords: Convective onset, convective parameterizations, climate model diagnostics, radio occultation

1.47 Precipitation Estimation Based on Specific Differential Phase Using the MZZU Radar

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The estimation of precipitation is a longstanding goal in hydrological use of radar. Radar-derived hourly and daily accumulations are useful because the rainfalls have a small-scale variability. The advent of dual-polarization radar has improved radar precipitation estimation by introducing polarimetric variables, such as differential reflectivity and specific differential phase (Kdp). This study investigates the Kdp-based rainfall rate estimation using the X-band dual polarization radar of the University of Missouri (MZZU). The specific differential phase is estimated by a Gaussian mixture method, and its statistical errors σ(Kdp) are also derived in the calculation of the range derivative of differential phase shift. Subsequently, Kdp is used to retrieve the rain rate R via a power-law relation, R = cKdpb, where the parameters c and b are optimized for the MZZU radar in central Missouri. Meanwhile, σ(Kdp) is inherited by the statistical errors of rain rate σ(R) via (σ(R))/R=b (σ(Kdp))/K_dp. To evaluate the performance, the radar-derived hourly rain accumulations are compared to the rain gauge measurements, yielding good agreement in terms of root mean square error, normalized bias, and Pearson correlation.

Keywords: Polarimetric radar, quantitative precipitation estimation, specific differential phase

1.48 Real-time Precipitation Maps from Satellite Broadcast Signals

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Geostationary broadcast satellites bring information on rainfall rates along their path, through signal attenuation caused by raindrops. We exploited this feature with novel two-way (transmit-receive) devices named SmartLNB (Smart Low-Noise Block converter), which can be seen as constituting networks of sensors of opportunity, in any urbanized areas. Albeit not specifically developed for meteorology, two-way receivers centralize attenuation data, ready to be processed for rainfall estimation, every minute. The high rate of real-time measurements provided by SmartLNBs suggested approaching the rainfall retrieval problem as a trajectory assessment in a phase space, using an ensemble Kalman filter, to produce rainfall fields over a given spatial domain. SmartLNBs provide average measurements along quasi-parallel non-nadir satellite-receiver paths, so that information on the structure of the intercepted rainfall system must be known to retrieve ground precipitation. MSG satellite observations can be used for the purpose and as initial and boundary conditions, while atmospheric motion vectors from the same data source are used in the propagation model of the Kalman filter. A cross-shaped experimental network of a dozen SmartLNBs has been deployed in Florence (Italy) with co-located rain gauges and one Doppler polarimetric X-band radar for cal/val objectives. In this work, we present the measurement concept, the signal processing algorithm, the method for estimating the rainfall fields, and the results, which revealed insights far beyond our expectations. First, some significant synthetic case studies are illustrated, for various precipitative events with different intensities, dynamics, and morphologies, and for various sensor distributions. Real measurement retrievals (single and collective) from the project network are shown and results discussed, with attention to the technique's sensitivity to receiver density, satellite link geometry, and rainfall system characteristics.

Keywords: Rainfall estimation, satellite broadcast, satellite meteorology, Kalman filter

1.49 Understanding Global Precipitation Particle Sizes with the GPM Satellite

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The Global Precipitation Measurement (GPM) core satellite has been sampling precipitation globally for more than five years. It carries the first spaceborne dual-frequency precipitation radar (DPR), which provides quantitative estimates of precipitation particle size distribution (PSD). The estimated size parameter, often called "mass weighted mean diameter" (Dm), may offer new physical insights into microphysical properties of precipitation around the globe. The GPM precipitation particle size parameters are retrieved with two sets of algorithms. One is based on the DPR observations only, while the other one uses observations from DPR and the GPM passive microwave imager (GMI)—called the combined (CMB) product. This research compares the characteristics of Dm retrieved by the DPR and CMB algorithms. We analyze the difference between the two algorithms according to latitudes and vertical levels, as well as over ocean vs land surfaces and for convective vs stratiform types of precipitation. We found that Dm retrieved with the DPR algorithm is generally larger than with the CMB product. Depending on latitudes and altitudes, their zonal mean difference could be 0.1 to 0.2 mm. For the convective component, their differences are larger. Differences between the algorithms are also apparent over the mid-latitude oceanic storm track and high-latitude land. Since the PSD parameters are critical physical quantities that ensure consistency in a hierarchy of GPM retrieval products with radar, radiometer, and combined radar-radiometer algorithms. Our study will not only improve our understanding of the global distribution of the precipitation particle sizes but also document the current status of the algorithms, which may provide a reference for future refinement.

Keywords: GPM, precipitation particle sizes

1.50 Toward a Generalized GPM DPR Rainfall Retrieval Error Diagnostics and Correction Framework in Mountain Regions

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GPM DPR retrieval errors are tied to 1) contamination of near-surface reflectivity profiles due to ground-clutter, 2) spatial variability of precipitation and non-uniform beam filling, and 3) microphysics. These errors are enhanced in regions of complex terrain with strong diurnal and seasonal cycles linked to elevation and landform. In the interior of mountain regions, the ambiguity of compounded errors poses a significant challenge that is not suitable for statistical modeling. This work's premise is that it is possible to isolate different errors' dominant signatures from systematic analysis of the vertical structure of DPR measurements, aided by high-resolution NWP simulations to develop a comprehensive data-driven physically-based framework for identifying, quantifying, and correcting retrieval errors. The Southern Appalachian Mountains (SAM) and the Eastern Andes Slopes (EADS) are selected for demonstration and independent evaluation. Rain gauge and disdrometer observations, ground-based radar data from Multi-Radar/Multi-Sensor (MRMS) and High-Resolution Rapid Refresh (HRRR) forecasts in the SAM, and a mix of rain gauge, disdrometer, and radar systems in the EADS, along with WRF simulations and downscaled reanalysis products (ERA5), as well as other collocated space-based observations (A-Train and others) when available, will be used to populate dataspace. The dataspace consists of cross-scale (universal) metrics of the spatial structure of rain rate conditional on precipitation type, as well as vertical structure of reflectivity (Ku and Ka band), microphysics, water vapor, cloud water, and rain water. This work will show that generalized functional associations (independent of geographic location) among satellite-based measurements, model forecasts, and retrieval errors can be identified through a deep-learning algorithm with embedded physical constraints that can be used to predict retrieval error type and amplitude operationally where ground observations are not available.

Keywords: GPM, orographic precipitation, remote sensing

1.51 Impacts of Aerosols on Snowfall and Its Melting Process Over Sierra Nevada Glaciers in California

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The snowpack in the Sierra Nevada mountain range is California's primary water source. Many studies have shown that the increase in aerosols could lead to a reduction of the snowpack in this region. This study focuses on evaluating changes in snowpack during the winter and summer seasons from 2000 until 2016 and determining the relationship between aerosols and the retreat of glaciers in the Sierra Nevada. The change detection analysis has shown reductions of 76.4% and 91.4% in the snowpack during winter and summer, respectively. Utilizing the aerosol optical depth (AOD), Angstrom exponent, snow depth anomalies, snowfall, radiation fluxes, and albedo, the effect of aerosols on snowfall over the Sierra Nevada glaciers has been examined for this 17-year period. We observed and analyzed an emerging dust case that decreased the snow surface albedo, resulting in increased absorbed longwave radiation and snow surface temperature. Overall, the correlation analysis and case studies suggest that a negative relationship exists between the AOD and the snowfall in Sierra Nevada.

Keywords: Aerosol, snowpack, Sierra Nevada, glacier retreat

1.52 Harmonic and Correlative Analysis of the Relationship between Precipitation Vegetation and Soil Moisture in the MENA Region

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Arid and semi-arid environment characterizes the Middle East and North Africa (MENA) region. Climate change poses significant forcing in these regions by causing them to be drier and to suffer water scarcity, especially in recent years. In this research, we built a harmonic analysis model with data from a MODIS enhanced vegetation index (EVI) dataset to investigate the drying trend over the MENA countries in the past 20 years. The models performed well, and different vegetation changes among the MENA were observed. The results revealed a changing behavior over different areas among the MENA countries: regions such as Iraq and middle Saudi Arabia suffer from a drier climate, whereas parts of Iran are more humid. Meanwhile, we also used correlative analysis to compare with two soil moisture products: namely, NASA-USDA's Global Soil Moisture Data (SMAP) and Global Land Data Assimilation System (GLDAS). Results show that GLDAS's soil moisture data is better correlated with the EVI dataset, especially in regions such as the Nile Delta and Red Sea coast along Saudi Arabia. A strong correlation between precipitation and EVI is also observed along the coastal Mediterranean and Mesopotamia.

Keywords: EVI, vegetation, MENA, soil moisture, harmonic analysis

1.53 Validation of Satellite Rainfall Estimates in the Blue Nile Basin

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The demand for accurate satellite rainfall products is increasing, particularly in Africa, where ground-based data are mostly unavailable, untimely, and unreliable. This study assessed the accuracy of three widely used, near-global, high-resolution satellite rainfall products (CMORPH, TMPA-RT v7, TMPA-RP v7), with a spatial resolution of 0.25 degrees and a temporal resolution of 3 h, over the Blue Nile River Basin, a basin characterized by complex terrain and tropical monsoon. The assessment is made using relatively dense experimental networks of rain gauges deployed at two, 0.25 degrees x 0.25 degrees, sites that represent contrasting topographic features: lowland plain (mean elevation of 719 m.a.s.l.) and highland mountain (mean elevation of 2268 m.a.s.l.). The investigation period covers the summer seasons of 2012 and 2013. Compared to the highland mountain site, the lowland plain site exhibits marked extremes of rain intensity, higher mean rain intensity when it rains, lower frequency of rain occurrence, and smaller seasonal rainfall accumulation. All the satellite products considered tend to overestimate the mean rainfall rate at the lowland plain site, but underestimate it at the highland mountain site. The satellite products miss more rainfall at the highland mountain site than at the lowland plain site, and underestimate the heavy rain rates at both sites. Both sites have uncertainty (root mean square error) values greater than 100% for 3 h accumulations of <5 mm, or daily accumulations of <10 mm, and the uncertainty values decrease with increasing rainfall accumulation. Among the satellite products, CMORPH suffers from a large positive bias at the lowland plain site, and TMPA-RP and TMPA-RT miss a large number of rainfall events that contribute nearly half of the total rainfall at the highland mountain.

Keywords: TRMM, validation, Blue Nile, mountain

1.54 Quantifying Rain Evaporation Using a Microrain Radar

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Assessing the amount of rain that evaporates between cloud base and ground is important for several reasons. First, as surface rainfall is increasingly estimated from radar observations that sample above the surface, the accuracy of precipitation totals can be improved by accounting for evaporation. Second, the precipitating system's latent heat and moisture budgets can be better understood when the evaporation is correctly modeled, and the storm dynamics, including downdraft strength, can be more precisely determined. In this work we describe comparisons between vertical profiles of raindrop size distributions and liquid water contents retrieved from a vertically pointing microrain radar when the rain is falling through unsaturated air, and model drop size distributions profiles informed by in situ sounding data. It is shown that the model can replicate the vertical evaporation profile observed, but the evaporation is very sensitive to vertical wind speed. As updraft velocity controls the residence time of different diameter drops in a drying layer, the atmospheric water and latent heat budget is captured accurately only if the vertical air velocity is well represented in the model.

Keywords: Rain, evaporation, drop size distribution, radar

1.55 Opportunistic Sensing of Rainfall Using Microwave Links from Cellular Communication Networks in Africa and Asia

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Microwave backhaul links from cellular communication networks provide a valuable "opportunistic" source of high-resolution space–time rainfall information, complementing traditional in situ measurement devices (rain gauges, disdrometers) and remote sensors (weather radars, satellites). Over the past decade, a growing community of researchers, in close collaboration with cellular communication companies, has developed retrieval algorithms to convert raw microwave link signals, stored operationally by their network management systems, to hydrometeorologically useful rainfall estimates. Operational meteorological and hydrological services as well as private consulting firms are showing an increased interest in using this complementary source of rainfall information to improve the products and services they provide to end users from different sectors, from water management and weather prediction to agriculture and traffic control. The greatest potential of these opportunistic environmental sensors lies in those geographical areas over the Earth's land surface where the densities of traditional rainfall measurement devices are low: mountainous and urban areas and the developing world. We present several examples of high-resolution rainfall monitoring over countries in Africa and Asia, both for densely populated urban areas and for rural areas. We also discuss some of the challenges and opportunities regarding continental-scale rainfall monitoring using microwave links from cellular communication networks.

Keywords: Opportunistic sensing, microwave links

1.56 Accounting for Satellite Precipitation Uncertainty in a Landslide Hazard Model

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Uncertainty in satellite multisensor precipitation products (SMPPs) presents a challenge to fully utilizing these near real-time sources of global precipitation. Landslides are caused by static factors, which can be assessed ahead of time, and dynamic factors, specifically rainfall, which require near real-time information to incorporate into landslide hazard models. The global Landslide Hazard Assessment for Situational Awareness (LHASA) model uses the SMPP IMERG to estimate landslide hazard worldwide in near real-time, issuing moderate or high hazard "nowcasts" to regions with landslide hazards. However, SMPPs, including IMERG, are susceptible to systematic bias and random error, which are a significant source of uncertainty within the LHASA model. SMPP uncertainty is especially relevant to LHASA because SMPPs have been shown to exhibit high uncertainty for the high rainfall magnitudes that trigger landslides. This study applies the Censored Shifted Gamma Distribution (CSGD) framework for characterizing SMPP uncertainty to precipitation estimates used in the LHASA model at a daily scale. We develop a probabilistic LHASA model with a probabilistic landslide hazard nowcast scale to reflect the uncertain nature of precipitation input. The probabilistic LHASA model incorporates SMPP uncertainty and outperforms the operational LHASA model in a study area in the southeastern U.S. during the 2002-2018 study period. This study shows that moving from SMPPs as unknown sources of uncertainty to SMPPs as known sources of uncertainty can significantly improve model performance, even without being able to deterministically derive true precipitation from SMPP observations.

Keywords: Uncertainty, probabilistic, landslides

1.57 Societal Response and Human Resilience to Water Cycle Pollution and Extreme Weather Events Along the Nigeria Coast

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Impacts from natural and anthropogenic hazards, like storms, (water and air) pollution, erosion, and flooding, are substantial and increasing significantly with climate change and poor coastal development decisions, putting more people and property at risk. This fact implies that high densities of vulnerable people are more likely to be exposed to floods and heatwaves in coming decades. Recent discussions and emphasis on issues concerning the societal response and human resilience to climate change justify the need for this research by assessing the environmental performance communities along the coastal cities in Nigeria. The study employed cross-sectional methods of field surveys where observational guides and questionnaires were administered respectively in surveying the study area hotspots. Descriptive statistics methods were used to analyze results obtained from the field survey. Interpretations from the results affirmed that local communities could play a valuable role in generating knowledge and developing locally relevant approaches for building resilience. In addition, ecosystem-based and hybrid interventions can contribute significantly to reducing flood risk, as well as delivering wider environmental, economic, and social benefits. Coastal development and adaptation policies that consider social, economic, and environmental risks simultaneously can reduce social and economic vulnerability and maximize the risk reduction benefits that natural habitats can provide. Results further showed that the cost–benefit ratio of human resilience to government intervention is 1:0.4, which means that the benefits of societal responses/human resilience outweigh the costs borne by government agencies.

Keywords: Hazards, droughts, emergency, risk

1.58 Spatio-Temporal Changes in Non-extreme Precipitation Variability Over North America

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Precipitation variability encompasses attributes associated with the sequencing and duration of events of the full range of magnitudes. However, climate change studies have emphasized extreme events. Our analysis of long-term weather station data demonstrates that high-frequency events, such as the fraction of wet days in a year and average duration of wet and dry periods, are undergoing significant changes across North America. The median increase in the fraction of wet days in a year indicates that in 2010, North America experienced an additional 11 days of precipitation compared to 1960 (when the median number of wet days was 96), and wet periods that were 0.14 days longer than those in 1960 (when the median was 1.78 days). Further, these changes in high-frequency precipitation are more prevalent and larger than those associated with extremes. Such trends also exist for events of a range of magnitudes. Results reveal the existence of localized clusters with opposing trends to those of broader geographic variation, which illustrates the role of microclimate and other drivers of trends. Such hitherto unknown patterns have the potential to significantly inform our characterization of the resilience and vulnerability of a broad range of ecosystems as well as agricultural and socioeconomic systems. They can also set new benchmarks for climate model assessments.

Keywords: High-frequency precipitation, nonstationarity, variability, sequencing

1.59 On Changes of Global Wet-bulb Temperature and Snowfall Regimes

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This study documents the spatiotemporal changes in global snowfall from 1979 to 2017, using the wet-bulb temperature processed from three reanalysis products together with the Pentad precipitation from the Global Precipitation Climatology Project (GPCP). The changes in potential snowfall areas, snowfall transition latitudes, and the annual snowfall to precipitation ratio are studied. The temporal changes and their significance are quantified through linear trend analysis using the Theil-Sen estimator and the moving block bootstrap Mann-Kendall test.

It is found that over the Northern Hemisphere (NH) land (oceans), the maximum likelihood of ensemble annual mean wet-bulb temperature has increased at a rate of 0.34 (0.35) °C per decade (pd), causing the potential areas of annual snowfall dominant regimes to shrink by 0.52 (0.34) million sq. km. pd. The results also show that over the NH, snowfall-to-rainfall transition latitude is retracting toward the North Pole at a rate of 0.7° and 0.45° pd over Europe and Central Asia. Combining wet-bulb temperature and precipitation data suggests a decreasing trend in snowfall-to-precipitation ratio over polar and cold climate regimes, at 1.50 and 0.95% pd, respectively. Furthermore, important mountain regions of the world, such as the Alps and High Mountain Asia, are losing a significant proportion of snowfall, at 1.75 and 1.38% pd.

Keywords: Global snowfall, snowfall to precipitation ratio, wet-bulb temperature

1.60 Analysis of Snow Measurement Data for Estimating Quantitative Snow Water Equivalent (SWE) Data

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Accurate snow observations are important to reducing damage from heavy snowfall in the winter season. However, snow measurement is greatly affected by wind speed, temperature, and humidity, so it is not a simple problem to determine quantitative snowfall data. In recent years, the use of a weighing precipitation gauge that estimates snowfall amount by measuring precipitation weight has increased. Studies to determine the snow water equivalent (SWE), which is used to quantify the water resources stored in snow, have been performed to catch snowfall events. Snowfall can be easily calculated using SWE because SWE is less affected by precipitation density. However, in a heavy snow season, observation systems exhibit problems due to snow capping and errors. This study proposes a new quality control (QC) process for SWE data by comparing snow observation data. Pluvio, one of the weighing precipitation gauges, was used to estimate SWE and to analyze snow data from particle size velocity (PARSIVEL) disdrometers and snow depth meters (using laser or ultrasonic). A quality control method for SWE was developed by applying the particle size distribution from the PARSIVEL disdrometer. This study improved data from three cases of disaster events caused by heavy snowfall. As a result, the improved SWE data was superior to other snow measurement data.

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Keywords: Snow observation, SWE, Pluvio, PARSIVEL, snow depth meter

1.61 Precipitation in Extratropical Cyclones: A GCM Evaluation

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Using four years of gridded precipitation information from the NASA Integrated Multi-satellite Retrieval for GPM (IMERG) product, we explore precipitation rates and distribution in extratropical cyclones over the oceans. This work is performed with a cyclone-centered compositing and conditional sorting method. The same cyclone tracking and compositing method is applied to two reanalyses (MERRA-2 and ERA-interim) and two free-running GCMs using recent versions intended for CMIP6. The four modeled cyclone-centered precipitation composites are compared to observations to evaluate precipitation in models in the dynamically rich cyclones. We find that in all these models mean precipitation is well represented: the biases are small. However, all models tend to slightly overestimate precipitation where it is weak in the cyclones, while underestimating precipitation where it is strong. This is because: 1) the models tend to predict greater frequencies of precipitation occurrence than observed everywhere in the cyclones, for the same minimum rate when precipitating in models and observations; and 2) the models underestimate rates in the region of ascent in the cyclones, and overestimate them in the cold sector (dominated by subsidence). Interestingly, the biases are consistent across models, with only small variations in their magnitude, despite different spatial and temporal resolutions, sample sizes, and cyclone mean characteristics. Additionally, we will explore precipitation's sensitivity to changes in large-scale cyclone properties. For this effort we will compare precipitation characteristics in strong versus weak cyclones and in moist versus dry environments. Preliminary results suggest a lower sensitivity to both cyclone characteristics in models than observations. We will discuss the details of these differences in sensitivity and the implications for reliable future climate predictions of mid-latitude precipitation and extreme events.

Keywords: Extratropical cyclones, GCM, reanalysis, precipitation frequency and rate, compositing

1.62 Future Changes in the Most Extreme Atmospheric River-driven Storms Over California and Their Hydrologic Impacts

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A majority of annual precipitation along the U.S. West Coast (including California) originates from a few intense atmospheric river (AR) events each year. Winter over 2016-2017 in California embraced the state's most extreme wet season since 1895, after an extraordinarily long-term drought. We are trying to understand how heavy precipitation events will change in the future and how snowpack and flooding risk will be affected. To answer these questions, a selection of the most extreme U.S. West Coast atmospheric river (AR) events from a historical period (1996-2005) and a future period (2071-2080) is studied under the dynamical downscaling method and large-ensemble CESM output. At the same time, both dynamical and thermo-dynamical features of the modeled top ARs are diagnosed for the underlying changes under the RCP8.5 scenario by the end-of-21st-century from the recent past. One of the goals is to attribute the main underlying dynamical and physical mechanisms that drive the changes of AR-derived storm events over complex study regions using multi-scale modeling. It is argued that the highest-resolution simulations (less than 10 km) can reveal important fine-scale features such as orographically-forced vertical motion, and are capable of reproducing strong low-level wind speeds and anomalous convective instability. It is demonstrated that high-resolution simulations are not only an effective tool for studying atmospheric river-induced precipitation extremes in general, but are also necessary to capture extrema of various meteorological quantities that are critical in producing many of the natural hazards associated with these events (i.e., flooding, mudslides/debris flows, and wind damage). The impacts of ARs' changes on precipitation, snowpack accumulation, and streamflow at specific watershed regions over the most-affected mountainous regions have also been analyzed, to better inform policy-makers in regulating climate change adaptations.

1.63 Investigating Precipitation Microphysical Variability Induced by Orographic Enhancement in Northern California

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Quantitative Precipitation Estimation (QPE) in the coastal mountain area of Northern California is challenging due to the complex precipitation microphysics as a result of land–ocean interaction in the coastal regions and orographic enhancement in the mountainous regions. A number of previous studies have investigated precipitation characteristics in this complex domain, using remote sensing instruments such as S-band profiling radars (e.g., White et al. 2003) or in situ measurements of raindrop size distributions (DSD) at the surface (e.g., Martner et al. 2008). This study extends the earlier work by including new DSD measurements both from the valley (Santa Rosa) and the mountains (Middletown), so as to characterize orographic precipitation enhancement. In particular, DSD observations collected during two wet winter storm seasons (January–February 2017, January–February 2019) are used to diagnose rainfall's bulk microphysical properties. Three rainfall types—namely, nonbright band, bright band, and hybrid rain—are classified based on observations from profiler radars. Several DSD and rainfall parameters are computed from the observed raindrop spectra and examined for different rainfall types and terrains (i.e., valley vs mountain). The microphysical characteristics are quantified to achieve a better understanding of rainfall processes involving orographic enhancement. In addition, polarimetric radar measurements at both S and X bands are simulated based on the DSD data, and their distributions are investigated for different types of rainfall and topography, in order to provide implications for quantitative precipitation estimation using NEXRAD and/or gap-filling radars in such complex terrains.

Keywords: QPE, complex terrain, DSD, precipitation microphysics, Northern California

1.64 Revisiting the Intensity Distribution of Rain Rates in Global Climate Models and Its Simulated Change Under Climate Warming

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A previous examination of the change in rain rates' intensity distribution under a warming climate scenario in a global climate model found that the predicted change in the frequency of intense rain events depended substantially on the formulation of the cumulus convection parameterization. This phenomenon includes the cumulus closure, convective triggering, and other factors that influence instability in the column and the rate at which convection is assumed to respond to it. Subsequent work has shown that a portion of the change in extreme rain rates can be predicted from changes in the atmosphere's gross thermodynamics, but also that a substantial portion depends on local dynamics, including processes strongly linked to the convection parameterization in global models. Here, we revisit the variability in rain rate intensity distribution among models by drawing on the CMIP5 archive. The variability among models is examined in relation to the differences in the parameterization of cumulus convection and the differences in climate sensitivity among models.

Keywords: Extreme events, climate modeling, climate change

1.65 Looking Behind the Curtain of Advanced Snowpack Estimation in the Sierra Nevada, CA

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Continuous and reliable snowpack estimates will become increasingly important with a rising snow line, limited station data, and altered accumulation and melt dynamics due to a changing climate. However, inconsistencies across different snowpack estimates can propagate to discrepancies downstream and have operational consequences, especially in snow-dominated basins, where water and energy budgets and streamflow are more sensitively affected by snowpack. This work compares long-term, continuous (spatially and temporally) snow-water equivalent (SWE) reconstructions from a Bayesian reanalysis and a land surface model over the California Sierra Nevada, identifying possible key factors that drive similarities and differences between the two estimates. Wet season (November-March) SWE and snow accumulation rates are generally comparable, likely due to compensating differences in snowfall and partial snow cover. On the other hand, melt rate estimates are systematically biased, resulting in large melt season (April–June) SWE differences, especially during wet years. Melt season discrepancies are found to be driven primarily by strong differences in snow albedo parameterizations. This study highlights how melt-season snowpack is complicated by multiple inputs (relative to wet season snowpack, driven primarily by precipitation), pointing to the careful attention needed to capture it.

Keywords: Snow water equivalent, data intercomparison, California

1.66 Lifecycle of Vertical-scale Invariance Structure of Wind and Moisture Fields During Cold Air Intrusions, with Implications for the Predictability of Orographic Precipitation Extremes in the Andes

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Accurate forecasting of heavy precipitation remains a challenge for numerical weather prediction models, especially over complex topography. Previously, high-resolution atmospheric model simulations exhibited different scaling behavior of vertically averaged horizontal wind (u,v) and moisture (q) in the mesoscales for convective (spectral slopes β -5/3) and non-convective (β -11/5) conditions along the eastern slopes of the Andes (EADS) in South America. Further, analysis of 16+ years of TRMM precipitation revealed significant enhancement of precipitation below the orographic maximum (1,500m) during Cold Air Intrusions (CAIs), in agreement with ground-based observations in the EADS of Peru. Here, the focus is on the transient behavior of horizontal scaling in the vertical during CAI events. The work is extended to the GPM era, and in particular to the Remote sensing of Electrification, Lightning, And Meso-scale/micro-scale Processes with Adaptive Ground Observation (RELAMPAGO) experiment domain, where comprehensive data are available to support interpretive analysis. Simulations of two CAI events with and without enhanced convection are contrasted against an intense convective event in the absence of CAI to follow the evolution of moist convective processes vis-à-vis orography under distinct synoptic regimes. The model results suggest significant precipitation enhancement from intense shallow convection at the CAI frontal boundary, amplified by orographic lifting as it propagates northward, attached to the eastern slopes of the eastern Andes. Synthesis of scaling analysis conditional on atmospheric stability metrics provides a pathway for improving the representation of moist processes in complex terrain toward improving the predictability of orographic precipitation extremes.

Keywords: Rainfall, Andes, cold front, extreme events, water cycle

1.67 Multi-sensor and Modeling Assessment of Vegetation and Precipitation Changes Influenced by ENSO Events in Saudi Arabia

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An arid environment with limited vegetation and scarce water resources characterizes Saudi Arabia (SA). Therefore, changes and trends in vegetation conditions are very important, especially since climate change may significantly impact living standards and food security in the coming years. In this research, we used the enhanced vegetation index (EVI) as an indicator of drying trends over the SA region in the past 20 years. The soil moisture products, vegetation, and precipitation-based products were assessed to monitor and predict the variability of vegetation distribution. Overall, the vegetation in SA exhibits a declining trend in most habitats, with the exception of regions with cropland reclamation. Most of the wild sparse vegetation areas (such as grassland and shrubland) suffer decreasing trends in the southwestern mountains. It was found that soil moisture of different vegetation categories (forest, cropland, mosaic, and sparse) reacts differently to precipitation. Interestingly, a comparably positive relationship between SA's NDVI and Trans-Niño Index (TNI) is shown over the other El Niño indices, with increasing lag correlation from 0 to 11 months. This may indicate the teleconnection between El Niño events, eastern Pacific El Niño in particular, and precipitation-related vegetation richness in SA.

Keywords: EVI, NDVI, vegetation, Saudi Arabia, soil moisture, precipitation, ENSO

1.68 Satellite-based Estimates of Groundwater Depletion in the Basin of the Sinai Peninsula, Red Sea, East Coast, and Western Desert and Delta in Egypt

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Groundwater is a primary source of fresh water in many parts of the world, especially in arid areas like the Middle East. This study uses observations from the Gravity Recovery and Climate Experiment (GRACE) to evaluate groundwater storage trends in the basin of the Dead Sea, Sinai Peninsula, Red Sea, East Coast, and the Western Desert and Delta in Egypt from January 2003 to December 2016, and spatiotemporally correlates them with ancillary data, which include land surface model outputs, remote sensing observations, and field data. Google Earth Engine is used to process a petabyte catalog of satellite imagery and geospatial datasets and detect changes, map trends, and quantify differences in the above data. The study finds that anthropogenic factors likely cause the steadily decline of groundwater in the above areas. Sustainable groundwater usage management should be taken into account before socioeconomic stresses occur there.

Keywords: GRACE, MENA, Egypt, groundwater, Google Earth Engine

1.69 Estimating Tropical Cyclone Precipitation Risk in North America from Observations and Models

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Freshwater floods generated by extreme Tropical Cyclone Precipitation (TCP) are a significant threat to coastal communities in both the U.S. and Mexico. There is an urgent need to understand historical variations and possible future changes in the risk of TCP and its hydrological impacts, especially in light of the significant damages caused by extreme inland flooding by Hurricanes Harvey and Hurricane Florence in recent years. This study will look at the spatial and temporal variability of TCP risk at 0.25 degree grids by using TCP obtained from rain gauges, as well as synthetic and dynamic models. Future work will focus on modeling stream flow magnitude and inundation area and estimating flooding risk for hotspots (such as urbanized areas) by using the TCP information obtained from this study.

Keywords: Tropical cyclones, precipitation, climate

1.70 Impact of Climate Variability on Ecohydrology of Upper Alaknanda Basin, Western Himalaya, India

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The present research investigates the issues concerning ecohydrology and potentiality of water in high mountain areas of Western Himalaya. The Upper Alaknanda Basin of the Western Himalaya region is the source of perennial streams feeding the south- and east-flowing rivers of Ganga Plain, which supplies almost half of the Indian population. For the climate, people, economy, and ecology, the Upper Alaknanda Basin of the Western Himalaya region is known as the "Water Tower" as it supplies drinking water for humans and animals, water for irrigation and other agronomic practices, and a very mountain-specific use: hydropower depends on water from the Upper Alaknanda Basin. Increasing population and economic transformations have exerted considerable pressure on land and water resources in Western Himalaya. Such changes have brought modifications in water flows, nutrients, sediments, and pollutants as well as loss of biodiversity. Hence, the ecohydrological processes in headwater regions of Western Himalaya have been degraded. The role of natural processes, impact of human interference and climate variability on the availability of water, highland–lowland interactive linkages, and sustainable use of water require attention for planning and conservation. Therefore, there is an urgent need for a better understanding of the land–water system's vulnerability to human activities and climate variability impacts in the high mountain region of Western Himalaya. The present research will suggest sustainable pathways toward resilience for mountain communities which will help them to develop strategic plans against climate variability and water potentiality in high altitude basins of Western Himalaya.

Keywords: Climate variability, mountain sustainability, ecohydrology, Alaknanda Basin

1.71 Stationarity Considerations in Stochastic-dynamic Hydrometeorological Models

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Modeling in stochastic hydrometeorology has relied heavily on stochastic processes that include a deterministic component. In this setting, the present work sheds some light on the effect of both the deterministic and the non-deterministic ("random") component of such a model, on the process's stationary probability distribution function. Different applications are presented, and climate-scale implications are considered.

Keywords: Stochastic-dynamical, stationary distribution, climate variability

1.72 Evaluating Fire-induced Hydrologic Responses with a Dynamic Vegetation Model

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The Southeast region of the U.S. (SE US) observes the most fires and largest burn area annually, which impact regional coupled carbon-water cycles. Further, extreme drought conditions over the past two decades allow for larger and more intense fire events, which severely limit the region's capacity to uptake atmospheric carbon, reducing its role as a carbon sink. This work characterizes the long-term co-adaptive responses of ecosystems (i.e., water and energy budgets) through high spatial and temporal resolution (4 km and 30-min) simulations of regional carbon assimilation rates and canopy development patterns under fire and non-fire regimes with the Duke Coupled land-surface Hydrology Model with Prognostic Vegetation. In a case study of the 2007 Okefenokee Swamp fire in southern Georgia, we find differences in the post-fire recovery time among gross primary productivity, fraction of photosynthetically active radiation (FPAR), and leaf area index (LAI) after the disturbance, with FPAR recovering first and LAI never fully recovering before a second fire in 2011. Wildfire events in this area significantly reduce vegetation canopies, with losses in potential carbon uptake rates as high as 400 g C/m2, half of annual productivity under non-fire conditions. Decreases in water use efficiency precede large fire events, suggesting that antecedent conditions comprise either changes in plant water use strategies and/or composition. The first-order impacts of fire events are observed through the energy budget by altering surface albedo and vegetative land cover. Frequent turnover in land cover serves as the largest source of uncertainty within the model, but demonstrates high spatial organization at regional scales. This work highlights the importance of energy budget feedbacks in addition to land cover changes when investigating coupled water-carbon cycles under disturbance regimes.

Keywords: Coupled carbon-energy-water cycles, dynamic vegetation modeling, fire-induced ecosystem responses

1.73 Simulating Precipitation Using a Climate-Informed k-NN Algorithm

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Non-stationarity in a particular region's climate can be manifested either as secular or cyclical trend. Global climate models may satisfactorily replicate the long-term secular trend, but fail to capture internal variability. We show that utilizing historical data along with information from climate in a stochastic modelling framework can capture both components and offer improved simulations, particularly for near-term local climate projections.

Keywords: Non-stationarity, Climate-informed k-NN model, Precipitation

Poster Session 2

2.01 Rainfall and Flood Frequency Analysis Using Stochastic Storm Transposition and Precipitation Remote Sensing

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Conventional methods for modeling rainfall and flood frequency face both theoretical and practical limitations. Intensity-duration-frequency (IDF) curves derived from rain gauge observations, for example, only represent point-scale rainfall extremes and are generally based on long rainfall records that may not be representative of current conditions due to climate nonstationarity. Annual peak flow observations and flood frequency estimates based on them, meanwhile, face even greater limitations in terms of nonstationarity due to effects of land use and channel modification, and are applicable only in regions with high stream gauge density. Both provide only limited insight into the hydrometeorological and hydrological processes that drive rainfall and flood extremes. Here, we present a probabilistic framework known as stochastic storm transposition (SST). SST "lengthens" the rainfall record by resampling storm events derived from rainfall observations from ground-based or space-based sensors. We have codified the SST approach in RainyDay, an open-source, web-based tool for quickly generating large numbers of realistic extreme rainfall scenarios that can be used for both rainfall and flood frequency analysis. This presentation highlights some advantages and limitations of SST. We show several examples of RainyDay's capabilities. These include creating "up-to-date" IDF curves for arbitrary areas, such as specific watersheds and performing "bottom-up" process-based flood frequency analysis to elucidate the physical drivers of flood frequency and how they are changing. We also discuss the technique's limitations and recent work that attempts to address these constraints.

Keywords: Rainfall remote sensing, floods, extremes, frequency analysis

2.02 The Simplified Metastatistical Extreme Value formulation (S-MEV): Modeling Extreme Precipitation Emerging from Multiple Synoptic Conditions

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We present the Simplified Metastatistical Extreme Value formulation (S-MEV) as a tool to model hydro-meteorological extremes emerging from multiple nonstationary underlying processes. S-MEV explicitly includes the processes' average intensity and probability of occurrence, neglecting inter-annual variabilities, allowing us to parsimoniously model changes in these quantities to infer changes in extreme quantiles. In particular, S-MEV allows: (a) frequency analyses of extremes emerging from multiple underlying processes; and (b) computationally efficient analyses of the sensitivity of extreme quantiles to changes in the characteristics of the underlying processes; moreover, (c) it provides a robust framework for explanatory models, nonstationary frequency analyses, and climate projections. We show an application to daily precipitation in the eastern Mediterranean: S-MEV provides spatially consistent estimates of extreme quantiles, in line with regional GEV estimates and generally characterized by reduced uncertainties. Sensitivity of extreme quantiles to changes and uncertainty in the intensity and yearly occurrences of events generated by different synoptic classes are examined; and an application of S-MEV for future extremes projections is provided.

Keywords: Extreme value analysis, Metastatistical Extreme Value, nonstationary processes, climate change, daily precipitation

2.03 Exploring the Relationship between Cyclone-related Precipitation and Stability

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The impact of global warming on large-scale dynamic and thermodynamic precipitation controls is expected to increase the intensity and frequency of strong events. Controls such as (1) stability, (2) moisture flux convergence (MFC), and (3) vertical motion are crucial to generating precipitation events. This presentation will explore the relationship between precipitation events associated with storms across the cyclone spectrum—including extratropical cyclones, tropical cyclones, and extratropical transitioning cyclones—and these large-scale controls, with an emphasis on stability, a less understood factor in precipitation events. Using high spatial and temporal resolution data from the Tropical Rainfall Measurement Mission 3B42 product, we compare the cyclone lifecycle accumulated precipitation and 48-hour precipitation totals. Extratropical cyclones generate the largest amount of 48-hour precipitation totals among all storm types. Extratropical transitioning cyclones, however, generates the heaviest lifecycle accumulated precipitation. The sensitivity of these results is analyzed against the three large-scale controls listed above by analyzing the spatial and vertical distribution of stability, MFC, and vertical motion in storms as they evolve. Then, to explore the relative influence of the large-scale controls on precipitation in the cyclones, we apply conditional sorting to the precipitation by these large-scale controls. Finally, we present a new approach to quantify how sensitive different storm types are to these changing variables in the current climate.

Keywords: Precipitation, cyclones, stability

2.04 Spatial Extreme Precipitation Modeling Using Satellite Information and Bayesian Hierarchical Models

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Extreme precipitation models are necessary for flood risk analysis, and for hydrologic infrastructure design and management. Given the sparsity and shortness of the observational data, especially in remote and mountainous areas, statistical modeling of extreme precipitations has been a challenging task. Furthermore, extreme hydrological events typically manifest spatial dependence, which is important but difficult to capture in extreme value models. Max-stable processes, as the extension of the extreme value theory to infinite dimensional scale, are suitable tools for modeling spatial extremes. In this study, PERSIANN-CDR, a long-term satellite-based precipitation dataset, is employed in a Bayesian hierarchical framework to spatially model extreme precipitation in Washington State. Our experiments used hierarchical models with various dependence structures, namely, the hierarchical kernel extreme value process (HKEVP), which accounts for the spatial dependence in the data, and the latent variable model (LVM), which has an underlying conditional independence assumption. The applied models were assessed in terms of marginal behavior and their abilities to model spatial dependence. Results show that both models produce comparable estimates of the extreme return levels, with a slight advantage for the HKEVP model due to its smaller standard errors. Furthermore, it is shown that the LVM fits better to the data's marginal distribution; however, it provides a poor fit to the data's joint distribution. This study's results also demonstrate that the PERSIANN-CDR is a viable tool for spatial extreme precipitation modeling, especially in poorly instrumented regions.

Keywords: Extreme precipitation, PERSIANN-CDR, Bayesian hierarchical framework, Max-stable processes, Washington State

2.05 Analysis of Changes in Precipitation Characteristics Over the Contiguous USA in Recent Decades

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Possible temporal changes in precipitation characteristics (e.g., magnitude, frequency, number of dry days, average annual precipitation) can have profound impacts on humans and the environment. In recent years, changes in precipitation mean and extremes have been studied intensively. For the United States, the majority of the studies have shown an increasing pattern in precipitation frequency and/or magnitude, especially for extreme precipitation. However, the important question remains whether the observed precipitation data showing the character of recent precipitation is distinct from the long-term averages. In what part of precipitation distribution (precipitation quantiles ranging from 0.1 to maxima) can we observe the highest temporal changes in precipitation characteristics in recent decades? What part of the precipitation distribution is contributing more to total annual precipitation? In this study, daily gridded precipitation observations over the contiguous United States are used to investigate previous observed changes in precipitation distribution characteristics. Analyses are based on the Climate Prediction Center daily precipitation data from 1948 to 2017. We analyze the changes in precipitation distribution for three periods: 1948-1971, 1972-2017, and the entire record from 1948 to 2017. The results primarily demonstrate that for the period of 1948 to 2017, the precipitation magnitude for different quantiles shows a decreasing trend, while precipitation frequency shows an increasing pattern. However, using the same methodology for 1972 to 2017 period showed opposing results, where the magnitude is increasing while the frequency of precipitation events is decreasing. Here, we demonstrate that depending on the timeframe, we acquire opposing results for possible changes in precipitation characteristics. Therefore, precipitation trend analysis requires great care in interpreting the results.

Keywords: Precipitation characteristics, trend analysis

2.06 Atmospheric River-CONNECT (ARC): Lifecycle AR Detection with Machine Learning

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CONNected-objECT (CONNECT) is utilized with the integrated water vapor transport (IVT) dataset from the NASA Modern-Era Retrospective Analysis for Research and Applications Version-2 (MERRA-2) reanalysis product for the period 1983-2017 to extract continuous IVT "objects." CONNECT is an object-oriented algorithm that extracts spatiotemporal characteristics useful for statistical and machine learning analyses—e.g., extent, duration, genesis, and terminus locations, along with the large-scale climate variability nodes. Furthermore, recent improvements to CONNECT introduced Earth variable (EV) mapping to IVT objects, which are used to quantify and generate additional characteristics for analysis. Specifically, precipitation from the PERSIANN-Climate Data Record (CDR) algorithm, along with integrated water vapor (IWV) and snowfall from MERRA-2, is used to quantify the totals and ratio of atmospheric and precipitated water of IVT objects, which can help differentiate different "flavors" of storms. A machine learning model is trained to differentiate between atmospheric river (AR) and non-AR objects using the generated spatiotemporal characteristics to create the AR-specific flavor of CONNECT, AR-CONNECT (ARC), along with a global climate data record of ARs. This catalog allows for statistical analysis of the trends among AR objects' characteristics, which can be used to analyze ARs' relationship to California's water cycle. Additionally, trend analysis results can be used to project natural hazards associated with AR events such as floods and mudslides into the seasonal scale.

Keywords: Atmospheric river, extremes, machine learning

2.07 DiPMaC: Disaggregation Preserving Marginals and Correlations

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Precipitation is often measured or simulated by climate models at coarser spatiotemporal scales than those needed for operational purposes. This practice has motivated more than half a century of research in developing disaggregation methods that break down coarse-scale time series into finer scales aiming to: (1) reproduce the statistical properties of the fine-scale process and (2) preserve the original coarse-scale data. Existing methods either preserve a limited number of statistical moments at the fine scale, which is often insufficient and can lead to unrepresentative approximations of the actual marginal distribution, or are based on a limited number of a priori distributional assumptions, for example, log-normal. Here we present a recently published disaggregation method, named Disaggregation Preserving Marginals and Correlations (DiPMaC), which disaggregates coarse-scale time series to any finer scale, while reproducing the fine-scale process's probability distribution and linear correlation structure. DiPMaC is also generalized for arbitrary nonstationary scenarios to reproduce time-varying marginals. DiPMaC is augmented by a novel and computationally efficient algorithm, based on Bernoulli trials, in order to optimize the disaggregation procedure and guarantee preservation of the coarse-scale values. We demonstrate the method by disaggregating monthly precipitation to hourly and climate model projections exhibiting trends. Finally, we show the potential of DiPMaC to disaggregate based on general nonstationary scenarios.

Keywords: Disaggregation, stochastic modeling

2.08 Studying Extreme Land Surface Temperature Records of the Hottest Place on Earth

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LUT desert in Iran, with less than 100 mm annual precipitation and nearly uninhabitable conditions, has been known as the place with the highest land surface temperature (LST) on Earth. The lack of moisture and evaporation leads the arid regions and deserts to absorb more heat and to experience higher surface temperatures than semi-arid and vegetated areas. This study analyzes daily maximum surface temperature records in LUT desert since 2002. The collection 6 land surface temperature product of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard AQUA satellite from July 4, 2002, to January 15, 2019, has been studied here. With an acquisition time of around 1:30 local solar time in the afternoon, near daily maximum surface temperatures are assumed in the study. The results show that this desert experienced a maximum land surface temperature record of 80.83 °C in July 2018, which is much higher than widely reported and than the known maximum temperature record on Earth based on previous studies (70.7 °C). This desert not only has a very high maximum temperature, but also undergoes extreme day and night temperature differences of up to 80 °K in early summer, which makes the region’s ecology unique. The area in the desert known as the “hidden sea” showed the highest LST values in the desert despite having an apparent high soil moisture and salty groundwater. The trend analyses reveal that both daily maximum and minimum temperatures are increasing in the region; however, the rate of changes in nighttime temperatures is higher.

Keywords: Arid regions, surface temperature, extremes, low precipitation

2.09 An Advanced Deep Learning framework for Near-real-time Precipitation Estimation from New Generation of Geostationary Multispectral Satellite Imageries - Application of the conditional Generative Adversarial Networks (cGANs)

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Improving the accuracy of near-real-time quantitative precipitation estimation from remotely sensed data is a more achievable goal nowadays with recent developments in satellite technologies along with advancements in data-driven methods. In this study, a state-of-the-art framework for near-real-time precipitation estimation from multispectral satellite imageries using advanced Deep Neural Networks (DNNs) is presented. The new generation of geostationary satellite data (GOES-16) with high temporal, spatial, and spectral resolutions along with the ground truth data (Multi-Radar Multi-Satellite system) are utilized to first provide a Rain/No Rain (R/NR) binary mask by classification of the pixels and then to apply a regression to estimate the amount of rainfall for rainy pixels. A specific Fully Convolutional Network (FCN) called U-net is used as a regressor to accomplish an end-to-end image translation task and predict precipitation estimates. Both the conditional Generative Adversarial Network (cGAN) and the mean squared error (MSE) objective functions are serving as loss terms to train the network and generate results that match the distribution of the ground truth data. A log-normal distribution is assumed for the ground truth data to handle skewed distributions and let the network better learns the parameters to fit the observed data. Performance is evaluated using a number of common performance measures and is compared with a Convolutional Neural Network as a baseline model, and with Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks–Cloud Classification System (PERSIANN-CCS) as an operational product. Visual and statistics performance gains represent an improvement of the precipitation retrieval task.

2.10 A Review of Global Precipitation Datasets: Data Sources, Estimation, and Intercomparisons

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In this paper, we present a comprehensive review of the data sources and estimation methods of 30 currently available global precipitation datasets, including gauge-based, satellite-related, and reanalysis datasets. We analyzed the discrepancies among the datasets at daily to annual timescales and found large differences in both the magnitude and the variability of precipitation estimates. The magnitude of annual precipitation estimates over global land deviated by as much as 300 mm/yr among the products. Reanalysis datasets had a larger degree of variability than the other types of datasets. The degree of variability in precipitation estimates also varied by region. Large differences in annual and seasonal estimates were found in tropical oceans, complex mountain areas, northern Africa, and some high-latitude regions. Overall, the variability associated with extreme precipitation estimates was slightly greater at lower latitudes than at higher latitudes. The reliability of precipitation datasets is mainly limited by the number and spatial coverage of surface stations, the satellite algorithms, and the data assimilation models. The inconsistencies described limit the products' capability for climate monitoring, attribution, and model validation.

Keywords: Global precipitation dataset, gauge, satellite-related, reanalysis

2.11 The Ongoing Challenge of Retrieving Precipitation's Fine-scale Spatial and Temporal Variability from Satellites

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The quantitative estimation of precipitation from satellites has proven its utility, and satellite estimation products are now widely used for various applications, ranging from climate studies to hydrological modeling. While the numerous available products show similar climatic patterns at the global scale and generally agree well with each other and with ground-based observations and model reanalyses at coarse resolutions, large uncertainties persist when it comes to reproducing precipitation's sub-mesoscale variability (typically, hourly and sub-hourly scales and scales finer than 100 km). The instruments' limited resolution and the temporal sampling of the observations are not the only factors making the retrieval of fine-scale variability so challenging. Even with high instrumental resolution and pointing accuracy, the observation geometry may induce uncertainties into the location of the measured signals' source. For passive retrievals (infrared and microwave), the scale dependence in the relationships between the measured radiances and precipitation is also a key factor. Another factor is the inherent uncertainty deriving from the underdetermination of the radiance's inversion. Given the uncertainties, to minimize retrieval errors, or to provide the most likely estimate, most retrieval algorithms tend toward smooth solutions (meaning that a small variation in the observed variables will lead to a small variation in the estimate). The retrieval operators' smoothness naturally leads to smooth spatial and temporal variations in the retrieved precipitation fields. Here we present a quantitative analysis of the effect of the above-mentioned limiting factors on precipitation's retrieved spatio-temporal variability from satellites using a spectral framework. Moreover, we show that getting away from the "pixel-wise" retrieval approach by utilizing the spatial information in the observed variables allows the retrieval uncertainty to be reduced.

Keywords: Satellite, passive, microwave, GPM, spectral

2.12 Probabilistic Quantitative Precipitation Estimation

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Progress in precipitation estimation is critical to advancing weather and water budget studies and to predicting natural hazards caused by extreme rainfall events from the local to the global scales. An interdisciplinary challenge in remote sensing, meteorology, and hydrology is the impact, representation, and use of uncertainty. Understanding hydrometeorological processes and applications requires more than just one deterministic "best estimate" to adequately cope with the intermittent, highly skewed distribution that characterizes precipitation. Yet the uncertainty structure of quantitative precipitation estimation (QPE) from ground-based radar networks like NEXRAD and satellite-based active and passive sensors of the Global Precipitation Measurement and the GOES-16 missions is largely unknown at fine spatiotemporal scales near the sensor measurement scale. We propose to advance uncertainty's use as an integral part of QPE for ground-based and spaceborne sensors. Probability distributions of precipitation rates quantify the relationship between sensor measurement and the corresponding "true" precipitation. This approach preserves the sensor's sampling properties and integrates sources of error in QPE. It provides a framework for diagnosing uncertainty when instruments sample raining scenes or processes challenging QPE algorithms' assumptions. Precipitation probability maps compare favorably to deterministic QPE. Probabilistic QPE is shown to mitigate systematic biases from deterministic retrievals, quantify uncertainty, and advance the monitoring of precipitation extremes. It provides the basis precipitation ensembles needed for multisensor merging and precipitation assimilation, hydrometeorological hazard mitigation, decision making, and hydrological modeling. Perspectives on improved understanding and parameterizations of precipitation processes, estimation at multiple scales, hydrological prediction, and risk monitoring will be presented.

Keywords: Probabilistic QPE, remote sensing, uncertainty, extremes, radar, satellite

2.13 The Role of X-band Radars in Estimating Rainfall for Urban and Complex Terrain Applications

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Considering the current trend of rapid urbanization worldwide, urban society's vulnerability to floods is ever increasing. One of the key factors important for accurate rainfall estimation from radars is low-level coverage over cities, which demands deployment of radars in close proximity to urban regions (due to Earth's curvature). The deployment of large S-band radars in urban real estate is expensive and difficult due to the large social footprint. The CASA program demonstrated the benefits of the network of X-band radars. This model has found very good applications for urban regions, mainly due to its economic sustainability, and many cities around the world are building urban X-band radar networks, including the cities of Dallas and Fort Worth, Tokyo, Beijing, Shanghai, and Hong Kong, among others. This paper reviews the performance of the urban radar network for mapping rainfall and places in context with other urban radar deployments around the world. The X-band radars, which operate around 9.4 GHz, have a good spatial resolution when range is limited to about 50 km. Because they are so much smaller in size and cost, we can easily deploy a network of these radars to cover large metropolitan regions. These radars provide high-quality rainfall observation because the dual-polarization parameter, specific differential phase (Kdp), is more accurate at the X band compared to the lower frequencies such as the S band. Based on the above reasons and their ease of deployment, X-band radars and their network servers are a perfect tool for measuring rainfall in urban regions. This paper summarizes the DFW X-band radar network for urban weather disaster detection and mitigation from the perspective of tracking and warning about hail, tornadoes, and floods. The architecture for various product systems is described, including a real-time, high-resolution quantitative precipitation estimation system. A system-level comparison to other X-band radar networks in the world is also discussed.

Keywords: Urban radar network, mega city, complex terrain

2.14 Estimating Precipitation from Remotely Sensed Information Using Deep Neural Networks

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Providing accurate precipitation estimates is critical for a wide range of hydrological applications, such as flood forecasting. Despite having high-resolution information from satellites, estimating precipitation from remotely sensed information still suffers from methodological limitations. State-of-the-art deep learning techniques, developed in the field of artificial intelligence for learning from a massive amount of data, seem well suited to the task of estimating precipitation. On the other hand, a few recent studies have shown that using multispectral satellite imageries, especially the combination of infrared (IR) and water vapor (WV) channels, can enhance the accuracy of satellite-based precipitation estimation. Thus, in this study we investigate the effectiveness of Convolutional Neural Networks (CNN) for retrieving precipitation estimates from a combination of IR and WV channels. A case study was conducted by applying the CNN technique for estimating the precipitation rate over the central United States (30 – 45 N°, 90 – 105 W°) at a spatial resolution of 0.08 degrees and at an hourly time scale. Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS), which is a commonly used operational product, and PERSIANN-Stacked Denoising Autoencoder (PERSIANN-SDAE), which is a recent study in applying deep learning to satellite imagery for precipitation retrieval, are employed as baseline models. Preliminary results showed that the applied CNN-based method (PERSIANN-CNN) was able to provide more accurate precipitation estimates compared to the baseline models. It was shown that PERSIANN-CNN outperforms PERSIANN-CCS (PERSIANN-SDAE) by 54% (23%) in terms of Critical Success Index (CSI) over the verification period. Furthermore, the Root Mean Squared Error (RMSE) of the rainfall estimates decreased by 77% (16%) compared to the PERSIANN-CCS (PERSIANN-SDAE) estimates.

Keywords: Precipitation estimation, PERSIANN-CCS, Deep Neural Network

2.15 On the Evaluation of Micro Rain Radar: A Comparative Study with Disdrometers and S-band Polarimetric Radar

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Level-I science requirements of NASA's Global Precipitation Measurement (GMI) mission include detecting falling snow by dual-frequency precipitation radar and GPM microwave imager with effective resolutions of 5 km and 15 km, respectively. Both sensors are capable of quantifying snow water equivalent (SWE) at their lowest clutter-free bin after determining the precipitation phase. Toward validating these products, the GPM ground validation program has been operating a field site at Marquette, Michigan (MQT) for the past two winters. The site consists of 10 Pluvio weighing bucket gauges. One of the Pluvio sites, at the National Weather Service (NWS) Office in Marquette, also hosts an Autonomous PARSIVEL2 Unit (APU) disdrometer, a Precipitation Imaging Package (PIP), and a Micro Rain Radar (MRR).

This study aims to construct radar-based SWE maps utilizing the MQT radar and these in-situ measurements. Event-based reflectivity–SWE (Z-S) relationships will be derived by employing collocated APU, PIP, and Pluvio measurements. The APU has a built-in algorithm to determine the precipitation phase, and the PIP provides more accurate particle size distribution and snow depth estimates. The Pluvio provides SWE at one-minute resolution, but is more reliable for integration periods of 20 minutes or longer. Bulk density will be determined from the ratio of event snow depth to event SWE total. The NWS measures the snow depth and SWE independently, and this study will include the comparison of these measurements between the two sources. The study also will include comparisons of radar SWE that are based on selected Z-S relationships from the literature. Pluvio gauges outside the NWS site will be used as validation of the radar SWE products

Keywords: Radar-based snowfall estimate

2.16 Applying Recurrent Neural Networks in Spatiotemporal Precipitation Forecasts

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Predicting short-range quantitative precipitation is very important for flood forecasting, early flood warnings, and other hydrometeorological purposes. This study aims to improve precipitation forecasting skills using a recently developed and advanced end-to-end Artificial Neural Network that includes an advanced recurrent layer named Long Short-Term Memory (LSTM). The proposed network learns clouds' changing temporal and spatial patterns from Cloud-Top Brightness Temperature images, retrieved from the infrared (IR) channel of the Geostationary Operational Environmental Satellite (GOES). After learning the clouds' dynamics, the proposed model predicts the upcoming IR imagery using an iterative approach. The proposed model is then merged with a precipitation estimation algorithm termed Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) to provide precipitation forecasts. The results of merging the IR forecast model with PERSIANN are compared to the results of an end-to-end Elman-type Recurrent Neural Network (RNN) merged with PERSIANN and Final Analysis of Global Forecast System model over the states of Oklahoma, Florida, and Oregon. Each model's performance is investigated during three storm events, each located over one of the study regions. The results indicate the outperformance of merged proposed model forecasts compared to the numerical and statistical baselines in terms of Probability of Detection (POD), False Alarm Ratio (FAR), Critical Success Index (CSI), RMSE, and correlation coefficient, especially in convective systems. The proposed method shows superior capabilities in short-term forecasting over compared methods.

Keywords: Short-term precipitation forecast, machine learning, deep learning

2.17 Translating the Physics of Snowfall to Radar-Based Validation of GPM

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To validate Snow Water Equivalent Rates (SWER) estimated by the Global Precipitation Measurement (GPM) mission, we have implemented an approach that leverages detailed point-based observations of snow physical characteristics to improve and verify more distributed ground radar estimates of SWER. The approach is anchored by a variety of multi-year, multi-regime, in situ measurements of falling snow using instruments such as Pluvio gauges, precipitation imagers (PIP), and micro rain radars (MRRs). The instrument networks were located in Marquette, Michigan; Hyytiälä, Finland; and Ontario, Canada. The in situ observations reveal SWER process variability as a function of regime (e.g., rimed vs. low-density aggregates, lake effect vs. synoptic), and serve to both inform and independently verify radar-based approaches for estimating SWER as a function of regime variability/physics. The radar measurements of SWE provide a means to translate between point and GPM footprint to swath-scale measurements.

Radar-based SWER estimates are derived from CONUS-scale GPM Validation Network (VN) WSR-88D dual-pol radar (DP) datasets, Finnish FMI Ikalinen C-band DP, and the ECC-Canada King City C-band DP radars. DP methods and modified Z-S approaches are used to tune regime/case-based snow properties and are compared to GPM. Probabilistic quantitative precipitation estimates (PQPE; Kirstetter et al., 2015) are also independently applied to VN data. PQPE provides a means to quantify the uncertainty and distribution of Z-S values created from a distribution of Z-S equations based on a large collection of U.S. radar-gauge observations. PQPE 25th, 50th, and 75th percentile Z-S ensembles are used with the VN to represent the distribution of possible SWER values as compared to GPM DPR estimates.

Preliminary results indicate that GPM DPR and GMI estimates generally underestimate ground-radar SWER, the bias depending on the estimator used. Further analysis will be presented.

Keywords: Snowfall, radar, precipitation, satellite estimation

2.18 Comparing Precipitation Estimates Using a GPM-constellation Retrieval Scheme

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Estimating global precipitation from satellite sensors is now well established. The launch of the GPM satellite, with the GPM Microwave Imager (GMI) and the Dual-frequency Precipitation Radar (DPR), brought about a new era in satellite precipitation measurements. The GPM's low inclination orbit allows it to intersect the swaths of other sensors in the GPM constellation.

The official GPM precipitation retrieval scheme, the Goddard Profiling (GPROF) scheme, is based on a database of about 400 million matched observations between GMI and DPR. The databases for the other sensors in the constellation are generated from this GMI-DPR database by modeling differences in the observation frequencies and the footprint resolutions. However, the accuracy of these databases relies on the models' ability to correctly extrapolate the information to each of the constellation sensors. An alternative method is to exploit the GPM-constellation intersections to populate these databases, thus relying on actual constellation sensor–DPR observations. The main advantage of such a scheme is that it relates to actual observations in the databases.

This paper compares precipitation retrievals from the current official GPROF retrieval scheme with DPR-constellation matched retrievals. The results indicate significant similarities between the two schemes, particularly so for sensors that are radiometrically similar in terms of channel selection. In addition, sensors with the greatest range of channels suggest that their reliance on background surface constraints is much less than that of sensors with relatively few channels. Indeed, for sensors such as SAPHIR that rely on six frequencies around 183.31 GHz, the use of additional constraining information is critical to excluding ambiguous precipitation in the retrieval process.

Keywords: Satellite, precipitation, intercomparison

2.19 Toward Consistency between the Near-Surface and Vertical Precipitation Structure in the GPM Precipitation Constellation Data Record

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Long-term satellite-based precipitation data records are constructed from multiple data sources, including various series of low Earth-orbiting, passive microwave (PMW) radiometer sensors. Each sensor operates over a finite lifetime, and possesses unique orbital, spectral, and spatial resolution characteristics. The merging of these constellation data is a key objective of the 20+ year combined Global Precipitation Measurement (GPM) and Tropical Rainfall Measuring Mission (TRMM) satellite era. The desired signal from the precipitation is embedded within the background signals owing to the Earth surface and wet/dry troposphere (e.g., water vapor), and not readily extracted against these other emission sources. As a result, different PMW sensors provide differing sensitivities to precipitation depending on the underlying geophysical conditions.

Physically, the near-surface precipitation rate is coupled with the vertical precipitation profile above and the associated water vapor structure. A goal of this study is to spread the vertical structure information from the single GPM DPR (Dual-Frequency Precipitation Radar) among the PMW-only satellite sensors. Since most passive MW observations are gathered under non-precipitating conditions, orbit-intersecting scenes between GPM/DPR and each of the ATMS, MHS, AMSR2, and SSMIS constellation radiometers are collected for estimating global surface emissivity variability regardless of surface type. This information is used in an inversion technique to discriminate the presence of precipitation-affected observations against this natural background variability. This presentation shows comparisons of the resultant precipitation profile estimates among the various GPM constellation radiometers to emphasize self-consistency in surface precipitation estimates and DPR-observed Ku/Ka-band reflectivity profiles, notably when transitioning across complex mixed land-water scenes.

Keywords: GPM, radar, precipitation, surface, microwave

2.20 Identifying Cloud Types from New Generation of Geostationary Satellite Multispectral Images for Precipitation Estimation Using Deep Learning Techniques

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The interaction between cloud microphysics and precipitation is one of the most sophisticated components in hydrometeorology science. LEO satellite sensors are recognized as reliable sources for diagnosing meteorological conditions and precipitation mechanisms, but the derived data are limited in spatiotemporal coverage. GEO satellite measurements have been used mainly for precipitation estimate algorithms due to their frequent sampling and high spatial resolution. Although GEO-based precipitation retrievals carry significant potential, they lack the accuracy required for hydrological applications. Thus, multisatellite algorithms have been developed by integrating multisensor measurements to increase precipitation estimation accuracy. Our study focuses on providing important information about cloud types to improve high spatiotemporal satellite precipitation retrievals. We proposed a Deep neural network Cloud-Type Classification system (DeepCTC) which utilizes multi-sensor multisatellite data to simulate the vertical structure of clouds at GEO-based images. The availability of unique CloudSat measurements, together with multispectral information from the latest GEO-based sensors (e.g., GOES16), makes it possible to implement an automatic data processing pipeline to generate a large training dataset to distinguish different cloud types. We applied and tested a state-of-the-art deep learning approach, DeepCTC, for rapid cloud labeling, including cumulus, stratus, altocumulus, altostratus, nimbostratus, high, and deep convective clouds. The preliminary verification has found a total accuracy of 85%. This investigation provides crucial data toward developing more accurate precipitation estimation algorithms. Specifically, improved representation of vertical cloud structure from DeepCTC is able to be combined with automatic cloud top feature extraction techniques to recognize more cloud properties while mapping rain rate to separated cloud structures.

2.21 25th Anniversary of a Scaling Law for Raindrop Size Distribution

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A quarter-century ago, Sempere Torres et al. (1994) published “A General Formulation for Raindrop Size Distribution,” in which they proposed “a general phenomenological formulation for drop size distribution (DSD), written down as a scaling law.” Their scaling law formulation accounted for all previously published parameterizations for the DSD. The proposed expression’s main implication was that integral rainfall variables (such as rain rate and radar reflectivity) were related by power laws, in agreement with experimental evidence. The proposed formulation naturally led to a general methodology for scaling all raindrop size data in a unique plot, which yielded more robust fits of the DSD.

In this presentation we will review 25 years of interpretations and applications of this scaling law for the DSD, with extensive references to earlier work (dating all the way back to the beginning of the 20th century) as well as an outlook for the future, including implications for ground-based and spaceborne remote sensing of precipitation. In addition, we will provide a statistical interpretation of the law’s scaling exponents in terms of different modes of controlling DSDs’ space-time variability, namely, size-control vs. number-control. Also, ongoing work concerning the parameterization of the scaled DSD’s shape will be discussed. Finally, an attempt will be made toward interpreting the scaling exponents’ values and the scaled DSD’s shape in terms of the (micro)physical processes producing the DSD.

Sempere Torres, D., J.M. Porrà, and J. Creutin, 1994: A General Formulation for Raindrop Size Distribution. J. Appl. Meteor., 33, 1494–1502, https://doi.org10.1175/1520-0450(1994)033<1494:AGFFRS>2.0.CO;2

Keywords: Raindrop size distribution, radar rainfall estimation, remote sensing of precipitation

2.22 Constraining the Deconvolution of Oversampled Satellite Microwave Observations to Enhance Rain Estimates' Spatial Resolution

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To obtain higher spatial resolution from a vertically-profiling precipitation radar with a given aperture size, one can consider a judicious use of spatial oversampling (which may require frequency diversity to achieve in hardware, but does not require any increase in real aperture). Deconvolution alone cannot be guaranteed to produce physically meaningful results, as noise in the input measurements can produce numerical outputs that have unrealistic values in significant portions of the domain. Two different constraints can be placed on the deconvolution: a variational constraint, adding an a priori first guess to the minimization problem; and a reformulation of the problem to force the measurements in neighboring resolution elements to have the same correlations as those resulting from empirical high-resolution analyses. This approach has been tested successfully on oversampled passive observations, and is adapted to the case of reflectivity-factor measurements by radar. The project's success—i.e., a sufficiently low error in the results of this guided disaggregation—will enable the design of a future satellite radar that could achieve up to five times better resolution than today's, with straightforward changes in the system design and, most significantly for a spaceborne system, no added mass or volume or unmanageable complexity.

Keywords: Precipitation radar, microwave radiometer

2.23 Regime-Dependent Differences in Active Satellite Rainfall Products

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The current spaceborne precipitation observing system is vital to understanding global precipitation distribution and, in turn, Earth's hydrological cycle. Several previous studies have used CloudSat, a mission providing enhanced sensitivity to light precipitation and clouds, to identify biases in rainfall observed by the Global Precipitation Mission Dual Frequency Precipitation Radar (DPR). Here we use CloudSat precipitation retrievals to compare against DPR over the mid-latitude oceans. We place these results in a meteorological context by compositing results around mid-latitude cyclones using a regime-dependent framework based on column water vapor and cloud liquid water path. We develop two separate statistical distribution-merging techniques to blend the CloudSat and DPR data. Importantly, we find that a large part of the discrepancy between the merged distribution and the DPR does not result from missed detection of light rainfall, but rather from differences between the rain rates derived from CloudSat and the DPR. The differences in rates derived from the two platforms point toward algorithmic uncertainties related to drop-size-distributions and sensor resolution that are difficult to resolve from non-coincident data-streams. This emphasizes the need for a platform in the spaceborne precipitation observing system that utilizes both low- and high-frequency microwave radars to sense clouds, convection, and precipitation.

Keywords: Active remote sensing, precipitation, instrument comparison

2.24 A Millennial-scale Perspective on Modern Precipitation Trends, Mean, and Variance in the Levant Based on Reconstructed Precipitation of the Past 4,500 years

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A novel quantitative assessment of Late Holocene precipitation in the Levant is presented, including mean and variance of annual precipitation and their trends. A stochastic framework was utilized and allowed, possibly for the first time, linking of high-quality, reconstructed rises/declines in Dead Sea levels with precipitation trends in its watershed. We determined the change in mean annual precipitation for 12 specific intervals over the past 4,500 years, concluding that: (1) The Late Holocene representative mean annual precipitation is 75% of the currently used mean. During this period, mean annual precipitation ranged between -37% and +25% of present-day conditions. (2) The driest intervals were 1500–1200 BCE and AD 755–890. The wettest intervals were 2500–2460 BCE, 130–40 BCE, AD 350–490, and AD 1770–1940. (3) Lake-level rises and declines probably occurred in response to trends in precipitation means and are less likely to occur when precipitation mean is constant. (4) Average trends in mean annual precipitation during 200-year intervals did not exceed 15 mm per decade. Precipitation trends probably reflect shifts in eastern Mediterranean cyclone tracks. And (5) such trends cannot be detected statistically over decadal-scale intervals due to the typically high precipitation variance. However, they are well detected when transformed into lake-level changes, where the signal-to-noise ratio is much higher. The research has several practical implications for understanding modern changes in our region's precipitation regime: (1) The beginning of the 20th century was substantially wetter than most of the Late Holocene, and it is a large positive anomaly biasing our perspective on standard conditions. And (2) given the above anomaly, the recent regional drying can be partly explained as a return to the "normal" drier conditions, superimposed by anthropogenic-related climatic change.

Keywords: Precipitation regime and trend, precipitation reconstruction, Levant paleoclimate, Late Holocene, stochastic framework

2.25 From Scalar to Vector Multifractal Precipitation Modelling

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At the beginning of the 1980s, the introduction of multifractals was a major breakthrough in the analysis and simulation of clouds and precipitation. They were physically based on the idea of interacting cascades of dynamics and water content across scales: i.e., on the interactions between the components of a 4D vector field. For various reasons—e.g., the classical use of rain rate as the basic observable, computer limitations, and the lack of vector multifractal simulations—these coupled cascades were reduced to a scalar valued cascade of the rain rate. This oversimplification was initially quite helpful to enable scientists to quickly grasp qualitatively new insights, in particular, for applications (e.g., extremes and radar meteorology), and it became widespread without being questioned. Nevertheless, it also introduced limitations and discrepancies with empirical data that it is timely to resolve, especially due to the increasingly greater availability of high-resolution radar data.

Multifractal vector fields have been considered since the 1990s, but they have remained rather abstract until recently. We first show how a combination of symmetries as simple as orthogonal rotations and mirror symmetries yields a Clifford algebra—a broad generalization of complex numbers—of Lévy-stable generators of cascades that define multifractal vector fields having both robust algebraic and universal statistical properties. We then discuss the necessary extensions of the classical multifractal scalar analysis tools—e.g., the Double Trace Moment—and their applications to wind and precipitation data.

This research was partially supported by the Chair “Hydrology for Resilient Cities,” endowed by Veolia (hmco.enpc.fr/portfolio-archive/chair-hydrology-for-resilient-cities/).

Keywords: Multifractal, intermittency, cascade, precipitation, modelling

2.26 Estimates of Accumulated Rainfall of Mei-Yu Front in Taiwan Using GSMaP Measurements

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The Global Satellite Mapping of Precipitation (GSMaP) was used to estimate the accumulated rainfall in May from the Mei-Yu front in Taiwan. Rainfall estimation from GSMaP during 2002-2015 was evaluated using more than 400 local gauge observations, collected from the Taiwan Central Weather Bureau (CWB). Studies have demonstrated that the GSMaP rainfall estimation estimates can be biased, depending on the target region, elevation, and season. In this experiment, we evaluated GSMaP over three elevation ranges. The GSMaP systemic errors for each elevation range were identified and corrected using regression analysis. The results indicated that GSMaP estimation can be improved significantly through adjustment over three elevation ranges (elevation less than 50 m, elevation of 50–100 m, and elevation higher than 100 m). For these three elevation ranges, the correlation coefficient between the GSMaP estimations and CWB rainfall data was 0.76, 0.78, and 0.59, respectively. This observation indicated that the GSMaP estimation was more accurate for low-elevation regions than high-elevation regions. After the proposed approaches were employed to correct the errors, the bias and root-mean-squared error were respectively improved by 7.8 and 3.8 mm on average. This study demonstrated that local correction approaches can be used to improve GSMaP estimation of Mei-Yu rainfall in Taiwan.

Keywords: Mei-Yu front, global satellite mapping of precipitation (GSMaP), accumulated rainfall, regression equation

2.27 Future Responses of the Intertropical Convergence Zone under Global Warming

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Future changes in the location of the intertropical convergence zone (ITCZ) under global warming are of high importance, since they could substantially alter precipitation patterns and water cycle dynamics in the tropics and subtropics, and greatly affect ecosystem and rainforest vulnerability. Although recent studies report a likely average northward shift and contraction of the ITCZ, predictions remain uncertain and highly variable among climate models. Moreover, most studies have focused on the zonal mean changes in the ITCZ, lacking information on regional ITCZ responses, and possibly masking model agreements over particular areas. Here we use a longitudinally explicit probabilistic method to track the ITCZ and explore future ITCZ trends in all seasons and longitudes of the globe, under an increased CO_2 emissions (scenario RCP8.5). After accounting for double-ITCZ biases in the models, we reveal a robust northward shift of the ITCZ over Africa and Asia, and a southward shift in the eastern Pacific and Atlantic basins. We provide evidence that these diverging ITCZ responses cannot be explained by internal climate variability, but rather, are driven by accelerated atmospheric energy imbalances due to global warming.

2.28 Improvement of Winter Climate Forecasts for the Great Lakes Region with a Coupled Climate Forecast System-Lake Model

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In this study, we coupled the two-layer one-dimensional Freshwater lake (FLake) model into Climate Forecast System (CFS) version 2 to improve the delineation of the Great Lakes' effects on winter climate forecasts in that region. We first incorporated the global lake fraction and depth data into the coupled CFS-FLake through a subgridding system. An interface between the CFS and FLake was then developed to link the two models for energy and water flux exchanges. The lake scheme was only triggered if the lake fraction was more than 10% in one CFS grid. We conducted the ensemble retropective forecasts with CFS-FLake for the period of 1997 through 2016 with nine monthly leads. These forecasts were assessed to obtain a better understanding of the Great Lakes' role in the climate system for the winter season, when significant lake-effect precipitation often occurs. Our results indicated that the forecasts of lake surface water temperature (LSWT), precipitation, and lake ice coverage (LIC) with CFS-FLake were consistently better than those with CFS. The major improvements resulted from the land use-type changes for the Great Lakes from the ocean and land in CFS to the lakes in CFS-FLake. When the change was from the ocean to the lake, LSWT mostly decreased with the increased LIC, resulting in lower surface heat and water fluxes to the atmosphere during the winter. However, when the change was from the land to the lake, LSWT increased, leading to higher heat and water fluxes. In the meantime, precipitation predicted by CFS-FLake was reduced quite significantly over the Great Lakes when compared to that by CFS. Such a reduction was caused by the suppressed rising motion due to the increased stability in the lower atmosphere as a result of the lowered surface heat and water fluxes. The results from this study indicate that the local and mesoscale surface and atmospheric processes significantly affect regional climate forecasts.

Keywords: Climate forecasts, CFS, FLake, lake-effect precipitation

2.29 Impacts of fuel moisture and fuel treatment on wildland fire behavior

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Fire suppression activities in the past few decades in North America has led to higher fuel accumulations, which coupled with shifting hydroclimatic patterns has led to an increase in frequency and severity of wildland fires. Prescribed fires and fuel treatments such as mechanical thinning are deemed to be effective tools to manage fuel loads and establish a higher degree of control over landscape management and restoration against catastrophic megafires. However, assessing the effectiveness of fuel treatments is rendered complicated due to several factors such as wind, fuel moisture and fire-atmospheric interactions at the fine scales. The present work explores this issue by simulating a fire on a flat landscape, while varying the degrees of fuel treatments and fuel moisture, as observed during different stages of fuel management. Systematically varying these parameters yield widely different fire behavior patterns. Detailed analyses on turbulent heat and energy exchange are conducted to understand the fundamental processes governing varying regimes of fire intensity, fire spread and fuel consumption under different conditions of fuel moisture and treatment. The conclusions are generalized to highlight the importance of considering vegetation response to hydrometeorological events, coupled with fine scale fire-atmosphere interactions while managing for wildland fire behavior.

2.30 CloudSat Based Assessment of GMI and ATMS Snowfall Observation Capabilities

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In the last years, the exploitation of observational datasets built from coincident space-borne active and passive microwave sensor datasets, has improved the development of snowfall detection and retrieval techniques for passive MW radiometers. Several studies (e.g., *Panegrossi et al., 2017*) have shown that supercooled droplets can critically affect passive microwave snowfall-related signal, especially at the higher latitudes where the majority of cloud structures presents a supercooled water layer on the cloud top. Recently, a new algorithm for snowfall detection and retrieval for the *Global Precipitation Measurement* (GPM) *Microwave Imager* (GMI) (SLALOM, Rysman et al., 2018) based on the use of coincident CloudSat Cloud Profiling Radar (CPR) observations, has been developed. The algorithm is able to detect snowfall (also in presence of supercooled water), and reproduces quite well CloudSat snowfall climatology, but with a much better spatial and temporal coverage up to 65° latitude. From a forward-looking perspective, it is very important to investigate the potential of cross-tracking scanning radiometers, in particular the *Advancing Technology Microwave Sounder* (ATMS), for snowfall detection and retrieval. In this study, observational datasets built from ATMS and CloudSat/Calipso coincident observations is used to investigate the potentials and limitations of the 7 ATMS high-frequency channels, 89 GHz, 157 GHz and 5 channels in the 183.31 GHZ water vapor absorption band, for snowfall detection and retrieval. The response of the ATMS high frequency channels and their combination to snowfall is analyzed. In particular, the presence of supercooled water and the influence of different background surface conditions (e.g, wet or dry snow cover, sea ice type and concentration, ocean, land) on the microwave signal is investigated.

Within the development of passive microwave snowfall detection and retrieval techniques, the characterization of the frozen background surface (snow cover and sea ice conditions) at the time of the overpass appears to be a relevant task. ISAC-CNR has developed two surface classification scheme based mainly on the GMI and ATMS low frequency channels (i.e. >36 GHz). Case studies with coincident ATMS and GMI observations will be analyzed, and the surface classification results will be compared with other products over the US.