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BOOK OF ABSTRACTS

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Book of Abstracts

Preface

In an effort to bring together people interested in Atmospheric River Science and applications, the Center for Western Weather and Water Extremes initiated and hosted the first and second International Atmospheric River Conferences (IARC 2016 and IARC2018, Ralph et al. 2017 and Ramos et al. 2019, respectively), which were held at the Scripps Institution of Oceanography in La Jolla, California, USA. This was followed in June 2019 by the AR Colloquium Summer School (Wilson et al. 2020), focused on training a new generation of AR experts, also hosted at Scripps. During that event we decided a third version was warranted and agreed to further expand the transcontinental reach of our conference by holding it in Santiago, Chile.

In late 2019 we began the preparation for 3-IARC (aka IARC-2020), scheduled for the first week of October 2020, assembling our Scientific Steering Group (SSG), selecting conference themes and even considering the options for a trip to the Andes. The first circular was sent in November 2019 and the web site was ready in January 2020….and then came COVID-19.

We all have been affected by this pandemic and we sympathize with those suffering the most. In spring 2020 the SSG faced a decision, to proceed with planning a fall 2020 conference despite the uncertainty or postpone until 2021. In the spirit of optimism, and in hopes that holding the conference in fall 2020 would offer a focus for individuals to anticipate coming together, the SSG proceeded with planning for the fall. By May we realized that an in-person conference was not possible during 2020 and we considered several options. Considering that postponing 3-IARC to the second half of 2021 would slow-down our momentum, and acknowledging that a virtual event is not a full conference, we decided to hold a Virtual Symposium by the International Atmospheric Rivers Conference (IARC) Community during the first week of October 2020.

The call for abstracts was sent in June 2020 and we were delighted to receive 121 abstracts from authors on all continents, and roughly 200 registrants (as of a month before the conference). This represents a continued growth in presentations (from 75 to 100, then 121) and attendance (100, 125, 200) from IARC meetings in 2016, 2018 and now 2020.

We really want to thank everyone who has contributed their work to this *Book of Abstracts* and who are participating in the symposium. We also want to thank the Center for Western Weather and Water Extremes (University of California San Diego/Scripps Institution of Oceanography) and the Center for Climate and Resilience Research (Universidad de Chile) for their sponsorship of key underlying costs incurred in planning and carrying out the virtual meeting. This has helped make it possible to hold the symposium without charging registration fees. It reflects the work of a vibrant community that continues advancing the science and applications of Atmospheric Rivers despite the extraordinary circumstances under which we are living.

We hope that our virtual symposium is a valuable opportunity to share ideas, explore new directions and encourage collaboration among a diverse and global community of researchers and practitioners, so we look forward seeing you in October 2020. And sooner or later we hope to see you in person at the Andes foothills in an upcoming full conference.

Scientific Steering Group

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Session 1

Dynamical & Physical Processes in ARs

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IARCS/001

Analysis of an extreme precipitation event in the Atacama Desert on January 2020 and its relationship to humidity advection along the Southeast Pacific

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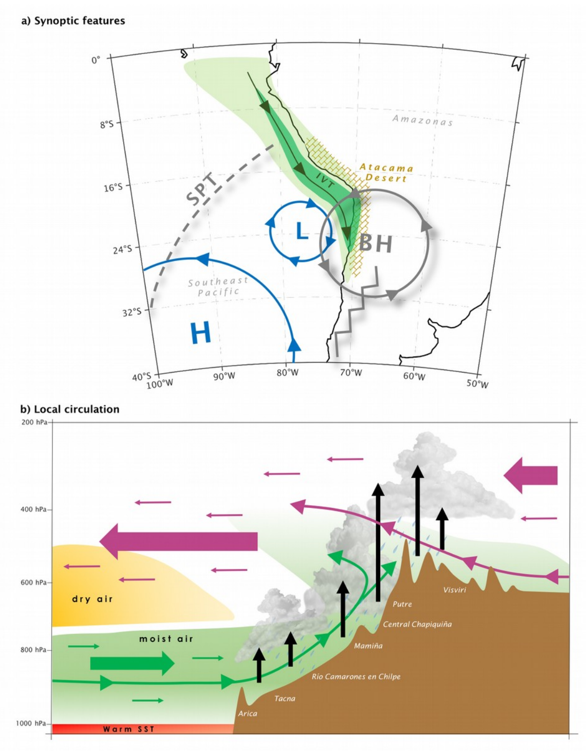
An extreme precipitation (EP) event took place during the second half of January of 2020 in the Atacama Desert. From Tacna, Perú to Iquique, Chile rainfall extended for several days producing floods, major damage to infrastructure, and affectation to the population in one of the driest deserts of the world. Analysis of surface-weather stations and reanalysis seems to agree that the most intense precipitation occurred in areas below 3,600 m.a.s.l. The analysis of this EP event also suggests that at least four major factors were present to produce record-breaking precipitation in the Atacama Desert: (i) a southward displacement of the Bolivian High and a high troposphere trough over the subtropical southeast Pacific, in combination with a low-level cyclonic circulation offshore Atacama, (ii) the advection of humidity trough a kind of atmospheric river trapped to the coast in the front of the cyclonic circulation, increasing precipitable water vapor amounts over the Atacama Desert, (iii) above normal sea surface temperature that increase moist conditions in the lower part of the troposphere and (iv) a reinforced local circulation, generating topography forced ascent of humid air in the west slope of the Andes Cordillera, enhancing precipitation not only in the coast but also inland in the pampas and precordillera. Analysis of previous summer precipitation days from 2008 to 2020 suggests that this dynamic mechanism is highly linked to the majority of the EP days in Southern Perú and Northern Chile, becoming in an important configuration to predict futures EP events in the Atacama Desert.



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IARCS/011

The role of Indian Summer Monsoon and North West Pacific atmospheric rivers in modifying the North American Summer Monsoon

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Monsoon is one of the most dramatic climate phenomena on the globe with far-reaching environmental and societal impacts. Even the paleoclimate studies show how the whimsies in Monsoon lead to the extinction of various species from the earth. The monsoon winds bring in abundant moisture and rainfall over Asia during the June-September (JJAS) and account for nearly 75% of the annual rainfall. The economic growth of Asian countries like India depends on agriculture, which is the primary source of income for the majority of the population. Hence the seasonal monsoon rainfall is a crucial factor that decides the annual economy and well being of the humans on the Indian subcontinent. It has observed that the Indian summer monsoon (ISM) exhibits robust regularity in its occurrence but does not maintain consistency in the intensity and amount of rainfall received each year. This vagaries in the monsoon rainfall can lead to large-scale droughts and excessive floods over different parts of India and cause significant socio-economic consequences. These variations are related to extreme weather and climate events associated with the South West Monsoon. Interestingly, the Indian Monsoon has a far-reaching impact on the global climate, achieved through teleconnections. The influence of ISM on the Mediterranean region through the monsoon desert mechanism, the inverse relationship between ISM rainfall and southern Japan precipitation, positive correlation with northern China rainfall, and out of phase relationship between South Korean summer rainfall variability are few examples for such teleconnections.

During JJAS, parallel with ISM, there exists a North American summer monsoon (NASM) system over North America. Though NASM also takes place during JJAS, it is not as strong as ISM. But both have many similarities. The annual cycle of Asian Monsoon displays seasonal reversal of winds and precipitation, and the same is the case with NASM. During boreal summer, the heating over the elevated terrain of Mexico, and the western United States play a crucial role in the initiation and development of the NASM. This feature is similar to the heating over the Tibetan Plateau in the case of the ISM. With these similarities in background, the present study examines the possibility of a link between Indian summer monsoon, atmospheric river over the western Pacific pacific, and the NASM.

To understand the link between ISM and NASM, analysis of observational, satellite, and reanalysis data were carried out for the period 1951-2014. The preliminary results obtained by comparing the precipitation over ISM and NASM region using the India meteorological department and University of Delaware datasets indicate a linear relationship between the ISM and precipitation over California Coast and an inverse relationship with rainfall over Mexico-South West US region. This feature is evident in figure 1, representing JJAS precipitation anomalies during 1983 (a strong ISM year) over the ISM and NASM regions. Further analysis and climate model simulations are required to fully understand the air-sea interaction processes over the ISM and the western Pacific regions, and the role of Atmospheric Rivers over these regions in affecting the NASM rainfall during strong/weak ISM. The results of this study will be a teleconnection between ISM and NASM.

Keywords: Monsoon, teleconnections, Atmospheric Rivers, Air-Sea interaction

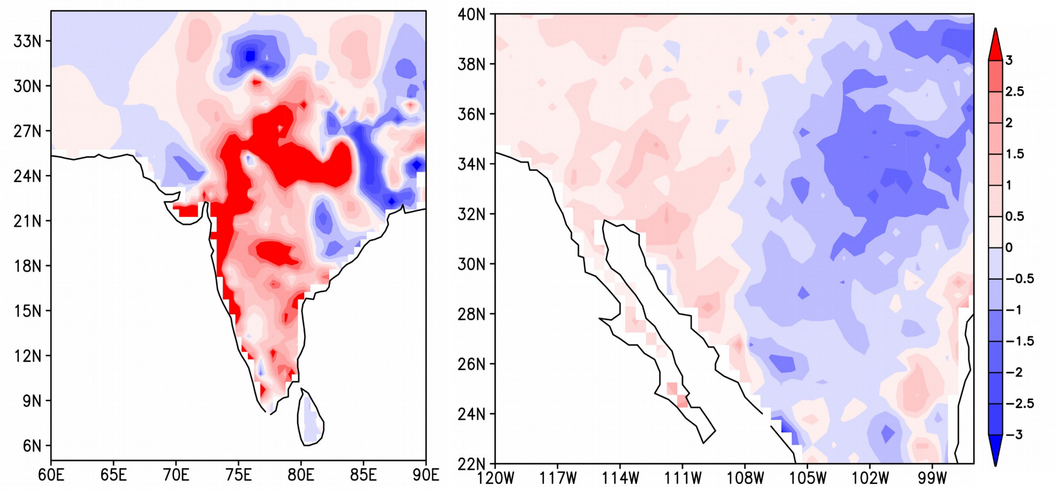

Figure 1. The 1983 JJAS precipitation anomaly over the regions of (a) India (b) North America. Climatological data is based on the University of Delaware monthly precipitation data for the period 1951-2014.

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IARCS/013

Linked Extreme Weather Events over the Western United States during February 2019 Resulting from North Pacific Rossby Wave Breaking

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February 2019 was a stormy and cold month over much of the western CONUS. Record-breaking snowstorms and rainstorms were observed in parts of Washington, Oregon, California, and Arizona during this month. The upper-level flow pattern over the North Pacific Ocean was characterized by a retracted western Pacific jet stream, anticyclonic wave breaking (AWB) over the eastern Pacific, and a persistent northern storm track from the central Pacific to Alaska. Individual cyclones moving northeastward along this storm track supported sequential ridge building events, strong warm-air advection, a parade of moisture-laden atmospheric rivers, and frequent heavy precipitation. A deep trough downstream of the region of AWB enabled Kona low development near Hawaii, subtropical jet stream (STJ) formation, and an active southern storm track from near Hawaii toward the West Coast. The purpose of this presentation is to show how the formation of this storm track enabled the occurrence of multiple extreme weather events over the western CONUS associated with individual northeastward-moving cyclones.

Kona low formation near Hawaii occurred along the southwestern end of a deep, positively tilted trough over the eastern Pacific. This deep trough allowed anomalously cold air to overspread the Pacific Northwest, California, and the subtropical eastern Pacific. A prominent baroclinic zone at the southern end of this deep trough along with a strong STJ allowed frequent landfalling atmospheric rivers (ARs) on the West Coast and supported widespread inland storminess. The interaction of eastward-moving moisture-laden air masses associated with the STJ and midlatitude upper-level baroclinic disturbances moving southward in the deep trough off the West Coast resulted in the occurrence of multiple extreme weather events (EWEs) over the western CONUS during a two-week period in February 2019. Notable EWEs included a record-breaking snowstorm in Seattle, WA, on 9 February, the biggest snowstorm in Redding, CA in 50 years on 13 February, the third wettest day on record in Palm Springs, CA, on 14 February, a record-breaking snowstorm in Flagstaff, Arizona on 24–25 February, and a record-breaking snowstorm in Oregon on 25 February. We will show how these individual EWEs can be related to the configuration of the large-scale North Pacific flow.

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IARCS/027

Benefit of microwave remote sensing for analysing the thermodynamic structure of Atmospheric Rivers

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The vertical structure of Atmospheric Rivers (ARs) has already been studied using dropsondes from research aircrafts and satellite-based radio occultation from Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission. These approaches provide a high vertical but limited horizontal resolution. Compared to dropsondes and radio occultation, the microwave observation systems onboard the High Altitude and LOng Range research aircraft (HALO) provide much higher horizontal resolutions with a measuring rate of 1 Hz. The thermodynamic structure of an AR event, that has been observed by HALO during the North Atlantic Waveguide and Downstream impact EXperiment (NAWDEX) campaign, will be analysed. Along the absorption bands of oxygen and water vapour in the microwave spectrum, temperature and humidity profiles are retrieved from the multi-channel microwave radiometer onboard HALO via cubic regression and optimal estimation.

The results regarding the structure of an AR are compared with interpolated dropsonde measurements and simulations of a numerical weather prediction model (IFS). Subsequently, the benefit of microwave observations to analyse the structure of ARs is evaluated. Furthermore, the capability of satellite-based microwave sounders, such as the Advanced Microwave Sounding Unit (AMSU), to examine or monitor the AR structure, can be assessed.

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IARCS/028

Ice microphysical processes in winter storms encountering complex terrain

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Atmospheric river events produce a substantial portion of precipitation in mountainous regions of western North America, and often are associated with hazardous weather conditions and flooding. Still, winter storms in complex terrain remain a challenging forecast scenario. In particular, precipitation forecasts can be greatly underestimated during major atmospheric river events. Some uncertainty in precipitation forecasts is due to poor parameterization of ice-phase microphysics in numerical weather prediction models and the need for improved understanding of the modification of ice processes by terrain. Previous studies using ground-based dual-polarization radar data from the Olympic Mountains Experiment (OLYMPEX) during winter 2015-16 showed a frequent enhancement of radar reflectivity above the melting level on the windward side of the Olympic Mountains when compared to over the upstream ocean, which was most enhanced during atmospheric river events. In this study, we use OLYMPEX radar and in situ aircraft observations of ice-phase microphysical properties in this upper-level reflectivity enhancement as precipitating clouds encounter complex terrain to improve our understanding of the processes contributing to this enhancement.

To objectively distinguish stratiform radar echo and approximate the melting level height, we have designed a bright band detection technique specific to the NASA S-band dual-polarization radar (NPOL) that scanned over the ocean and over the terrain of the Olympic Mountains. In stratiform periods, we find that an elevated, local maximum in radar reflectivity regularly occurs within a layer approximately 2 to 2.5 km above the bright band and is often enhanced in magnitude over the windward slopes of the terrain when compared to over the ocean. Enhancements of this layer over the terrain are most pronounced during three atmospheric river events: 12-13 November, 03 December, and 08 December 2015. This layer typically occurs between -6°C to -12°C temperatures and is often, but not always, just below a local maximum in differential reflectivity which is suggestive of dendritic ice growth. However, coincident in-situ aircraft observations indicate that these regions often also contain appreciable amounts of supercooled liquid water and rimed ice particles. Persistent riming due to a continuous supply of supercooled liquid water accelerates the growth and aggregation efficiency of the ice particles, likely affecting the regions of fall out or advection of the largest particles. Ground-based precipitation measurements from OLYMPEX at varying elevations will be studied to explore the role of ice-phase processes within the enhanced reflectivity layer in modulating the intensity and distribution of precipitation reaching the surface across windward and lee slopes of the terrain and the variability of those processes with synoptic environment, including in these atmospheric river events.

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IARCS/030
Vorticity and Thermodynamics in a Gulf of Mexico Atmospheric River

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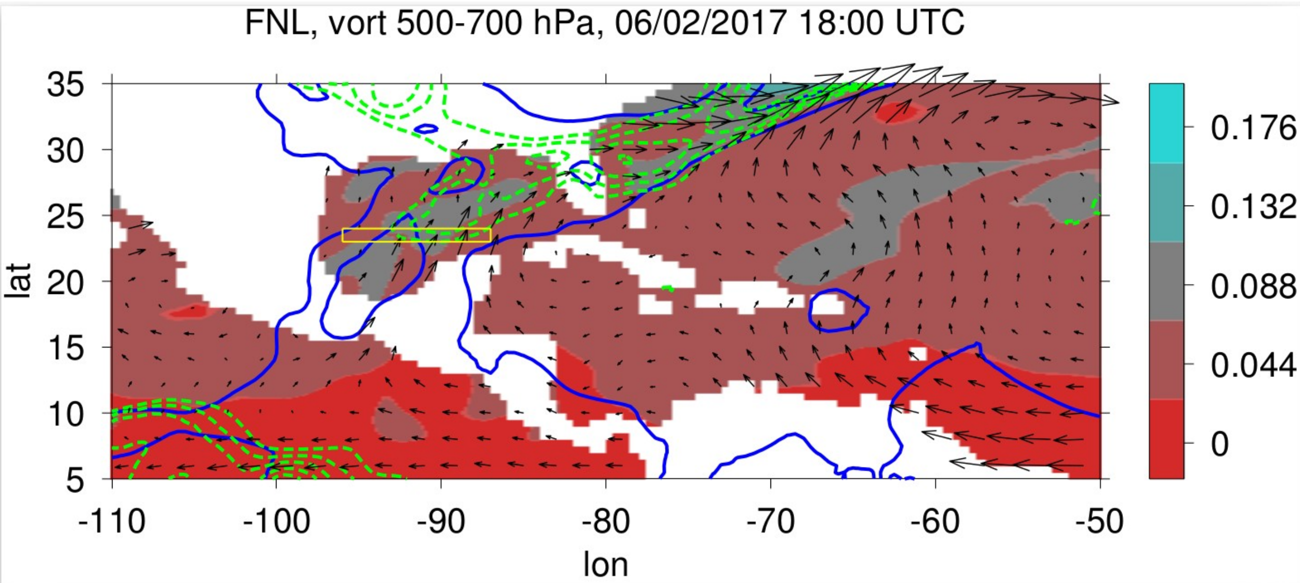
Atmospheric rivers (ARs) are large-scale moisture transport systems in the atmosphere, characterized by poleward-moving moisture plumes in narrow corridors, extending through mid-latitudes often into the tropics. The physical processes related to tropical moisture exports (TME) are much less understood than the moisture fluxes in higher latitudes. Part of the challenge arises from the definition of AR transport, a predominantly horizontal characterization in which a majority of the moisture flux is expected to be uncoupled from vertical motions associated with convection. We examine the interaction of tropical moisture with an atmospheric river. Our analysis is focused on dropsonde data, collected during the fifth day of the Convective Processes Experiment (CPEX), launched over an area of interest over the central Gulf of Mexico, where a pre-existing mid-level vortex is embedded within an extensive region of stratiform cloudiness. Based on the large-scale picture obtained through satellite imagery, complemented with a broader perspective obtained with NCEP FNL analysis, it appears that this region is under the influence of an AR. Results in this study show an eastward-tilting pattern of mid-level vorticity, coupled with high column relative humidity and low mid-tropospheric moist convective instability in the region. An inverse relation between column relative humidity and mid-tropospheric moist convective instability, as indicated by moisture quasi-equilibrium (MQE), is found in a previously dominant convective regime. Strong vertical shear signals that the vorticity pattern within this stratiform system is being advected poleward into midlatitudes. We present an alternative description to characterize the moisture mechanism of atmospheric rivers near the tropics, in which vorticity is ultimately responsible for the convection, which is associated with the observed moisture convergence. This description includes the upward forcing of moisture leading to precipitation as part of the AR system, in contrast with the conventional paradigm.



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IARCS/035

Atmospheric Rivers in Association with Boreal-summer Heavy Rainfall over Yangtze Plain of China

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Atmospheric Rivers (ARs), referring to long and narrow bands of enhanced water vapor transport, mainly from the tropics into the mid-latitudes in the low atmosphere. They often contribute to heavy rainfall generations outside the tropics. However, there is a lack of such AR studies in East Asia and it is still unclear how ARs act on different time scales during the boreal summer when frequent heavy precipitation events take place over the region. In this study, climatological ARs and their evolutions on both synoptic and sub-seasonal time scales associated with heavy rainfall events over the Yangtze Plain in China are investigated. Furthermore, its predictability is assessed by examining hindcast skills from an operational coupled seasonal forecast model. Results show that ARs embedded within the South Asian monsoon and Somali cross-equatorial flow provide a favorable background for steady moisture supply of summer rainfall into East Asia. We can call this favorable background as a climatological East Asian AR which has close connections with seasonal cycle and climatological intra-seasonal oscillation (CISO) of rainfall in the Yangtze Plain during its Meiyu season. The East Asian AR is also influenced by anomalous anti-cyclonic circulations over the tropical West Pacific when heavy rainfall events occur over the Yangtze Plain. Different from orography-induced precipitation, ARs leading to heavy rainfall over the Yangtze Plain are linked with the intrusions of cold air from its north. The major source of ARs responsible for heavy precipitation events over the Yangtze Plain appears to originate from tropical West Pacific on both synoptic and sub-seasonal time scales. By analyzing 23-yr hindcasts for May-June-July with start date of 1 May, we show that the current operational coupled seasonal forecast system of the Australian Bureau of Meteorology (named as ACCESS-S1) has skillful rainfall forecasts at lead-time of 0 month (i.e. forecasting May monthly mean with initial conditions on 1 May), but the skill degrades significantly at longer lead time. Nevertheless, the model shows skills in predicting the variations of low-level moisture transport affecting the Yangtze River at longer lead time, suggesting that the ARs influencing summer monsoon rainfall in the East Asian region are likely to be more predictable than rainfall itself. This provides a potential of utilizing the skill from the coupled forecast system in predicting ARs to guide its rainfall forecasts in the East Asian summer season at longer lead time.

Key words
Atmospheric rivers; heavy rainfall; sub-seasonal forecasts; Yangtze Plain; predictability; intra-seasonal oscillation

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IARCS/036

Diabatic Intensification along Atmospheric Rivers: A Pathway for Cyclone Clustering?

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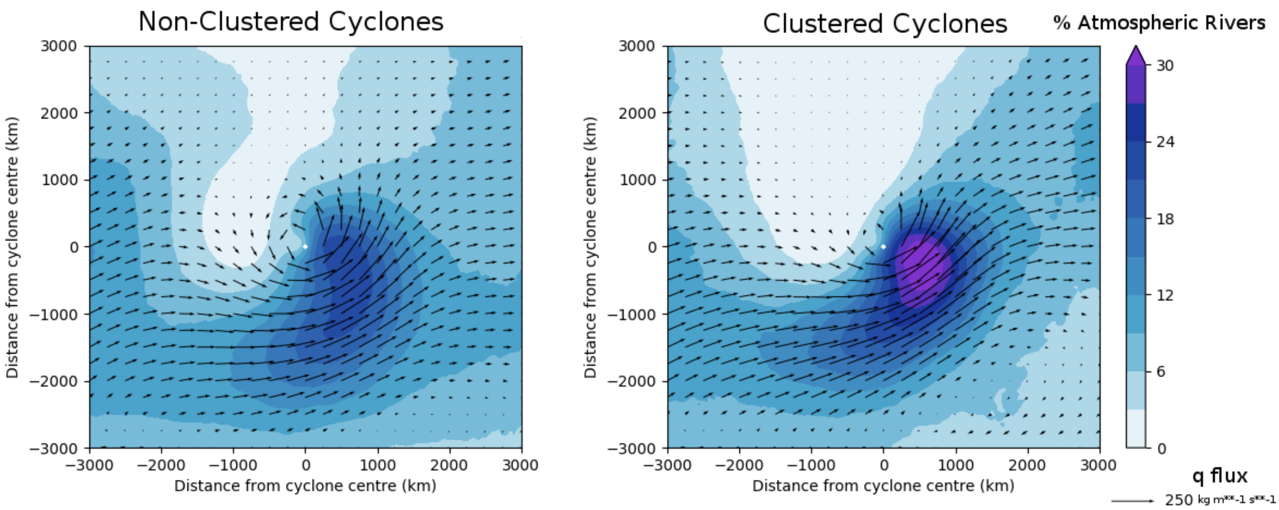
The occurrence of atmospheric rivers is occasionally associated with the succession of multiple cyclones, which is referred to as cyclone clustering. These atmospheric rivers are reinforced by advection of water vapor along the trailing cold front of one of the leading cyclones in the cluster, while the diabatic processed associated with the moisture also influence the cyclones directly. We present a case study in which diabatic processes associated with an atmospheric river intensified the slope of the isentropic surfaces along the cold front of the cyclone Dagmar, thereby intensifying the baroclinicity in the rear of the cyclone. Succeeding storms evolved along this increased baroclinity, resulting in a sequence of severe cyclones. We hypothesise that this could be a general pathway for cyclone clustering.

We further test our hypothesis by using a new cyclone clustering diagnostic based on the spatio-temporal distance between cyclone tracks. We analyse cyclone clustering for the period 1979 until 2016 using ERA-Interim. We complement this analysis with an atmospheric river diagnostic in conjunction with a baroclinicity diagnostic based on the tendency of the slope of isentropic surfaces. With the isentropic slope and its tendencies, the relative roles of diabatic and adiabatic effects associated with extra-tropical cyclones in maintaining baroclinicity are assessed. The life cycle of these storms is discussed in terms of how the storm changes and uses its environment to attain its intensity. We compare these findings to composites of clustered and non-clustered cyclones (see Figure) to quantify how consistent the proposed clustering mechanism is and its relation to changes in the frequency of atmospheric rivers.



IARCS/040

Applying Semi-Supervised Learning to Infer Drivers Associated with West Coast Atmospheric Rivers

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Despite advances in understanding and characterizing atmospheric rivers in recent years, major questions remain about their drivers that impact on questions of predictability. A semi-supervised learning approach is taken to explore the relationship between large-scale meteorological patterns on atmospheric river days in western North America and the features of the jet stream that drive them. Using reanalysis, we focus on the historical period and first select a broad set of days with atmospheric river conditions, to better distinguish the variability in the large-scale meteorological patterns on such days. To do so, a self-organizing map is used to group days with atmospheric river conditions into nodes that share common features in related meteorological fields -- simultaneously using not just column water vapor but also 700mb level zonal winds and 500mb heights as input fields. Finally, these large-scale meteorological patterns, labeled 1 through 6, are used as the labels in a neural net for classification. Because the labels for the training data are derived from an earlier automated step, instead of generated via manual categorization, this overall approach is referred to as semi-supervised. We use layerwise relevance propagation to visualize the regions the neural net relies upon to predict a particular type of AR-conducive meteorological arrangement, and make inferences about the aspects of the jet that are driving these variations. Some of those arrangements display higher potential for predictability than others, for example the node capturing more of the weaker events is also the least distinct and predictable. Those nodes with better predictability tend to be associated with the jet exit region at various lead times. The jet drivers are explored for nodes with distinct angles of approach and generally stronger IVT at landfall.

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IARCS/049

The Influence of Antecedent Atmospheric River Conditions on Extratropical Cyclogenesis

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Some extratropical cyclones (ETC) begin their development in close proximity to a pre-existing atmospheric river (AR). This study investigates the differences between these cyclogenesis events and those that begin without an AR nearby.

Well-established ETC and AR detection methods are applied to reanalysis over the North Pacific during the 1979-2009 cool seasons (November-March). Of the 3137 cyclogenesis cases detected, 35% are associated with a nearby AR at the time of initial cyclogenesis. Of all 186 cyclones that deepened explosively in the 24 h after their initiation, 64% began with a pre-existing AR nearby.

The roles of both dry and diabatic processes that contribute to cyclogenesis are examined, specifically, low-level baroclinicity (Eady growth rate), upper-level forcing (potential vorticity), water vapor inflow (vertically integrated vapor transport - IVT) and latent heating. ETCs that develop near a pre-existing AR receive ~80% more water vapor inflow on average, enhancing latent heating and intensifying cyclogenesis. In contrast, neither low-level baroclinicity nor upper-level PV exhibit statistically significant differences between cyclogenesis events with and without an AR. Cyclogenesis events associated with an exceptionally strong AR at the ETC initial time (maximum IVT > 1250 kg m^{-1} s^{-1}) deepen even more rapidly, indicating that the intensity of an antecedent AR can modulate cyclogenesis. About half of the cyclogenesis cases off the US West Coast are associated with ARs at their initial time. These results imply that errors in initial conditions related to ARs contribute to errors in both AR and ETC predictions, as well as their concomitant impacts.

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IARCS/061

Tropical Atmospheric Rivers

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Atmospheric rivers (ARs) are long, narrow jets of moisture transport that account for over 90% of the total poleward water vapor transport across the mid-latitudes. Moreover, they are often associated with extreme wind and/or precipitation events that can adversely affect human life and society. Most previous research has focused on ARs in the mid-latitudes, where they occur most frequently, while ARs in low latitudes are only now starting to garner scientific interest. Motivated by the lack of studies on tropical ARs relative to their extratropical counterparts, this study examines and characterizes ARs in the tropical regions between 25N and 25S. Utilizing our global database of AR events based on MERRA-2 data, we analyze AR frequency of occurrence, AR-related precipitation, and population density to quantitatively identify subregions of the Tropics where ARs are expected to have the greatest societal impact. We then produce composite, synoptic descriptions of the ARs for each identified subregion based on 6-hourly fields of MERRA-2 data and hundreds of AR occurrences particular to each subregion. These localized descriptions include a plan view of the composite ARs, displaying average AR shape as well as contours of vertically integrated water vapor (IWV), integrated water vapor transport (IVT), clouds, precipitation and boundary-layer wind fields. They also include a vertical cross section across a transect of the composite ARs displaying specific humidity, temperature, and horizontal wind speed. Our work will help extend the consideration of ARs to regions currently understudied and help to better understand the unique characteristics of ARs in different regions across different climatologies.

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IARCS/087

The role of air-sea fluxes for the water vapour isotope signals in the cold and warm sector of extratropical cyclones over the Southern Ocean

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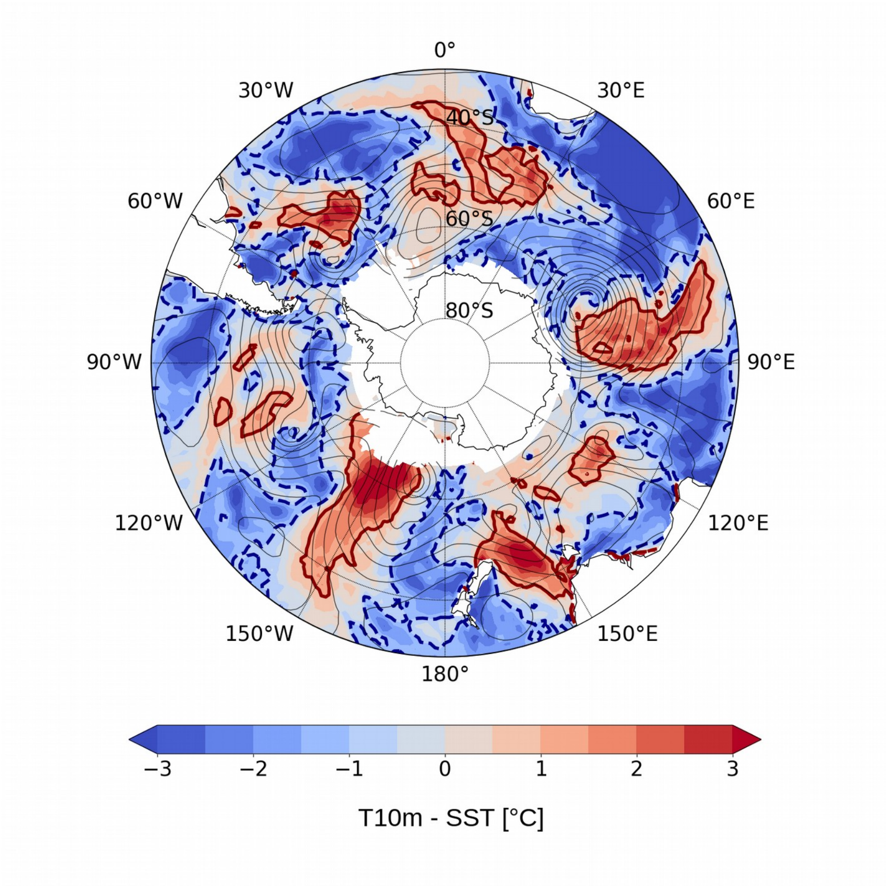
Meridional atmospheric transport is an important process in the climate system and has implications for the availability of heat and moisture at high latitudes. A large part of this meridional transport is associated with extratropical cyclones. In the cold sector of cyclones, cold and dry air masses are transported equatorward, e.g. during cold air outbreaks. In the warm sector, warm and moist air masses are transported poleward, frequently co-occurring with atmospheric rivers. In this context, the near-surface advection of cold and warm air masses over the ocean leads to important air-sea exchange. In this study, we investigate the impact of these air-sea fluxes on the stable water isotope composition of water vapour in the Southern Ocean's atmospheric boundary layer. Stable water isotopes (SWIs) serve as a tool to trace phase change processes involved in the atmospheric water cycle and, thus provide important insights into moist atmospheric processes associated with extratropical cyclones. Here we combine a three-month ship-based SWI measurement dataset around Antarctica with numerical model simulations from the isotope-enabled numerical weather prediction model $COSMO_{iso}$. We objectively identify cold and warm temperature advection based on the air-sea temperature difference applied to the measurement and the simulation datasets. A Lagrangian composite analysis of cold and warm temperature advection based on the $COSMO_{iso}$ simulation data is compiled to identify the main processes affecting the observed variability of the isotopic signal in marine boundary layer water vapour. This analysis shows that the cold and warm sectors of extratropical cyclones are associated with contrasting SWI signals. Specifically, the measurements show that the median values of $\delta^{18}O$ and $\delta^{2}H$ in the atmospheric water vapour are 3.6‰ and 23.2‰ higher during warm than during cold advection. The second-order isotope variable deuterium excess d, which can be used as a measure of non-equilibrium processes during phase changes, is 5.9 ‰ lower during warm than during cold advection. These characteristic isotope signals during cold and warm advection reflect the opposite air-sea fluxes associated with these large-scale transport events. The SWI signals in the cold sector are mainly shaped by ocean evaporation. In the warm sector, the air masses experience a net loss of moisture due to dew deposition as they are advected over the relatively colder ocean, which leads to the observed low d. We show that additionally the formation of clouds and precipitation in moist adiabatically ascending warm air parcels can decrease d in boundary layer water vapour. These findings illustrate that SWIs in water vapour are strongly altered due to air-sea interactions during transport. SWIs can thus potentially be useful as tracers for meridional air mass advection and other characteristics associated with the dynamics of the storm tracks over interannual timescales.



An example of cold and warm temperature advection events in the Southern Ocean at 12 UTC 26 Dec 2016 from ERA-Interim showing the air-sea temperature difference ΔT_{ao} using the air temperature at 10 m a.s.l. and sea surface temperature. Land and areas covered by sea ice are blanked. Contours of ΔT_{ao} =−1.0°C (blue, dashed) indicate cold and of ΔT_{ao} =1.0 °C (red, solid) warm temperature advection events, respectively. Black contours show sea level pressure in 5 hPa intervals.

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IARCS/093

Dynamics of long-duration heavy precipitation events linked to atmospheric rivers in the western and central United States

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This study investigates dynamical processes governing long-duration (lasting for ≥3 days) heavy precipitation events (HPEs) that occur in the western and central U.S. in conjunction with atmospheric rivers (ARs). A long-term (1979–2019) climatology of long-duration HPEs linked to ARs is constructed using historical gauge-based gridded precipitation analyses combined with a reanalysis-based catalog of ARs. Two samples of events, occurring in domains over the western coast of the U.S. and the south-central U.S., respectively, are examined. Composite analyses are constructed to investigate processes that contribute to the long-duration HPEs in each domain. The analyses indicate that the western U.S. events tend to occur in persistent large-scale flow patterns over the North Pacific and western North America that are characterized either by a zonally extended jet stream or by atmospheric blocking. These patterns characteristically promote serial clustering of landfalling extratropical cyclones and associated ARs along the U.S. coast for periods of several days, thereby supporting sustained heavy precipitation. The central U.S. events tend to involve high-amplitude wave patterns over North America that exhibit an elongated slow-moving upper-level trough over the western U.S. established through Rossby wave breaking. Heavy precipitation is sustained by a persistent, strong AR stretching from the Caribbean Sea and the Gulf of Mexico into the central U.S. downstream of the trough. The composite results highlight two key factors that support the persistence of the AR for the central U.S. HPEs: 1) impeding of the upper-level trough by diabatically enhanced ridge building due to latent heat release linked to the HPE, and 2) formation of a quasi-stationary lee trough along the eastern coast of Mexico in association with sustained downslope flow forced by the upper-level trough. The relevance of these two factors for the persistence of the AR, and thus for the prolongation of heavy precipitation, is corroborated by numerical model experiments for selected events.

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IARCS/095

Cloud and precipitation microphysics during atmospheric river events at the Antarctic Peninsula

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Atmospheric river (AR) events highly influence Antarctic coastal climate, warming and moistening the lower troposphere, causing both precipitation and surface melting processes. These consequences could be crucial in the Antarctic Peninsula region, where the highest warming rate over the continent has been observed during recent decades. There are still significant knowledge gaps in understanding of microphysical processes in Antarctic clouds that form precipitation and also have significant impact on the surface radiative balance. A particular challenge is understanding processes responsible for changes in precipitation phase during AR events and their representation in polar weather and climate models.

In this study we investigate spatial and temporal evolution of precipitation, including its intensity and phase transition, and associated atmospheric and cloud properties during AR events affecting the Antarctic Peninsula in austral summer. Two case studies, during the first week of December 2018, are analyzed, using observations conducted in The Year of Polar Prediction Special Observing Period (YOPP-SOP) over the Antarctic Peninsula region, particularly at the Escudero and Vernadsky stations. The two stations represent different regional and micro-climates around the Antarctic Peninsula: Escudero station is situated on King George Island at the northern tip of the peninsula, while Vernadsky station – is on Galindez Island at the western (upwind) closer to the north-central side of the peninsula. Both stations have maritime coastal Antarctic climate but an important feature of Vernadsky station site, for this research, is possible orographic enhancement of precipitation (Fig. 1).

We use ground-based observations of meteorology, clouds and precipitation, snow height, radiosonde profiles, and total precipitable water data. ERA-5 reanalysis is evaluated using observations and used for large-scale analysis of clouds and precipitation type.

Both AR events were associated with precipitation phase transition from snow to rain, while a transition from rain into snow was also observed during the first AR event. ARs had two slightly different pathways and landfall locations that caused different timing responses in the onset of precipitation at both stations. Both AR events caused higher precipitation amounts at Vernadsky station compared to Escudero, which is possibly a result of the orographic enhancement by the Antarctic Peninsula ridge (Fig. 1). Figure 1 highlights the fast transition of the AR and a short (<4 hours) period with intense precipitation at the upwind side of the Peninsula. Further, we analyze microphysical characteristics of clouds and precipitation associated with the AR events using the ERA5 reanalysis and Polar-WRF model. Evolution of precipitation is investigated together with the evolution of vertical tropospheric profiles derived from radiosondes.

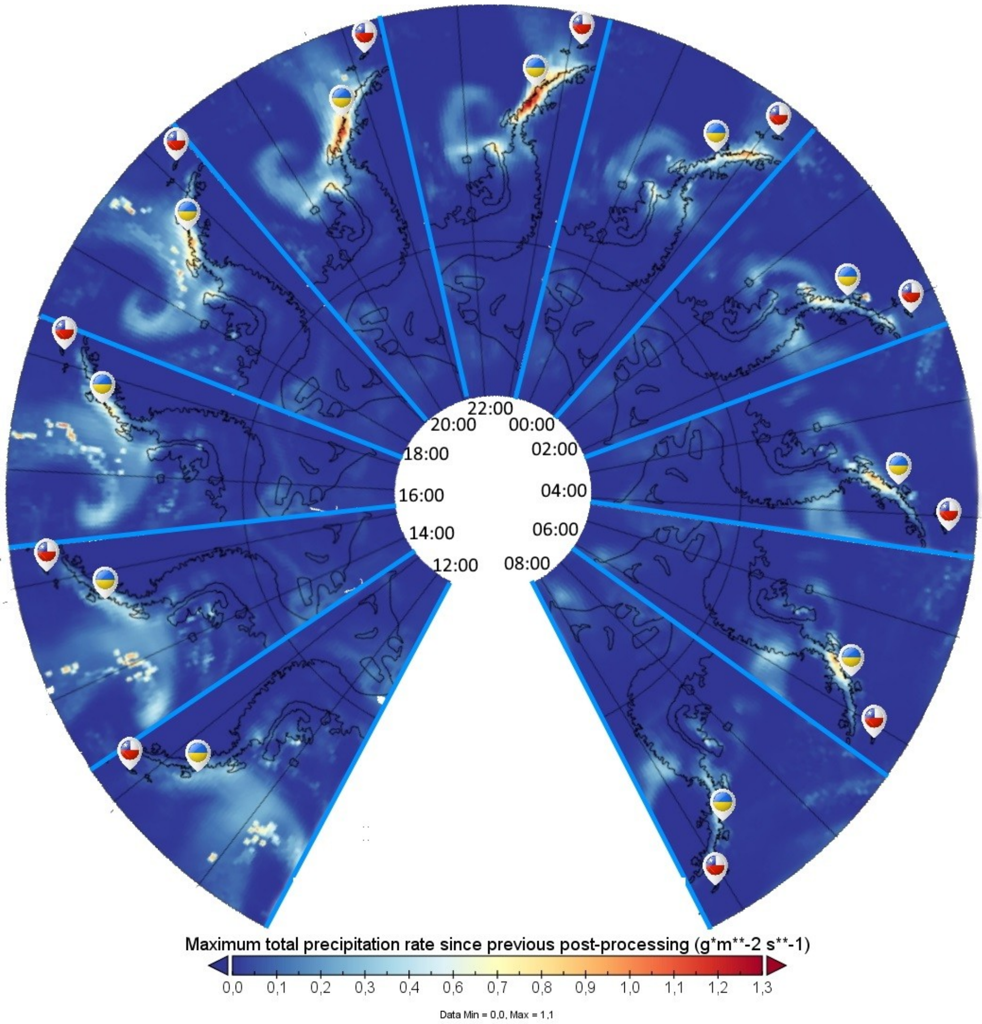

Figure 1 Precipitation rate during an AR at the Antarctic Peninsula from 1 December 12 UTC to 2 December 8 UTC 2018, based on ERA5 reanalysis hourly data (every second hour presented). The station locations are represented with corresponding country flag colors (Vernadsky/Ukraine and Escudero/Chile).

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IARCS/102

Atmospheric river sectors: Definition and characteristics observed using dropsondes from 2014-2020 CalWater and AR Recon

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Atmospheric rivers (ARs) are responsible for intense winter rainfall events impacting the U.S. West Coast, and have been studied extensively during the CalWater and AR Recon field programs (2014-2020). A unique set of 858 dropsondes deployed in lines transecting 33 ARs are analyzed, and integrated vapor transport (IVT) is used to define five sectors: AR core, cold and warm sectors, and non-AR cold side and non-AR warm side.

The mean widths of the three AR sectors are approximately 280 km. However, the AR core contains roughly 50% of all the water vapor transport (i.e., the total IVT), while the others each contain roughly 25%.

A low-level jet occurs most often in the core and warm sector with wind speeds comparable to previous studies, although with heights approximately 300 m lower than previously reported. The presence of moist neutral profiles has been shown in several AR studies, however, we find that in the core of the AR, lower tropospheric (1000 to 2000 m) moist neutral static stability is only present in 65% of the dropsonde profiles. The mean lifting condensation levels in the all of the AR sectors are low enough to be lifted by the California coastal range to cause saturation, leading to orographic precipitation.

The vertical distribution of IVT, which modulates orographic precipitation, varied across sectors: 75% of IVT is found below 3115, 3370, 2679 m in the core, cold sector, and warm sector, respectively.

IARCS/104

Diabatic Contributions to the Formation of Mesoscale Frontal Waves and Modulation of Atmospheric River Events Along the U.S. West Coast

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Atmospheric rivers (ARs) often provide necessary water resources to regions such as the western United States; however, ARs can also be responsible for damaging flood events due to the production of extreme precipitation. The severity of the flooding impact associated with an AR event is determined by its strength and persistence. A factor in the maintenance of ARs is the presence of mesoscale frontal waves (MFWs), which can increase the longevity of ARs and therefore, threat of extreme precipitation. To improve precipitation forecasts, it is necessary to understand the dynamics of the interactions between ARs, mesoscale frontal waves, and extreme precipitation events.

To build on this growing area of research, we have simulated two AR events based on the presence of MFW features during the evolution of the event using the Model for Prediction Across Scales (MPAS). We utilized the 10–60-km variable resolution mesh, centering the high-resolution area just north of Hawaii to encompass the majority of the North Pacific Basin and Western United States. Our control simulations are initialized 48-h prior to MFW formation and integrated through the end of each event; results are verified using the ERA5 reanalysis. Simulating each event with the effects of latent heating removed allows us to quantify the relative contributions of diabatic processes in each event, and therefore, assess the importance of latent heating to MFW formation and evolution.

Previous work suggests that while diabatic processes play a significant role in the formation and/or maintenance of frontal waves, sufficient upper-air support is often needed for the wave to intensify into a secondary cyclone. In the context of AR events, however, not all MFW result in secondary cyclogenesis. Nevertheless, the presence of MFWs have a large impact on the intensity and position of ARs and consequently, the landfalling precipitation. Therefore, by sampling a variety of AR events with various MFW evolutions, we aim to identify key mechanisms in determining the structure of MFWs in the context of ARs with the hopes of improving the predictability of high-impact precipitation events.

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IARCS/108

Terrain Trapped Airflows and Precipitation Variability during an Atmospheric River Event

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This study examines thermodynamic and kinematic structures of terrain trapped airflows (TTAs) during an Atmospheric River (AR) event impacting Northern California 10–11 March 2016 using Alpha Jet Atmospheric eXperiment (AJAX) aircraft data, in situ observations, and Weather and Research Forecasting (WRF) model simulations. TTAs are identified by locally intensified low-level winds flowing parallel to the coastal ranges and having maxima over the near-coastal waters. Multiple mechanisms can produce TTAs, including terrain blocking and gap flows. The changes in winds can significantly alter the distribution, timing, and intensity of precipitation. We show here how different mechanisms producing TTAs evolve during this event and influence local precipitation variations.

Three different periods are identified from the time-varying wind fields. During Period 1 (P1), a TTA develops during synoptic-scale onshore flow that backs to southerly flow near the coast. This TTA occurs when the Froude number (Fr) is less than 1, suggesting low-level terrain blocking is the primary mechanism. During Period 2 (P2), a Petaluma offshore gap flow develops, with flows turning parallel to the coast offshore and with Fr > 1. Periods P1 and P2 are associated with slightly more coastal than mountain precipitation. In Period 3 (P3), the gap flow initiated during P2 merges with a pre-cold frontal low-level jet (LLJ) and enhanced precipitation shifts to higher mountain regions. Dynamical mixing also becomes more important as the TTA becomes confluent with the approaching LLJ. The different mechanisms producing TTAs and their effects on precipitation pose challenges to observational and modeling systems needed to improve forecasts and early warnings of AR events.

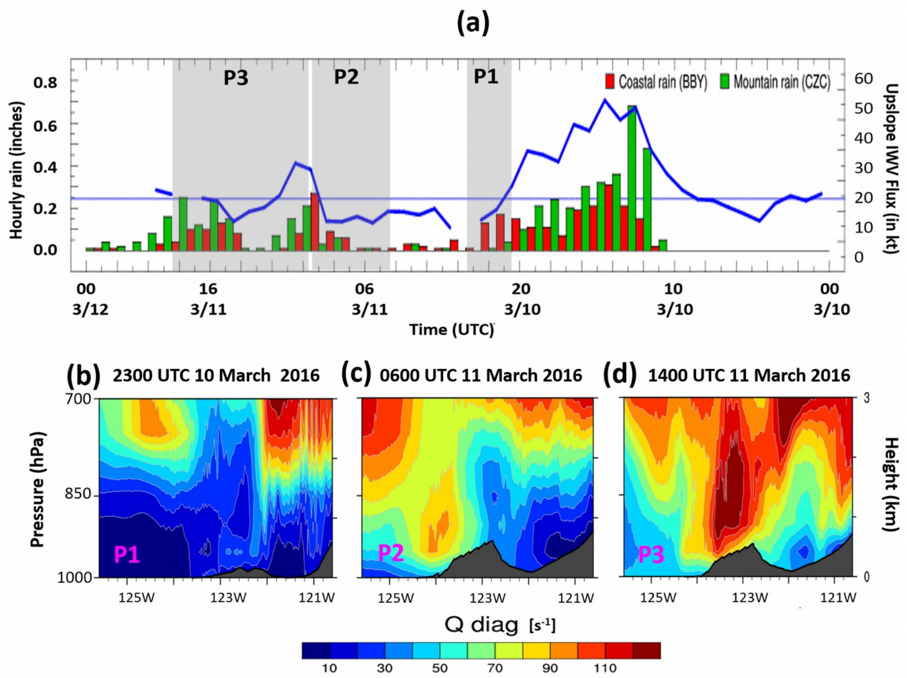

Figure. Time series of **(a)** observed hourly precipitation (inches) over the BBY (coast, red) and the Cazadero (CZD, mountain, green) sites, with the upslope integrated water vapor flux (blue, in knots) observed by the wind profiler at BBY from 0000 UTC 10 March to 0000 UTC 12 March 2016. Gray-shaded boxes identify the time periods: P1 between 2100 – 2300 UTC 10 March, P2 during 0500 – 0900 UTC 11 March, and P3 during 1000 – 1800 UTC 11 March 2016. **(b-d)** Longitude-height cross-section of dynamic mixing diagnostic (Q diagnostic, in s^{-1}) using WRF-simulated wind averaged over 38-38.5ºN at 2300 UTC 10 March, averaged over 36.5-40ºN at 0600 UTC 11 March and 1400 UTC 11 March 2016, respectively. The dark gray shading in (b-d) represents the topography.

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IARCS/109

The Role of Warm Rain Processes in Atmospheric River Events during the Olympic Mountains Experiment (OLYMPEX)

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The Olympic Mountains Experiment took place over the Olympic Mountains in the northwest corner of Washington State during the 2015 – 2016 winter season. One of the goals of OLYMPEX was to document the precipitation processes in winter cyclones and how they are modified when storms encounter a coastal mountain range. Participation in OLYMPEX included several US government agencies (NASA, NSF, Olympic National Park, US Forest Service), several Universities, the Environmental and Climate Change Canada and the Quinault Indian Nation. Instrumentation during OLYMPEX was placed to strategically sample both the windward and lee sides of the Olympic Mountains. They included an array of rain gauges and disdrometers placed at a variety of elevations, supplemental soundings on the Washington coast and on Vancouver Island, multi-frequency (S-, Ka/Ku, and X-band) ground-based dual-polarization radars, micro rain radars, and three instrumented aircraft (NASA's DC-8 and ER-2 and the University of North Dakota's Citation). This presentation will highlight the characteristics of several warm midlatitude frontal systems sampled during OLYMPEX that could be classified as atmospheric rivers.

It has become clear from several observational and modeling studies of these events that the most pronounced orographic enhancement of precipitation processes occurs during environmental conditions found predominantly during the warm sector periods of midlatitude cyclones. These conditions include high melting layer height, high values of integrated water vapor transport, near-neutral low-level stability, and strong low-level flow impinging orthogonally on the barrier (the Olympic Mountains). These same conditions are also consistent with the Atmospheric River definition. When events exhibit these environmental characteristics, moist low-level flow is easily lifted over terrain due to the near-neutral low-level stability, with the warm-rain processes of collection and coalescence making significant contributions to the total observed rainfall on the windward slopes. In addition, broad lifting of the entire moist column enhances the ice-layer above the melting level over complex terrain compared to the same levels over the ocean. This ice layer enhancement not only contributes to precipitation fall out on the windward slopes, but some of the ice particles are lofted and advected across the high terrain contributing to precipitation on the leeside. Together, these processes contribute significantly to the enhancement of precipitation on the windward slopes, where totals are as much as 5 times greater than on the coast. Model verification studies have shown that most microphysical schemes have difficulty with accurately reproducing the distribution of precipitation on the windward slopes and the leeside, especially during the heavy-rain producing warm sector periods of cyclones. Ongoing work is addressing these model short-comings with the focus on improving the warm-rain processes within model microphysics schemes. This important outcome of the OLYMPEX results will contribute to more accurate prediction of precipitation in landfalling Atmospheric River events that can be applied to coastal mountain regions worldwide.

IARCS/113

Sudden Shifts and Trends of Atmospheric Rivers Since the last Ice Age in the Northeastern Pacific Implied by Stable Isotopes in Precipitation

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Atmospheric River impacts are reflected in the ice core records from high mountains rimming the northeastern Pacific. The focus of this paper are the records from the highest summit in Canada (Mt Logan) which show a uniquely sensitive but complex response to climate change and volcanic eruptions. Atmospheric rivers not only feed in to create the strongest storms in mid-latitudes but also enhance storm feedbacks which intensify the mid latitude jet stream. Atmospheric rivers are responsible for the major precipitation events reaching high elevations in mid to northern latitudes. The mountains of the St. Elias form a tremendous barrier that reaches above 5000 m in the atmosphere. The special isotopic character of the precipitation near the summit of Mt Logan has puzzled scientists and generated multiple competing views on what controls the isotopic signature, and why the records from Mt Logan are so different than elsewhere on earth. Some say the moisture at Mt Logan is derived from different sources and others say it has to do with the intensity of the moisture stream directed towards the St Elias. These differences of opinion result in opposite interpretations of the Aleutian low and west coast ridge using the same ice core data. For this paper, the distinctive vertical step in precipitation stable isotopes for the highest elevations is explained by the physics of fractionation of supercooled water droplets in the presence of ice crystals and water vapor at temperatures below minus 20 C. This same physics can explain how atmospheric river variations can be detected in the high mountain ice cores, and why there is so much moisture at times, thrown so high and so out of normal equilibrium isotopically at Mt Logan but not elsewhere.. Using this new physical reasoning, the shifts and trends in the ice core record are interpreted back 18,000 years as atmospheric river flux using a Storminess/AR index (Fig 1). Results demonstrate that high mountain ice cores are not only valuable for verification of cloud physics using isotopes but also for understanding climate and environmental change for as long as the ice core is reliable. The thicker corrected ice core layers in recent years at Mount Logan are consistent with glacier behavior in the St. Elias, but only if we have more precipitation with warmer temperatures. For example, the Hubbard glacier (which headwaters at Mount Logan) is now once again advancing towards Yakutat, AK as it did during the climate optimum around 1100 AD, when most all glaciers at lower elevations retreated. The sulfuric acid, volcanic ash and other geochemical tracers in the ice core records further support a sensitive response to some volcanic eruptions, but not all. The shifts and trends implied for atmospheric river flux in the northeastern Pacific are best explained by factors that control the Aleutian low, the west coast high pressure ridge, and tropical convection in the western and central Pacific and are consistent with the precipitation stable isotopes of the St Elias region.

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IARCS/116

A New Look Atmospheric Rivers from an Energy Perspective

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Atmospheric Rivers (ARs) are narrow corridors of enhanced water vapor transport that extend from the tropics to the mid-latitudes and are often associated with transient eddies. Nearly 90% of the poleward moisture transport in Earth's atmosphere occurs through ARs. These extreme weather phenomena, which are characterized by strong low-level winds and high-water vapor content, result in direct poleward transport of tropical moisture and are associated with local moisture convergence along the cold front of extratropical cyclones. Synoptic and mesoscale circulations, such as convective vertical motion, Kelvin waves, and coupling of the upper-level jet stream with frontal waves (called a jet-front system), have all been suggested to affect the intensity and duration of the ARs (Ralph et al., 2011; Cordeira et al., 2013). However, our knowledge about the details of these interactions with ARs is still limited (Rutz et al., 2014).

Our preliminary study has suggested a methodology to further address the dynamics of the ARs by examining the energy and momentum budgets of the eddies underlying the AR tracks. We have implemented advanced diagnostics tools to investigate the propagation of energy from the source of instability across the ARs. This approach can reveal valuable insight into the AR characteristics from an energetic point of view.

Session 2

Impacts of ARs

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IARCS/066

Antarctic Atmospheric River Climatology and Impacts

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The surface mass balance of Antarctica is sensitive to intrusions of extremely warm, moist airmasses from the mid-latitudes in the form of atmospheric rivers (ARs). These storms provide a sub-tropical link to the Antarctic continent and are very consequential to the surface mass balance (SMB) of the ice sheet. Using an AR detection algorithm designed for Antarctica and regional climate simulations from MAR, we created a climatology of AR occurrence and their associated impacts on surface melt, ice shelf stability, and snowfall.

Despite their rarity of occurrence over Antarctica (maximum frequency of ~1.5% over a given point), ARs have a relatively large impact of the surface melt processes in West Antarctica and snowfall patterns of East Antarctica. In West Antarctica, AR landfalls and their associated radiative flux anomalies and foehn winds accounted for around 40% of the total summer surface melt on the Ross Ice Shelf (approaching 100% at higher elevations in Marie Byrd Land) and 40-80% of total winter surface melt on the ice shelves along the Antarctic Peninsula from 1979-2017. During the summer season along the Larsen ice shelves, ARs contribute less to the total surface melt, but cause 60-80% of the most intense melt, runoff, and high temperature extremes. Through a combination of melt pond formation and subsequent hydrofracturing initiated by leeward Foehn winds and radiative fluxes, and sea ice disintegration that allows swells to stress the ice shelf margins, ARs can trigger major ice shelf collapse events. Intense AR landfalls coincided with the collapse of the Larsen A in January 1995 and the Larsen B in the summer of 2002.

In East Antarctica, ARs are responsible for 20-30% of snowfall and a majority of the heaviest precipitation events with ramifications for past climate reconstruction using ice cores. Despite ARs having a modest impact on total precipitation, annual snowfall trends across East Antarctic were primarily driven by trends in AR frequency while ARs controlled the inter-annual variability of precipitation across most of the Antarctic ice sheet from 1980-2018.

Our results suggest that atmospheric rivers play a significant role in the Antarctic surface mass balance. Thus any future changes in atmospheric blocking or tropical-polar teleconnections, which control AR behavior around Antarctica, may have significant impacts on future surface mass balance projections and subsequent sea level changes.

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IARCS/002

Large summer rainfall events and their importance in mitigating droughts over the South Western Cape, South Africa

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Although the South Western Cape receives most of its rainfall between May and September, there are substantial rainfall events in some summers. These events are of interest in themselves as well as for their possible role in mitigating the frequent winter droughts that the region suffers from. Most recently, greater Cape Town suffered a devastating drought during 2015-2018 known as the Day Zero drought as there was a risk of the urban area running out of piped water from the supply dams. Estimated data from the City of Cape Town show that major dam levels in the South Western Cape increased more than 1% in some cases after large rainfall events (LREs) in the summer of 2018/19. This increase is significant as dam levels often decrease by several % per month during the hot summer. In this study, LREs over the South Western Cape derived from South African Weather Service (SAWS) station data during the drier summer months (October – March) are investigated together with dam level data from the City of Cape Town authority.

Atmospheric rivers and cut-off lows are the cause of most summer LREs. Atmospheric rivers are a common contributor to winter rainfall and are associated with strong winds and large quantities of rain. Cut-off lows are also featured in the winter months and are known to also occur more frequently during the transition months. Cut-off lows and atmospheric rivers differ in duration, extent and intensity but both produce LREs. Cut-off lows tend to have a longer duration and cover larger areas compared to atmospheric rivers. In contrast, atmospheric rivers can be described as relatively short bursts of intense rainfall with most of the rain concentrated around the Greater Cape Town region. Large rainfall can have positive effects on the catchment areas in the South Western Cape. The large rainfall events ability to contribute considerably to dam level increases makes them key in times of drought recovery. In particular, atmospheric rivers and cut-off lows derived LREs have reached up to 1.24-5.08% in average dam level increases in the extended summer. These dam level increases are significant given that dams typically decrease by 1.2-1.6% per week during the peak of summer. Moreover, LREs produced by these rain bearing systems can occur after particularly dry winters like that of 1980, 1984, 2003, 2004 and most recently following the Day Zero drought. Their considerable contribution makes these rain bearing systems essential during times of drought recovery.

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IARCS/006

New Zealand Extreme Rainfall Associated with Atmospheric Rivers

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Atmospheric Rivers (ARs) are narrow regions of intense horizontal water vapour transport. There has been considerable work understanding Northern Hemisphere ARs and their relationship with extreme precipitation, and studies have shown that ARs are a key driver of heavy rainfall and flooding (Lavers et al., 2011; Neiman et al., 2013; Ralph et al., 2006). While there has been very little work on ARs in the Southern Hemisphere, global climatologies such as by Guan and Waliser (2015) suggest that ARs are just as common in the Southern Hemisphere. Moreover, New Zealand in particular is located in a region of high AR frequency (Guan and Waliser, 2015). This study aims to test the hypothesis that ARs play a role in New Zealand heavy precipitation and flooding events. We used the Reid et al., (in review) AR identification method and daily station data across New Zealand to test the concurrence of ARs and extreme rainfall. We found that the 70-100% of the top ten heavy precipitation days between 1980 and 2018 were associated with AR conditions, and nine of the ten most expensive floods in New Zealand between 2007 and 2017 occurred during AR events. These results have important implications for understanding extreme rainfall in New Zealand and the global impacts of ARs.

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IARCS/018

Atmospheric Rivers Will Become More Damaging In the Western United States

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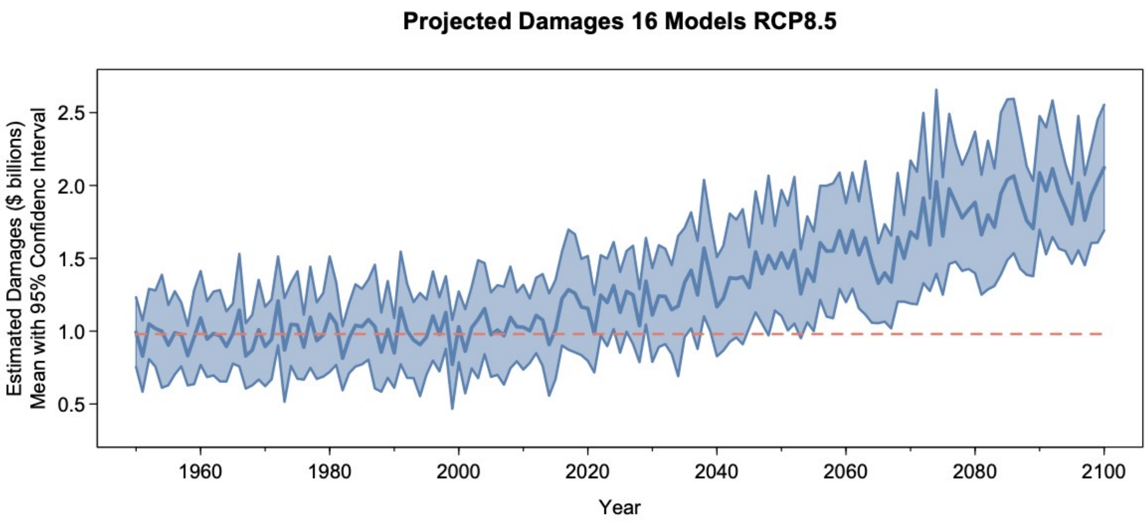
Atmospheric rivers (ARs) are extratropical storms that produce extreme precipitation on the west coasts of the world's major landmasses. ARs are the primary driver of economic flood damage in the western United States. They are projected to increase in intensity with climate change, but their future costs have not yet been modeled.

40 years of flood damages from the National Flood Insurance Program (1978 to 2018) over the western states of California, Nevada, Oregon, and Washington are linked to a catalog of atmospheric rivers to develop a model of damages as a function of AR scale and latitude-specific storm total IVT. The model is then applied to 16 GCMs for which ARs can be detected, under the RCP8.5 scenario.

The model projections predict that direct economic flood damages in the westernmost United States due to ARs will double by the 2090s relative to the 1990s, holding spatial patterns of exposure and vulnerability constant. Increases in damages are most concentrated in the Sierra Nevadas, and at the border of Northern California and Southern Oregon. Rising population, and increased development in flood plains may further increase the impact.



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IARCS/023

Global Analysis of Atmospheric Rivers Precipitation using Remote Sensing and Reanalysis Products

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Atmospheric rivers (ARs) are elongated narrow corridors of water vapor transport in the low-level jet layer of the atmosphere. ARs are typically longer than 2000 km, less than 1000 km wide, and are often made of poleward and lateral moisture transport. Several studies have demonstrated the key contribution of ARs to total and extreme precipitation at the regional scale. In the present study, and in light of the availability of global datasets, a global analysis of AR precipitation is conducted using various precipitation products covering 18 years starting in 2001. More specifically, (1) the frequency of ARs occurrence is investigated, (2) precipitation intensity and volume of AR and Non-AR events are compared, and (3) precipitation extremes and their relationship with AR events are studied.

Extreme events are defined as the daily precipitation rates at or above the 95th percentile for all daily precipitation rates in a year. Extreme events are investigated both globally at each grid cell and zonally averaged using remote sensing and reanalysis precipitation products. Besides, regions over land where ARs have a large impact (e.g. floods due to ARs' precipitation) are specifically explored.

AR precipitation from four widely used products (IMERG V6, GPCP Daily V1.3, bias-adjusted CMORPH V1, PERSIANN-CDR), and two well-known reanalysis products (MERRA-2 and ERA5) are also compared to assess potential differences between satellite and reanalysis products concerning capturing AR-related precipitation in terms of frequency, intensity, and extremes.

Over the oceans (especially the Southern Ocean), the contribution of ARs to the total precipitation and extreme events is larger than overland. However, some coastal areas over land (e.g., the Western US) are highly affected by ARs. The results also indicate that there is a better agreement among products over the tropics than in higher latitudes. The largest inconsistencies among the products occur over the Southern Ocean where IMERG shows the highest percentage of ARs' contribution to total precipitation and extreme events. This study also reveals that IMERG/CMORPH and GPCP/PERSIANN-CDR pairs have higher spatial correlations globally which is expected given the similarities in their retrieval algorithms. It also should be mentioned that reanalysis products deviate significantly from satellite-based products over a few selected regions over land (e.g., North Africa) that might be related to the lack of in situ observations for satellite calibration and for assimilating into reanalysis products in these regions.

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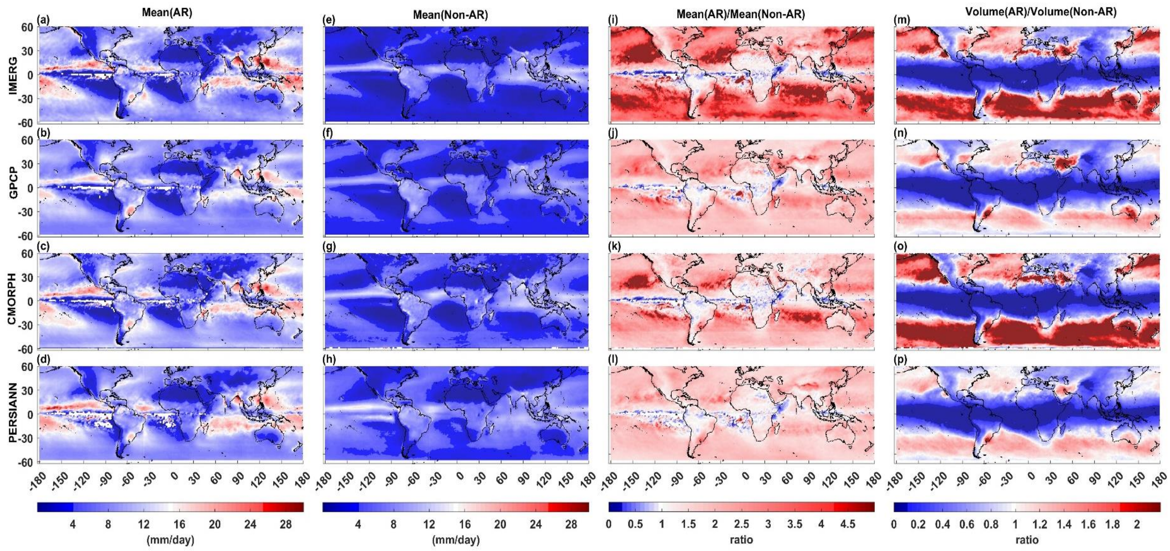

Mean of daily AR-related precipitation (mm/day) (Column 1), mean of Non-AR daily precipitation (mm/day) (Column 2), the ratio of the mean AR-related precipitation intensity to non-AR's (Column 3), and the ratio of the total volume of AR-related precipitation to non-AR's (Column 4) for four precipitation products (IMERG V6, GPCP V1.3, PERSIANN-CDR, and CMORPH) for the period of 2001-2018.

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IARCS/024

Linking atmospheric rivers to annual and extreme river runoff in British Columbia and southeastern Alaska

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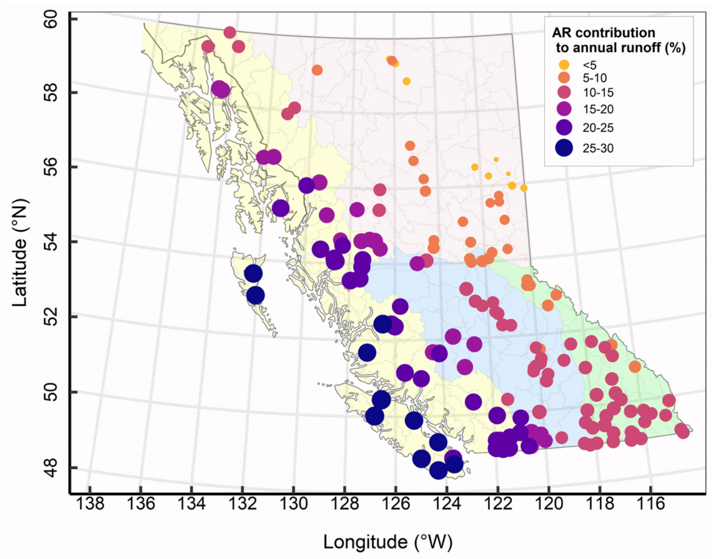
Atmospheric rivers (ARs) periodically impact hydrological processes of the British Columbia, Canada and southeastern Alaska, the USA (BCSAK). However, understanding of the linkages between ARs, river runoff, and flooding events of this region remains limited partly owing to complexities associated with hydrological regimes (e.g., pluvial, nival, glacial, and their hybrids). In this study, we use an empirical approach based on annual water budgets and quantify the contribution of ARs to annual and maximum river runoff. Further, we evaluate the relationships between watershed characteristics and AR-related maximum river runoff. Datasets used include gauged runoff from 168 unregulated watersheds, topographic characteristics of those watersheds, a regional AR catalog, and integrated water vapor transport fields for water years (WYs) 1979 to 2016.

ARs contribute ~22% of annual river runoff along the Coast and Insular Mountains watersheds; this decreases inland to ~11% in the watersheds of the Interior Mountains and Plateau. Average association between ARs and annual maximum river runoff attains >80%, >50%, and <50% along the watersheds of the western flanks of the Coast Mountains, the Interior Mountains, and Plateau, respectively. There is no significant change in AR-related extreme annual maximum runoff across BCSAK during 1979-2016. AR conditions occur during 25 out of 32 of the flood-related natural disasters in BC during WYs 1979-2016. AR-related annual maximum runoff magnitude is significantly higher than non-AR-related annual maximum runoff for 30% of the watersheds studied. Smaller and steeper watersheds closer to the coast are more susceptible to AR-related annual maximum runoff than their inland counterparts. These results illustrate the importance of AR activity as a major control for the distribution of peak runoff in BCSAK. This work provides insights on the hydrological response of watersheds of northwestern North America to landfalling ARs that may improve flood risk assessment and disaster management in this region.



The contribution of ARs to total annual runoff (in %) across BCSAK, WYs 1979-2012.

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IARCS/037

The Impact of Atmospheric Rivers on Glaciers in Fuego-Patagonia

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Fuego-Patagonia hosts the largest volume of glacier ice outside Antarctica in the Southern Hemisphere. Besides a multitude of smaller mountain glaciers and ice caps these huge ice masses are stored in three continental ice fields: the North Patagonian Ice Field, the South Patagonian Ice Field, and the Cordillera Darwin. All three major ice-fields are located along the southernmost section of the Andean Cordillera. The permanent advection of moisture from the Pacific Ocean, land-falling atmospheric rivers and the orographic barrier of the Andes perpendicular to the mean wind flow provide the conditions for enormous amounts of total annual precipitation. These circumstances are globally exclusive conditions for studying the response of outlet glaciers from the major ice-fields to large-scale atmospheric variability.

The outlet glaciers of the ice fields reach either down or close to sea level, and large areas of the ice are in temperate conditions throughout the year. Many glaciers terminate into fjords or proglacial lakes, so that extensive mass loss is due to calving. Strong ablation events in the austral summer due to warm phases interrupted by land-falling atmospheric rivers have been observed in the past. We presume that this combination is responsible for an event-based immense ice loss of the glaciers in Southern Patagonia and might become a more frequent recurring phenomenon under future climate conditions as a response to global climate warming.

Three camera systems, one at the Glacier Grey (South Patagonian Icefield) and two at the Glacier Schiaparelli (Cordillera Darwin), monitor the variability of ice flow velocity in the terminus of the glaciers since 2016. The time series offer an opportunity to study the influence of land-falling atmospheric rivers on calving flux. In combination with automatic weather stations, water isotope analysis and reanalysis data from numerical prediction models, we aim at investigating the local interaction between the atmo-, hydro- and cryosphere in detail. The results of this ongoing study will contribute to the understanding of the atmospheric variability in the recent climate history, and to projections of glacier change in South Patagonia and Tierra del Fuego. The presentation will provide an overview on the conceptual framing of the study and provide first results derived from time lapse photography and isotope analysis.

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IARCS/038

Isotopic anomalies in water vapor during an atmospheric river event at Dome C, East Antarctic plateau, controlled by large-scale advection and boundary layer processes

Cécile Agosta, Cécile Davrinche, Christophe Leroy-Dos Santos, Antoine Berchet, Amaëlle Landais, Elise Fourré, Anaïs Orsi, Frédéric Prié, Charles Amory, Vincent Favier, Xavier Fettweis, Christophe Genthon, Christophe Kittel, and Dana Veron

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On December 19-21 2018, an atmospheric river hit the French-Italian Concordia station, located at Dome C, East Antarctic Plateau, 3 269 m above sea level. It induced an extreme surface warming (+ 15°C in 3 days), combined with high specific humidity (multiplied by 3 in 3 days) and a strong isotopic anomaly in water vapor (+ 15 ‰ for δ 18 O). These changes in the isotopic composition of the water vapor may be due to (1) changes in the initial moisture uptake area, (2) fractionation along long-range air mass transport, and (3) enhanced boundary layer mixing during the event. In this study we quantify the influence of each of these processes on the isotopic composition of water vapor.

In order to estimate the contribution of moisture uptake and large-range advection, we perform back-trajectories with the "FLEXible PARTicle dispersion model" FLEXPART. We retrieve meteorological conditions along the different trajectories between the moisture uptake area and Concordia, and use them to compute isotopic fractionation during transport with the MCIM model. While intermediate conditions along the trajectory do not seem to have a major impact on the final isotopic composition (less than 0.1 ‰), the latter appears sensitive to surface conditions (temperature, pressure and specific humidity) in the moisture uptake area (±5.1 ‰).

Then we demonstrate the strong influence of boundary layer processes on the isotopic composition of the water vapor using observations and simulations from the regional atmospheric model MAR, ran with and without blowing snow. The specific meteorological conditions, related to the intrusion of warm and moist air, enabled the formation of mixed-phase clouds, which increased significantly downward longwave radiative fluxes. It led to high turbulent mixing in the boundary layer which remained thicker than 300 m, even at night. Furthermore, high wind speed, up to 12 m s^{-1} , recorded on December 20-21, caused heavy blowing snow (white-out conditions). Using MAR simulations, we show that a large part of the surface atmospheric water vapor originates from sublimation of blowing snow particles removed from the snowpack. Consequently, the isotopic signal monitored in water vapor during this atmospheric river event reflects more the interactions between the boundary layer and the snowpack than the long-range advection. Only specific meteorological conditions driven by the river can explain these strong interactions.

IARC-Sponsored Symposium
5-9 Oct. 2020

IARCS/039

Atmospheric Rivers contribution to the snow accumulation over the southern Andes

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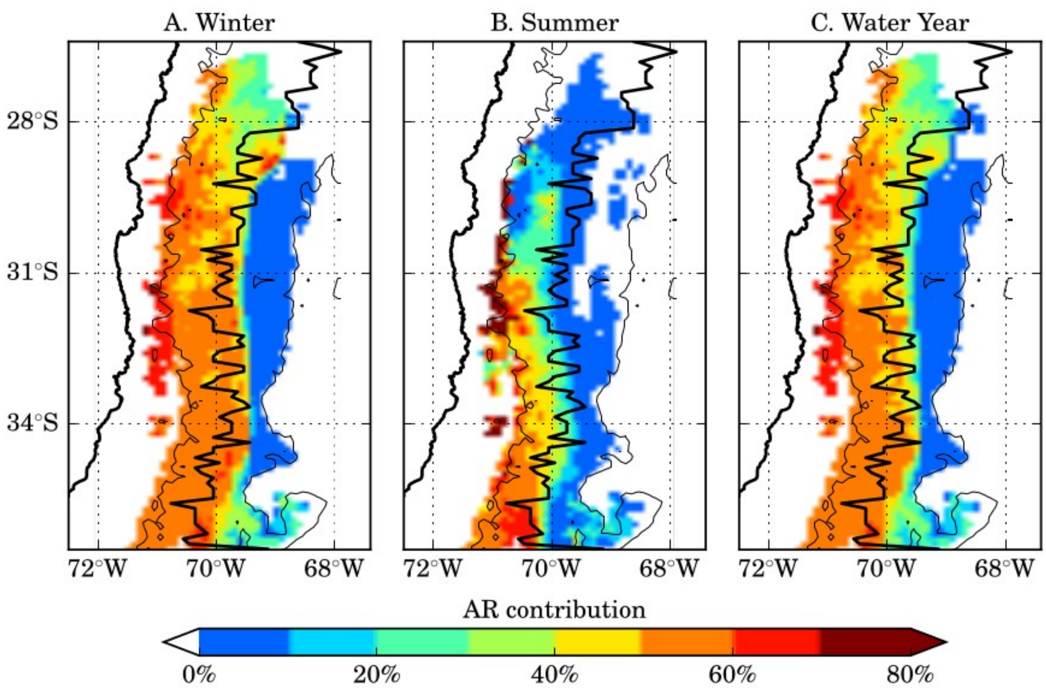
In this work, we quantify the historical contribution of atmospheric rivers (ARs) to annual snow accumulation in Central Andes Cordillera (26.5°S-36.5°S). We use an AR identification algorithm, and a high-resolution snow water equivalent reanalysis dataset, both specially developed for this region over the 1984-2014 period. AR events explain approximately 50% of the annual snow accumulation over the study area and AR snowfall events are 2.5 times more intense than non-AR snowfall events. Annual snow accumulation and AR storms contribution to this accumulation are, on average, 7 and 12 times larger on western than on eastern slopes of the mountain range due to orographic precipitation enhancement on the western slope and a prominent rain shadow effect on eastern slopes. Analysis of teleconnections with El Niño Southern Oscillation shows a reduction in the AR frequency across the study area during La Niña episodes and, consequently, a lower contribution to snow accumulation. For weak El Niño episodes AR activity and their snow contribution increase in the entire study area. However, we find that moderate to strong El Niño episodes displace AR landfall northward reducing the partial contribution south of 32°S.



IARC-Sponsored Symposium
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IARCS/042

A Performance-Based Framework to Quantify Atmospheric River-Induced Flooding

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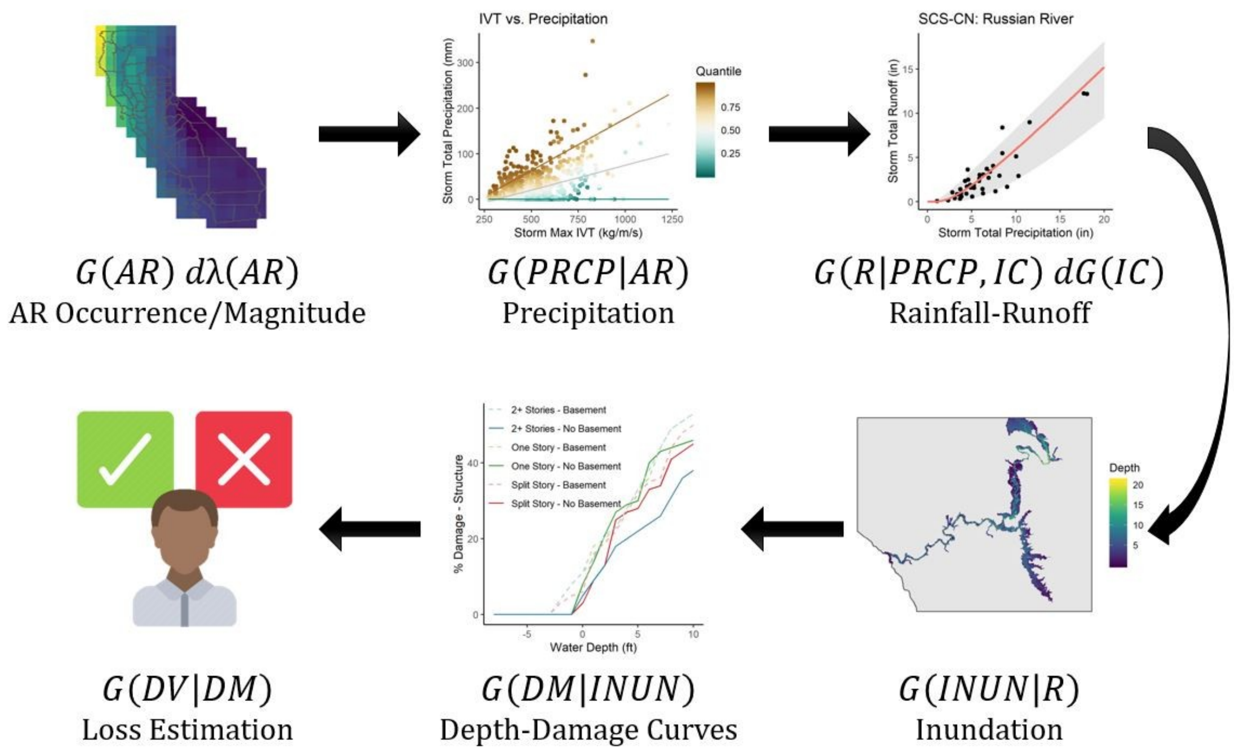
Atmospheric rivers (ARs) cause over a billion dollars of damage annually across the western US. While our ability to observe and forecast these storms has been steadily improving, our capacity both to predict the expected value of damage from an AR event and to evaluate confidence bounds around that value are limited by the challenges in connecting research across multiple disciplines. In particular, there have been few attempts to downscale AR damage estimates from the broad regional level to the community level where flood mitigation decisions are made. Here we develop a novel performance-based atmospheric river risk analysis (PARRA) framework to estimate the impacts of AR-induced flooding. The framework links research related to atmospheric forcings, hydrologic impacts, and economic consequences, combining them into one cohesive workflow that encompasses the entire modeling process from AR occurrence all the way to community loss estimation.

This work takes performance-based risk analysis concepts, which came from the field of earthquake engineering but have since been used to evaluate hurricanes, fires, and many other hazards, and translates them for application in an AR context. The resulting PARRA framework is organized around a series of “handoff” variables that streamline the modeling process and improve workflow flexibility. The variables are: AR characteristics (AR), precipitation (PRCP), river discharge (R), hydrologic initial conditions (IC), flood inundation height (INUN), damage measures (DM), and decision variables (DV), which are then organized into six main component models as shown in the attached figure. Once each component model is calibrated, the entire framework is then solved numerically by generating Monte Carlo realizations at each step and propagating those realizations through the rest of the equation to get an empirical distribution of losses. The effectiveness of the framework is demonstrated by predicting the distribution of anticipated AR-induced losses due to fluvial flooding along the Russian River in Sonoma County, California, a location which has historically been very prone to AR-induced flooding.

The proposed risk analysis framework has several benefits. Its modular nature allows users to propagate uncertainty through successive model components and generate confidence bounds on the estimates of AR-induced loss. The full treatment of uncertainty offers a quantitative measure to compare how much irreducible error is inherent in each component model, which can be used to direct future modeling efforts and prioritize improvements. The framework also has the ability to forecast community impacts from previously unseen conditions. For example, we can estimate the impacts of more extreme ARs under future climate change scenarios, or conduct cost-benefit analyses for communities considering different flood mitigation investments. Cities and counties that experience repetitive AR-driven flooding can use this model as a tool to identify areas of high exposure and vulnerability within their communities and reduce the risk they face from AR events.


IVT vs. Precipitation
Storm Total Precipitation (mm)
Storm Max IVT (kg/m/s)
Quantile
SCS-CN: Russian River
Storm Total Runoff (in)
Storm Total Precipitation (in)
$G(AR)\, d\lambda(AR)$
AR Occurrence/Magnitude
$G(PRCP|AR)$
Precipitation
$G(R|PRCP, IC)\, dG(IC)$
Rainfall-Runoff
2+ Stories - Basement
2+ Stories - No Basement
One Story - Basement
One Story - No Basement
Split Story - Basement
Split Story - No Basement
% Damage - Structure
Water Depth (ft)
Depth
$G(DV|DM)$
Loss Estimation
$G(DM|INUN)$
Depth-Damage Curves
$G(INUN|R)$
Inundation

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IARCS/043

High-Impact Weather Events over Hawaii and southwestern United States in February 2019 Due to North Pacific Large-Scale Flow Evolution

Tyler C. Leicht and Lance F. Bosart

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Highly amplified upper-level flow pattern over the central and eastern North Pacific and western North America during February 2019 was associated with several high-impact and difficult to predict weather events in Hawaii and the southwestern United States. Persistent Kona Low conditions lowered snow levels and produced below average temperatures in Hawaii while frequent trough passages over western North America resulted in multiple rounds of high-impact precipitation events over the southwestern United States. This presentation will discuss aspects of this weather regime including a persistent time-mean upper-level trough near the east coast of Asia, a retracted western Pacific jet, cyclonic wave breaking (CWB) in the exit region of this jet, repeated upstream enhancement of a persistent ridge over the Gulf of Alaska, and downstream troughing over western North America.

Periodic CWB events over the west-central Pacific between 1–10 February precluded the Pacific jet from extending eastward across the Dateline toward North America. This retracted jet allowed for the formation and maintenance of a persistent ridge from 1–15 February in the Gulf of Alaska. This persistent ridge was enhanced periodically due to several episodes of CWB near the Dateline. The first round on 8–9 February built the ridge further west toward the Aleutians and lead to the formation of a cutoff cyclone northeast of Hawaii due to anticyclonic wave breaking (AWB). A second CWB event from 12–13 February resulted in further westward shifting of the persistent ridge over western Alaska on 14–15 February. Both periods of ridge buildup were directly linked with a strong AR on the western edge of the ridge. Strong northerly flow east of this anticyclone throughout the lifecycle of the persistent ridge drove cold air southward across western North America.

High-latitude ridge building over Alaska and northwestern Canada supported repeated potential vorticity streamer (PVS) formation over the eastern Pacific between 10–15 February. This DRR is the result of AWB across the central Pacific, leading to the formation of PVSs to the south and east of the ridge. Cutoff cyclones formed from the southern ends of these PVSs repeatedly reinforced the Kona Low northeast of Hawaii. We will show that the predictability time scale of the aforementioned high-impact weather events depended on the extent of Kona Low interaction with upper-level disturbances moving southward along the West Coast of North America east of the persistent Alaskan ridge.

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IARCS/045

Using ARTMIP Data to Examine the Relationship between Atmospheric Rivers and NWS Watches/Warnings/Advisories

Jonathan Rutz, Jason Cordeira, Juan Lora, Christine Shields and Samuel Bartlett

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The atmospheric river (AR) science literature contains dozens of peer-reviewed methods for identifying and tracking ARs, which has led to widely disparate results in terms of AR climatology and AR-related impacts. Over the past few years, the Atmospheric River Tracking Method Intercomparison Project (ARTMIP; Shields et al. 2018) has collected a vast library of data that describes, on a common data set, when and where these methods identify ARs. This ARTMIP data has enabled quantification of the uncertainty in recent/current AR climatology (Rutz et al. 2019), ongoing work to quantify the uncertainty in future AR climatology, and an evaluation of consensus and disagreement amongst methods (Lora et al., in review). However, there has been no comprehensive effort to relate ARs, as identified by individual ARTMIP methods, to high-impact weather events that endanger lives and threaten property.

In this study, we use watches, warnings, and advisories (WWAs) issued by the U.S. National Weather Service as a proxy for local storm reports, which are severely limited by sample size (lack of reporting even during big events) and by demographics/geography (lack of reports in less populated regions). This study examines, for each individual method, when and where identified AR footprints overlap with WWAs of various types (i.e., winter weather, hydrologic, wind). We view each AR footprint as a "WWA forecast" and each WWA issued as a "WWA observation". This allows for calculation of a contingency table describing hits, false alarms, misses, and correct negatives, from which we calculate the probability of detection (POD) and false alarm rate (FAR), as well as other metrics, for each method. This allows for some discussion of which methods "undercount impacts" (i.e., low POD), "overcount impacts" (i.e., high FAR), or fall somewhere in between. Examples will be shown to highlight both the method used and the characteristics of unique cases.

Rutz, J. J., Shields, C. A., Lora, J. M., Payne, A. E., Guan, B., Ullrich, P., et al. (2019). The atmospheric river tracking method intercomparison project (ARTMIP): quantifying uncertainties in atmospheric river climatology. Journal of Geophysical Research: Atmospheres, 2019; 124: 13777– 13802. https://doi.org/10.1029/2019JD030936

Shields, C. A., Rutz, J. J., Leung, L.-Y., Ralph, F. M., Wehner, M., Kawzenuk, B., Lora, J. M., McClenny, E., Osborne, T., Payne, A. E., Ullrich, P., Gershunov, A., Goldenson, N., Guan, B., Qian, Y., Ramos, A. M., Sarangi, C., Sellars, S., Gorodetskaya, I., Kashinath, K., Kurlin, V., Mahoney, K., Muszynski, G., Pierce, R., Subramanian, A. C., Tome, R., Waliser, D., Walton, D., Wick, G., Wilson, A., Lavers, D., Prabhat, Collow, A., Krishnan, H., Magnusdottir, G., and Nguyen, P.: Atmospheric River Tracking Method Intercomparison Project (ARTMIP): project goals and experimental design, Geosci. Model Dev., 11, 2455–2474, https://doi.org/10.5194/gmd-11-2455-2018, 2018.

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IARCS/050

Catastrophic Impact of an Atmospheric River on southern Brazil

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On June 30th 2020, a strong extratropical cyclone formed near the southern Brazil coast associated with the propagation of a cold front. At that particular day, an Atmospheric River (AR) was active transferring large amounts of water vapor from the Amazon region towards the south. The formed cyclone was classified as a "bomb cyclone" because its center near surface atmospheric pressure dropped more than 24 hPa in less than 24 hours. Associated with the presence of the cyclone and the AR, a squall line formed over the west domain and crossed towards the east coast. This strong squall line produced catastrophic winds and rainfall causing 11 fatalities and damages on 208 cities of the state of Santa Catarina (SC) affecting about 70% of the state area. This squall line was classified as a Derecho, a meteorological system that in general causes strong downdraft wind effects on the surface. Estimate damages over SC were in the order of 100 million dollars. To better characterize this event, winds and the integrated vapor transport were obtained from the ECMWF ERA5 reanalysis hourly data. Atmospheric maps for the 18:00 UTC (15 LT) showed that the vapor transport reached more than 1000 (kg $m^{-1} s^{-1}$) over the SC state. This transport was carried from the northwest where the winds (at 850 hPa height) reached speeds greater than 70 km/hr. Preliminary analysis showed that the presence of an AR and a strong extratropical cyclone were responsible for the formation of a catastrophic Derecho squall line on the southern Brazil. The results show that monitoring these AR phenomena and improving their forecasting capacity is of fundamental importance for the local region.

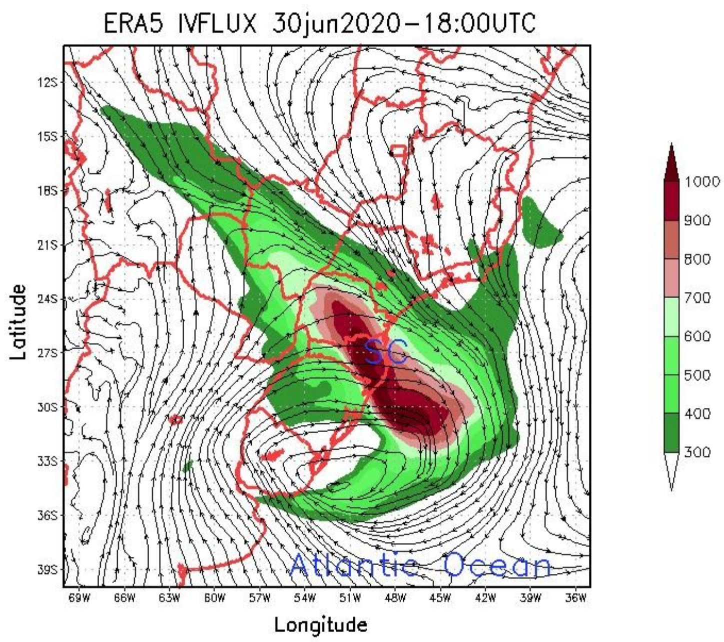

Figure – ERA5 reanalyses Integrated Vapor Transport (kg $m^{-1} s^{-1}$) and wind flow (at 850 hPa) for 30 June 2020 18:00 UTC. SC represents the State of Santa Catarina (Brazil).

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IARCS/054

The role of ARs in producing large snowfall events in the Southern Alps of New Zealand

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Snow is an essential component of the mountain cryosphere (Bales et al., 2006; Hock et al., 2019) providing water for more than one billion people across the globe (Barnett et al., 2005). Hydrological processes in alpine catchments are influenced by timing and magnitude of snow accumulation and subsequent melt events. Large snowfall events, in particular, are of special interest from hydrological and meteorological standpoints because of their considerable socio-economic impacts on snow-fed rivers (Lute and Abatzoglou, 2014). In this study, records from three automatic weather stations (Mahanga, Mueller Hut and Mt Larkins) near the Main Divide of the New Zealand Southern Alps were used to identify large snowfall events. The large snowfall events are defined based on the 90th percentile of daily snowfall at each site. ERA-Interim reanalysis data were used to characterize the hydrometeorological characteristics of the selected events. In the mid-latitude regions such as New Zealand Southern Alps, a large portion of moisture flux is transported through narrow corridors of strong water vapour flux (L ≥2000 km, L/W ≥2, and IVT ≥ IVT 85th), known as atmospheric rivers (ARs). The contribution of landfalling ARs to large snowfall events in the Southern Alps has been quantified. Results showed that approximately 61% of such events at Mahanga (13 out of 21 events) were associated with ARs. The contributions of ARs to the large snowfall events at Mueller Hut and Mt Larkins were 70% (12 out of 17 events) and 71% (10 out of 14), respectively. The close correlation between ARs and large snowfall events has implications on predictability of extreme winter precipitation in the Southern Alps.

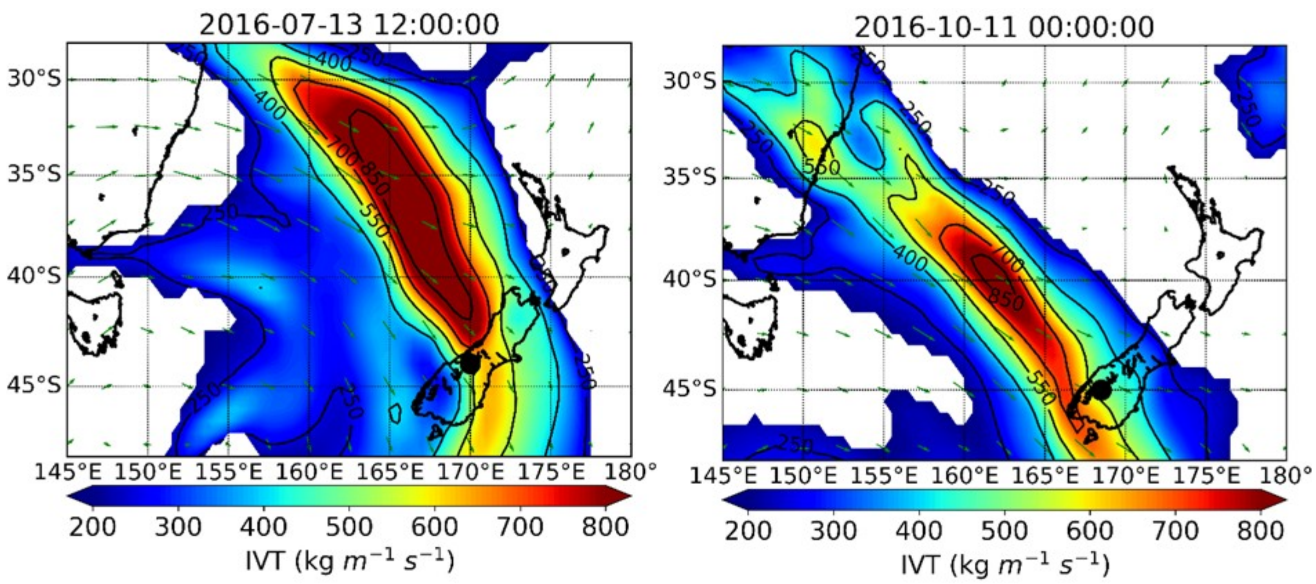

Figure 1. Examples of snow-generating ARs in the Southern Alps during July 2016 and October 2016 snowstorms.

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IARC-Sponsored Symposium
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IARCS/056

European West Coast Atmospheric Rivers: A scale to characterize strength and impacts

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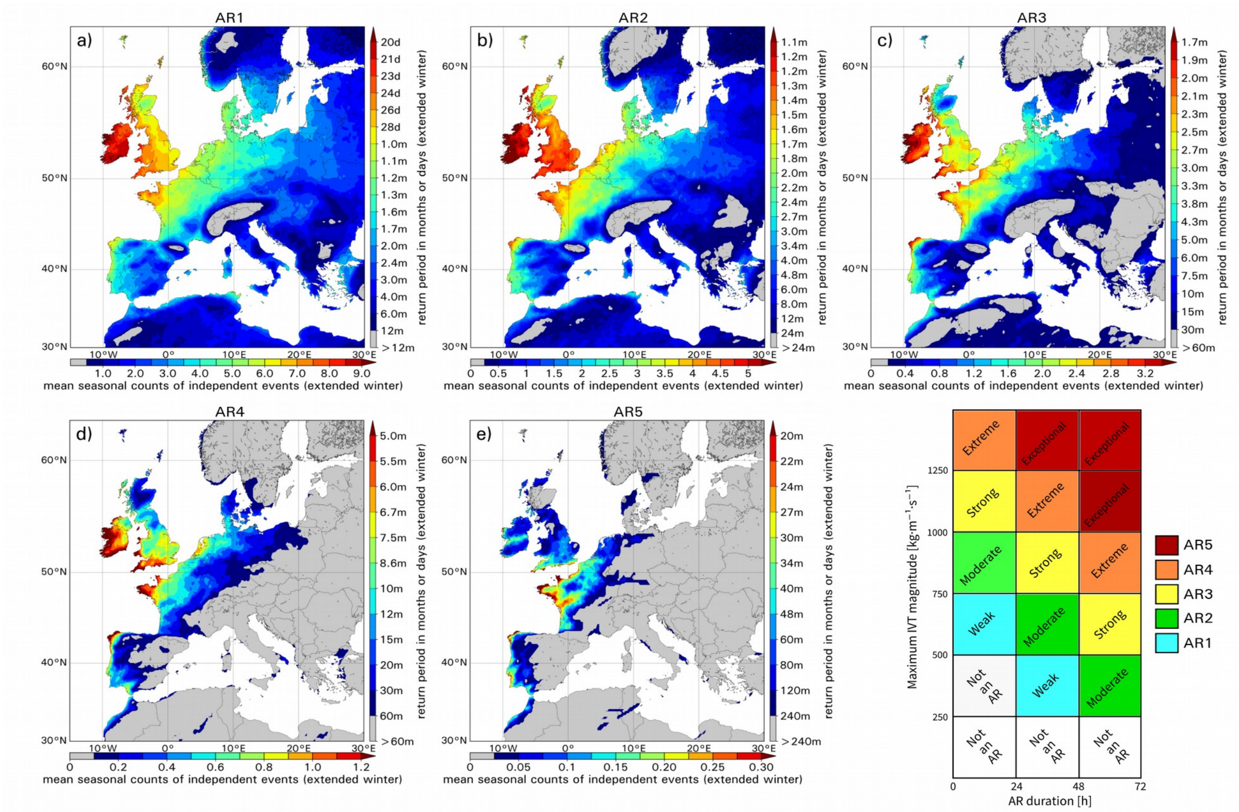
This manuscript applies the recently-created atmospheric river intensity and impacts scale (AR Scale) to the European continent. The AR Scale uses an Eulerian perspective based solely upon the time series of integrated vapor transport (IVT) over a given geographic location (often represented by a model or reanalysis "grid cell"). The scale assigns events with persistent, strong IVT at that location to one of five levels (AR1 to AR5), or if the IVT is too weak or short-lived it is determined not to be an AR. AR1 events are primarily beneficial, AR2, 3 and 4 include a mix of beneficial and hazardous impacts, while AR5s are primarily hazardous. The frequency of occurrence, the associated probability of anomalous precipitation and the amount of precipitation explained by each AR rank are provided across Europe for the extended winter season (from October through March). AR1 and AR2 events are the most frequent and explain most of the observed precipitation, but they are associated with a low probability of extreme rainfall. Although AR3, AR4 and AR5 events are much less frequent, and normally provide a smaller fraction of annual precipitation, they are associated with a high probability of extreme rainfall. These results show remarkable variability among the different regions of the European continent. This manuscript also provides an AR detection catalog over Europe for the period 1980-2019, and a simplified version of the algorithm used to rank the events from AR1 to AR5.



IARCS/062

On the origin of the anomalous uptake of water vapor by landfalling Atmospheric Rivers

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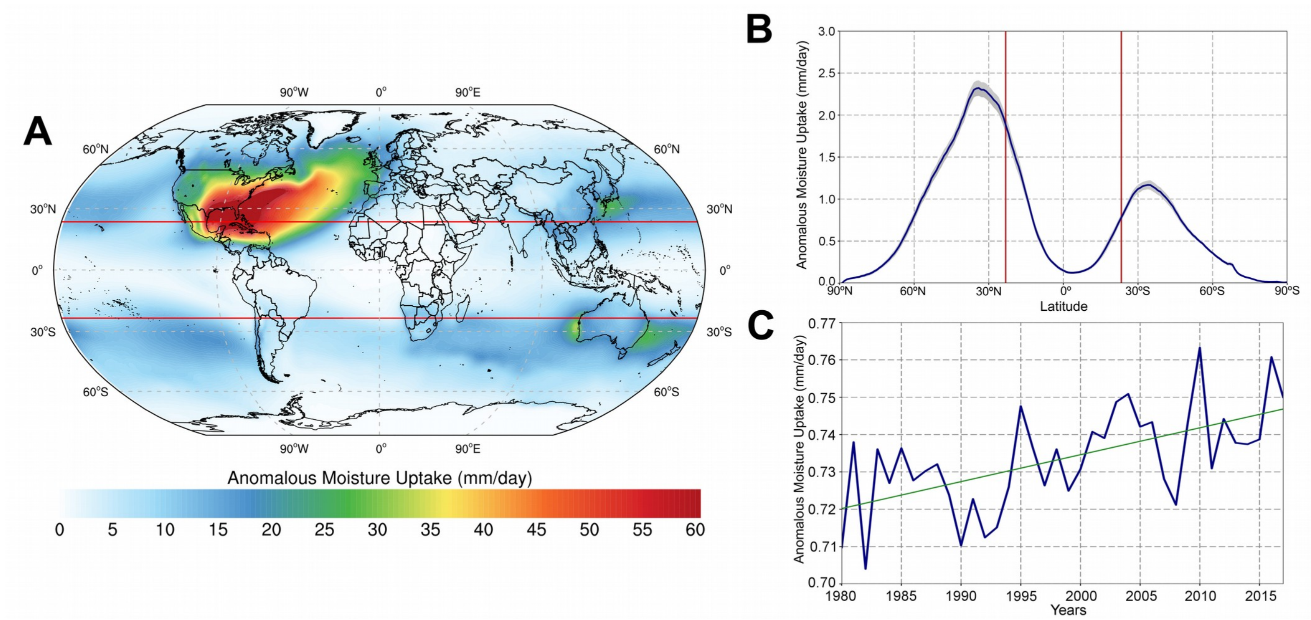
One of the most robust signals of climate change is the relentless rise in global mean surface temperature, which is linked closely with the water-holding capacity of the atmosphere. A more humid atmosphere will lead to enhanced moisture transport due to, among other factors, an intensification of atmospheric rivers activity, which provide the main mechanism of moisture advection from subtropical to extra-tropical regions. Here we show an enhanced evapotranspiration rates in association with landfalling atmospheric river events. These anomalous moisture uptake (AMU) locations are identified on a global scale. The interannual variability of AMU displays a significant increase over the period 1980-2017, close to the Clausius-Clapeyron (CC) scaling, at 7 % per degree of surface temperature rise. These findings are consistent with an intensification of AR predicted by future projections. Our results also reveal generalized significant increases in AMU at the regional scale and an asymmetric supply of oceanic moisture, in which the maximum values are located over the region known as the Western Hemisphere Warm Pool (WHWP) centred on the Gulf of Mexico and the Caribbean Sea.

Keywords Atmospheric Rivers, moisture transport, Anomalous Moisture Uptake



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IARCS/063

Impact of Atmospheric Rivers on Arctic climate: techniques for a better quantification of precipitation

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The Arctic has been experiencing significant warming and moistening with several potential factors at play. In general, the warming amplifies the Arctic hydrological cycle. There are two processes which could affect the water vapour content in the Arctic. These are the enhanced local evaporation due to the missing insulation effect of sea ice and the poleward moisture transport from lower latitudes. This poleward moisture transport is often associated with Atmospheric Rivers (ARs). Both processes could affect precipitation amounts and properties in the Arctic.

Snowfall and rainfall are critical components in the Arctic climate system. They influence the atmospheric thermodynamic due to phase changes and the surface characteristics like snow depth, mass balance and albedo. Snowfall has different effects over land and ocean. Over land it increases the albedo. However, over the ocean, snow enhances the thermal insulation which reduces the sea ice growth in winter. In contrast, rain on sea ice decreases the albedo and is related to sea ice melting. Recent studies have shown that an increase of precipitation have been observed over the last decades. Furthermore, the warming in the Arctic leads to a phase change with the consequence that the dominant type of precipitation is rain. Nowadays, it is still a challenge to quantify the frequency and type of precipitation in the Arctic due to the sparse observations in the Arctic – especially over the ocean and sea ice.

In this study, we analyse the relationship between the poleward moisture transport by ARs and the precipitation in the Arctic. For this purpose, we use comprehensive measurement campaigns conducted at Svalbard (ACLOUD May/June 2017, AFLUX March/April 2019) and analyse in detail several AR events.

For the detection of ARs, existing AR catalogues from global and polar-specific algorithms with the input of reanalyses data are used. For analysing the type and frequency of precipitation for the detected AR events, we analyse multiple parameters such as precipitation intensity and phase, particle number and size distribution, the liquid and total water content, the brightness temperature, and the radar reflectivity factor from different observational and model datasets (ERA5 reanalysis, satellite, in-situ measurements by research aircraft POLAR6, ground-based remote sensing measurements). To compare reanalysis with observational data, we apply the Passive and Active Microwave radiative TRAnsfer (PAMTRA) model. PAMTRA allows to calculate the brightness temperature as well as the radar reflectivity factor for different microphysics precipitation schemes. Furthermore, the radar reflectivity factor gives information about the vertical profile of hydrometeors and thus on the transition from snow to rain.

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IARCS/064

Summarizing the Relationship between IVT and Watershed Mean Areal Precipitation across California

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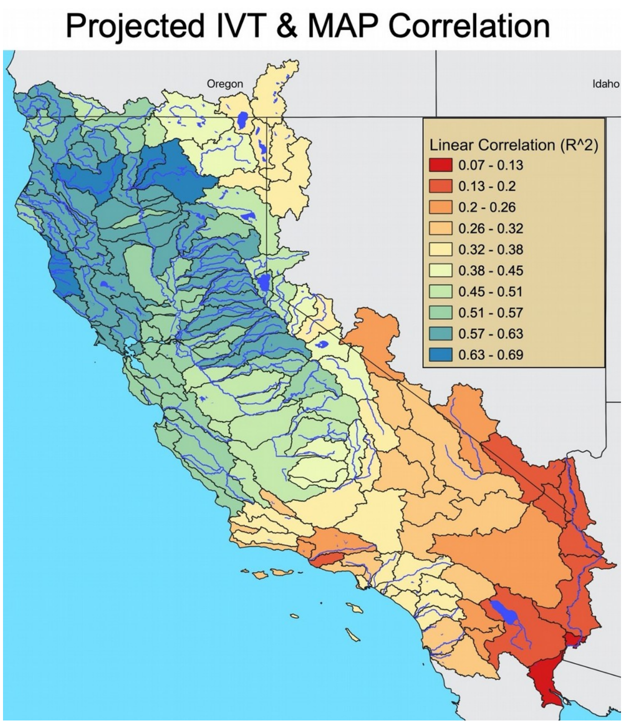
Atmospheric Rivers (ARs) are responsible for >90% of water vapor transport around the globe and contribute to large fractions of annual precipitation in regions with complex terrain along the western coastlines of mid-latitude continents (e.g., 30–50% along the U.S. West Coast in California). In this study, we further investigate this relationship between landfalling ARs, herein defined using the daily average integrated water vapor transport (IVT), and HUC-8 watershed mean areal precipitation (MAP) precipitation for a 38-year period over California, among other climatological characteristics of California's watershed MAP. On average, the daily average IVT magnitude explains ~34% of the annual variance in watershed MAP across all 140 watersheds. We further project the daily IVT vector, 850-hPa water vapor flux vector, and 925-hPa water vapor flux vector from 25 coastal locations onto different directions in order to identify the landfalling AR location, IVT direction, and vertical flux characteristics that produces the highest explained variance (r^2) in MAP at each watershed. In other words, for a given watershed, where, what direction, and what vertical location is most important to any individual watershed's MAP? Projecting daily average IVT increases the explained variance in MAP an average of 11% to 45%; highest values of 65% occur over North-Coastal California. Focusing on projecting 850 and 925-hPa water vapor flux increases the variance explained in MAP to >50% on average. The results of this study help to summarize the relationships between IVT and MAP from a watershed perspective, emphasize the importance of IVT direction and water vapor flux elevation to watershed MAP, and will help inform development of watershed-centric forecast tools.



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IARCS/067

A climatology of New Zealand atmospheric rivers

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The occurrence of extreme precipitation events in New Zealand regularly results in devastating impacts to the local society and environment. An automated atmospheric river (AR) detection technique (ARDT) is applied to construct a climatology (1979-2019) of ARs in New Zealand, an under-represented region in AR research. A distinct seasonality exists in AR occurrence aligning with seasonal variations in the mid-latitude jet streams and consequently, mid-latitude cyclone tracks. The formation of the Southern Hemisphere winter split jet enables AR occurrence to persist through all seasons in northern regions of New Zealand, while southern regions of the country exhibit a substantial (50%) reduction in AR occurrence as the polar jet shifts southward during the cold season. ARs making landfall on the western coast of New Zealand (90% of all events) are characterised by a dominant north-westerly moisture flux associated with a distinct dipole pressure anomaly; low pressure to the south-west and high pressure to the north-east of New Zealand. Precipitation totals during AR events on the windward side of the central Southern Alps (South Island) increase with AR category (five-point scale), with the largest events (Category 5 ARs) producing 3-day precipitation totals exceeding 1000 mm. ARs account for 76% of total precipitation and up to 93% of extreme precipitation on the West Coast of the South Island. The synoptic- and meso-scale atmospheric controls of AR-related extreme precipitation along the central West Coast of the South Island of New Zealand should remain a priority to comprehend the role of ARs on local hydrological extremes.

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IARCS/068

Genesis locations of the costliest atmospheric rivers impacting the western United States

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Extreme weather events associated with atmospheric rivers (ARs) have the potential to produce substantial economic damages on the West Coast of the USA. Recorded flood damage costs, sourced from the National Flood Insurance Program, are paired with an AR tracking algorithm to examine the life cycles of the most damaging ARs in the western United States over the last 40 years. The genesis location of landfalling ARs on the West Coast of the USA shifts westward with increasing damages, particularly for ARs that make landfall across northern regions of the West Coast of the USA. Landfalling ARs in Washington and Oregon that originate from the northwest region of the Pacific, westward of 170° W, are more than twice as likely to cause extreme damage (90th percentile of damage costs) than ARs originating from the northeast region of the Pacific. In Oregon, only 5% of ARs originating eastward of 170° W are found to cause extreme damage (exceeding $25 billion) which increases to 12% for ARs originating westward of 170° W. Furthermore, in Washington, the majority (61%) of ARs that bring extreme damages originate from the northwest Pacific, while only 40% of all Washington ARs originate in this location. For ARs that make landfall in California, the genesis location does not change the probability of extreme damage. ARs generating further west (in the northwest Pacific Ocean) are typically associated with higher moisture fluxes and persist for longer, both of which contribute to a higher potential for severe flood damage. A better understanding of the conditions favourable for AR genesis in these key regions may help improve forecasts of these most damaging events.

IARCS/071

Recent Changes in United States Extreme 3-Day Precipitation Using the R-CAT Scale

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Extraordinary precipitation events have impacted the United States recently, including Hurricanes Harvey (2017) and Florence (2018), with 3-day precipitation totals larger than any others reported in the United States during the past 70 years. The rainfall category (R-CAT) scaling method is used here to document extreme precipitation events and test for trends nationally. The R-CAT scale uses thresholds of 3-day precipitation total in 100-mm increments (starting with 200 mm) that do not vary temporally or geographically, allowing for simple, intuitive comparisons of extremes over space and time. The paper that introduced the scale only required levels 1–4 to represent historical extremes, finding that R-CATs 3–4 strike the conterminous United States about as frequently as EF 4–5 tornadoes or category 3–5 hurricanes. Remarkably, Florence and Harvey require extending the scale to R-CAT 7 and 9, respectively. Trend analyses of annual maximum 3-day totals (1950–2019) here identify significant increases in the eastern United States, along with declines in Northern California and Oregon. Consistent with these results, R-CAT storms have been more frequent in the eastern, and less frequent in western, United States during the past decade compared to 1950–2008. Tropical storms dominate R-CAT events along the southeastern coast and East Coast with surprising contributions from atmospheric rivers, while atmospheric rivers completely dominate along the West Coast.

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IARCS/072

Unprecedented 2020 Austral Winter Sea Ice Loss over the Amundsen Sea Triggered by Atmospheric Rivers

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Atmospheric rivers (ARs) can affect hydro-climatic and cryospheric processes over the Antarctic continent by transporting warm and moist laden air from the mid- to high-latitudes. During the late June and early July 2020, West Antarctic (WA) experienced an anomalous warming accompanied with unprecedented sea ice loss (~300,000 km^2) over the Amundsen Sea. We use satellite products, surface station and reanalysis data to examine the synoptic-scale driving mechanisms of this event and its regional cryospheric consequences. Reanalysis data (ERA5 & NNR) indicates that a blocking anticyclone located over the Drake Passage / Antarctic Peninsula and a deeper than average low-pressure center over the Amundsen-Bellingshausen Sea were instrumental for transportation of relatively warm and humid air from the mid-latitudes towards the WA. Integrated vapor transport analysis suggests that the region was influenced by several ARs (> 250 kg m^{-1} s^{-1} at landfall) with north-south and northwest-southeast orientations at the eastern flank of the blocking anticyclone (Figure 1a). These conditions persisted between 20 June and 10 July, and surface stations recorded anomalous warming during this period reaching values near 0oC, a condition more typical to occur in summer months. A further analysis with satellite products (SSMIS+AMSR2, 6.25 km) indicates that 1-15 July 2020 period represented the minimum sea ice cover over the Amundsen-Bellingshausen Sea in the last two decades (2003-2020). Notable sea ice losses were detected (> 50%) off the coast during the 1-15 July 2020 period with respect to the climatology (Figure 1b). We highlight that an anomalous source of water vapor enhancing the ARs towards the WA can play a key role in the occurrence of winter sea ice losses, although sea ice compaction into high latitudes driven by the persistent northerly flow is another plausible mechanism. Further studies including modeling efforts and biogeochemical aspects are needed to monitor and assess the regional extent and consequences of this event during the rest of the year.

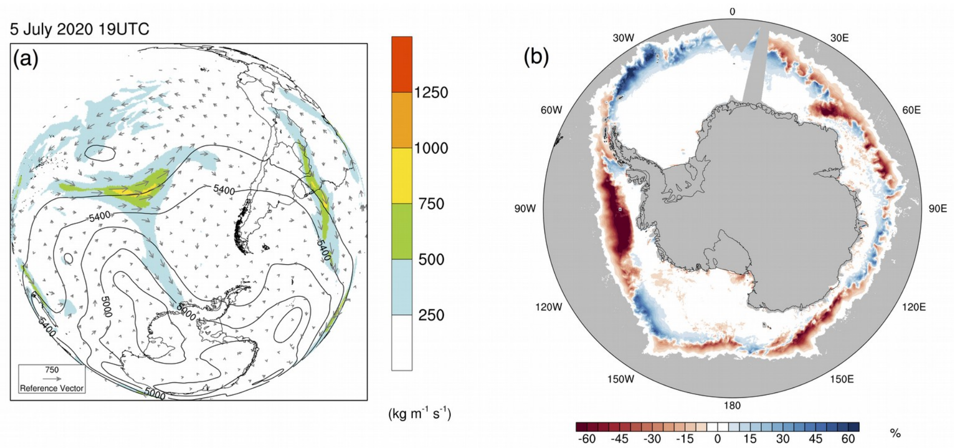

Figure 1. (a) Integrated vapor transport for July 5th, 2020 (19:00 UTC) showing an AR landfalling in WA due to the blocking anticyclone over the Drake passage (data source: ERA-5). (b) Sea ice concentration anomaly for the period 1-15 July 2020 with respect to the climatology (1-15 July, 2003-2019) (data source: SSMIS+AMSR2).

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IARCS/073

Knowing your enemy: landslides and ARs in western Patagonia

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Western Patagonia is the narrow strip of land between the Pacific Ocean and the Southern and Austral Andes extending from 40-50°S in South America. Copious precipitation (3,000 – 7,000 mm/year) is delivered year-round by the frequent arrival of mid-latitudes storms embedded in the Southern Hemisphere (SH) westerly wind belt, further enhanced by orographic uplift over the western side of the Andes, feeding large rivers, hundreds of glaciers and two massive ice fields. Indeed, surveys of Atmospheric Rivers (ARs) identify western Patagonia as one of the regions with the largest number of ARs landfalling in the global extratropics. The rugged terrain of Patagonia is mostly cover by evergreen, vegetation but a customary inspection reveals a large number of scars in the steep canyon walls suggesting a rather common occurrence of landslides including debris flows and rock avalanches. Although some of these event may have a seismic origin here we document that the majority of them are triggered by intense precipitation events. Despite the low population density in Patagonia (<1 inhab/km^2) these events cause damaging impacts in the public and private infrastructure, and even in some cases have resulted in dozens of fatalities.

The local conditions and synoptic environment accompanying the seven most damaging landslides since 2000 were analyzed. Five of these events occurred during periods of exceptionally large rainfall accumulation (up to 300 mm in three days), sustained high rain rates (>10 mm/hr during 12-24 hours) and relatively warm temperatures resulting in a freezing level over 1,500 m ASL near the top of the Andean ridge. All these conditions were recurrent during the landfalling of well-defined atmospheric rivers (AR) to western Patagonia, characterized by integrated water transport in excess of 600 kg s^{-1}m^{-1}. The ARs axis were mostly oriented in the zonal direction, thus impinging near normal against the Andes mountains, just ahead of a stationary front that also resulted in a very slow south-to-north displacement of the AR and the inland area of heavy rainfall (e.g., Fig. 1).

Given the complex topography of Patagonia and the intrinsic difficulties of quantitative precipitation forecast, predicting the AR category and latitudinal range of its landfalling emerges as a useful way to convey meteorological information relevant for landslide risk assessment, preparedness and management. Yet, the damaging ARs identified in our study ranked in category 3 –moderate: balance between beneficial and hazardous- using the ranking developed for the western United States (Ralph et al., 2019), stressing the need for reexamine such categories for other locations. Given our experience, the freezing level during the ARs (in addition to their IVT and duration) and the angle at which an AR impinged the coast may be two useful metrics to add in that can help in a more realistic categorization of AR in western Patagonia. Another important distinction currently under research is the type of damage caused by these AR, some of them causing a single but massive landslide and other leading to multiple landslides.

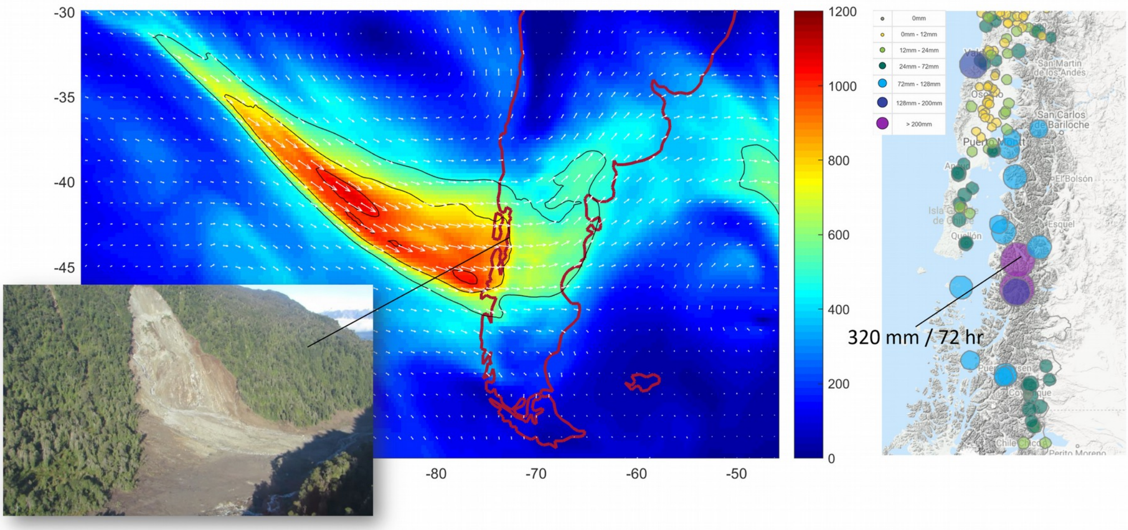

Figure 1. Images of the he last major event in NW Patagonia occurred on May 14-16, 2020. An intense AR deliver more than 300 mm in a 3 day period (mostly concentrated in May 15) causing several landslides with major impacts on road infrastructure and one person missing.

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IARCS/075

Cold-season subtropical air mass intrusions into eastern North America: thermodynamic and dynamic impacts

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We investigate the thermodynamic and dynamic impacts of extremely warm and moist air masses that travel into regions surrounding four middle-latitude stations in eastern North America, whose latitudinal locations range from 31 through 45° N. To identify such extreme air masses, we utilize the equivalent potential temperature (θ_e), maximized between the 700 and 900 hPa pressure levels (max θ_e). The utility of using θ_e is its property of conservation even in the presence of large-scale, moist-adiabatic condensation during an air parcel's ascent. The pressure level of max θ_e represents the lower boundary of the θe coupling index calculation that modulates the strength of vertical circulations.

To perform our analysis, we utilize the ECMWF Reanalysis-5 (ERA5) extending from 1979 through the present. Our period of consideration includes the cold season (December, January, February) from December 1979 through February 2020.

We produce a cold-season climatology of max θ_e for this 41-year period, and find max θ_e values ranging from 289K for the northernmost station Montreal, Quebec to 312K for the southernmost station Mobile, Alabama. Not surprisingly, we find a positive trend in max θ_e throughout eastern North America, though significantly so in the southeastern US (SEUS). The dominant contributor to the significance of this upward trend in max θ_e over the continental regions of the SEUS is water vapor, and not potential temperature.

To examine the thermodynamic and dynamic impacts of the most extreme subtropical air mass intrusions, we find the 10 most extreme three-day mean max θ_e values at each of Montreal (~45° N), Burlington, VT (~44° N), Raleigh-Durham, NC (~36° N), and Mobile (~31° N). The most extreme max θ_e values range from ~335K at Mobile to ~314K at Montreal. Each of the four stations' max θ_e extreme positive anomalies range from +20 to +25K.

The implications of these anomalies are examined in the context of a simple expression for precipitation, P = RD, where P is the total precipitation, and R is the precipitation rate, averaged through the duration, D, of the event. R incorporates thermodynamic and dynamic factors driving the air's ascent. This ascent is associated with a change of water vapor mixing ratio, as an air parcel's moisture condenses following a moist adiabat. This simple precipitation computation matches well with the ERA5 reanalyses of precipitation during several of the 40 most extreme max θ_e events.

These 40 most extreme max θ_e cases, though identified at one location, are primarily associated with anomalously large-scale, persistent, extreme precipitation regimes identified in an independent study. Extreme subtropical air mass intrusions are associated with reduced static stability, anomalously high precipitable water, anomalously elevated dynamic tropopause heights, and persistent, slow moving upper-level features. An anomalously strong subtropical anticyclone's flow is responsible for the water vapor transport into these stations' regions of extreme precipitation.

Finally, we assess the relationship between daily-averaged max θ_e values and daily measurable precipitation, and find a strong relationship, particularly for Montreal, where the correlation is 0.54. Thus, max θ_e accounts for 29% of the daily precipitation variation.

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IARCS/076

Atmospheric rivers and flooding in south-central Chile

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South-central Chile (35°-40°S, along the west coast of South America) features a temperate climate with annual mean rainfall from 600-2000 mm/year. Many rivers originate in the upper part of the Andes and flow downstream for 100-200 km until reaching the Pacific coast, thus providing fresh water for inhabitants along the central valley and coastal plains, agriculture, electric generation and many other uses. Previous research has shed light on the synoptic-scale environment that characterize winter precipitation events in central Chile, mostly caused by cold fronts rooted in midlatitude cyclones.

In the present work we advance our knowledge of extreme events focusing on major floodings in the four largest rivers crossing this region: Maule (35°S), Itata (36°S), Biobío (37°S) and Toltén (38°S). For each river we analyzed runoff records at stations close to their outlet and identified those events in which the daily flow was in the upper 1% of the distribution. A customary inspection of press reports revealed that most of these events caused major flooding of urban and rural sectors with detrimental impact on the population (including fatalities in the worst cases) and infrastructure. In some cases peak flows occurred in four (or three) of the rivers, but most of the time the events were geographically independent, suggesting a rather localized extreme precipitation event. Indeed, the peak flow tends to occur 1 or 2 days after a rainfall with accumulations as large as 100 mm/day over the western slope of the Andes. Then, one key question is what differentiate an ordinary storm from those causing these devastating flooding events.

Our preliminary synoptic analysis reveals that Zonal Atmospheric Rivers (ZARs) are a recurrent synoptic pattern causing the episodes of peak flow/extreme rainfall. These ZARs ahead of stationary fronts can extend thousands of kilometers across the South Pacific with a zonal direction and little displacement in the cross-front direction. When these ZARs reach the continent, Integrated Vapor Transport typically ranges between 500 and 800 Kg/m/s, concentrated in a latitudinal swath of 100-200 km that remain stationary for 1-2 days. A key aspect is that most of the precipitation that ZARs deliver occurs in the warm, prefrontal air mass, thus causing rain (instead of snow) well high over the Andes and substantially increasing the water available for immediate runoff. The prefrontal environment is also less stable resulting in a more concentrated ascent near the Andes foothills relative to more common storms where the blocking effect of the mountains can extends well offshore. A last ingredient that seems to contribute to the extreme rainfall during ZARs (and the subsequent flooding) is the lack of northerly flow in the lower troposphere, that otherwise would have entrained dry air (as is observed in ordinary storms). The role of these different elements in causing extreme rainfall / flooding during ZAR episodes are highlighted in Figure 1 and will be gauged by performing sensitivity experiments using a numerical model.

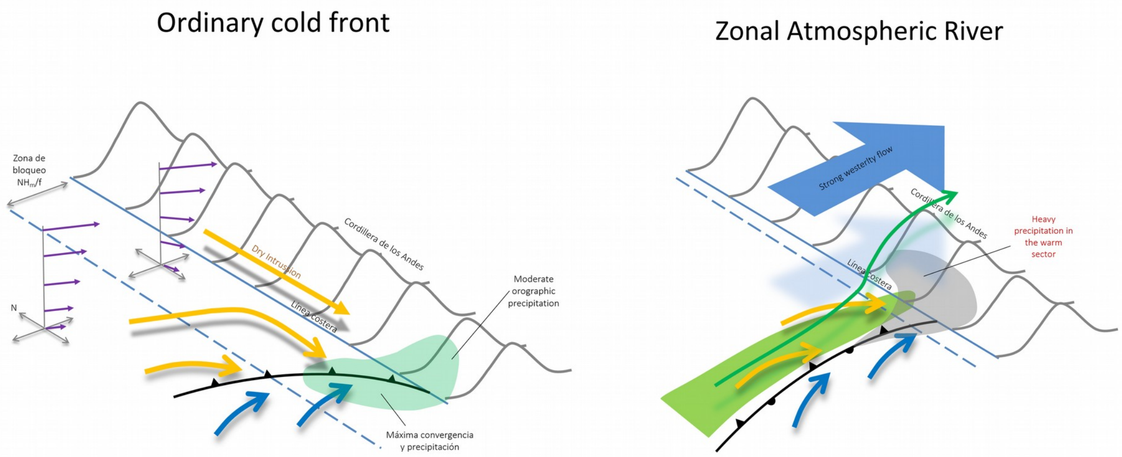

Figure 1: Conceptual models of an ordinary cold front causing moderate precipitation over the Andes and a Zonal AR ahead of an stationary front causing intense rainfall over the Andes and subsequent flooding in the lowlands and coastal zone of south-central Chile

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IARCS/078

Assessing uncertainty in daily precipitation datasets: the case of extreme precipitation in two Atmospheric Rivers events

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An understanding of both weather and climate extremes has been point out as one of the World Climate Research Programme Grand Challenges in the future. Here we use the Frequent Rainfall Observations on GridS (FROGS) database. It is composed of gridded daily-precipitation products on a common 1°×1° grid to ease intercomparison and assessment exercises. The database includes satellite, ground-based and reanalysis products. A total of 22 precipitation products is used in this work.

Atmospheric rivers are characterized by intense moisture transport usually from the tropics to the extra-tropics, which can produce precipitation on landafall. They can be both beneficial or can have important social economic impacts like extreme precipitation inducing floods. Here we analyse the uncertainty in gridded precipitation datasets (FROGS) in the case of extreme precipitation in two atmospheric rivers events in two Mediterranean climates: one in California, USA and the other in Portugal.

Results show that the precipitation dataset based only on satellite data or combined reveal the poorest performance in capturing the ARs daily precipitation, both over land in western US and Portugal. The reanalysis and the gauges-based datasets possess the best agreement with local ground stations. As expected, there is an overall underestimation of precipitation by the different products.

Acknowledgments
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IARCS/083

A Climatological Study of National Weather Service Watches, Warnings and Advisories in Association with Atmospheric Rivers in the Western U.S. 2006–2018

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A recently published scale to characterize the intensity and duration of atmospheric rivers (AR) by Ralph et al. (2019) summarizes a range of typical impacts associated with these storms from weak and beneficial to strong and hazardous. This study investigates the spatial and temporal relationship between landfalling ARs along the U.S. West Coast and potentially hazardous weather as identified by National Weather Service watches, warnings, and advisories (WWAs) during 2006–2018. The results of this study re-affirm that landfalling ARs occur in association with various types of high-impact weather including high wind, hydrologic extremes (e.g., heavy rainfall and flooding), and cold precipitation (e.g., snow) by presenting qualitative relationships between NWS products and ARs.

Across the western U.S., 30–70% of days with any type of WWA were associated with landfalling ARs of any intensity. In the northern (Pacific Northwest) and central (Northern California and Great Basin) regions hydrologic-related and wind-related WWAs were more frequently (40–80%) associated with more intense and longer duration ARs classified as AR3, AR4, or AR5 events according to the Ralph et al. (2019) scale as compared to less intense and shorter duration AR1 or AR2 events. This relationship decreases for cold precipitation-related WWAs, where stronger ARs were more likely to result in rain than snow. While an approximate majority of days with WWAs occurred in association with landfalling ARs, not all landfalling ARs are associated with high-impact weather. For example, days with landfalling ARs occurred in association with WWA days of any type on 20–50% of cool-season days across high-elevation regions of the northern Cascades, Sierra Nevada, and southern California coastal ranges. This association increased to 40–60% for more intense and longer duration AR3, AR4, and AR5 events, especially for landfalling ARs in southern California and hydrologic-related WWAs over the southwest U.S. These results are summarized by an investigation of the WWA hazard footprint association with landfalling ARs that illustrates a quasi-exponential increase in the average cumulative area headlined by WWAs across the Western Region as the intensity and duration of a landfalling AR increases from an AR1 to an AR5 event, particularly for landfalling ARs in California and for hydrologic- and wind-related WWAs.

NWS Watches, Warnings, and Advisories Associated with Cool-Season ARs

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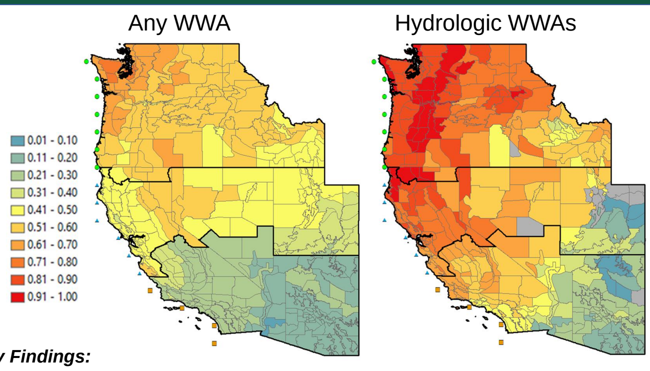
Plymouth State University

Shown is the likelihood that a WWA day occurred in association with a regional AR along the coast in each Public Forecast Zone

- 13-year NWS WWA catalog was developed using the Iowa State University archive.
- AR database developed from the Rutz et al. (2014) catalog using NASA MERRA-2 reanalysis IVT for 17 latitudes along the coast.
- Latitudes of the AR catalog were grouped into three regions (northern, central, southern).



Key Findings:
- During the cool season, 30–60% of days with any WWA in a PFZ occurred on days when there was an AR along the coast (left).
- On days with hydrologic WWAs in each PFZ, 70–100% of WWA days occurred in association with an AR along the coast (right).
- Cool-season WWA days were most frequently associated with ARs for coastal PFZs and those in the northern and central regions.

IARCS/088

Reservoir Flood Pool Sensitivity to Freezing Level Forecast Uncertainty: Examples from Lake Oroville and New Bullards Bar Reservoirs in California

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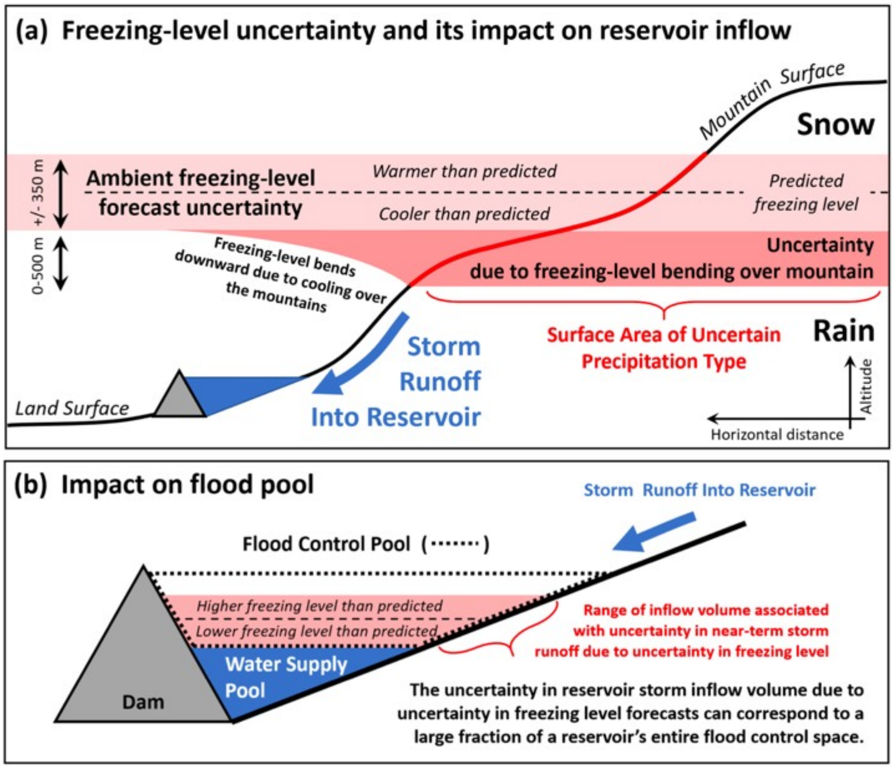
The atmospheric freezing level (Z_{FL}) determines the rain-snow transition zone at the surface, how much rainfall is available for runoff, and the flood risk during a precipitation event. Thus, an accurate Z_{FL} forecast is critical for reservoir operation, particularly during an intense and flood-capable atmospheric river storm. The importance of Z_{FL} forecast accuracy is heightened in mountain watersheds with narrow elevation bands like the Yuba-Feather in Northern California, where a 500-m elevation gain can amount to >50% of the watershed area. In this study, we investigated the impact of Z_{FL} forecast uncertainty on runoff generation and the flood pools of Lake Oroville and New Bullards Bar reservoirs in the Yuba-Feather watersheds. We first identified 3-day precipitation events using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) record from 1981 to 2018. We subsequently grouped the precipitation event magnitudes into five return-period categories based on the PRISM record, i.e., <2 years, 2-5 years, 5-10 years, 10-20 years, and >20 years. The watershed runoff associated with each return-period category was then estimated using the Soil Conservation Service Curve Number method. Using a ±350-m Z_{FL} forecast uncertainty, we found inflow volume uncertainties of <10% to >50% of the flood pool storages at Lake Oroville and New Bullards Bar reservoirs in the Yuba-Feather watersheds, depending on the Z_{FL}, antecedent moisture condition, and the precipitation event magnitude. The uncertainties increased by up to >3% per inch of precipitation, depending on the Z_{FL} and antecedent moisture condition. This result offered a "guide curve" for reservoir sensitivity to Z_{FL} forecast uncertainty, and emphasized the importance of Z_{FL} forecast accuracy to support Forecast Informed Reservoir Operations in mountain watersheds.



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IARCS/111

Relationships between integrated vapor transport (ivt), water vapor flux and precipitation in southern california

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Atmospheric rivers (AR) are well-known to create heavy rainfall in southern California. For example, in San Diego County, all calendar day (24-hour) rainfall amounts of greater than 50 mm at San Diego International Airport (KSAN) (1980-2019) and daily rainfall amounts of greater than 100 mm at Palomar Mountain (2004-2019, San Diego County) were associated with ARs with an IVT of greater than 350 kg m^{-1} s^{-1} (Merra dataset, 33 °N, 117.5 °W). Both IVT (Merra dataset) and water vapor flux (San Diego Miramar RAOBs) for different height levels were correlated with daily precipitation at stations throughout southern California (with focus on stations within the San Diego National Weather Service forecast area, especially KSAN and Palomar Mountain) for each month of the year.

Best correlation coefficients (R) were found between December and March, with R values between IVT and daily rainfall as high as 0.59 for KSAN in January and 0.70 for Palomar Mountain, also in January. Much lower R values were found between May and October, when conditions are normally drier across the region.

Water vapor flux (product of mixing ratio and velocity, g H_20 kg^{-1} air * ms^{-1}) was analyzed within 50-hPa deep layers in the lower troposphere, with break points at 950, 900, 850, 800 and 750 hPa. R values between the maximum water vapor flux within each layer and daily precipitation at the stations were mostly equal to or less than those between IVT and daily precipitation, which suggests that IVT should be the primary tool for analyzing precipitation, with water vapor flux being a secondary tool. The best correlations, which were mostly just slightly below those for IVT were in the 950-900 hPa layers at KSAN and Palomar Mountain, though values almost as high were found in the 900-850 hPa layers and 850-800 hPa layers, with much lower values above 800 hPa and below 950 hPa.

There were notable cases where IVT was high but yet no precipitation was recorded during the same calendar day. While most of these cases occurred outside of the December-March period where IVT correlations had the best skill, some cases did occur during the winter months, primarily due to dynamical forcing remaining to the north of the stations. At KSAN, there were five cases of IVT greater than 600 kg m^{-1} s^{-1} at 33 °N, 117.5 °W but with no measurable precipitation, though in four of these cases, precipitation occurred either the next day or two days later. The anomalous case of 22 March 2018 will be analyzed further as no measurable precipitation occurred at KSAN either that day or during the following two days.

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IARCS/112

Interaction of storms with complex terrain during extreme events in south-central Chile

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South-central Chile (35 – 38°S) includes a coastal mountains range with elevations ranging from 700 to 1300 m, a central valley, and the Andes with elevations from 1000 to 2000 m. The valley relies on precipitation and snow pack from the Andes as a water supply. This precipitation falls mostly during the austral winter from frontal systems impinging the west coast and it can also lead to hydro-meteorological disasters such as landslides or floods. This is particularly true for extreme events, usually characterized by the arrival of atmospheric rivers from the Pacific, and the orographic enhancement of precipitation produced by the interaction of these storms with complex terrain. Numerous studies along the west coast of North America have shown that extreme events are also associated with the development of a terrain locked barrier jet, characterized by wind blowing parallel to the terrain. These barrier jets contribute to enhancement of precipitation, helping to transport water vapor flux to higher latitudes and increasing convergence between the jet and the frontal system. Along the Chilean Andes, there has been limited research done about this feature.

Using daily station data from 2000 to 2017, we identify extreme (90th percentile) precipitation events over the central valley and the Andes of south-central Chile. We classify two subsets of events representative of storms that lead to strong and weak orographic enhancement. We use the Weather Research and Forecast Model (WRF, version 4.0.3) to simulate and compare selected cases from these different subsets. We perform a composite analyses to identify topographically induced features, as blocking and the barrier jet that modulate orographic precipitation enhancement and their connection with land-falling of atmospheric rivers, as well as similarities and differences between weak and strong orographic enhancement events.

Session 3

AR modeling & Forecasting

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IARCS/003

Numerical modeling Study of Atmospheric Rivers and associated Heavy Precipitation over the West Coast of India using WRF-ARW model

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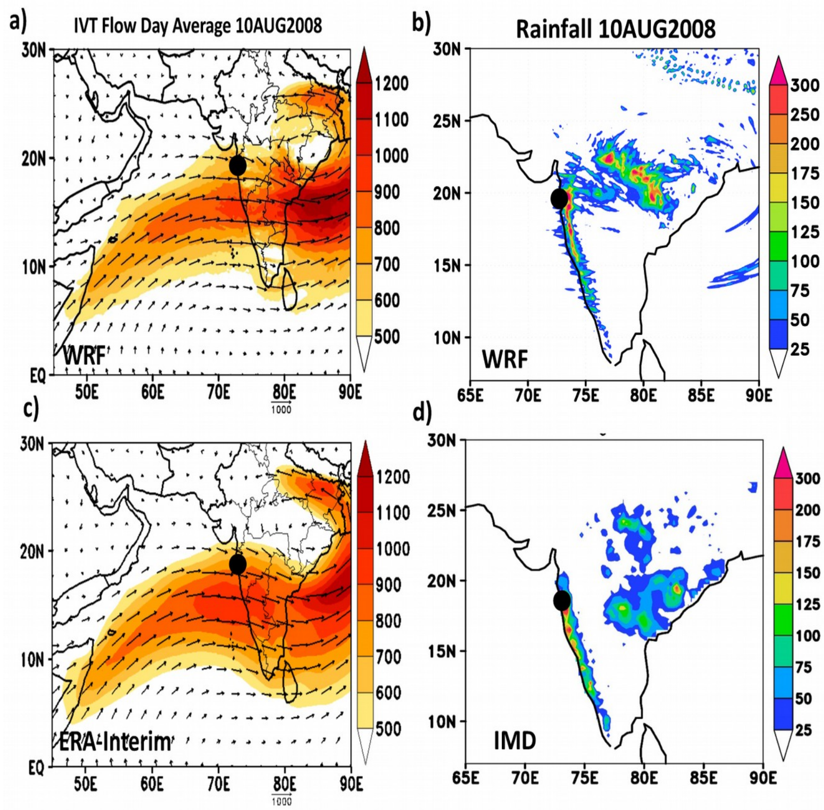
Heavy precipitation events (HPEs) associated with the occurrence of atmospheric rivers (ARs) are identified during summer monsoon season in the previous studies over the Indian region. Numerical prediction of HPEs associated with ARs in west coast region of India (WCI) was analyzed and compared to observations. The main aim of the present study is to verify whether the WRF-ARW model can capture various features such as atmospheric circulation, landfall location of ARs responsible for HPE episodes. Eight cases (totalling 19 events) are chosen during the summer monsoon period 2003 to 2013. Further, three cases (totalling 7 events) model simulations were performed with five different microphysical and cumulative physical parameterizations during 2011, 2014 and 2015 HPE events. The model results of HPE are validated with the high-resolution gridded rainfall data obtained from the India Meteorological Department and other available data sets during the study period. ARs are identified using integrated vapour transport (IVT) algorithm. The model results clearly demonstrate the reasonably simulated landfall location of the AR. The WRF model configuration with microphysics schemes of Lin, Thompson and Morrison and cumulative physics schemes of KF, Grell3D were found to perform best in simulating all the events. However, the model showed the tendency to overestimate the relative humidity and larger deviations were observed in the prediction of winds. The validation of the simulated results using statistical analysis has been conducted with available data sets revealed that the model had performed reasonably well in representing the state of the atmosphere during the ARs. Findings suggest that high-resolution model simulations are significant tool for investigating ARs in contexts where fine scale spatial structure and realistic maximum water vapor transport are important.

Keywords Indian summer monsoon; integrated water vapor transport; atmospheric rivers; heavy precipitation



IARCS/007

Atmospheric Rivers over the Arctic with the ICON model

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The Arctic climate changes faster than the ones of other regions, but the relative role of the individual feedback mechanisms contributing to Arctic amplification is still unclear. Atmospheric Rivers (ARs) are narrow and transient river-style moisture flows arriving from the sub-polar regions. The integrated water vapour transport associated with ARs can explain up to 70% of the precipitation variance north of 70°N. However, there are still uncertainties regarding the specific role and the impact of ARs on the Arctic climate variability.

For the first time, the high-resolution ICON modelling framework is used over the Arctic region (from 13 km down to ca. 6 and 3 km) to investigate processes related with anomalous moisture transport into the Arctic. Based on a case study for Svalbard, the representation of the atmospheric circulation and the spatio-temporal structure of water vapour, temperature, and precipitation and snowfall within the limited-area mode (LAM) of the ICON model is assessed. Preliminary results show that the moisture intrusion is relatively well represented in the ICON-LAM simulations. The impact on the surface energy budget will also be calculated.

IARCS/009

Diagnosing Multi-scale Forecast Sensitivity of Atmospheric Rivers Using Adjoints

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Adjoint models can provide valuable insight into the practical limitations of our ability to predict weather systems, such as extratropical and tropical cyclones, and their associated high-impact weather. An adjoint model can be used for the efficient and rigorous computation of numerical weather prediction forecast sensitivity to changes in the initial state or an earlier point in the forecast. The sensitivity calculations can help to unravel complex instabilities and influences on extratropical and tropical cyclone evolution that occur over a wide range of scales. Adjoints also can be used to explore the rapid growth of small perturbations that lead to large errors on multiple scales and limit the forecast accuracy of high-impact atmospheric river events.

The adjoint, tangent linear, and nonlinear models for the nonhydrostatic COAMPS are applied with high-horizontal resolution (5 to 35 km) to the Valentine's Day 2019 (Feb. 12-15, 2019) atmospheric river event observed during the Atmospheric River Reconnaissance (AR Recon) observing program. This event featured an atmospheric river that impacted nearly the entire state of California, producing record precipitation and localized flooding throughout the state. We quantify the multi-scale sensitivity and predictability of the Valentine's Day AR for various forecast lead times using several different adjoint response functions including: i) kinetic energy, ii) accumulated rainfall, iii) integrated vapor transport, and iv) potential vorticity. The adjoint sensitivity results underscore the importance of the low- and mid-level moisture distribution in a tropical moisture export region, the role of a Kona low, and sensitivity to a potential vorticity (PV) streamer associated with an anticyclonic wave break. We demonstrate that small perturbations of moisture, winds, and temperature in these multi-scale sensitive regions rapidly evolve into disturbances that impact the predictability of downstream high-impact weather associated with the atmospheric river. The forecast sensitivity to diabatic heating is also explored using the adjoint to provide insight into the implications of model error associated with microphysical parameterizations. The results underscore the need for more accurate moisture observations and data assimilation systems that can adequately assimilate these observations in order to reduce the forecast uncertainties for these high-impact events, which is a central goal of the AR Recon program.

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IARCS/034

Naval Research Laboratory Analysis of AR RECON Buoy and Dropsonde Impacts

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Under the multi-year Atmospheric River Reconnaissance (AR RECON) Program, both dropsondes and drifting buoys have been deployed in the northeastern Pacific to help improve forecasts of high-impact weather on the North American west coast. At the US Naval Research Laboratory Marine Meteorology Division, we assimilate this data to improve forecasts and are also using this data to learn about our data assimilation and modeling system characteristics and deficiencies, and the relative impact of different observation types. Here we describe results using the Navy Global Environmental Model (NAVGEM)-NRL Variational Data Assimilation System Accelerated Representer (NAVDAS-AR) hybrid 4DVAR system, including the Forecast Sensitivity Observation Impact (FSOI) technology that allows for the quantification of the impact of each observation on the 24-h global forecast error total energy.

For the 2019 season, the forecast error reduction from the surface pressure observations from the 32 AR RECON buoys was comparable to that of the other drifting buoys (numbering between 24 and 31) in the northeastern Pacific. The buoy surface pressure observations are complementary to the dropsonde observations and both provide information on model biases. Evaluation of the buoy observation – model background innovations indicates that the model surface pressure tends to be biased high for low-pressure observations, and biased low for high-pressure observations. This is similar to the findings from the dropsonde wind innovations, indicating that the model has a low wind-speed biases at high wind speeds, and high wind-speed bias at low wind speeds. The impact of the buoy surface pressure observations tends to be larger when the surface pressure is relatively low. Some case studies suggest that the surface pressure observations in or near ARs tend to have a larger impact on average than observations in other regions, but further research and larger sample size are needed for general conclusions on this point. In addition to the results for the 2019 season summarized here, we plan to report on results for the 2020 season, in which both the number of drifting buoys and number of reconnaissance flights were significantly increased over the previous years.

IARCS/047

Atmospheric River Reconnaissance Dropsonde Data Impact in the NCEP Operational GFS

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Atmospheric Rivers (ARs) are crucial to precipitation and water supply for the West Coast of the United States. AR Reconnaissance (Recon) campaign is a collaborative effort led by Center for Western Weather and Water Extremes (CW3E), Scripps Institution of Oceanography (SIO), University of California San Diego (UCSD) involving several partners in the U.S. and abroad, with experts on midlatitude dynamics, ARs, airborne reconnaissance, and numerical modeling. Environmental Modeling Center (EMC) of the National Weather Service (NWS) National Centers for Environmental Prediction (NCEP) has developed a Research and Operations partnership with CW3E, US Naval Research Laboratory (NRL), National Center for Atmospheric Research (NCAR), European Center for Medium Range Weather Forecasts (ECMWF) and other academic partners to support improved prediction of landfalling ARs in the U.S. West Coast.

In this study we used NCEP GFS version 15 (GFSv15) to examine the impact of the AR supplemental observations dropsonde data on GFS forecast. GFSv15 was implemented in operations in June 2019; it has been developed with the finite volume cubed-sphere dynamical core (FV3) and microphysics from GFDL, and 4D-Hybrid En-Var data assimilation (DA). The dropsonde data used were from the AR Recon campaigns, including 17 intensive observation periods (IOPs) from 2020. Global control and denial experiments were conducted by using or denying the dropsonde data in the GFS.

Preliminary analysis indicates that there is systematic improvement for the precipitation prediction over the U.S. West Coast when the dropsonde data are used. This is associated with improvement of the water vapor transport (IVT) forecasts and better representation of large-scale circulation. The AR supplemental observations have helped to fill the data gap that is needed for the data assimilation to provide better initial conditions for GFS. In this presentation, the overall GFSv15 performance and the associated dropsonde data impact on AR forecasts will be examined.

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IARCS/048

AQPI: Evaluating Experimental and Operational RAP/HRRR Model Forecasts of AR Events in California

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Atmospheric River (AR) events can cause flooding and deaths and are responsible for nearly half of California's annual precipitation. We evaluate forecasts from the experimental and operational versions of the RAP/HRRR mesoscale weather model for numerous AR events that have occurred over the past few years by running retrospective simulations and downloading existing model output. We compare model Quantitative Precipitation Forecasts (QPF) to several Quantitative Precipitation Estimation (QPE) products including Stage IV and the Mesonet gauge network via several statistical techniques including closest-grid-point and neighborhood maximum. While the HRRR model versions have some differences in spatial/temporal QPF accuracy, all model versions predict QPF reasonably well, but have some consistent spatial biases, such as overprediction of rainfall in the Sierra Nevadas, and underprediction of rainfall in the Bay Area. We explore possible causes of these biases by comparing to nearby meteorological observation networks including the Atmospheric River Observatories, the impacts of running a high-resolution (1km) HRRR nest, and the impacts of adding X-band radar reflectivity to the HRRR data assimilation.

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IARCS/051

Sources of subseasonal-to-seasonal predictability of atmospheric rivers and precipitation in the western United States

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Atmospheric rivers (ARs) account for a large portion of total precipitation in the western United States (WUS), specifically in winter months. Interannual variability of precipitation is also high in this region, as exemplified by the recent shift from drought in 2012–2016 to an extremely wet 2016–2017 in California, which was largely associated with variability in landfalling ARs. Thus, accurate subseasonal-to-seasonal prediction of AR activity and associated precipitation is critically important to assist governments and stakeholders to manage water resources and drought and flood risks. However, prediction of ARs and precipitation remains challenging due to large noise associated with internal variability, the nonlinear response of ARs to variability in sea surface temperature and atmospheric circulation, and relatively short observational records.

To improve the prediction of landfalling ARs and precipitation, we examine the relationships between two prominent climate modes, namely the El Niño/Southern Oscillation (ENSO) and Madden–Julian oscillation (MJO), and winter ARs and associated precipitation (AR precipitation) by using observations and a large ensemble of regional climate model (RCM) hindcasts over the period 1981–2017. The RCM data were generated by downscaling a 6-hourly global reanalysis (NCEP-DOE AMIP-II Reanalysis, 2.5° × 2.5° resolution) with the Weather Research and Forecasting (WRF) model to a higher resolution (27 km).

We found that WRF reproduces the spatial and temporal patterns of AR frequency, including the climatological mean and interannual variability. WRF is also capable of reproducing the mean and variability of seasonal total precipitation in WUS and captures the variability of AR precipitation, despite an underestimation of AR precipitation. Composite analysis shows that ENSO events have distinct effects on AR activity at local, regional, and basin scales. ENSO has little effect on North Pacific basinwide averaged ARs and grid-scale ARs in WUS. But ENSO-related latitudinal shifts of ARs are found over the North Pacific region. Some MJO phases can lead to anomalously high/low AR activity, depending on the phase of MJO, time lag, and subregion of WUS. We also found that ENSO substantially modulates the MJO-AR relationship. Depending on the phase of ENSO, the MJO-AR relationship can produce different anomalies in AR frequency (Figure 1). If we compare El Niño-MJO and La Niña-MJO periods, only ~50% of their anomalies in AR frequency have the same sign (i.e. both positive or negative). A parallel analysis for AR precipitation further confirms the joint influence of ENSO-MJO on AR precipitation. Our findings highlight the necessity of evaluating concurrent effects of different climate modes on ARs and precipitation, and they may shed light on a path toward accurate subseasonal-to-seasonal prediction of ARs and precipitation over WUS.

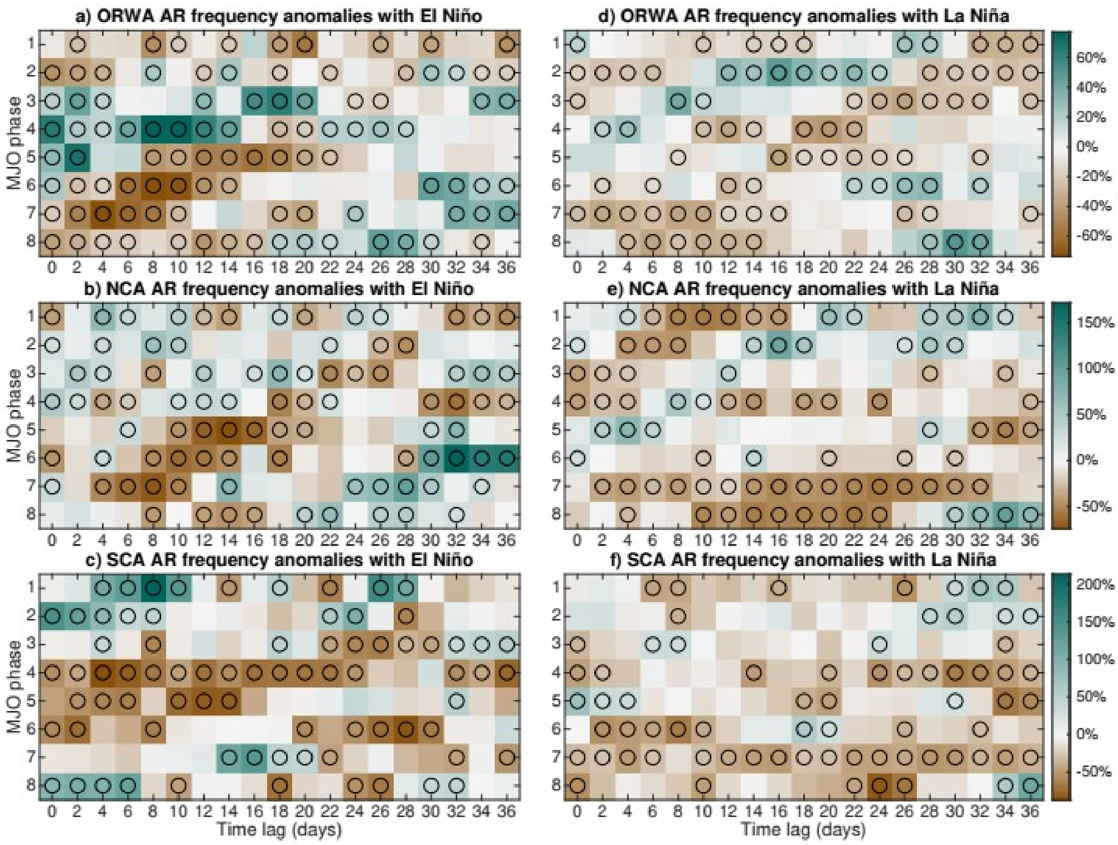

Figure 1. Anomalies in simulated AR frequency (percentage difference in relative to all winter days) by ENSO (a-c: El Niño, d-f: La Niña) and MJO phase over (a, d) Oregon and Washington (ORWA), (b, e) northern California (NCA), and (c, f) southern California (SCA). Circle represents a significant difference in AR frequency between respective MJO lagged days and all winter days using two sample t-test (α=0.05) with the p values adjusted by controlling the false discovery rate at the 0.05 level.

IARCS/069

Evaluating GFS and ECMWF Ensemble Forecasts of Integrated Water Vapor Transport Along the U.S. West Coast

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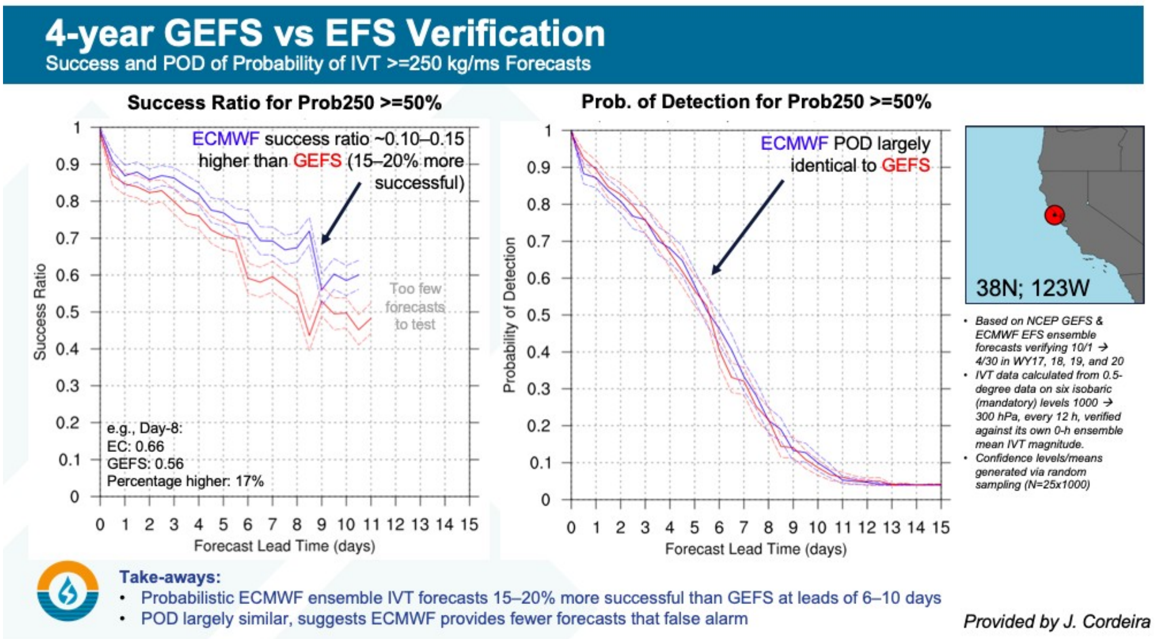
The ability to provide accurate forecasts and improve situational awareness of atmospheric rivers (ARs) is key to impact-based decision support services and applications such as forecast-informed reservoir operations. The purpose of this study is to quantify the cool-season water year skill for 2017–2020 of the NCEP Global Ensemble Forecast System (GEFS) and ECMWF Ensemble Forecast System (EFS) forecasts of integrated water vapor transport along the West Coast that is commonly observed during landfalling ARs. This skill is summarized for ensemble probability-over-threshold forecasts of IVT magnitudes ≥250 kg m^{-1} s^{-1} (referred to as P250). The P250 forecasts near North-Coastal California at 38°N, 123°W were reliable and successful at lead times of ~8–10 days with an average success ratio >0.50 for P250 forecasts ≥50% at lead times of 8 days and Brier skill scores >0.1 at a lead time of 8–10 days.

The EFS forecasts provided on average an additional 1-to-2 days of relative forecast skill (e.g., success ratio, Gilbert Skill score) as compared to the GEFS forecasts yet with similar prediction skill (e.g., POD). The highest (lowest) success ratios and probability of detection values for P250 forecasts ≥50% occurred on average across northern California and Oregon (southern California), whereas the average POD of more intense and longer duration landfalling ARs was 0.10–0.20 higher than weaker and shorter duration events at lead times of 3–9 days. We also use the GEFS forecasts to demonstrate that the potential for these forecasts to provide enhanced situational awareness may also be improved, depending on individual applications, by allowing for flexibility in the location and time of verification; the success ratios increased 10–30% at lead times of 5-to-10 days allowing for flexibility of ±1.0° latitude and ±6 hours in verification.



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IARCS/070

Response of Landfalling Atmospheric Rivers on the U.S. West Coast to Local Sea Surface Temperature Perturbations

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Atmospheric rivers (ARs) play a crucial role in the hydroclimate of the U.S. west coast. While the impact of large-scale sea surface temperature (SST) patterns on ARs is well recognized, the specific roles of local SST on ARs have not been systematically investigated. This study analyzed the landfalling ARs from two regional climate simulations that differ only in the local SST. With local SST warming, AR frequency increases across the U.S. west coast, with comparable contributions from the spatial expansion of ARs and emergence of new ARs. AR landfalling area, inland intrusion distance, and intensity also increase, with landfalling area showing the largest sensitivity. Although local SST warming only increases the AR moisture by 0.4% / K, AR-related precipitation increases by 3% /K, demonstrating the important impact of local SST warming on intensifying storms. Hence local SST is critical for accurate depiction of ARs and precipitation in western U.S.

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IARCS/084

A Web Site with Atmospheric Rivers forecast tools for the West Coast of Southern South America

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Atmospheric Rivers (AR) coming from the Southern Pacific Ocean usually produce high-impact weather when they make landfall on the mountainous west coast of southern South America. The collision of this strong corridor of water vapor against the coastal and the Andes mountain ranges typically produce intense orographic precipitation, as well as they often produce severe downslope windstorm on the eastern foothills of the Andes and adjacent low lands in Argentina, locally known as Zonda windstorms. In order to provide a useful guidance for weather forecasters and scientists from Argentina and Chile, we have developed a web site that contains a number of visualization products derived from the GFS model output focuses on the forecast of the AR arrival along the west coast of South America. The visualization products are also combined with a regional AR identification algorithm applied to the GFS model output to estimate the forecasted strength and landfalling location of the coming ARs. The AR forecast products are operationally updated twice a day at *https://ianigla.mendoza-conicet.gob.ar/rios_atmosfericos* in Spanish and English languages, and are presented in the IARC Symposium in order to discuss and share experiences with the increasingly growing AR scientific and forecaster community all around the world.

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IARCS/085

Application of Ensemble Sensitivity during the AR Recon 2020 Experiment

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Atmospheric Rivers (AR) are the source of significant precipitation along the West Coast of the United States. These features originate over the open Pacific Ocean, meaning that they are not often sampled by a dense network of in situ observations. As a consequence, modeling systems could be characterized by significant initial condition uncertainty associated with these features, which in turn could translate into higher forecast variability. 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. This study evaluates the sensitivity of California precipitation forecasts for cases during the 2020 AR Recon experiment. Here, sensitivity is computed using the ensemble-based sensitivity method applied to real-time ECMWF ensemble forecasts. This methodology includes a dynamic forecast metric definition scheme that highlights regions and patterns of large precipitation variability. Preliminary results indicate that the precipitation forecast sensitivity is primarily associated with the position of shortwave troughs that moved through the planetary-scale pattern that was present during this period. The evolution of these features subsequently modulated various aspects of the AR and in turn impacted the location where the precipitation was maximized.

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IARCS/094

Observations and Predictability of a High-Impact Narrow Cold-Frontal Rainband over Southern California on 2 February 2019

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Short-duration, high-intensity rainfall in Southern California, often associated with narrow cold-frontal rainbands (NCFR), threaten life and property. While the mechanisms that drive NCFRs are relatively well understood, their regional characteristics, specific contribution to precipitation hazards, and their predictability in the Western U.S. have received little research attention relative to their impact. This manuscript presents observations of NCFR physical processes made during the Atmospheric River Reconnaissance field campaign on 2 February 2019 and investigates the predictability of the observed NCFR across spatiotemporal scales and forecast lead time. Dropsonde data collected along transects of an atmospheric river (AR) and its attendant cyclone during rapid cyclogenesis, and radiosonde observations during landfall 24 hours later, are used to demonstrate that a configuration of the Weather Research and Forecasting model (WRF) skillfully reproduces the physical processes responsible for the development and maintenance of the impactful NCFR. Ensemble simulations provide quantitative uncertainty information on the representation of these features in numerical weather prediction and instill confidence in the utility of WRF as a forecast guidance tool for short-to-medium range prediction of mesoscale precipitation processes in landfalling ARs. This research incorporates novel data and methodologies to improve forecast guidance for NCFRs impacting Southern California. While this study focuses on a single event, the outlined approach to observing and predicting high-impact weather across a range of spatial and temporal scales will support regional water management and hazard mitigation, in general.

IARCS/096

Seasonal Prediction of western North America Atmospheric Rivers

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Atmospheric rivers (ARs) - narrow filaments of concentrated moisture transport that bring heavy precipitation and flooding - exert significant socioeconomic impacts along the West Coast of North America. About 30%of the annual precipitation over the coastal California and Washington/Oregon is determined by ARs that occur in less than 15% of winter time, indicating both the benefits to water sup-ply and the hazard from extreme precipitation when an AR makes landfall. While most prevailing research has focused on the subseasonal prediction (≤5 weeks) of ARs, only limited efforts have been made for AR prediction on seasonal to multiseasonal timescales (3months to 1 year) that are crucial for water resource management and disaster preparedness. Through the analysis of observational data and retrospective predictions from GFDL new seasonal forecast system, SPEAR (Seamless System for Prediction and Earth System Research), this research shows the existing potential of seasonal AR fore-casts over western North America with predictive skills 9 months in advance. Additional analysis of leading AR variability indicates the Pacific Decadal oscillation (PDO) and Central Pacific type El Niño are potential predictability sources for AR seasonal prediction. The challenge of seasonal AR forecast over certain locations in western North America is also elaborated in this study.

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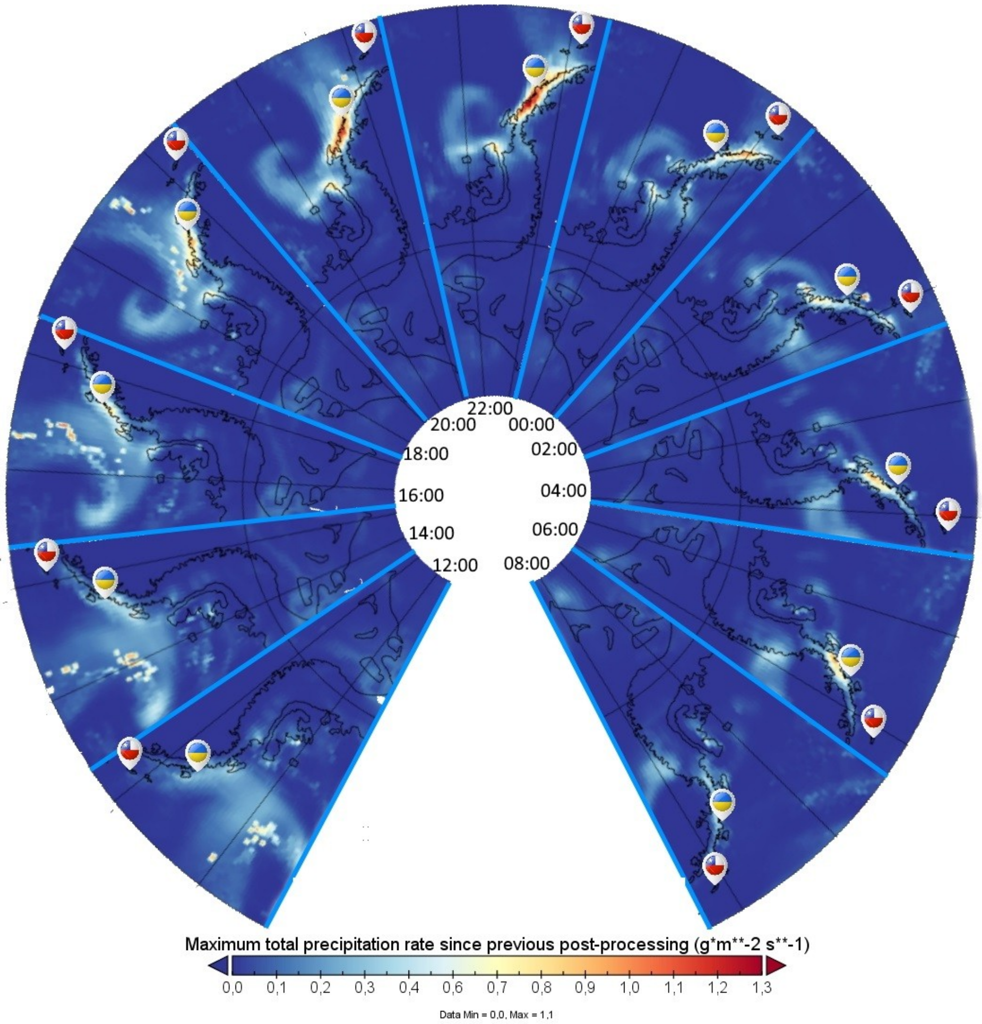

Figure 1 Precipitation rate during an AR at the Antarctic Peninsula from 1 December 12 UTC to 2 December 8 UTC 2018, based on ERA5 reanalysis hourly data (every second hour presented). The station locations are represented with corresponding country flag colors (Vernadsky/Ukraine and Escudero/Chile).

IARCS/097

Inland Penetration of Atmospheric Rivers over the Patagonian Andes in the Esquel city area 43°S of Argentina

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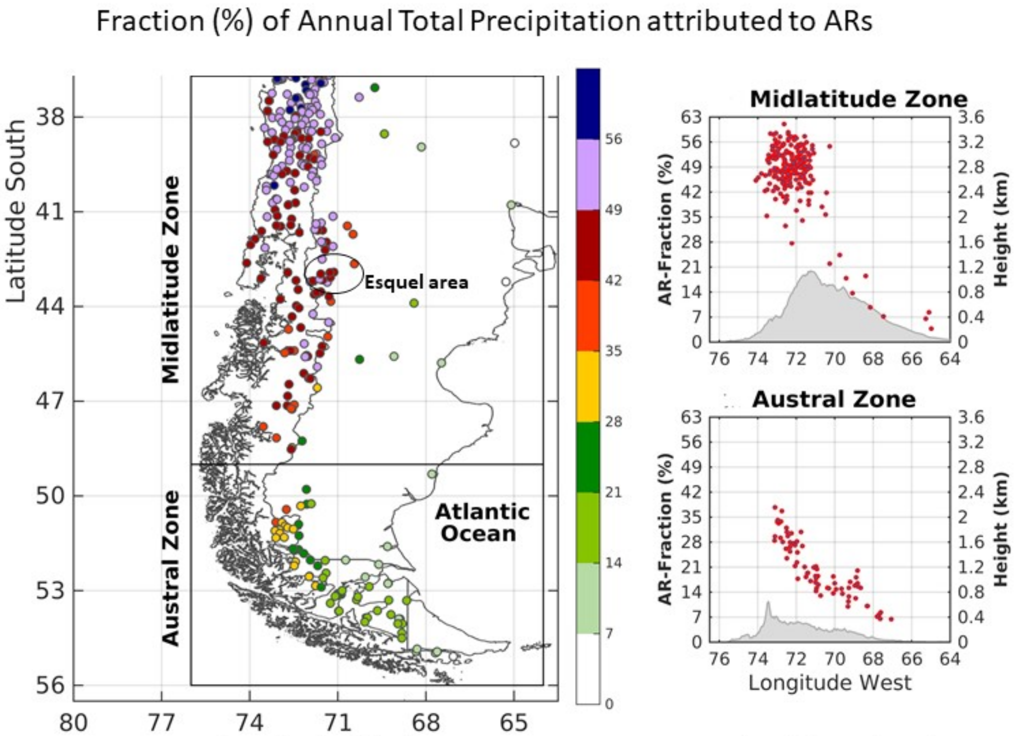
The Andes in western Patagonia are relatively low (1-1.5km height) and the frequency of landfalling atmospheric rivers (AR) coming from the Pacific Ocean is high compared to those in the western subtropical coast (40°-30°S). Consequently, the impacts of AR on precipitation immediate east of the crest of the Patagonian Andes are as important as those in the western (windward) side. The contribution of AR storms to the annual total precipitation is very similar in the western side and immediate east of the crest of the Andes, as well as the higher precipitation intensity during AR conditions as documented a previous study. However, few kilometres farther east from the crest the contribution of AR storms to the annual total reduces rapidly denoting a prominent decay of the AR influences, likely by water vapor depletion and/or strong orographic effects. In this study, we investigate the synoptic and mesoscale conditions by which some ARs penetrate farther east of the crest producing intense precipitation events on the Esquel city area about 43°S in Argentina. The city of Esquel is located in a valley just west the Patagonia steppe and about 60 km east of the crest. There are also two smaller towns in between the crest and the main city, so the weather forecast for the whole populated area east of the Andes is really challenging. Our preliminary results suggest that the intensity of the AR and its associated winds are the dominant factor, although others factors such as the freezing level and the AR orientation also play a role. Further results will be presented and discussed in the conference.



Adapted from Viale et al. 2018

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IARCS/098

Parameter Perturbations to Microphysical and Turbulence Schemes for Convection-Permitting Ensemble Forecasts of Orographic Precipitation

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Some of the largest impacts of atmospheric rivers (ARs) occur over coastal mountain ranges. However, forecasting these impacts can be difficult, due in part to uncertainties in the representation of small-scale physical processes that must be parameterized in numerical weather prediction models, including cloud and precipitation microphysics (MP) and planetary boundary layer and surface layer (PBL/SL) turbulence. One way to account for uncertainty in these parameterizations is to design convection-permitting ensemble forecasts that use methods such as stochastic parameter perturbation (SPP) to vary parameters within these physics schemes. We are working to evaluate and improve the utility of SPP for representing uncertainty in ensemble forecasts of high-impact cool-season orographic precipitation, including precipitation associated with ARs. This research focuses on: (1) quantifying the sensitivity of orographic precipitation to specific uncertain MP and PBL/SL parameters and (2) evaluating SPP as a method for improving convection-permitting ensemble forecasts by representing this uncertainty.

Our initial efforts focus on a case from the Olympic Mountains Experiment (OLYMPEX) that occurred during 12–13 November 2015, with observed precipitation amounts in excess of 370 mm on the western slopes of the Olympic Mountains in Washington state, USA. This case was associated with a storm that included an AR and had several distinct precipitation periods (pre-frontal, warm sector, and post-frontal), useful for studying parameterization uncertainties across a range of thermodynamic environments. We run nested simulations of the event at convection-permitting horizontal grid spacing using the Weather Research and Forecasting (WRF) model configured similarly to the operational High-Resolution Rapid Refresh model. All simulations use Thompson-Eidhammer aerosol-aware MP and Mellor-Yamada-Nakanishi-Niino (MYNN) PBL/SL schemes. Sensitivity experiments are conducted by varying fixed parameters within these schemes, including those that control: snow mass and fall speed, diffusional growth of ice, cloud water and snow particle size distribution shape parameters, warm rain formation, turbulent mixing length, sub-grid cloud fraction, surface roughness lengths, and the relative amount of turbulent mixing of momentum versus heat.

Fixed-value experiments are performed to evaluate the sensitivity of orographic precipitation to each individual parameter. Results of these experiments are used to design SPP ensemble simulations that strategically perturb a subset of these parameters. Results from the WRF simulations are compared to precipitation observations from OLYMPEX, including rain gauges and disdrometers, research aircraft, and ground-based scanning and profiling radars. In this manner, the appropriateness of SPP perturbations and the realism of the perturbed forecasts can be physically constrained by observations.

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IARCS/100

The role of air-sea interactions in atmospheric river events: Case studies using the SKRIPS regional coupled model

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Atmospheric rivers (ARs) play a key role in California's water supply and are responsible for most of the extreme precipitation events along the west coast of North America. Given the high societal impact, it is critical to improve our understanding and forecasting ability of ARs. In this study we use a regional coupled ocean-atmosphere modeling system to make hindcasts of ARs up to 14 days. We investigate the role of air-sea interactions in AR events by comparing coupled model hindcasts to hindcasts made using persistent sea surface temperature (SST). Two groups of coupled runs are highlighted in the comparison: (1) ARs occurring during times with strong SST cooling and (2) ARs occurring during times with weak SST cooling. During the events with strong SST cooling, the coupled model simulates strong upward air-sea heat fluxes associated with ARs; on the other hand, when the SST cooling is weak, the coupled model simulates downward air-sea heat fluxes in the AR region. Validation data shows that the coupled model is able to skillfully reproduce the evolving SST, as well as the surface turbulent heat transfers between the ocean and atmosphere. To evaluate the influence of the ocean on ARs, we analyze the vertically integrated water vapor (IWV) and integrated vapor transport (IVT). During strong SST cooling AR events the simulated IWV is improved by about 12% in the coupled run at lead times greater than one week. For IVT, which is about 1.8 times more variable, the improvement in the coupled run is about 5%.

IARCS/105

A Narrow Cold Frontal Rainband within an AR impacting on the coastal Piuchén cordillera in the Chiloé Island, Chile

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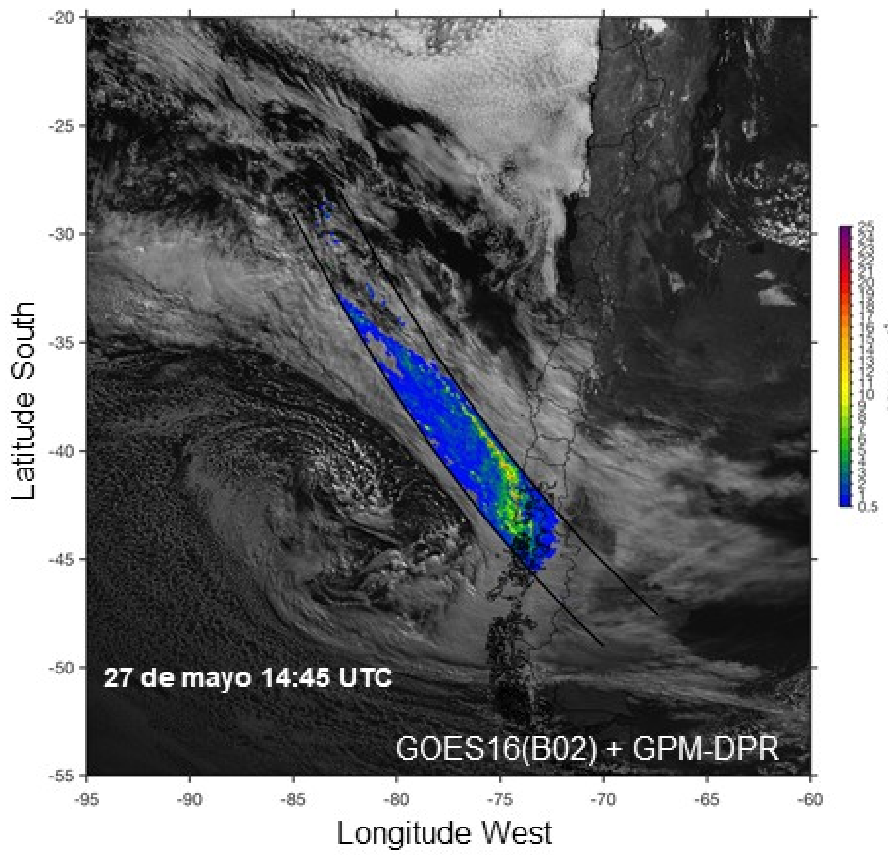
Mesoscale rainbands within a strong frontal precipitation system coming from the Pacific Ocean and making landfall on the west coast of southern Chile is investigated using data from the new Global Precipitation Measurement (GPM) satellite, and from model simulations with the Weather Research Forecasting (WRF). The selected case study is representative of heavily precipitating winter storms characterized by an “atmospheric river” in the pre-cold frontal environment. GPM Dual-Polarized Radar data capture well the frontal system whose main precipitation fell from a narrow cold-frontal rainband (NCFR) when it moves equatorward during the 27 May 2018 over the corrugated west coast. The numerical simulations and sensitivity experiments with the WRF model were used to explore and document the strong influences of the coastal Piuchén cordillera (~800m height) on the NCFR as it moves over the Chiloé island in southern Chile (~42°S). The findings of this study suggest that, the new GPM radar data may contribute largely to the understanding of the orographic precipitation processes in frontal systems moving over the remote and inaccessible southern Andes.



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IARCS/106

Description and Validation of the 34-Year West-WRF Reforecast

Daniel Steinhoff, Luca Delle Monache, Brian Kawzenuk, Caroline Papadopoulos, Rachel Weihs, David Reynolds, and F. Martin Ralph

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The Center for Western Weather and Water Extremes (CW3E) has produced a dynamically-downscaled reforecast product covering 34 winter seasons (December 1985 through March 2019) using the West-WRF model. The West-WRF reforecast features a 9-km domain out to 168 hours covering much of the Eastern Pacific Ocean and the Western U.S., and a 3-km domain out to 120 hours covering most of California and offshore areas. The Global Ensemble Forecast System (GEFS) reforecast is used as input and lateral boundary conditions. The goals of this reforecast effort are to 1) Assess the benefits of a West-WRF high-resolution reforecast to California-Nevada River Forecast Center (CNRFC) hydrology ensemble modeling operations; 2) Enhance CW3E predictive capabilities by exploring post-processing techniques and machine learning to reduce raw model output biases; and 3) Perform in-depth process-based studies. Here we describe the West-WRF setup for the reforecast simulations; present some model verification results across the model domain, for specific watersheds, and for individual observing stations; and discuss current and future applications of the reforecast product.

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IARCS/107

Analysis of a Tuned Version of the WRF Model's Prediction of Rainfall over the Russian Basin During Land-Falling Atmospheric Rivers

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It is well understood that Atmospheric Rivers (ARs) are the dominate cause of major flooding along the West Coast and produce the bulk of flood damages as Ralph and colleagues have reported. The Russian River Basin has been the focus of AR studies for well over a decade and for the past 5 years the focus of a project called FIRO or Forecast Informed Reservoir Operations for Lake Mendocino in Northern California. As part of this study a version of the West-WRF model has been developed specifically tuned to improve AR forecasts and their impacts along the West Coast. Additionally a large effort was completed to produce a reforecast database consisting of 32 years of daily forecasts (Dec-Mar) of the most up to date version of the WRF configuration called West-WRF. For these runs the Global Ensemble Forecast System V10 control run was used to initialize West-WRF. The reforecast database was used to analyze all land-falling ARs in the Russian River Basin (including Lake Mendocino) above an intensity scale of 3 (Ralph et al. (2019) using the SIO_R1-Catalog (Gershunov et al (2017). The analysis consisted of comparing a 5-day period of observed vs forecast 6-hr MAP centered on the maximum IVT 6-hr period of the AR from 1985 to 2017. Twenty-Five ARs of this magnitude were observed. There was a consistent under-estimation by West-WRF of 6-hourly basin wide rainfall or Mean Areal Precipitation (MAP) for almost all of these ARs. Over the past 4 years analysis of seasonal rainfall totals (Dec-Mar) have been analyzed for West-WRF predictions and have also noted a serious underestimation of rainfall for the wettest locations within the basin (Venado for example), Figure 1. However analysis of a location just to the lee of the basin's eastern border (Whispering Pines) shows a tendency to overestimate rainfall. Analysis of model predicted IVT, vertical motions, and microphysics parameterizations are used to try to explain these results. Many National Weather Service offices along the US West Coast run a high resolution version of WRF. The results of this study may be relevant to how WRF output is interpreted in these offices during land falling ARs.

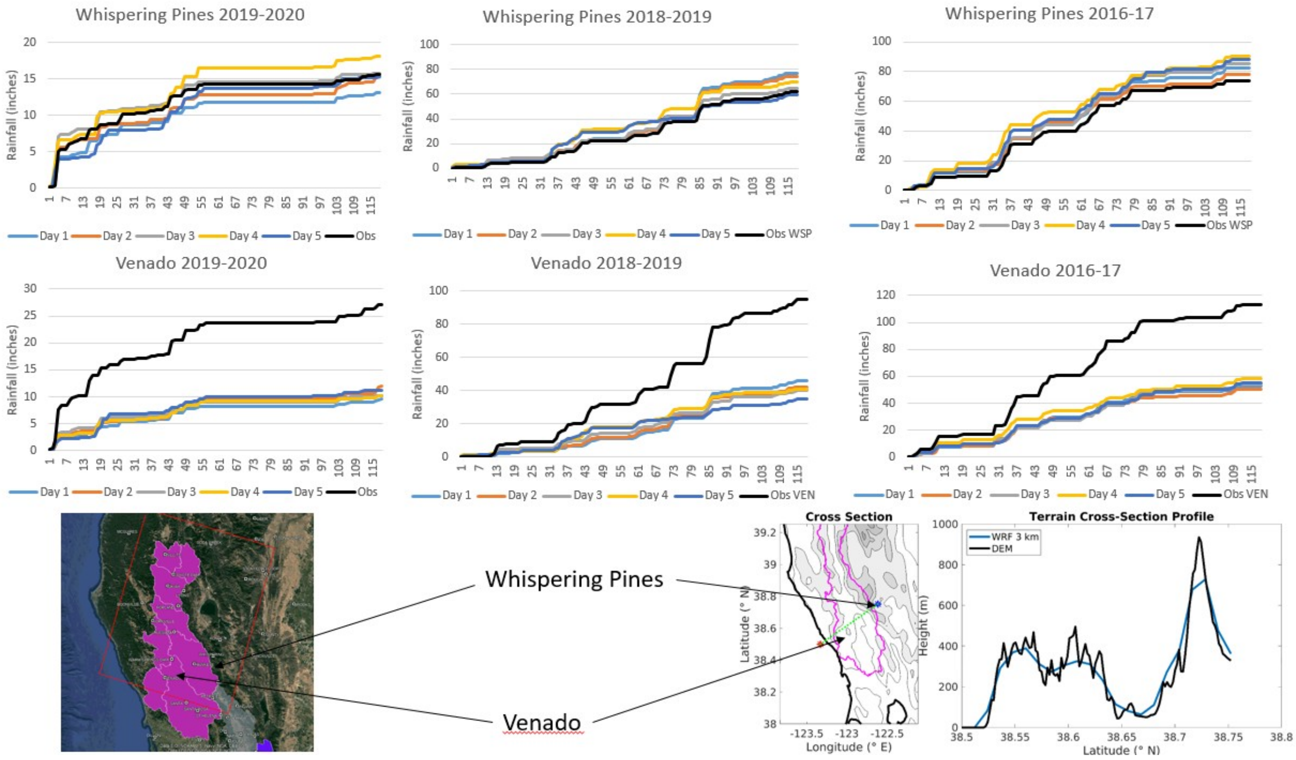

Figure 1 top Gridpoint 24-hr rainfall for Whispering Pines from Dec-Mar for WY's 2017, 2019 and 2020, middle: same as above but for Venado. bottom: locations of Whispering Pines and Venado gages with the Russian Basin (outlined by color shading) along with actual terrain from USGS (black line versus model terrain(blue line) as indicated in cross-section diagram.

Ralph, F. M., J. J. Rutz, J. M. Cordeira, M. Dettinger, M. Anderson, D. Reynolds, L. J. Schick, and C. Smallcomb, 2019: A Scale to Characterize the Strength and Impacts of Atmospheric Rivers. *Bull. Amer. Meteor. Soc.*, **100**, 269–289, https://doi.org/10.1175/BAMS-D-18-0023.1.

Gershunov, A., T. Shulgina, F. M. Ralph, D. A. Lavers, and J. J. Rutz (2017), Assessing the climate-scale variability of atmospheric rivers affecting western North America, Geophys. Res. Lett., 44, doi:10.1002/2017GL074175.

IARCS/110

Impacts of Assimilating Dropsonde Observations from Atmospheric River Reconnaissance on Forecasts of Landfalling Atmospheric Rivers and the Precipitation across the Western United States

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Landfalling Atmospheric Rivers (ARs) over the northeastern Pacific Ocean are responsible for up to 50% of the annual precipitation over the western U.S. They have large socioeconomic impacts as they contribute to both beneficial water resources and damaging extreme events. Accurate forecasts of a landfalling AR can improve water management decisions and reduce the flooding risks. Sparse conventional observations over the central and eastern Pacific Ocean have limited the improvement of forecast skill for the Western U.S. due to the poor upstream initial conditions. While the numerical weather prediction reaps the benefits of satellite data over the oceans, those data are known to poorly represent the low-level circulation and the vertical structure of water vapor in ARs. A targeted field program called AR Reconnaissance (Recon) was initiated in February 2016 to better understand and reduce forecast errors of landfalling ARs at 1-5–day lead times. The program developed as a multi-year research and operation partnership among the Center for Western Weather and Water Extremes (CW3E) of the Scripps Institution of Oceanography, at the University of California San Diego, NOAA NCEP, the U.S. Air Force, and other major stakeholders in water management. In 2016, 2018, and 2019, 15 Intensive Observation Periods (IOPs) were conducted to sample upstream conditions for the landfalling ARs over the western U.S. The dropsondes were released during these missions to gather high temporal and vertical resolution meteorological observations within the AR core and nearby dynamically active regions (i.e., upper-level jet, PV streamer, and parent cyclone). In this study, the impact on the forecast accuracy of landfalling ARs by assimilating these dropsonde data is evaluated.

Data denial experiments are conducted using the Weather Research and Forecasting (WRF) model with the Gridpoint Statistical Interpolation (GSI) 4DEnVar system developed at CW3E, including NoDROP with the conventional data (including satellite wind data) assimilated, and WithDROP with both conventional data and AR Recon dropsondes assimilated. Comparisons between NoDROP and WithDROP show that AR Recon dropsondes have positive impact on reducing the root-mean-square error in both IVT and in-land precipitation forecasts within the western U.S. and its surrounding oceans in 11 out of 15 IOPs averaged. For spatial correlation, dropsondes have improved the spatial pattern forecast in all 15 IOPs. Significant skill improvements are beyond short-range forecasts (i.e., day 4). It was also found that consecutive flights have most positive impact in terms of improving the forecast skill over the western U.S.

IARCS/117

The Pacific Northwest flooding event of 5-7 Feb 2020: a case study for Airborne Radio Occultation data assimilation

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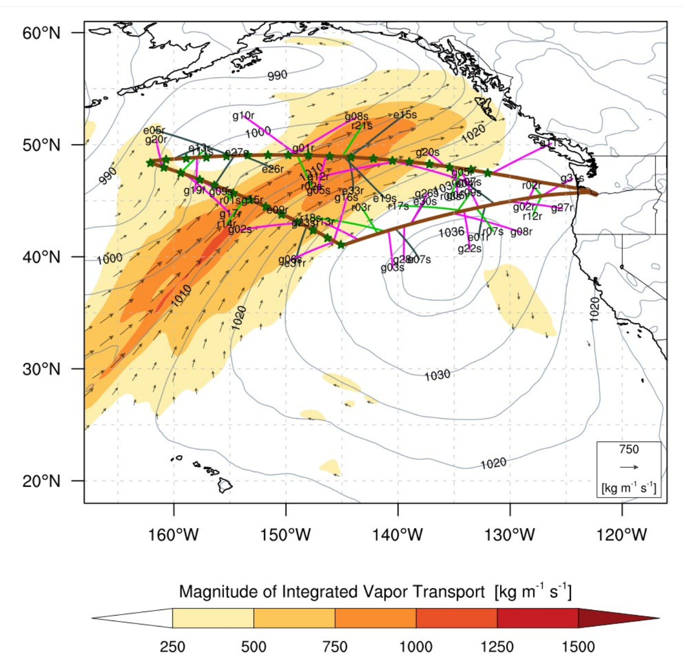
The 3-day period of heavy rainfall in Washington and Oregon from 5-7 Feb 2020 followed an early season start and a higher than average number of winter storms. The Snoqualmie River and other rivers in the region reached flood stage. The Governor issued an emergency proclamation for 19 counties, and water flows from one of the dams had to be increased to accommodate the heavy runoff, leading to evacuations in one county. The uncertainty in the forecast was manifest in clearly faster movement of the upper level trough and the atmospheric river (AR) across the northern Pacific in the National Center for Environmental Prediction (NCEP) operational Global Forecast System (GFS) model than in the European Center for Medium-range Weather Forecasting operational Integrated Forecast System (IFS) model. This led to different forecast event durations at landfall. There was also a mesoscale frontal wave on the back end of the trough that was not captured by either model. In order to better understand the predictability of this high-impact AR event, initial condition sensitivities need to be investigated and data denial experiments can be employed to quantify the initial condition error source if an independent dataset is available for the numerical model. As part of a targeted field program run by the Center for Western Weather and Water Extremes (CW3E) called AR Reconnaissance, airborne radio occultation (ARO) profiles were collected and processed for the National Oceanic and Atmospheric Administration Gulfstream-IV (G-IV) aircraft deployment leading to a complete dataset from that aircraft of 54 ARO and 30 dropsonde profiles. These profiles in addition to 36 profiles from the Air Force C-130s were assimilated in an offline version of the CW3E West-WRF model developed at UC San Diego to examine the potential impact of the two types of observations. Preliminary results show a similar tendency in the impact on forecast of the accumulated precipitation over the western U.S. for the two datasets. These independent ARO data span the region of high sensitivity at the edges of the AR, but ARO data were also collected on the outbound ferry flight in regions which were not identified with high sensitivity, thus they represent a potentially useful dataset for investigating the relation between the initial condition sensitivity and forecast impact.



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IARCS/118

The Impact of Additional Surface Pressure Observations over the Northeast Pacific Ocean on the Data Assimilated Analysis and Forecast of Atmospheric Rivers During Feb – Apr 2019

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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 on the ECMWF IFS data assimilated analysis and forecasts using data denial runs from 28 January – 30 April 2019. Verification metrics for mean sea level pressure, surface variables as well as integrated water vapor, a key quantity for ARs will be presented.

Session 4

Identification, Tracking and Inventories

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IARCS/005

The Sensitivity of Atmospheric River Identification using Integrated Water Vapour Transport to Resolution, Regridding method and Threshold

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Atmospheric Rivers (ARs) are elongated narrow bands of enhanced water vapour that can cause intense rainfall and flooding. ARs only appeared in the literature within the last 30 years and there has been much debate about how to define ARs, and how to identify them. As a result, a wide range of AR identification algorithms have been produced with variations in the conditions required for an object to be classified as an AR, and differences in the input data. One of the key conditions in most AR identification algorithms is a minimum threshold of water vapour or water vapour flux, along with geometric criteria. The main aim of this study is to explore uncertainties in global AR identification based on a single IVT-based identification method. We conduct a sensitivity analysis under one algorithmic framework to explore the effects of different Integrated Water Vapour Transport (IVT) thresholds, input data resolutions and regridding methods using one identification method during the Years of Tropical Convection operational analysis (May, 2008 – April, 2010). We found that the resolution and regridding method affects the number of ARs identified but the seasonal cycle is maintained. AR identification is highly sensitive to the choice of IVT threshold, which can impact the number of ARs identified and modify the AR spatial distribution. Importantly, the commonly used 250 kg m^{-1} s^{-1} IVT threshold is not appropriate for global studies with detection methods that also include a restrictive geometric condition as this combination can lead to the strongest systems failing to be identified. The uncertainties within a single AR detection method and input data parameters may be almost as large as uncertainties across AR detection methodologies.

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IARCS/008

An examination of global mid-latitude atmospheric river lifecycles using an object-oriented methodology

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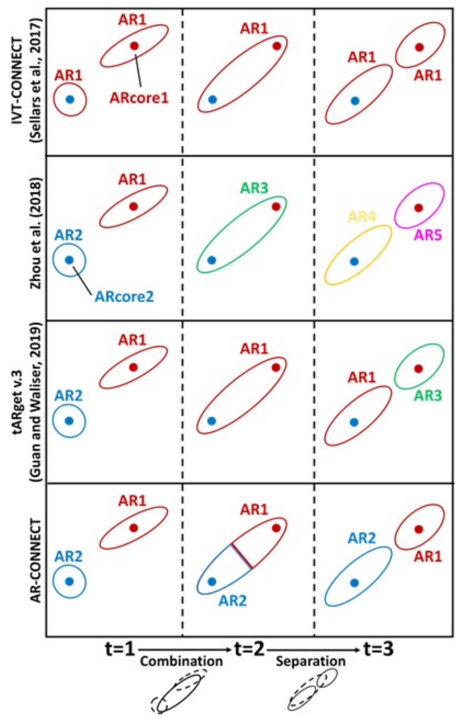
Tracking atmospheric rivers (ARs) across their lifecycles is a field of recent interest with a multitude of emerging methodologies. The CONNected-objECT (CONNECT) algorithm is adapted for the tracking of global mid-latitude AR lifecycles and associated precipitation by implementing a seeded region growing segmentation algorithm, creating the AR-CONNECT algorithm. One of AR-CONNECT's goals is to track atmospheric water vapor anomalies before evolving into AR geometries, effectively tracking AR genesis farther back than other studies. To accomplish this, AR-CONNECT is without hard-coded geometric criteria yet is still proven to extract synoptic-scale elongated objects >99.99% of the time. With the aid of sub-daily satellite-derived rain data from PERSIANN-CDR, we investigate the climatology, trends, and patterns of AR lifecycles from 1983-2016 and compare with other AR tracking studies. We find that AR frequency, genesis, and terminus locations are in generally good agreement with other AR tracking methodologies and that AR frequencies in each hemisphere are determined by the number of AR hotspots. Furthermore, we uncover evidence that certain AR characteristics, such as frequency, size, and duration, show evidence of increasing trends. In terms of precipitation, mid-latitude precipitation uncovered by AR-CONNECT shows contributions up to 50% over land and 65% over the ocean. Trend analysis of AR precipitation show an increase in precipitation associated with Southern Hemisphere and Saharan ARs, among others, but is determined not to be a driver of changes in global precipitation.



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Symposium
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IARCS/017

Uncertainties in Atmospheric River Life Cycles by Detection Algorithms: Climatology and Variability

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In the past decade, many AR detection algorithms have been developed to automatically identify ARs in climate data. The diversity of these algorithms has introduced appreciable uncertainties in quantitative measures of AR properties and thereby impedes the construction of a unified and internally consistent climatology of ARs. We compare eight global AR detection algorithms from the perspective of AR life cycles following the propagation of ARs from origin to termination in the MERRA2 reanalysis over the period 1980-2017. Uncertainties related to lifecycle characteristics, including number, lifetime, intensity, and frequency distribution are discussed. Notably, the number of AR events per year in the Northern Hemisphere can vary by a factor of 5 with different algorithms. Although all algorithms show similar AR frequency distribution with maximum origin (termination) frequency over the northwestern (northeastern) Pacific, significant disagreements occur in regional distribution. Spreads are large in AR lifetime and intensity. The number of landfalling AR events produced by the algorithms can vary from 16 to 78 events per cool season, i.e. by almost a factor of five, although the agreement improves for stronger ARs. By examining the AR's connection with the Madden-Julian Oscillation and El Niño Southern Oscillation, we find that the overall responses of ARs (such as changes in AR frequency, origin, and landfalling activity) to low-frequency climate variabilities are consistent among algorithms.

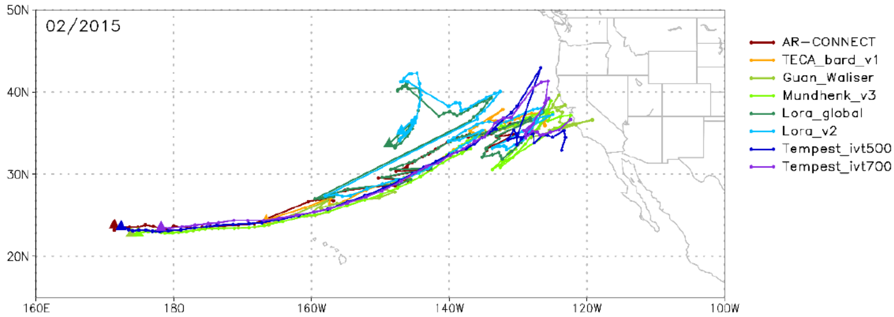

Fig.1 Example of the propagation tracks of a landfalling AR event in early February 2015. Solid triangles mark the locations of AR origins detected by algorithms.

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IARCS/044

Tracking Atmospheric Rivers Globally: Spatial Distributions and Temporal Evolution of Life Cycle Characteristics

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The Tracking Atmospheric Rivers Globally as Elongated Targets (tARget) algorithm is further developed to version 3, adding the capability to track AR life cycles along with other refinement. The results indicate AR genesis is more frequent toward the western boundaries of midlatitude ocean basins and nearby upstream land areas (~1 month^{-1}) compared to the eastern boundaries (~0.5 month^{-1}), and least frequent in tropical and polar areas (reaching toward zero). AR termination is more frequent toward the northeastern sectors of North Pacific/Atlantic and adjacent downstream land areas and in the Southern Ocean near Antarctica (~1 month^{-1}) compared to the adjacent ocean sectors (~0.5 month^{-1}), and least frequent in tropical areas and interior Antarctica where AR genesis is similarly infrequent. ARs tend to be longer-lived when the genesis (termination) occurs toward the western (eastern) boundaries of midlatitude ocean basins and adjacent land areas (maximum lifetime >72 h) compared to the opposite side of the ocean basins (24–72 h), and when terminated at high latitudes. AR travel speed is higher in the midlatitude ocean basins and strongly steered by the zonal wind around 650 hPa. AR tracks are nearly linear in most cases, with the overall travel direction closely correlated with IVT direction (r=0.69) although being more zonal than the latter. Temporally, ARs tend to be longer/stronger around the middle of the life cycle. Seasonal variations in AR life cycle characteristics are also examined. The handling of AR separations/mergers contributes the largest sensitivity in tracking result compared to selection/resolution of input data.

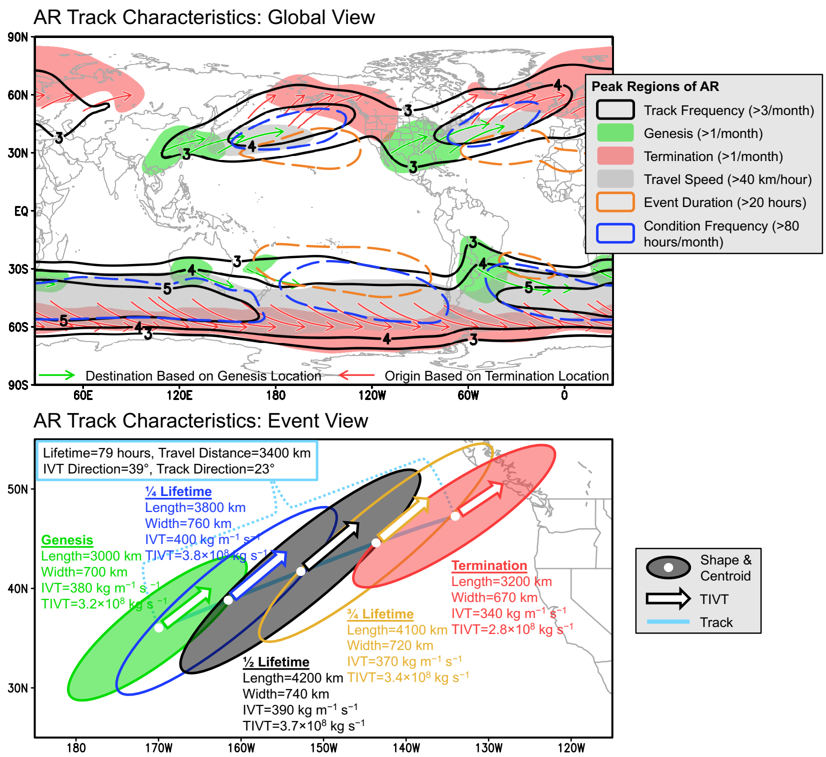

Figure Life cycle characteristics of atmospheric rivers (ARs) tracked by the tARget algorithm, version 3 (Guan and Waliser, 2019; https://ucla.box.com/ARcatalog). **(upper)** Spatial distributions of the long-term climatology. Smoothing was applied to highlight the most pronounced features. **(lower)** Temporal evolution of a typical/composite AR life cycle. Locations of the AR centroids (white dots) and track (light blue curve) are determined by propagating an AR centroid from an arbitrary starting point (here, 170°W, 36°N) forward in time based on the composite travel speed/direction at each stage of its life cycle. Results are based on ~126,000 AR tracks in MERRA-2 during 1980–2017. Similar results are obtained with ERA-Interim (not shown).

IARCS/046

ARTMIP: An Overview and Update

KEYNOTE PRESENTATION

Christine Shields, Jonathan Rutz, Ashley Payne, Travis O'Brien and Allison Collow

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The goal of the Atmospheric River Tracking Method Intercomparison Project (ARTMIP; Shields et al. 2018) is to understand and quantify uncertainties in atmospheric river (AR) science that arise based on differences in AR identification/tracking methods, of which there are dozens. Since inception, ARTMIP has compiled an impressive set of data from an international set of AR-science researchers and is beginning to compile an equally impressive set of results. As the project moves from examining current AR climatology to examining future AR climatology, impacts, and sources of uncertainty, it is clear that interest in ARTMIP will continue to grow.

This presentation will provide an overview and update of the ARTMIP program and ARTMIP-related studies, both completed and ongoing. Because ARTMIP encompasses such a broad scope, different individuals have led different programs within ARTMIP, and for this reason, we plan to use a team approach with multiple presenters speaking:

1) Christine Shields will describe the genesis and overarching goals of the ARTMIP program.

2) Jonathan Rutz will discuss the Tier 1 analysis, which quantified the uncertainty in global and regional AR climatology that arises as a result of different methods being used. Two additional side projects will be discussed.

3) Ashley Payne will discuss the ongoing Tier 2 - Climate Change analysis, which quantifies uncertainty in AR climatology under climate change scenarios.

4) Travis O'Brien will discuss the ongoing Tier 2 – CMIP 56 analysis, which quantifies and compares AR detection uncertainty and model uncertainty in future scenarios.

5) Allison Collow will describe the upcoming Tier 2 – Reanalysis study, which will examine uncertainty in AR climatology that arises as a result of different reanalyses.

Shields, C. A., Rutz, J. J., Leung, L.-Y., Ralph, F. M., Wehner, M., Kawzenuk, B., Lora, J. M., McClenny, E., Osborne, T., Payne, A. E., Ullrich, P., Gershunov, A., Goldenson, N., Guan, B., Qian, Y., Ramos, A. M., Sarangi, C., Sellars, S., Gorodetskaya, I., Kashinath, K., Kurlin, V., Mahoney, K., Muszynski, G., Pierce, R., Subramanian, A. C., Tome, R., Waliser, D., Walton, D., Wick, G., Wilson, A., Lavers, D., Prabhat, Collow, A., Krishnan, H., Magnusdottir, G., and Nguyen, P.: Atmospheric River Tracking Method Intercomparison Project (ARTMIP): project goals and experimental design, Geosci. Model Dev., 11, 2455–2474, https://doi.org/10.5194/gmd-11-2455-2018, 2018.

IARCS/052

On the consensus and disagreement in atmospheric river detection in ARTMIP global catalogues

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Research on the global distribution, frequency of occurrence, and other climatological characteristics of atmospheric rivers (ARs) has heretofore relied on a diverse assortment of detection methodologies applied to various datasets, with differing detection criteria originating from diverse science questions. This diversity has complicated comparisons, and hindered progress on questions such as whether there is consensus on what features constitute ARs globally and what climatological AR behavior is, particularly in places where in situ measurements are not possible. The AR Tracking Method Intercomparison Project (ARTMIP) provides a platform for comparing such methodologies that has already yielded important results, albeit from largely local and regional perspectives. Here we investigate ARs as detected by an ensemble of ARTMIP algorithms with global coverage, which enables an initial assessment of the above questions. We find that the frequency of AR occurrence as suggested by the ensemble average is not particularly robust, but the frequency of occurrence of the majority-consensus ARs provides a robust distribution, featuring five hotspots over the extratropical oceans and few occurrences elsewhere. A comparison of individual algorithms' results to this ensemble majority statistic yields interesting insights into the underlying similarities and differences between detection methodologies, and we find that the dominant source of disagreement stems from detections or non-detections of weak features that can only marginally be considered ARs. The algorithms otherwise tend to agree remarkably well on the footprints of ARs, despite the apparent spread suggested by the ensemble mean frequency and its standard deviation.

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IARCS/081

Atmospheric River Representation in E3SM

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The Energy Exascale Earth System Model (E3SM) Project is an ongoing, state-of-the-science Earth system modeling, simulation, and prediction project developed by the US Department of Energy (DOE). We evaluate E3SM version v1.0 for its ability to represent atmospheric rivers (ARs) globally in different resolutions (low resolution at 1 degree and high resolution at 0.25 degrees) and configurations (historical and Shared Socioeconomic Pathway 5 [SSP5]). The characteristics and impacts of ARs in E3SM are compared to the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2).

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IARCS/099

What do we do with non-atmospheric rivers or hybrids that produce heavy rainfall and result in high impacts?

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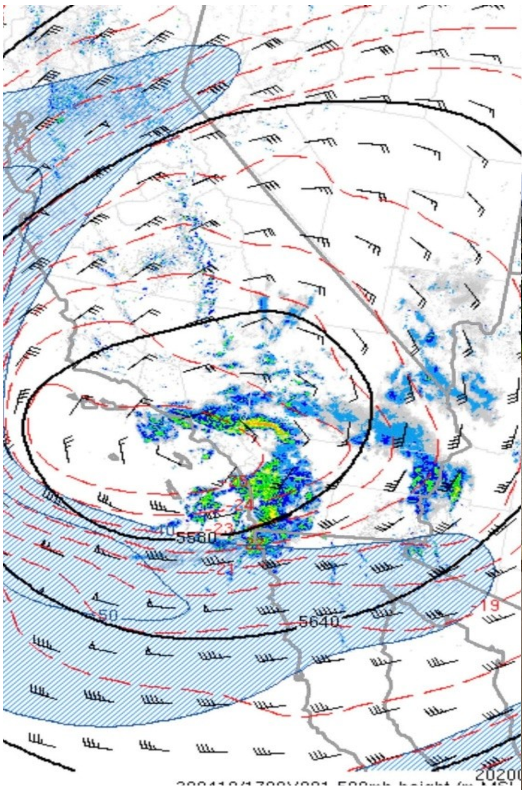
Over the past decade much attention has been devoted to understanding atmospheric rivers and better prediction of their occurrence and impacts. This expanded a prior decade research on synoptic weather patterns that led to "Pineapple Express" episodes in southern California. In the past 2 winters, southern California has experienced synoptic patterns dominated by closed upper level low pressure systems and this has resulted in scattered heavy rainfall versus widespread heavy precipitation more common in the atmospheric river such as February 14, 2019. Of these events, December 6, 2018 and April 10, 2020 both stood out as anomalous since they produced record rainfall rates and storm totals. What made the events more impactful was the intense rainfall that occurred over major metropolitan areas, and resulted in flash floodingdamage in San Diego County. This study will demonstrate that atmospheric rivers as a precursor were important to the heavy rainfall in both events. However, if we were to just focus on the atmospheric river transport and quantity (e.g., such as a scale level) then the impact of the instability and dynamics would have been greatly underestimated.



Session 5

ARs in the Past and the Future

IARCS/010

Meridional heat transport and atmospheric rivers under climate change

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Although moisture transport by atmospheric rivers has been extensively studied, heat transport has received less attention. Here, we look at both sensible and latent heat transport explicitly for landfalling atmospheric rivers impacting western North America and western Europe, and find that the sign of the climate change is dependent on the upper level meridional wind. Changes in the AR signature and eddy driven jet across the Atlantic Ocean are more robust than those in the eastern Pacific, and latent heat transport from ARs increase. Sensible heat responses area regionally dependent with the largest uncertainty in the eastern Pacific AR life cycle region. Uncertainty is assessed by evaluating Atmospheric River Tracking Method Intercomparison Project (ARTMIP) catalogues produced from both MERRA-2 reanalysis and the International CLIVAR C20C+ Detection and Attribution project (Tier 1 and Tier 2). In addition to ARTMIP catalogues, high resolution fully coupled climate model CESM simulations are also analyzed. Agreement across algorithms is regionally dependent, but generally, the sign of the climate change is consistent for landfalling regions, yet, significantly, the magnitude of the change is highly variable.

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IARCS/012

Future Changes in the Hydrologic Cycle Associated with Flood-Producing Storms in California

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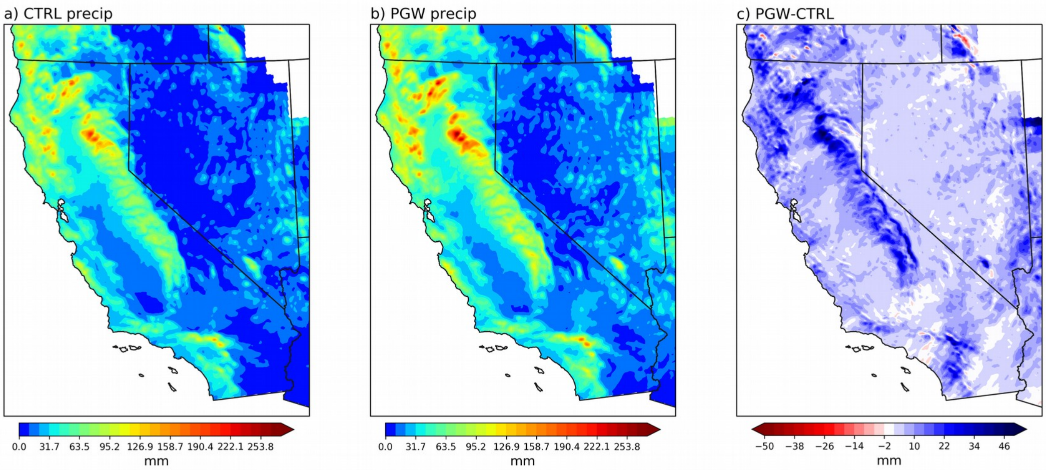
Changes in the hydrologic cycle in a future, warmer climate are critical to understand in California, which is a water-stressed region that alternates between droughts and floods due to its Mediterranean climate. While much of the necessary precipitation is delivered by atmospheric rivers during California's cool-season, these systems can also have detrimental impacts such as flooding. For example, in the winter of 2017, the emergency spillway of the Oroville dam was damaged due to an anomalous number of atmospheric rivers that produced heavy precipitation, partial melting of snowpack, and excessive runoff. Due to both the helpful and harmful impacts atmospheric rivers can cause in California, it is crucial to understand how these systems might change in a future, warmer climate.

While many aspects regarding the future changes in atmospheric river frequency and intensity have been simulated, few have used convection-permitting climate simulations that more accurately resolve topography, mesoscale dynamics, and orographic rainfall processes. Resolving these processes are necessary because they are important factors in determining the intensity and spatial distribution of heavy precipitation associated with atmospheric rivers. This study utilizes a set of high-resolution convection-permitting simulations to examine the changes in California's cool-season precipitation and runoff from 2000–2013 in a future, warmer climate using a pseudo-global warming approach, specifically in floods associated with atmospheric rivers. In 45 flood-producing storms, a warmer climate is associated with decreased snow water equivalent and increased precipitation, leading to more future runoff, especially over the Sierra Nevada Mountains. The future changes in hydrologic characteristics associated with atmospheric rivers are consistent with the broader future changes in the cool-season precipitation. Such results suggest that conditions associated with atmospheric rivers could be more intense in a future, warmer climate leading to more intense storms and detrimental impacts, which should be considered in future water management strategies.



IARCS/021

Thermodynamic and Dynamic Controls on the Recent Poleward Shift of Atmospheric Rivers in the Southern Hemisphere

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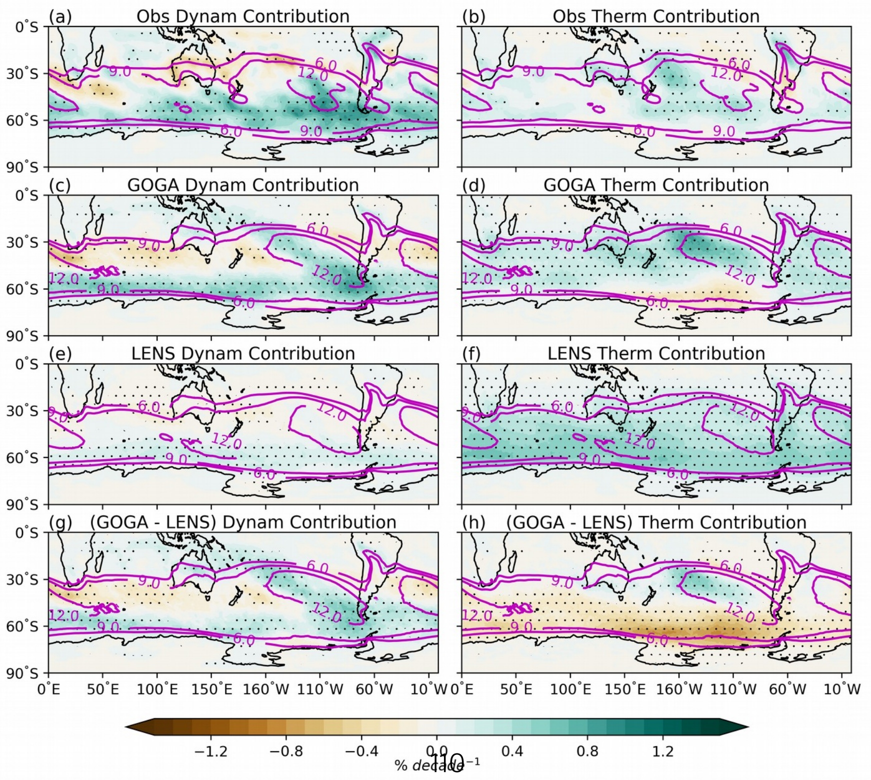
The trends in atmospheric river (AR) frequency over the Southern Hemisphere are investigated using three reanalyses and two Community Earth System Model (CESM) ensembles. The results show that AR frequency has been increasing over the Southern Ocean and decreasing over lower latitudes at around S in the past four decades. Consistent with the trends in AR frequency, the annual total AR-induced precipitation over the Southern Ocean has also been increasing due mostly to the changes in AR frequency, with changes in AR-induced precipitation intensity playing a negligible role. Further analysis on the trends of AR centroid latitude, poleward tip latitude and landfall location reveals that AR events have been systematically shifting poleward during this period. To investigate the driving mechanisms, a scaling method is developed to separate the dynamic and thermodynamic contribution to the AR trends. Results show that the observed trends are mostly driven by circulation changes owing to the poleward shift of westerly jet while the thermodynamic contribution confines mostly within the Pacific basin. Decomposing the trends in the fully-coupled CESM experiments indicate that anthropogenic forcing would result in positive trends in AR frequency over the Southern Ocean due mostly to moisture changes while the changes in circulation only play a minor role. The difference between the observed trends and anthropogenically driven trends in the coupled model can be largely reconciled by the atmosphere-only CESM simulations forced by observed sea surface temperatures (SSTs): SST variability characteristic of the negative phase of the Interdecadal Pacific Oscillation (IPO) strongly suppresses the moisture-driven trends while enhances the circulation-induced trends over the entire Southern Ocean, thus bringing the simulated trends into closer agreement with the observed trends.



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IARCS/022

Much more than a name change for aircraft crews: The transformation from Winter Storm Reconnaissance to Atmospheric River Reconnaissance (2013-2020)

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Between 2013, the last year of the OFCM NWS Winter Storms Reconnaissance (WSR) Program, and 2020, the latest season of Atmospheric River Reconnaissance (AR Recon), a major transition occurred advancing targeted observation of impactful winter seasonal weather over the Pacific basin. In such a short span, US Air Force Reserve and NOAA operational flying units pivoted from a purely reactive function, such as NHC tropical cyclone reconnaissance, to a truly integrated science and operations mode. That period featured at least three iterations of the National Winter Season Operations Plan (NWSOP – the name changed from “Winter Storms” to reflect the seasonal span of AR Recon) responding to the numerous changes to mission planning and execution as reflected in the latest NWSOP. Serving sometime daily flight requirements while providing the flexibility needed to satisfy shifting science goals based on updated observations has required an optimistic vision, multi-year collaboration and certainly some compromises, yet the goal is now mostly realized; an annual science and operations program suited to the needs of the North American west coast. We contrast the past and present means of planning and execution, including entirely new funding streams required when the NWS temporarily dropped the WSR program, transition to customized flight patterns to serve the science, and a welcome seat at the research and forecasting table for flight planners and aircraft managers. We highlight the year-round collaboration between the NOAA Aircraft Operations Center and Dr. Jennifer Haase and the UCSD ROC-2 instrument, as it has steadily evolved over her history with AR Recon. More challenges lie ahead, including optimal basing of aircraft to combine targeting coverage with functional logistics, and the proposed shift of the East Coast and Gulf of Mexico winter storm reconnaissance to follow the AR Recon model.

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IARCS/025

Projecting the role of atmospheric rivers in Chilean hydroclimatic extremes using variable-resolution CESM

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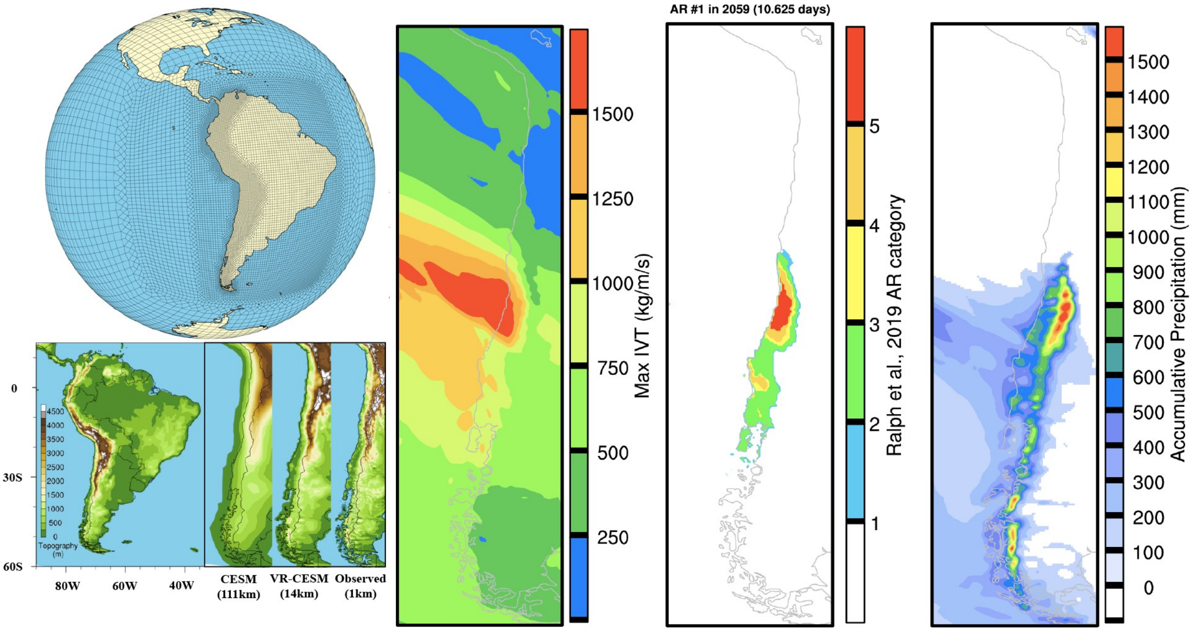
Anthropogenic climate change poses a significant risk to the South American continent through its control on heat extremes, hydrologic cycle alterations, and near-irreversible changes to the cryosphere. Chile faces a particularly increased risk to these changes as it spans a myriad of different microclimates each with their own unique risk factors. For example, Andean watersheds in Chile are relatively unmanaged due to sharp elevational gradients and significant infrastructure and maintenance costs, particularly the Maipo Basin which supplies water to over a third of all Chileans who reside in its capital city of Santiago. Therefore, climate change-induced alterations to precipitation location, magnitude, phase, and/or timing in Chilean mountainous headwater regions, such as the Maipo basin, will have a marked influence on both Santiago's water availability and quality.

Coupled to these climatic risks is the need for a climate modeling strategy that can work across disparate spatiotemporal scales such as large-scale climate modes of variability (e.g., El Niño Southern Oscillation) with regional-to-local scale interactions in mountainous watersheds (e.g., landfalling atmospheric rivers and seasonal snowpack dynamics). We will present preliminary results using one such model that affords this capability, the variable-resolution enabled Community Earth System Model (VR-CESM), to investigate hydroclimatic extremes in Chile across a historical 30-year (1985-2014) and two 30-year high-emission scenario projections at mid-century (2030-2059) and end-century (2070-2099). The VR-CESM based simulations have a 1-degree global resolution with 28km refinement over all South America and 14km refinement over the Andes. The simulations are performed under Atmospheric Model Intercomparison Project (AMIP) protocols (i.e., monthly prescribed sea-surface temperatures and sea-ice extents).

Our work first investigates the climatic shifts and seasonal trends in precipitation and temperature that could face Chile in the coming century and then breaks down some of the phenomenological drivers of these changes. To do this, we leverage new frameworks that enable atmospheric river tracking over the South Pacific through landfall on the Chilean coast and evaluate shifts in mountainous watershed hydrology. We find a significant increase and trend in Chilean winter (JJA) average surface temperatures at both mid-century (+1.7 K) and end-century (+3.8 K), yet a non-statistically significant change and trend in precipitation in either season. However, changes in the nature of the most extreme storms in Chile, particularly in the north, does occur with a significant increase in the number of Ralph et al., 2019 AR category 4 or 5 events by mid-century. The largest of these future ARs can represent nearly 20% of the total precipitation in JJA (Figure 1). Importantly, both AR and non-AR storms are more rain inducive with a systematic decrease in Chilean mean accumulative snowfall at mid-century (-33%) and end-century (-62%). These changes in warming and rain-snow partitioning also have clear signatures in perennially snow-covered and glaciated regions of Chile. The combined effects of a warmer world with more extreme storms that are more rain-producing will create numerous challenges for natural resource management, tourism, and public health if we continue along a high-emissions scenario.


0
30S
60S
80W
60W
40W
Topography (m)
CESM (111km)
VR-CESM (14km)
Observed (1km)
Max IVT (kg/m/s)
1500
1250
1000
750
500
250
AR #1 in 2059 (10.625 days)
Ralph et al., 2019 AR category
5
4
3
2
1
Accumulative Precipitation (mm)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0

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IARCS/029

Atmospheric river response to global warming in an idealized GCM with Earth-like global circulation and hydrological cycle

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Atmospheric rivers (ARs), narrow intense corridors of horizontal moisture transport, are responsible for most of the poleward moisture transport in midlatitudes. While many recent studies have characterized the AR features and associated hydrological impacts in a warming climate in observations and comprehensive climate models, the fundamental dynamics for changes in AR statistics (e.g., frequency, length, width) are not well understood. Idealized models, in contrast, have been valuable in understanding the fundamentals of atmospheric general circulation and midlatitude storms, but many idealized models have no explicit hydrological cycle (i.e., dry atmosphere) or unrealistic boundary conditions (i.e., aquaplanet) and thus cannot simulate realistic spatial distributions of ARs. Here we present a new idealized GCM with Earth-like global circulation and hydrological cycle, in which mean temperature resembles the observations through relaxation to prescribed equilibrium temperature with an iterative method, and water vapor and clouds are modeled as passive tracers with cloud microphysics and precipitation processes but without cloud radiative effects or latent heat release. As compared with observations, this idealized GCM produces qualitatively similar global moisture transport, precipitation minus evaporation (P-E), and cloud distributions, with remarkable simulations in the spatial distributions of ARs. We further show that the projected AR changes in response to global warming in the comprehensive climate model can be well reproduced in this idealized model forced by uniform tropospheric warming. These results demonstrate the basic dynamics of ARs in a warming climate can be understood as passive water vapor and cloud tracers, and thus provide a theoretical tool for understanding changes to AR statistics under global warming.

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IARCS/031

“But Chinook-Wind returned in the form of rain”: Indigenous Knowledge of Atmospheric Rivers, Winter Storms, and Great Floods on the Pacific Slope

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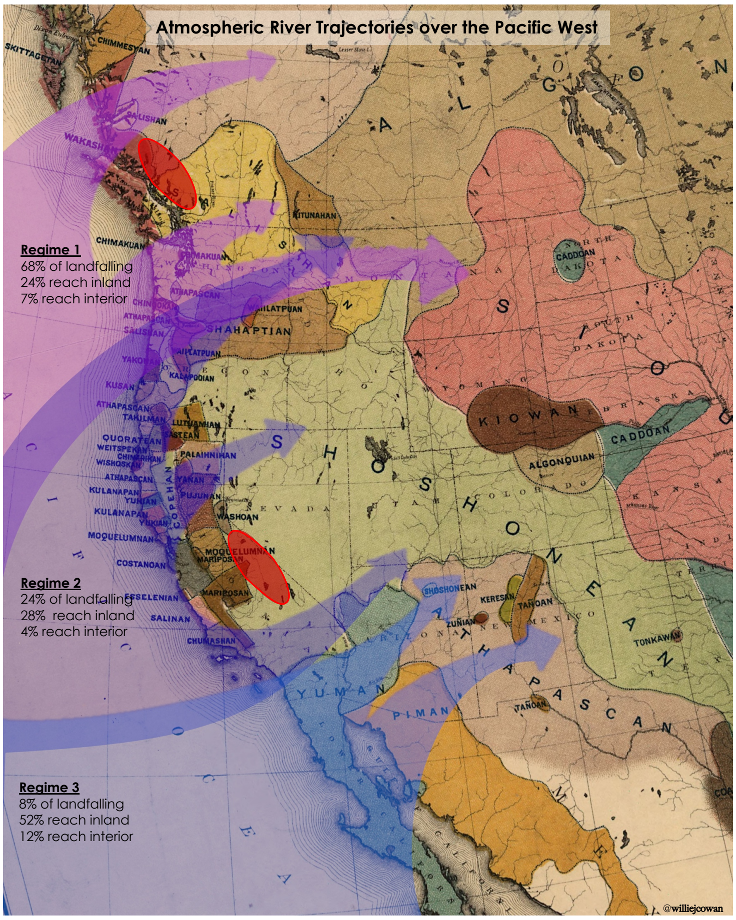
The First Peoples of the Pacific West maintain long-standing oral archives that are a vital component in better understanding atmospheric rivers–a phenomenon that is key to extremes in weather and water on the Pacific Slope of North America. These rivers in the sky nurse rivers on the land and are fundamental to the region’s precipitation, drought, and wildfire regimes. This talk will share a small set of histories from the Lil’ Wat, Chinook, Wasco, and other Indigenous Peoples of the Pacific Northwest. Cowan argues that along with conveying knowledge of the cosmos and history, these accounts reveal technical descriptions of the processes that produce the West Coast’s most significant storms and floods. Furthermore, the accounts show the interconnections between meteorology, disaster history, Indigenous memory, and storytelling as well as how narrative is critical in disseminating practical knowledges of place.

Illustration of composites of primary AR pathways on the Pacific slope of North America in three regimes. Red regions represent areas of AR decay. Based on J. J. Rutz,, W. J. Steenburgh, and F. M. Ralph, “The Inland Penetration of Atmospheric Rivers over Western North America: A Lagrangian Analysis,” *Mon. Wea. Rev.*, 143, 2015, 1924–1944. Base map excerpted from John Wesley Powell, *Map of linguistic stocks of American Indians*, S.l, 1890, Library of Congress and is not meant to represent the spectrum of Indigenous polities and peoples through time.



IARCS/041

Atmospheric rivers influenced by stationary wave changes in model of mid-Pliocene climate

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In a warmer climate, atmospheric rivers (ARs) will likely impact the intensity, frequency, and regional distribution of the heaviest precipitation in ways that are not yet well understood. Studying how ARs may have behaved in past climates can improve our knowledge of conditions and processes that impact the hydrologic cycle. The mid-Pliocene warm period roughly 3 million years ago, during which atmospheric CO_2 concentrations were comparable to those of the present, is often invoked as our best recent analog for a future warmer climate.

We analyze simulations of the mid-Pliocene warm period climate with the University of Toronto Version of the Community Climate System Model Version 4 (UofT-CCSM4). We find that two areas where ARs have a strong influence on local weather and climate – the Pacific coast of North America and the Pacific coast of Chile – experience opposite patterns of change in extreme precipitation compared to the pre-industrial control simulation. Using an AR tracking algorithm previously vetted for paleoclimate studies, we identify ARs through anomalies in vertically-integrated water vapor transport. We link changes in extreme precipitation to dynamical changes in AR behavior, especially in the Northern Hemisphere winter. In particular, a Northern Hemisphere stationary wave train present in the preindustrial control nearly disappears in the mid-Pliocene simulation, corresponding with fewer ARs making landfall over western North America. We also analyze the sensitivity of these stationary wave patterns to applied model boundary conditions to better understand the response of Northern Hemisphere stationary waves to mid-Pliocene ice sheets and orography, independent of CO_2 forcing.

Our results demonstrate the susceptibility of mid-latitude regional hydroclimate to changes in boundary conditions, and strengthen our understanding of how stationary waves affect ARs. In addition to exploring the links between regional responses to past and future climate changes, this study has implications for the design of future experiments with Pliocene climate models, and for future efforts to improve reconstructions of the mid-Pliocene cryosphere, continental configuration, and hydroclimate.

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IARCS/053

Climate Model Evaluation of Atmospheric Rivers over the Continental United States

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Atmospheric rivers (ARs)–long corridors of intense atmospheric water vapor transport–significantly influence the hydrologic cycle and regional hydrometeorological extremes across the continental United States (CONUS). Ongoing and future climate change may alter AR characteristics and impacts, making confident climate model projections of future change, especially at regional scales, of critical importance. In order to better constrain uncertainty in such projections of future change, we perform a comprehensive climate model evaluation of AR climatology over the CONUS. Using an established AR detection algorithm, here we evaluate the representation of ARs in historical simulations (1984-2013) from a suite of models participating in the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Models are evaluated against the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) reanalysis. Model performance for individual models and the multi-model mean is presented for AR frequency, intensity, geometry, and seasonality in order to highlight systematic biases. Results are summarized over the seven US National Climate Assessment regions. Results suggest that most CMIP6 models reproduce the reanalysis AR climatology and features with broadly reasonable fidelity, however some notable biases exist and some models provide more realistic representations than others. These results help inform future AR projection studies for the CONUS, identifying in which regions and variables we can place greatest confidence.

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IARCS/055

Future changes in Western Europe moisture transport and precipitation regimes in a warming planet

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Moisture transport and Atmospheric Rivers (ARs) over the Northeastern Atlantic are a determinant atmospheric process for the inter-annual variability of precipitation over Western Europe. Relying on a long-term transient simulation (spanning 850-2100CE) from the CESM model, we have analyzed the link between moisture transport towards Western Europe (using the vertically integrated horizontal water vapor transport, IVT) and tropospheric temperature fluctuations, showing that IVT has been increasing consistently and significantly since the industrial revolution. This clear anthropogenic fingerprint is revealed in the recent observed global warming trend, but also notoriously when looking at projected changes (using RCP 8.5). The latter significantly exceed the range given by inter-annual to inter-decadal internal/external variability observed during the last millennium, leading moisture content and transport in the lower troposphere to unprecedented levels.

We have checked the emergence of the temperature, IVT and precipitation signals in Iberia and the UK, showing that while the first two variables have now clearly emerged from the pre-warming state, precipitation series are still slightly below that threshold. Projections for the 21st century show a remarkable increase in rainfall at higher latitudes, in line with the expected warmer and moister atmosphere. Contrarily, a decrease is projected at lower latitudes, significantly decoupled from the overall increase in moisture availability. We have explored the role played by large-scale circulation and atmospheric dynamics for these contrasting latitudinal projections. Our results show that a poleward migration of moisture corridors and ARs explains a significant fraction of the projected trends. Furthermore, and based on the Clausius–Clapeyron relation, we have separated the thermodynamical from dynamical changes (Figure 1). Our analysis shows that a significant increase in subtropical anticyclonic activity over Iberia is responsible for: i) dynamical circulation changes; ii) a shortening of the wet season; iii) less efficient precipitation regimes in the region. These results highlight the significant drying trend expected in Mediterranean-type climates, as a consequence of global warming and subtropical expansion, and consequently, the urge to take serious mitigation policies regarding water management under climate change.

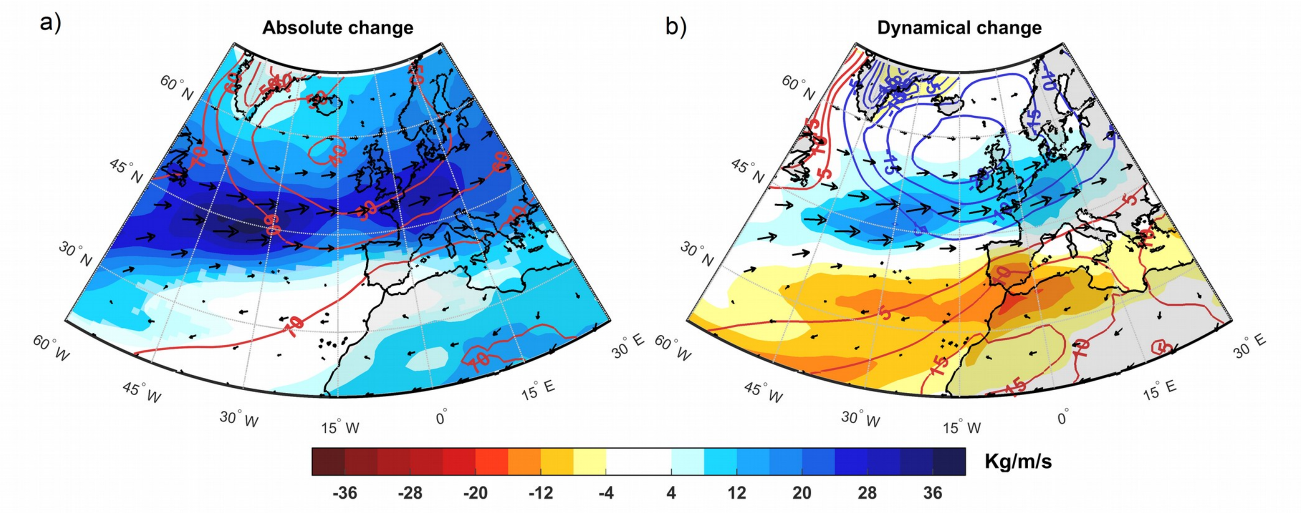

Figure 1 Projected changes in mean moisture transport during extended winter (2070-2099 minus 1981-2010). Shading represents changes in IVT (kg/m/s), red/blue contours represent increases/decreases in the 1000-500 hPa geopotential height thickness. Arrows represent the change in the IVT direction and magnitude. a) Projected absolute changes, with transparent shading denoting areas where changes are not significant at the 98% level of confidence. b) Changes in the previous fields attributable to dynamical modifications, i.e., after removing the moisture increase associated to the warming signal.

The financial support for this work was possible through the following FCT project: HOLMODRIVE - North Atlantic Atmospheric Patterns influence on Western Iberia Climate: From the Lateglacial to the Present [PTDC/CTA-GEO/29029/2017]. Alexandre M. Ramos was supported by the Scientific Employment Stimulus 2017 from FCT (CEECIND/00027/2017).

IARCS/059

Climate Change Effects on Atmospheric Rivers over the Continental United States

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A uniform regional approach across the continental United States (CONUS) is used to quantify how atmospheric rivers (ARs) change between Coupled Model Intercomparison Project Phase 6 (CMIP6) historical simulations and future projections under the shared socioeconomic pathway (SSP) 585 warming scenario. An objective AR detection algorithm, using a relative threshold consistent for the current and future climate, is applied to CMIP6 to characterize climate change impacts on AR frequency, geometry, intensity, and associated precipitation. Future changes in AR characteristics and associated precipitation are computed at the grid point scale and summarized over the seven US National Climate Assessment (NCA) regions across the CONUS. The projections indicate that increases in AR days will occur across the West Coast in the winter, the central and southeastern US in the spring, parts of the East Coast in the summer, and the Pacific Northwest and interior West in the fall by the end of the century (2071-2100). AR IVT magnitude shows notable increases across the eastern US with little change in mean AR IVT direction regionally in the future. Changes in AR occurrence, magnitude, and direction will likely influence regional patterns of extreme precipitation distribution and intensity. Results from this study aim to inform the continued efforts of the NCA concerning anticipated changes in weather and hydrology extremes across the CONUS.

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IARCS/074

Does the Atmospheric River Story Have a Prequel in the 1930s? A Revisit to the Moist Tongues Identified by Rossby and His Collaborators

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Long, narrow, and transient corridors of strong horizontal water vapor transport are known as atmospheric rivers (ARs). The concept of AR has been around since the 1990s, and can even be dated back to the 1970s when narrow moist low-level jet streams ahead of cold fronts were called "warm conveyor belts". A look further back in history reveals the attempts made in the 1930s by Carl-Gustaf Rossby and his collaborators to investigate tongues of dry and moist air over continental North America on selected isentropic charts. This study serves as a revisit to their moist tongues from a modern perspective of AR analysis. Data from the NOAA 20th-Century Reanalysis (20CR) are used to re-examine the three-dimensional structures and day-to-day evolutions of these historical moist flows, with detailed case studies focusing on three events in 1936 and 1937. It is shown that not all but some of them fit well with the modern conceptual model of AR. These moist tongues appeared as narrow belts of moist air driven by large-scale cyclonic or anticyclonic eddies. They were often accompanied by surface cold fronts in close proximity. As pointed out in their papers, the heavy rainfalls associated with some moist tongues were caused mainly by the motion of moist air up the steep isentropic slopes over warm fronts or topographical features. It is demonstrated that the unique technique of cross-sections they developed to analyze the moist tongues can be tailored and applied for the modern AR analysis. This study also serves to illustrate the usefulness of the CR20 for investigating some high-impact weather events in the history.

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IARCS/082

Joint Operations of AR Recon 2020 and IMPACTS 2020 for Simultaneous Aircraft Sampling of USA West Coast and East Coast Winter Weather Systems

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For the first time, two projects designed to improve understanding through basic research and improved forecast accuracy through real-time sampling for model Data Assimilation of Winter Weather Systems were conducted during the same time period in mid-late winter 2020. The Scripps Atmospheric Rivers Reconnaissance (AR Recon) program was flown as a component of the National Winter Systems Operational Program (NWSOP) sampling AR systems within the Central and Eastern Pacific Oceans (CPAC/EPAC) forecasted to impact the U.S. West Coast as well as Hawaii and Alaska. This plan, also describing East Coast and Gulf of Mexico operations, is published by the Office of the Federal Coordinator: https://www.ofcm.gov/publications/nwsop/nwsop2.htm. This program was focused on enhanced sampling of over-ocean atmospheric conditions with air-deployed dropsondes from two Air Force Reserve Command 53rd Weather Reconnaissance Squadron (AFRC/ 53rd WRS) aircraft plus a NOAA G-IV high-altitude surveillance aircraft. These observations were supplemented with ocean surface observations from air- and ship-deployed drifting buoys along with ARGO profiling floats. Additionally, enhanced radiosonde and weather radar sampling along the West Coast was also conducted.

Simultaneously, the NASA IMPACTS program was flown over the continental eastern U.S. as well as along and offshore from the U.S. East Coast to improve understanding of winter system basic physics, especially cloud microphysics. This was the first of a planned three-year flight and ground-based observational program utilizing two NASA aircraft: the NASA Armstrong ER-2 and the NASA Wallops P-3 aircraft, both equipped with enhanced radar and cloud microphysics sampling instruments. Additionally, the P-3 was equipped with dropsondes. An NWSOP East-Coast operational program was also planned to obtain real time flight level and dropsonde data for improved operational Data Assimilation and model forecast accuracy utilizing the AFRC/ 53rd WRS WC-130J aircraft.

Joint observations were obtained during two joint Intensive observing periods involving AR Recon and IMPACTS aircraft. These were conducted on 5 February and 21 February 2000, as shown in the figure below. The third joint sampling period was between IMPACTS aircraft and the 53rd WRS WC-130J on 26 February. This was the next system downstream from the EPAC system flown during ARR IOP#11 on 23-24 Feb 2020. The attached figure illustrates the weather system configuration, aircraft flight tracks, dropsonde locations during the joint flights on 26 Feb, 2020 and locations of supplemental radiosonde launches. This paper will further discuss the observational data obtained during these joint flights as well as those on 5 Feb 2020 and the WC-130J flight on 26 Feb 2020.

The potential for utilizing these flight observations as a template for a future expanded AR Recon program for the U.S. East Coast and western Atlantic, possibly in conjunction with ECMWF, UKMET and EU partners, will be discussed.

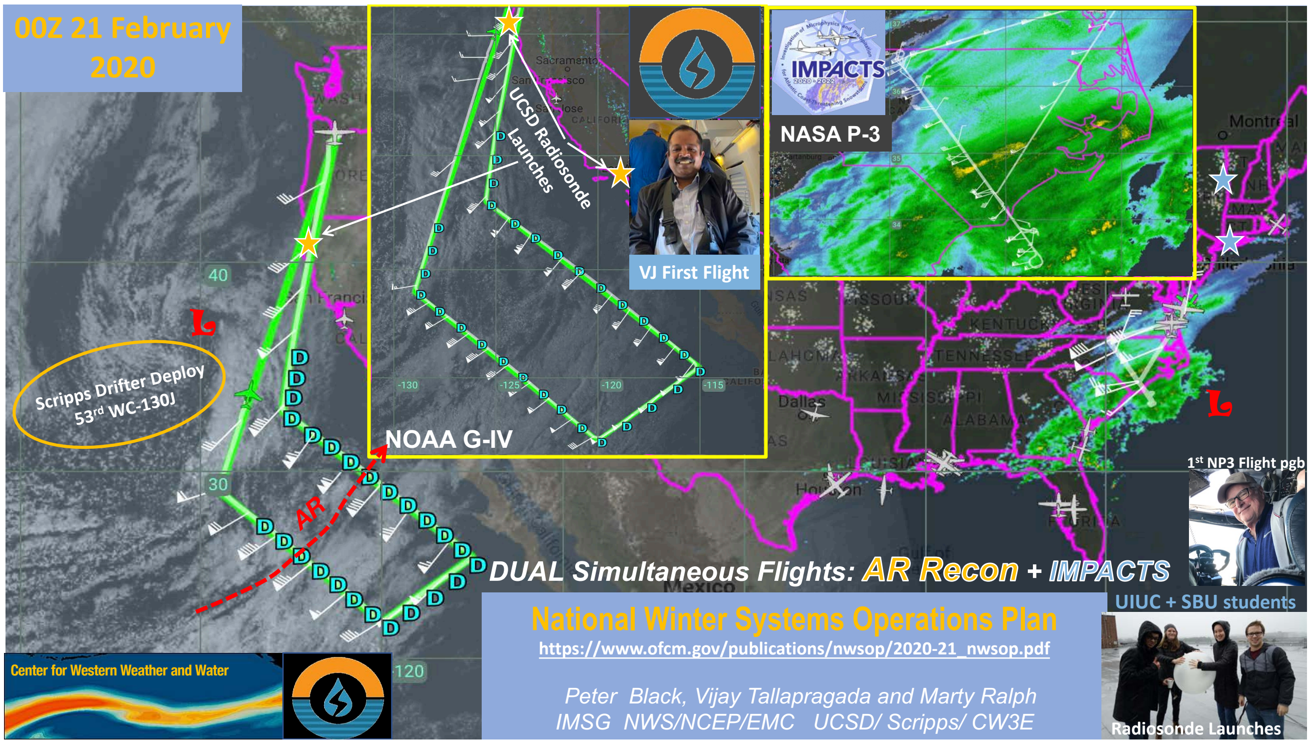

Figure 1 Joint CW3E/NOAA/53rdWRS AR Recon and NASA IMPACTS flights collaborating with NWSOP on 21 Feb 2020.

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IARCS/086

Uncertainty in Current and Projected Atmospheric Rivers: A call for process-oriented constraints on AR detection

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International research efforts related to ARs have expanded substantially in the past 10 years, with numerous articles related to AR variability, AR impacts, ARs impacts on the global and local hydrologic cycle, and the effects of climate change on ARs. A large set of these recent advances in AR science have benefitted from application of objective, automated AR detection methods. A growing number of AR detection methods have been applied in the literature, and recent research associated with the Atmospheric River Tracking Method Intercomparison Project (ARTMIP) has shown that uncertainty related to AR detection may be important for some scientific questions.

In order to quantify the impact of this uncertainty, we analyze output from the ARTMIP Tier 2 CMIP5/6 experiment (multiple AR detection algorithms run on multiple historical and future CMIP models) and from a the TECA Bayesian AR Detector (TECA BARD v1.0.1). We show that (1) there is broad agreement among AR detection methods on the spatiotemporal characteristics of ARs, (2) AR detection uncertainty dominates uncertainty in future changes in ARs in many regions, (3) there is considerable spread in how experts identify ARs, and (4) expert uncertainty leads to scientific uncertainty in ARs. We argue that these results highlight a need for more process-oriented research on ARs, specifically aimed to constrain AR detection methods, including: physical theories of AR genesis and dissipation, theoretical constraints on bulk AR properties (e.g., count and size), and more physics-grounded theories for ARs and climate change.

IARCS/089

Data Gaps within Atmospheric Rivers over the Northeastern Pacific

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Conventional observations of Atmospheric Rivers (ARs) over the northeastern Pacific Ocean are sparse. Satellite radiances are affected by the presence of clouds and heavy precipitation, which impact their distribution in the lower atmosphere and in precipitating areas. The goal of this study is to document a data gap in existing observations of ARs in the northeastern Pacific, and to investigate how a targeted field campaign called AR Reconnaissance (AR Recon) can effectively fill this gap.

When reconnaissance data are excluded, there is a gap in AR regions from near the surface to middle troposphere (below 450 hPa), where most water vapor and its transport are concentrated. All-sky microwave radiances provide data within the AR object, but their quality is degraded near the AR core and its leading edge, due to the existence of thick clouds and precipitation. AR Recon samples ARs and surrounding areas to improve downstream precipitation forecasts over the western United States. This study demonstrates that despite the apparently extensive swaths of modern satellite radiances, which is critical to estimate large-scale flow, the data collected during 15 AR Recon cases in 2016, 2018, and 2019 supply about 99% of humidity, 78% of temperature, and 45% of wind observations in the critical maximum water vapor transport layer from the ocean surface to 700 hPa in ARs. The high-vertical-resolution dropsonde observations in the lower atmosphere over the northeastern Pacific Ocean can significantly improve the sampling of low-level jets transporting water vapor to high-impact precipitation events in the western United States.

IARCS/090

Connecting Research of Past, Present, and Future Atmospheric Rivers to the Central Valley Flood Protection Plan

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Over the past 20 years, extensive research has been done identifying, characterizing, and relating atmospheric rivers to flooding events and their impacts in California. Over the past decade the Central Valley Flood Protection Plan (CVFPP) has identified needed improvements to the State Plan of Flood Control facilities and associated actions to make the Central Valley more resilient to flood events. This includes incorporating climate change considerations which will have a significant impact on the San Joaquin watershed. For the 2022 update of the CVFPP, an effort is being made to link the developments and increased understanding of atmospheric rivers to the technical studies that evaluate the performance of the flood management infrastructure under current and future climate conditions. In this presentation, an overview of the CVFPP will be provided. Elements of atmospheric river research that connect to elements of the CVFPP will be identified and opportunities for continued collaboration and integration will be suggested.

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IARCS/091

Trends & Impacts of Moisture vs. Wind Dominated Flavors of Atmospheric Rivers

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Here we introduce and quantify the AR moisture dominance metric using an AR catalog and the MERRA-2 reanalysis. We decompose IVT into moisture- and wind-varying components ($IVT_{q'}$ and $IVT_{u'v'}$, respectively) and characterize landfalling U.S. West Coast ARs into “wet” or “windy” flavors. We show that moisture dominance is associated with weaker surface winds and significant differences in precipitation, the sign and magnitudes of which non-monotonically depend on IVT. We investigate the large-scale environmental conditions associated with each flavor and find that windy ARs are associated with lower 500 hPa height anomalies near landfall. Notably, US West Coast AR moisture dominance has been increasing the past four decades, which may have implications for water supply and flood risk. Northern AR moisture dominance has significantly ($p=0.05$) increased through a combination of increasing moisture term ($IVT_{q'}$) and decreasing wind term ($IVT_{u'v'}$), while southern AR moisture dominance has slightly increased through an increasing moisture term ($IVT_{q'}$). Increased $IVT_{q'}$ is coincident with previously documented trends in AR temperature over the same regions. We discuss potential applications of the moisture dominance framework, including: forecasting, sub-seasonal prediction, and climate projections of AR moisture dominance.

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IARCS/119

Atmospheric river changes shaped mid-latitude hydroclimate since the mid-Holocene

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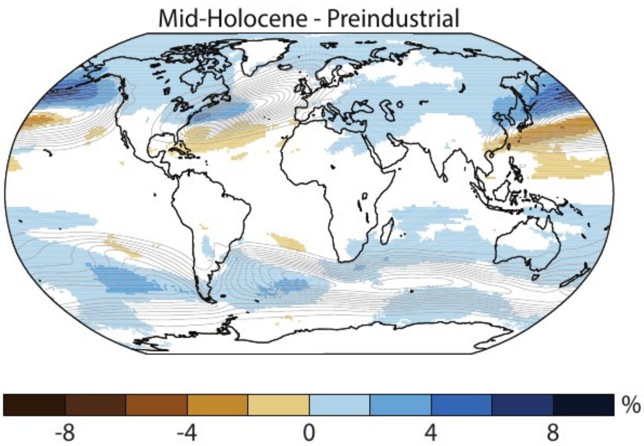
Paleoclimate proxies indicate widespread hydrologic changes during the Holocene in regions that currently experience atmospheric rivers (ARs). While an abundance of evidence suggests ARs are sensitive to background climate state, examination of AR behavior during past climates is generally lacking, limiting our interpretation of the climate signals recorded in these proxies. Here, we use the Community Earth System Model (CESM) and a new AR algorithm designed to facilitate comparison of ARs within different climate states, to explicitly examine the role of ARs in shaping hydrologic change since the mid-Holocene (6 ka B.P.). We find that enhanced seasonality during the mid-Holocene increased summer season AR vapor content and displaced ARs poleward of their present-day trajectories. Changes in AR location and intensity are particularly pronounced in western North America and East Asia, where ARs account for greater than 10% more of total precipitation during the mid-Holocene. The AR changes across the Holocene are consistent with modern-day relationships between ARs and the strength and positioning of semi-permanent atmospheric pressure systems and mid-latitude storm tracks. The model results also agree with a variety of moisture-sensitive proxies, including lacustrine cores from the Andes that indicate changes in the frequency of heavy rainfall events during the Holocene, and lake diatom oxygen isotope values from the Aleutian Islands that indicate changes in moisture sourcing since the mid-Holocene. Overall, the results indicate that ARs are sensitive to insolation forcing and suggest that ARs likely contributed to hydroclimate changes throughout Earth's past.



Change in the annual mean AR frequency (percentage of timesteps with an AR) between the mid-Holcoene and the Preindustrial period from CESM (shading). AR frequency from the Preindustrial period are overlain (contours). Grid cells that do not exhibit statistically significant changes in are shaded white.

Session 6

Regional Flavors

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IARCS/014

Influence of African Atmospheric Rivers on the Hydrometeorology of the Near East's Highlands in the Snowmelt Season

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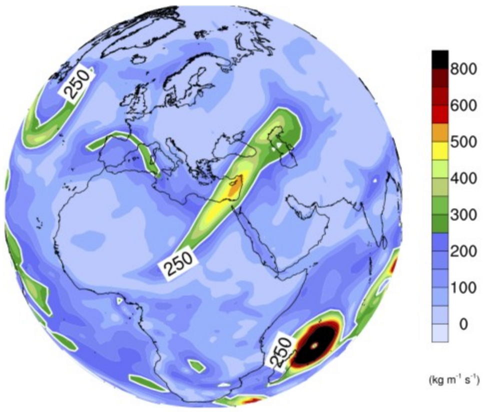
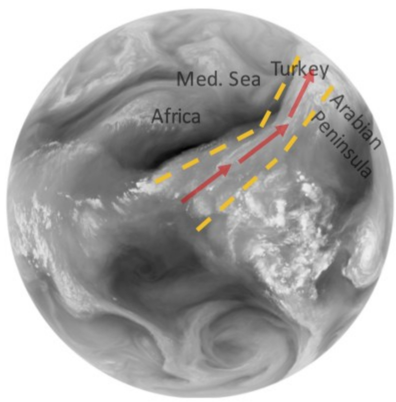
Atmospheric rivers (ARs) mostly prevail over the oceans and primarily landfall on the western coasts of the midlatitude continents as a result of westerly flow of the midlatitudes. Apart from the large ocean basins, certain ARs can develop and propagate over continents, which has received less scientific attention. ARs travelling thousands of kilometers over arid North Africa including the great Saharan Desert could interact with the highlands of the Near East (NE), and thus affect the region's hydrometeorology and water resources. In this respect, this study aims to show how overland African ARs developing in the snowmelt season can influence the NE's highlands, which are essential for satisfying the water need of lowland areas of Mesopotamia that are potentially at risk of water scarcity and conflicts. We use a state-of-the-art AR tracking database, and reanalysis and observational datasets to investigate the climatology (1979-2017) and characteristics of these ARs in snowmelt season (March-April, MA). AR days exhibit enhanced precipitation over the crescent-shape orography of the NE region in MA. A notable increasing trend in AR frequency and intensity exist in MA over the highlands of the NE. The ARs are typically associated with the eastern Mediterranean trough positioned in the central Mediterranean and a blocking anticyclone over the NE-Caspian region. Subtropical African jet tends to entrain the tropical air toward the mid-latitudes and interact with the eastern Mediterranean trough. These ARs are mostly weak, however strong ones (IVT > 275 kg $m^{-1} s^{-1}$) do also exist (~ 8%). Mean AR days indicate wetter (up to +2 mm day^{-1}) and warmer (up to +1.5°C) conditions than all-day climatology. Depending on elevation, snowpack could decrease by up to 30% and increase by up to 8% on AR days compared to all non-AR days. A further analysis with the aid of observations and reanalysis indicates that ARs coinciding with large scale sensible heat transport can influence surface hydrometeorological conditions by raising temperatures over freezing point and increasing daily discharges. These results suggest that ARs can have notable impacts on the hydrometeorology and water resources of the region, particularly of lowland Mesopotamia, a region that is famous with great floods in the ancient narratives.





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IARCS/016

On the Rivers in the Euro-Atlantic Sky

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In the present work, we use long term reanalysis datasets over the north Atlantic Ocean to test widely used methods and parameters study the Atmospheric Rivers (AR) over Euro-Atlantic sky. The atmospheric parameters like winds, temperature and specific humidity at different pressure levels from 20CRv2, NCEP-NCARv2, NCEP-CFSR, MERRA-2, ERA-Interim, and ERA5 during 1979 to 2018 were to study the spatio-temporal variability of water vapor transport integrated between 1000-300 hPa (IVT300) as a proxy to ARs. The standard deviation (200 kg m^{-1} s^{-1}) of ARs is around 60 percent of the climatology (>300 kg m^{-1} s^{-1}) in all reanalysis datasets in the north Atlantic. High frequency AR occurrence over western Europe in winter half year (WHY) has 6% lower intensity compared to the low frequency of ARs in summer half year (SHY) with 3% higher intensity than annual mean. While all the reanalysis data sets show similar spatial patterns, bias in mapping ARs using different reanalysis products is around 40-60 kg m^{-1} s^{-1} compared to ERA5. The intensity of ARs in the north Atlantic has been increasing in the recent times with large decadal variability and poleward shift in landfalling of intense events. The magnitude of atmospheric parameters in the lower atmosphere below 750 hPa dominates the total column water vapour and intensity of ARs. Synoptic weather conditions studied using 500 hPa geopotential and mean sea level pressure anomalies show significant impact of the North Atlantic Oscillation and Scandinavian blocking on the location of landfalling of the ARs along the western Europe. Surface latent heat flux anomalies shows the latitudinal dependence of source of moisture flux in the open ocean contributing to formation and enhancing ARs strength. This work also highlights the need to use high resolution and accurate atmospheric parameters at least up to 500 hPa to minimize the bias in detecting and tracking the ARs in the north Atlantic Ocean.

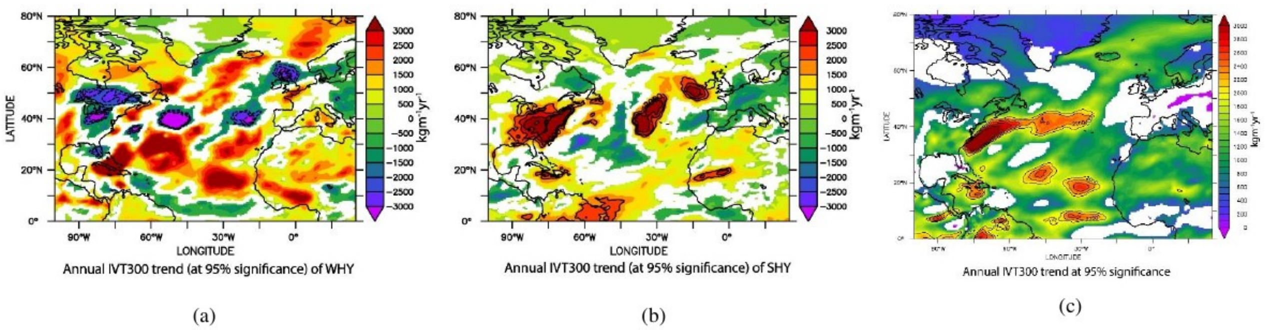

Figure: Spatial trend analysis (at 95% significance) of daily IVT300 during (a) winter half year (WHY) (b) summer half year (SHY) and (c) Annual.

IARCS/019

Atmospheric river statistics for Southeast Alaska comparing point based CFSR IVT values to station precipitation data

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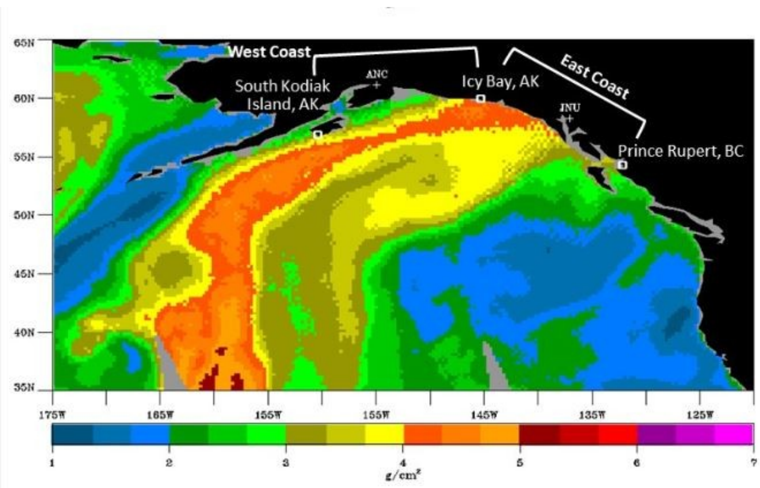
The biggest and most damaging floods in Alaska, outside of the ice jamming processes during breakup season, can usually be tied to a single causative event, atmospheric rivers (ARs) in the extratropical atmosphere. ARs can develop over the North Pacific anytime of the year and when they happen in the winter months they can impact communities with significant amounts of snow, heavy rain on snow to cause flooding, or bad freezing rain events. Also AR events in Alaska can contribute to large debris flows that impact infrastructures, block roadways and result in casualties.

This research study primarily looked at AR events over southeast Alaska from Icy Bay in the northern Gulf of Alaska to Prince Rupert British Columbia, Canada (see map). Events were defined as having an integrated water vapor transport (IVT) value greater than 250 kg m^{-1} s^{-1} from the climate forecast system reanalysis (CFSR) within the region of focus. This list of AR dates from the CFSR at 00z and 12z for the period of record from 1981-2017 were matched up with precipitation data from eight automated surface observing systems (ASOS) and 21 cooperative observer program (COOP) stations. Strength of AR events in southeast Alaska were based on IVT values, duration of each event, optimal transport direction, and precipitation amounts. Monthly-standardized IVT anomalies, wind roses with respect to transport direction and IVT values, and scattered plots with respect to precipitation, IVT values and duration of events were calculated for each site. Radiosonde observations (RAOB) of IVT and transport direction were collected to gain confidence in the CFSR data from the two RAOB stations in the study area, Yakutat and Annette.

This study analyzed IVT values, transport direction and precipitation that could cause flooding and debris flows events in greater depth than previous studies. Preliminary results show transport directions from the south and southwest are favored for this region. A combination of longer duration events with transport directions out of the south and southwest generally indicate higher precipitation events also. Future work will combine these findings with data from river gauges associated with high impact flooding events and from a debris flows database to create a five category classification system for ARs in southeast Alaska. Similarly to a study published in BAMS February 2019 for the west coast of the US, "A Scale To Characterize The Strength And Impacts Of Atmospheric Rivers". This study will also aid National Weather Service forecasters in predicting heavy precipitation and impactful flood events associated with ARs in southeast Alaska by providing a backbone to develop tools for improving situational awareness.



IARCS/020

Atmospheric rivers and precipitation in the Middle East and North Africa (MENA)

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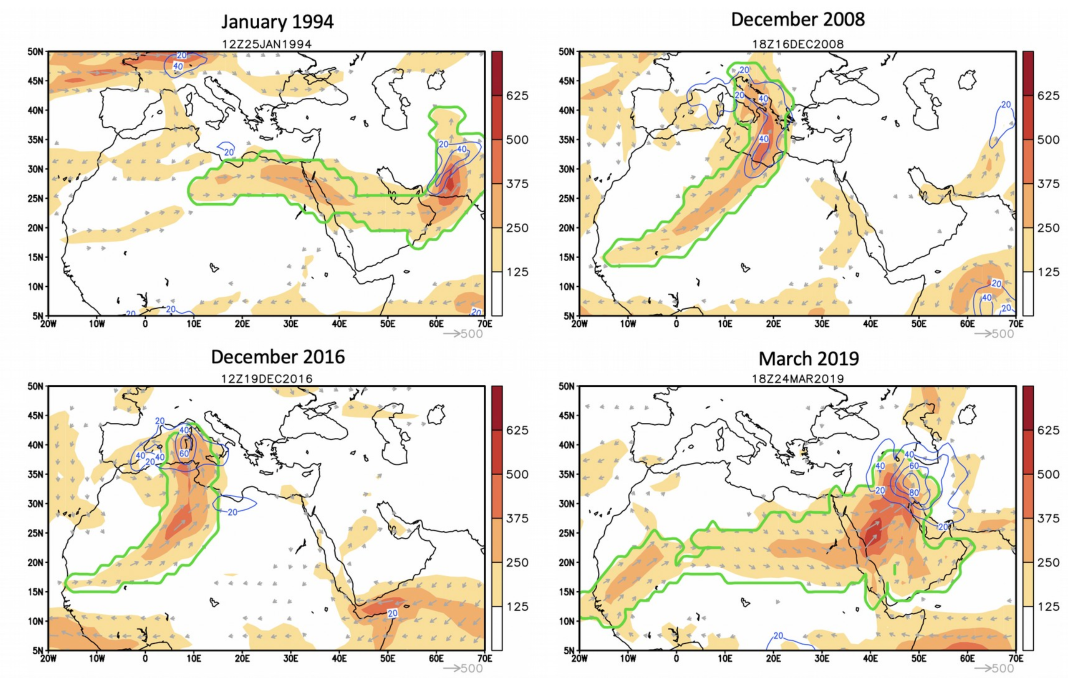
This study investigates historical climatology and future projected change of atmospheric rivers (ARs) and precipitation for the Middle East and North Africa (MENA) region, using a suite of models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) historical and RCP85. Despite its arid-to-semi-arid climate, parts of the MENA region experience strong ARs, which contribute a large fraction of the annual precipitation in mountainous areas of Turkey and Iran. This study shows that by the end of this century, for the North Africa and Mediterranean areas, including Turkey and Iran, AR frequency is projected to increase (~20-40%), however, mean precipitation is projected to decrease (~15-30%). For the rest of the Middle East, including the Arabian Peninsula and Egypt, no significant changes in AR frequency (+/- 10%) are expected, yet total precipitation is projected to increase (~50%). Lastly, the expected sign of change in AR frequency shows to be opposite to the expected sign of change of total precipitation for most areas within the MENA region.



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IARCS/032

Atmospheric Rivers in Association with Boreal-summer Heavy Rainfall over Yangtze Plain of China

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Atmospheric Rivers (ARs), referring to long and narrow bands of enhanced water vapor in the low atmosphere, act as carriers of moisture transport from the tropics for the mid-latitudes. It often support heavy rainfall generations outside the tropics and therefore have great social and economical significances. However, in East Asia, there is a lack of AR studies and it is still unclear how ARs act on different time scales during boreal summer when frequent heavy precipitation events take place over the region. In this study, climatological ARs and evolution of ARs on both synoptical and sub-seasonal time scale connecting with heavy rainfall events over the Yangtze Plain are investigated by using statistical analysis and evaluation of its predictability by examining hindcast skills from an operational coupled seasonal forecast modelACCESS-S1.Results show that ARs associated with the South Asian monsoon and Somali cross-equatorial flow provide background for the boreal summer rainfall in East Asia. There is a climatological East Asian AR related with seasonal cycle and climatological intra-seasonal oscillation (CISO) of rainfall in the Yangtze Plain during East Asian Meiyu season. The East Asian AR is influenced by anomalous anti-cyclonic moisture transport circulation over the west Pacific to the South China Sea when heavy rainfall events occur over the Yangtze Plain. Different with heavy orographic precipitation, ARs leading to heavy rainfall over the Yangtze Plain are connected with intrusions of cold air from the north. The major source of ARs responsible for heavy precipitation events over the Yangtze Plain appears to originate from the West Pacific on both synoptic and sub-seasonal time scales. The sub-seasonal forecasts of rainfall and its ARs from the ACCESS-S1 model are skillful during summer up to 2-month lead times. Due to its skilful performance for forecasting large IVT associated with extremely heavy rainfall brought by ARs from tropics, the ACCESS-S1 also shows relatively good skill in forecasting extremely heavy precipitation over the Yangtze Plain with 15-45 days leading time, which provides potentials for sub-seasonal forecast of both ARs and heavy precipitation over the Yangtze Plain.

Key words
Atmospheric rivers; heavy rainfall; sub-seasonal forecasts; Yangtze Plain; predictability; intra-seasonal oscillation

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IARCS/033

The role of atmospheric rivers for the Atacama Desert

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In hyper-arid regions, such as the Atacama Desert in northern Chile, very rarely occurring precipitation events can leave long lasting geomorphological traces and have a strong impact on biota. While precipitation events can trigger the spectacular "blooming desert" (Chávez et al., 2019) and germination of many species (Pliscoff et al., 2017), they pose a threat to surface soil microbial species which are exquisitely adapted to persistent hyper-aridity (Azua-Bustos et al., 2018). For instance, various microbial species vanished in a lagoon within the hyper-arid core of the desert (near Yungay) which ponded after a heavy precipitation event on 07 June 2017 (Azua-Bustos et al., 2018). This event was related to an atmospheric river (AR) which made landfall at the coast of the Atacama Desert. Enhanced integrated water vapor transport (IVT) associated with an upper level trough fueled the Atacama Desert with moisture from the northwest (Figure 1). This case illustrates the impact of ARs on this unique ecosystem.

Within the German Science Foundation funded Collaborative Research Center "Earth -- Evolution at the dry limit" our overarching goal is to understand the moisture supply to the Atacama Desert and its variability driven by synoptic and large scale patterns. Here, we investigate the impact of ARs under the following guiding hypothesis:

i) A substantial amount of winter precipitation within the Atacama Desert is due to atmospheric rivers.

ii) The main origin of the AR related moisture is the Amazon Basin.

iii) AR related moisture transport and precipitation formation mostly takes place in mid- and upper tropospheric layers and is decoupled from the maritime boundary layer (elevated ARs).

For our study, we use the AR catalog by Bin Guan (https://ucla.box.com/ARcatalog); Guan and Waliser, 2015 and Guan et al., 2018). AR related precipitation is analyzed using a long-term simulation with the regional climate model WRF, which suitably represents precipitation according to a validation against station measurements (Reyers et al., 2020, in press). To determine origin and pathways of the AR related moisture, we calculate backward trajectories and quantify the IVT at different height levels based on reanalysis data. In a case study, we investigate the interplay between ARs and the maritime boundary layer near the coast of the Atacama Desert based on vertical cross sections from the WRF-model output and radio soundings. The aim is to distinguish precipitation related to the elevated ARs and precipitation which results from drizzling maritime stratus.

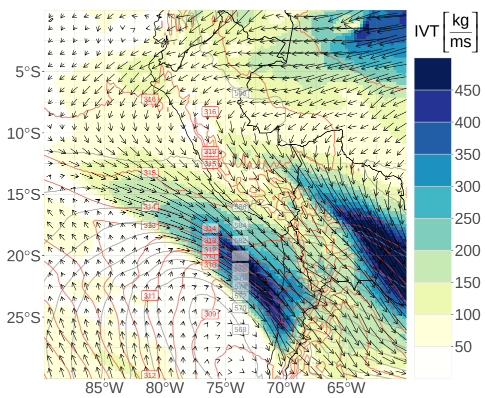

Figure 1

Integrated water vapor transport (IVT), here between 850 hPa and 200 hPa (arrows and shading) and geopotential at 500 hPa (gray contours; in gpdam) and 700 hPa (red contours; in gpdam) derived from the ECMWF 5th generation reanalysis (ERA5) for 07 June 2017 at 6 UTC. The Atacama Desert is located on the land area roughly between 18°S and 30°S and 71°W and 68°W. Red circles mark coastal cities Arica, Iquique, Antofagasta (radio sounding station), and Taltal from North to South at the Pacific edge of the Atacama Desert.

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IARCS/057

Structure of an Atmospheric River over Australia and the Southern Ocean. Part I: Tropical and Mid-Latitude Water Vapor Fluxes

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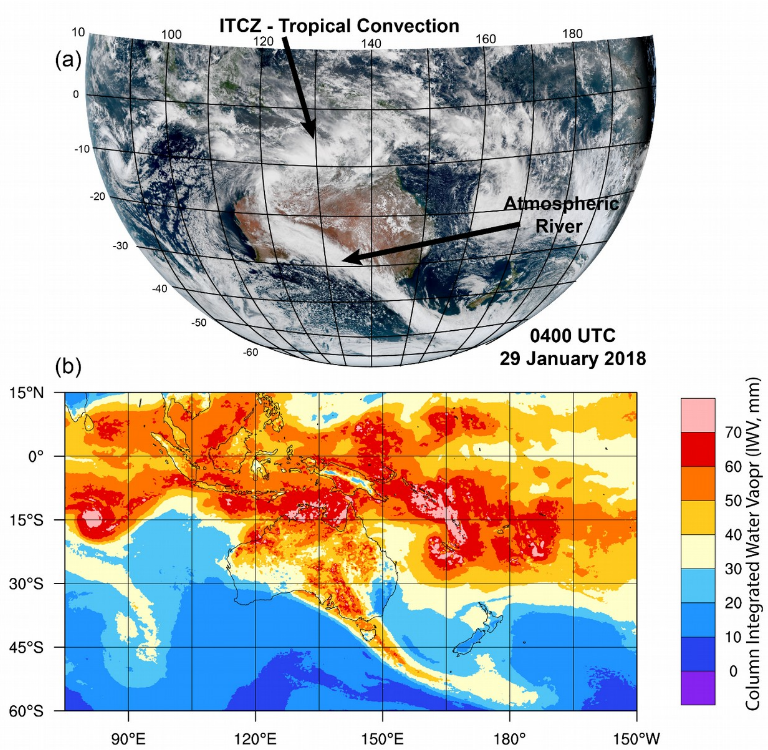
An atmospheric river (AR) impacting Australia-Tasmania and the Southern Ocean during the Austral summer on 28-29 January 2018 during the SOCRATES campaign is analyzed using a modeling and observational approach. Gulfstream-V dropsonde measurements and GPM radar analyses were used in conjunction with Weather Research and Forecasting model simulations with water vapor tracers to investigate the relative contributions of tropical and mid-latitude moisture sources to the AR. Moisture associated with a monsoonal tropical depression became entrained into a mid-latitude frontal system that extended to 60°S, reaching the associated low-pressure system 850 km off the coast of Antarctica – effectively connecting the tropics and the polar region. Tropical moisture contributed to about 50% of the precipitable water within the AR as the flow moved over the Southern Ocean near Tasmania. The tropical contribution to precipitation decreased with latitude, from > 70% over Australia, to ~50% off the Australian coast, to less than 5% poleward of 55°S. The integrated vapor transport (IVT) through the core of the AR reached above 500 kg $m^{-1} s^{-1}$ during 1200 UTC 28 January to 0600 UTC 29 January 29, 1.29 times the average amount of water carried by the world's largest terrestrial river, the Amazon. The high IVT strength might be attributed to the higher water vapor content associated with the warmer temperatures across Australia and the Southern Ocean in Austral summer.



(a) Visible satellite image of the Southern Hemisphere from the Himawari 8 Satellite showing the cloud field associated with the atmospheric river and tropical convection along the Intertropical Convergence Zone (ITCZ) at 0400 UTC 29 January 2018; **(b)** Satellite imagery of total column water vapor (IWV) at the same time as the visible satellite image. (data from http://tropic.ssec.wisc.edu/real-time/mtpw2/)

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IARCS/058

Structure of an Atmospheric River over Australia and the Southern Ocean. Part II: Microphysical Evolution

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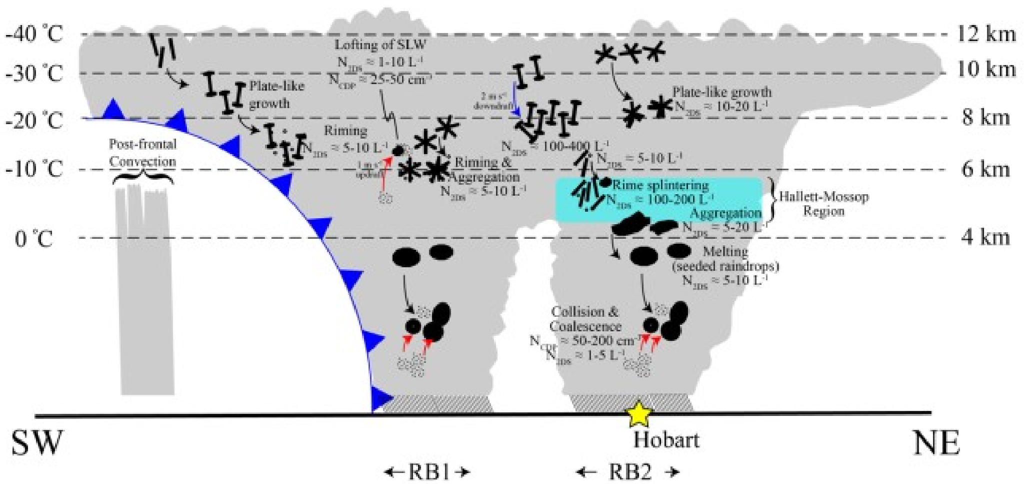
An atmospheric river affecting Australia and the Southern Ocean on 28–29 January 2018 during the Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study (SOCRATES) is analyzed using nadir-pointing W-band cloud radar measurements and in-situ microphysical measurements from a Gulfstream-V aircraft. The AR had a two-band structure, with the westernmost band associated with a cold frontal boundary. The bands were primarily stratiform with distinct radar bright banding. The microphysical evolution of precipitation is described in the context of the tropical- and mid-latitude-sourced moisture zones above and below the 0°C isotherm, respectively, identified in Part I. In the tropical-sourced moisture zone, ice particles at temperatures less than -8°C had concentrations on the order of 10 L^{-1}, with habits characteristic of lower temperatures, while between -8°C and -4°C, an order of magnitude increase in ice particle concentrations was observed, with columnar habits consistent with Hallett-Mossop secondary ice formation. Ice particles falling though the 0°C level into the mid-latitude-sourced moisture region and melting provided “seed” droplets from which subsequent growth by collision-coalescence occurred. In this region, raindrops grew to sizes of 3 mm, and precipitation rates averaged 16 mm hr^{-1}.



Schematic depicting the precipitation structure and processes observed within the AR. Number concentrations broadly represent values observed at the temperature indicated. Arrows denote the general transport of particles within the clouds.

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IARCS/060

Winter and Spring Atmospheric Rivers in High Mountain Asia: Climatology, Dynamics and Variability

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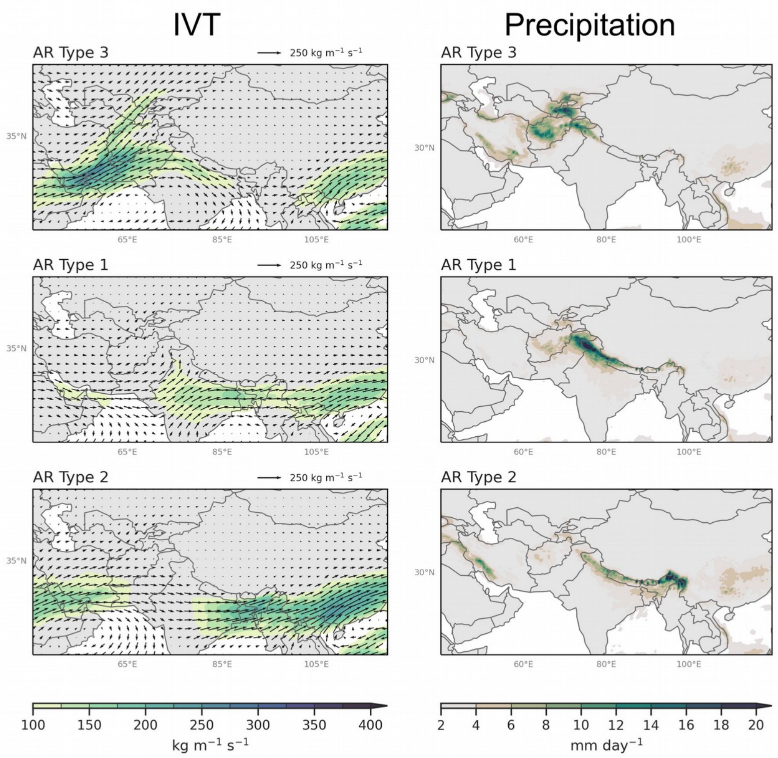
Atmospheric Rivers (ARs) occur on average 30 days a year in High Mountain Asia (HMA), and have been shown to be associated with precipitation extremes and flooding in Nepal and the Bay of Bengal. The goal of this research is to explain the dynamical mechanisms associated with the development of HMA ARs in an effort to determine the hydrological impacts in a region critical to water resources for hundreds of millions of people. Principal component analysis is applied to HMA AR days using 500 hPa geopotential height and winds across the region 0° N to 50° N and 20° W to 110° W. Cluster analysis defined by the first two principal components uncovered three subtypes of AR events with distinct synoptic characteristics for winter (DJF) and spring (MAM) seasons. Composite analysis shows that one DJF HMA AR subtype results in enhanced southwesterly integrated vapor transport (IVT) and precipitation in the Karakorum that is associated with a deep trough in 250 hPa heights and anomalous anticyclonic circulation over northwest India. The other two DJF HMA AR subtypes resulted in enhanced precipitation and IVT in central and eastern Himalayas related to eastward propagating synoptic storms. Composite analysis of MAM HMA AR subtypes show anomalous precipitation, particularly east of Bangladesh and strong southwesterly IVT across the Bay of Bengal and the South China Sea, but these events are associated with weaker troughs and ridges compared to DJF HMA ARs. This research also investigates interannual and multidecadal variations in HMA ARs and examines their relationship with El Niño Southern Oscillation and Pacific Decadal Oscillation. Finally, this research identifies changes in intensity and frequency in HMA ARs and their associated vertically integrated moisture transport in recent decades.



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IARCS/065

Atmospheric Rivers over South Asia: Climatology, Associated Precipitation, and Modulation by Climate Variability Modes

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Atmospheric rivers (ARs), long and narrow jets of enhanced water vapor transport in the lower troposphere, are influential for regional extreme precipitation. Although the significant hydrologic and agricultural impacts of ARs in South Asia are starting to generate scientific interest, tropical/subtropical ARs in general have been considerably understudied relative to their midlatitude counterpart. This study is motivated by the evaluative opportunities presented by the dearth of analyses on AR-driven rainfall in the low latitudes, especially in the densely populated South Asian region, and its modulation by the modes of intraseasonal and interannual climate variability. AR events are objectively demarcated here by applying a detection algorithm to the integrated water vapor transport fields obtained from the Modern-Era Retrospective Analysis for Research and Applications, version 2 reanalysis. Annual and seasonal distribution of the objectively detected ARs reveals prominent regional variability. Climatological AR frequency is highest in summer along the western coasts of India and Myanmar, reflecting moisture transport from the tropical Indian Ocean, and in winter over Madagascar and the Arabian Peninsula. Precipitation attributed to AR events is shown to be a substantial proportion of the annual total precipitation in the Arabian Peninsula and during non-monsoon months over India. The influence of the El Niño Southern Oscillation and the Madden-Julian Oscillation on ARs is examined. The impact on AR frequency is shown to vary depending on the phase of ENSO episode, leading to an enhancement during El Niño summers in the northern Bay of Bengal and weakening during La Niña summers over parts of Indochina and the South China Sea. In summer, MJO is associated with propagation of negative AR frequency anomalies during phases 1-3 from the Arabian Sea to southeast Asia followed by propagation of strong positive anomalies with a twofold frequency amplification during phases 4-7 over this region. This analysis of AR impacts, and especially their seasonal and regional variation, presents new avenues to explore hydrometeorological extremes in the Indian subcontinent.

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IARCS/077

The role of Atmospheric Rivers in the wintertime precipitation anomalies in central-south Chile during El Niño and La Niña events

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This work goes deeper into the study of the interannual relationship between moisture transport and winter precipitation in south-central Chile as a continuation of the work presented at IARC-2018 (Campos and Rondanelli, IARC-2018).

Using monthly data from ERA-Interim reanalysis, daily precipitation from meteorological stations in south-central Chile, daily radiosondes profiles and daily data from the Atmospheric Rivers (ARs) catalog from Guan and Waliser (2015), it was found that during El Niño winters there is an increase in moisture transport from the equatorial Pacific to the coast of South America at mid-latitudes throughout the entire atmospheric column associated with an increase in the precipitable water content. In the South Pacific, this increase in moisture transport is mainly related to an increase in the intensity of the wind (subtropical jet), while near the coast of South America with an increase in the moisture content in the column. This increase in moisture content and transport favors a greater frequency of atmospheric rivers reaching the south-central zone of Chile. During La Niña winters the opposite situation occurs.

The physical mechanism associated with the transport and moisture content anomalies is related to the propagation of an anomalous quasi-stationary barotropic Rossby wave that develops a subtropical low pressure and a blocking high pressure at high latitudes. In the northern part of the anomalous subtropical low, the greatest positive anomalies of moisture flow and ARs frequency were observed which would be associated with two main factors: (1) anomalous frequency of disturbances in the middle troposphere related with a diffluence of the flow and the storm-track produced by the presence of the blocking high and (2) a south-east displacement of the South Pacific Convergence Zona (SPCZ). These features are shown in figure 1.

As a consequence of these large-scale anomalies, ARs that make landfall south-central Chile during El Niño winters are more intense in moisture transport and moisture content than those that arrive in neutral or La Niña winters. In consequence, the El Niño-ARs cause more intense rates of daily precipitation which on the seasonal scale translates into a positive anomaly in precipitation.

In summary, on El Niño winters, the same number of landfalls of ARs in south-central Chile will leave higher amounts of precipitation causing winter, in general, to be rainier compared to winters without the presence of El Niño.

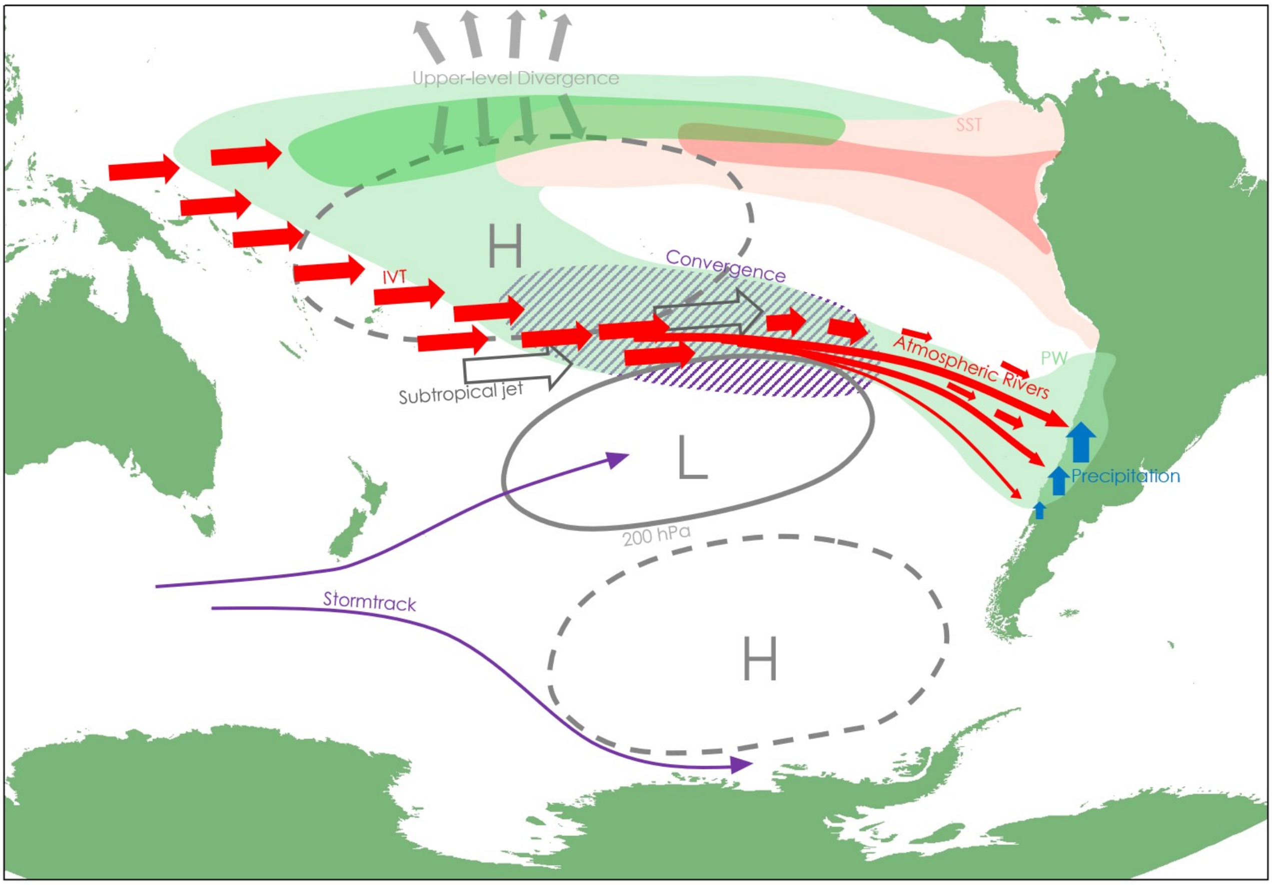

Figure 1 Conceptual scheme of the main anomalies observed during El Niño years associated with moisture transport and precipitation in south-central Chile.

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IARCS/079

Atmospheric Rivers on the East coast of South America

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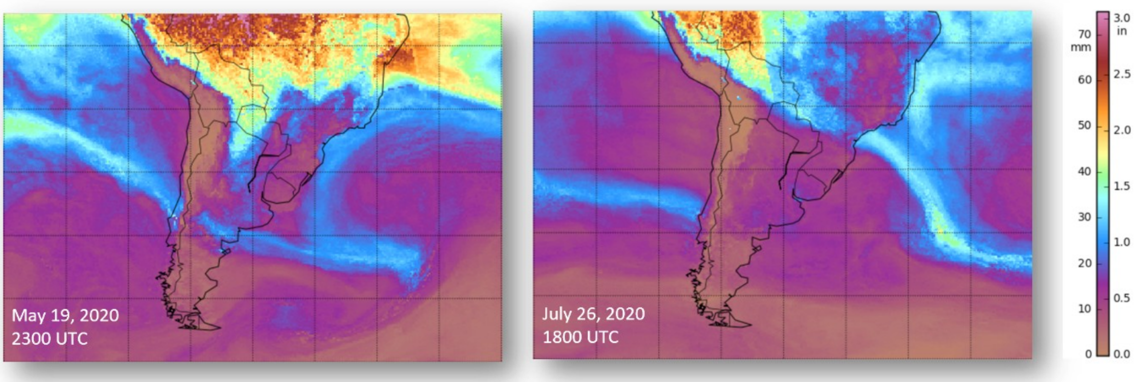
Most of the research in Atmospheric Rivers (AR) in South America has focused on ARs coming from the Pacific Ocean and landfalling along the west coast of the continent, where they deliver substantial precipitation (rain and snow) over the western slope of the Andes. Nonetheless, ARs extending from the east coast into the South Atlantic Ocean are also a common feature all year round. In this work we provide the first systematic survey of such east coast ARs based on a regional AR identification algorithm that use Integrated Vapor Transport from CFSR reanalysis data and trajectory analyses to identify the moisture source feeding these ARs. Our preliminary results reveal two main patterns.

The first pattern, termed as a Trans-Andean Atmospheric River, occurs when all the moisture comes from the Pacific Ocean (e.g., Fig. 1, May 19, 2020). Despite of the marked drying that occur as the air masses cross the mountain, some moisture filament can cross the Andes to continue downstream into the Argentinean lowlands and then into the Atlantic ocean. Most Trans-Andean ARs occurs over the austral Andes (40°-50°S) where the average mountain height is 1000-1500 m ASL. Although the moisture transport is relatively low over eastern Patagonia, Trans-Andean AR may have a significant impact on regional precipitation. Only a fraction of Pacific ARs landfalling in western Patagonia become a Trans-Andean AR and we are currently investigating the synoptic conditions that foster these crossing, but they seems connected with a midlatitudes depression that rapidly moves over the southern tip of the continent and often deepens over the South Atlantic.

The second pattern correspond to an AR leaving the east coast without a counterpart in the Pacific. These cases are more prevalent to the north of 35°S in winter (e.g., Fig. 1, July 26, 2020) or even farther south in summer. Moisture is originated in the interior of the continent or the tropical Atlantic, transported poleward by the low-level jet east of the Andes and the subtropical anticyclonic circulation, and subsequently entrained into a mid-latitude frontal circulation over the Atlantic Ocean. This reorganization process of moisture convergence effectively connects tropical moisture sourced in the Amazon/Atlantic basin to mid-latitudes regions, which looks like refilled ARs in the snapshot satellite images of precipitable water starting from the subtropical east coast to the adjacent Atlantic Ocean.

In between these two patterns we found many cases in which an AR over the east coast of South America is feed by moisture coming from both the Pacific and the interior of the continent, with varying contributions as the associated mid-latitude frontal systems displace equatorward.



IARCS/092

Deployment of Additional Surface Pressure Measurements over the Northeast Pacific to Support Atmospheric River Forecasts on the US West Coast

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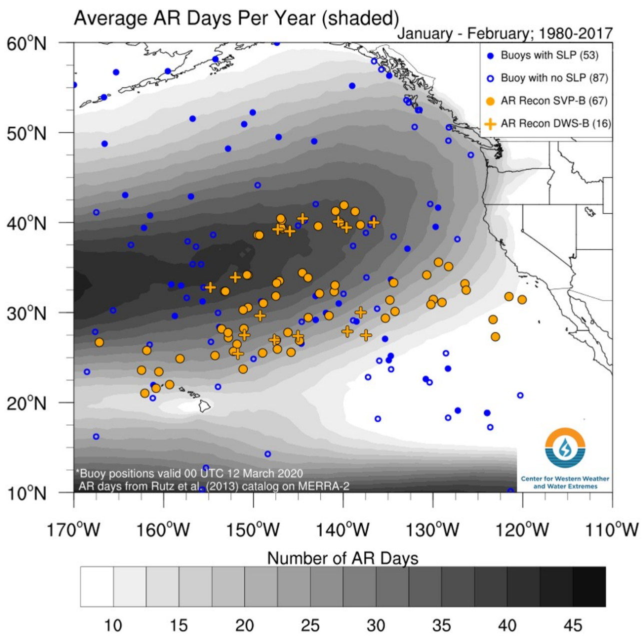
Atmosphere River Reconnaissance (AR Recon) is an interagency, international collaborative research and operations partnership, including global operational weather prediction centers such as the U.S. National Centers for Environmental Prediction, U.S. Navy, and the European Centre for Medium-Range Weather Forecasts. AR Recon collects 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. These observations, including drifters at the ocean surface and dropsondes released from aircraft, are now officially called for in the U.S. National Winter Season Operations Plan released by the Office of the Federal Coordinator for Meteorology. Since 2019, the group has 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. In 2019, 32 Surface Velocity Program-Barometer drifters were deployed via US Air Force Reserves aircraft. In 2020, 48 SVP-B drifters were deployed and 16 Directional Wave Spectra-Barometer (DWS-B) drifters were deployed, via a combination of ships of opportunity and aircraft. This presentation will provide an overview of the deployment strategy and some preliminary results addressing the novel wave measurements from the DWS-B drifters and the additional pressure measurements from all drifters.



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IARCS/101

Atmospheric rivers in the Arctic: case studies during a field campaign near Svalbard

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The Arctic region shows high sensitivity to global warming (known as "Arctic Amplification") with significant implications for both regional and global climate. Recently, significant increase in the atmospheric moisture content has been documented over this region, which is partially explained by the reduction of sea-ice cover, enhancing the local evaporation. Others argue that the predominant reason is the recent enhanced poleward moisture flux, which is expected to continuously increase in the future. This might be due to several factors or a combination of them, such as changes in the atmospheric circulation patterns, increased moisture transport intensity, and/or higher evaporation rates in the lower-latitude moisture source regions. Our study focuses on the anomalous moisture transport events confined to long, narrow and transient corridors, known as atmospheric rivers, which are expected to have a strong influence on Arctic mass and energy budget.

Here we focus on three case studies – 30 May, 6 June and 9 June 2017 – with anomalous moisture transport identified as atmospheric rivers reaching Ny-Ålesund, during the ACLOUD campaign (Arctic Cloud Observations Using airborne measurements during polar Day) that took place in Svalbard during 22 May to 28 June 2017. We explore the temporal and spatial evolution of the atmospheric rivers by means of two tracking algorithms [regional – Gorodetskaya et al. (2014, 2020), adapted to the Arctic – and global – Guan et al. (2018)] and multireanalysis products – ECMWF's ERA-Interim and ERA5, NASA's MERRA-2, JMA's JRA-55, and NCEP's CFSR – in synergy with regional climate model simulations – HIRHAM5. To assess their performance, we analysed the measurements from the AWIPEV research station in Ny-Ålesund, including ground-based remote sensing measurements from Humidity and Temperature Profiler (HATPRO), GPS, and vertical profiles of the atmosphere by radiosondes. Point ground-based observations are combined with spatial fields from satellite products. The dynamics of the atmospheric rivers and the associated precipitation patterns, including changes in the phase of precipitation (rain/snow) and the resulting impacts, are assessed using both multireanalysis products and HIRHAM5 model simulations.

Building on the detailed case studies analysis, this work is now being extended to longer time periods from the recent past (using reanalyses) and into the future using global climate models from CMIP6.

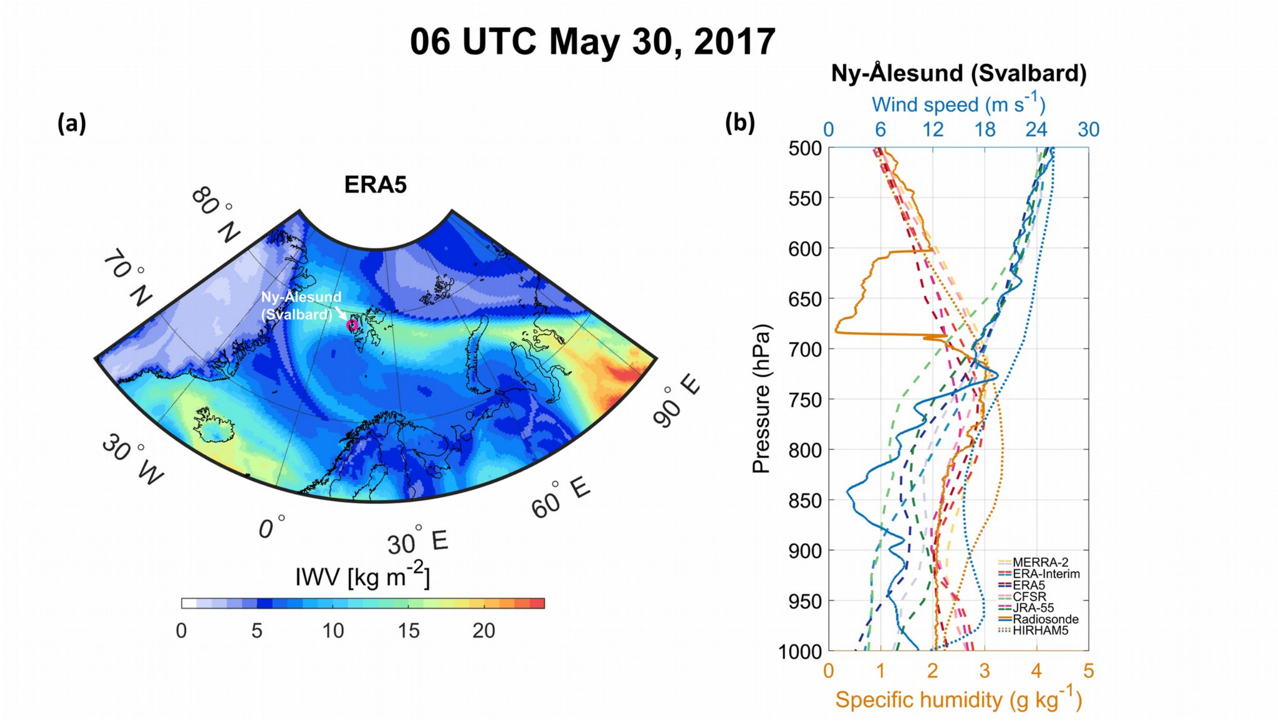

Figure. (a) Maps of the integrated water vapour (IWV, kg m^{-2}) for the 06 UTC May 30, 2017 based on ERA5. Magenta dot shows Ny-Ålesund location. **(b)** Vertical profiles of specific humidity (g kg^{-1}, warm colours) and wind speed (m s^{-1}, cold colours) at Ny-Ålesund based on radiosonde (solid lines), reanalysis (ERA-Interim, ERA5, CFSR, JRA-55, MERRA-2, dashed lines) and HIRHAM5 model (dotted lines), during 06 UTC May 30, 2017.

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IARCS/103

From Pacific Ocean to South America and to Antarctic Peninsula: a short story of several long atmospheric rivers with important impacts

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Atmospheric rivers (ARs) play an important role in the Antarctic ice sheet surface mass balance as they transport large amounts of both heat and moisture from subtropical and mid-latitude regions. In coastal East Antarctica ARs are known for prominent signatures in moisture and wind profiles (Gorodetskaya et al, 2020) and for their role in intense precipitation (Gorodetskaya et al 2014). At the same time in West Antarctica, ARs have been more studied in relationship to the air temperature records (Bozkurt et al., 2018) and major surface melt events (Wille et al 2019). Antarctic Peninsula has shown a much stronger recent warming compared to the rest of the ice sheet and other land areas in the Southern Hemisphere with continued warming and increased number of days above 0°C predicted under future scenarios (Siegert et al, 2019). Moreover, recent occurrence of temperature records at the Peninsula (observed in March 2015 and February 2020) is alarming. In this study, we explore the ARs double role, as carriers of both heat and moisture, in their impacts on both precipitation and air temperature at the Antarctic Peninsula, specifically paying attention to the transition between snowfall and rainfall and cloud radiative forcing. Observations from three Year of Polar Prediction (YOPP) endorsed sites/projects are used - two sites on King George Island (north of the Antarctic Peninsula), namely Escudero (project CAALC - the Characterization of the Antarctic Atmosphere and Low Clouds) and King Sejong station, as well as Punta Arenas (southern Chile) site with project DACAPO-PESO (Dynamics, Aerosol, Cloud, And Precipitation Observations in the Pristine Environment of the Southern OCEAN). These projects employed a set of ground-based remote sensing instrumentation for water vapor, cloud and precipitation observations, as well as frequent radiosonde launches during the YOPP Special Observing Period in austral summer 2018/2019. We present case studies characterizing the temporal evolution of ARs, focusing on thermodynamic and dynamic conditions accompanying the transition between snowfall and rain. We also show the added value of increased frequency in radiosonde observations in improving the forecast of weather conditions during ARs, including precipitation, which have important consequences for air, ship and station operations in Antarctica.

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IARCS/121

Atmospheric rivers dominate extreme precipitation over Antarctica

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Atmospheric rivers (ARs) impacting Antarctica travel southward from the midlatitudes, carrying long, narrow bands of warm and moist air. They contribute up to 20% of the total precipitation over the Antarctic Ice Sheet per year, and account for the highest precipitation rates (24 mm w.e. per hour and above) in MERRA-2 reanalysis (1980-2016). Here, we examine a major AR event over Thwaites Glacier in West Antarctica that occurred in February 2020. By combining in-situ snow height observations on Thwaites ice shelf, and MERRA-2 and ERA5 reanalyses over Thwaites Glacier, we identify the atmospheric patterns associated with the AR event and its impacts on snow accumulation. We then compare the spatial signature of this event with regional AR flavors (defined by precipitation type and intensity, wind speed, and temperature) along the Amundsen Sea coastline to develop a comprehensive picture of AR-driven extreme precipitation in West Antarctica. Finally, we examine the relationship between the temporal and spatial patterns of AR events and large-scale modes of atmospheric variability to recognize how these extreme events and their consequent impacts on accumulation and surface melt will influence future Thwaites Glacier mass balance.

Session 7

Emergent Topics

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IARCS/004
A Tool for Forecasting Areas of Cyclogenesis Tendency out to 30 Days

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Fox Weather, LLC provides a weather forecasting service for clients desiring extended planning guidance in the 10-30 day period. Our purpose was to create more consistent and stable extended forecast guidance or second opinion for the Day10 to Day30 period. The aim was to improve our methodology of using a quantity derived from Sea Surface Temperature Anomaly (SSTA) to diagnose cyclogenesis potential in the eastern North Pacific and far western United States. To predict cyclogenesis potential, we needed to map the longer term, underlying latent and sensible heat environment that provides inputs to extratropical cyclones that move across our region of interest.

We developed, tested and implemented a methodology consisting of a supervised machine learning algorithm, random decision forest [1]. Our goal was to obtain better predictive performance for moisture transport, than available from GFS or other NWP driven forecasts in our extended period of interest. The result is twofold: a) Fox Weather's CyclogenIVT™ [2] outputs, and b) an improved methodology for analyzing areas of cyclogenesis tendency, and assembling analysis rules. CyclogenIVT™ uses an indexed-integrated vapor transport value with basic moisture and wind characteristics, expressed as IVTinit. The guidance product is a map of IVTinit across the central and eastern North Pacific to the United States and Mexico west coasts.

CyclogenIVT™ uses daily sea surface temperature (SSTA) to predict IVTinit as an index for cyclogenesis potential. Model results are achieved by training a Random Forest algorithm using daily Sea Surface Temperature Anomaly data. The historical SSTA data was from NOAA/NESDIS. The IVT databases were included in the MERRA-2, provided by Brian Kawzenuk, Center for Western Weather and Water Extremes (CW3E). We focused on an active period for extratropical cyclones in December 2014.

CyclogenIVT's output is IVTinit™. IVTinit™ differs from IVT and TIVT, because it addresses a longer time interval into the future. Conceptually, IVTinit is different from CW3E's IVT. Instead of NWP forecast inputs, IVTinit's principal argument is SSTA. Durations of IVTinit™ patterns are one to three weeks, depending on persistence of the SSTA field. Comparable durations for IVT features are one to three days.

In the initial phase, we produced daily IVTinit™ analysis maps. We sampled a variety of systems, including wave cyclones, atmospheric-rivers, and upper lows. For this project, the IVTinit™ analysis period comprised December 15, 2019 to June 30, 2020. Midlatitude waves, wave cyclones, and fronts propagated across the IVTinit features, and underwent local intensity changes across a sub-regional spatial scale. We found good agreement with CW3E tau0 to tau24 time-integrated vapor transport (TIVT) maps. They provided good validation for developing our forecast rules. Methods of analysis will be discussed in the presentation and conference paper.

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IARCS/015

Atmospheric Aerosol Rivers: Climate and Air Quality Impacts

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This presentation introduces the application of the "atmospheric river" (AR) concept to aerosols as a new/alternative approach for understanding and quantifying aerosol transport extremes, hereafter "Atmospheric Aerosol Rivers" (AARs). With the motivations associated with the study of (water vapor) ARs in mind, namely their importance in helping shape Earth's climate and accounting for an important segment of extreme weather events, this work seeks to leverage the value and success of the AR perspective for understanding, predicting and communicating the impacts of these hydrometeorology extremes (e.g. Ralph et al. 2020) to the study of aerosol transport extremes. Our presentation will highlight: 1) the development of a global AAR detection algorithm based on the Guan and Waliser (2015) AR detection algorithm, 2) its application to the MERRA-2 multi-decade aerosol reanalysis (Randles et al. 2017) that separately accounts for dust, black & organic carbon, sulphate and sea salt aerosol, 3) global descriptions of the AAR climatological features, including mean frequency and transport values, significant features of AAR temporal/spatial variability, etc, 4) AAR contributions to major large-/global-scale aerosol transport pathways and radiative forcing patterns, and 5) illustration and discussion of extreme AAR events that resulted in significant impact on local air quality.

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IARCS/026

ARkStorm 2.0: Developing a new extreme atmospheric river storm scenario for 21st century California

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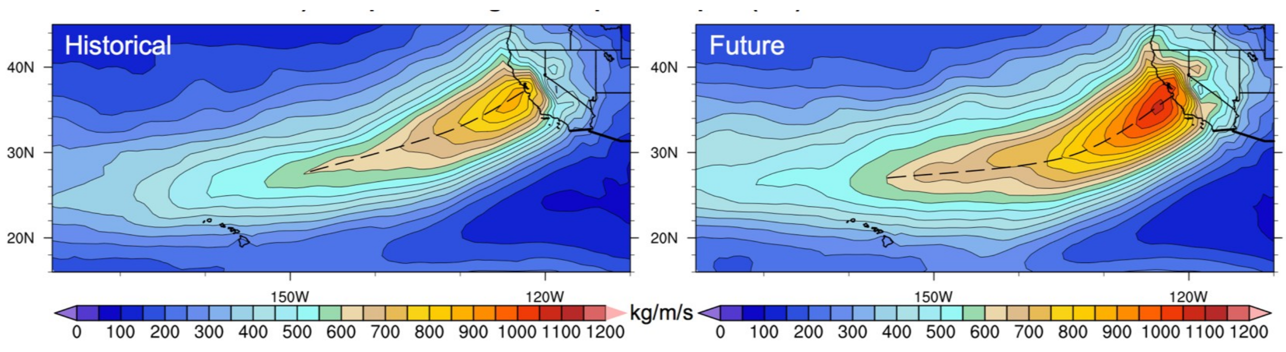
Atmospheric rivers can be a blessing or a curse, depending on the context. Responsible for 50% of California's water supply but also nearly 95% of the region's flood damages, atmospheric rivers are arguably the single most important physical phenomena defining California's hydroclimate. Recent work, however, has suggested that climate change will likely bring about even greater "precipitation whiplash" against the backdrop of an already highly variable climatology–whereby California experiences even larger swings between extreme dry and extreme wet conditions. Our recent research hones in on the shifting "extreme wet" side of the precipitation distribution by considering how the region's most extreme atmospheric river storms may change in a warming climate by combining a climate model large ensemble (CESM-LENS) with high-resolution weather model simulations (3km WRF). We find that the atmospheric rivers in California's near future are likely to become substantially stronger, wetter, and warmer than their historical counterparts–changes that may seriously challenge existing water and flood management paradigms in California.

While there has (understandably) been much recent focus on extreme drought and wildfire-related impacts in California, the region is no stranger to extreme flood risk. A historical repeat of the "Great Flood of 1862"–a weeks-long deluge that left most of the Central Valley underwater and inundated what are now densely populated urban areas in coastal southern California–would be economically devastating and likely lead to a humanitarian crisis due to long-term displacement of hundreds of thousands of Californians. Such a disaster scenario was the impetus for the original "ARkStorm" exercise, originally published in 2011, which explored the physical and societal implications of a modern recurrence. New evidence has come to light since then, however, that suggests that 1) an "1862-like" storm sequence is more likely than previously believed even in the present climate (with a recurrence interval of 150-200 years), and 2) that climate change is rapidly increasing the risk of such an event in the near future (with a cumulative risk of around 50% over the next 40 years).

Given these recent revelations, as well as considerable advancements in meteorology and climate science over the past decade, we are seeking to reimagine the ARkStorm scenario using models and methods appropriate for the 21st century. This effort is now formally underway as of August 2020, though we continue to invite support, funding, and collaboration for this multi-displinary, multi-institution effort. In this presentation, we will summarize recent climate science findings regarding atmospheric rivers in a warming climate in a California-specific context, and then discuss ARkStorm 2.0 scenario development and early results from initial modeling.



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IARCS/080

Assessment of wintertime streamflow forecast skill in an atmospheric river-influenced river basin on the lee side of the Sierra Nevada

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In the Truckee River basin, both water supply and floods are strongly linked to wintertime atmospheric rivers (AR). Expected increases in atmospheric river storm intensities, rain:snow ratios, and a transition to earlier runoff under warming climate will stress current infrastructure and reduce the effectiveness of reservoir operations that were designed for stationary climate. Forecast-informed reservoir operations (FIRO) has the potential to mitigate against these impacts; however, in its position on the lee side of the Sierra Nevada mountains (CA/NV, USA), several unique forecast uncertainties exist that could make implementation here particularly challenging despite the substantial recent improvements in forecasting these events at long lead times. For example, the timing and amount of spillover precipitation onto the lee side remains a key uncertainty. In addition, storm runoff volumes in this basin are highly sensitive to rain-snow elevation, which is also difficult to forecast. Finally, antecedent snowpack and soil conditions have the potential to modulate runoff volumes but factors controlling the strength of these modulations are incompletely understood and monitored. In this study, we assess streamflow forecast skill in the Truckee River to provide a preliminary understanding of potential forecast-related challenges and opportunities for FIRO. To accomplish this, we used an archive of available short-range Hydrologic Ensemble Forecast System winter (Oct-Apr) streamflow hindcasts for water years 2015-2020 and compared these to observed daily flows at lead times of 0 to 15 days. R^2 values between observed and forecast ensemble median daily flows show visible improvement at lead times less than 6 days for all winter days and for days on which ARs occurred, though AR days tend to have lower R2s at longer lead times. Average R2s across 12 sites at a 1-day lead time are 0.75 for all winter days and 0.68 for winter AR days and are 0.56 (all days) and 0.37 (AR days) at a 5-day lead. Average probabilities of at least one ensemble member correctly detecting the exceedance of a 90th percentile historical daily flow threshold are 74% and 58% for 1- and 5-day lead times respectively. There is a bias toward under-forecasting larger streamflow volumes, even at short lead times. The influences of antecedent conditions and AR attributes on streamflow forecast skill will also be analyzed and reported.

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IARCS/114

Towards Improved Decision Support in Snow-Dominated Watersheds During Extreme Weather

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Extreme weather, including warm, windy, wet conditions associated with atmospheric river landfalls and multi-day heat waves over snow-dominated watersheds adds a level of uncertainty for runoff forecasting and flood management. Antecedent snowpack and soil moisture conditions can increase or decrease runoff efficiency and the onset of rain or windy and humid conditions can rapidly change the snowpack in ways that are difficult for models to skillfully capture. Borrowing from similar decision support tools for multi-hazard impact-based warning services, we can leverage existing observations in novel ways and apply those with new technologies to act as early warning services for snow-dominated watersheds.

Here, we propose a Snow Runoff Readiness Advisory approach to provide information regarding the likelihood and magnitude of impactful snowmelt-derived runoff and flooding during extreme weather events. The advisory could be coupled with the recently-developed Atmospheric River Category Scale to allow forecasters, reservoir operators, and other decision-makers to better understand the potential timing and contribution of the snowpack and land surface conditions to runoff. This advisory is intended to be developed in a case-by-case manner for specific watersheds using readily accessible historic observations. This discussion explores the strengths and weaknesses of developing a novel decision support approach for informing flood forecasting and natural hazards early warning in snow-dominated regions during cool season extreme weather.

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IARCS/115

A Convolutional Neural Network for Improved Precipitation Prediction

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Systematic and random errors in dynamical model forecasts mask valuable information about precipitation patterns in extreme weather events. Machine learning based post-processing methods can be used to tackle both kinds of error. In this study, we leverage a 34-year reforecast developed by the Center for Western Weather and Water Extremes, which is based on CW3E's version of the Weather Research and Forecasting (WRF) model tailored for the prediction of extreme events over the Western U.S. (West-WRF). We use a U-Net architecture convolutional neural network (CNN) to identify and reduce errors in the 24-hour accumulated precipitation over the North American west coast. The Parameter-elevation Relationships on Independent Slopes Model (PRISM) climate dataset is used as the ground truth in the training phase and for forecast verification. The U-Net CNN training and testing phases show a consistent 15 % improvement in root mean squared error (RMSE), a 10 % improvement in mean absolute error (MAE), and a 1-3 % improvement in correlation compared to the raw West-WRF forecast. We also report improvements for severe precipitation events over California, which covers most of the spatial domain considered in this study.

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IARCS/120

Depth of Penetration of GNSS Radio Occultation Observations in Atmospheric Rivers

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Increasing the density of spaceborne radio occultation (RO) with Smallsats as well as increasing the quality and signal to noise ratio of RO with the next generation Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (COSMIC-2) is expected to improve analyses of the atmospheric state, which is crucial for accurate numerical weather forecasts. RO provides high vertical resolution observations of water vapor which could be useful in determining the depth of a moist layer and its vertical structure, for example in atmospheric rivers (ARs). These bands of enhanced low-level horizontal water vapor direct moisture from the tropics to the west coasts of continents, often resulting in heavy precipitation. The AR Reconnaissance campaigns have extensively sampled ARs over the northeastern Pacific with dropsondes in multiple intensive observation periods over several winter seasons. The in-situ observations from the dropsondes provide an invaluable dataset with which to validate RO retrievals in the lower troposphere. We use these dropsondes as well as the European reanalysis 5 (ERA5) product to evaluate the quality of operational RO data from the various RO missions that has been collected and processed by CDAAC including COSMIC-2. The ability of the various RO datasets to resolve moisture in the low-level jet, subsiding air poleward of the front, and ascending moisture in the warm sector and core of the AR is described. Quantitative comparisons are made with dropsondes that were near occultations in time and space. The full RO dataset is compared to ERA5 and the height below which the two datasets differ is identified and characteristics of these discrepancies are described. The RO observations are also evaluated with data assimilation (DA) experiments that use the DA system's quality control algorithm as an objective measure of data quality.