

Advancing South American Water and Climate Science through Multidecadal Convection-Permitting Modeling

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The South America Affinity Group (SAAG) was established in early 2019 by the National Center for Atmospheric Research (NCAR) Water Systems Program as a community effort focused on improving hydroclimate science over South America. SAAG supports large research efforts such as the ANDEX Regional Hydroclimate Program (Espinoza et al. 2020) as well as individual research groups. The group started with a dozen members and quickly grew to over 100 participants from more than 10 countries. For the past four years, the SAAG has been meeting online every two weeks and has organized sessions at international conferences such as the American Geophysical Union Fall Meeting and the Convection-Permitting Climate Workshop (Prein et al. 2022). At the core of the SAAG effort are two multidecadal convection-permitting (CP) model simulations with 4-km grid spacing for historical and future climates over the South American continent. Additionally, a major observational data collection effort has been undertaken, including in situ station data from South American meteorological and water services, gridded products, satellite-based observations, and field campaign data (NCAR 2023a). This article discusses the research needs and scientific goals that drive this community of scientists with diverse backgrounds and interests.

Motivation

South America's hydroclimate sustains vibrant communities and natural ecosystems of extraordinary biodiversity including the Andes Cordillera, and the Orinoco, La Plata, and

Amazon basins. Global warming and land-use change are endangering ecosystem health, exacerbating hydrometeorological extremes, and threatening water and food security for millions of people on the continent (Castellanos et al. 2022). Reductions in rainfall and streamflow have been observed in southern Amazonia, the Cerrado region, northeast Brazil, and Chile (Muñoz et al. 2020; Garreaud et al. 2020; Espinoza et al. 2019; Fu et al. 2013). The increased aridity has affected agricultural yield, water supply for reservoirs, hydro-power generation and impacted tens of millions of people in the large metropolitan areas of São Paulo, Rio de Janeiro, and Santiago de Chile (Nobre et al. 2016). Andean glaciers, an important source of water, have lost 30% of their area in the tropics and up to 60% in the southern Andes—the highest glacier mass loss rates in the world (Braun et al. 2019; Dussaillant et al. 2019; Reinthaler et al. 2019; Masiokas et al. 2020; Fox-Kemper et al. 2021). Conversely, southeastern South America is facing increasing annual rainfall and intensification of heavy precipitation since the early twentieth century (Doyle et al. 2012; Barros et al. 2015; Pabón-Caicedo et al. 2020; Arias et al. 2021; Gutiérrez et al. 2021; Morales-Yokobori 2021; Seneviratne et al. 2021). Extreme precipitation is projected to intensify throughout the continent (Arias et al. 2021; Seneviratne et al. 2021). This poses significant risk to people and infrastructure along the Andes and other mountainous areas, particularly for lower-income communities living in informal housing (Poveda et al. 2020; Ozturk et al. 2022).

Sustainable development in the region requires improved understanding of key hydroclimate processes and their evolution in a changing climate. There are several barriers to our understanding of, and adaptation to, climate change over South America. First, there is insufficient data coverage, as observations are sparse (Condom et al. 2020; Lagos-Zúñiga et al. 2024). This limits our physical understanding and quantification of trends, which hinders climate attribution studies. Furthermore, state-of-the-art global climate models (GCMs) and regional climate models (RCMs) routinely used to make future climate projections are unable to capture details of the continental hydroclimate and have significant biases. Part of the problem is their coarse spatial resolution, with typical grid spacing of \sim 100–200 km for GCMs, \sim 50 km for high-resolution Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016) HighResMIP GCMs (Haarsma et al. 2016), and \sim 25 km for RCMs (Giorgi et al. 2022). Complex topography is not captured at coarse resolutions, causing large biases in orographic precipitation/snowfall, mountain snowpack/glaciers (Rasmussen et al. 2011; Pabón-Caicedo et al. 2020), and a misrepresentation of the climate in regions downstream of the Andes (Carril et al. 2012; Solman et al. 2013). In addition, key hydrometeorological features such as cyclones, low-level jets, and organized moist convection are poorly represented in GCMs and remain a challenge even in RCMs (Crespo et al. 2022; Falco et al. 2019). CP simulations, at kilometer-scale horizontal grid spacings, can alleviate many of the problems in GCM and RCM simulations because parameterizations of deep convection are not used, and surface heterogeneities are represented in greater detail (Kendon et al. 2021; Lucas-Picher et al. 2021). Consequently, these simulations significantly reduce many existing coarser-model biases and represent hydroclimate processes with unprecedented detail (Liu et al. 2017; Gutowski et al. 2020; Bettolli et al. 2021; Paccini and Stevens 2023).

Science goals and questions

The overarching goals of the SAAG community are twofold: improved physical understanding and application-relevant research. Two multidecadal convection-permitting simulations are at the heart of SAAG. The historical simulation will allow us to validate the model and better understand detailed hydroclimate features over the continent, while the future climate simulation will show the projected changes of these features in a warmer climate. Furthermore, SAAG

scientists are working directly with local communities, so the information can be used for improved decision making. The specific goals and science questions are as follows:

Goal 1—Physical understanding: Advance insights and improve prediction of key hydroclimate processes in the region including projected changes in a changing climate.

- 1) How well can convection-permitting simulations represent and improve our understanding of critical multiscale features of the hydroclimate over South America?
- 2) How does climate change affect the hydroclimate of South America including the spatiotemporal distribution of precipitation, evaporation, and intensity/duration/frequency of extreme events?

Goal 2—Applications: Provide information that can be used by local communities and stakeholders for better informed decision-making in a changing climate.

- 1) How can SAAG provide information related to water availability and extreme hydrometeorological events in a changing climate that informs societally relevant decisions?

Table 1 provides a comprehensive overview of the broad topics and specific areas of ongoing research by SAAG research groups.

Simulations

We use the Weather Research and Forecasting (WRF) Model version 4.1.5 (Skamarock et al. 2019) with 4-km grid spacing over a domain of $1,472 \times 2,028$ grid points with 61 vertical levels extending to 10 hPa encompassing the entire South American continent and nearby waters (Fig. 1). The historical and future convection-permitting simulations are unprecedented in their spatial resolution, continental scale, and length. The major subgrid parameterizations are summarized in Fig. 1. A 22-yr retrospective/control simulation (January 2000–December 2021) was completed in 2022. Hourly, 0.25° ECMWF atmospheric reanalysis (ERA5) data (Hersbach et al. 2020) provide boundary and initial conditions. Before the simulation began, the SAAG community agreed on the subgrid parameterizations based on sensitivity experiments and similar simulations over North America (Rasmussen et al. 2023). The group also agreed on the output variables that include many hydrological variables not available in the default WRF output. Sensitivity experiments showed negligible difference between simulations with and without spectral nudging, and therefore, spectral nudging was not used. The length of simulations was constrained by computational cost. The historical 22-yr simulation required ~ 24 million core hours, which corresponded to a wall-clock time of ~ 225 days when 124 full nodes were used on NCAR’s Cheyenne supercomputer (Computational and Information Systems Laboratory 2019). The 22-yr 3D raw hourly WRF output is approximately 1 petabyte (PB). Reduced-size files of key variables at hourly temporal resolutions were extracted and made easily available to facilitate file transfer and analysis for the global research community (Rasmussen et al. 2022). A select group of variables, including accumulated surface precipitation, were saved every 15 min.

The future simulation follows the pseudo global warming (PGW) approach (Schär et al. 1996; Rasmussen et al. 2011; Liu et al. 2017). In PGW, reanalysis-derived initial and boundary conditions for the same 22-yr current climate period are perturbed with climate change signals. The climate change signals are obtained from the mean of the 100-member large ensemble (LENS2) of climate change projections using the Community Earth System Model version 2 (CESM2) (Rodgers et al. 2021). The LENS2 simulation follows the historical and SSP3-7.0 scenario provided by CMIP6 (Eyring et al. 2016). The SSP3-7.0 is a relatively high emissions scenario, useful for separating the forced changes from natural variability

Table 1. (left) Broad topics and (right) specific areas of ongoing research by SAAG research groups to address the goals of (top) improved physical understanding and (bottom) application-driven research.

Broad topic	Specific areas of investigation
	Goal 1: Improved physical understanding
Hydrometeorological extremes and severe weather	Floods, droughts, severe storms, warm- and cool-season tornadoes, heat waves, extreme temperature, vapor pressure deficit, seasonality, frequency/duration/intensity of extreme events
Mountain weather and climate	Glacier mass balance, rainfall vs snowfall partitioning, feedbacks from snow-cover retreat, rain-on-snow events, elevation-dependent warming
Moist convection	Deep convection initiation and upscale growth, identification and tracking, mesoscale convective system, severe storms, system life cycle controls and impacts, orographic interactions, diurnal, seasonal, and geographic variability
Low-level jets (LLJ) and atmospheric rivers	South American, Choco, Caribbean, and Orinoco LLJ interactions and effects on clouds and precipitation, moisture transport, barrier jet and blocking processes, intraseasonal-to-interannual variability, orographic effects on atmospheric rivers
Land–atmosphere interactions, land-use and land-cover change	Surface heterogeneity, urban climates, urban heat island, groundwater effects, snowpack dynamics, turbulent flux analysis, soil moisture–vegetation–atmosphere interactions, precipitation and evapotranspiration recycling, deforestation, slash and burn, fires including effects on clouds and precipitation
Atmospheric waves	Tropical, mountain, gravity, equatorial and easterly waves
Hydroclimate	Precipitation–evapotranspiration interactions, interannual (e.g., ENSO), intraseasonal (e.g., MJO), and diurnal precipitation variability
Goal 2: Application-driven research	
Hydrology and water resources	Forcing for hydrologic and hydrodynamic models for runoff and streamflow evaluation, snow spatiotemporal distribution, rain-on-snow events, heavy rainfall on steep slopes, hydrologic hazards such as floods and landslides, coupling land surface–atmosphere models
National weather services	Comparison of SAAG and local weather service models
Framework to collect stakeholder/end-user feedback	Mechanisms for effective collaboration through shared/codesigned experiments and simulations, and effective translation of model output into stakeholder/community partner contexts
Regional downscaling	Comparison with the Coordinated Regional Downscaling Experiment (CORDEX) and other regional simulations including high-resolution modeling over subregions and metropolitan areas
Model improvement	Intercomparison of models including the Unified Model from the Met Office (Halladay et al. 2023) and CAM model from NCAR
Guidance for observational strategies	Optimal design of monitoring networks for climate and land-use change, weather events, and key land and atmosphere processes
Impacts of weather extremes	Impacts from severe weather, winds, flooding, heat waves, and weather facilitating fires and poor air quality with modulation by factors such as ENSO, urban heat islands, and land-cover change

(O'Neill et al. 2016). LENS2 components use nominal 1° horizontal resolution and 32 vertical levels. Figure 1 shows the 2-m temperature and precipitation for the ensemble average of 100 LENS2 individual realizations for the period 2000–21.

We derive monthly LENS2 climatologies, corresponding to the 2000–20 period and the 2060–80 period. We choose the period 2060–80 from the future period as it corresponds to a $\sim 3^{\circ}\text{C}$ change in global mean 2-m temperature from preindustrial and a change of $\sim 2.5^{\circ}\text{C}$ in 2-m temperature over South America. These monthly data are interpolated to the WRF grid and the ERA5 pressure levels. The same monthly deltas are applied to all the 22 years. The physical fields perturbed in the PGW approach include horizontal winds, geopotential, temperature, relative humidity, sea surface temperature, soil temperature, sea ice, and sea level pressure. Greenhouse gasses are changed according to the SSP3-7.0 emission scenario. The mathematical expression for the PGW simulation is shown in Eq. (1):

$$\begin{aligned} \text{WRF}_{\text{input}} &= \text{ERA5}_{(\text{Jun 1999–Dec 2021})} + \text{DLENS2}_{\text{SSP3-7.0}}, \\ \text{DLENS2}_{\text{SSP3-7.0}} &= \text{LENS2}_{2060–80} - \text{LENS2}_{2000–20}, \end{aligned} \quad (1)$$

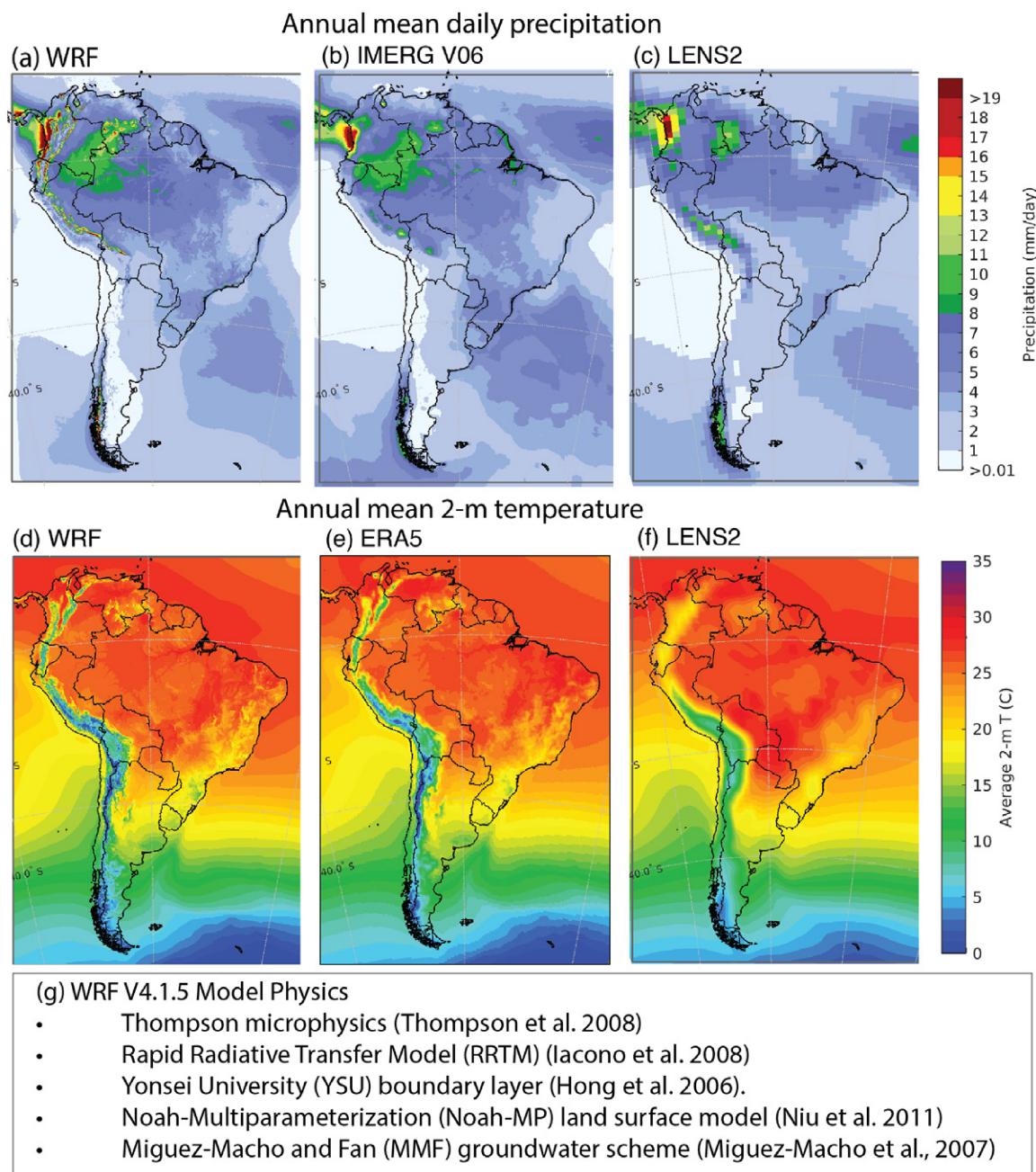


Fig. 1. Climatological (2000–21) annual precipitation from (a) WRF, (b) Integrated Multi-satellitE Retrievals for GPM (IMERG), and (c) a 100-member LENS2 ensemble; climatological (2000–21) annual-mean 2-m temperature from (d) WRF, (e) ERA5, and (f) a 100-member LENS2 ensemble; and (g) parameterizations used in the WRF simulations (Thompson et al. 2008; Iacono et al. 2008; Hong et al. 2006; Niu et al. 2011; Miguez-Macho et al. 2007).

where LENS2 indicates the ensemble monthly averages for the time periods indicated in the subscript. Figure 2 shows the future LENS2 projected changes in 2-m temperature, relative humidity (RH), and precipitation. The global model ensemble projects greatest increases in temperature and decreases in RH and precipitation in the northern and central parts of the continent, while over the southern and eastern parts of the continent, there are increases in RH and precipitation with smaller increases in temperature.

PGW is computationally more efficient than alternative downscaling methods, enabling us to harness the capabilities of CP simulations to project future climate. PGW relies on a historical simulation driven by reanalysis, not GCM simulations. Hence, the representation of historical climate is closer to observations and enables users to assess the model's downscaling ability. The PGW climate change response is primarily related to thermodynamic

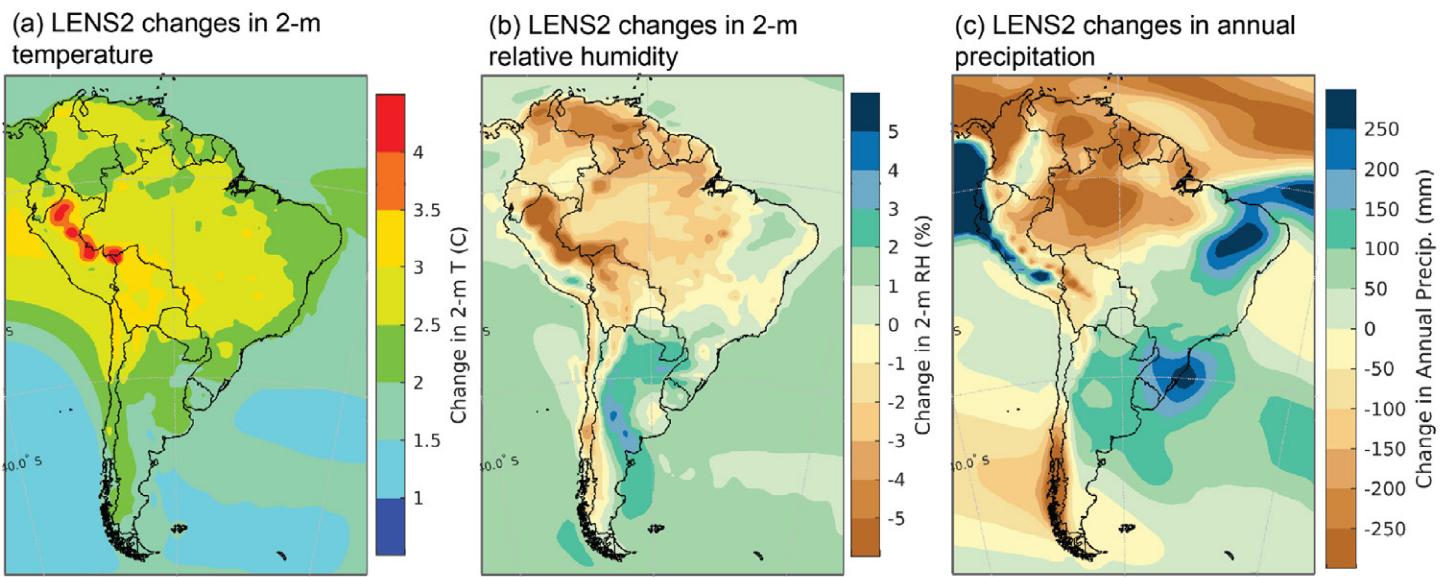


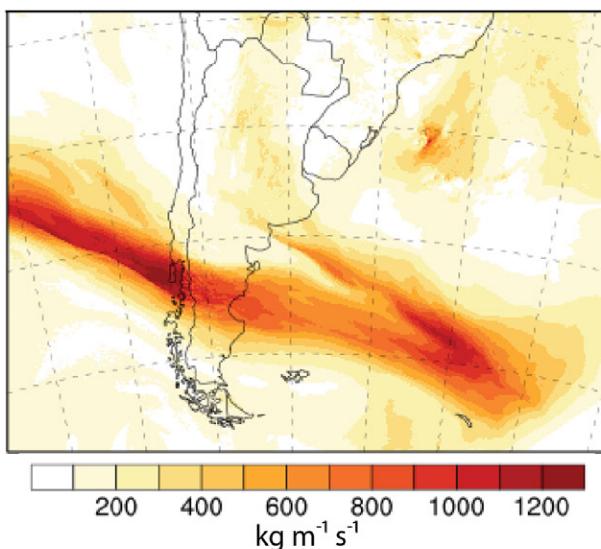
Fig. 2. LENS2 ensemble difference between 2060–80 and 2000–20 for (a) annual surface air temperature, (b) annual surface relative humidity, and (c) annual surface precipitation.

changes and lapse rate differences (Prein et al. 2016). However, the PGW perturbations include winds and geopotential heights; therefore, the atmospheric circulations between the historical and PGW simulations are not identical. The PGW approach provides unique and critical information that complements traditional climate models for improved decision-making by providing a detailed and physically consistent picture of what future weather might look like (Hazeleger et al. 2015). As an example, precipitation associated with an atmospheric river (AR) that impacted Chile on 8 March 2021 is well captured in the WRF-CTL simulation (Figs. 3c,d). The projected changes in a warmer climate show more intense vapor transport and a shift of this AR, resulting in enhanced precipitation around 45°S but decreased precipitation north of this region (Figs. 3b,e). Current work is evaluating the climatological changes in the population of simulated ARs as projected by the PGW simulation. A disadvantage of the PGW approach is that it does not represent potential systematic changes in synoptic circulations that will influence future weather events since the forced climate signal is added to current climate. In addition, the sequence of synoptic circulations does not change, and this impacts slow-response features such as terrestrial moisture and temperature.

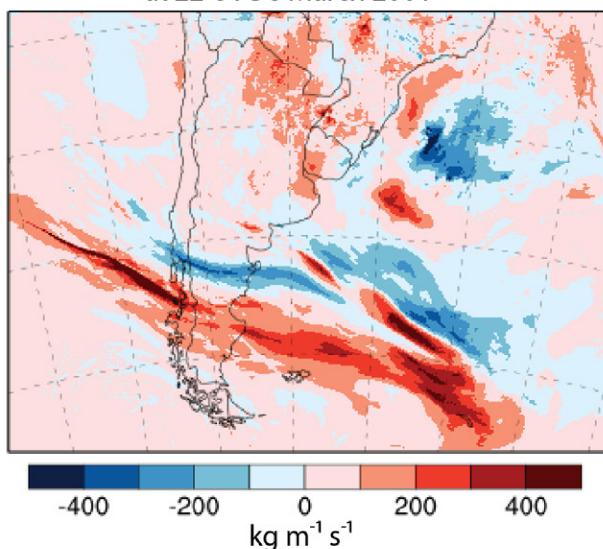
Model evaluation

While the historical 22-yr simulation was in production, the team continuously evaluated the WRF output results. An important challenge associated with the evaluation of the simulation is the lack of reliable high-spatiotemporal-resolution observations, particularly subdaily extreme events (Lucas-Picher et al. 2021) and this is especially challenging over South American mountainous regions. As such, a major observational data collection effort leveraging the community networking has brought together in situ meteorological station data, radiosondes, field experiment datasets, gridded products, and satellite-based observations for model evaluation. NCAR (2023a) presents a summary of all products including links to the data. Additional information is also presented in Condom et al. (2020). The process is streamlined in an online dashboard (NCAR 2023b), which facilitates real-time monitoring and discussion of model performance. Annual and seasonal analyses for the continent and subregions can be easily visualized using the dashboard. The subregions follow the same delineation as in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Iturbide et al. 2020). The dashboard shows that WRF simulated precipitation and 2-m temperature averaged over

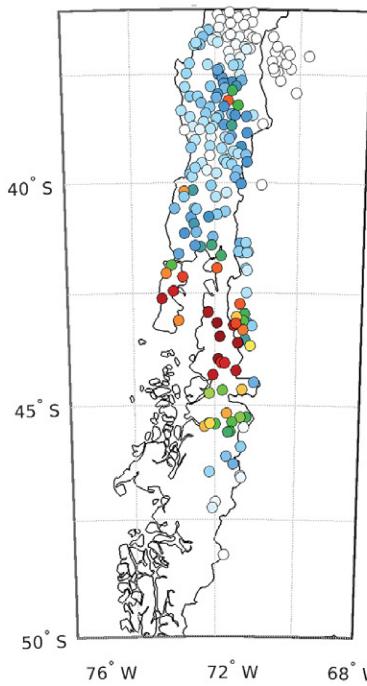
(a) IVT from CTL at 22 UTC 8 March 2001



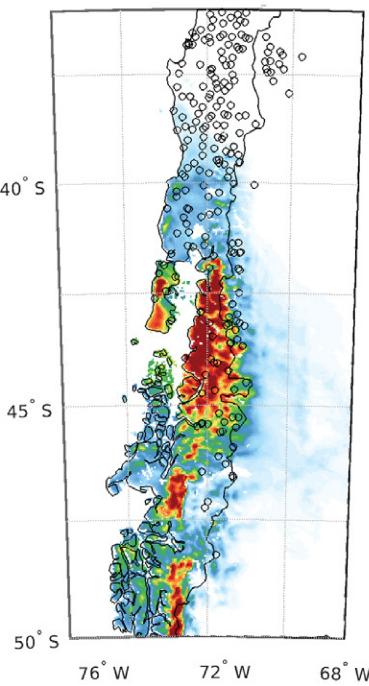
(b) Difference (PGW-CTL) in IVT at 22 UTC 8 March 2001



(c) Observed precipitation 6 - 9 March 2001



(d) Precipitation from CTL 6 - 9 March 2001



(e) Difference (PGW-CTL) in precipitation 6 - 9 March 2001

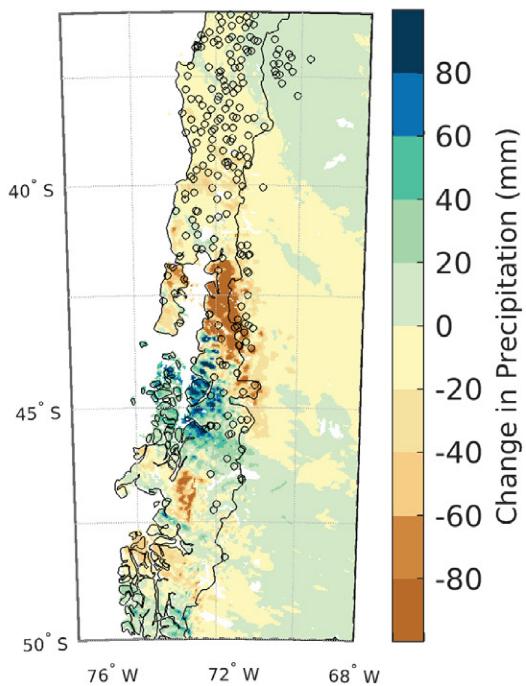


Fig. 3. WRF CTL and PGW representation of an atmospheric river event that impacted Chile in March 2001. (a) Integrated vapor transport (IVT) from WRF CTL simulation and (b) WRF PGW-CTL IVT at 2200 UTC 8 Mar 2021; accumulated precipitation for 6–9 Mar 2001 from (c) station observations, (d) WRF CTL, and (e) WRF PGW-CTL.

the continent are within the envelope of uncertainty estimated from various observational and reanalysis products. The spatial pattern is well represented. Spatial correlation between WRF annual-mean 2-m temperature and various observational and reanalysis products is above 0.95. Annual-mean precipitation has correlations that range between 0.65 and 0.8. Areas over the tropical and high-latitude Andes show larger discrepancies. Kilometer-scale models tend to overestimate the intensity of heavy rainfall events since convection is not fully resolved (Kendon et al. 2021). Furthermore, observations over mountainous regions are limited and remote sensing retrievals are highly uncertain with likely biases (Birkel et al. 2022). Further comparisons with surface stations are needed to assess the value added by WRF in mountainous areas.

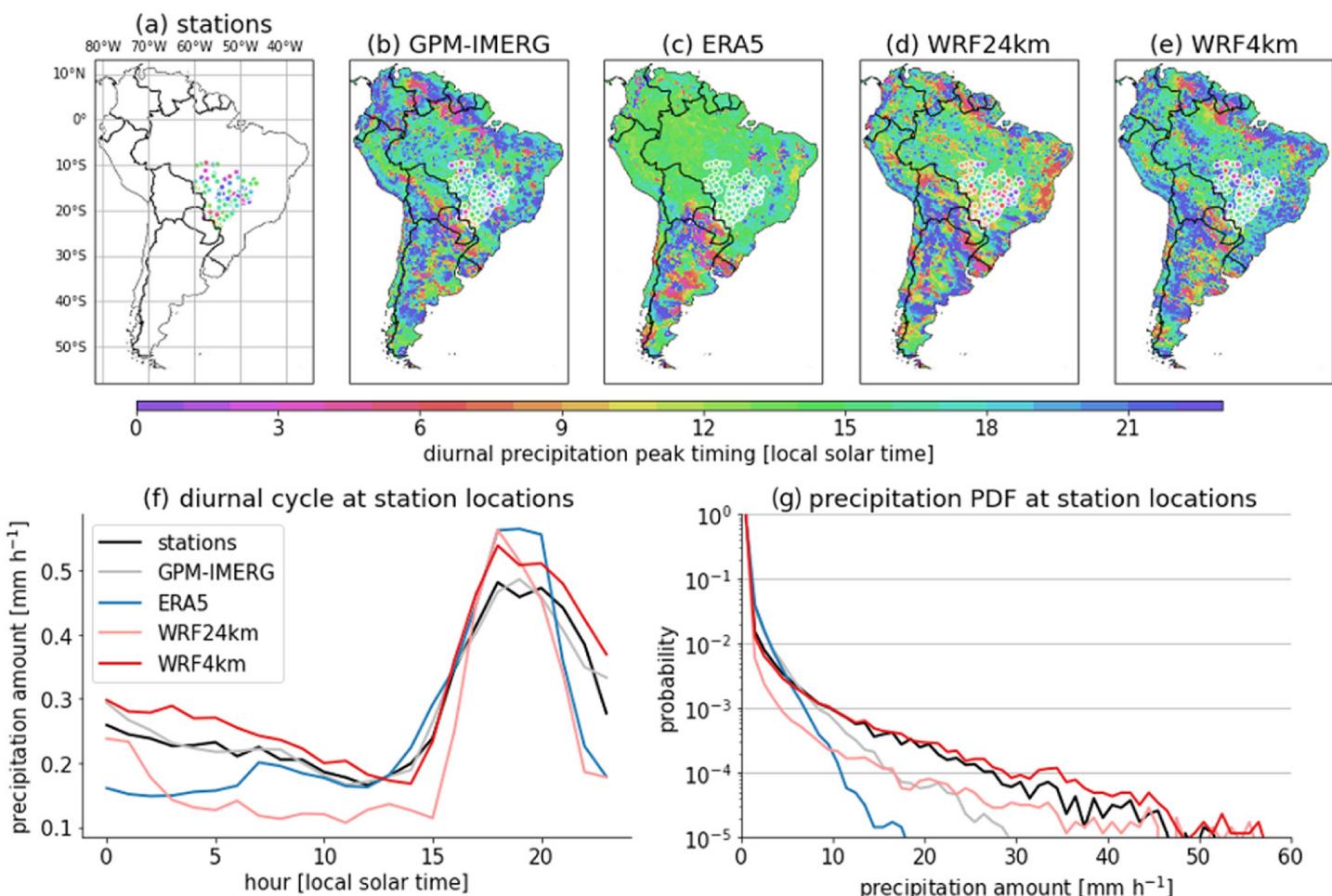


Fig. 4. Diurnal precipitation peak at local solar time for November 2018–March 2019 for (a) surface stations in southwest Brazil, (b) IMERG, (c) ERA5, (d) 24-km WRF, and (e) 4-km WRF. (f) The average precipitation diurnal cycle at surface station locations (circle symbols in maps) and (g) the hourly precipitation probability density function are shown for the same period and datasets.

The accuracy and value of the 4-km WRF simulation in representing precipitation is already evident when analyzing a single Southern Hemisphere warm season (Fig. 4). When compared to GPM IMERG, the diurnal timing of peak precipitation is better captured by the 4-km WRF simulation than by ERA5 and a test 24-km WRF simulation (Figs. 4a–e). Similar improvements were obtained in 4.5-km CP simulations with the Met Office Unified Model (Halladay et al. 2023). The 4-km WRF simulation can capture the evening and nocturnal peaks in precipitation just inland of many coastlines of the continent (Figs. 4a–e). Comparison with surface station observations over southwestern Brazil clearly shows the improvement in nocturnal precipitation (Fig. 4f), where 4-km WRF also captures station-observed high-intensity events that are not captured by 24-km WRF, ERA5, or GPM IMERG (Fig. 4g).

Lessons learned

The success of SAAG has relied on a process that benefits individual researchers' interests, while working toward the common goal of improving understanding and projection of South America's hydroclimate for better-guided societal decisions as the climate changes. For four years, researchers from more than 10 (mostly South American) countries have consistently attended online meetings that were open to all. The online format has enabled participation from different locations. During the meetings, respectful and open communication has facilitated the exchange of ideas and promoted collaboration between different individuals and groups. This dialogue led to an agreed-upon experimental design of the WRF simulations, and identification of key science questions concerning the hydroclimate of South America.

From these, science topical subgroups have been formed to facilitate collaborative research around the simulations. In addition to online meetings, several sessions at international meetings have promoted in-person exchanges and social cohesion. In particular, the 2022 Convection-Permitting Climate Modeling Workshop held in Buenos Aires, Argentina, was a way to bring together the international CPM community with a focus on South America (Prein et al. 2022).

All SAAG members are invested in the success of the WRF historical and future simulations. The computational cost prohibited individual research groups from performing the simulations, so having NCAR perform them was critical. High-performance computing resources from the University of Illinois and the U.S. Department of Energy National Energy Research Scientific Computing Center (NERSC) provided shared solutions to store the 2 PB of hourly output. Open discussion about the numerical details (parameterizations, nudging, output variables, output frequency) ensured that individual research needs were addressed. The online dashboard has been an important tool for real-time analysis, verification, and discussion. Finally, reduced size output of key variables has been made available through NCAR's Research Data Archive service (<https://rda.ucar.edu/datasets/ds616-0/>). This has facilitated the use of this very large dataset, although data challenges remain.

The computational burden of analyzing such high-resolution continental-scale simulations is a major barrier to usage. There are currently no computational facilities in South America to perform or adequately analyze kilometer-scale climate simulations. A possible solution is the formation of a centralized computational facility where SAAG and other data are stored for access and processing without the need for data downloading. This hub could also be a regional center for education, outreach, and capacity building for a diverse set of users including scientists, stakeholders, and decision-makers interested in using kilometer-scale climate data.

Future areas of interest/focus and invitation to the research and applications community

We have only begun to analyze the SAAG simulations, but their potential uses are much wider. We include a noncomprehensive list of possible topics for future research in Table 2. We invite the community to join the SAAG effort by reaching out to Andreas Prein (prein@ucar.edu), Roy Rasmussen (ramsus@ucar.edu), Francina Dominguez (francina@illinois.edu), or any of the authors of this work.

Table 2. Noncomprehensive list of possible topics for future research.

Potential future areas of research
Impact of deforestation on water and energy budgets at continental, regional, and local scales, including changes caused by altered circulations
Impacts of aerosols (particularly biomass burning) on clouds and precipitation
Changes in moisture transport by LLJs and atmospheric rivers affecting regional sources of water
Future changes in severe convective storm environments
Changes in spatial patterns of convective precipitation due to changes in soil moisture, vapor sources, and circulations
Compound extremes such as extreme heat and drought or serial flood events
Groundwater assessment (observation/baseline), extraction, and recharge
Impacts of climate change and air pollution on human health outcomes
Understanding the physical mechanisms associated with the formation and movement of floods in South America
Revisiting and updating adaptation plans to climate change

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Data availability statement. Hourly and 15-min output of SAAG simulations for select variables is available at NCAR CISL Research Data Archive (Rasmussen et al. 2022). Publicly available in situ observations and satellite and reanalysis data used in our analysis can be found in NCAR (2023a).

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