2024 International Atmospheric Rivers Conference (IARC)
Scripps Institution of Oceanography – La Jolla, California
June 24 – 27, 2024
cw3e.ucsd.edu/iarc2024/

Book of Abstracts

First edition: June 18, 2024

This document includes all the abstract submitted to IARC 2024. The abstracts are presented as submitted by the authors, sorted by session. We hope they are useful for the broad research and professional community working on the science and impact of Atmospheric Rivers.

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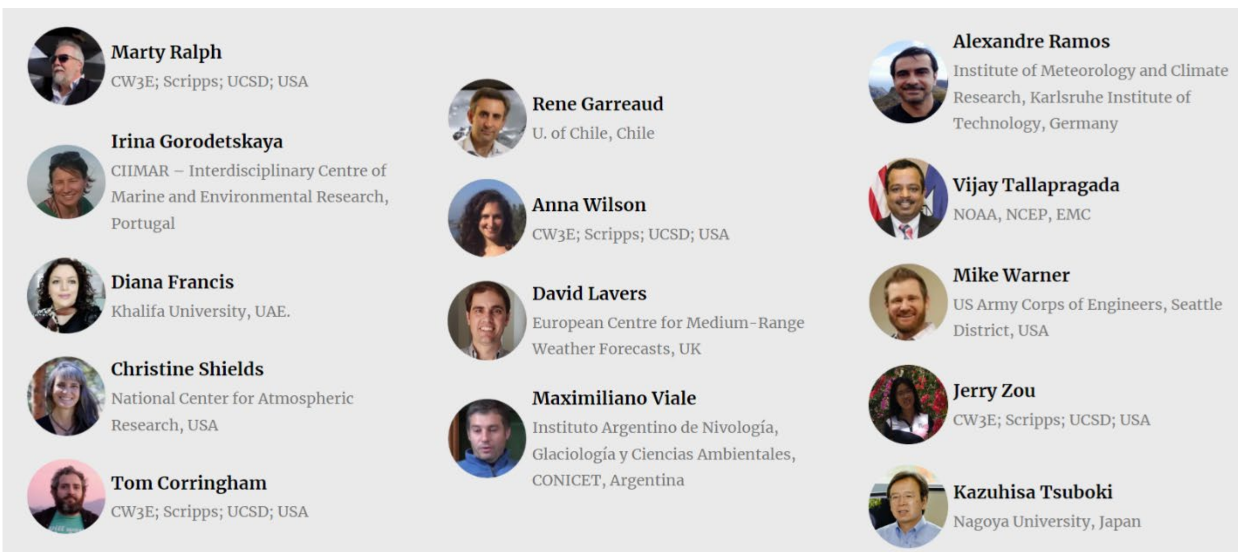
International Atmospheric River Conference 2024 (IARC 2024)

The International Atmospheric River Conference 2024 was organized by an ad-hoc implementation committee integrated by an international, multi-disciplinary group of researchers, led by five co-chairs: René Garreaud, Anna Wilson, Alexandre Ramos, Irina Gorodetskaya, and Marty Ralph.



We specially acknowledge Sam Babbitt, CW3E – UCSD, for managing much of the conference organization and Francisca Muños, CR2 Universidad de Chile, for crafting this Book.

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We acknowledge the contribution of several institutions that help to support the IARC 2024

General Index

International Atmospheric Rivers Conference 2024
June 24 – 27, 2024

Session:

AR1- ARs as a component of compound events

[4] | Temporal Clustering of the U.S. West Coast Atmospheric Rivers: Characteristics and Large-scale Patterns

First Author: Yang Zhou

Lawrence Berkeley National Laboratory / United States

Co-Authors: Michael Wehner Lawrence Berkeley National Lab, William Collins Lawrence Berkeley National Lab UC Berkeley

From late December 2022 to mid-January 2023, California experienced a series of nine consecutive atmospheric rivers (ARs) making landfall. These intense weather events led to devastating consequences, including severe flooding and mudslides, widespread power outages, and at least 22 fatalities. However, limited research has focused on the spatiotemporally compounding ARs. In particular, linkages among the variation of the intervals between AR landfalls, different land responses, and the large-scale circulation remain undocumented. Utilizing an unsupervised machine learning technique, we define an AR cluster as a short period that consists of back-to-back ARs. Here we show that the characteristics and impacts vary significantly by cluster density, which is the fraction of AR conditions within a cluster. Focusing on the landfalling ARs over the U.S. West Coast, we found that clusters with high density (such as the 2023 series of nine ARs in three weeks) consist of higher AR categories and higher likelihood for extreme precipitation and severe land surface response. By using reanalysis and model simulation, we showed the key circulation pattern for AR clusters is mainly attributed to subseasonal variability. In addition, the third mode of geopotential height variability modulates the occurrence and density of AR clusters. Furthermore, we demonstrated that AR clusters with higher density and category will be more frequent in warming climates. Our study highlights the important role of AR clusters in the planning and development of climate adaptation and resilience.

[5] | The Impacts of Atmospheric Rivers on Snowmelt Induced Landslides in the Northern Anatolian Mountains (Türkiye)

First Author: Harun Aslan

Eurasia Institute of Earth Sciences, Istanbul Technical University / Türkiye

Co-Authors: Tolga Gorum, Deniz Bozkurt, Omer Lutfi Sen, Yasemin Ezber

Landslides triggered by snowmelt, as one of the main hydrometeorological triggering factors, and their interaction with Atmospheric Rivers is not adequately elucidated. During the February–April 2022 period in the Northern Anatolian Mountains rapid snowmelt event triggered more than 300 landslides. Accordingly, based on local and national news sources as well as public institution reports, an inventory was created by mapping 330 landslide events that occurred as a result of rapid snowmelt during this period. This landslide inventory compiled for the Northern Anatolia Region, one of the most susceptible regions in Europe, as well as Türkiye in terms of landslide events, provides a unique opportunity to understand the process dynamics underlying snowmeltinduced landslides. Revealing the combined and/or individual roles of meteorological weather events such as sudden temperature rises and rain-on-snow events associated with ARs or synoptic-scale weather events, in triggering these landslides is essential for better understanding possible such events in the near-future and to taking effective measures to mitigate socio-economic losses.

The spatio-temporal distribution of snowmelt, air temperature, and snow-water equivalent (SWE) variables at daily and monthly scales for the February to April 2022 period according to long-term climatology (1993–2022) as well as landslide events triggered by ARs were analyzed. Over the study area during February–April 2022, both monthly SWE and snowmelt values had positive anomalies, while air temperature values showed positive anomalies only for February and April. The analysis of landslide events triggered by ARs based on a 5-day window for AR passages showed that ARs as a triggering factor were responsible for 62% of total landslide events.

[6] | Characterizing ARs associated with persistent flow regimes

First Author: Tyler C. Leicht

University at Albany, SUNY / United States of America

Co-Authors: Lance F. Bosart, University at Albany, SUNY

Persistent flow regimes (PFRs) regimes are a useful framework for identifying and describing low-frequency variability in the extratropics. Focusing on the low-frequency variability of PFRs also offers a potential increase in forecasting skill on the lower end of the subseasonal-to-seasonal (~2–4 week) timescale. In general, weather regime identification is based around mid- to upper-tropospheric geopotential patterns and not explicitly linked to observed surface weather conditions. Assessing the characteristics of, typically extreme, weather events during PFRs allows us to better connect forecasts of the large-scale flow to the observed weather occurring during those regimes. While a variety of extreme weather could be considered, this study will focus on ARs that are and are not associated with PFRs, and link AR characteristics to the development and evolution of PFRs

PFRs will be identified as periods of widespread persistent anomalies as defined by Dole and Gordon (1983) and further modified by Miller et al. (2020) using CFSR reanalysis data for DFJ from 1979–2022. All PFRs will be aggregated into five clusters using k-means clustering on the 500-hPa geopotential height data at the start of each PFR. To compare these PFRs with ARs, AR events will be taken from the Guan and Waliser AR Reanalysis Database using ERA-Interim data at 1.5°. AR-centered composites of ARs that are and are not associated with PFRs will form the bulk of the analysis. The aforementioned composites are intended to document potential differences in the AR characteristics. In addition, dynamical metrics (e.g., integrated moisture flux convergence) will be calculated in order to assess the impacts of ARs on the PFRs.

[7] | Severe Flooding in Pakistan in August 2022 Associated with an Unusually Amplified Large-Scale Flow Pattern that Facilitated Robust Midlatitude-Tropical Interactions

First Author: Lance Bosart

DAES, University at Albany/SUNY / United States

Co-Authors: Lance F. Bosart, Bruno Z. Ribeiro, Alexander K. Mitchell, and Tyler C. Leicht

Widespread heavy rains caused catastrophic flooding over Pakistan in August 2022. The extensive flooding killed more than 1500 people and caused billions of dollars in damages and economic losses. The Pakistan flooding was associated with heavy monsoon rains, westward-moving Bay of Bengal tropical depressions, and a tropical moisture surge from the Arabian Sea. Severe flooding that occurred earlier across Pakistan and India was linked to a severe weather outbreak over southern Europe in mid-August 2022 that was associated with an unusually strong summer 500-hPa cutoff cyclone that deepened southeastward across France into the Mediterranean Sea and northern Italy.

This cutoff cyclone subsequently turned northeastward and weakened as it moved toward central Europe to the west of a strong blocking anticyclone situated over higher-latitude eastern Europe and western Russia. This blocking anticyclone served as a “meteorological traffic cop” for a series of eastward-propagating, upper-level cyclonic disturbances from western Europe that crested this anticyclone and reached central and eastern Asia. These upper-level troughs subsequently dropped southeastward toward a trough near the Tibetan Plateau. This flow configuration resulted in the formation of a rare and unusually intense and equatorward-displaced westerly jet to the north of the Tibetan Plateau.

A persistent quasi-stationary 700-hPa cutoff cyclone associated with the above Tibetan Plateau trough facilitated the transport of very moist air (precipitable water values > 60 mm and integrated water vapor transport values > 1000 kg/m/s) across the Arabian Sea, western India, and Pakistan. Moisture plumes associated with Bay of Bengal tropical disturbances moving westward across India merged with eastward-moving Arabian Sea moisture plumes. Equatorward jet-entrance region dynamics associated with the aforementioned rare and unusually strong equatorward-displaced upper-level jet stream north of the Tibetan Plateau enabled deep tropical moisture to reach northern Pakistan where it exacerbated already heavy and persistent monsoon rainfall across Pakistan.

[9] | Characteristics, Impacts, and Historical Perspectives of Atmospheric Rivers along the U.S. East Coast during Winter 2023–2024.

First Author: Jason M. Cordeira

Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, University of California San Diego / U.S.A.

Co-Authors: Nicholas D. Metz Hobart and William Smith Colleges, Xun Zou CW3E, Emily A. Slinskey CW3E, F. Martin Ralph CW3E

The Northeast and Mid-Atlantic regions of the U.S. have a high number of extreme high streamflow days and floods by watershed as compared to the rest of the U.S. with a significant increasing trend in flood magnitudes due to climate change. This region of the U.S. is particularly susceptible to both warm-season flash flooding and cool-season “compound” flooding due to snow and ice cover, with the latter closely related to atmospheric rivers (ARs).

Recent research has demonstrated that ARs are as frequent or more frequent across the Northeast U.S. as compared to the Western U.S. Along with an increased frequency, previous studies have shown that >30% of non-summer precipitation can be related to ARs in this region, including >90% of non-summer extreme precipitation, >85% of flood/flash flood watches, warnings, and advisories, and 95% of ice jam and related flood events.

This presentation will focus on the characteristics, impacts, and historical perspectives of East Coast ARs from the lens of several ARs during Winter 2023–2024 that produced widespread heavy precipitation and compound flooding, along with high winds, storm surge, and power outages. The results will focus on a series of five East Coast ARs between during December 2023–January 2024, with particular emphasis on the impacts of two extreme events on 18 December 2023 and 10 January 2024.

View Image

[10] | Atmospheric rivers contribute to Eastern China's humid heat event

First Author: HUANG Wen

HONG KONG university of science and technology / China

Co-Authors: Yurong Song HKUST, Mengqian Lu HKUST

ARs are closely associated with the occurrence of hydrometeorological extremes, such as heavy rainfall and flooding, and have garnered significant attention in research. However, there has been limited investigation into the influence of ARs on humid heat events, with existing studies primarily focusing on specific cases. Therefore, our study aims to explore the circulation characteristics and physical mechanisms of AR related humid heat events in eastern China from 1979 to 2018. ARs are located ahead of cold fronts and are typically located within the low-level jet. Where warm and cold air masses meet, the warm air is forced upward, resulting in precipitation in frontal area. The humid heat region is located on the warm side of the frontal zone, adjacent to the precipitation region, exhibiting distinct north-south distribution characteristics. In humid heat region, influenced by the subsiding airflow from the high-pressure system, the water vapor brought by the ARs concentrates in the lower troposphere and the low-level clouds decrease significantly. This allows more solar radiation to reach the surface, resulting in increased temperatures. Specifically, the area with the surface air temperature anomaly located on the warm side of the frontal zone receives supply of moisture through ARs, contributing to the occurrence of humid heat events.

[11] | Atmospheric Rivers and their Correlation with Severe Convective Storm Events

First Author: Kamran Chowdhury

The Ohio State University / United States

Co-Authors: Dr. Jana Houser, The Ohio State University

It is well known that atmospheric rivers (AR's) are frequently accompanied by high-impact precipitation events that lead to flooding, especially along the West Coast of the U.S. However, their correlation with other hazardous weather types has not been investigated. This study focuses on severe weather events east of the Rocky Mountains, and offers a preliminary view on the spatio-temporal relationship of ARs with severe weather for the calendar year 2021. Severe reports including tornadoes, hail and thunderstorm winds are acquired from the SPC OneTor storm report database, and processed in ArcGIS to get areal extents for severe weather outbreaks over the US East. To be included, a severe weather outbreak is required to meet at least one of the following criteria: 1) ≥ 10 tornado reports, 2) ≥ 30 hail reports, 3) ≥ 30 wind reports, of 4) ≥ 50 total reports comprised up of any combination of tornado, hail or wind within a qualitatively identified region considered spatially contiguous. ERA5 data are used to identify all calendar days when there is an AR over the U.S., east of the Rockies. Three IVT thresholds: > 250, 500, and 1000 kg m^(-1) s^(-1), are identified for consideration. The total number of AR events, total number of severe weather days, and the mutual overlap of the two types of events are determined. Further, the geospatial intersection of the AR's with respect outbreak areas and event timing are investigated in order to assess the qualitative correlation between ARs and severe weather events. Preliminary findings suggest that severe storm outbreaks, particularly the high-end well-organized events, occur with AR's, but there also are many AR events that are not associated with severe weather.

[View Image]

[14] | Convective Triggers Interacting with Quasi-Stationary Convergence Zones Producing Extreme Rainfall Rates and Impacts in Southern California During Atmospheric River Events

First Author: Ivory Small

NOAA, National Weather Service, San Diego / United States

Co-Authors: Ivory J. Small, NOAA, National Weather Service, San Diego, CA

On 22 January 2024 and 1 February 2024, synoptic and mesoscale patterns over Southern California were favorable for very heavy rainfall rates/accumulations as seen in past cases (even during tropical events like 21 August 2023). Rates 1.5 inches to locally 3+ inches in an hour resulted from storm cell collisions with convergence zones near the coast (highly unusual). On 1 February 2024 the Seal Beach Area near "Surf City" (Huntington Beach) saw a closure of scenic Pacific Coast Highway as nearly 2 inches of rain fell in an hour. Downtown San Diego saw 3+ inches in one hour with numerous roads, homes and businesses flooded. Both were collisions of storm cells with a quasi-stationary convergence zone.

A Negative Tilt Diffluent Trough Pattern (NTDTP) can indicate that highest rates may be pushed closer to the coast by lowland convergence and its interactions with approaching triggers. Long-lived convergence zones consisting of southerly flow to the south and easterly flow in the north can easily develop under such conditions. Small vorticity maxima rotating around a parent low that are strengthening can produce a similar impact.

During such volatile patterns when the models show precipitation cores in terrain-rich regions such as Southern California, spotting where convergence zones are likely is essential. For example, model predicted cores over an inch in the low-res models and over about 2 inches in the higher res models for 6-hour forecasts along with convergence zone identification is important for timely messaging during these patterns. 6-hour low-res MOS site values of 0.50 inches or more are also key. Historical examples, tools, and thoughts on how to anticipate these damaging events and their associated impacts for improved IDSS will be shown.

[15] | California Coastal Response to 2022-2023 Winter Storms

First Author: Angelica Rodriguez

NASA Jet Propulsion Laboratory / US

Co-Authors: Brett Buzzanga JPL, Sarah Giddings SIO, Ben Hamlington JPL, Luc Lenain SIO, Matthew Mazloff SIO, Mark Merrifield SIO, Adam Young SIO

Sea level rise along the United States West Coast is accelerating, leading to more frequent high tide coastal flooding events. When storm surge and elevated wave energy, which often occur during land-falling atmospheric rivers (ARs) and extra tropical cyclones in the region, coincide with high astronomical tides, coastal flooding, infrastructure failure, erosion, and beach cliff collapse can be disastrous for coastal communities. These impacts can also be compounded by upstream flooding from intense precipitation and river runoff. Such a confluence of events played out in the winter of 2022-2023 along the California coast when elevated wave heights were accompanied by anomalously high sea levels. Airborne lidar surveys revealed the most significant coastal erosion and infrastructure impacts along the central California coast. In this presentation, we examine the timing of increased wave energy relative to storm landfall and the partitioning of energy between the sea and swell bands. Additionally, we describe the relative contributions of the background sea level anomaly in the context of steric height driven by a developing El Niño and atmospheric forcing arising from wind and pressure fluctuations that accompanied the successive storms.

[16] | Regional Patterns and Impacts of Temporally Clustering Atmospheric River Events in Southern South America

First Author: Surabhi Biyani

UCLA / USA

Co-Authors: Surabhi C. Biyani UCLA, Emily A. Slinskey CW3E, Alex Hall UCLA, J. David Neelin UCLA

Atmospheric Rivers (ARs) making landfall in Southern South America (SSA) are linked with extreme precipitation events and their associated hydrologic hazards. When ARs occur in succession, or temporally cluster, these compounding events lead to heightened impacts. Here, we investigate the temporal clustering of historic wintertime (MJJA) ARs over the western coast of SSA. We identify AR events with the Guan and Waliser (2019) detection algorithm, which uses a percentile-based IVT threshold. We apply a statistical framework utilizing the Ripley-K function to compare observed AR clustering rates in reanalysis data with synthetic randomly distributed sequences of ARs. Following this, we determine the locations, years, and timescales at which sequences of ARs exhibit statistically significant (greater-than-random) clustering. We identify significant clustering in the regions between 30-38 S (0.5-1.5 clusters per season) and 46-55 S (1-2 clusters per season). The northern region contains clusters up to 25 days long with 2-4 AR events each, while the southern region has longer-lived cluster durations up to 35 days, each containing 3-4.5 AR events. Notably, the region in between (38-46 S) exhibits little to no significant clustering despite the high frequency of AR events, which indicates random distribution of AR events. In the regions with significant clustering, 30-60% of all ARs are associated with a cluster. Future analysis will include quantifying the contribution of precipitation from these significantly clustered AR events, and analyzing the influence of ENSO on the temporal clustering of ARs. While this study focuses on SSA, it provides a framework that can be applied to similar regions, and results offer a historical context for understanding successive ARs that will serve as a comparison when studying future precipitation extremes.

Session:

AR2- ARs in past, present, and future climates

[107] | Historical changes in atmospheric river characteristics in reanalysis datasets

First Author: Alexa Henny

NASA Goddard Space Flight Center/NASA Postdoc Program (NPP) / USA

Co-Authors: Kyu-Myong Kim NASA GSFC

Atmospheric rivers (ARs) are projected to increase in frequency and intensity in a warming climate. With leading reanalysis datasets now spanning 44 years (MERRA-2) to as much as 84 years (ERA5), it is important to document the changes that have taken place in ARs in the historical record. Are the expected trends - widespread increases in AR moisture content, slowing or unchanged wind speeds, poleward shift - evident in the historical global mean? If so, how rapid is this change relative to the atmospheric moistening rate? Using MERRA-2, JRA-55, and ERA5 data, we employ a range of detection methodologies in order to cover a large space of potential AR subsets and determine whether a global consensus exists. Variables examined will include: frequency, area, and mean and maximum latitude, IVT, IWV, and wind speed, as well as changes in the global distribution. Potential caveats of reanalysis-based trends will also be discussed.

[108] | Temporal clustering of unique atmospheric river events impacting the Western U.S.: seasonality and relationship to climate mode variability

First Author: Zhiqi Yang

UCSD SIO CW3E / U.S.

Co-Authors: Zhiqi Yang*1, Michael J. DeFlorio1, Agniv Sengupta1, Jiabao Wang1, Christopher M. Castellano1, Alexander Gershunov1, Kristen Guirguis1, Emily Slinskey1, Bin Guan2,3, Luca Delle Monache1, F. Martin Ralph1

1Center for Western Weather and Water Extremes (CW3E), Scripps Institution of Oceanography, University of California, San Diego, CA, USA

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3Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Atmospheric Rivers (ARs) exhibit intense horizontal water vapor transport in a narrow region, influencing annual precipitation, global floods, and water resources. Apart from considering the frequency and duration of AR events, characterizing periods of temporal clustering of unique AR events is crucial in assessing their association with extreme precipitation and subsequent impacts (e.g., flooding and debris flows). Previous studies detected multiple AR events related to climate modes of variability that occurred in rapid succession over Northern California. However, understanding the clustering of unique AR events in time and their physical mechanisms still needs to be improved. In this study, we focus on the temporal clustering of unique AR events that impact the Western U.S. and highlight the role of major climate modes of variability (i.e., AO, PNA, MJO, QBO, ENSO, PDO) in modulating temporal unique AR clustering and AR orientation. We apply the Guan and Waliser (2015) algorithm to identify daily unique AR events and use a novel method, Cox regression analysis, to identify the magnitude of unique AR clusters, focusing on winter from November to March 1982-2019. To understand the seasonal differences in the influence of climate modes, we compare clusters in the early (NDJ) and late (JFM) winter. We found that unique AR events exhibit subseasonal temporal clustering in the Western U.S. during wintertime (November to March). Moreover, the impact of climate modes on spatial clustering patterns differs significantly, with a notable shift observed between early and late winter. QBO (PDO) exerts predominant influences on the southwest (California) in late winter, while AO impacts northern California primarily in early winter. Late winter witnesses a more southerly AR orientation than early winter in the Western U.S., underscoring a pronounced seasonality in AR orientation.

[109] | High-Resolution Modeling of the December 2022 – January 2023 High Impact Series of Landfalling Atmospheric Rivers Along the U.S. West Coast

First Author: Hunter Martinez-Buehrer

Master's Student at Northern Illinois University / United States

Co-Authors: Allison Michaelis Northern Illinois University, Jason Cordeira CW3E, Alexander Gershunov CW3E, Alex Haberlie Northern Illinois University, Victor Gensini Northern Illinois University, Walker Ashley Northern Illinois University, F. Martin Ralph CW3E

Current modeling studies suggest regional decreases in the number of precipitation days, but an increase in extreme precipitation events, especially in regions like California. This impact on California's precipitation is most evident through atmospheric rivers (ARs). The beneficial vs. severe nature of ARs varies between each individual event, ranging from weaker/short lived ARs that are primarily beneficial to strong/long-lived ARs that are primarily hazardous. Multiple ARs that occur in succession of one another within a certain aggregation period (e.g., an AR family) often result in multiple distinct pulses of precipitation over one area with varying intensities, leading to a variety of onshore impacts post landfall, and creating compounding challenges for water resource management. Recent work has suggested that not all individual ARs, and consequently, not all AR families, will respond similarly to a warming climate.

Here, we examine a recent sequence of landfalling ARs from 26 December 2022 – 19 January 2023 under different climate environments using the Model for Prediction Across Scales – Atmosphere (MPAS-A). During this period, a family of nine ARs made landfall throughout California, producing about half of California's annual precipitation. Heavy rain and snow over this three-week period were beneficial in building the snowpack across the mountainous regions and alleviating drought conditions in several areas; however, flooding, mudslides, and power outages were also common occurrences, underscoring the beneficial vs. hazardous nature of ARs. We hypothesize that climate change intensifies each individual AR event with the warmer, more meridional ARs experiencing strengthening in terms of both vertically integrated water vapor transport (IVT) and resultant precipitation. We also expect climate change to shorten the timing between events, effectively reducing the recovery time between onshore impacts.

[110] | The global response of atmospheric rivers to glacial conditions and their influence on ice sheets at the Last Glacial Maximum

First Author: Juan M. Lora

Yale University / United States

Co-Authors: Christopher B. Skinner U. Massachusetts Lowell, Seung Hun Baek LLNL, William Rush Santa Clara U., Clay Tabor U. Connecticut, Jiang Zhu NCAR

We investigate atmospheric rivers (ARs) globally at the Last Glacial Maximum (LGM) using simulations with the Community Earth System Model version 2. Reconstructions and simulations of hydroclimate during glacial periods suggest that the locations and mechanisms of atmospheric moisture transport have changed considerably through Earth's past. We find overall global decreases of AR activity, as well as mean and extreme precipitation, at the LGM, except over southwestern Patagonia, Iberia, and southwestern North America. In each of these, the associated LGM moisture transport changes are different, with increased transport and AR activity mainly occurring only in the North Atlantic and impacting Iberia. The AR moisture transport response of the LGM climate is dominated by the response to LGM ice sheets, and comparison of our results to previous work suggests that the response is highly sensitive to the ice sheet reconstruction used. We also investigate the contribution of ARs to ice sheet hydroclimate specifically. Despite lower-than-modern AR activity in the relevant regions, we find that ARs provide large fractions—up to more than half—of total precipitation along the margins of the northern hemisphere ice sheets. In addition, though the LGM climate is on average 6.7ºC colder than our control simulation, in line with proxy estimates, AR events over ice sheet margins lead to above-freezing conditions and more liquid than solid precipitation. Consequently, we find that ARs contribute more to melting than snowfall accumulation, and lead to negative average surface mass balance over all ice sheets. Our results indicate the importance of ARs in ice sheet growth and retreat during glacial periods.

[111] | Synoptic Drivers of Heavy Precipitation Days in the Upper Yuba Watershed of California

First Author: Emma Russell

Portland State Univeristy / United States

Co-Authors: Paul C. Loikith Portland State University

The Sacramento Valley of California has historically experienced impactful flooding. While efforts to reduce flood risks have been implemented, forecasting of extreme precipitation remains a challenge in regions with complex terrain and dynamic meteorological drivers. Here we aim to better understand the meteorological mechanisms resulting in wet-season (October-March) heavy precipitation in the Upper Yuba Watershed, which sits in the foothills of the Sierra Nevada Mountains above the Sacramento Valley. We implement a variant on the Self-Organizing Maps (SOMs) approach to cluster integrated water vapor transport (IVT) patterns leading up to heavy precipitation days into 12 3-day node patterns. Patterns show a range of storm types, characterized by different patterns of enhanced moisture transport with atmospheric rivers (ARs) present in nearly all cases. Heavy precipitation days are also associated with anomalously low 300 hPa geopotential heights and a surface cyclone offshore of Washington and Oregon in most cases. Results show that heavy precipitation within the watershed is possible from a range of storm types with different dynamical configurations and AR intensities. Precipitation intensity and duration also vary with storm type, which may lead to differing regional impacts based on meteorological conditions. This evaluation will not only aid in better understanding the key meteorological drivers of extreme precipitation in the Upper Yuba watershed, but may provide a basis for improved hydrometeorological forecasting and extension to other societally important watersheds.

[112] | Characterizing Present and Future Atmospheric Rivers Globally in CMIP6 Models

First Author: Lujia Zhang

The Hong Kong University of Science and Technology / China

Co-Authors: Mengqian Lu, The Hong Kong University of Science and Technology

Understanding the present and future features of atmospheric rivers (ARs) is critical for effective disaster prevention and mitigation efforts. This study comprehensively assesses the performance of ARs in Phase 6 of the Coupled Model Intercomparison Project (CMIP6) models on both seasonal and interannual timescales within the historical period and investigates the future projection of ARs under different emission scenarios on a global scale. The multi-model mean results obtained using the PanLu detection algorithm consistently exhibit agreement with the observational AR climatology and capture interannual fluctuations as well as the relationships with large-scale drivers. The future projections reveal increased AR frequency, intensity, duration, and spatial extent and decreased landfall intervals with regional variations and seasonal fluctuations. Besides, the AR frequency increase will accelerate around the middle of the century, attributed to a non-linear rise in surface temperature. Furthermore, mid-latitude ARs are gradually shifting toward higher latitudes in both hemispheres under SSP585, with Greenland experiencing a substantial increase in AR frequency and AR-induced precipitation. The hydrological implications arising from more frequent ARs are manifested more prominently in AR-induced heavy precipitation (HP), with regions historically characterized by lower AR occurrence also receiving a higher percentage of precipitation from ARs. At last, an incremental decomposition highlights the dominant role of thermal effects and relatively limited contributions from dynamical effects in AR changes. Besides, the interplay between regionally divergent temperature amplification results in different dynamically driven AR responses across the globe.

[113] | Changes in the concurrence of atmospheric rivers and explosive cyclones in the North Atlantic

First Author: Ferran Lopez-Marti

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The explosive development of extratropical cyclones and the presence of atmospheric rivers play a crucial role in driving some types of extreme weather in the mid-latitudes, like compound flood-windstorm events. Although these phenomena are individually well-established and their relationship has been studied previously, there is still a gap in our understanding of how a warmer climate may affect their concurrence. Here, we focus on evaluating the current climatology and assessing changes in the future climate of the concurrence between atmospheric rivers and explosive cyclones in the North Atlantic.

We use both the ERA5 and ERA-Interim reanalysis between 1980 to 2009 from October to March to evaluate the concurrence of atmospheric rivers and explosive cyclones in the current climate. To accomplish this, we first independently detect and track atmospheric rivers and extratropical cyclones. Next, we classify each cyclone as either explosive or non-explosive and define concurrence with an atmospheric river if the latter is detected within 1500 km of the minimum sea level pressure of the cyclone. We further analyze several CMIP6 climate models for the historical scenario (1980-2009) and for the future scenarios SSP1-2.6, SSP2-4.5 and SSP5-8.5 at the end of the century (2070-2099). Our findings reveal that atmospheric rivers are more often detected in the vicinity of explosive cyclones than non-explosive cyclones in all datasets. Moreover, we identified a significant increase in the concurrences and the atmospheric river intensity in all the future scenarios analyzed. As such, our work provides a novel statistical relation between explosive cyclones and atmospheric rivers in climate projections, a characterization of both in future climates and a new climatology of the concurrences for a higher-resolution reanalysis.

[114] | Climatological and Atmospheric Analysis of the Winter 2023 Atmospheric Rivers in Northern California

First Author: Sachit Parekh
BASIS Independent Fremont / United States
Co-Authors:

Atmospheric Rivers (ARs) are long, narrow corridors of moisture that account for 90% of all water vapor flux and 30-50% of yearly total precipitation for the West Coast of the United States. ARs bring heavy rain and wind for areas they impact, posing a multitude of hazards that include flash floods and high wind gusts. During the winter months of 2023, atmospheric rivers bombarded the Northern California region, leading to widespread flooding and damages. The primary aim of this research is to evaluate the Northern California ARs of the winter of 2023 in the context of previous years, in both a climatological and atmospheric aspect.

A study conducted by Rutz et al. (2014) established a global catalog of AR events which provides Integrated Vapor Transport (IVT) values and AR presence for every 3 hours starting from January 1, 1980. The threshold that establishes the presence of an AR as established by the study is a length of greater than 2000 km as well as an IVT value that is greater than 250 kg/m*s. The data for a single point along the California Coast closest to Bodega Bay, CA, from 1980 to 2023, is analyzed. A preliminary analysis revealed the winter of 2023 to be above average (1980-2022) in average AR duration and average IVT per AR. Further analysis including category information using the AR Scale established by Ralph et al. (2019) will be presented.

Starting from 2017, data from radiosonde deployments by the Center of Western Weather and Water extremes at multiple locations has been published. Radiosonde data from missions conducted at the Bodega Marine Laboratory, near to the aforementioned data point, is also analyzed and will provide information about the atmospheric dynamics of recent AR events.

[115] | A Holistic Probabalistic Model of Multi-day Precipitation Events

First Author: Alexander Weyant

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Co-Authors: Alexander Weyant SIO, Sasha Gershunov SIO, Anna Panorska UNR, Tomasz Kozubowski UNR, Julie Kalansky SIO/CW3E

In the western United States, much of the annual precipitation falls during relatively few storm events. When precipitation is measured as daily (or hourly, etc.) accumulations, these events appear as sequences of various durations. Previous probability modeling has characterized precipitation accumulations over prescribed durations, but herein we show that a trivariate probability distribution can be used to describe multi-day events in terms of their durations, magnitudes, and maximum intensities. This trivariate distribution, in its most straightforward application, describes precipitation events composed of daily observations at most long-term weather stations across the western United States, allowing for a flexible assessment of specific event probabilities and return intervals with respect to their three defining elements. This characterization opens the door to further understanding of risk and to design applications through statistical modeling of the trivariate distribution's parameters.

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[116] | The Role of Interdecadal Climate Oscillations in Driving Observed Arctic Atmospheric River Trends over 1981-2021

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Atmospheric rivers (ARs) are long, narrow corridors of intense moisture transport in the atmosphere, responsible for a significant portion of atmospheric moisture transport into the Arctic and for driving weather extremes in the region. However, our understanding of the factors controlling Arctic AR trends on multi-decadal timescales remains limited. Through the analysis of multi-source observations and model experiments, we identified a distinct spatial pattern, with ARs increasing more rapidly over the Atlantic sector than over the Pacific sector from 1981 to 2021. This contrasts sharply with the uniform positive AR trend across the Arctic, as simulated by climate models driven by anthropogenic forcing. By employing maximum covariance analysis and inter-member regression approaches, we discovered that observed phase shifts in the Interdecadal Pacific Oscillation (IPO) and Atlantic Multidecadal Oscillation (AMO) are crucial for explaining the discrepancies between observed and simulated trends. We demonstrated that the observed shift from a positive to a negative phase in the IPO and from a negative to a positive phase in the AMO promotes an increase in ARs over the Atlantic sector and a reduction over the Pacific sector. Given the significant influence of the IPO and AMO on the decadal variability of Arctic ARs, we further illustrate how these oscillations can be leveraged to constrain near-future projections of Arctic ARs.

[117] | Changes in the moisture sources of Atmospheric Rivers affecting the US East Coast: a Lagrangian approach

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Atmospheric rivers (ARs) have been recognised as an main mechanism for large-scale advective transport of precipitable water in the extratropics, but are also sensitive to variations under the climate change. This study uses a dynamic downscaling methodology based on the Lagrangian dispersion model FLEXPART with the Eulerian mesoscale WRF model (FLEXPART-WRF) to analyze the projected changes in mid-century (MC: 2036-2065) and end-of-century (EC: 2071-2100) associated with landfalling ARs (LARs) on the East Coast of North America (AR_ENA) and the Gulf of Mexico (AR_GM). The Anomalous Moisture Uptake (AMU) is considered to characterize changes associated with ARs. AMU was determined as the difference between the moisture source pattern for each day with the occurrence of LAR and the climatological moisture source pattern in the 30 years considering the occurrence or absence of LAR. In addition, the CESM2 climate model outputs are used as initial and boundary conditions for the projections. In general, a significant increase in winter is projected for the AMU associated with AR_GM across the Gulf of Mexico region, especially for the EC. Concerning AR_ENA, an increase in AMU of 0.5 mm/day is projected for both MC and EC, while the rest of the seasons show more complex pattern. For this season, the relative change values are close to 33% for both EC and MC. However, in summer, decreases in AMU dominate with relative values close to 10% and 14%.

[118] | Effects of Local SST Perturbations on an AR Event in Chile, using WRF Model

First Author: Vicente Antonio Cuevas Acuña

Universidad de Chile / Chile

Co-Authors:

Atmospheric rivers (ARs)play an important role in precipitation in Chile, contributing between 40% - 55% of precipitation along the mid-latitude west coast. While the large-scale effects of sea surface temperature (SST) on atmospheric rivers are well known, the effects of local SST have not been investigated for Chile. This study examines the AR event of April 27, 2023, which reached continental Chile, resulting in precipitation exceeding 100 mm. Seven simulations were analyzed, with only local SST modifications. For cases of local SST warming, an increase in intensity and precipitation was observed, for dew point temperature above 10°C rainfall varying exponentially by 7% per degree Celsius. Up to 10°C, change to 14% per degree Celsius. Additionally, the 0°C isotherm shows a variation of ~125 m per degree Celsius. This study highlights the importance of local SST perturbations of ARs and their effects on rainfall and snow cover in Chile.

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[119] | Atmospheric River Detection Under Changing Seasonality and Mean-State Climate: ARTMIP Tier 2 Paleoclimate Experiments

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There are numerous methods for detecting and tracking atmospheric rivers (ARs). These atmospheric river detection tools (ARDTs) rely upon different parameters such as absolute or relative IVT thresholds, differing geometries, and differing temporal requirements, leading to uncertainty in AR size, count, and frequency, particularly under different climate states. This study seeks to better understand how different ARDTs respond to changes in climate states utilizing single-forcing model experiments under the aegis of ARTMIP (Atmospheric River Tracking Method Intercomparison Project). We test how the ARDTs respond to changes in seasonality and mean climate state using CESM simulations with altered orbital configuration and low CO2 levels, respectively. The former uses early Holocene orbital parameters and the latter Last Glacial Maximum CO2 levels. Relative to pre-industrial, the Holocene simulation results in a change in the spatiotemporal distribution of hydrologic features rather than any marked global changes, whereas the low CO2 simulation results in a decrease in moisture transport to high latitude sites, decreased precipitation nearly globally, and a decrease in evaporation in the subtropics, consistent with a less energetic hydrologic cycle. We find good agreement among the algorithms in response to the changing orbital configuration, with a poleward shift in AR frequency that tracks seasonal poleward shifts in water vapor and zonal winds. On the other hand, while the algorithms generally agree on a global decrease in AR frequency in the low CO2 simulation relative to the pre-industrial, there is a much greater spread in the magnitude of that decrease, indicating that mean-state changes lead to considerably larger uncertainty in AR detections. This disagreement likely arises primarily from differences between algorithms in the criteria for thresholds for water vapor and its transport used for identifying ARs.

[120] | Atmospheric river activity over the past ~56 million years in an unprecedented set of high-resolution Community Earth System Model simulations

First Author: Sophia Macarewich

NSF NCAR / United States

Co-Authors: Bette Otto-Bliesner NSF NCAR, Jiang Zhu NSF NCAR, Esther Brady NSF NCAR, Ran Feng Univ. of Connecticut, Clay Tabor Univ. of Connecticut, Juan Lora Yale Univ., Chijun Sun UC Davis

Atmospheric rivers (ARs) cause extreme precipitation, floods, and drought events, and were likely an important component of past hydrologic change. Nevertheless, our understanding of ARs in past climate states has been partially limited by low resolution (>1°) Earth system simulations, which are necessary for the long spin-up times of paleoclimate states. Previous work has demonstrated that low resolution simulations severely underestimate AR strength and precipitation compared to observations. Increasing the grid resolution can alleviate these deficiencies by improving the representation of AR integrated vapor transport and orography in landfalling regions. To improve our understanding of AR activity in the past, we present a set of high-resolution paleoclimate simulations, including time slices of the mid-Holocene (~6 ka), Last Glacial Maximum (~21 ka), mid-Pliocene (~3 Ma), and Eocene (~56 Ma) that sample extreme climate states (190 to >1700 ppmv CO2). We use a configuration of the Community Earth System Model version 1.3 with water isotopes that includes a horizontal resolution of ~0.25° for the atmosphere and land models and ~0.1° for the ocean and sea-ice models. Preliminary analysis suggests that overall the frequency, intensity, and geographic distribution of ARs increases (decreases) in past climate states with higher (lower) CO2 relative to pre-industrial, yet there are exceptions to this general rule over land. These simulations are an important step toward improving our understanding of ARs in a warming world by providing estimates of ARs in extreme climates that can be evaluated against paleoclimate proxy data.

Session:

AR3- Environmental and socioeconomic impacts of ARs

[77] | Coherence of atmospheric and ocean conditions along the coast of central Chile during Atmospheric Rivers

First Author: Yosvany

Department of Oceanography, University of Concepcion, Chile / Chile

Co-Authors: Diego Narvaez University of Concepcion Chile Irina Gorodetskaya CIIMAR Portugal, Martin Jacques University of Concepcion Chile

Atmospheric rivers (ARs) are important components of the global water cycle causing extreme precipitation events and strong winds, largely on the western coasts of the midlatitude continents. In central Chile, ARs contribute between 45% and 60% of the total annual rainfall and changes in wind patterns, which, respectively, provide freshwater and affect the circulation and hydrography of the coastal ocean. Here we examine various AR events that affected Chile between 30° and 40°S during winter (1979-2018). Observations from sea surface temperature and tide gauges were used in conjunction with reanalysis data from ERA5 and GLORYS12V1, and satellite data from OSTIA. In addition, a dedicated winter campaign was carried on in July 2022 at the coast (36.5° S), using a vertical profiler (Wirewalker) equipped with a CTD. Two main patterns of ARs were analyzed: zonal (ZAR) and meridional (MAR). Both types produce intense winds towards the coast during AR landfalling, generating strong coastward ocean surface currents and subsequent downwelling and increase in local sea level. MARs induce stronger vertical Ekman velocity leading to downwelling of surface waters close to the axis of the ARs, and ZARs are related to upwelling processes in the equatorward part of the systems. In July 2022 we captured 4 ARs, and here we focus on one of them, a MAR. Right after the landfalling, intense coastal ocean vertical mixing occurs, causing homogenization of salinity, oxygen, chlorophyl and turbidity in the entire water column (18m depth). When the AR weakened, stratification increased due to freshwater input (causing low salinity and high turbidity) in the upper 5m from a nearby tributary, lasting for 2 days. River discharges from larger rivers around the study area increased, producing a stronger effect in the coastal ocean by the buoyant river plumes, indicating implications for marine ecosystems and the fishing sector.

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[78] | The role of Atmospheric Rivers in the Record-breaking Precipitation Event of December 2022 in Portugal

First Author: Tiago Ferreira

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Co-Authors: Tiago M. Ferreira IDL-FCUL, Ricardo M. Trigo IDL-FCUL, Alexandre M. Ramos IMK-TRO-KIT, Tomás H. Gaspar IDL-FCUL and Joaquim G. Pinto IMK-TRO-KIT

Most extreme precipitation events in western Iberia are triggered by intense extratropical cyclones and associated frontal systems. However, in the last decade several studies have shown the important role played by Atmospheric Rivers (ARs) in the occurrence of such events. In this study we analyse the all-time 24h record-breaking precipitation value recorded in Lisbon (134.6 mm), between the 12 and 13 December 2022 in terms of the synoptic background. The previous record was registered on the 18 February 2008, with a value of 118.4 mm. We obtained a comprehensive synoptic characterization of the atmospheric circulation between the 1st and 15th of December.

Results show that on the 8 December by 06 UTC an extratropical cyclone was present in the middle of the North Atlantic, with a high moisture content and that by 18 UTC on the following day a cut-off low was formed in the northwest Atlantic. This cut-off system was well characterized by relatively high vertical velocities and convergence at the low levels, combined with high rates of evaporation acquired over the Gulf Stream, intensifying the moisture content to its south side. Both systems converged on 10 December by 12 UTC and by the 18 UTC the detection algorithm identified an AR located southward of the extratropical cyclone. The combination between high IVT values, with maxima ranging between 947 kg m-1 s-1 and 1227 kg m-1 s-1, with a dynamical component characterised by winds above 20 m/s, as well as a suitable vertical motion, allowed the system to evolve and maintain the AR characteristics for 72h. The AR progressed towards Iberia, affecting Portugal as an extreme AR event, leading to the 24h precipitation record of 134.6 mm measured at the Geophysical Institute in Lisbon, the highest value since continuous measurements started in the early 1860s.

[122] | The hazards and Socio Cultural Impacts of Atmospheric Rivers in Himalayan Region : Role of Information and Communication Technology and Digital Tools for Post Rehabilitation.

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Shah and Anchor Kutchhi Engineering College and ISDR / India

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The Presentation focuses on the Atmospheric Rivers and flood in Himalayan region on 16 th Jun 2013 caused by a sudden rapid melting of ice from Chorabary glacier and snow on the Kedarnath Mountain and cloudburst at 3800 meters high altitude in Himalayan Mountain. This great quantities of rains produced heavy flood which instigated losses worth US $1 billion, mortality at a gory high of 5000 deaths and led to an equal number still being reported as missing. This phenomenon caused environmental and social impacts in this region. The Information and Communication technology and digital tools played a vital role in understanding the Atmospheric Rivers in glacier region. The presentation aims to discuss the long term Socio- Cultural and economic impacts of this Atmospheric rivers and floods caused due to this which needs review of Global Climate change system coupled with human dimensions to mitigate the post disaster impacts.

[123] | Impacts associated with atmospheric rivers in the Baja California Peninsula, Mexico

First Author: Daniela Fernanda Cuauhtémoc Vargas

Universidad Nacional Autónoma de México / México

In Mexico, atmospheric rivers (AR) have not been studied in depth, however, their occurrence has been identified through satellite products and precipitation models, mainly for the Baja California Peninsula, where these events occur more frequently during the winter season. This research analyzed the impacts of atmospheric river events in Baja California, Baja California Sur and Sonora, highlighting the issuance of warnings by the Civil Protection of these states in the event of adverse conditions such as heavy rains and strong winds. Most of the AR events were attributed to cold fronts and winter storms and were not officially identified as atmospheric rivers, although similar events occurred on coinciding dates in the United States attributed to AR. Impacts reported in Mexico included flooding, landslides, and power outages. Most of the events with significant impacts had cumulative rainfall greater than 100 mm and lasted at least three days, with torrential and heavy rains. However, in some cases, multiple impacts were recorded despite a cumulative rainfall of less than 100 mm, suggesting the influence of other atmospheric conditions. This analysis highlights the need to better understand the complexity of atmospheric river conditions for Mexico and their impacts to improve preparedness and response to these events.

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[124] | Influences of Atmospheric Rivers on Seasonal Precipitation and Snowmelt Patterns in Upper Mesopotamia

First Author: Deniz Bozkurt

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Co-Authors: Deniz Bozkurt Universidad de Valparaíso, Yasemin Ezber Istanbul Technical University, Ömer L. Şen Istanbul Technical University

In Upper Mesopotamia, encompassing the highlands of the Near East and the headwaters of the Euphrates-Tigris Basin, atmospheric rivers (ARs) originating from the Red Sea and tropical Africa play a crucial role in shaping its hydrometeorology across different seasons. This region, significantly influenced by ARs, is critical for water resources due to its reliance on snow-fed river systems.

During the winter, ARs have a pronounced impact on the headwaters of the Euphrates-Tigris Basin by bringing warmer and wetter conditions. These conditions are essential for replenishing the snowpack, which, in turn, feeds the river systems throughout the drier months. The contribution of ARs to total winter precipitation is substantial, averaging 60% over a 40-year period, with considerable year-to-year variability. On average, snowpack contributions from ARs account for 27% of the seasonal average, although this figure demonstrates significant spatial and temporal variations. The south-facing parts of the mountain range experience signicant snowmelt, with contributions ranging from 15–80% for different years. This variability reflects the semi-arid characteristics of the region and the occurrence of rain-on-snow events, where rain falling on existing snowpack leads to rapid snowmelt.

In the spring, the influence of ARs extends to affecting snowmelt patterns in the region's highlands. The warmer and wetter conditions associated with ARs during this season can accelerate snowmelt processes, affecting water availability in downstream areas. The impact on snowpack in the spring varies, with some areas experiencing reductions in snowpack due to these warmer conditions, which can significantly influence the hydrology and water resources of Upper Mesopotamia.

Overall, ARs play a crucial role in Upper Mesopotamia's water availability, significantly influencing winter precipitation and spring snowmelt. Their complex effects on the region's water cycle underscore the importance of ongoing research to enhance understanding of AR dynamics and develop adaptive water management strategies.

[125] | Characterising river flow response to atmospheric moisture transport in New Zealand

First Author: Nithin Krishna Bala Murali

University of Otago / New Zealand

Co-Authors: Dr. Daniel G Kingston, University of Otago; Dr. Sarah M Mager, University of Otago

The dynamics of atmospheric moisture transport in New Zealand are highly susceptible to midlatitude cyclones and westerly circulation that influence precipitation patterns, leading to significant variations in river flows across New Zealand. Previous research has identified isolated locations in NZ where atmospheric rivers (ARs) are a key driver of extremes in river flow, but there has been no systematic nationwide analysis of the role of ARs in flooding. Here, we investigate the relationship between river flow and IVT at 160 sites distributed across the country. The highest correlation between IVT and river flows occurred on the western coast of South Island and in the southern North Island. The presence of ARs were highly evident in the top 20 river flow days. Catchments with the highest correlations between IVT and flood peaks also showed that multi-day AR events provided a high level of association with extreme flow events (> 90th percentile), suggesting that AR events are the principal cause of flooding extremes, but only in specific regions of the country. Conversely, east coast locations had poor correlation between river flow and IVT: these are exacerbated by long temporal lags between IVT events and river response which are not satisfactorily explained by catchment storage or flow length. These locations had fewer ARs in the top flood events thereby suggesting a strong spatial variability in the attribution of high river flows to AR incidence. Of the flow sites strongly correlated to ARs hydrographic analysis and flood statistics were generated for high IVT and AR days to understand how changes in moisture transport drive river flows. In particular, these locations showed that extreme IVT can be an effective explanatory variable for river flows at these locations and may be a useful tool for augmenting incomplete or damaged flow records during extreme events

[126] | An Ingredients-Based Analysis of Storm Types Associated with High-Impact Mesoscale Precipitation Events in the U.S.

First Author: Samuel Bartlett

CW3E / United States

Co-Authors: Samuel Bartlett (CW3E), Matthew Steen (CW3E), Jason Cordeira (CW3E), and Emily Slinskey (CW3E)

Mesoscale Precipitation Discussions (MPDs) are issued by forecasters at the Weather Prediction Center (WPC) MetWatch desk with a focus on short-term forecasts of high-impact precipitation. These products include graphics highlighting areas of concern for flash flooding and written discussions of the storm type, atmospheric ingredients, and magnitude of impacts expected. A climatology of MPDs issued in NWS county warning areas (CWAs) between 2013–2023 is developed to contextualize the locations and seasonal distribution of MPDs across the U.S. These distributions are complemented by a keyword analysis of the MPD text product, pulling out words associated with various storm-typing ingredients (e.g., "MCS", "cold front", "atmospheric river", etc.). This dataset provides a unique catalog of storm events associated with high-impact weather and their ingredients as described by forecasters issuing the MPDs. The keyword analysis is also used to investigate the spatial and temporal distribution of atmospheric river (AR) related MPDs. In the text of each MPD, the term "atmospheric river" is primarily reserved for only MPD discussions along the US West Coast; however, the present study aims to also quantify how often MPDs in the central and eastern US may also be associated with ARs by retrospectively categorizing these events using AR classification techniques.

[128] | Earth Surface Impacts of Hydrological Extremes along Global Atmospheric River Networks: The ARNETLAB project

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As the global water cycle intensifies, the Earth's surface will experience more extreme weather and climate events. Increasingly intense and frequent hydrological extremes, such as heavy precipitation events (HPEs), will result in unprecedented alteration of terrestrial ecosystem processes and more severe societal impacts. Prior research has successfully catalogued weather phenomena that act as drivers of hydrological extremes, such as atmospheric rivers (ARs). Recent advances in the catalogization of ARs offer great predictive potential for hydrological extremes and their impacts on the Earth's land surface. However, few approaches consider AR transport patterns at a global scale with a suitable methodological framework. Furthermore, our understanding of how controls of hydrological extremes propagate to changes in land-surface dynamics remains limited. I will introduce the new "ARNETLAB" project which aims to address these research gaps using tools from complexity science. We propose that the complex interplay between ARs, HPEs and ecosystem impacts can be disentangled using a complex network approach. Complex networks are a powerful paradigm that encodes interactions between the system's units through interlinked nodes. Recent applications illustrate that complex networks reveal novel insights into climate teleconnection patterns, synchronization of extremes and vegetation-atmosphere feedbacks. I will showcase preliminary findings on a novel transport network method for global AR trajectories. The introduced framework will allow us to link AR transport patterns to synchronized HPEs along their tracks and, in turn, to their impacts on terrestrial surface processes. Moreover, longer-term past, present and projected future changes in the network characteristics and associated synchronised extremes will be analysed. Using the novel PIKART catalogue of global ARs, we will go beyond coastal AR impacts by devoting special attention to their inland penetration. This talk demonstrates how tools from complexity science open up exciting research avenues to study the dynamics and impacts of ARs.

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[129] | When Nature Collides: The 2023 Türkiye-Syria earthquake disaster exacerbated by an atmospheric river

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Strong earthquakes affecting mountainous landscapes not only precipitate widespread slope failures but also set off subsequent chains of post-seismic hydro-geomorphic hazards. These hazards, when intersecting with extreme hydrometeorological phenomena—particularly atmospheric rivers (ARs), which are massive moisture transport systems—dramatically intensify the threats of floods, erosion, and landslides. The interplay of seismic and climatic extremes, especially in the wake of significant seismic events, creates compounded natural disasters of unprecedented scale and complexity, presenting new challenges in hazard assessment and emergency management. Our research documents for the first time the compounded effects of seismic activities and atmospheric phenomena, specifically through the case of the February 6, 2023, Türkiye-Syria earthquakes (Mw 7.8 and 7.6). This sequence, the most significant in the region's recorded history, was followed by a severe precipitation event (200mm/20h) triggered by an AR, occurring merely thirty-six days after the earthquake. This unique situation prompts questions about the potential impacts of similar compound hazards in other regions, particularly those that are densely populated. Current rapid hazard assessment protocols must be revised and enhanced to account for compound events and their sequential nature. Such adjustments represent a forthcoming challenge for the geoscientific community.

[130] | Quantifying the Hydrologic Impacts of Atmospheric Rivers in Chile

First Author: Mariana Webb

Desert Research Institute / U.S.

Co-Authors: Deniz Bozkurt (University of Valparaíso), René Garreaud (University of Chile), Christine Albano (Desert Research Institute)

Atmospheric rivers (ARs) are a dominant driver of water-related benefits and hazards in Central Chile, a region that hosts the majority of the country's population and economic activities. However, existing literature on floods caused by ARs has primarily focused on the West Coast of the U.S. and has not addressed how flood magnitudes vary relative to the Ralph et al. (2019) AR scale in other geographies. Much like the Western U.S., Central Chile has Mediterranean climate characteristics, prominent topography, and has experienced recent megadroughts and floods. However, Central Chile has distinct AR storm types influenced by tropical-subtropical origins, orographic enhancement, and coastal-valley transitions within the Andes. The unique interplay between large-scale climate patterns and regional geographical features is further compounded by local hydrological conditions and water management practices. Here, we quantify the relative contribution of ARs to flooding in Central Chile. We characterize the storm and hydrologic conditions that result in higher, often damaging, streamflows. Using the AR scale, we assess how flooding increases with AR strength and explore the influence of other AR intensity features such as storm orientation and temperature. Furthermore, we examine how differences in local climate, land surface, and water management practices may mediate or enhance flood risk. This research aims to enhance knowledge of AR hydrologic impacts along this Chilean transect, contributing to improved forecasting, risk communication, and mitigation of flooding during ARs globally.

[131] | Unprecedented atmospheric rivers as a stress test for empirical climate impact models

First Author: Christopher Callahan

Stanford University / USA

Co-Authors: Marshall Burke (Stanford), Noah Diffenbaugh (Stanford)

A large recent literature has used observed data on climate conditions and socioeconomic outcomes to empirically assess the effect of climate change on economic well-being. This strategy has been successful at empirically grounding our understanding of climate impacts, but does not necessarily incorporate the increasing risk of unprecedented and unobserved extreme events—events which, by definition, are not included in historical data on climate impacts. One such event is a hypothetical atmospheric river (AR) that could produce catastrophic flooding in California similar to the “Great Flood” of 1862, an event that is not included in the relatively short observational records of precipitation and flood damages in California. The likelihood of a similar AR is increasing due to global warming, but it remains unclear how the costs of such an unprecedented event could be measured given our empirical flood impact models. Here we combine high-resolution simulations of rainfall from an extreme AR scenario with empirically derived relationships between rainfall and flood damages in California, and perform a multi-dimensional sensitivity analysis to assess the potential costs of this unprecedented event. We assess the sensitivity of projected costs to assumptions about baseline economic growth, the functional form of the rainfall-damages relationship, and the potential spatial compounding of flood impacts. This approach allows us to produce a distribution of estimated costs, which we compare to other historical natural disasters and projected climate impacts to benchmark the magnitude of our estimates. Beyond the details of these cost estimates, our proposed approach highlights both the challenges and opportunities in incorporating unprecedented extreme events into climate impact analyses.

[132] | Hydrologic Effects of the 2018 Lake Mendocino Complex Fire in the Upper Russian River Watershed

First Author: Sarah Ogle

CW3E / United States

Co-Authors: Garrett McGurk CW3E, Morgan Levy UC San Diego: Scripps Institution of Oceanography and Global Policy School

Climate change is expected to contribute to a combination of increased wildfires, drought, and less frequent but more intense precipitation events---mainly from atmospheric rivers---in California. This combination can have dramatic effects on soil and vegetation, and may therefore significantly alter hydrology in burned basins, with effects such as flash flooding, decreased groundwater recharge, and post-fire debris flows. Over the past decade, many fires have affected the Lake Mendocino watershed, including the 2018 Mendocino Complex Fire, which is among the largest California fires on record. Preliminary explorations of precipitation, soil moisture, and streamflow downstream of and adjacent to burned areas of the Lake Mendocino basin demonstrate several post-fire hydrologic signatures: (i) increased post-fire quickflow, (ii) decreased post-fire baseflow, and (iii) altered soil moisture profiles. Understanding of the mechanisms generating these patterns requires further confirmatory research, but these signatures may indicate increased overland flow and reduced infiltration during precipitation events due to a combination of reduced evapotranspiration and soil hydrophobicity, as well as changes in soil structure (e.g., preferential flow in soil cracks vs. typical infiltration). From a water management perspective, such hydrologic changes are of concern because they can result in increased sediment and debris transport in rivers and reduced groundwater infiltration, the time scales of which are unknown. Thus, these dynamics are relevant to surface water and groundwater management activities in highly managed river basins like the Mendocino basin.

[133] | The impacts of atmospheric rivers on road safety and mobility in California

First Author: Tom Corringham

Scripps Institution of Oceanography / United States

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Atmospheric rivers (ARs) are key drivers of extreme precipitation and related hydrological disasters worldwide. Their influence is particularly pronounced in California, where they contribute significantly to the region's annual snow and rainfall. Despite extensive research on the hydrological and meteorological effects of ARs, their impact on road transportation infrastructure is less understood. This gap is critical, as road transportation is essential for commuting and freight in California. Weather-related disruptions present significant socio-economic challenges. This study aims to quantify the relationship between ARs and road network disruptions in California. By analyzing accidents and traffic flow rates combined with AR events and meteorological information, we develop an framework to explore these dynamics. Our research offers insights into how climate phenomena affect transportation infrastructure, aiding policymakers, urban planners, and engineers in climate change adaptation and resilience efforts. By bridging a notable gap in existing literature, the study underscores the importance of incorporating AR data into transportation planning and management.

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[134] | Responses of Harmful Algal Bloom Causing Phytoplankton Taxa to Atmospheric Rivers Along the California Coast

First Author: Jeri Wilcox

CW3E / United States of America

Co-Authors: Jason Cordeira CW3E, Peter Franks UC San Diego, Matthew Mazloff UC San Diego

This study aimed to understand the impact of Atmospheric Rivers (ARs) on Harmful Algal Bloom (HAB) causing phytoplankton taxa by asking two questions when specific HAB-causing phytoplankton taxa are present: are the phytoplankton abundances correlated with the Integrated Vapor Transport (IVT) magnitude the week prior, and are there consistent differences in the count distributions when the IVT was classified as an AR the week prior versus when the IVT was not an AR? In order to understand the relationship between phytoplankton and IVT, I calculated the Linear, SemiLog, and LogLog correlation coefficients between the IVT magnitude and the phytoplankton counts of 13 different taxa at 12 different monitoring stations along the California Coast. To understand if the presence of an AR had a significant impact on the abundance of HAB-forming phytoplankton taxa, I separated all of the phytoplankton counts based on if there was an AR the week before the count, and performed a Wilcoxon Rank Sum test to determine if they are statistically different distributions. This study confirmed for the first time that there are statistically significant correlations between these variables, and concluded that there is a complex relationship between IVT and the presence of ARs and HAB-causing phytoplankton taxa. In reference to the correlations between the IVT magnitude and the phytoplankton, relationships were strongest amongst dinoflagellate species, which showed consistent positive correlations in the more northern latitudes and different dinoflagellate species had more consistent negative correlations in southern latitudes. In reference to the understanding of phytoplankton counts when there was an AR the week before, there were negative correlations across latitudes, with a few weak positive correlations. Further research should be conducted to understand the mechanisms behind these correlations and dive deeper into the nuances of these relationships, as they have great implications for human and ecosystem health.

[135] | Improving Atmospheric River Predictions with User-Driven Research

First Author: Chris Davis

NSF National Center for Atmospheric Research / United States

Co-Authors: Christopher Davis NSF NCAR, Julie Demuth NSF NCAR, Andrea Schumacher NSF NCAR, Robert Prestley NSF NCAR, Rebecca Morss NSF and NSF NCAR, Gabrielle Wong-Parodi Stanford University, Natalie Herbert Stanford University

In this presentation, we apply the value cycle concept coupled with a risk communication approach to atmospheric river forecasts. A great deal of literature exists on the concept of value cycles, or value chains, for various prediction problems including hurricanes and tornadoes, among other things. Furthermore, there are decades of research about the risk communication approach to developing risk messages based on users' decision contexts. We highlight how these approaches apply to atmospheric rivers, namely, how users of forecast information help define impacts and decisions that are used to identify where and how to add to the observations of the natural system. Those observations enhance the numerical prediction accuracy and allow better risk information and products to be developed, provided, and used. Importantly, like with all value cycles and risk communication research, there are aspects that can be strengthened. We hypothesize where those might be based on analogies with forecasts of other phenomena, and we highlight aspects that are unique to the forecasts of atmospheric rivers.

[136] | Influence of Atmospheric Rivers on Southern California Wildfire

First Author: Ian Campbell

Scripps / United States

Co-Authors: Kristen Guirguis (CW3E), Alexander Gershunov (CW3E)

With expanding major population centers bordering burn-prone ecosystems, Southern California poses complex challenges in fire-management. In December 2017 alone, Southern California experienced six major wildfires, creating over three billion dollars in damages, and forcing nearly a quarter million people to evacuate. While many of the region's wildfires begin with accidental human ignitions, current and preceding environmental conditions influence the severity of the burn. The response of vegetation growth and subsequent wildfire risk after ARs has been researched in Western ecoregions (Albano, 2016), yet less is understood about this correlation on the smaller scales of plant habitats and ecotones. Understanding how Southern California plant communities respond to winter precipitation over different timescales, from several months to years, may aid in understanding the contribution of ARs to regional wildfire risk.

In this study, we investigate the relationship between atmospheric rivers, vegetation growth, and wildfire hazard using historical records of cumulative precipitation during AR peak season (November - March) along with indices of vegetation growth, including the Normalized Difference Vegetation Index (NDVI) and fuel moisture content. We present results from over 30 years of observations relating winter AR activity with subsequent vegetation growth and drying to better understand how ARs contribute to a productive growing season, which can create excess fuel for wildfire in the months to follow. Results suggest the strength and lag of the relationship between winter AR precipitation and vegetation growth depend on a multitude of factors including altitude and plant composition. This research also explores how Southern California landscapes dominated by invasive species, such as the ever spreading black mustard (Brassica nigra), respond to winter precipitation.

These results have implications for wildfire management and long-lead decision support, which is increasingly important as climate change is expected to enhance drying of vegetation between rain events.

[137] | Two Giant Atmospheric Rivers in the same season over the subtropical Andes. Hydrological impacts over the lee Argentinean side

First Author: Maximiliano Viale

Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA - CONICET) / Argentina

Co-Authors: Pierre Pitte and Hernan Gargantini, IANIGLA-CONICET, Moira Doyle and Florencia Ghetti, Departamento de Ciencias de la Atmósfera y los Océanos, Universidad de Buenos Aires

Two powerful atmospheric rivers (AR) in the last 2023 austral winter have been the primary water source for the first wet water year in the subtropical Andes region since 2016. The subtropical Andean region irrigates from rivers draining on both slopes of the Andes to large populated and desert areas in Argentina and Chile. These terrestrial rivers, in turn, mostly originate by a few AR storms per winter in the Andes. The two giant 2023 ARs ranked as category 4 in the Ralph scale and lasted 4 days. An AR category 4 occurs every 3 years or more equatorward of 35°S, but in 2023 arrived two of them in the same season. The first one occurred in 22-25 June and featured by a warm environment with the freezing level around 3000-3500m, while the other occurred in 19-22 August and has a cooler environment with the freezing level around 2500-3000m. Consequently, the hydrological hazardous impacts during and just after each of the events on the lee Argentinean side of the Andes were quite different and will be detailed by using key mountain stations. Basically, the warmer caused extraordinary quick river overflows, while the cooler one brought record-breaking snowpacks. Both caused severe damages and even fatalities in the short term. In the annual time scale, all rivers draining to the Atlantic Ocean experience a wet year after the last El Niño season in 2016. Some dams were opened in recent summer to avoid overcharge, leading to the first refilling of dry lakes farther east in the desert since 20 years, event which was largely celebrated by local people.

[138] | Assessing Atmospheric Rivers Damages and Impacts in South America

First Author: Maximiliano Viale

Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA-CONICET) / Argentina

Co-Authors: Ricardo A. Abarca, Manuel E. Olivares, Tamara Venegas, and Pabla Quintana, Dirección Meteorológica de Chile

The West coast of southern South America is one of the most strongly affected region in the world by Atmospheric Rivers (ARs). When these strong water vapor corridors, fueled on the vast southern Pacific Ocean, make landfall, they discharge tons water vapor over the extremely long and high Andes Mountain range through efficient orographic precipitation processes. In this work, we evaluate the impact of ARs, according to its features and categories in the Ralph scale, on the precipitation-related social and economic damages. The Chilean National Weather Services has been gathering social and economic damage datasets associated with precipitation events, which has been generated by disaster reduction and civil protection agencies of Chile (i.e., SENAPRED and SERNAGEOMIN). These damages datasets are combined with AR datasets derived from the ERA5 reanalysis to assess the AR impacts. The preliminary results of this assessment will be presented in the conference, which basically can be divided into two distinct subregions, the dry and populated subtropical sector and wet and isolated extratropical sector of the west coast of southern South America.

[139] | The Role of Atmospheric Rivers in the Snowpack over the Upper Colorado River Basin during Water Year 2023

First Author: Zhenhai Zhang

CW3E, SIO UCSD / USA

Co-Authors: Martin F. Ralph, CW3E

The Colorado River is the most important surface water source in the U.S. Southwest. The natural streamflow of this river is mainly generated by the snowpack in the Upper Colorado River Basin (UCRB), which experiences large year-to-year variability. Atmospheric rivers (ARs) can penetrate significant amounts of water vapor from the coastal region to the interior of the western U.S. and has a great impact on the precipitation inland. During water year (WY) 2023, an unusually large number of ARs made landfall along the U.S. West Coast, penetrating inland and bringing heavy precipitation over the western U.S., including the UCRB. In this study, we investigate the role of ARs in the historic snow water equivalent (SWE) accumulations in the UCRB in WY 2023. The SWE data from the snowpack telemetry (SNOTEL) stations across the UCRB is used to analyze the SWE accumulation and the extreme snow events. The integrated water vapor transport (IVT) and other relevant fields from ECMWF Reanalysis version 5 (ERA5) are utilized to examine the AR characteristics and the related large-scale weather patterns. The contributions of inland AR penetration are quantified across all the sub-basins and the preferred AR penetration pathways are explored. Preliminary results show that inland AR penetrations play a critical role in the SWE accumulation over the UCRB during WY 2023, especially in the extreme snow events. This case study of the wet WY 2023 can improve the understanding on the role of ARs in the snowpack over the UCRB and provide support to the long-term objective of more water resilience there.

[146] | Summer AR’s in eastern Australia – consequences for lower catchment water quality

First Author: Scott Johnston

Southern Cross University / Australia

Co-Authors: Damien T. Maher; Catchments, Coasts and Communities Research Cluster, Southern Cross University, Australia

Summer atmospheric rivers contribute ~20-35% of annual rainfall in south-east Australia and are often associated with flooding in coastal catchments. In Feb-March 2022 a blocking high-pressure system southeast of Australia and a low-pressure system on the east coast transported moist air from the Coral Sea to coastal catchments. Intense, sustained rainfall (up to 1000 mm over 24h) on already saturated landscapes led to record flooding in the town of Lismore. This was the costliest flooding event in Australia’s history (estimated AU$3.35 billion in insured losses) and caused major disruptions to community food, fuel, transport, significant damage to infrastructure and the loss of over 20 human lives.

While the socio-economic impacts of summer AR events on human communities can be devastating, they can also lead to severe impacts to aquatic ecosystems. This talk explores how the intersection between seemingly disparate phenomena can lead to large-scale, sustained river hypoxia events with widespread fish-kills and prolonged impacts on the entire estuarine food-chain and dependent industries. The seemingly disparate phenomena include summer AR’s followed by high pressure systems driving elevated post-flood temperatures, the geomorphic characteristics of east Australia’s coastal floodplains, and radically altered floodplain-river connectivity due to post-European land management practices. We discuss the scale and scope of these events, their hydrological and biogeochemical drivers, and briefly examine potential solutions as well as challenges to adopting those solutions.

[148] | A Vision for Climate Resilient Water Management in California

First Author: Mike Anderson

Dept of Water Resources, CA / USA

Climate change is already showing influences in the timing, pace, and scale of atmospheric river events that make up the foundation of water supply and flood risk during California's wet season. The Atmospheric River Research to Operations Partnership has spent the last decade developing observational and forecast capabilities to better understand and predict the character of atmospheric river events. These advances are enabling the development of water management capabilities to increase managed water capability providing supply reliability and mitigating flood risk. As climate change continues to progress, expectations are for variability and extremes to increase. This talk will present a vision for using observations, forecasts, and decision support services to enable climate resilient water management for California for the coming decades.

Session:

AR4 - Forecasting of ARs

[30] | Forecasting extreme precipitation from atmospheric rivers in New Zealand

First Author: Daniel Kingston

University of Otago / New Zealand

Co-Authors: Liam Cooper, University of Otago, New Zealand

David Lavers, European Centre for Medium-Range Weather Forecasts, UK

David Hannah, University of Birmingham, UK

With mountainous topography and high exposure to mid-latitude westerly storms resulting in frequent atmospheric river (AR) landfall, medium-range forecasting of extreme precipitation is a critical research and practical imperative in New Zealand. Previous research (focussed mostly on western Europe) has found that the forecasting of extreme precipitation associated with ARs is often more successful when the forecast focus is on vertically integrated atmospheric water vapour transport (IVT) rather than precipitation itself – but this finding has yet to be widely tested in other locations. Here, the European Centre for Medium-Range Weather Forecasts Extreme Forecast Index (EFI) is applied to total precipitation (TP-EFI) and IVT (IVT-EFI). A case study approach is adopted, focussing on three recent and damaging New Zealand ARs that each correspond to a markedly different synoptic situation. The case studies corresponding to ARs that make landfall primarily on either the western or eastern coast of New Zealand reveal that the TP-EFI outperforms the IVT-EFI in capturing the associated extreme precipitation events. For the north coast AR landfall case study the results are reversed, with the IVT-EFI providing much more extreme EFI values. Correspondingly, these findings demonstrate some important differences to existing work on forecasting AR-driven extreme precipitation. Further, they highlight the need to test our conceptual understanding of the drivers of extreme mid-latitude precipitation in different atmospheric circulation settings.

[31] | Atmospheric Water Vapour Transport in ACCESS-S2 and the Potential for Enhancing Skill of Subseasonal Forecasting of Precipitation

First Author: Kimberley Reid

Monash University / Australia

Co-Authors: Debbie Hudson BoM, Andrew King Uni. of Melbourne, Todd Lane Uni. of Melbourne, Andrew Marshall BoM

Extended warning of above average and extreme precipitation is valuable to a wide range of stakeholders. However, the sporadic nature of precipitation makes it difficult to forecast skilfully beyond one week. Subseasonal forecasting is a growing area of science that aims to predict average weather conditions multiple weeks in advance using dynamical models. Building on recent work in this area, we test the hypothesis that using large-scale horizontal moisture transport as a predictor for precipitation may increase the forecast skill of above median and high precipitation weeks on subseasonal timescales. We analysed retrospective forecast (hindcast) sets from the Australian Bureau of Meteorology's latest operational subseasonal-to-seasonal forecasting model, ACCESS-S2, to compare the forecast skill of precipitation using integrated water vapour transport (IVT) as a proxy, compared to using precipitation forecasts directly. We show that ACCESS-S2 precipitation generally produces more skilful forecasts, except over some regions where IVT could be a useful additional diagnostic for warning of heavy precipitation events.

[32] | Subseasonal Potential Predictability of Horizontal Water Vapor Transport and Precipitation Extremes in the North Pacific

First Author: Tim Higgins

CU Boulder / USA

Co-Authors: Aneesh Subramanian CU Boulder, Will Chapman NCAR, David Lavers ECMWF, Andrew Winters CU Boulder

Accurate forecasts of weather conditions have the potential to mitigate the social and economic damages they cause. To make informed decisions based on forecasts, it is important to determine the extent to which they could be skillful. This study focuses on subseasonal forecasts out to a lead time of four weeks. We examine the differences between the potential predictability, which is computed under the assumption of a "perfect model", of integrated vapor transport (IVT) and precipitation under extreme conditions in subseasonal forecasts across the northeast Pacific. Our results demonstrate significant forecast skill of extreme IVT and precipitation events (exceeding the 90th percentile) into week 4 for specific areas, particularly when anomalously wet conditions are observed in the true model state. This forecast skill during weeks 3 and 4 is closely associated with a zonal extension of the North Pacific Jet. These findings of the source of skillful subseasonal forecasts over the US West Coast could have implications for water management in these regions susceptible to drought and flooding extremes. Additionally, they offer valuable insights for governments and industries on the US West Coast seeking to make informed decisions based on extended weather prediction.

[33] | Comparing IVTinit-estimated Day0 Total One-Day IVT with Daily GFS Day0 TIVT24 out to 30 Days

First Author: Alan D. Fox

Fox Weather, LLC / United States

Co-Authors: Alan D. Fox, Fox Weather, LLC, Leonard M. Montenegro

Our task is to provide better consistency and stability to forecasts of precipitation for systems approaching California from the North Pacific. In 2019 we developed IVTinit™, a one-day total IVT calculated daily from sea surface temperature anomaly (SSTA) via AI application. The general process of calculating total one-day TIVT from SSTA was contained in our report (Fox and Montenegro,2020, IARC004, CW3E). Although termed 'cyclogenesis index' IVTinit's best description is: "estimated Day0 TIVT, using SSTA as primary argument". IVTinit features shown by our daily maps appear similarly to small atmospheric features, i.e. fronts, troughs, small lows. Our literature review, revealed that mesoscale ocean eddies (200-800 km extent) move and evolve at a much slower rate than meso-alpha-size atmospheric lows and troughs at 850-700 hPa. To aid forecasting, we review sea surface temperature anomaly patterns associated with mesoscale ocean eddies of 200-500 km horizontal extent, and estimated surface to 0.8 km depth. Our CyclogenIVT™ produces the daily IVTinit map. We manually annotate the zones of expected cyclogenetic maxima. Since December 2022, we have compiled daily day0 Total IVT (TIVT24) from the Center for Western Weather and Water Extremes (CW3E) from the Dateline to North American West Coast (~120W). Seven day means of TIVT24 are compared via centered pattern correlation for each day out to 30 days beyond the IVTinit date.

The most interesting results so far: a) maximum correlations are between Day18 and Day28 beyond IVTinit date, b) maximum coastal rainfalls occur near downstream portion of positive IVTinit gradients in SW-NE flow, c) group of ocean mesocyclones, each ~150 km, appears to add energy to develop fronts and troughs. Our conference paper will include method, figures including the centered pattern correlation plots, results summary, and next steps.

[34] | Development of Machine Learning Methods for Freezing Level Forecasts over FIRO Watersheds

First Author: Vesta Afzali Gorooh

CW3E SIO / United States

Co-Authors: Vesta Afzali Gorooh, Agniv Sengupta, Mohammadvaghef Ghazvinian, Shawn Roj, Jason Cordeira, Duncan Axisa, Luca Delle Monache,

Center for Western Weather and Water Extremes, Scripps Institution of Oceanography University of California, San Diego

In the face of escalating climate variability and the urgent need for efficient water management, the Forecast-Informed Reservoir Operations (FIRO) initiative seeks to enhance reservoir management using advanced weather and water forecasts. A critical challenge is the outdated Water Control Manuals (WCMs), which need to address the forecast uncertainties affecting water storage and distribution. This study introduces a novel postprocessing approach to improve dynamical model forecasts, such as those from the Center for Western Weather and Water Extremes (CW3E)'s West Weather Research and Forecasting (West-WRF) model by employing machine learning (ML) methods for freezing level (FZL) forecasts over FIRO watersheds.

We propose an end-to-end and robust FZL-ML postprocessing framework for CW3E'S West-WRF predictions, using a decade's worth of reforecasts and the observed data at 6-hourly resolution from the California Nevada River Forecast Center (CNRFC), derived from the NOAA High-Resolution Rapid Refresh (HRRR) model. This approach crucially addresses the limitations of raw forecast dynamics and biases, enhancing predictive accuracy.

Our findings demonstrate a significant improvement in the skill of raw forecasts, extending up to 7 days. The FZL-ML model effectively captures the spatiotemporal variability of FZL, particularly during Atmospheric River (AR) events, which are pivotal for predicting precipitation and reducing flood risks in the FIRO watersheds. This advancement serves to aid in refining reservoir operation strategies and sets a precedent for integrating ML in hydrometeorological forecasting within the FIRO framework.

[35] | Differentiating between impactful and non-impactful Atmospheric River events in Southeast Alaska

First Author: Deanna Nash

Center for Western Weather and Water Extremes / USA

Co-Authors: Jon Rutz CW3E, Aaron Jacobs NWS Juneau, AK

In Southeast Alaska, extreme precipitation triggered by atmospheric rivers (ARs) can result in impacts such as floods and landslides. Recent work (Nash et al. 2024) has demonstrated a strong relationship between AR strength and extreme precipitation in Southeast Alaska. However, the National Weather Service (NWS) Juneau office has found that forecasted AR magnitude and duration does not sufficiently explain impacts to the public and emergency management personnel. Therefore, ongoing collaborative efforts with NWS Juneau are pursuing the development of AR-based forecasting tools that leverage the strong relationship between AR strength and extreme precipitation, but also consider other important factors such as freezing level, AR direction, and the occurrence of multiple ARs.

Using the NOAA's Global Ensemble Forecast System, version 12 (GEFSv12) reforecast data, we generate a Model Climate (M-Climate) for integrated water vapor transport (IVT), the freezing level, and low-level winds, which places these important forecast elements in the context of reforecasts with the same lead time and at similar times of year. For example, large M-Climate IVT anomalies indicate ensemble-mean IVT values that are large for a given lead time. This has an advantage over comparisons to reanalysis climatologies, which typically feature smaller forecast anomalies at longer lead times due to averaging of ensemble members. With a catalog of impactful floods and landslides provided by NWS, we apply M-Climate analysis to better differentiate between impactful and non-impactful ARs with otherwise similar characteristics. This methodology can be applied to future forecasts to improve NWS Juneau forecasters' situational awareness and Impact Decision Support Services (IDSS) messaging before and during high impact weather events. At the same time, linking impacts to ARs will allow NWS Juneau to effectively communicate impact information caused by ARs to deep core partners and the public so that they can prepare for impactful weather events.

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[36] | Seasonal Variation of River Discharge and Precipitation in the Nigeria River Basin Authority.

First Author: Akinnubi Rufus Temidayo

Adeyemi Federal University of Education, Ondo / Nigeria

The Nigeria River Basin Authority (NRBA) encompasses various river systems crucial for agricultural, domestic, and industrial activities in Nigeria. Understanding the seasonal variation of river discharge and precipitation within this basin is essential for water resource management, flood forecasting, and sustainable development. This study utilizes long-term hydrological and meteorological data collected from gauging stations across the NRBA. Statistical analysis, including trend analysis, seasonal decomposition, and correlation techniques, is employed to elucidate patterns and relationships between river discharge and precipitation. Analysis reveals distinct seasonal patterns in river discharge across the NRBA. The Niger and Benue rivers exhibit pronounced seasonal fluctuations, with peak discharge during the rainy season (June to September) and low flow during the dry season (November to April). Conversely, rivers in the northern regions, such as the Sokoto-Rima basin, demonstrate a single peak discharge coinciding with the rainy season. Precipitation patterns exhibit variability across the NRBA, influenced by factors such as the West African Monsoon, regional topography, and local weather systems. Southern regions experience bimodal rainfall regimes, with peaks in March-April and September-October, while northern regions typically have a single rainy season from June to September. Understanding the seasonal dynamics of river discharge and precipitation is crucial for various sectors, including agriculture, water supply, and hydropower generation. However, challenges such as data scarcity, hydrological alterations due to anthropogenic activities, and climate change impacts pose significant hurdles to effective water resource management in the NRBA.
Keywords: Nigeria River Basin Authority, River Discharge, Precipitation, Seasonal Variation, Water Resource Management.

[37] | Does El Niño affect MJO-AR connections over the North Pacific and associated North American precipitation?

First Author: Laís Fernandes

Portland State University / United States

Co-Authors: Paul Loikith Portland State University

This study investigates how the El Niño phase (EN) of the El Niño-Southern Oscillation (ENSO) influences the Madden-Julian Oscillation (MJO) modulation of cool-season North Pacific atmospheric rivers (ARs) and associated AR-landfall North American precipitation between 1980 and 2020. EN changes the key drivers of MJO-AR connections by shifting MJO-driven convection east of 180° in MJO phases 6-8 and extending the northern Pacific subtropical jet eastward. Under these conditions, the MJO tropical-extratropical teleconnection is triggered east of 180° in phases 7-8, and a persistent cyclonic flow anomaly develops along the United States west coast. Anomalous northeastward integrated water vapor transport (IVT) within the cyclonic flow coupled with the MJO convection over the western (phase 7) and central (phase 8) Pacific increases AR frequency, shifting it to the east over regions that do not show a relationship with EN or MJO alone. Besides enhancing AR activity, EN background conditions increase the number of AR events, their lifetime, and mean intensity from MJO phases 6 through 8, as well as the number of MJO active days, AR initiations, and ARs making landfall over North America in phases 8-1. The positive precipitation anomalies and increased frequency of extreme precipitation events associated with landfalling North Pacific ARs related to MJO are also shifted to the east in EN, enhancing and extending rainfall over western North America in phases 6-1. Results provide new insight into the drivers of AR activity and associated precipitation along the west coast of North America with implications for improving subseasonal-to-seasonal predictions.

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[38] | West-WRF 200-Member Ensemble and Deep Learning for the Prediction of Extreme Events Associated with Atmospheric Rivers

First Author: Luca Delle Monache

CW3E/SIO/UCSD / USA

Co-Authors: Luca Delle Monache (CW3E/SIO/UCSD), Dan Steinhoff (CW3E/SIO/UCSD), Rachel Weihs (CW3E/SIO/UCSD), Matthew Simpson (CW3E/SIO/UCSD), Mohammadvaghef Ghazvinian (CW3E/SIO/UCSD), Agniv Sengupta (CW3E/SIO/UCSD), Vesta Afzali Gorooh (CW3E/SIO/UCSD), Patrick Mulrooney (CW3E/SIO/UCSD), Caroline Papadopoulos (CW3E/SIO/UCSD), Weiming Hu (James Madison University), Brian Kawzenuk (CW3E/SIO/UCSD), Nora Mascioli (CW3E/SIO/UCSD), F. Martin Ralph (CW3E/SIO/UCSD)

The Center for Western Weather and Water Extremes (CW3E) mission is to provide 21st Century water cycle science, technology, and outreach to support effective policies and practices that address the impacts of extreme weather and water events on the environment, people, and the economy of Western North America. To fulfill its mission, CW3E scientists and engineers develop predictive capabilities based on physics-based models as well as machine learning algorithms to provide water managers across the Western US with accurate and reliable estimates of precipitation and other atmospheric and hydrologic variables over their watersheds at the lead times needed for effective reservoir operations, as part of the Forecast Informed Reservoir Operations Program. In this presentation, we will provide examples of the computing and dynamical modeling capabilities we are developing at CW3E, which include the Weather Research and Forecast (WRF) atmospheric model that has been optimized for weather prediction in the Western US, called West-WRF, and a regional 200-member ensemble at 9-km resolution based on West-WRF. We will then describe a deep learning algorithm that leverages only 10 months of training data from the large ensemble to further improve its skill, particularly for extreme events.

A throughout assessment of the skill of the probabilistic systems is assessed by evaluating specific attributes of probabilistic predictions including resolution, reliability, sharpness, and their ability to quantify the prediction uncertainty, which is one of the main reasons these systems are implemented. CW3E's predictive capabilities will be compared to state of the science prediction systems, as the US National Weather Service's Global Forecast System, and the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System. We will also analyze the performance of these systems for specific impactful events associated with Atmospheric Rivers.

[40] | Atmospheric River Forecast Errors and their Associated Precipitation Forecast Errors

First Author: Leif Swenson

CIRES - CU Boulder, NOAA - PSL / United States

Co-Authors: Benjamin Moore, NOAA - PSL

We analyze the winter of 2022-2023 in terms of forecast errors associated with atmospheric rivers (ARs) and precipitation in the Global and Integrated Forecast Systems (GFS and IFS) as well as the much higher resolution, purpose built, Atmospheric River Analysis and Forecast System (AR-AFS) over lead-times from one to ten days. This study utilizes the Method for Object-based Diagnostic Evaluation (MODE) from the Developmental Testbed Center on both integrated vapor transport (IVT) and precipitation. Using a simple distance metric, we relate precipitation objects to AR objects. This is done to ascertain the attributes of an AR system, which the correct forecast of, are most related to an accurate precipitation forecast. The attributes tested include the outer extent of an AR, the location of the core of an AR, the angle and curvature of an AR, the magnitude of the IVT within an AR, the propagation speed of an AR, as well as the presence/proximity of an extratropical cyclone center. Two sub-periods are further analyzed to investigate the relationship between forecast skill and the large-scale flow regime. To place this winter in context, we extend the analysis described above to the deterministic reforests from the NOAA GEFS reforecast dataset for 2000-2019. This is done over full winter seasons and subdivided by flow regime. This work quantitatively documents both biases in AR forecasting and their relationship to precipitation forecast skill. Additionally, we find a set of AR attributes associated with skillful precipitation forecasts.

[41] | Do AI models produce better atmospheric river forecasts than physics-based models? A quantitative evaluation

First Author: Isaac Davis

CU Boulder / United States

Co-Authors: Aneesh Subramanian CU Boulder, Tim Higgins CU Boulder, Luca delle Monache CW3E

The recent surge in using state-of-the-art machine learning (ML)-based techniques for weather prediction systems like Google's Graphcast, Nvidia's Fourcastnet, and Huawei's Panguweather have demonstrated remarkable accuracy and efficiency compared to traditional numerical weather prediction (NWP) methods. As these methods integrate into our forecasting toolbox, it's crucial to assess the capability of current machine learning models in simulating high-impact weather phenomena. They perform as well or better than the European Centre for Medium-range Weather Forecasts (ECMWF) system on most metrics. Yet, no comprehensive study has looked at their ability to predict atmospheric rivers (ARs). This study will examine the AR prediction skill of these new ML-based models on the U.S. West Coast at lead times up to 10-days. Skill and accuracy will be evaluated during a few key case studies as well as over long-term averages. These results will then be compared with the ECMWF's state-of-the-art High-Resolution Forecast (HRES) model.

[42] | Atmospheric rivers as disruptors of seasonal precipitation prediction in the Western US

First Author: Rosa Luna-Niño

CW3E / United States

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Water Year 2023 (WY2023) challenged the seasonal precipitation prediction of statistical and dynamical models, which predominantly forecasted the canonical La Niña anomalies: dry Southwestern and wet Northwestern United States. However, an outstanding Atmospheric River (AR) season caused unexpected near-record wetness in the Southwestern US (SWUS). In this study, we identified other La Niña WYs, such as 2011 and 2017, which were also unexpectedly wet in the SWUS due to strong AR activity. In California, precipitation during those anomalous WYs was comparable to or even surpassed those of the strong El Niño WY 1998, during which AR activity was close to climatology. Aiming to understand why the observed anomalies were opposite to what expected based on ENSO conditions, we reexamined the influence of Niño3.4 SST on the precipitation in the Western US splitting it into AR and non-AR precipitation. We found a stronger relationship between ENSO and non-AR precipitation which comes mainly from its frequency. Although ARs can disrupt the ENSO signal of precipitation and the link between ENSO and AR activity is weak, composites during El Niño and La Niña years show that there's still influence of ENSO in AR frequency and intensity in Desert Southwest.

[43] | Application of data-driven neural weather models for characterizing the evolution of atmospheric rivers in the Western U.S

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Atmospheric rivers (AR) are long, narrow corridors of water vapor in the atmosphere transporting moisture from the equator to the middle latitudes. ARs account for a large fraction of the total precipitation received every year along the West coast of the United States (US) and therefore are key sources of water availability in the region. However, extreme ARs often lead to disastrous flooding causing economic damages and human losses. Moreover, climate change simulations project future scenarios with potentially more frequent and more intense AR events. Therefore, there is an increasing interest in the development of forecasting tools that are able to characterize the evolution of atmospheric rivers a few days in advance, for decision management or the allocation of resources more effectively. Our current state-of-the-art predictive systems involve Numerical Weather Prediction (NWP) models. Despite their impressive success in reproducing the evolution of the atmosphere, they require enormous computational resources to produce high-resolution ensembles of forecasts. This limits the number of members and can potentially negatively affect our confidence in the forecast, which could have devastating consequences for extreme ARs.

In this work, we explore the use of novel Neural Weather Models (NWM) to characterize the evolution of ARs. NWMs have recently made landmark contributions to the field of meteorological forecasting as they offer cost-effective solutions to the computationally demanding NWP in efficiently generating 4D, multivariate, global ensemble forecasts. In particular, we examine EnAFNO, which is a probabilistic model that builds on top of FourCastNet to generate a 540-member ensemble in just 10 minutes on a cluster of 64 P100 GPUs. We select a few impactful ARs over the Western US and compare the results against operational probabilistic NWP.

[44] | Novel Approaches to Improving Operational Flood And Water Supply Forecasting Across the Sierra Nevada

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The California-Nevada River Forecast Center (CNRFC) provides daily hydrologic forecasts at nearly 200 locations across two states. These forecasts provide vital support to the National Weather Service (NWS) flood warning program and the water resources management programs. For example, the California Department of Water Resources (DWR) serves over 41 million people living within these flood-prone basins, including the $17 billion farming economy throughout the Central Valley. As anthropogenic climate change alters both the severity and frequency of atmospheric rivers (ARs), which provide up to half of the precipitation across California, operational agencies are having to recalibrate their planning and forecasting models to account for stronger storms. Traditionally, the CNRFC has calibrated their models over the past 40 years of historic discharge and weather data to provide daily streamflow and seasonal water supply forecasts. In recent years, the CNRFC has coupled their Sacramento-Soil Moisture Accounting (SAC-SMA) and SNOW-17 models with the Hydrologic Ensemble Forecast Service (HEFS) to help quantify uncertainties in their streamflow forecasts. HEFS combines near-term weather forecasts from the Global Ensemble Forecast System (GEFS) and historical weather possibilities (climatology) out to 365 days to supplement DWR's Bulletin 120 water supply forecasts. The probabilistic streamflow forecasts from HEFS operate seamlessly across lead-times of hours to seasons, and thus enhance both the flood warning and water supply aspects of the DWR and CNRFC missions. However, HEFS is still a relatively young technology and stands to benefit from improvements over time, specifically to its ability to accurately and reliably forecast the fast and heavy runoff that ARs often generate.

Here, we explore the West Weather Research and Forecasting (West-WRF) model, produced by the Center for Western Weather and Water Extremes (CW3E) at Scripps Institute of Oceanography (SIO), as a novel source of input variables (forcings) to CNRFC hydrologic models to calculate streamflows for a collection of recent, large storms. West-WRF has been calibrated and tested to better capture ARs and precipitation extremes throughout the West, and produces both deterministic and ensemble forecasts. Using the West-WRF forcings, we compare agreements between streamflow simulations and observations for several large ARs. We also compare our

West-WRF driven streamflow ensembles to those produced by CNRFC's HEFS, as well as to those generated from machine learning (ML)-enhanced procedures that we are exploring through NWS Cooperative Institute for Research to Operations in Hydrology (CIROH)-funded work. This project aims to improve HEFS by integrating ML in the pre- and post-processing steps of the forecasting system. We strive to continually work with operational partners like the CNRFC and DWR to develop and enhance techniques for improving hydrologic forecasts using state-of-the-art measurements, meteorological inputs, and models, and ultimately to help provide the best possible streamflow and water supply forecasts across the region.

[45] | What is the ideal ensemble size to reduce the uncertainty in the skill of West-WRF hydrometeorological forecasts over California?

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Ensemble prediction is used to assign uncertainty to numerical weather prediction forecasts, but numerical weather prediction ensembles often suffer from being underdispersive as well as having a lack of correlation between forecast spread and skill. Here, we explore how the number of members used impact performance, uncertainty and spread-skill relationships for forecasts of precipitation, snow water equivalent, and temperature from the 200-member West-WRF large ensemble produced by the Center for Western Weather and Water Extremes (CW3E) for the winter season (December-March) of 2021-2022 over ten hydrologic regions in California. A key aim of the West-WRF modeling efforts is to quantify the uncertainty of and improve precipitation forecasts associated with atmospheric rivers. The West-WRF ensemble samples the key sources of forecast uncertainty by utilizing a suite of perturbed initial and lateral boundary conditions, varying model physics parameterizations, and applying a stochastic perturbation to account for unresolved subgrid-scale processes.

Model skill is assessed by comparing to daily data from The University of Arizona (UA) snow product for snow water equivalent and Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset for precipitation and temperature. A methodology is proposed to identify the ideal ensemble size based on the reduction in uncertainty in skill scores. We also explore how ensemble size affects the spread-skill relationship. Ensemble size has little effect on the spread-skill relationship, but there is a separation between the spread-skill relationship in December 2021 between days initialized on days when atmospheric rivers were making landfall along the California coast as opposed to the other days. We will also explore how various methods of postprocessing affect forecast performance, uncertainty and the ideal ensemble size. With this, we will provide recommendations as to how many ensemble members are needed to produce a useful regional numerical weather prediction ensemble for hydrometeorological prediction with and without post-processing.

[46] | A Deep Learning-based Ensemble Post-processing Method for Atmospheric Rivers and Associated Precipitation Forecasts on Sub-seasonal Scale for the U.S. West Coast

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Atmospheric Rivers (ARs) play a pivotal role in triggering intense precipitation events, often resulting in flooding and other detrimental consequences, particularly in regions like the U.S. West Coast. These elongated channels of concentrated moisture, spanning hundreds of kilometers in width and thousands in length, transport vast quantities of water vapor, akin to the flow of the Mississippi River. These phenomena are most prominent during the winter season. Sub-seasonal forecasting, offering prediction windows of two weeks to a month, serves as a crucial link between short-term weather predictions and long-term climate outlooks. However, forecasting ARs and their associated precipitation on this scale presents challenges due to the loss of memory of initial atmospheric conditions, impacting forecast accuracy compared to shorter and longer-range predictions. Statistical post-processing techniques are often employed to enhance the reliability and skillfulness of forecast guidance. Reforecasting plays a vital role in validating and refining weather and climate models, aiding in identifying errors and predicting rare or extreme events. NOAA NCEP has introduced the GEFSv12 system with consistent reforecast data from 2000-2019, and multiple ensembles available daily, extending up to a 16-day lead time, and up to 35 days once a week. This research introduces an innovative post-processing method based on deep learning, applied specifically to the GEFSv12 reforecast datasets focusing on weekly initial conditions. The aim is to improve the prediction accuracy of ARs and associated precipitation on a sub-seasonal scale for the U.S. West Coast during the winter months (October through February). Leveraging advanced neural network techniques, this method seeks to enhance the resolution and precision of AR forecasts, thus mitigating the inherent uncertainties in predicting these impactful weather events weeks in advance. The effectiveness of this neural network approach is assessed against ERA5 Reanalysis data and compared to traditional statistical post-processing methods for detecting ARs and associated precipitation over the CONUS on a sub-seasonal scale. This evaluation utilizes standard skill metrics for both deterministic and ensemble probabilistic forecasts.

[47] | Assessing the Impact of Dropsonde Data on NCEP Operational GFS Forecasts during the 2023-2024 Atmospheric River Reconnaissance

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Atmospheric Rivers (ARs) are a critical global weather phenomenon responsible for horizontal water vapor transport beyond the tropics, notably serving as a primary source of precipitation and water supply along the U.S. West Coast. The AR Reconnaissance (AR Recon) observations have been incorporated into the U.S. National Winter Season Operations Plan (NWSOP) as an operational requirement starting from the 2020 winter season.

During the winter of 2023-2024, AR Recon campaign has conducted 40 intensive observing periods (IOPs) thus far. These IOPs have significantly enhanced conventional data by incorporating dropsonde observations and high density flight level data, allowing for comprehensive atmospheric profiles encompassing water vapor, temperature, and wind within and surrounding ARs.

During the same period, near real-time data impact experiments were carried out utilizing the NCEP operational global forecast system (GFS) version 16 (GFSv16) to evaluate the influence of dropsonde data on GFS forecasts, with a particular focus on landfalling ARs and associated precipitation. Preliminary findings from the 2023-2024 AR Recon indicate improvements in GFS initial conditions upon assimilating dropsonde data, resulting in enhanced precipitation forecast accuracy along the U.S. West Coast. Additionally, improvements were noted over the Pacific North American region (180E-320E, 20N-75N) due to enhancements in GFS analysis. Specifically, for 500hPa Geopotential height, there was approximately a 1% improvement in 5-day anomaly correlation over the North Pacific (140E-240E, 10N-50N), with a root-mean-square error reduction of approximately 4%.

We aim to present detailed insights into the impact of dropsonde data on GFS forecasts derived from the AR Recon missions of 2023-2024.

[48] | Application of Ensemble Sensitivity to ECMWF Forecasts During AR Recon

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Co-Authors: Jason Cordiera CW3E, Minghua Zheng CW3E, F. Martin Ralph CW3E

Atmospheric Rivers (AR) are often associated with significant precipitation along the West Coast of the United States. These features form over the open Pacific Ocean and previous research has shown that are often characterized by a lack of observations, including from satellites. Consequently, these features may have significant initial condition uncertainty, which in turn can translate into higher variability and error in numerical model forecasts. Despite this, there have been relatively few studies that have quantitatively documented how uncertainty in specific aspects of the AR (e.g., wind, moisture content) and surrounding synoptic features (e.g., position of upper troughs) could impact the subsequent precipitation forecast over land. One method of quantifying this is through ensemble-based sensitivity analysis, which utilizes the statistics of a forecast ensemble to establish these associative relationships. Regions of large sensitivity denote locations where to direct additional observations that could improve the forecast.

This study describes the application of this method to real-time ECMWF ensemble forecasts, which was used for flight planning during AR Recon. In addition to precipitation-based metrics, the method contains the ability to calculate forecast sensitivity to other AR-based metrics, such as the shape and intensity of the AR and landfall IVT. For most initialization times, there is substantial consistency between these different metrics, which allows for customization depending on the case. Preliminary results indicate that the largest sensitivity is often associated with the position of shortwave troughs embedded within an Eastern Pacific upper level trough and lower tropospheric boundaries. This will be demonstrated through illustrative case studies.

[49] | Dynamics and subseasonal predictability of high-impact precipitation episodes over California during winter 2022–2023

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This study investigates the dynamics and subseasonal predictability of two prolonged (>2 weeks) high-impact precipitation episodes over California that spanned late December 2022 – mid January 2023 and late February – mid March 2023, respectively. These episodes occurred in connection with persistent large-scale flow patterns featuring repeated landfall of extratropical cyclones and atmospheric rivers (ARs) along the U.S. West Coast. The former episode featured a persistent elongated zonal jet stream over the North Pacific, whereas the latter exhibited more meridional flow and blocking. These large-scale patterns each appeared to form in response to tropical convection associated with Madden-Julian Oscillation (MJO) events propagating from the Indian Ocean into the western tropical Pacific. Analysis of operational model forecasts reveals that, for both episodes, the extratropical flow pattern and the California precipitation were poorly predicted at subseasonal lead times (e.g., weeks 3–4). These findings motivate the hypothesis that subseasonal forecast errors for the two precipitation episodes were related to a misrepresentation of conditions in the tropics associated with the MJO.

The hypothesis is tested with a set of 35-day 30-member ensemble reforecast experiments conducted with the NOAA Unified Forecast System model. Specifically, nudged forecasts, in which the state variables in the tropics are nudged to the ECMWF ERA5 reanalysis, are compared against corresponding control forecasts, which do not include nudging. The forecasts are initialized at 0000 UTC on 15 December 2022 and 2 February 2023. Results reveal that for both cases a “perfect” representation of the tropics in the nudged forecasts yields marked improvements in the weeks 3–4 forecast of the extratropical flow, the AR activity, and the concomitant precipitation over California. A detailed analysis of the forecasts is conducted to diagnose the chain of synoptic-dynamic processes linking improved representation of tropical processes, especially those related to the MJO, to reductions in extratropical forecasts errors.

[50] | Review of Progress in Advancing Aircraft Reconnaissance Observations for Improving Precipitation Forecasts Associated with Atmospheric Rivers

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NOAA/NWS/NCEP/EMC / USA

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Atmospheric River Reconnaissance (AR Recon) Field Program is designed to improve the water management and flood control in the western United States which are heavily influenced by AR storms that produce both beneficial water supply and hazards. AR Recon, started as a demo in 2016, has evolved into an operational requirement as documented in the Interagency Council for Advancing Meteorological Services (ICAMS) National Winter Season Operations Plan (NWSOP). The field campaign has expanded in scope both geographically, extending to Western Pacific/Guam in 2024, and temporally, adding November and March, resource permitting. AR Recon continued taking advantage of the Research and Operations partnership that was established between Center for Western Weather and Water Extremes (CW3E) and NOAA's National Center for Environmental Prediction (NCEP) in collaboration with NOAA Aircraft Operations Center (AOC) and US Air Force (USAF). AR Recon Program is benefiting from the involvement of a dedicated team of scientists from various US Federal agencies, international operational centers, academic community, and private sector for supporting operational missions, and the Modeling and Data Assimilation Steering Committee is helping to advance the science and outreach of the results obtained from this field program.

With data collected from more than eight years of successful AR Recon field campaigns (2016, 2018-2024) using objective sampling strategies, the forecast improvements in the 0-5 day period from NCEP operational Global Forecast System (GFS) are quite significant for the US West Coast, especially in the regions impacted by landfalling ARs. Expanding the field campaign to cover all winter storms over the Western Atlantic and Gulf of Mexico, and to the Western Pacific (Guam) will enable extending the forecast improvements to week 1 and beyond . This talk will highlight review of the AR Recon during the past few years, and lay out strategies for the future enhancements in the areas of sampling strategies, modeling, data assimilation and contributions to advancing the science of ARs.

[51] | Impact of Atmospheric River Reconnaissance Dropsonde Data on the Assimilation of Satellite Radiance Data in GFS

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Satellites provide the largest dataset for monitoring the earth system and constraining analyses in numerical weather prediction models. A significant challenge for utilizing satellite radiances is the accurate estimation of their biases. High-accuracy non-radiance data are commonly employed to anchor radiance bias corrections. However, aside from the impacts of radio occultation data in the stratosphere, the influence of other types of "anchor" observation data on radiance assimilation remain unclear. This study provides an assessment of impacts of dropsonde data collected during the Atmospheric River (AR) Reconnaissance program, which samples ARs over the Northeast Pacific, on the radiance assimilation using the Global Forecast System (GFS) and Global Data Assimilation System at National Centers for Environmental Prediction.

The assimilation of this dropsonde dataset has proven crucial for providing enhanced anchoring for bias corrections and improving the model background, leading to an increase of ~5–10% in the number of assimilated microwave radiance in the lower/middle troposphere over the Northeast Pacific and North America. The impact on tropospheric infrared radiance is small but also beneficial. Impacts of dropsondes on the use of stratospheric channels are minimal due to the absence of dropsonde observations at certain altitudes, such as aircraft flight levels (e.g., 150 hPa). Results in this study underscore the usefulness of dropsondes, along with other conventional data, in optimizing the assimilation of satellite radiance. This study reinforces the importance of a diverse observing network for accurate weather forecasting and highlights the specific benefits derived from integrating dropsonde data into radiance assimilation processes.

[141] | Sources of Seasonal Atmospheric River Predictability over North America Diagnosed from the GFDL SPEAR Model

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A recent study demonstrated that the Seamless System for Prediction and EArth System Research (SPEAR), the latest seasonal prediction model developed at the Geophysical Fluid Dynamics Laboratory and a contributor to the North American Multi-Model Ensemble (NMME), produces skillful seasonal (three-month) forecasts of atmospheric activity (AR) out to at least 9 months in some regions of the western U.S. Through an analysis of SPEAR retrospective and real-time seasonal AR activity forecasts, we explore the large-scale climate patterns that serve as the sources of seasonal AR predictability. We use both predictable component and skill component analyses to compare the most predictable with the most skillfully predicted patterns of seasonal AR activity. Finally, we explore how seasonal AR forecasts filtered by the most skillfully predicted modes may be able to inform the development of new seasonal AR forecast products over North America.

Session:

AR5- Observing, identification, and monitoring of ARs

[12] | Detection Uncertainty Matters in Quantifying Meteorological Extremes of Euro-Atlantic Atmospheric Rivers

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There are many factors impacting the uncertainty in mapping Atmospheric Rivers (ARs), including the data, methods, parameter type and parameter choices used. Thus, qualitative assessment of the magnitude and intensity of meteorological extremes caused by ARs and our scientific understanding depends on quantifying the uncertainty in the AR mapping. For example, results from the Atmospheric River Tracking Method Intercomparison Project (ARTMIP) indicate a broad range of plausible AR detectors and that scientific results can depend on the algorithm used. It is, therefore, imperative to use detection techniques that explicitly quantify the uncertainty associated with the detection of events. We use a Bayesian framework, which yields a set of "plausible" AR detectors from which we can assess quantitative uncertainty. This probabilistic AR detector has been implemented in the Toolkit for Extreme Climate Analysis (TECA). We tested the regional implementation of the TECA Bayesian AR Detector, TECA-BARD v1.0.1, on the ERA5 reanalysis on the Euro-Atlantic region and investigated the impact of the detection uncertainty on the qualitative understanding of AR-caused meteorological extremes over Europe during 1940-2022.

[53] | The Advanced Quantitative Precipitation Information (AQPI) Project: Building a State-of-the-Art Observation and Forecast System for the Greater San Francisco Bay Area

First Author: Jon Rutz

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Co-Authors: Ricardo Vilela (CW3E), Dale Roberts (Sonoma Water), V. Chandrasekar (Colorado State University / Cooperative Institute for Research in the Atmosphere [CIRA]), Rob Cifelli (NOAA), Marty Ralph (CW3E), Julie Kalansky (CW3E), Jay Jasperse (Consultant)

The Advanced Quantitative Precipitation Information Project (AQPI) is centered on the provision of supplemental radar observations across the Greater San Francisco Bay Area, particularly the installation of 5 (and possibly 6) X-band radars and 1 C-band radar across the region by 2024. These AQPI radars improve regional forecasts by filling gaps in existing radar coverage due to the complex terrain of the Bay Area, and by providing higher temporal and spatial resolution data across the region. Examples highlighting the enhanced resolution will be shown. These high-resolution observations are used directly by local stakeholders to optimize any number of operations such as wastewater management, flood response, emergency management, and more. The AQPI radar data can also be used indirectly through assimilation into weather forecast models and as a forcing variable for hydrology models – both of which are being explored by the project.

Of course, the primary benefits from these additional radars are accrued within the first ~6 hours of the forecast, whereas stakeholders have forecast needs within the Days 1-7 timeframe (e.g., placement of assets, staffing levels, etc). CW3E is addressing these concerns through the inclusion of other forecast products within the AQPI portfolio. The AQPI project is also developing an online dashboard that integrates new AQPI data streams and other existing forecast products into a state-of-the-art decision support platform for stakeholders.

[View Image]

[54] | Using Google Earth as a Flight Planning Coordination Tool for Developing Atmospheric River Reconnaissance Intensive Observation Period Mission Flight Tracks

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Preparation of Air Force C-130 and NOAA G-IV flight tracks for an Atmospheric River Reconnaissance (AR Recon) Intensive Observation Period mission occurs prior to and during Center for Western Weather and Water Extremes (CW3E) weather briefings that are held when potentially impactful AR storms are within flight range. Flight tracks, designed using free Google Earth software, identify routes the aircraft will take and define exact locations for releasing dropsondes that sample atmospheric characteristics and phenomena in and near ARs. Dropsonde data are then ingested into global weather models to help improve model initial conditions and help progress AR science.

Preliminary flight tracks are designed by the flight track coordinator (lead) ahead of the briefing, with guidance from an aircraft lead, to target specific key areas of the AR and regions most sensitive to changes in forecast conditions, which often overlap. During the briefing, AR Recon scientists provide input for real-time design and revision of flight tracks. The procedure has evolved throughout the last few AR Recon seasons into a streamlined and mostly automated process for displaying flight tracks and dropsonde release locations over various CW3E forecast graphics and sensitivity plots. Aircraft flight range, military warning zones, and other areas that must be avoided are also shown in Google Earth.

After the briefing, a finalized flight track image and spreadsheet that contains waypoints and dropsonde release locations are emailed for approval from the mission director and appropriate Air Force and/or NOAA personnel. Without additional revisions the mission can be flown and critical data for improved forecasting of landfalling ARs along the US West Coast are collected. Although the work is fast paced with strict time constraints, the process-based nature of the tool has made it possible for CW3E to train UCSD undergraduate students to serve as the lead.

[55] | Application of the Atmospheric River Scale in conjunction with a Global AR Tracking Algorithm over the Western United States

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Co-Authors: Emily A. Slinskey CW3E, Jonathan Rutz CW3E, Bin Guan JIFRESSE UCLA JPL

The Atmospheric River (AR) scale (Ralph et al. 2019), broadly characterizes the strength of ARs using categorical rankings from 1-5 based on the peak integrated water vapor transport (IVT) and duration of AR conditions (i.e., IVT ≥ 250 kg m-1 s-1) at a given location. Since the AR scale does not account for objects geometry, it detects some events associated with strong and persistent IVT that are not considered ARs (e.g., tropical storms and monsoon surges). This study uses "tARget v3" (Guan et al. 2019), a well-known AR detection tool (ARDT) that utilizes various climatological, geometric, and directional thresholds to identify ARs, applied to the European Centre for Medium-range Weather Forecasts (ECMWF) Re-Analysis v5 (ERA-5) to "filter" the AR scale over the Western U.S. (west of 105°W) – this allows events detected using the scale, from category 1 to category 5, to be differentiated between ARs and other event types. Not surprisingly, the AR scale "filtered" by the ARDT detects less ARs overall compared to the sole AR scale itself. During individual events, the spatial extent of "unfiltered" and "filtered" objects can differ dramatically (typically, the spatial footprint of "filtered" objects is smaller), with greater differences apparent across the weaker, lower category ARs compared to the higher category ARs. The climatological AR frequencies from 1949-2022 for each of the 5 AR categories for both techniques reveal higher category ARs occur less frequently than lower category ARs, with the greatest disagreement confined to the North Pacific. Over the Western U.S., disagreement between these two versions is much less, partly due to the lower overall AR frequency over land.

The two versions of the AR scale ("unfiltered", and "filtered" using the ARDT) will soon become an official climate data record at NCEI and will be made available in both spatial map and time series formats. This will serve as a valuable resource for the academic community as well as for users who rely upon historical norms to plan their operations. Future work may include investigation of long-term trends, geographic expansion beyond the Western U.S., and assessing the relationship between the scale and precipitation.

[56] | Inland-penetrating Atmospheric Rivers and Hydrometeorological Impacts in Colorado

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Atmospheric rivers (ARs) play a leading role in high-impact weather and long-term hydroclimate across the Western U.S., being both the primary drivers of flood damage and major contributors to water supply across much of this region. In response, the community has developed an extensive knowledge of AR frequency, intensity, impacts, key meteorological processes, and predictive skill, but this knowledge is primarily focused on ARs at or near landfall on the U.S. West Coast. Relatively little work has been done to understand AR characteristics further inland and this is especially true for Colorado, where high and complex topography, as well as distance from the coast, hinder attempts to track ARs, AR-derived moisture, and AR-related impacts. While a large volume of anecdotal evidence suggests that ARs play a fundamental role in extreme precipitation and longer-term hydroclimate across Colorado, this relationship is yet to be systematically analyzed and quantified. This work uses novel methods to explore the role of ARs, their landfalling intensity (using the AR Scale [Ralph et al. [2019]), and their interannual variability on hydrometeorological extremes and impacts across the state, focusing on the relative contribution of inland-penetrating ARs to heavy precipitation events and seasonal snowfall (accumulated snow water equivalent) in the Upper Colorado River Basin (UCRB).

We show that while the overhead AR frequency across the UCRB is very low, moisture sourced from landfalling ARs affects this area much more frequently, penetrating inland along relatively low-elevation corridors through the Interior West. Consequently, AR contributions to precipitation across Colorado are higher than previous studies suggest, and exhibit substantial geographic and interannual variability. In addition, we highlight new forecast tools that enable better prediction of these events, developed in collaboration with National Weather Service offices across the state.

[59] | The June 2023 Madeira event: synoptic analysis and extreme rainfall assessment

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This study aims to characterize the rainfall exceptionally and the meteorological context for June 5 and 6 2023 in Madeira Island (Portugal). A new daily precipitation record of 494.3 mm was recorded in a mountain station on 6 June. However, the highest precipitation value for consecutive 24-hour period was observed starting at June 5 at 14:00 UTC with 615 mm. Precipitation register at the 20 available stations in the island was used to evaluate the temporal evolution of the rainstorm.

These outstanding new record values clearly surpass all previous 24-hour records, including 20 February 2010 (333.8 mm). It is worth noting that this new record was obtain during the summer season, usually a dry period in sub-tropical island of Madeira, would not be expected to witness such an event. The synoptic-associated situation responsible for this extreme precipitation event (EPE) was analysed using different sources of information: weather charts, reanalysis data, Meteosat images and radiosounding data, with a focus on two main issues:

(1) the dynamic conditions that promoted such anomalous humidity availability over the Madeira region during the EPE and (2) the uplift mechanism that induced deep convection activity. Based on this study, it is concluded that the combination of factors, such as upper-air divergence, the relative position of the jet stream, and the presence of heat, along with a narrow band of intense water vapor transport, corresponds to the likely formation of an Atmospheric River. These conditions provided sufficient factors contributing to the occurrence of an extra-tropical cyclone named OSCAR, which affected the Madeira archipelago. Furthermore, the complex orography of the island exacerbated the abnormal duration and intensity of the storm.
The advance in the knowledge of the synoptic conditions that cause this kind of extreme event is useful to prevent and minimize their damage.

[60] | West Pacific Atmospheric Rivers: their Climatology and Impacts

First Author: Laurel DeHaan

CW3E / United States

Co-Authors: Joshua Mumford SIO, Kristen Guirguis CW3E, Sasha Gershunov SIO, and Dan Cayan SIO

There has been much research on Atmospheric Rivers (ARs) over the Eastern North Pacific Ocean where they contribute to water supplies and impact populations and infrastructure in Western North America. However, comparatively little has been done for the Western Pacific (WestPac) where ARs can cause disruptions to maritime activities and present hazards to sea vessels and crew in the open ocean as well as populations along the coast of Eastern Asia.

Here we report on WesPac AR results from four decades of ERA5 reanalysis data, looking at the temporal and spatial variability. WestPac ARs vary considerably across months and years, and their tracks and intensity display important spatial structure. In the WestPac, ARs occur frequently, and they exhibit strong surface wind and precipitation outcomes in continental, island and maritime settings. In contrast to the winter-dominated AR climatology in the Eastern North Pacific and Western North America, AR occurrence in much of the WestPac is similar in summer and winter, with some regions having higher occurrence in summer. In addition, AR precipitation is higher in summer.

We also investigate the relative contributions of tropospheric wind and moisture to ARs, a question that is provoked by contrasting ocean temperatures and thus differing potential for water vapor input across the WestPac. Additionally, an analysis of the occurrence of high surface winds during WestPac AR days and precipitation contributed by WestPac ARs will be presented, furthering our understanding of the impacts of ARs in that region.

[61] | Advancements in Atmospheric River Science from the WindMapper Mission Concept

First Author: Alejandro Soto

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Co-Authors: Scot Rafkin SwRI, Michael Kelly NASA Goddard, Juan Lora Yale U., Kevin Maschhoff BAE Systems, Chris Ruf U. Michigan, David Santek U. Wisconsin, Sara Tucker BAE Systems

WindMapper is an Earth System Explorer class mission concept that will generate breakthrough observations of atmospheric river (AR) systems through the retrieval of accurate, height-resolved, global winds. The three-year on-orbit mission would use three, identical, small spacecraft (s/c) each with the same three instruments: a hyperspectral imaging sounder (MISTiC), a mid-infrared stereo imaging camera (CMIS), and a global navigation satellite system (GNSS) occultation and reflectometry instrument (OREO). The mission focuses on filling the tropospheric wind observation gap while also capturing ocean surface wind speed. Both observations are labeled as "most important" by numerous Decadal Survey Science Objectives. With these wind retrievals, coincident with water vapor and temperature profiles, cloud top height and cloud top vertical velocity, WindMapper will advance AR formation and evolution science and greatly improve the quantity and quality of observations assimilated into Earth system models.

The WindMapper goal is to reveal the precursor mechanisms responsible for extreme moisture transport by ARs and to improve their representation in models of Earth's changing climate system. WindMapper focuses on two objectives: 1) Discover, identify, and quantify the relative importance of the mechanisms responsible for the genesis and evolution of atmospheric rivers; and 2) Fill the mid-tropospheric gap in vertically resolved wind observations, quantify the corresponding improvement in atmospheric analyses, and quantify the sensitivity of Earth System models to such observations.

We will present the WindMapper mission concept, including an overview of the spacecrafts and instruments. We will also present examples of the AR data that will be collected by WindMapper. We will trace this wind data to the specific WindMapper investigations that we have developed to answer some of the most fundamental and outstanding questions about atmospheric rivers.

[62] | Influence of the Sierra Barrier Jet and Atmospheric rivers on the distribution of precipitation in Northern California

First Author: Yazmina Rojas Beltran

CW3E / United States

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Atmospheric rivers (ARs) are usually associated to extreme precipitation events and flooding, as they play a key role in the transport of moisture from the ocean to the continent, responsible for 20-50% of the annual precipitation in California. Mesoscale processes from the interaction of frontal systems with topography can influence orographic precipitation in the region. One important mechanism is the Sierra Barrier Jet (SBJ), which is defined as a low-level jet blowing parallel to the Sierra Nevada and forms in response to the deceleration of stably stratified south-southwesterly flow as it approaches the west slope of the Sierra Nevada. Previous studies suggest that a majority of extreme precipitation events during the cold season occur in association with ARs in conjunction with SBJs, increasing orographic precipitation in the area and modifying the precipitation distributions across the Sierra Nevada and at the north end of the Central Valley. This study will highlight the results of a ~20-year climatology of the SBJ using wind profiler observations, their associations with landfalling ARs, and their influence on modulating climatological variability, spatial variability, and orographic gradients in precipitation across northern California.

[63] | On the relationship between atmospheric rivers and precipitation over the Southern Ocean as observed at Macquarie Island

First Author: Abhishek Kumar

Monash University / Australia

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Extensive studies on Atmospheric Rivers (ARs) and their impacts have been conducted over the Northern Hemisphere, whereas similar studies over the Southern Hemisphere, particularly over the remote Southern Ocean (SO) and Antarctica, are relatively scarce, due primarily to limited observations. Macquarie Island (MAC; 54.5° S, 158.9° E) is a small island located along the Southern Ocean storm track with meteorological records dating back to 1948. These observations have been used extensively over the past decade to better understand precipitation processes across the SO. In this work we employ these observations to study the relationship between ARs and precipitation over the remote Southern Ocean. We examine periods when ARs are associated with heavy precipitation events and periods when ARs produce no surface precipitation, extending the analysis to the synoptic meteorology of the storm track.

We have used the ERA5 reanalysis for calculating the IWV (integrated water vapour) and vIVT (meridional integrated water vapour transport) and defining the synoptic scale meteorology. The Wille et al. (2019) algorithm is used to identify Atmospheric Rivers. In total 96 ARs (719 hours) have been identified over a 10-year period (2013-2022). Surface precipitation is provided by the Australian Antarctic Division (AAD). We have used the Pearson correlation methodology to see the association between IWV, vIVT with rainfall.

Both the IWV and vIVT decrease in magnitude when moving from lower latitudes to higher latitudes across the SO. Neither IWV nor vIVT alone are particularly good indicators of precipitation over MAC, yielding a weak correlation of 0.29 and 0.30, respectively. When ARs pass over at MAC island, rainfall is recorded ~55.5% of the time, extreme rainfall recorded ~28% of time, Conversely, no precipitation is recorded ~44.5% of time when ARs is passing over. We extend the analysis through case studies of extreme precipitation and no precipitation.

[64] | The PIKART Catalog: A Global and Comprehensive Compilation of Atmospheric Rivers

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Co-Authors: Tobias Braun: PIK and Leipzig University, Norbert Marwan: PIK and University of Potsdam, and Jürgen Kurths: PIK and University of Potsdam

Detection and tracking of atmospheric rivers (ARs) are fundamental tasks to study and understand their lifecycles, dynamics, and impacts. However, addressing these tasks globally comes along with substantial challenges caused by regionally and temporally varying climate conditions. Therefore, most available AR catalogs have regional extent. Yet, only AR catalogs with global extension record large-scale heterogeneities in AR transport. Building on previously published approaches, we designed a thorough detection-, tracking- and post-processing scheme from which we compile the novel PIKART catalog of ARs. Contrary to traditional methods that detect AR conditions by thresholding the atmospheric moisture transport, PIKART is based on the anomalous vapor transport characteristics of ARs. Furthermore, we extended previous tracking strategies to allow for physically-sound temporal gaps in AR trajectories, resulting in improved representation of long-lived ARs. PIKART is a global compilation of AR trajectories and AR conditions that covers 83 years (1940-2022) with 6-hourly resolution and a high spatial resolution of 0.5°. It extends the scope of previous catalogs by providing secondary AR properties, e.g., a novel index of inland penetration, land-intersection locations, and AR levels. Comparing PIKART with other global AR catalogs, we found overall consistency. However, we also discovered considerable differences in lifecycles and land-falling locations, especially accentuated for long-lived AR trajectories as well as tropical and polar AR conditions. Exploring the applicability of PIKART to study AR lifecycles, land-falling locations, impacts, and long-term trends, we revealed i) additional AR hotspots (particularly in the tropics), ii) inland penetration into less-studied regions (e.g., north-western Africa), iii) exposure to considerable AR impacts in less-studied continents (South/East Asia and Oceania), and iv) a poleward shift of southern hemispheric ARs. We are happy to introduce and share the PIKART catalog with the AR community and hope that it will provide a valuable and alternative resource for future studies in AR science.

[65] | Detection and Characteristics analysis of the Atmospheric Rivers that causes Heavy Rainfall in the Japan region

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Co-Authors: Yusuke Hiraga Tohoku University, So Kazama Tohoku University

In Japan, localized heavy rainfall caused by Quasi-stationary Band-Shaped Precipitation Systems, called "Senjo-Kousuitai" has been increasing. In numerous past research, they are shown to have connection to Atmospheric Rivers. But these past studies have yet to generalize the conditions of the ARs that causes heavy rainfall and only analizing from rainfall's perspective. In this study, the goal is to analyze the characteristics of the ARs that causes heavy rainfall in Japan from ARs' perspective. We used ERA-5 reanalysis data to calculate the IVT and compared it with rainfall data from RadarAMeDAS. First, we detected the ARs from 1940 to 2023 using the algorithm made by Kennett (2021) with a small modification added. Then we used those data to calculate the rainfall, IVT, and IVT direction of the area where ARs intersected the land of Japan. We also calculated the duration of each event by categorizing the ARs when there is more than 24 hours of intervals between the time of its detection. We found out that when the water vapor is coming from southwest or south, rainfall caused by those ARs tend to be more intense. Also, ARs with longer duration tend to have more impact on the rainfall as well.

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[66] | Impact of ARRecon Surface Pressure Observations over the Northeast Pacific Ocean on the Data Assimilated Analysis and Forecast of Atmospheric Rivers

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Atmosphere River Reconnaissance (AR Recon) is an interagency, international collaborative project to collect unique dropsonde and other in-situ observations in and around ARs off the U.S. West Coast to improve AR landfall forecasts and associated weather during the winter. Global modeling centers (U.S. National Centers for Environmental Prediction, U.S. Navy, European Centre for Medium-Range Weather Forecasts) that assimilate these data in near real-time have developed a research and operations partnership to assess impacts and improve outcomes. Beginning in 2019, the group partnered with the Global Drifter Program to explore the potential of drifting ocean buoys with surface pressure sensors, in concert with dropsondes and data assimilation efforts, to support the project's forecast improvement objectives. The hypothesis was that adding surface pressure observations to the data-sparse Northeast Pacific Ocean can improve the representation of large-scale circulations in global weather prediction models, which is essential for accurate AR landfall forecasts. This presentation will focus on the impact of these additional sea level pressure measurements in the ECMWF IFS data assimilated analysis and forecasts using data denial runs during the years 2019 and 2020. Verification metrics for mean sea level pressure, surface variables as well as integrated water vapor, a key quantity for ARs will be presented.

[67] | Detection of Atmospheric Rivers Associated With Extreme Precipitation over the Indian Subcontinent

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Co-Authors: Ranjan Kumar IIT Kharagpur, Amey Pathak IIT Kharagpur, Pramod chouhan IIT Kharagpur

An atmospheric river is a narrow band of concentrated moisture in the atmosphere, transporting considerable amounts of water vapor over long distances, influencing regional weather patterns and precipitation extremes. This study examines the occurrence of Atmospheric Rivers (ARs) associated with extreme precipitation in three different regions of India, namely South Peninsular India (SPI), Core Monsoon Zone (CMZ), and East India Box (EIB), using ERA5 reanalysis data from 1991 to 2021.The modified trajectory algorithm is used to identify ARs based on length, width, Integrated Vapor Transport (IVT), and the included angle. Our analysis reveals that a total of 148, 168, and 102 ARs were detected in SPI, CMZ, and EIB region, respectively. The study proposes a novel approach for classifying ARs and non-atmospheric rivers using Convolutional Neural Networks (CNN).The proposed CNN model was trained on a large dataset of atmospheric data and achieved an accuracy of 95% on the training set and 93% on the testing set, demonstrating its effectiveness in identifying ARs.The proposed model can be a useful tool for identifying ARs, aiding in weather forecasting and disaster preparedness. Moreover, this proposed model has the potential to be used in real-time applications for monitoring and predicting extreme weather events. The moisture transport associated with the ARs events over different sub-regions was analyzed, and the results showed that generally, in SPI and CMZ region, the moisture comes from the Central Indian Ocean and the Arabian Sea, while in EIB, it comes from the Indian Ocean and the Bay of Bengal. These findings offer valuable insights into the atmospheric moisture transport mechanisms and associated extreme weather occurrences in the studied regions of India. These insights are crucial for enhancing our understanding of regional climate dynamics and can inform future research and policy interventions aimed at mitigating the impacts of extreme weather events in the region.

Keywords: Extreme precipitation; Moisture transport; Indian Summer Monsoon; Central India; Atmospheric River.

View Image

[68] | Collaborative Opportunities to Leverage Tomorrow.io's Satellite Precipitation Radars for Atmospheric River Science

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Tomorrow.io / United States

Co-Authors: Forest Cannon, John L'Heureux, Ethan Nelson, Joe Munchak, Stelios Flampouris, and Arun Chawla (Tomorrow.io)

Atmospheric river (AR) evolution is in part driven by precipitation processes and their subsequent feedbacks on circulation via latent heating. These processes typically occur within deep cloud structures over the global oceans, and are difficult to observe with the current generation of geostationary and orbiting weather satellites. The observation gap translates to a significant challenge in understanding and modeling AR evolution, which contributes to forecast errors in AR landfall characteristics. Leveraging new technologies is crucial for improving AR predictability and bolstering confidence in forecast applications, ranging from water resources to emergency management.

The Tomorrow-R1 Radar Pathfinder satellite, launched on April 14, 2023, and its counterpart, Tomorrow-R2, launched on June 12, mark the initial deployment of the Tomorrow.io precipitation constellation, which is set to transform global precipitation measurement. The constellation is scheduled to consist of 30 satellites, including 10-12 Smallsat Ka-band radars and up to 18 Cubesat microwave sounders, by the end of 2025.

While Tomorrow.io is developing this observation capability for operational real-time precipitation estimation, nowcasting, and data assimilation applications, this presentation explores the potential benefits of the constellation's Ka-Band radars for scientific studies of ARs. Pathfinder radar profiles transecting ARs during the 2023/2024 winter season are evaluated against global NWP and existing observation capabilities. Relative to NASA’s research-grade GPM Ka-Band radar, the planned constellation’s enhanced resolution and 10-12x revisit rate improvement will augment our ability to monitor AR precipitation processes, identify feedbacks on evolution, and assess sources of uncertainty in the representation of AR thermodynamics in NWP. This presentation aims to foster collaboration between the academic community and Tomorrow.io, encouraging joint efforts to exploit the constellation for fundamental research.

[69] | How does dynamical forcing during impactful atmospheric rivers affect snowfall rates and spatial patterns in Western US mountains?

First Author: Ty Brandt

SIO-CW3E / US

Co-Authors: Kayden Haleakala, Christopher Castellano, Ava Cooper, Gabriel Lewis, Deanna Nash, and Taylor Dixon

Atmospheric rivers (ARs) play a key role in the water cycle and hydroclimate variability in the western US. When ARs impinge on mountain ranges they can produce substantial amounts of rainfall and/or snowfall depending on the atmospheric freezing level. Studies of ARs and their impacts on mountain hydrology typically treat this meteorological phenomenon as a daily binary metric—was an AR present, or not? However, AR precipitation is rather the end product of a complex set of atmospheric drivers that vary in both space and time, including but not necessarily limited to: integrated water vapor transport (IVT) magnitude and direction, synoptic and mesoscale dynamical forcing (i.e., vertical lift), atmospheric thermodynamics, and orographic effects. Additionally, the intensity and spatial distribution of AR precipitation can vastly differ between mountain ranges directly exposed to maritime air masses (e.g., the Sierra Nevada) and those in continental climates (e.g., the Colorado Rockies). Here, we examine two impactful ARs from water year 2023 that made landfall in California and penetrated the interior western US. The two events differ in their AR characteristics and associated dynamical forcing, but both led to significant precipitation across both California and Colorado. We place these ARs into context relative to a climatology of other events for large snowfall years (1952, 1969, 1983, 2017, 2019 and 2023). We then use hourly in situ snow measurements to compare and contrast these events' snowfall rates and spatial patterns as they relate to their atmospheric drivers.

[70] | Atmospheric river impacts on the upper ocean: a study using Argo floats

First Author: Donata Giglio

University of Colorado Boulder / USA

Co-Authors: Lauren Hoffman UC San Diego, Bill Katie-Anne Mills University of Colorado Boulder, Sarah Purkey UC San Diego, Jacopo Sala University of Colorado Boulder, John Gilson UC San Diego, Aneesh C. Subramanian University of Colorado Boulder, Brian Kawzenuk CW3E, Anna Wilson CW3E, Marty Ralph CW3E

Atmospheric Rivers (ARs) are elongated structures in the atmosphere that transport water vapor from the tropics to mid-latitudes over the oceans in highly episodic events. They are shown to be a major source of rainfall in the western United States, they impact Greenland and Antarctic ice melt events, and they play a role in exchanges of heat and freshwater at the air-sea interface. Our understanding of air-sea exchanges during ARs is limited, especially in the open ocean, as they occur at relatively short time scales and on small spatial scales, and they depend on the preconditioning of the system, hence they are challenging to observe and model.

For the first time, an experiment was designed to observe AR-related changes in the upper ocean using Argo floats. Argo profile measurements show upper ocean freshening and (in some cases) cooling at the passage of the AR, if wind stress at the ocean surface is low. The observed freshening is consistent with AR-related precipitation. Results from this pilot experiment are presented in the context of seasonal changes in ocean salinity associated with the passage of ARs and in the context of the seasonal salt budget in the region, based on the Estimating the Circulation and Climate of the Ocean (ECCO) state estimate.

[71] | Observing Air-Sea Interaction Impacts from Space on Atmospheric River and AR Family Development

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Derek J. Posselt, Jet Propulsion Laboratory-California Institute of Technology

Latent (LHF) and sensible heat fluxes (SHF) within the marine boundary layer are believed to play a significant role in the genesis and evolution of Extratropical Cyclones (ETCs) and Atmospheric Rivers (ARs). However, consistent observations of air-sea interactions with in-situ observatories are limited in both time and space, and polar-orbiting satellites may miss large swaths in the lower midlatitudes due to their orbits, leading to daily gaps in coverage where the most robust fluxes often occur and change rapidly. Satellite missions like CYGNSS (Cyclone Global Navigation Satellite System) have filled in data gaps, providing improved observations over the lower midlatitudes of LHF/SHF. These improved air-sea observations, coupled with cloud and precipitation observations within ARs from other satellites, like GPM and MODIS, can begin to link the correlations between surface heat fluxes to changes in the mesoscale features within these synoptic-scale systems. Previous studies have shown the correlation of observed LHF/SHF to precipitation and cloud thickness increases along the frontal regions. Still, they have only looked at the connections between ETCs and ARs when LHF and SHF were at their strongest or the peak intensity of the system, not during its early formation (or just before formation) when they may be at their strongest.

Recent studies have examined through idealized models how LHF/SHF can impact the development of ETCs and ARs upstream of the primary cyclone and enhance upstream ARs. Improved observations of real-world conditions can help us better understand the interplay within these systems. This presentation will highlight the role air-sea interactions may have during the genesis and early evolution of ETCs and ARs, the correlations to cloud and precipitation structure changes, the upstream impacts, and setting the groundwork that will be able to show that air-sea interactions directly impact the development of these systems.

[72] | An Overview of Flight Planning for Atmospheric River Reconnaissance

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Atmospheric rivers (ARs) making landfall in the western US can contribute half of the annual precipitation. Accurate forecasts of these events are crucial for water management and flood risk mitigation. Since 2016, the Atmospheric River Reconnaissance (AR Recon) program, led by Center for Western Weather and Water Extremes of Scripps Institution of Oceanography at UC San Diego, addresses observation gaps and enhances forecasts over the US West Coast at 1–5-day lead times. This collaborative Research And Operations Partnership (RAOP) involves CW3E/UCSD and five other universities, NOAA, Air Force Reserve Command 53rd Weather Reconnaissance Squadron, Naval Research Laboratory, NCAR, ECMWF, and water agencies. In winter, AR Recon sends out research aircraft to release dropsondes over the North Pacific, collecting meteorological data during their descent to the surface. Simultaneously, airborne radio occultation data is collected. The AR Recon team also deploys additional ocean surface drifting buoys and land-based radiosondes. Till now, AR Recon has established a gap-filling three-dimensional observing network. Since January 2020, AR Recon has been officially part of NOAA's National Winter Season Operations Plan.

Since 2016, AR Recon research aircraft have flown on 165 intensive observing period (IOP) days. These unique observations have proven highly efficient in enhancing the forecast skill of ARs and precipitation over the US West. Additionally, they have played a vital role in advancing our understanding of AR-related atmospheric dynamics and processes. The presentation will provide an overview of how flight planning is completed during AR Recon operations. We will summarize how the ARs are targeted and how the flight tracks are customized. We will also discuss the importance of using customized flight tracks designed for each synoptic environment and illustrate how this process is key to AR Recon's success, in particular operational forecast improvement.

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[73] | Atmospheric River Reconnaissance – Accomplishments in Water Year 2024

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Atmospheric River Reconnaissance (AR Recon) is an interagency, international Research and Operations Partnership (RAOP) that, since 2016, has collected unique observations in the North Pacific to improve AR landfall forecasts and their impacts during the wet season (November – March). This presentation will provide a review of the various data streams that were collected during AR Recon and disseminated for use in global numerical weather prediction in real time during water year 2024, from vertical profiles of key characteristics collected by dropsondes, to drifting buoys and profiling floats, to radiosondes. It will also discuss innovative data streams undergoing testing for inclusion in operational modeling efforts, including Airborne Radio Occultation and long-duration drifting balloons, as well as efforts to monitor the evolution of ARs as they make landfall and move inland. Data impact studies continue to illustrate quantitative forecast improvement with the data and provide information useful for the team to continue to refine our targeting strategies. The RAOP that enables this work with multiple integrated and engaged partners will be highlighted, including its growth in the past year.

[74] | The North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign (NAWDIC)

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NAWDIC is an initiative for an international field campaign aiming to advance our understanding and modelling of the synoptic- to micro-scale dynamical and physical processes associated with the triggering of severe wind gusts, heavy precipitation, and cold air outbreaks in the North Atlantic-European region. More specifically, NAWDIC will focus on the physical understanding and quantification of the dry intrusion airstream for the evolution of high-impact weather related to extratropical cyclones in winter. Though initiated as a campaign with the German high-altitude, long-range aircraft (HALO), NAWDIC has now become a modular international effort being scheduled for January – February 2026. It consists of six major components, which are planned as stand-alone measurement campaigns by different groups in Europe and North America, but will benefit from synergies if coordinated under the umbrella of NAWDIC.

Further, the measuring activities will be complemented by a modelling component – in collaboration with weather services – that aims to transfer the heterogeneous observations into a structured model using data assimilation systems across scales. In this talk, we will provide a detailed overview of NAWDIC's scientific aims, the individual components, and how these are interlinked. In addition, a case study of Storm Eunice (2022) will be presented. Eunice developed in the North Atlantic and produced high impact weather in western Europe. Based on hypothetical flight patterns, we will illustrate how the international components could act to conduct synergistic measurements across various ocean basins.

[140] | A new benchmarking metrics framework for evaluating atmospheric rivers in reanalyses and climate models

First Author: Bo Dong

LLNL / US

Co-Authors: Paul Ullrich LLNL, Jiwoo Lee LLNL, Peter Gleckler LLNL, Kristin Chang LLNL

We present a new AR metrics tool package that is designed for easy analysis of AR characteristics and statistics in gridded climate datasets such as model and reanalysis. This package is expected to be particularly useful for climate models evaluation. The tool is developed to conform with the PCMDI metrics package (PMP) framework, and once completed will be publicly available to the community. The AR metrics developed from this work can be routinely applied for model benchmarking and during development cycles to trace performance evolution across model versions or generations and set objective targets for the improvement of models. It can also be used for operational centers to perform near real-time climate and extreme events impact assessment along with their forecast cycles.

The included metrics-based analyses are very efficient for diagnosing systematic AR biases in climate models. For example, the package identifies that in CMIP5 and CMIP6 models, AR tracks in the south Atlantic are positioned farther poleward compared to the ERA5 reanalysis, while in the south Pacific, tracks are biased towards the equator. For the landfalling AR peak season, we found that most climate models simulate a completely opposite seasonal cycle over western Africa. The AR metrics tool is also useful for discovering new AR features in historical and future periods. For instance, ARs at the end of the 21st century in the RCP8.5 and SSP5-85 simulations show significantly longer duration of landfall and shorter intervals between landfall events over most regions across models.

[145] | Long-Duration Weather Balloons and Their Impacts on Forecasts of Atmospheric Rivers

First Author: Todd Hutchinson

WindBorne Systems / United States

Co-Authors: Todd Hutchinson WindBorne Systems, Xingren Wu NOAA, Michael Mueller NOAA, Vijay Tallapragada NOAA, Lidia Cucurull NOAA

WindBorne Systems has developed a novel balloon-based observation system, enabling constellations of balloons to be flown throughout the troposphere for extended periods of time. Each balloon can fly for up to 2 weeks while being remotely directed to ascend and descend from a few hundred meters above the earth surface to the lower stratosphere, collecting vertical profiles of pressure, temperature, humidity, wind speed, and wind direction. During February and March of 2022, 60 balloons were launched from South Korea and Hawaii and traveled across the Pacific Ocean. Between November 2023 and March of 2024, 370 balloons were flown throughout the Northern Hemisphere with over half of those balloon flights traversing the Pacific Ocean. Observations collected by these balloons provided complementary observation coverage to support the Atmospheric Rivers Reconnaissance program. The impact of these observations is being assessed in observation simulation experiments (OSEs) using the NCEP Operational Global Forecast System. The overall results from the OSEs along with specific case studies will be presented at the meeting.

The flight paths of 316 balloons that were launched between 1 November 2023 and 28 February 2024 are shown below.

View Image

Session:

AR6- Physical, dynamical, microphysics and aerosol aspects of ARs

[1] | Seasonal Variations of Aerosols Concentrations and Aerosol Optical Properties along the Indus and Gangetic plain in South Asia

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Emissions of atmospheric pollutants are rapidly increasing over South Asia. A greater understanding of seasonal variability in aerosol concentrations over South Asia is a scientific challenge and has consequences due to a lack of monitoring and modelling of air pollutants. Therefore, this study investigates aerosol patterns and trends over some major cities in the Indo-Gangetic Plain of the South Asia, i.e., Islamabad, Lahore, Delhi, and Dhaka, by using simulations from the Modern -Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) model and satellite measurements (Moderate Resolution Imaging Spectroradiometer, (MODIS)) from 2000 to 2020. The results show that seasonal MODIS–aerosol optical depth (AOD) during 2000−2020 in Lahore is 0.5, 0.52, 0.92, and 0.71, while in Islamabad 0.25, 0.32, 0.45, and 0.38, in Delhi 0.68, 0.6, 1.0, and 0.77, and in Dhaka 0.79, 0.75, 0.78 and 0.55 values are observed during different seasons, i.e., winter, spring, summer, and autumn, respectively. The analysis reveals a significant increase in aerosol concentrations by 25%, 24%, 19%, and 14%, and maximum AOD increased by 15%, 14%, 19%, and 22% during the winter of the last decade (2011–2020) over Islamabad, Lahore, Delhi, and Dhaka, respectively. In contrast, AOD values decreased during spring by −5%, −12%, and −5 over Islamabad, Lahore, and Delhi, respectively. In Dhaka, AOD shows an increasing trend for all seasons. Thus, this study provides the aerosol spatial and temporal variations over the South Asian region and would help policymakers to strategize suitable mitigation measurements.

[2] | The role of atmospheric rivers in dust storms over the Middle East

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Large amounts of dust in the air can disrupt daily activities and pose a threat to human health. In May 2022, consecutive major dust storms occurred over the Middle East resulting in severe environmental, social and health impacts. In this study, we investigate the exceptional factors driving these storms and the effects of the dust clouds. Using a combination of satellite, in-situ and reanalysis datasets, we identify the atmospheric triggers for the occurrence of these severe dust storms, characterize their three-dimensional structure and evaluate the dust radiative impact. The dust emission was promoted by density currents emanating from deep convection over Turkey. The convective systems were triggered by cut-off lows from mid-latitudes fed by moisture from African atmospheric rivers. Data from the Infrared Atmospheric Sounding Interferometer (IASI) showed that the dust clouds were transported southward at 4 km in altitudes but sunk to ground levels when they reached the southern Arabian Peninsula due to strong subsidence. At a station in coastal UAE, the dust caused a 350 W m^{-2} drop in the surface downward shortwave flux and a 70 W m^{-2} increase in the longwave one during the dust episodes. This contributed to a 9 °C increase in nighttime temperatures which exacerbated the effects of the heat for the population. The newly highlighted mechanism for dust emission in the Middle East, in which a cut-off low interacts with an atmospheric river, as well as direct observations of the dust impact on the radiative budget can contribute to reducing associated uncertainties in climate models.

[3] | Modelling aerosol-cloud-precipitation processes in the Iberian Peninsula using the WRF-CHIMERE coupled model: Storm Ana case study

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Atmospheric rivers (AR) have an important role in the hydrological cycle and are often associated with extreme precipitation events in the Iberian Peninsula (IP). Precipitation formation strongly depends on cloud microphysics and cloud-aerosol interactions. This work aims to better understand aerosol-cloud-precipitation processes occurring in the ARs that affect the IP. In this sense, we used the WRF-CHIMERE coupled model (online coupling between the WRF meteorological model and the CHIMERE chemical transport model) to investigate the aerosol properties and their role as cloud condensation nuclei (CCN) and ice nuclei (IN) during an AR case study. This modelling system provides information on the spatial and temporal variability of emissions, transport and deposition, aerosol composition and size distribution, and simulates the two-way interaction between meteorological and chemical variables. A set of numerical simulations was performed using three nested domains with horizontal resolutions of 27, 9 and 3 km. As a case study, we have selected an AR that affected the IP on 9-11 December 2017. This AR was associated with the explosive cyclogenesis of a storm named Ana and caused intense rainfall, snowfall in the mountains, strong winds, and considerable socioeconomic losses in the northwest of IP. This presentation will explore the impact of changes in aerosol amounts and properties on cloud microphysical properties and precipitation formation. Additionally, we will examine the importance of the simulated aerosols in the generation of extreme precipitation. This work contributes to a better understanding of the importance of aerosols as CCN and IN, and their contribution to intense rainfall and snowfall in the IP.

This work was supported by the Portuguese Foundation for Science and Technology (FCT) through the ATLACE research project (CIRCNA/CAC/0273/2019) and a PhD grant (2023.03574.BD) for Diogo Luís.

[79] | RAIN SHADOW EFFECT IN THE NEUQUEN ANDES

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The phenomenon of rain shadow is described as a region of sharply reduced precipitation on the lee side of an orographic barrier, as compared with regions upwind of the barrier. This definition does not have a clear specification about their time scale, how far from the barrier it's extended, the physics mechanism that generated it or how to quantify that sharply reduced precipitation. In this study, we focus primarily on methods of quantifying the rain shadow, analyzing two case studies that are associated with two AR events that penetrate the northern Patagonia Andes in the north of the Neuquen province (Argentina).

The hourly and daily rainfall data, from the study region, defined between 36°S- 38°S and 70°W-73°W, was obtained from 131 rain gauges for June 8-11 (Event 1) and June 26-27 (Event 2) 2018. These observations, after performing a quality control and partitioning the daily data, were used to quantify the rain shadow in each event applying 3 different methods. The first one consist of making the subtraction between the total precipitation on the west side minus that on the east side; for the second one, the ´total precipitation´ and ´rain shadow´ indexes were calculated, after normalize the values from the data set, as the sum and subtraction between the rain gauge that is furthest to the east of the region and the one that is furthest to the west, respectively.The third one are the spillover fraction every 6 h and their distance calculated, after normalize and apply Cressman analysis in one dimension using a grid spacing of 2.5 km and a radius of influence of 10 km, by using the curves of best fit from each time. Preliminary results indicate that the first event is showing a weaker rainshadow than the second one.

Further investigation of the events includes the analysis of the associated synoptic conditions to understand the influence of circulation on rain shadow and comparing rain gauge data with other precipitation products such as satellite and model data sets.

[80] | Upper Ocean Variability and Euro-Atlantic Atmospheric Rivers

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We use a long-term ERA5 reanalysis dataset over the North Atlantic Ocean to study the impact of the upper ocean variability on Euro-Atlantic Atmospheric Rivers (EAARs). The significant increase in the sea surface temperature (SST) over the Gulf Stream, coupled with its poleward shift in recent decades, impacts the intensity and frequency of ARs over the region. The intensity of ARs in the North Atlantic has been increasing in recent times with large decadal variability and poleward shift in landfalling of intense events. Surface latent heat flux anomalies show the latitudinal dependence of the source of moisture flux in the open ocean contributing to the formation and enhancing ARs strength. These flux changes, along with the SST decadal variability, drive the decadal spatial deviations in the path and landfalling ARs over the Euro-Atlantic region. The increasing zonal and meridional components of winds in the central Atlantic drive the excess moisture from the western Atlantic towards western Europe. While mesoscale eddies could impact the ARs, upper ocean parameters such as SST in the open ocean and sea level anomalies near the coasts of western Europe vary with AR occurrence and landfalling.

[81] | Large-Scale Circulation Context for North American West Coast Atmospheric Rivers: Influence of the Subseasonal NPO/WP Teleconnection

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Co-Authors: Justin Hicks UMD, Sumant Nigam UMD, Alfredo Ruiz-Barradas UMD

Understanding the variability of atmospheric rivers (ARs) on subseasonal time scales is pivotal for efficient water resource management along the west coast of North America. ARs during 1980-2018 based on the MERRA-2 reanalysis are analyzed to quantify the modulation of winter (December-February) landfalling ARs in the western US by leading subseasonal teleconnections, focusing on pentad evolution rather than seasonal-mean patterns. The growth phase of the North Pacific Oscillation/West Pacific (NPO/WP) teleconnection – the second leading pattern in 200-hPa geopotential heights in boreal winter – is found to be particularly influential in modulating the number of landfalling ARs in this region. In the positive phase of NPO/WP growth, the presence of anomalous low pressure centered just south of Alaska (i.e., a strengthening of the Aleutian Low) and anomalous high pressure around Hawaii results in moisture convergence in the central and eastern Pacific, bringing southwesterly moisture fluxes to the coast and inland. The modulation by NPO/WP is stronger than by commonly-considered climate variability modes, such as the Pacific/North American (PNA) pattern. Although southwesterly fluxes are stronger over the Pacific Ocean during the positive phase of PNA, they tend to transition to southerly fluxes before extending inland, resulting in smaller overland impacts in the western US. The analysis of temporal evolutions indicates AR activity peaks 5 days after the mature phase of NPO/WP growth, as in the case of PNA. Overall, the study suggests potential subseasonal predictability of US West Coast ARs from incipient-phase knowledge of the leading teleconnection patterns, especially the NPO/WP.

View Image

[82] | Global impacts of atmospheric rivers on surface temperatures and heat fluxes

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Atmospheric rivers (ARs) are known to transport large quantities of moisture, but they also transport significant amounts of heat. Here we use MERRA-2 reanalysis data at an hourly timescale to show that ARs have strong warming effects on surface temperatures: during AR events, average 2-meter temperature anomalies are on the order of +5°C in the midlatitudes and +10°C in polar regions. Across Eastern North America, Europe, and other areas in the midlatitudes, more frequent ARs are correlated with warmer-than-average winter temperatures. These warm temperature anomalies during ARs are due to increases in downwelling longwave radiation and sensible heat flux. Downwelling longwave anomalies are due to a transient greenhouse effect of enhanced water vapor content, while downwelling sensible heat flux anomalies are related to horizontal convergence of sensible heat in the AR core. In addition, we find that ARs are associated with a large fraction of extreme temperature anomalies, accounting for greater than 80% of extreme hourly excursions in some regions. These results are robust across multiple AR-identification algorithms tested in the Atmospheric River Tracking Method Intercomparison Project (ARTMIP). Our results demonstrate that ARs significantly impact surface temperatures and heat fluxes on a wide array of timescales, and that they may play a larger role in heat transport than previously recognized.

[83] | Water Vapor and Heat Budget Evaluation in Atmospheric Rivers Associated with Heavy Rainfall Events in the Southern Andes

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Atmospheric rivers (AR), the elongated, narrow channels of large column-integrated water vapor (IWV), transport moisture and heat poleward. Along with beneficial rainfall, occasionally they produce heavy to extreme rainfall in the southern Andes. The prevailing transport mechanisms along ARs may significantly influence the intensity and duration of precipitation during their landfall. To understand the transport mechanisms of water vapor and heat and their possible feedback pathways during ARs, in this study, we evaluated water vapor and heat budgets for 50 landfalling zonal ARs that caused heavy to extreme rainfall in the Southern Andes. The ARs are identified based on a global AR detection algorithm included in the ARTMIP (Guan and Waliser, 2018). The budget terms for all the ARs are calculated using the ERA5 reanalysis datasets along a backward trajectory obtained from the HYSPLIT trajectory model at 6-hour intervals. The budget analysis suggests that while mass convergence dominates the vertically integrated water vapor transport (IVT) over the open ocean, the advection of moisture is significantly enhanced near the coast and the landfalling region. It is shown that the enhanced IWV bands of sub/tropical origin can merge along the AR channel, thereby maintaining the along-AR IWV values. The convergence of the IWV bands occurs in a region between a stationary subtropical anticyclone and a midlatitude trough, which migrates toward the continent. The merging of the tropical IWV bands warms the AR channels, further facilitating moisture transport. A simulation experiment of a landfalling AR using the WRF model shows that the positive vertical gradient of latent heating along the AR may influence the mass convergence into the AR. Our study suggests that a synergistic action between moisture and heat enhances IVT convergence along the ARs, the landfalling of which produces heavy to extreme rainfall in the southern Andes.

[84] | Atmospheric Rivers in South-central Chile: Landfalling angle is (almost) everything

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The extratropical west coast of South America has one of the largest frequencies of landfalling atmospheric rivers (ARs), with dozens of events per season that account for ~50% of the annual precipitation and can produce extreme rainfall events in south-central Chile. Most ARs form an acute angle with the Andes, but, in some cases, the moist stream impinges nearly perpendicular to the mountains, referred to as Zonal Atmospheric Rivers (ZARs). Enhanced surface-based and upper-air measurements in Concepcion (38°S) and numerical simulations were used to characterize a ZAR and a meridionally oriented AR in July 2022. They represent extremes of the broad distribution of winter storms in this region and exhibit key features that were found in a composite analysis based on larger samples of ZARs and tilted ARs. The latter are associated with an upper-level trough, broad-scale ascent, extratropical cyclone, and cold front reaching southern Chile. Instead, ZARs are associated with tropospheric-deep, strong zonal flow and a stationary front across the South Pacific, with ascent restricted upstream of the Andes. Consequently, ZARs have minimum precipitation offshore but a marked orographic precipitation enhancement and exhibit relatively warm temperatures, thus resulting in augmented risk of hydrometeorological extreme events.

[85] | Impacts of mesoscale frontal waves and secondary cyclogenesis on atmospheric rivers that result in heavy precipitation in the Green River Watershed, Washington.

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Co-Authors: Emma Russell PSU, Paul Loikith PSU

In this study we identify and characterize the key meteorological drivers of heavy precipitation within the Green River Watershed (GRW) in Washington. 205 high precipitation days (95th percentile) were identified in the GRW between the years 1980 and 2021. To better characterize the range of meteorological conditions and storm types associated with heavy precipitation days, we use the self-organizing map (SOM) approach to cluster daily integrated water vapor transport (IVT) on heavy precipitation days. To further diagnose the meteorological drivers, composites of several other diagnostic fields are constructed for each SOM cluster and the days preceding the heavy precipitation days. Together, these results illustrate common storm types expected to produce heavy precipitation in the GRW. Each storm type closely resembles an atmospheric river (AR) with IVT ranging from ~350 kg m-1 s-1 and ~650 kg m-1 s-1 and producing daily total precipitation between 49.2mm and 72.5mm. However, the strength, orientation, and size of the corridors of enhanced IVT vary considerably. We then evaluate the importance of mesoscale frontal waves and secondary cyclogenesis in each storm type and how the presence or absence of such features modulates the duration and intensity of the associated precipitation.

[86] | Characteristics of Precipitation Patterns in Moist-dominated versus Wind-dominated Atmospheric Rivers Making Landfall on Western North America

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We categorize atmospheric rivers (ARs) that make landfall between Baja California to British Columbia coastline during the 1980-2019 period into two types: moist-dominated (moist-ARs) and windy-dominated ARs (windy-ARs). Although moist- and windy-ARs have similar duration and magnitudes of integrated water vapor transport (IVT) at the AR core after they make landfall, their accompanying precipitation patterns are different. The average cumulative precipitation over the duration of AR shows that windy-ARs produce higher precipitation at the coastline, while moist-ARs produce higher precipitation in the inland area. One exception is that windy-ARs that make landfall at Baja and south California coastline bring more precipitation in the central U.S. than moist-ARs. We explore the mechanisms lead to the precipitation pattern differences between moist- and windy-ARs from both dynamical and thermodynamical perspectives. Windy-ARs are associated with enhanced trough at 500 hPa and low pressure at sea level, which provides stronger low-level wind with a more southerly direction and colder temperature. These together leads to stronger IVT and relative humidity in the lower-level of atmosphere although windy-ARs have weaker moisture. The windy-ARs are also associated with stronger IVT convergence and stronger synoptic scale ascent forcing near the coastal regions than moist-ARs. All the factors above favor stronger precipitation at the coast and over mountains which are more perpendicular to the incoming IVT direction, such as the Sierra Nevada, Olympic Peninsula, and Canadian Coast Mountains. Moist-ARs are associated with a weaker but more zonally extended trough anomaly at 500 hPa, which leads to stronger zonal wind and IVT that favor moisture penetrating inland. Moist-ARs also have stronger integrated water vapor and column relative humidity over the ocean and inland, as well as at the upper-level of atmosphere near the coast, than windy-ARs. These together favor stronger precipitation in the Cascade Range and inland area for moist-ARs.

[87] | Similarities in Large Scale Meteorological Patterns Associated with Atmospheric River Detection Tools during landfall along the West CONUS

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Many atmospheric river detectors (ARDTs) have been developed over the past few decades to capture atmospheric rivers (ARs). However, different ARDTs have been observed to capture different frequencies, shapes and sizes of ARs. Due to this, many questions including investigating the underlying phenomena for ARs in the ARDTs have been posed. In this paper, we assess four different ARDTs and investigate the underlying meteorological phenomena during landfalling ARs. We find that during landfalling ARs events, there exists a prevalent low-pressure and high-pressure confluence that enhances moisture influx toward the landfalling site. The strength of the pressure gradient in the confluence region enhances the influx of the integrated vapor transport. The four ARDTs predominantly capture similar atmospheric processes, nonetheless, they have statistically different magnitudes.

[88] | The Modification of Air-sea Fluxes within Atmospheric Rivers by Mesoscale Sea Surface Temperature Structures

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Atmospheric rivers (ARs), moisture filaments extending from the tropics or extratropics, have significant impacts on western North America and also account for the majority of California's annual rainfall. Understanding factors contributing to AR intensity, defined by maximum integrated water vapor transport (IVT) and AR duration, provides information on improving AR forecasts. Recently, a study showed that 1000 km scale sea surface temperature (SST) anomalies (SSTAs) enhance vertical moisture fluxes, which in turn cause stronger ARs. Mesoscale SSTAs are also able to modify air-sea fluxes, as demonstrated through high-resolution observations and simulations. Hence, there is value in understanding how SSTAs impact ARs through the modification of air-sea fluxes across different scales.

The SSTA amplitudes may correlate positively with surface wind stress anomalies. These positive correlations lead to the key idea that SSTAs can impact the marine atmospheric boundary layer (MABL) by modifying the near-surface atmospheric convergence, curl, and therefore heat, moisture, and momentum fluxes. While many studies discuss how this correlation is driven by SSTAs, few studies have systematically examined how SSTAs modify sensible and latent heat fluxes, computed as the product of surface wind speed and air-sea temperature and humidity difference, respectively.

In this study, we explore the sensitivity of air-sea fluxes to idealized sinusoidal SSTA structure using a high-resolution atmospheric model with an AR-like atmospheric profile. We vary the SSTA amplitude, spatial scale, and background wind speed to understand how sensible and latent heat fluxes are modified. Our preliminary results show that the 100 km SSTAs may alter sensible heat fluxes by 40%/K and latent heat fluxes by 20%/K.

[89] | Characteristics and skill of atmospheric river-related and non-atmospheric river-related extreme precipitation over the Southeast U.S.

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The results of prior work indicate that the Southeast United States (SEUS) region contains extreme Quantitative Precipitation Forecast (QPF) skill that is lower than other regions in the U.S. (e.g., the Western and Northeast US). Similarly, previous investigations have identified that atmospheric rivers (AR) play a key role in extreme precipitation events in this region (e.g., Nashville flood on May 2, 2010) and that such non-tropical processes with higher integrated vapor transport (IVT) potentially have greater QPF skill than those with lower IVT. In this study, KMeans clustering is used to identify six distinct synoptic patterns leading to extreme precipitation in Tennessee during the period 2001-2020. These patterns exhibited distinct seasonality, with three patterns occurring in the cool season, two in the warm season, and one in the transition season. The identified patterns also demonstrate that extreme precipitation events are strongly associated with enhanced IVT and ARs over the SEUS., in addition to tropical cyclones and mesoscale convective systems. An analysis of the QPF skill associated with each pattern, derived from the GEFS Reforecast dataset, illustrates that the cool season pattern with the highest IVT and largest fraction of ARs has better skill, whereas the warm season pattern with the highest CAPE and IWV has worse skill at multiple lead times. These results provide insights into the dynamical characteristics and predictability of extreme precipitation by storm type across the SEUS.

View Image

[90] | Atmospheric Rivers over the Arabian Peninsula and Their Role in Extreme Rainfall Events

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The mesoscale dynamics of record-breaking Atmospheric Rivers (ARs) that impacted the Middle East in recent years and caused property damage and loss of life are investigated using model, reanalysis and observational data. Gravity waves triggered by the complex terrain in Saudi Arabia further intensified their effects. Given the rising frequency of ARs in this region, AR Rapids may be even more impactful in a warming climate, and need to be accounted for in reanalysis and numerical models. In this work, we present the recent advancements in the understanding of ARs dynamics in the Arabian Peninsula region and their impacts on extreme rainfall events.

[91] | A FORECAST EVALUATION OF THE NORTH PACIFIC JET STREAM

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The term jet stream generally refers to a narrow region of intense winds near the top of the troposphere. Along the jet stream, instabilities and waves can develop into synoptic-scale systems, or midlatitude cyclones, which thus makes it critical for atmospheric development and predictability. Furthermore, their key role in cyclogenesis means they can be linked with atmospheric rivers and warm conveyor belts, yielding high-impact weather including extreme precipitation and flooding, severe winds, and ocean waves. Given the impacts associated with the jet stream, it is therefore important that numerical weather prediction (NWP) systems can accurately forecast the magnitude and the structure of jet streams.

Observations gathered during the Atmospheric River Reconnaissance (AR Recon) observational campaign provide a unique opportunity to investigate the structure of the North Pacific jet stream. In each winter season, AR Recon uses research aircraft to probe (with dropsondes) atmospheric rivers and other dynamically active regions, with their observations assimilated in real-time into global NWP systems. This helps to improve the initialization of the next forecast. In this research, we use a subset of dropsondes deployed by the National Oceanic and Atmospheric Administration Gulfstream IV-SP aircraft in the 2020, 2021, and 2022 seasons to evaluate the jet stream in the European Centre for Medium-Range Weather Forecasts Integrated Forecasting System. Results show that on average the model has a slow wind bias for winds ≥ 50 ms-1, but that this is largely corrected via data assimilation. The computation of the cross jet-axis potential vorticity (PV) gradient highlights model issues in resolving the sharp PV gradients across the jet in the tropopause region. Case studies and composite analysis illustrate this finding. Potential model improvements that could be considered for better modelling of the jet stream will also be discussed.

[92] | Moisture Fluxes during Three Atmospheric Rivers in September and October 2021 in British Columbia's Upper Nechako Watershed

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Atmospheric rivers (ARs) that influence the hydroclimatology of British Columbia (BC) are concentrated streams of water vapor associated with extratropical cyclones originating over the Pacific Ocean. ARs making landfall in BC undergo orographic lifting along the windward side of the Coast Mountains, leading to intense precipitation and strong winds. To better understand ARs making landfall in north-central BC, the Tahtsa Ranges Atmospheric River Experiment (TRARE) collected detailed hydrometeorological data in BC's upper Nechako Watershed in September and October 2021. This study aims to quantify moisture fluxes and understand the impact of three ARs (Events 3, 5, and 10) recorded during TRARE on the upper Nechako Watershed over the event duration. Hydrometric stations showed sharp peaks in runoff (>40 mm/day, Event 3) that correspond to a surge of intense rainfall (>80 mm/day) and strong winds (>15 m/s). Major variations in the integrated water vapor transport (IVT) defining ARs were observed over the upper Nechako, owing to geographical and hydrometeorological differences between Events 3, 5, and 10. Events 3 (~600 kg/m/s) and 5 (~500 kg/m/s) surpassed and Event 10 (~200 kg/m/s) fell below a minimum IVT threshold of 250 kg/m/s, indicating ARs near the TRARE study area. Event 10 originated after a historical bomb cyclone southwest of BC, where air pressure dropped up to 50 hPa/day, breaking the record for the lowest sea-level pressure (942 hPa). ARs associated with Events 3 and 5 experienced southwestern paths with IVT steadiness factor (ISF) >80% and consequently similar wind direction due to the presence of a single low-pressure center located off the coast of northern BC and Alaska. Event 10 experienced a northeastern path with ISF 80% due to the enhanced water vapor caused by the passage of a historical bomb cyclone.

[93] | Atmospheric river variability over the last millennium driven by annular modes

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Atmospheric rivers (ARs) are filamentary conduits of intense moisture transport crucial for water delivery to mid-latitude coastal regions. How ARs have responded to extratropical climate variability remains poorly understood despite ARs being features of the extratropical atmosphere. Here, using “Last Millennium” simulations, we characterize the role of annular modes of extratropical variability (modes of the jet stream) on ARs and moisture transport. We find that positive(negative) phases of the annular modes intensify(weaken) and weaken(intensify) ARs over the subpolar and subtropical latitudes, respectively, with up to ~20–25 mm/month associated changes in precipitation. Importantly, the annular modes comprise the primary mode of AR variability over the last ~1000 years. We also separately examine the annular modes’ influence on storm track activity and find it distinct from that on ARs and moisture transport, despite the storm tracks being associated with ARs and overlapping with strong moisture transport. Lastly, our results provide a robust paleoclimate baseline from which to contextualize projected 21st century AR intensification.

*This work was performed in part under the auspices of the US Department of Energy (DOE) by Lawrence Livermore National Laboratory under contract no. DE-AC52-07NA27344 LLNL-ABS- 861437

[94] | Relationship between Tropical Diabatic Heating and Atmospheric Rivers under the Indian Summer Monsoon System

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Tropical heating anomalies associated with organized convection can impact weather systems in the mid-latitude region by interacting with extratropical regions. These anomalies can affect the formation of atmospheric rivers (ARs) and their moisture supply from various sources. Our study investigates the relationship between tropical diabatic heating and cross-Pacific ARs under the Indian summer monsoon system, focusing on the Indian Monsoon region (ISM) and the Philippine Sea-Western North Pacific region (PWNP). These regions are characterized by maximum intraseasonal diabatic heating variability, with different combinations of heating anomalies (heating or cooling sources) that accompanied by the subseasonal features (onset/peak/withdrawal) of the Indian summer monsoon. Our findings reveal that the different combinations of heating anomalies act as precursors for AR activity, affecting the landfall location, length, strength, and duration of ARs across the Pacific during the boreal summer. The dipolar heating anomaly in the ISM and PWNP is identified as a strong signal positively correlated with long cross-Pacific ARs that make landfall on the West Coast of North America. Furthermore, we investigate the variabilities of moisture sources and transport for ARs under different abnormal tropical heat sources by applying the three-dimensional Lagrangian FLEXible PARTicle dispersion model (FLEXPART). The atmospheric circulation pattern triggered by the tropical perturbation creates favorable atmospheric conditions for moisture transport and influences the landfall location of ARs. Our study highlights the importance of considering tropical heating in forecasting AR activity in the North Pacific and mitigating associated risks.

[95] | Investigation of an Atmospheric River and Explosive Cyclogenesis over the US Central Plains in March 2019

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An atmospheric river (AR) associated bombing cyclone event occurred in Colorado in March 2019, resulting in widespread blizzard conditions and high winds causing damage in neighboring states. High-resolution West WRF experimental simulations are conducted to investigate the impacts of AR on cyclogenesis. Our results reveal that the resilient AR5 originating from the Gulf of Mexico contributed moisture to the base of the Warm Conveyor Belt (WCB), accelerating the deepening of the pre-existing lee cyclone and promoting the formation of downstream upper-level ridges. The release of latent heat 1) generated positive potential vorticity (PV) anomalies in the lower troposphere; 2) promoted air ascent along the WCB and the formation of an upper-level ridge, both contributing to the deepening of the cyclone. The removal of latent heat release reduced the upper-level PV hook and lower troposphere PV anomalies (PV tower), causing an 18hPa weakening of the cyclone center with an eastward shift and a notable alteration in precipitation patterns. Additionally, the amplified pressure gradient force arising from the coupled low-pressure and blocking high system, facilitated the influx of moisture from lower latitudes, and ultimately strengthened the existing AR. This bombing cyclone case offers a unique opportunity to investigate the direct and indirect impacts of AR on extreme weather further inland.

[96] | Diabatic Amplification of Atmospheric River Intensity by Marine Heatwaves: Multi-Scale Air-Sea Interaction and Implications for Marine Heatwave Dissipation

First Author: Christoph Renkl

Woods Hole Oceanographic Institution / USA

Co-Authors: Christoph Renkl WHOI, Hyodae Seo WHOI, Anthony Wilson SIO/UC San Diego, Élise Beaudin Brown University, Art Miller SIO/UC San Diego, and Emanuele Di Lorenzo Brown University

The climate along the US West Coast is profoundly affected by extratropical ocean and air-sea interactions near the coast, influencing moisture transport and valuable precipitation that play an important role in agricultural and water resource management efforts. On a basin scale, seasonal to interannual anomalies in the atmospheric circulation can create persistent upper-ocean temperature anomalies known as marine heatwaves (MHWs). These anomalous SST conditions have direct impact on air-sea fluxes, thereby influencing diabatic processes associated with synoptic-scale weather patterns, such as atmospheric rivers (ARs). Given the heat and moisture pickup by ARs from the oceans, these multi-scale MHW-AR interactions may also represent a potential mechanism for dissipation of MHWs. This study examines diabatic multi-scale coupled air-sea interaction processes between persistent MHWs and synoptic-scale ARs, and evaluate their downstream effects on the coastal and inland climate.

Here, we present a comprehensive analysis based on observations and high-resolution, large-ensemble regional coupled model simulations targeting a series of landfalling ARs that interacted with warm SST anomalies during the Northeast Pacific MHW event in winter 2014/2015. Sensitivity simulations are conducted where various aspects of the observed MHW feature are removed from the ocean component of the coupled model to quantify the diabatic modification of the AR moisture and energy budgets. Our results show that MHWs exert diabatic forcing of the lower troposphere via enhanced latent heat flux from the ocean to the atmosphere and an associated increase in evaporation. This ultimately represents a nontrivial moisture source leading to an amplification of AR intensity indicated by an earlier onset and prolonged duration of precipitation inland. Ongoing sensitivity simulations will be used to assess the role of the large-scale structure of the MHW and mesoscale eddies in the AR intensification. Implications of MHW dissipation arising from the diabatic interaction between ARs and MHW will be discussed.

[97] | Atmospheric Rivers in the Eastern and Midwestern United States Associated with Baroclinic Waves

First Author: Travis A. O'Brien

Indiana University Bloomington / USA

Co-Authors: Travis A. O'Brien IU LBNL, Burlen Loring NVidia, Amanda Dufek LBNL, Mohammad Rubaiat Islam NCAR, Diya Kamnani IU, Kwesi Quagraine IU, Cody Kirkpatrick IU

It is well established that atmospheric rivers (ARs) significantly impact the hydrological cycle and associated extremes in western continental regions. Recent studies suggest ARs also influence water resources and extremes in continental interiors. Numerous AR detection tools indicate that AR conditions are relatively frequent in areas east of the Rocky Mountains. The origin of these ARs, whether from synoptic-scale waves or mesoscale processes, is unclear. This study uses meteorological composite maps and transects of AR conditions in multiple locations during the four seasons. The analysis reveals that ARs east of the Rockies are associated with long-wave, baroclinic Rossby waves. This result demonstrates that eastern North American ARs are dynamically similar to their western coastal counterparts, though mechanisms for vertical moisture flux differ between the two. These findings provide a foundation for understanding future climate change and ARs in this region and offer new methods for evaluating climate model simulations.

View Image

[98] | Atmospheric River Sensitivity to Convection: Insights from WRF Simulations

First Author: Rosa Luna-Niño

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This study aims to examine the sensitivity of AR development to convection, hypothesizing that AR characteristics, such as intensity and propagation, are influenced by the representation of convection. The investigation began by analyzing recent AR events that impacted the Western United States, causing precipitation and flooding, with a particular focus on the Valentine's Day storm of February 2019.

A series of numerical model experiments were conducted using the Weather Research and Forecasting (WRF) model with various physical configurations to explore the effect of different convection schemes on AR development. Preliminary results indicate that synoptic variables like sea level pressure, geopotential height, and integrated water vapor transport (IVT) are less affected by the physical combinations of cumulus, microphysics, and planetary boundary layer schemes. However, convective precipitation over ocean showed notable differences between the Grell and Tiedke convection schemes, with Tiedke producing an area of convective precipitation behind the main rain band. However, the grid-scale precipitation contributes significantly more to total rainfall than convective precipitation.

[99] | Seasonality of Atmospheric River Frequency Depends on Location, Year and Detection Algorithm

First Author: Diya Kamnani

Indiana University Bloomington / United States of America

Co-Authors: Diya Kamnani Indiana University Bloomington, Travis A. O'Brien Indiana University Bloomington, Lawrence Berkeley National Lab, Samuel Smith University of Chicago, Paul W. Staten Indiana University Bloomington

Understanding the regional and year-to-year variations in atmospheric river (AR) seasonality is vital to help anticipate them. Previously, ARs were perceived as a winter phenomenon. However, recent studies highlighted regional dependence for AR seasonal patterns. Considering that AR analysis is strongly influenced by the detection algorithm used, our research builds on existing studies by examining how AR seasonality varies based on location and detection algorithm. We also investigate the interannual variability in the peak season of AR activity and evaluate the strength of the seasonal pattern based on these three parameters. We introduce a consistency scale to measure the extent of deviation from the presence of a dominant season while considering the cyclic nature of seasons. Our findings reveal that only some regions have a strong seasonal pattern. To understand the extent of consistency in the dominant seasonal cycle, we use five categories with a decreasing strength of a strong seasonal pattern. Highly Consistent regions, such as India and Central Asia, have a consistent dominant season. Consistent regions (e.g., British Columbia and the Gulf of Alaska) experience some outliers from the dominant season of AR activity. Following this, there are Moderately Consistent, Inconsistent, and Highly Inconsistent regions. Some regions, such as the South Atlantic and parts of Australia, lack a clear seasonal pattern. Furthermore, different algorithms can detect a seasonal pattern while disagreeing on the dominant season. Integrated Vapor Transport (IVT) is used to understand whether inconsistencies in seasonal patterns are due to the algorithm design or an underlying feature of the atmospheric state. However, identifying the seasonal patterns over some regions remains challenging due to discrepancies between the algorithms and IVT. This suggests that AR seasonality is complex, with the interplay between location, year, and detection algorithm playing a crucial role.

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[100] | An MPAS Model Case-Study Examining how Convection Embedded in an Atmospheric River Influences Jet Stream Evolution and Predictability

First Author: Alexander Lojko

University of Michigan / USA

Co-Authors: Andreas Prein NCAR, Christiane Jablonowski University of Michigan

Embedded convection within Atmospheric Rivers (ARs) alters mid-latitude large-scale flow by rapidly redistributing potential vorticity (PV) along the tropopause. Using higher horizontal resolution meshes presents an avenue to more realistically simulate atmospheric convection. However, the extent to which higher-resolution also equates to improved coupling between convection with the large-scale flow remains an open question.

We examine an AR case over the West Atlantic in late April 2020, associated with rapid predictability degradation of a Rossby wave in the Global Forecast System (GFS) (~30 km resolution). Utilizing a subset of GFS ensemble members for initialization, simulations are performed using the Model for Prediction Across Scales (MPAS) at resolutions ranging from 60 to 3.75 km. We output diabatic heating components (microphysics, convection, radiation) to provide mechanistic insights into their interaction with the jet stream across resolutions.

Our case-study shows that MPAS outperformed the GFS in forecasting Rossby wave evolution, even at 60 km resolution. Higher resolution enhances diabatic heating accumulation in ARs, mainly driven by microphysics, while parameterized convection dominates heating at coarser resolutions. The different components of diabatic heating also lead to changes in the kinematic profile of the jet stream due to significant differences in the redistribution of PV along the tropopause at different resolutions. Additional experiments weakening latent heating at 60 km favor more cyclonic Rossby wave breaking, consistent with the GFS.

Our findings emphasize the jet stream's sensitivity to model representation of latent heating within ARs with embedded convection. Ongoing research explores the relationship between diabatic heating magnitude and Rossby wave breaking direction. More holistic insight is also provided on regions where ARs with embedded convection are prevalent, such as over the West Atlantic and West Pacific.

[101] | Using Complexity Science to Reveal the Dynamics and Impacts of Atmospheric Rivers in North America

First Author: Sara M. Vallejo-Bernal

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Recently, atmospheric rivers (ARs) have been identified as primary drivers of heavy precipitation events (HPEs) and precipitation-induced disasters in Western North America. Although it is undisputable that ARs trigger HPEs along the coastline when making landfall, the spatial and temporal extension of their lag-dependent impacts following landfall remains unresolved. Furthermore, while the association of ARs with floods, avalanches, and extreme winds has received substantial interest, the causal relation between ARs and precipitation-induced landslides is yet to be verified and quantified. Tools from complexity science provide great opportunities to contribute to these research gaps, where non-linear and time-delayed interactions need to be carefully considered. In this talk, we briefly introduce the concepts of event synchronization, climate networks, and probabilistic attribution, which are the building blocks of a powerful methodological framework to study AR dynamics and impacts. Our results reveal that inland-penetrating ARs are the drivers of cascading HPEs evolving in a temporally coherent manner from the Western Coast of North America to Canada. Moreover, synchronization concepts allow us to discover characteristic synoptic patterns and seasonality of these ARs. Using probabilistic attribution and non-linear time series analysis, we demonstrate that precipitation from land-falling ARs preceded more than 80% of days with precipitation-induced landslides in WNA between 1996 and 2018. With these two applications, extendable to broader regional and global analyses, we show that complexity science is a robust tool for exploring land-atmosphere couplings and precipitation-induced hazards. The complexity science machinery contributes crucial insights to enhance our understanding of ARs, improve forecasting accuracy and bolster mitigation strategies.

[102] | The role of Dry Intrusions in the formation and intensification of Atmospheric Rivers in the North Atlantic

First Author: Alexandre M. Ramos

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Extra-tropical storms over the North Atlantic often leads to socio-economic impacts over Western Europe, associated with strong winds and precipitation. Such storms can be associated with so-called Atmospheric Rivers (ARs). In turn, the moisture availability along the cyclone path and the ARs lifetime can be impacted by boundary layer processes. For example, the occurrence of Dry Intrusions (DI) associated with previous cyclones can strongly destabilize the planetary boundary layer (PBL) leading to enhanced moisture uptake over the ocean. This can support the formation and/or intensification of the ARs themselves.

The objective of this study is to understand the influence of DI on the moisture uptake in the PBL and transport associated with ARs impacting France. With this aim, an adapted version of the detection algorithm developed by Ramos et al. (2015), was applied to ERA-5 reanalysis targeting events impacting the Atlantic coast of France. A total of 300 AR-events were detected over the extended winter (ONDJFM) spanning the years 1979 to 2023.

For a subset of these AR-events, occurring between 1992 and 2022, the Lagrangian FLEXPART model using ERA5-data was applied to calculate the moisture sources for these events. This approach allows for the tracking of air masses 10 days backward in time from the target region in western France. Additionally, the occurrence of DI outflows (from 1979 onward) was based on its Lagrangian detection in ERA5 to assign possible DI outflows overlapping with the source regions of moisture uptake.

Our results suggest a relationship between the areas of DIs and moisture uptake, indicating the possibility of the DI exerting influence on the formation and intensification of ARs. Overall, this work serves as a preliminary investigation for the upcoming North Atlantic Waveguide, Dry

Intrusion, and Downstream Impact Campaign (NAWDIC) recently endorsed by the World Weather Research Programme (WWRP).

Theme: Physical, dynamical, microphysics and aerosol aspects of ARs

[103] | Role of atmospheric rivers in the variation of rain shadow strength over the southern Andes

First Author: Yazmina Rojas Beltran

CW3E / United States

Co-Authors: Justin Minder.

University at Albany, SUNY

The topography of southern South America (34-38°S) varies significantly, with a coastal mountain range, a central valley and the Andes, with elevations ranging from 1000-2500 m. This topography can disrupt frontal systems approaching from the Pacific Ocean, that are often accompanied by an atmospheric river (AR). These storms lead to enhanced orographic precipitation on the west side of the Andes, and suppressed precipitation on the leeside, producing a strong climatological rain shadow. Event-to-event variability suggests that some storms produce substantial spillover precipitation over the Argentinian side, leading to variation in the rain shadow strength. The processes and mechanisms, and the role of atmospheric rivers in modulating the differences between strong and weak rain shadow remain to be studied.

Using rain gauge observations, we classify variability of heavy precipitation events as strong or weak rain shadow events over the southern Andes mountains. ERA5 reanalysis was used to characterize synoptic and atmospheric conditions of these events, as well as the differences in AR intensity and direction between events. Composite analysis shows that strong rain shadow events can be produced by the landfall of ARs to the area, increasing precipitation upstream and decreasing the rain shadow. Representative strong and weak rain shadow events are simulated with the Weather Research and Forecasting Model to improve spatial and temporal resolution of the data. Water budgets were analyzed to quantify the role of water vapor from ARs in the variation of rain shadow strength. Results indicate that during the weak rain shadow case less water vapor is depleted by the Andes, allowing for water vapor to reach the leeside.

[104] | January 2023 Auckland flooding- Extratropical Transitioning and ARs?

First Author: Hamish Prince

University of Wisconsin - Madison / United States

Co-Authors:

On January 27th, 2023, Auckland, New Zealand received a record-breaking precipitation event, bringing 245 mm of rain in 24 hours, 50% more precipitation than the previous record (since the 1960's). The synoptic setup was dominated by an extratropical transitioning cyclone, which began as a tropical depression near New Caledonia before being steered poleward and underwent full transitioning. The cyclone entered into the New Zealand region, bringing warm, moist air and a substantial vapor flux directed poleward towards Auckland city. The synoptic setup was complex, with the passage of a warm-front kicking off a sequence of multiple deep convective systems, fully glaciated aloft, over the following 12 hours. The magnitude of this event was badly forecast, with 150% more precipitation falling in Auckland city than was forecast just 6-hours previously, with an individual convective cell delivering 65% of the rain within 4 hours, at a maximum rate of 70 mm/hr. Through various media releases, this event was described as an atmospheric river (AR) which presents some interesting questions. While this transitioning cyclone did develop frontal features, it remained distinctly tropical. The occurrence of ARs directly associated with extratropical transitioning cyclones remains broadly unexamined. I will discuss the dynamical life-cycle of this event, the tropical characteristics, and the implications of characterizing this extreme event for the study of future extremes in New Zealand.

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[105] | The distortions of bias correction on the Western United States Dynamically Downscaled Dataset and its effects on Atmospheric Rivers

First Author: Tim Corrie III

University of Wyoming / United States

Co-Authors: Stefan Rahimi University of Wyoming

Moisture from Atmospheric Rivers (ARs) is fundamental to western North American precipitation, snowpack, flood risk, and general water availability. In fact, 90% of tropical-to-extratropical moisture transport comes from ARs, being the most impactful during the winter months, accounting for 20-50% of California's cold-season precipitation. In a warmer future climate, cold seasons may be characteristically different from a current climate. Globally, a warmer future climate will increase the frequency and intensity of ARs, but these findings vary regionally because current GCMs are too coarse in spatial resolution to resolve AR moisture, precipitation, and topography. Thus, we consider a kilometer-scale dataset for multiple GCMs using the Western United States (US) Dynamically Downscaled Dataset (WUS-D3).

Previous studies show that dynamically downscaled GCMs ignore climate change signals and produce large structural uncertainties in their projection assessments. We aim to reduce these uncertainties by addressing such signals with the WUS-D3. To evaluate the distortionary effects of bias correction in these models, we will focus on the historical data in the WUS-D3 in order to get a direct comparison between models and observations (e.g. PRISM), as well as reanalysis (e.g. ERA5). We use an AR detection algorithm that focuses on AR events in the Eastern Pacific (i.e. the Western US coast) with Integrated Water Vapor Transport (IVT) maximum (max) above 250 kg m-1 s-1, among other criteria. Initially, the biases in the WUS-D3 produce much wetter events on average, both in terms of event IVT max and mean event-cumulative precipitation (MCP) in most dynamically downscaled GCMs. Once the AR detection algorithm has been run, these dynamically downscaled GCMs are compared to the ERA5 and PRISM dataset to assess the accuracy of bias corrections. These results will be ready and presented at the IARC 2024 meeting.

[106] | Advancing the Development of Atmospheric River Analysis and Forecast System (AR-AFS): Impacts of Physics and Domain Size on Precipitation Forecasts

First Author: Keqin Wu

Lynker at EMC/NCEP/NOAA / United States

Co-Authors: Xingren Wu, Axiom at EMC/NCEP/NOAA; M. M. Nageswararao, CPAESS, UCAR at NOAA/NWS/NCEP/EMC; Vijay Tallapragada, EMC/NCEP/NOAA; F. Martin Ralph, CW3E, UC San Diego

In order to provide numerical guidance for Atmospheric River (AR) forecasts and AR Reconnaissance (AR Recon), a high-resolution regional Atmospheric River Analysis and Forecast System (AR-AFS), targeted on the U.S. West Coast, has been developed. During AR Recon 2022 and 2023, it has been found that AR-AFS produced a large negative bias in precipitation forecast. Improving the skill of precipitation over the U.S. West Coast requires tuning and optimizing model configuration and key parameters. Given the important role of microphysics and planetary boundary layer (PBL) processes in the numerical simulations, we will examine the precipitation forecast sensitivity in AR-AFS to various parameterization schemes available from the Common Community Physics Package (CCPP). Specifically, we will test (i) GFDL vs. Thompson Microphysics scheme, and (ii) EDMF-TKE (turbulent kinetic energy-based moist hybrid eddy-diffusivity mass-flux) scheme vs. Yonsei University (YSU) PBL scheme. Since ARs contribute to non-convective precipitation events, we will also study the potential impact from enabling or disabling convection schemes within AR-AFS on precipitation forecast during an AR event. The size and location of the regional domain of a model may also impact on the forecasting skill, particularly in terms of spatial resolution and representation of local and synoptic features. We will also examine the potential impact of extending the domain to cover more of the Pacific region, on the precipitation forecast over the U.S. West Coast. The findings from these experiments will be used to improve the AR-AFS configuration for the next AR Recon season.

[142] | Are rapids in atmospheric rivers real?

First Author: Jason Box

Geological Survey of Denmark and Greenland / Denmark

Co-Authors: Jason E. Box, Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark

A detailed examination of atmospheric rivers (ARs) interacting with Greenland is made using a HARMONIE-AROME observational data assimilation system known as the Copernicus Arctic Regional Reanalysis (CARRA). Not only do the ARs bring flooding conditions to the ice sheet from numerous cases of 300 mm localized daily rainfall… Not only does the CARRA data resolve terrain and buoyancy-induced gravity wave oscillations over the ice sheet and coastal terrain… Not only does CARRA resolve orographic intensification of rainfall by up to a factor of four, consistent with the field data... The CARRA data reveal numerous along-flow updraft regions or 'rapids' embedded within ARs. The rapids specifically are along-flow updraft regions, 100–200 km in length, 5 to 15 km in width and 3 km deep, flowing 2 km above sea level at between 20 and 38 meters per second. While CARRA data resolve an atmospheric updraft jet 40–140 km offshore in an arc around southern Greenland, the CARRA data suggest that condensational buoyancy generation initiates and maintains the rapids. Some rapids begin upstream of an offshore updraft jet and also appear ~50 km offshore, west of the island, suggesting they are a more generally feature of the AR dynamics than just barrier wind-instigated. The presentation concludes with ideas for observational verification of the rapids to answer whether HARMONIE-AROME is hallucinating. Here is the associated publication https://doi.org/10.1002/met.2134 The CARRA data are 3-hourly, 1991 to present with 23 vertical levels at 2.5 km horizontal resolution, available from the Copernicus Climate Data Store.

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Session:

AR7- Role of ARs in the changing Cryosphere

[13] | When and why do atmospheric rivers influence Antarctic iceberg calving events?

First Author: Tristan Rendfrey

University of Michigan / United States

Co-Authors: Claire Pettersen University of Michigan, Jeremy Bassis University of Michigan, Catherine Walker Woods Hole Oceanographic Institute

Ice shelves, freely floating platforms of ice that surround the Antarctic ice sheet, can stabilize discharge from the grounded portions of the ice sheet. The retreat and collapse of certain ice shelves around the Antarctic ice sheet have renewed concerns that continued atmospheric and oceanic forcing could destabilize ice shelves, possibly triggering marine ice sheet or ice cliff instabilities. The retreat and collapse of Antarctic ice shelves is associated with the iceberg calving process. Recent work hints that instances of unusually strong water vapor transport in the atmosphere over an ice shelf can trigger iceberg calving events and disintegration through a combination of mechanical and thermodynamic processes. In this study, we examine the connection between the magnitude of water vapor transport over ice shelves and iceberg calving size and frequency. We examine integrated vapor transport (IVT) magnitude, wind velocity, near-surface temperature, and its monthly anomaly over ice shelves in the four week period leading to the calving of a tabular iceberg. We first assess whether strong IVT over an ice shelf is associated with iceberg calving. Our results show that a consideration of these atmospheric variables alone over an ice shelf alone cannot explain increased calving events. This work suggests instead that longer-term glaciological, oceanic, and atmospheric forcing can configure an ice shelf into a state in which it is vulnerable to calving triggered by strong water vapor transport. Efforts to predict the future stability of the Antarctic ice sheet must include an understanding of how and when these forcings enable strong IVT events to trigger iceberg calving.

[17] | Atmospheric river brings warmth and rainfall to the northern Antarctic Peninsula during the mid-austral winter of 2023

First Author: Deniz Bozkurt

Universidad de Valparaíso / Chile

Co-Authors: Deniz Bozkurt Universidad de Valparaíso, Jorge F. Carrasco Universidad de Magallanes, Raúl R. Cordero Universidad de Santiago de Chile, Francisco Fernandoy Universidad Nacional Andrés Bello, Álvaro G. Gómez Universidad de Chile, Benjamín Carrillo Universidad de Magallanes, Bin Guan University of California Los Angeles

While considerable attention has been given to the impacts of summer atmospheric rivers (ARs) on the Antarctic Peninsula, the effects during the winter months remain less explored. This study delves into a notable warming event from July 1 to 3, 2023, leveraging in-situ winter observations and ERA5 reanalysis data to shed light on the winter AR phenomena. On July 2, the Frei station documented an extraordinary winter rainfall accompanied by a temperature peak of 2.7°C, which led to a significant elevation in the freezing level—marking the first instance of observed Antarctic winter rainfall. This event was driven by a distinctive pressure dipole pattern over the Antarctic Peninsula, characterized by contrasting atmospheric circulations over the Bellingshausen and Weddell Seas. This setup facilitated the movement of an AR that transported warm, humid air from South America and the Atlantic, later shifting to pull air from the southeast Pacific. This atmospheric rearrangement resulted in precipitation with anomalous isotopic values, diverging from typical patterns observed in the region. Furthermore, trend analysis indicates a strengthening of the winter dipole pattern, correlated with an increase in AR frequency and elevated temperatures in the northern Antarctic Peninsula. These insights underscore the critical role of winter observations in understanding the dynamics and impacts of ARs, thereby filling a significant gap in our knowledge of winter AR behavior in the Antarctic Peninsula.

[18] | Atmospheric Rivers, and their effects on the Surface Radiation Balance in the Amundsen Sea Embayment

First Author: Georges Djoumna

Viamonde School Board / Canada

Co-Authors: David Holland, Courant Institute of Mathematical Science, New York University, New York, NY, USA

Over recent decades the primary climatic forcing on the ice shelves in the Amundsen Sea Embayment (ASE) has been the influx of warm water into sub-ice-shelf ocean cavities. By contrast, the contribution of a globally warming atmosphere has been negligible but may play a more significant role in the future. Warm, moist air intrusions from the ocean onto the ice sheet surface play an essential role in the surface energy budget and constitute the primary driver for surface melting in West Antarctica. This study employs observations from automatic weather stations deployed on the Pine Island Glacier and numerical model outputs from the Antarctic Mesoscale Prediction System to investigate Atmospheric River (AR) events and examine their impacts on surface glacier melt in the ASE. A deep low-pressure center over the Amundsen/Ross Seas and a blocking ridge over the southeast Pacific created favorable conditions for developing an atmospheric river that directs warm and moist air toward the ASE. An analysis of meteorological observations through 2013–2014 shows that 2013 received two times higher frequency ARS events than 2014. 2013 year coincides with more substantial pressure gradients in the western Ross Sea and the eastern Amundsen Sea. The February and March 2013 AR events induce about three days of surface melting over the Pine Island Glacier and the Thurston Island area. A continued increase in the large-scale advection of warm air from the midlatitudes toward the ASE could lead to an increased surface melting frequency with implications for ice shelves in the study area.

[View Image]

[19] | Antarctic Atmospheric Rivers in Present and Future Climates

First Author: Michelle Maclennan

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Atmospheric rivers (ARs) are long, narrow bands of moisture that propagate poleward from the midlatitudes and occasionally reach the Antarctic Ice Sheet. Despite occurring only ~1% of the time, Antarctic ARs contribute 10% of the annual precipitation and are major drivers for heatwaves, foehn events, and surface melting on ice shelves. While snowfall is currently the dominant impact of ARs over the grounded Antarctic Ice Sheet, the relative contribution of ARs to snowfall, rainfall, and surface melt may change in a warming climate, along with the frequency and intensity of AR events themselves. Here, we use the Community Earth System Model version 2 (CESM2) Large Ensemble to detect ARs during the current period (1980–2014) and future climate (2015–2100) under the SSP370 radiative forcing scenario. We use an AR detection threshold for the current period based on the 98th percentile of the meridional component of integrated vapor transport (vIVT). To account for projected future increases in atmospheric moisture content (Clausius-Clapeyron effect) and its impacts on vIVT, we scale our AR detection threshold for the future period by the relative change in integrated water vapor compared to the present-day climatology. We then describe how the frequency, intensity, and year-to-year variability in Antarctic ARs changes by the end of the 21st century by region, with links to changes in the large-scale atmospheric circulation accompanying ARs. Finally, we quantify AR-attributed precipitation, precipitation variability, and trends in the future climate, ultimately providing an early assessment of future AR-driven changes to Antarctic surface mass balance.

[20] | Synoptic and Planetary-Scale Dynamics Modulate Antarctic Atmospheric River Precipitation Intensity

First Author: Rebecca Baiman

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Co-Authors: Andrew C. Winters CU Boulder, Benjamin Pohl Université de Bourgogne Franche-Comté, Vincent Favier Institut des Géosciences de l'Environnement, Jonathan D. Wille ETH Zurich, Kyle R. Clem Victoria University of Wellington

Although rare, atmospheric rivers (ARs) substantially influence the interannual variability of Antarctic surface mass balance. Here we use MERRA-2 reanalysis to identify characteristics unique to Antarctic AR environments by comparing (1) Analog (environments that feature high-low pressure couplets, similar to AR environments, but no AR), (2) AR, and (3) Top AR (highest precipitation) timesteps during 1980–2019 around Antarctica. We find significant differences between AR and Analog environments including more intense and poleward-shifted mid-tropospheric geopotential height couplets as well as larger atmospheric moisture anomalies. We find similar significant enhancement in synoptic-scale dynamic drivers of Top ARs compared to all AR environments, but no significant difference in local integrated water vapor anomalies. Instead, our results highlight the importance of large-scale dynamic drivers during Top AR timesteps, including amplified Rossby waves excited by tropical convection.

[21] | Atmospheric Rivers can Prolong the Annual Breakup of Arctic River Ice

First Author: Russ Limber

Oak Ridge National Laboratory / United States

Co-Authors: Elias Massoud ORNL, Jitendra Kumar ORNL

Atmospheric Rivers (ARs) stand out as critical conduits of moisture and energy, exerting profound influence over our planet's cryosphere. Our study investigates the influence of ARs on river ice breakup dates in Alaska. We used in-situ river ice breakup dates from the Alaska Pacific River Forecast Center for 25 locations across interior Alaska, and analyzed them with AR data provided by the UCLA Global Atmospheric Rivers Database. ARs were cataloged using data from the National Centers for Environmental Prediction (NCEP) reanalysis product and the Guan-Waliser tracking algorithm. Thermal energy transfer was calculated between moisture introduced by ARs and the river ice surfaces. Thermal energy transfer was recorded in terms of positive or negative, indicating a heating of river ice or a cooling and subsequent buildup of river ice, respectively. Temporal information was embedded through the use of a bias function. Correlation analysis indicates that ARs occurring closer to the river freezing period with larger amounts of vapor transport appear highly influential in potentially delaying the breakup date and increasing river ice duration. Conversely, ARs that occur closer to the breakup date appear to have little influence over the breakup date regardless of temperature. This presentation will highlight the connection between the presence of ARs and the day-of-year in which the river ice break up dates occur for specific study sites in Alaska. These findings underscore the importance of considering the timing and intensity of AR events in understanding cryospheric processes and their implications for regional climate dynamics.

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[22] | Synoptic-Scale Extreme Sea Ice Reduction Events in the Antarctic associated with atmospheric processes

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Antarctic sea ice has been experiencing a significant decline in sea ice extent (SIE) during austral warm seasons (spring and summer) in recent years, with some cases suggesting that the accelerated ice reduction is linked to the synoptic-scale extreme sea ice reduction events (EREs). Nonetheless, the general contribution of the EREs and their underlying atmospheric processes remain unclear. Utilizing ERA5 reanalysis data and sea ice observation, this study demonstrates that individual EREs result in a reduction of SIE by 5%-15% within a few days, and their overall contribution to total SIE decline in the warm season is 25%-40%. The anomalously high sensible and longwave radiation under warm and moist conditions trigger the occurrence of EREs. This atmospheric process is linked to an intense dipole pattern characterized by high- and low-pressure anomalies downstream and upstream, respectively. The dipole pattern facilitates meridional warm-moist inflow and is associated with anomalously intense extratropical cyclones and blockings, accompanied by atmospheric rivers. Both the Southern Annular Mode and Zonal Wave 3 contribute to regulating the occurrence of this strong dipole pattern in the Ross Sea sector, potentially resulting in EREs and influencing sea ice retreat.

[23] | Influence of Atmospheric Rivers on Arctic Sea Ice Variability in Low- and High-Resolution Climate Models

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Recent studies have shown that the Arctic has exhibited increased sensitivity to anthropogenic-induced climate change compared to the rest of the globe. This increased warming has garnered further attention as a warmer atmosphere can have dire consequences for sea ice recovery on seasonal to decadal timescales. In particular, Arctic atmospheric river (AR) events that penetrate from the North Atlantic and Pacific basins have historically contributed to this variability. Furthermore, it is thought that dynamic and thermodynamic processes associated with these systems work to drive increased rates of sea ice loss due to changes to the atmospheric radiative budget. As a result, as the globe continues to warm, the Clausius-Clapeyron relation indicates that Arctic ARs may transport more water vapor, which will drive increases in downward longwave radiation and allow for further sea ice loss. This study uses the output from Historical simulations of the 6th phase of the Coupled Model Intercomparison Project (CMIP6) to explore how model resolution contributes to the uncertainties in modeled AR statistics and the response of Arctic sea ice to ARs. Specifically, we concentrated on models that participated in the High-Resolution Model Intercomparison Project (HighResMIP) and compared the simulations between the low-resolution versions and their high-resolution counterparts. Results from this study show that model resolution plays a role in detected AR statistics and is even more important in terms of exploring the relationship between Arctic sea ice and ARs. Overall, a high-resolution model better captures the observed melting effects that ARs exert on Arctic sea ice, indicating that increased model resolution allows for a more accurate representation of ice melt and formation processes. In other words, a more in-depth, holistic understanding of how mechanisms associated with ARs (i.e. intensity) influence sea ice area growth and variability is better resolved with the high-resolution models.

[24] | Quantifying the Impacts of Atmospheric Rivers on the Surface Energy Budget of the Arctic Based on Reanalysis

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We present a comprehensive analysis of Arctic surface energy budget (SEB) components during atmospheric river (AR) events identified by integrated water vapor transport exceeding the monthly 85th percentile climatological threshold in 3-hourly ERA5 reanalysis data from January 1980 to December 2015. Analysis of average anomalies in SEB components, net SEB, and the overall AR contribution to the total seasonal SEB reveals clear seasonality and distinct land – sea – sea ice contrast patterns. Over the sea ice-covered central Arctic Ocean, ARs significantly impact net SEB, inducing substantial surface warming in fall, winter, and spring, primarily driven by large anomalies in surface downward longwave radiation. We find that ARs make a substantial relative contribution to the mean SEB in spring (32 %), exceeding their corresponding occurrence frequency (11 %). However, in other seasons, ARs contribute relatively less to the mean SEB than their frequency, indicating a diminished role compared to their occurrence frequency. Over sub-polar oceans, ARs have the most substantial positive impact on net SEB in cold seasons, mainly attributed to significant positive turbulent heat flux anomalies, with a maximum contribution to the mean SEB in spring averaging 65 %. In summer, ARs induce negative impacts on net SEB, primarily due to reduced shortwave radiation from increased cloud cover during AR events. Over continents, ARs generate smaller absolute impacts on net SEB but contribute significantly to the mean SEB in cold seasons, far surpassing their corresponding frequency, highlighting their crucial role in determining the net SEB over continents during cold seasons. Greenland, especially western Greenland, exhibits significant downward longwave radiation anomalies associated with ARs, which drive large net SEB anomalies and contribute >54 % to mean SEB, and induce amplified surface warming year-round. This holds significance for melt events, particularly during summer. This study quantifies the role of ARs on surface energy budget, contributing to our understanding of the Arctic warming and sea ice decline in ongoing Arctic amplification.

[25] | The Atmospheric River and Foehn Warming Effects over the Antarctic Peninsula.

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The Antarctica Peninsula (AP) has experienced extreme weather and intense surface melting in the past few decades. The combined effects of Atmospheric Rivers (ARs), amplified leeside foehn warming, and surface snow melt pose threats to the stability of ice shelves, ultimately resulting in ice loss. This study utilizes high-resolution Polar WRF simulations driven by ERA5 to analyze more than 40 strong AR cases, selected based on the CW3E Polar AR scale, that occurred during austral summers post-2000. The primary focus is to investigate the relationship between ARs and foehn warming, orographic precipitation, as well as the combined impact on surface energy balance. Preliminary results suggest that the AR, including the direction, Integrated Vapor Transport (IVT) magnitude, and duration, significantly influence foehn-induced warming mechanisms, leading to distinct patterns of surface melting on the leeside. Increased incoming shortwave radiation from foehn clearance along with higher downward longwave radiation due to cloud formation from AR spillover, and stronger sensible heat flux towards the surface resulting from mountain waves contribute to an elevated surface energy balance and more melting. The contribution of each component varies depending on the characteristics of the AR, and we identify and quantify these contributions. Additionally, ARs can introduce intense rainfall and trigger rain-on-snow events, particularly on the upwind side. This study underscores the growing impacts of ARs over Antarctica in the context of climate change, while also emphasizing the efficacy of high-resolution model simulations in revealing regional-scale drivers and estimating the ice loss.

[26] | May the AR-Force Be with You : Unraveling Arctic Atmospheric Rivers and Sea-Ice Uncertainties

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The decline of Arctic sea ice in recent decades is closely associated with amplified warming and the heightened occurrence and intensity of storms in the region. Atmospheric Rivers which are usually associated with an extratropical cyclone, have the potential to impact Arctic sea ice through both thermodynamic and dynamic mechanisms. However, our current understanding of the evolving nature of ARs in a warming climate and their specific influence on sea ice remains incomplete. To address these knowledge gaps, we employed the Atmospheric River Detection and Tracking algorithm (ARDT) that utilizes meridional integrated vapor transport to identify ARs in the Arctic within the Community Earth System Model, Version 2 (CESM2). We evaluated CESM2's capacity to simulate intense ARs by comparing it to ERA5 reanalysis data. Our findings demonstrate that CESM2 generally captures the patterns and prominent hotspots of ARs, exhibiting agreement with ERA5 data during the 1980-2015 period. Furthermore, we investigated changes in AR behavior under the SSP370 scenario, which assumes high greenhouse gas emissions. We explore three different methods to detect ARs under a changing climate scenario by modifying the minimum threshold criteria of the AR detection algorithm. 1. Defining extremes based on present climate thresholds; 2. Scaling the threshold with projected changes in moisture for the future; and 3. Calculating a unique threshold for each decade. Our results reveal an increasing trend in AR occurrence for all the three methods, during winter, fall, and spring, accompanied by intensified ARs throughout all seasons.

Moreover, we assessed the impacts of ARs on sea ice for all the three different methods and consistently observed a net sea-ice loss impact through both dynamic movement of ice and thermodynamic heating. Overall, our findings suggest that the escalating frequency and intensity of ARs could exacerbate the decline of Arctic sea ice, leading to significant consequences for the Arctic ecosystem and global climate.

View Image

[27] | Investigating the role of atmospheric rivers in mass anomalies detected by GRACE/GRACE-FO

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In this study we use mass concentration (mascon) solutions for regional mass change estimates, derived from GRACE/GRACE-FO spherical harmonics to detect mass anomalies in the 2002-2024 time series. GRACE/GRACE-FO mascon solutions are available at monthly temporal resolution. In accordance with other studies conducted, investigating atmospheric river (AR) contribution to both high accumulation snowfall events (Gorodetskaya et al., 2014), as well as high relative rates of liquid precipitation, which can lead to surface melt (Wille et al., 2022), we use MERRA2 reanalysis at 3H time intervals from 2002-2024 to co-examine mass anomalies detected from GRACE/GRACE-FO. However, high accumulation snowfall events cannot always be directly linked to a corresponding AR, and here we investigate atmospheric anomalies, AR or otherwise, that are most likely drivers of an anomalous mass signal. We are interested in, not only, co-identifying mass anomalies with ARs, but also synopsizing sets of atmospheric conditions and parameters that are highly correlated with mass anomalies, not directly associated with landfalling ARs. We calculate additional metrics using variables, including IMFC (integrated moisture flux convergence), CRH (column relative humidity), and PCR (primary condensation rate); CRH and PCR are supplemental quantities presented by Mo et al., 2021, to aid in AR analysis. CRH and PCR may help to better describe large-scale precipitation associated with a landfalling AR in Antarctica. Using PCR, we are able to identify orographically enhanced regions along the coastline that experience relatively high snowfall rates, given the absence of ARs. Combining this approach with regional mascon solutions from GRACE/GRACE-FO we are able to calculate total net precipitation from atmospheric anomalies, including ARs, to be able to compare to monthly mass anomalies, and define the contribution of ARs to the detected signal.

[28] | Extending the CW3E Atmospheric River Scale to the Polar Regions

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Atmospheric rivers (ARs) are the primary mechanism for transporting water vapor from low latitudes to polar regions, playing a significant role as drivers of extreme weather, such as heavy precipitation and heat waves in both the Arctic and Antarctica. With the rapidly growing interest in polar ARs during the past decade, it is imperative to establish an objective framework to quantify the strength and impact of these ARs for both scientific research and practical application. The AR scale introduced by Ralph et al. (2019) ranks ARs based on the duration of AR conditions and the intensity. However, the thresholds of integrated water vapor transport (IVT) used to rank ARs are selected based on the IVT climatology at middle latitudes. These thresholds are insufficient for polar regions due to the substantially lower temperature and moisture content. In this study, we analyze the IVT climatology in polar regions, focusing on the coasts of Antarctica and Greenland. Then we introduce an extended version of the AR scale tuned to polar regions by adding lower IVT thresholds of 100, 150, and 200 kg m-1 s-1 to the standard AR scale, which starts at 250 kg m-1 s-1. The polar AR scale is utilized to examine AR frequency, seasonality, trends, and associated precipitation and surface melt over the Antarctic and Greenland coasts. The polar AR scale better characterizes the strength and impacts of ARs in the Antarctic and Arctic regions, and has the potential to enhance communications across observation, research, and forecasts for polar regions.

[29] | Atmospheric Rivers over Himalayan Basins: Understanding their Impacts and Dynamics

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Indian Institute of Technology Indore / India

Co-Authors: Rosa Vellosa Lyngwa, Munir Ahmad Nayak, and Mohd. Farooq Azam

Atmospheric rivers (ARs) significantly influence high-impact precipitation, especially in mid-latitude coastal mountains. Mountains located deep inland also experience ARs, making it crucial to understand how their hydrology is modified. Therefore, we examined ARs' influence on two major snow-and glacier-rich basins in Himalaya − Indus Basin (IB) and Ganga Basin (GB), which collectively support nearly a billion inhabitants. We assessed the physical mechanisms contributing to AR moisture/precipitation using moisture budget on the top AR events (highest IVT and longest duration) and selected two regions within the ARs to highlight Himalaya's significance: near the mountains and over the plains. ARs are identified using 6-hourly Integrated Water Vapor Transport (IVT) from ERA5 in a detection algorithm tailored for the Himalaya. IB and GB observed the largest floods in September 2014 and June 2013, respectively. The events are accompanied by category 5 ARs (IVT ≥ 1000 kg.m-1.s-1, duration ≥ 24-hours), that is primarily hazardous. During the events, precipitation generated is 30%–45% of the total annual precipitation, and discharge exceeded very high flood levels. ARs contributed 20%–30% on average to the total annual rainfall in IB and 5%–20% in GB, with spatial variability across the basins. ARs contribute the most in winter, with over 50% and 40% to rainfall and snowfall, respectively, in the mountains. They explained over 75%, 57%, 42%, and 30% of the winter precipitation variability in Karakoram, Hindu Kush, Central Himalaya, and Western Himalaya, respectively. High precipitation occurs over the mountains, with high-intensity precipitation resulting from strong positive convergence, positive advection, minimal evaporation, and small-time changes in atmospheric storage, while low-intensity precipitation results from low positive or large negative convergence, negative advection, increased evaporation, with high net accumulation in the atmospheric storage. Thus, ARs exert significant impacts on the Himalayan hydrology, necessitating further investigations to explore their broader impact.

[143] | Precipitation and melt over the Antarctic Peninsula: the role of intense atmospheric rivers

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Atmospheric rivers (AR) of high intensity occur rarely in the Polar regions but can play an important role in the regional climate-state extremes. In Antarctica, intense ARs have caused remarkable impacts during recent years, including record-high surface melt over the Antarctic Peninsula (AP) in February 2022 (Gorodetskaya et al., 2023) and the strongest heatwave ever recorded over East Antarctica bringing extreme inland snowfall and coastal surface melt in March 2022 (Wille et al., 2024). The AP event particularly demonstrated that an intense AR can induce a strong impact on the surface energy and mass balance in a short time (less than two days). Here we extend this analysis considering all AR events greater than category 3 (following classification described by Zhang et al, 2024) reaching the AP coast with a focus on 2022-2024. We analyse the time evolution of precipitation and surface melt using observations at the King Sejong station (northern AP) and Vernadsky station (northwestern AP) including thermodynamic structure of the troposphere measured with radiosondes and precipitation profiles from MRR-PRO radar. Further, we use high-resolution model simulations (regional climate model MAR and Polar-WRF) forced by ERA5

reanalysis, along with surface melt derived from microwave satellite observations, to show the spatial scale of specific events over the entire AP, regarding both snowfall to rainfall transition and surface melt.

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Appendix I: Long Abstracts

This document includes long abstracts submitted to IARC 2024. The abstracts are presented as submitted by the authors, sorted by session. We hope they are useful for the broad research and professional community working on the science and impact of Atmospheric Rivers

Theme: Observing, identification, and monitoring of ARs

[Long 12] | Detection Uncertainty Matters in Quantifying Meteorological Extremes of Euro-Atlantic Atmospheric Rivers

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1. Overview

There are many factors impacting the uncertainty in mapping Atmospheric Rivers (ARs), including the data, methods, parameter type and parameter choices used. Thus, qualitative assessment of the magnitude and intensity of meteorological extremes caused by ARs, and our scientific understanding depends on quantifying the uncertainty in the AR mapping. For example, results from the Atmospheric River Tracking Method Intercomparison Project (ARTMIP) indicate a broad range of plausible AR detectors and that scientific results can depend on the algorithm used. It is, therefore, imperative to use detection techniques that explicitly quantify the uncertainty associated with the detection of events. We use a Bayesian framework, which yields a set of "plausible" AR detectors from which we can assess quantitative uncertainty. This probabilistic AR detector has been implemented in the Toolkit for Extreme Climate Analysis (TECA). We tested the regional implementation of the TECA Bayesian AR Detector, TECA-BARD v1.0.1, on the ERA5 reanalysis on the Euro-Atlantic region and investigated the impact of the detection uncertainty on the qualitative understanding of AR-caused meteorological extremes over Europe during 1940-2022.

2. Data and Methods

We use ECMWF Reanalysis v5 (ERA5) 6-hourly instantaneous data (Hans et al., 2020) of specific humidity, zonal, and meridional wind components available during 1940-2020 at 0.25-degree horizontal resolution at all available vertical levels from 1000-300 hPa. This data obtained from the climate data store (CDS, https://cds.climate.copernicus.eu/) is used as input to TECA-BARD to map the ARs with inline uncertainty over the Euro-Atlantic region 100W- 25E;0-80N, as described in the following section. Ensemble mean precipitation, wind speed and minimum temperature data of E-OBS daily gridded data (V28.0e) for Europe (Jouke et al., 2023) from 1950 at 0.25-degree horizontal resolution have been used to study the impact of AR uncertainty on meteorological extremes and variability over Europe. While precipitation and minimum temperature (TN) are available from 1950, wind speed data is available from 1980. We processed over 16 terabytes of data from 1940 to 2022 to map ARs with uncertainty. We obtained the model results at 6-hourly time steps from 1940 to 2022, totalling data over 121264 time steps. Daily means (average of 4-time steps) of ARs (integrated water vapour transport, IVTs) are computed (Venugopal et al., 2022) to match with the temporal resolution of precipitation, wind speed, and TN for further analysis. Though the ERA5 data is available at 1-hour intervals and will be advantageous for short- term analysis and forecasting over a small area or location, it is computationally expensive when used for 83 years over a larger area and would not significantly impact the results. The TECA pipeline that makes up the TECA-BARD application can be found in Figure 7 of O'Brien et al. (2020).

Table 1: Ranges and priors in the AR detectors used in TECA-BARD

Description	Range
Percentile threshold for IVT	(0.8,0.99)
Size: Minimum area of contiguous region	(1×1011, 5×1012) m^2
Location: Zonal half width at half maximum of tropical filter	(5, 25)^{o}N

3. Uncertainty in AR detections and frequency

Figure 1 shows the statistics computed using individual detectors for the entire study period. This was done to illustrate the performance of all AR detector sets and their agreement/disagreement in mapping ARs over the Euro-Atlantic region. It was found that the 1024 AR detector parameter sets used to map ARs showed a large deviation in mapping individual ARs (counts). This deviation affected the aggregated probability (ARP) over a region or area. The number of ARs detected by individual detectors on 6-hourly time steps varies between 10^5-$2x10^5$, showing a difference of 2-fold more detections by some AR detectors. However, many detectors show a mean AR detection of at least 1 AR per time step during this period with a spread of ± 0.56 (figure 1a). TECA BARD uses the 128 MCMC samples generated for each expert group (i.e. for 8 experts, 1024 samples) of AR detections. The samples are stored in an input parameter table such that parameters from the same expert group are contiguous, which allows post hoc grouping of results/counts shown in Figure 1b (O'Brien et al.

2020). The differences in annual AR count show a distinct multimodality among AR detectors spread across different years and detectors. The number of ARs per year detected over each 6-hourly interval ranges from 10^3-$3x10^3$, 3-fold more detections by some AR detectors (parameters) identified by corresponding expert groups. These multi-modal bands in the annual number of AR detections have persisted for 83 years. This shows the consistency and stability of these AR detector sets in different seasons and are unaffected by different climate modes over the region. Moreover, this multimodality is manifested by three factors: (1) parameter dependence of the counts generated by the AR detector, which depends on the underlying thresholds listed in Table 1; (2) Variability in AR counts from 8 experts provided as input to developing the method; and (3) the addition of posterior distributions from each expert AR detections due to inherent distinct modes in each of them (O'Brien et al. 2020).

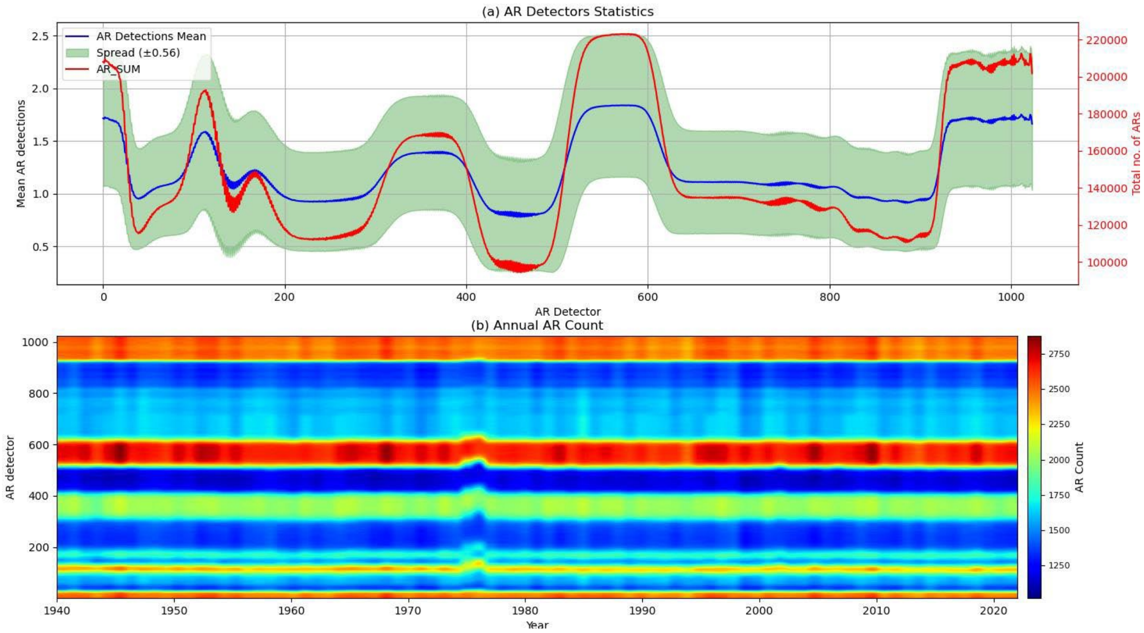

Figure 1: Performances of AR detector sets highlighted by statistical differences. (a) AR detector statistics showing mean, spread and the sum of ARs detected (b) Annual AR counts per each AR detector during the study period over the Euro-Atlantic region.

The detections made by AR detectors with low and high "confidence" in TECA-BARD have a similar effect to the variability of ARs' spatial frequency magnitude over the Euro-Atlantic region (Figure 2). The high "confidence" ARs (where ARP>=0.667, denoted as ARBT) are mainly limited to the United Kingdom and coastal Europe, above 45^{o}N, which is along the North Atlantic storm track (Figure 2b). However, ARBT cannot account for the occurrence of ARs over southern Europe (Iberian Peninsula) and the Scandinavian peninsula. Conversely, the frequency of ARP is high in these regions, along with Eastern Europe, leading to significant differences between ARP and ARBT in this area (as depicted in Figure 2c). The physical features, orography, have a significant impact on the frequency of ARs across Europe. The leeward side of high mountains, such as those found in the central plateau of the Iberian Peninsula and the Alps, creates AR "shadow" regions with low ARPs and almost no ARBTs.

Similarly, ARs occur frequently over inland Europe along the great European plains. The significant difference in the ARP and ARBT for a given number of AR detections is their area/footprint and the width of their lateral boundaries. The ARBT has narrow boundaries, whereas the ARP has a broader reach. Another reason could be the paths ARs follow. High "confidence" ARs embedded in the winter storm tracks move northward along coastal Europe and maintain high IVT due to the continuous supply of moisture from the adjacent ocean (David et al., 2010; Herald et al., 2013; Fraedrich et al., 1993). With favourable conditions and less orographic attenuation, weaker and moderate ARs (ARP) could move along the northeast to reach more inland areas.

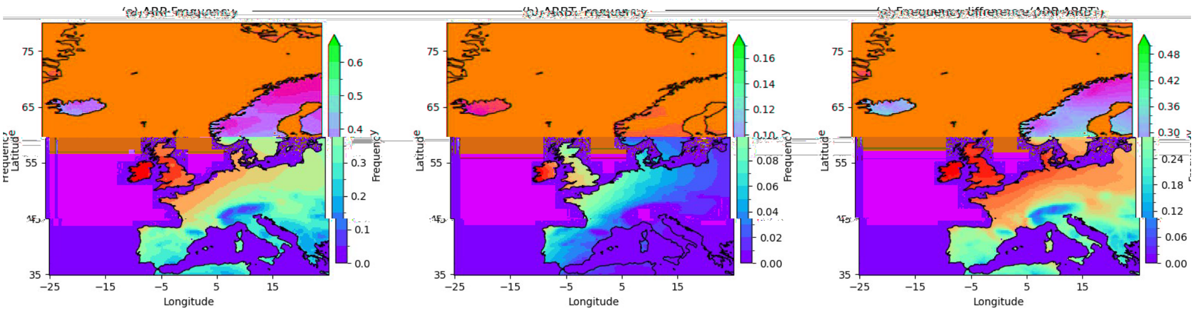

Figure 2: AR frequencies calculated over Europe using 6-hourly TECA-BARD output data (121264-time steps) during 1940-2022 from (a) ARP, (b) ARBT (ARP>=0.667) and (c) the difference between ARP and ARBT

4. Impact of ARP deciles on AR characteristics

The AR counts from TECA-BARD and ARTMIP agreed to the presence of “high confidence” ARs across the world (O’Brien et al. 2020). They showed less agreement over relatively small areas of the eastern United States and the central North Atlantic with high IVT due to the multi-modality in the posterior distribution of parameters in AR detectors, mainly due to the minimum area and the tropical filter (O’Brien et al. 2020). Figure 3 shows the impact of the selected ARP decile on the annual AR characteristics and associated meteorological parameters. Testing all the thresholds in the ARP is impossible, so the optimal decile method has been selected. This involves increasing the ARP by 10% at each iteration up until 90% and denoted by D00, D10...., and D90, respectively. This will narrow down the area represented by the ARP by increasing the confidence of AR detection, as shown in Figure 3a. The annual mean of the AR area represented by each decile, computed from the annual mean of the total area covered by an AR at each instance of landfall, shows a strong gradient from D00 to D90.

The IVT from selected deciles shows an opposite pattern with low annual values in D00 to high annual IVT in D90. Again, the increase in deciles leads to high confidence in AR regions and, thus, higher IVTs (Figure 3b). However, these similarities in area and IVTs do not resemble precipitation patterns. While selected deciles significantly impact the annual precipitation spread and magnitudes (Figure 3c), the ARPs above D40 show large interannual variability in representing the mean yearly precipitation from an AR event embedded in the decal variability. While there wasn’t a significant change in the area of impact of ARs and corresponding IVTs above D10 (Figure 3a, 3b), the selected deciles had a more substantial effect on the spread and magnitude of meteorological variables, as observed in Figures 3c, 3d and 3e. The causes of these large changes in magnitudes in the meteorological parameters due to a slight shift in IVT and AR sizes and their interannual and decadal variations are currently unclear. Further studies are required to explore the impact of climatic conditions, dynamics, thermodynamics, and the role of ever-changing climate modes on large-scale circulations affecting ARs over the region, which are currently not included in the study.

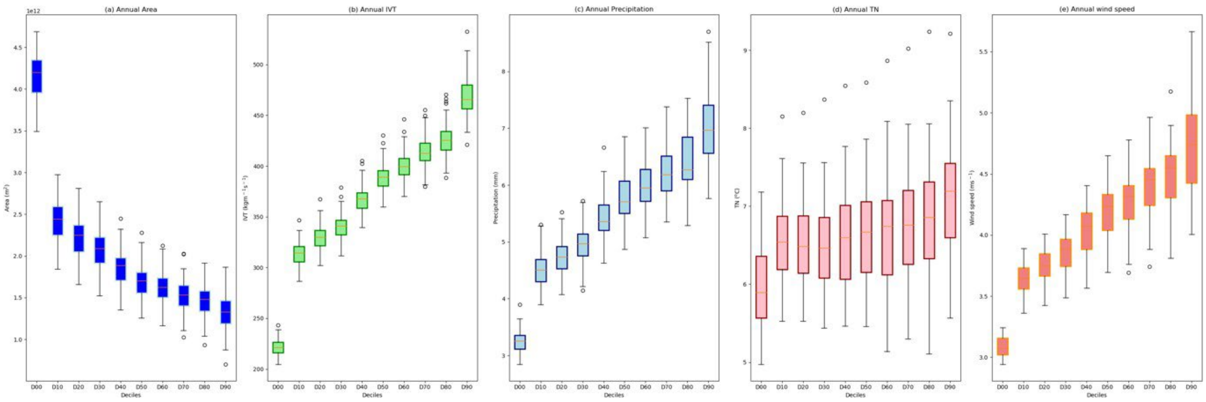

Figure 3: Whisker-box plot showing the spread of annual mean of AR characteristics based on selected deciles for (a) Area, (b) IVT, (c) precipitation, (d) TN, and (e) wind speed.

5. Impact on Compound and Concurrent Meteorological Extremes over Europe

Successive AR events, also known as AR families, can result in compound hydrological extremes due to limited recovery time between periods of precipitation (Meredith et al., 2022). This can lead to enhanced hydrological and economic impacts, particularly over the coasts of Europe, the U.S., and Norway (Corinne et al., 2024; Waliser and Guan, 2017; Payne et al., 2020; Luis Gimeno-Sotelo and Luis Gimeno, 2022; Monica et al., 2020; Nina et al., 2018). However, there is a lot of uncertainty around the occurrence and magnitude of compound meteorological extremes when individual AR landfalls (Waliser and Guan, 2017; Pagano et al., 2021), as the characteristics of individual ARs depend on the mapping techniques/algorithms and data used (Yang et al., 2021). This uncertainty is further compounded by the qualitative segregation of the different types of ARs (flavours) and their large-scale flow patterns (Albano et al., 2020; Meredith et al., 2022; Meredith et al., 2019; Benedict et al., 2019). To better understand the compound and concurrency of meteorological variables during individual AR landfall, we calculated the simultaneous Pearson's correlation coefficients (PCCs) among their anomalies. Figure 4 shows these PCCs for ARP and ARBT, which are calculated using daily anomalies of variables computed from daily climatologies of the data in the study period. Increased wind speeds along coastal Europe, the UK and northern Norway led to moderate changes in the ARP precipitation, further confined to narrow regions in the case of ARBT (figure 4a and 4d).

In contrast, inland areas lacking terrain features generally have much lower correlations. This variability can be attributed to vertical uplift and condensation factors that ultimately determine the efficiency with which water vapour is converted to precipitation, including the orientation of winds relative to terrain. Thus, the impact of wind speeds and directions during AR landfall on precipitation patterns depends on the region's topography and the storm's orientation (Albano et al., 2020). Similarly, increasing surface temperatures do not favour AR precipitation. Conversely, as temperatures decrease, condensation rates increase following the Clausius-Clapeyron relationship (Payne et al., 2020), increase precipitation efficiency. This means that colder surface temperatures can lead to more precipitation for a given amount of water vapour. Colder temperatures may enhance precipitation through ice-phase vapour deposition and riming, which convert supersaturated water vapour to precipitation more efficiently in cloud conditions (figures 4b, 4e). ARs are typically associated with strong winds that can transport warm, moist air from lower latitudes to higher latitudes. This warm air advected can subside with the AR landfall and increase surface temperatures in the regions affected by the AR (figures 4c, 4f), leading to positive PCCs with wind speeds over coastal Europe and Scandinavia. The mild/moderate ARs with lower probabilities can also lead to larger warming over land and thus causing PCCs to be higher in the case of ARP than in ARBT. For ARP or ARBT, no significant relationship was found between the precipitation and wind extremes. However, moderate PCCs are found more inland between ARP extreme precipitation and TN. Mild negative PCCs between extreme winds and TN over the UK, inland Europe and Scandinavia can be explained by the seasonal AR flavours (families) and orientation (Meredith et al., 2019, Griffith et al., 2020), which can advect cooler air from the north when dominated by the meridional IVT component.

In some cases, strong winds might follow the passage of a cold front, which could clear the sky. Clear skies at night allow for more effective radiative cooling of the Earth's surface, leading to lower minimum temperatures, especially during northerlies. Strong vertical stability can be established when surface temperatures are colder than the atmosphere due to the warmer atmosphere over a colder skin surface temperature. This creates more stable conditions that are opaque to momentum transfer to the surface from the AR jet. On the other hand, when the atmosphere is colder than a warmer skin surface temperature, it creates the opposite effect and is conducive to strong surface winds (Pagano et al., 2021). This could further lead to reduced radiative cooling from the surface.

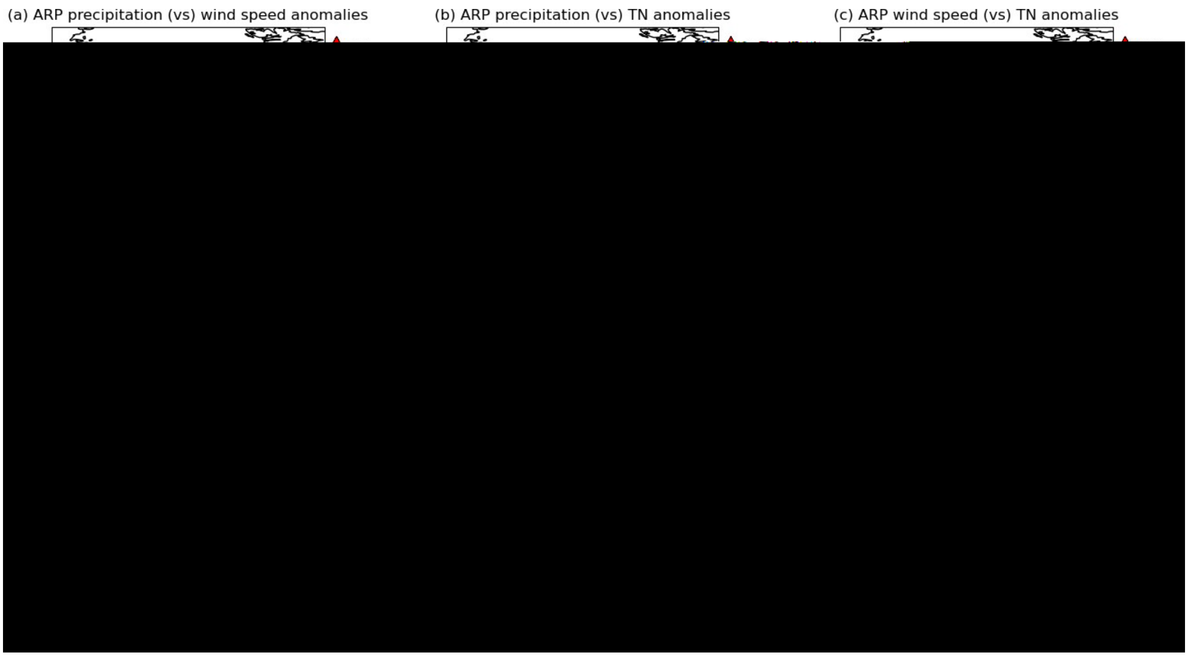

Figure 4: Compoundness and concurrency among anomalies of meteorological variables during AR landfall based on ARP (row 1: a, b, c) and ARBT (row 2: d, e, f). All PCC values shown are significant at 95%.

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Theme: Forecasting of ARs

[Long 33] | Comparing IVTinit-estimated Day0 Total One-Day IVT with Daily GFS Day0 TIVT24 out to 30 Days

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Our task is to provide better consistency and stability to forecast guidance of precipitation for systems approaching California from the North Pacific. In 2019 we developed IVTinit™, a one-day total IVT calculated daily from sea surface temperature anomaly (SSTA) via our AI application. Part of our purpose here is to add some background for linking IVTinit to cyclogenesis. Linking cyclogenesis in polar lows and troughs to their transit across a locally warm sea surface was the subject of simulation studies since Emanuel and Rotunno (1989), and recent work of Phillips and O'Neill (2020). The general process of calculating total one-day TIVT from SSTA was in our report, Fox and Montenegro (2020), for IARC2020. The best description for IVTinit is: "estimated Day0 TIVT, using SSTA as primary argument". IVTinit features shown by our daily maps appear similarly to small atmospheric features, i.e. fronts, troughs, small lows. Our literature review, revealed that mesoscale ocean eddies (200-800 km extent) move and evolve at a much slower rate than meso-alpha-size atmospheric lows and troughs at 850-700 hPa. To aid forecasting, we review sea surface temperature anomaly (SSTA) patterns associated with mesoscale ocean eddies of 200-500 km horizontal extent, and estimated surface to 0.8 km depth. Our CyclogenIVT™ produces the daily IVTinit map. The smallest IVTinit features appear similar in size to the larger warm mesoscale ocean eddies depicted in the NOAA OSPO daily SSTA maps.

Since December 2022, we have compiled daily day0 Total IVT (TIVT24) by the Center for Western Weather and Water Extremes (CW3E) from the Dateline to North American West Coast (~120W). Seven day means of Day0 TIVT24 are compared via centered pattern correlation for each day out to 30 days beyond the IVTinit date.

We also include some discussion and references to recent studies to provide some physical background for the IVTinit™ conceptual/model, developed by Fox Weather, LLC.

For manual analysis, we annotate the zones of expected cyclogenetic maxima to correspond with zones of IVTinit gradient. The most interesting results so far:

A) Maximum correlations are between Day18 and Day28 beyond IVTinit date,
B) Maximum coastal rainfalls occur near downstream portion of positive IVTinit gradients in WSW-ENE flow.
C) Groups of oceanic warm mesoscale eddies, individual eddies ~150 km, appear to add energy to develop fronts and troughs (Zhang, et.al. 2020).
D) Lowest pattern correlations occurred during the seasons with greatest tropical influence, i.e. August and September, or at times when the IVTinit signal was masked by an active MJO contribution to force the longwave pattern.
E) Long, narrow bands of high IVTinit (generally 3 to 5 x 107 kg m-1 day-1) appeared similarly to the classic atmospheric river signature, with major axis of front oriented in a WSW-ENE direction.

OBJECTIVES

1) Improve extended forecasts during periods of weak low latitude influence, mainly convection near equator (MJO-related).
2) Add cyclogenetic trend to our forecast discussions for midlatitude troughs and cyclones. Physically, IVTinit is calculated from one-day Day0 TIVT and linked to Sea Surface Temperature Anomaly (SSTA) at 1200 UTC (Fox and Montenegro 2020). The Day0 24-hour TIVT for each day is considered the best estimate of observed TIVT for this study.
3) Calculate by pattern correlation (PatCorr) a relationship between a single IVTinit analysis (units of TIVT) and one week mean of Day0 TIVTs, calculated in a daily time step, throughout a one month period. This shows the variation in TIVT7mean starting at each day through the 30 day period.
4) Provide a science-based background for using IVTinit as additional forecast guidance, and its use as a second opinion in forecast discussions, including regime changes.
5) Present one year of the monthly time series: observed IVTinit at beginning of the month compared to daily updated Day0 TIVT7mean. The pattern correlations refer to the one IVTinit compared to TIVT7mean beginning on each day of the month.

METHOD

A) We developed an AI application, CyclogenIVT™ (Fox and Montenegro, 2020). The estimated initial one-day TIVT (IVTinit) is calculated from input SSTA into CyclogenIVT™.

B) Using the IVTinit map on a particular initial date, we calculated pattern correlation (PatCorr) to 30 days for seven day mean of daily observed TIVT.

1. For calculating IVTinit, we used the same model and method as in Fox and Montenegro, 2020.
2. For Centered Pattern Correlation, we used the NCAR NCL system to calculate the daily values of PatCorr. The domain for calculating IVTinit was continued at 180W to the United States and Mexico West Coast regions, 55N to 20N, and nominally 180W to 118W.
3. Calculate by centered pattern correlation a relationship between a single IVTinit analysis for beginning of each month, and one week means of TIVT for each day of the respective month from December 2022 through February 2024.
4. As input for daily briefings plot the expected influence from positive IVTinit gradient measured equatorward, and downstream (generally eastward) in a pattern with westerly flow component.

Figure 1: Illustration of Analysis Method

Figure 2: Two consecutive examples of mean weekly TIVT's matched with initial IVTinit (day0 TIVI) for comparison.

Figure 3 and 4: Pattern Correlation Plots for December 2022 - March 2024 and December 2023 - February 2024 IVTinit at beginning of month.

SUMMARY AND CONCLUSIONS

1) Numerical comparison of our IVTinit™ with CW3E's TIVT24:
2) CW3E's TIVT24 is based on numerical model (GFS) derived calculations. Our IVTinit covers 24-hour period, but is based on SSTA only, not direct calculations from deterministic model data. The values of IVTinit are essentially the same scale as TIVT24. Generally, we should expect to see more variation into higher TIVT values from model data than from SSTA.
3) We used Centered Pattern Correlations from the NCL system (NCAR2024) to compare IVTinit at initial time to date-specific Day0 TIVT7mean, referenced as 'observed' for each day through the month.
4) Correlations (PatCorr) were calculated throughout the IVTinit domain from the Dateline to west coast and 20N to 55N. Therefore, the Pattern Correlation values include contributions from the entire domain, not simply between Hawaii and the coast of California. For a large domain, we would generally expect a lowering of PatCorr values.
5) Plots of PatCorr are presented in Figures 3 and 4. The domain covers North American West Coast to the Dateline (180) in the North Pacific, 20-55N.
6) Cases of IVTinit vs observed PatCorr and their approximate percentages: 0.2-0.3 low correlation, comprised 30% of cases, 0.30-0.45 is moderate correlation, comprising 25% of cases, .45-.65 is fairly strong correlation, comprising 15%. The best correlations we saw were .65 - 0.8 but comprised only about 10-15%. PatCorr of 0– .19, minimal or none, comprised about 15% of cases.
7) The pattern correlation plots indicate a 2.5 to 3.5 week maximum in PatCorr between original IVTinit and 7 day mean of daily TIVT.
8) To use IVTinit for forecast guidance, we recall that IVTinit is one of multiple influencers of cyclogenesis. The MJO exerts a stronger influence. IVTinit and the MJO each can add variation and uncertainty into the other's effect on cyclogenesis, and measurement of skill.
9) Despite the low pattern correlation numbers, IVTinit, when compared with TIVT7mean during weeks 2.5-3.5 generally showed a maximum of skill in predicting regime changes in east Pacific near California.

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