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Mu, Ye

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Dynamics and Projections of Northerly Low-Level Jets on the Eastern Slopes of the
Andes and Mesoscale Convective Systems in South America

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Geography

by

Ye Mu

Committee in charge:

Professor Charles Jones, Chair

Professor Leila M. V. Carvalho

Professor Qinghua Ding

June 2026

The dissertation of Ye Mu is approved.

Qinghua Ding

Leila M. V. Carvalho

Charles Jones, Committee Chair

April 2026

Dynamics and Projections of Northerly Low-Level Jets on the Eastern Slopes of the
Andes and Mesoscale Convective Systems in South America

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ACKNOWLEDGEMENTS

I once thought this would be the easiest part of the dissertation to write, yet I found myself hesitating for a long time, unsure where to begin. Reaching this final page signifies the end of my identity as a student. While life ahead remains long, I find myself overwhelmed with gratitude for the journey that brought me here.

First and foremost, I dedicate this work to my mother, who watches over me from another world. She lived a life of diligence and frugality for my sake, always respecting and supporting my every decision. She often told me, "Everything is predestined; one cannot outrun fate, so let things take their natural course." And that is true. She longed for me to grow up and succeed, but now that I have, the person who loved me most is no longer here. They say the loss of a loved one is not a sudden rainstorm but a lifelong dampness. I remain forever caught in that mist; in the most ordinary, fleeting moments, it still stirs into a storm within me. Mom, we did it—this dissertation is for you.

My deepest gratitude goes to the lamp-bearers who appeared when my sky was still dark. My master mentor, Dr. Trent Biggs, took me in when I had nowhere else to go and supported me through my master's degree, eventually introducing me to my Ph.D. advisor, Dr. Charles Jones, which allowed me to pursue my doctorate at UC Santa Barbara. I am profoundly grateful to Charles; though a man of few words, he possesses a remarkably kind heart. He supported me, respected my ideas and guided me, step by step, toward becoming a dedicated researcher. My co-advisor, Dr. Leila Carvalho, is the most patient and authentic person I have ever known. She not only supervised my research and writing with meticulous care but also taught me how to stand strong while living abroad. My third advisor, Dr. Qinghua Ding, taught

me how to navigate the academic world through countless meetings and conversations; he showed me how to fight for what I want. Special thanks to my mentors at NCAR: Dr. Lulin Xue, Dr. Changhai Liu, and Jerry Cycone, as well as my NESSI cohort, for providing the best possible academic and emotional support.

I am also indebted to my partner, who has been by my side from start to finish, resonating with my soul. Thanks to my cat, Latte, for his constant help on the recovery journey. To my best friends: thank you for giving me the courage to always believe in myself. Since childhood, I have often felt like an outsider, yet you embraced me for who I am, celebrating my uniqueness and offering immense companionship. We will all become the best versions of ourselves.

Finally, I want to thank myself. I still remember Jerry telling me on my last day at NCAR how impressed he was by my resilience. I am grateful to my resilient and hardworking self. In the days to come, I hope to remain true to who I am and become whoever I wish to be, unburdened by the labels and roles I carry.

While this dissertation is complete, the journey of research is endless. I will continue to explore the path I love and strive to become a better person.

VITA OF YE MU

June 2026

Ph.D. Candidate researcher | NASA Future investigator

Department of Geography

Ellison Hall, University of California Santa Barbara (UCSB), CA 93106

ymu@ucsb.edu | ymuclimate.com/

EDUCATION

Ph.D., Climate Science, University of California, Santa Barbara 2026

Committee: Charles Jones (Chair), Leila Carvalho, Qinghua Ding

M.S., Geography, San Diego State University 2021

Committee: Trent Biggs (Chair), Fernando De Sales, Samuel Shen

Thesis Title: Forests Mitigate Drought in An Agricultural Region of The Brazilian Amazon: Atmospheric Moisture Tracking to Identify Critical Source Areas

B.S., With Distinction in Geography, San Diego State University 2019

Honors: Magna Cum Laude Honors Degree

Concentrations: Geographic Information Science

RESEARCH APPOINTMENTS

NASA Future Investigator in Earth and Space Science and Technology (FINESST) 2023-2026

Graduate Student Researcher 2022-2025

- Earth Research Institute, University of California, Santa Barbara

NCAR Research Applications Laboratory (RAL) Visiting Researcher

2024 Aug

NCAR Earth System Science Intern (NESSI) 2023 May-Aug

- Research Application Laboratory (RAL), National Center for Atmospheric Research (NCAR)

- Mentor: Dr. Lulin Xue, Dr. Changhai Liu

Graduate Research Assistant, Geography Department, San Diego State University 2019-2021

Undergraduate Research Assistant, Geography Department, San Diego State University 2018-2019

PEER-REVIEWED PUBLICATIONS

19. **Mu, Y.**, C. Jones, L. M. V. Carvalho, J. Kukulies, A. F. Prein, L. Xue, and C. Liu, 2026: Convection-Permitting Projections of Low-Level Jets and Mesoscale Convective Systems in South America. Submitted to Journal of Geophysical Research – Atmospheres.

18. Ocasio, K. M. N., Dougherty, E. M., Xue, L., Moon, Z. L., Núñez, A. R., Morrison, M., Quagrain, K. T., **Mu, Y.**, Martinez, C., Narinesingh, V., Cavazos, T., Rios, G., Bacmeister, J., Amador, J. A., Herrera, D. A., He, C., Maloney, E. D., Rasmussen, K., Reed, K. A., et al. (2026). Advancing weather and climate science in Mesoamerica and the Caribbean: A novel regional multi-week convection-permitting simulation. *Bulletin of the American Meteorological Society*, BAMS-D-25-0023.1. <https://doi.org/10.1175/bams-d-25-0023.1>

17. **Mu, Y.**, Jones, C., Carvalho, L. M. V., Kukulies, J., Prein, A. F., Xue, L., & Liu, C. (2025). Impacts of northerly low-level jets on mesoscale convective systems east of the Andes. *Journal of Geophysical Research: Atmospheres*, 130, e2025JD043842. <https://doi.org/10.1029/2025JD043842>
16. **Mu, Y.**, Hu, Y., Jones, C., Biggs, T., Domingues, T., Funk, C., Peterson, P. (2025). Increasing Dry-Season Vapor Pressure Deficit in the Amazon Basin: Historical Trends, Future Projections, and Links to Deforestation. *Environmental Research Communications*, 7(10), 101001. <https://doi.org/10.1088/2515-7620/ae0c5b>.
15. Chun, K.P., Octavianti, T., Dogulu, N., Tyralis, H., Papacharalampous, G., Rowberry, R., Fan, P., Everard, M., Francesch-Huidobro, M., Migliari, W., Hannah, D.M., Marshall, J.T., Calasanz, R.T., Staddon, C., Ansharyani, I., Dieppo, B., Lewis, T.R., Ponce, J., Ibrea, S., Ferreira, T.M., Peliño-Golle, C., **Mu, Y.**, Delgado, M.D., Espinoza, E.S., Keulertz, M., Gopinath, D. and Li, C. (2025), Transforming Disaster Risk Reduction With AI and Big Data: Legal and Interdisciplinary Perspectives. *WIREs Data Mining and Knowledge Discovery*, 15: e70011. <https://doi.org/10.1002/widm.70011>
14. Wille, J., Favier, V., Gorodetskaya, I., Agosta, C., Baiman, R., Barrett, J., Barthelemy, L., Boza, B., Bozkurt, D., Casado, M., Chyhareva, A., Clem, K., Codron, F., Datta, R., Durán-Alarcón, C., Francis, D., Hoffman, A., Kolbe, M., Krakovska, S., Linscott, G., MacLennan, M., Mattingly, K., **Mu, Y.**, Pohl, B., Santos, C., Shields, C., Toker, E., Winters, A., Yin, Z., Zou, X., Zhang, C., & Zhang, Z. (2025). Atmospheric rivers in Antarctica. *Nature Reviews Earth & Environment*. <https://doi.org/10.1038/s43017-024-00638-7>
13. **Mu, Y.**, Jones, C., Carvalho, L. M. V., Xue, L., Liu, C., & Ding, Q. (2024). Pacific decadal oscillation and ENSO forcings of northerly low-level jets in South America. *Nature Climate and Atmospheric Science*, 7, 297. <https://doi.org/10.1038/s41612-024-00852-6>.
12. Prein, A. F., Feng, Z., Fiolleau, T., Moon, Z. L., Núñez Ocasio, K. M., Kukulies, J., Roca, R., Varble, A. C., Rehbein, A., Liu, C., Ikeda, K., **Mu, Y.**, & Rasmussen, R. M. (2024). Km-scale simulations of mesoscale convective systems over south America—A feature tracker intercomparison. *Journal of Geophysical Research Atmospheres*, 129(8). <https://doi.org/10.1029/2023jd040254>.
11. Tsitelashvili, N., Biggs, T., **Mu, Y.**, & Trapaidze, V. (2024). Regional Precipitation Regimes and Evaluation of National Precipitation Datasets against Satellite-Based Precipitation Estimates, Republic of Georgia. *Journal of Hydrometeorology*, 25, 591–600, <https://doi.org/10.1175/JHM-D-23-0116.1>.
10. Jones, C., **Mu, Y.**, Carvalho, L.M.V. & Ding, Q. (2023). The South America Low-Level Jet: form, variability and large-scale forcings. *Nature Climate and Atmospheric Sciences*, 6, 175. <https://doi.org/10.1038/s41612-023-00501-4>.
9. Dominguez, F., R. Rasmussen, C. Liu, K. Ikeda, A. Prein, A. Varble, P. A. Arias, J. Betancourt, M. L. Bettolli, P. Callaghan, L. M. V. Carvalho, C. L. Castro, F. Chen, D. Chug, K. P. Chun, A. Dai, L. Danaila, R. Porfírio da Rocha, E. Nascimento, E. Dougherty, J. Dudhia, T. Eidhammer, Z. Feng, L. Fita, R. Fu, J. Giles, H. Gilmour, K. Halladay, Y. Huang, A. Wong, M. Lagos-Zúñiga, C. Jones, J. Llamocca, M. Llopart, J. A. Martinez, J. C. Martinez, J. R. Minder, M. Morrison, Z. L. Moon, **Mu Ye, R. B.** Neale, K.M. Núñez Ocasio, S. Pal, E. Potter, G. Poveda, F. Puhales, K. L. Rasmussen,

- A. Rehbein, R. Rios-Berrios, C. B. Risanto, A. Rosales, L. Scaff, A. Seimon, M. Somos-Valenzuela, Y. Tian, P. Van Oevelen, D. Veloso-Aguila, L. Xue, and T. Schneider. (2023). Advancing South American Water and Climate Science through Multidecadal Convection-Permitting Modeling. *Bulletin of the American Meteorological Society*, 105, E32–E44, <https://doi.org/10.1175/BAMS-D-22-0226.1>.
8. **Mu, Y.**, Biggs, T. W., & Jones, C. (2023). Importance in shifting circulation patterns for dry season moisture sources in the Brazilian Amazon. *Geophysical Research Letters*, 50, e2023GL103167. <https://doi.org/10.1029/2023gl103167>.
7. Araki, R., **Mu, Y.**, & McMillan, H. (2023). Evaluation of GLDAS soil moisture seasonality in arid climates. *Hydrological Sciences Journal*. <https://doi.org/10.1080/02626667.2023.2206032>.
6. Burberry, C. M., Flatley, A., Gray, A. B., Gulinger, J. J., Hamshaw, S. D., Hill, K., **Mu, Y.**, & Rowland, J. C. (2022). Earth and Planetary Surface Processes Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science. *Earth and Space Science*, 9, e2022EA002414. <https://doi.org/10.1029/2022EA002414>.
5. **Mu, Y.**, & Jones, C. (2022). An observational analysis of precipitation and deforestation age in the Brazilian Legal Amazon, *Atmospheric Research*, 271, 106122, <https://doi.org/10.1016/j.atmosres.2022.106122>.
4. Blanken, P. D., Brunet, D., Dominguez, C., Goursaud Oger, S., Hussain, S., Jain, M., Koren, G., & **Mu, Y.**, et al. (2022). Atmospheric sciences perspectives on integrated, coordinated, open, networked (ICON) science. *Earth and Space Science*, 9, e2021EA002204. <https://doi.org/10.1029/2021EA002204>.
3. **Mu, Y.**, Biggs, T., Shen, S.P.S. (2021). Satellite-based precipitation estimates using a dense rain gauge network over the Southwestern Brazilian Amazon: Implication for identifying trends in dry season rainfall. *Atmospheric Research*, 105741, <https://doi.org/10.1016/j.atmosres.2021.105741>.
2. **Mu, Y.**, Biggs, T. W., De Sales, F. (2021). Forests mitigate drought in an agricultural region of the Brazilian Amazon: Atmospheric moisture tracking to identify critical source areas. *Geophysical Research Letters*, 48, e2020GL091380. <https://doi.org/10.1029/2020GL091380>.
1. **Mu, Y.**, Biggs, T., Stow, D., Numata, I. (2020). Mapping heterogeneous forest-pasture mosaics in the Brazilian Amazon using a spectral vegetation variability index, band transformations and random forest classification. *International Journal of Remote Sensing*, 41(22), 8682-8692. <https://doi.org/10.1080/2150704X.2020.1802529>.

OTHER PUBLICATIONS

- 2019 **Mu, Y.**, (2019). Student CEQA Practicum. The Environmentor: summer 2019, 7. Association of Environmental Professionals.
- 2018 Gutierrez, Jose, Paul Martin, Sam Orndoff, Aliona Galkina, McKenna Kull, Steven Webb, **Mu Ye**, and Kate Swanson. (2018). A Glance from Our Stance: Educational Experiences at SDSU. San Diego State University, San Diego.

FELLOWSHIP, AWARDS AND GRANTS

2023-2026	Mu, Y. South American Low-Level Jet (SALLJ) Dynamics and Impact on Precipitation. <i>Future Investigators in NASA Earth and Space Science and Technology</i> . Future investigator.	\$150,000
2025	Excellence in Research, UCSB Geography Awards Colloquium	\$1000
2024	Chinese-American Engineers and Scientists Association of Southern California (CESASC) Scholarship	\$1000
2023	20th Conference on Mountain Meteorology Student Travel Awards	\$500
2022	20th Conference on Mountain Meteorology Student Travel Awards	\$500
2022	American Association of Geographers (AAG) Climate Specialty Group student paper competition third place	\$100
2021&2022	Jack and Laura Dangermond Geography Travel Scholarship, UCSB	\$1600
2021	American Association of Geographers (AAG) Climate Specialty Group student annual meeting fellowship	\$330
2021	SDSU Student Success Fee (SSF) grant for geography students to attend the AAG conference	\$4,680
2021	SDSU Student Success Fee (SSF) grant for Geography Mentorship Initiative	\$5,000
2021	SDSU Student Success Fee (SSF) grant for Data Carpentry Workshops	\$5,000
2021	SDSU Student Success Fee (SSF) grant for Climate Talks: https://ggsa.sdsu.edu/ggsas-2021-virtual-climate-talks/	\$5,700
2020	SDSU Graduate Student Travel Fund (Spring Cycle)	\$500
2020	William & Vivian Finch Scholarship for Remote Sensing	\$5,818
2020	SDSU Student Success Fee (SSF) grant for geography students to attend the American Association of Geographers (AAG) conference	\$10,500

TEACHING AND MENTORING

Teaching Assistant, Department of Geography, University of California, Santa Barbara

Ocean Atmosphere (GEOG 3) Fall 2021
Global Warming (GEOG 8)

Winter 2021
Tropical Meteorology (GEOG 133)

Fall 2022
Climate Change (GEOG 119)

Spring 2023
Bren School of Environmental Science & Management
Climate Change Impacts and Adaptation (ESM237)

Spring 2025
Teaching Associate, Department of Geography, San Diego State University
Environmental Sciences (ENVS 100) Fall 2019

Undergraduate Student Mentor

Yiwen Hu, University of California, Berkeley

2023-2024

Poster Presentation: Historical and Future Rainfall Trends in the Amazon and La Plata Basins, UCSB Undergrad Research Symposium, May 10th, 2024

High School Student Mentor – UCSB Research Mentorship Program

Mia Ravishankar, Mountain View High School, CA

2024 Summer

Oral and Poster Presentation: Tracking Extreme Precipitation and Convective Systems in South America, UCSB RMP Research Symposium, July 31st, 2024

High School Student Mentor – UCSB Research Mentorship Program

Sihyeon Lee, Daegu International School, South Korea

2025 Summer

Oral and Poster Presentation: Urban Vulnerability to Evolving MCS Impacts in South America: A Geospatial Analysis, UCSB RMP Research Symposium, July 31st, 2025

PRESENTATIONS, TALKS, AND POSTERS

2026 **Mu, Y.**, Jones, C., Carvalho, L. V., Kukulies, J., Prein, A. F., Xue, L., & Liu, C. (2026, January 29). Convection-permitting projections of low-level jet and mesoscale convective system response in South America. *106th AMS Annual Meeting*, <https://ams.confex.com/ams/106ANNUAL/meetingapp.cgi/Paper/477593>

2024 **Mu, Y.**, Jones, C., Carvalho, L. V., Kukulies, J., Prein, A. F., Xue, L., Liu, C. (2024). Impacts of Northerly Low-level Jets on Mesoscale Convective Systems East of the Andes. In *AGU Fall Meeting 2024*, Washington D.C.

2024 (Invited Talk) **Mu, Y.** (2024). Impacts of Northerly Low-level Jets on Mesoscale Convective Systems East of the Andes. Research Application Laboratory seminar, *National Center for Atmospheric Research (NCAR)*, Boulder, Colorado.

[\[Link\]](#)

2024 **Mu, Y.**, Jones, C., Carvalho, L. V., Kukulies, J., Prein, A. (2024). Northerly Low-level Jets on the Eastern Andes and Mesoscale Convective Systems in South America. *Joint GEWEX-AOS-INCUS 'Convec7on Tracking' Workshop*, April. NASA GISS, New York. [\[Link\]](#)

2023 **Mu, Y.**, Jones, C., Carvalho, L. V., Xue, L., Liu, C., & Ding, Q. (2023). Global Scale Forcing of the South American Low-Level Jet (SALLJ) and Associated Local Impacts on Precipitation Extremes. In *AGU Fall Meeting 2023*, San Francisco.

2023 (Invited Talk) **Mu, Y.** (2023). Global scale forcing of SALLJ and associated local impacts on precipitation extremes. Research Application Laboratory seminar, *National Center for Atmospheric Research (NCAR)*, Boulder, Colorado. [\[Link\]](#)

2023 **Mu, Y.** (2023). Moisture recycling in the southwestern Brazilian Amazon. Climate Meeting seminar, *University of California, Santa Barbara*.

2022 Carvalho, L. V., **Mu, Y.**, & Jones, C. (2022). The South Atlantic Convergence Zone and the 2022 Extreme Precipitation Events in Petropolis, Brazil. In *AGU Fall Meeting 2022*, Chicago.

2022 **Mu, Y.**, Jones, C., & Carvalho, L. V. (2022). The South American Low-Level Jet Evolution in Two Episodes of Mesoscale Convective Systems. In *AGU Fall Meeting 2022*, Chicago.

2022 **Mu, Y.**, Biggs, T. W., & Jones, C. (2022). Forest and Oceanic Dry Season Moisture Sources in the Brazilian Amazon. In *AGU Fall Meeting 2022*, Chicago.

2022 **Mu, Y.**, and Jones, C. (2022). The South American Low-Level Jet and Its Role on Precipitation Distribution: A Case Study. *20th Conference on Mountain Meteorology*. Park City, Utah. Dynamics and Physics of Orographic Clouds and Precipitation III.

2022 **Mu, Y.**, and Jones, C. (2022). Variability of rainfall and associated mechanisms across the Brazilian Legal Amazon. *AAG Annual Meeting 2022*. Changes in Hydroclimates and Extremes 2.

2021 **Mu, Y.**, Biggs, T. W., and S. Shen. (2021). Detecting Trends in Dry Season Rainfall from the Satellite Precipitation Estimates and a Dense Rain Gauge Network over the Southwestern Brazilian Amazon. *AGU Fall Meeting 2021*, New Orleans, H15P-1235.

2021 **Mu, Y.**, Biggs, T. W., De Sales, F. (2021). Forests mitigate drought in an agricultural region of the Brazilian Amazon. *AAG Annual Meeting 2021*. Hydroclimatology session II.

2020 **Mu, Y.**, Biggs, T. W., and S. Shen. (2020). Improving the CHIRPS (V2. 0) precipitation estimates for rainfall extremes using a dense rain gauge network over the Brazilian Amazon. *AGU Fall Meeting 2020*, Everywhere, H200.

2020 **Mu, Y.** (2020). Land-Cover Classification Using Spectral Mixture Analysis and Random Forest. *Student Research Symposium*, San Diego State University.

REVIEW PANELS

2025 **NASA** Earth Science Division FINESST Weather and Atmospheric Dynamics Panel. NASA Headquarters, May 19-22nd, 2025.

PROFESSIONAL DEVELOPMENT

2024 **The Model for Prediction Across Scales (MPAS) tutorial**, National Center for Atmospheric Research (NCAR), Mesoscale & Microscale Meteorology (MMM), Virtual

2023 **Intern**, National Center for Atmospheric Research (NCAR) Earth System Science Internship, Research Application Laboratory (RAL), in Boulder, Colorado (Mentor: Dr. Lulin Xue, Dr. Changhai Liu)

2022 **Radiosonde Launcher**, Sundowner Winds EXperiment ([SWEX](#)) in Santa Barbara, California

SERVICE & DIVERSITY, EQUITY and INCLUSION ADVANCEMENT

True Colors, an inclusive and diverse workforce at UCAR/NCAR 2023 – 2024

Regional Director, Chinese-American Oceanic and Atmospheric Association (COAA) 2023 – 2024

Faculty Search Committee, University of California, Santa Barbara 2023 – 2024

Team Spirit Committee, University of California, Santa Barbara 2022 – 2023

Geography Equity, Diversity and Inclusion Group, University of California, Santa Barbara 2021 – 2022

Chair's Graduate Advisory Committee, University of California, Santa Barbara 2021 – 2022

Vice President, Geography Graduate Student Association, San Diego State University 2019 – 2021

Journal Reviewer (42)

- *Nature Communications* (2); *Nature Climate and Atmospheric Science* (1); *Journal of Climate* (2); *Water Resources Research* (1); *Climate Dynamics* (4); *Theoretical and Applied Climatology* (2); *International Journal of Climatology* (1); *Journal of Applied Meteorology and Climatology* (1); *Ecological Indicators* (1); *Atmospheric Research* (6); *Earth and Space Science* (1); *Meteorologische Zeitschrift* (2); *World Journal of Engineering* (3); *Journal of Hydrology: Regional Studies* (2); *Forest Science and Technology* (2); *Scientific Reports* (7); *Regional Environmental Change* (1); *Ocean-Land-Atmosphere Research* (1); *Environmental Monitoring and Assessment* (1); *Modeling Earth Systems and Environment* (1).

OUTREACH and PRESS

(In Spanish) Los Vientos que Moldean el Clima de un Continente, Published in ANDEX, Feb. 2025, [\[Link\]](#)

European Union, “Deforestation and Forest Degradation in the Amazon -Update for year 2023 and assessment of humid forest regrowth, Publications Office of the European Union, 2025, [\[Link\]](#)

Spring Nature Research Communities, “How ENSO and PDO Control South America’s Low-Level Jets and Rainfall Extremes”, Dec. 2024, [\[Link\]](#)

UCSB Geography, “Three Geography PhD Students win a NASA Early Career Research grant” Feb. 2024, [\[Link\]](#)

World Research Institute, “Restoring Degraded Forests Could Bring Back Lost Rainfall, Cooler Temperatures” Apr. 2023, [\[Link\]](#)

European Union, “Deforestation and forest degradation in the Amazon : status and trends up to year 2021”, [\[Link\]](#)

Eos Magazine, “How Climate Change Is Affecting Women in the Amazon” Nov. 2022, [\[Link\]](#)

Translational Ecology, “Arboreal Dimensions of Biodiversity” Aug.2021, [\[Link\]](#)

Water Production Connections, “Research Memo: Amazon rainforests mitigate drought in Rondônia” July. 2021, [\[Link\]](#)

Eos Magazine, “Editors' highlights: Upwind Forest Buffers Rondônia Cropland Against Regional Drought?” Apr. 2021, [\[Link\]](#)

American Association of Geographers Climate Specialty Group Student Spotlight. March.2021, [\[Link\]](#)
Water Production Connections, “Research Memo: Identifying Pasture with Trees in Satellite Imagery” Aug. 2020, [\[Link\]](#)

PROFESSIONAL TRAINING and AFFILIATIONS

American Geophysical Union (AGU); American Meteorological Society (AMS)
American Association of Geographers (AAG)
Young Earth System Scientists Community
Collaborative Institutional Training Initiative (CITI) Research Certificate (2023-2026)
The California Environmental Quality Act (CEQA) Practicum, Association of Environmental Professionals

ABSTRACT

Dynamics and Projections of Northerly Low-Level Jets on the Eastern Slopes of the Andes and Mesoscale Convective Systems in South America

by

Ye Mu

The South American hydroclimate is driven by the transport of heat, moisture, and momentum from the deep tropics into the subtropics. This moisture advection is primarily facilitated by northerly low-level jets (LLJs) channeled along the eastern slopes of the Andes, which serve as the primary catalyst for the continent's most extreme weather, specifically, Mesoscale Convective Systems (MCSs). However, predicting the variability of this coupled LLJ-MCS relationship across historical and future climates remains a critical challenge due to complex, multiscale atmospheric interactions. This dissertation investigates the spatiotemporal variability of northerly LLJs and their multiscale controls on Mesoscale Convective Systems (MCSs), spanning from historical oceanic teleconnections to high-resolution projections of future climate change. Chapter 1 investigates the synoptic-scale variability of distinct LLJ branches (Central, Northern, and Andes) driven by coupled oceanic teleconnections. This work demonstrates that constructive phase interactions between the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) dynamically dictate

regional precipitation. Coincident warm PDO and El Niño phases heavily favor the Central LLJ, driving intense moisture flux and extreme precipitation into the subtropics, whereas cold phases suppress the Central branch and shift moisture convergence toward the western Amazon. Chapter 2 quantifies the downstream thermodynamic and kinematic impacts of these jets on deep convection. Using kilometer-scale Weather Research and Forecasting (WRF) simulations and satellite-based feature-tracking, this research explicitly links LLJ intensity to MCS characteristics. Results indicate that enhanced Central and Andes LLJs generate profound low-level moisture flux convergence and vertical wind shear, significantly increasing the initiation frequency, spatial extent, duration, and peak precipitation rates of MCSs across the La Plata Basin. Chapter 3 projects the future evolution of this coupled atmospheric system under a $\sim 3^\circ\text{C}$ warming scenario using a Pseudo-Global Warming (PGW) framework. Multi-decadal convection-permitting projections reveal a widespread thermodynamic intensification of precipitation, characterized by a sharp dynamic bifurcation in storm structural evolution. In the subtropics, strengthened background northerly flow enhances vertical wind shear, facilitating the upscale growth of larger, longer-lived MCSs. Conversely, weakened Northern LLJs over the western Amazon shift historical squall lines toward loosely organized convective clusters. Altogether, by explicitly resolving storm-scale physics without reliance on convective parameterization, this research highlights a regime shift in South America's hydrometeorological hazard profile. The findings demonstrate that future extreme precipitation will be governed not merely by thermodynamic scaling, but by spatially distinct, dynamically driven changes in storm morphology, duration, and peak intensity.

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I. Introduction

The hydroclimate of South America is characterized by complex interactions between massive topographical features, vast terrestrial biomes like the Amazon basin, and large-scale atmospheric circulation patterns. Central to this coupled system is the transport of heat, moisture, and momentum from the deep tropics into the subtropics, a process primarily facilitated by northerly low-level jets (LLJs) channeled along the eastern slopes of the Andes mountains. The LLJ is a wind speed maximum that occurs at the boundary layer of the Earth's atmosphere, typically in the lowest few kilometers of the atmosphere. It is characterized by strong and sustained wind speeds that are accompanied by vertical and horizontal shear. LLJs transport heat, moisture, and momentum between the surface and the atmosphere (Stensrud 1996). Nocturnal low-level jets (NLLJ) have their peak cycles at nighttime and are often observed in North America, Africa, South America, and other parts of the world (Bonnor 1968; Stensrud 1996; Marengo et al., 2004; Montini et al., 2019; Munday et al., 2021).

A. Northerly Low-level Jets in South America

The most studied NLLJ for South America is called the South American Low-level Jet (SALLJ), located on the eastern slope of the Andes. The first extensive observations came from the South American Low-Level Jet Experiment (SALLJEX) (Vera et al., 2006), which resulted in 22 upper-air measuring stations and radiosonde launches during the austral 2002-2003 warm season. Besides SALLJEX, most studies rely on reanalysis, modeling, and satellites. The SALLJ reaches

maximum wind speeds near the 850-hPa level (Salio et al., 2002; Montini et al., 2019) and is identified in vertical wind profiles in Santa Cruz de La Sierra, Bolivia, and Mariscal Estigarribia, Paraguay (Montini et al., 2019). SALLJ exhibits spatial and temporal variability in its location, strength, and frequency of occurrence. It is present year-round but most frequent and intense during austral spring and summer, particularly over the central and southern portions of South America. The jet experiences strong diurnal cycles with maximum winds around 0600 - 1200 UTC (0200-0800 in Bolivia) (Marengo et al., 2004), and interannual variations due to changes in large-scale atmospheric circulation patterns. The climatological features of SALLJ have important implications for regional weather and climate, particularly in terms of precipitation patterns and extreme events such as floods and droughts.

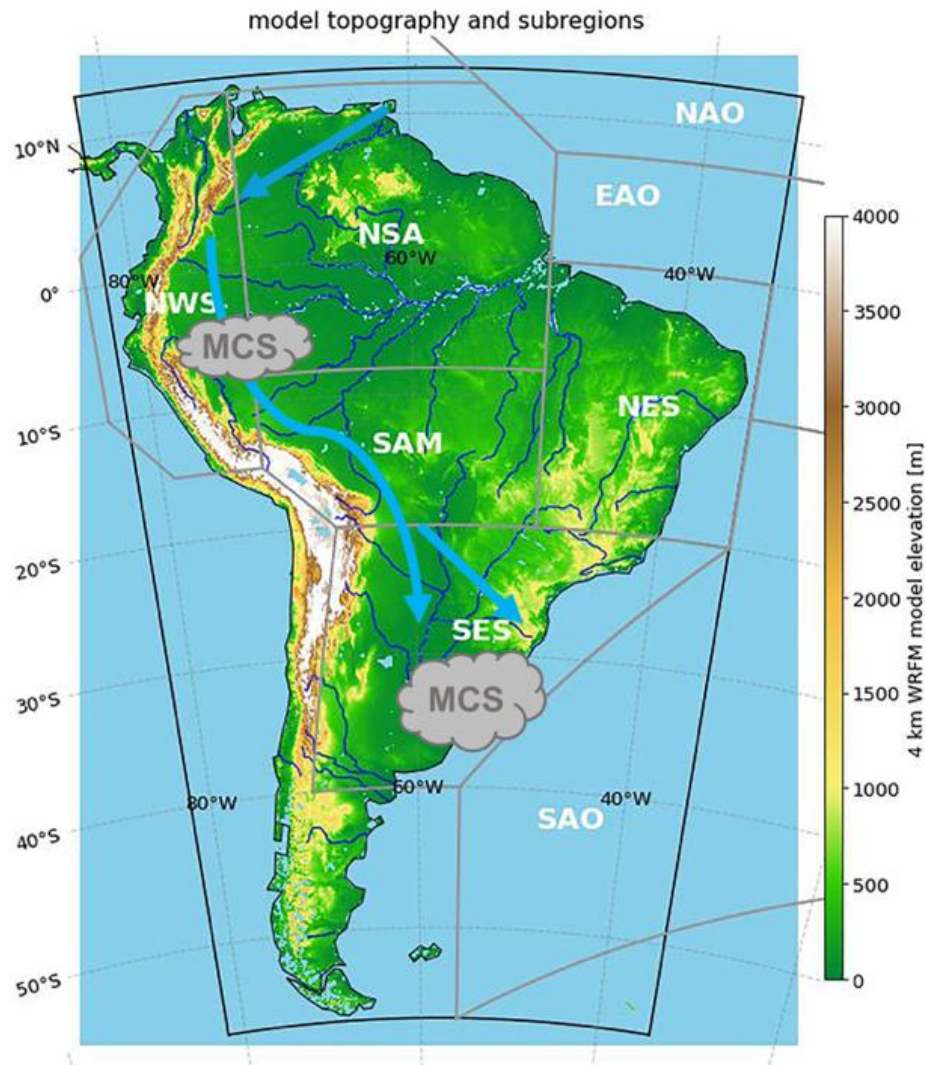


Figure 1.1. WRF Simulation domain (outline of filled contours), model topography (colored contour), Low-level Jet (blue arrow) and MCS diagram (cloud shape). The regions are the same as in the IPCC sixth assessment report) and include Northwest South America (NWS), Northern South America (NSA), Equatorial Atlantic Ocean (EAO), South American Monsoon region (SAM), Northeast South America (NES), Southeast South America (SES), and the South Atlantic Ocean (SAO). Figure adapted from Prein et al. (2024).

B. Large-Scale Forcings of Low-Level Jets

The transport of moisture across South America is a fundamental component of the continent's hydrologic cycle, heavily dependent on the LLJs. Operating near the 850-hPa level, the LLJ transports large amount of heat and moisture from the Atlantic Ocean and deep Amazonian tropics into the subtropical plains of the La Plata Basin (LPB) (Vera et al., 2006). While historically treated as a single, uniform entity, recent observational and reanalysis advancements have categorized these jets into distinct spatial branches, namely the Central, Northern, and Andes types, each exhibiting unique spatiotemporal life cycles and localized downstream atmospheric impacts (Jones et al., 2023).

Understanding the interannual and decadal variability of these specific LLJ types is critical, as fluctuations in their intensity dictate prolonged periods of drought or severe flooding. This variability is modulated by large-scale oceanic teleconnections, specifically the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Rojas et al., 2022; Adduca et al., 2025). Rojas et al. (2022) demonstrated that the phase combinations of ENSO and the PDO interact constructively to dictate regional climate anomalies across the Andes and the Altiplano. For instance, warm phases of the PDO and El Niño events create upper-level atmospheric conditions, such as the amplification of the subtropical jet, that heavily favor moisture transport into southern South America. Conversely, La Niña conditions and cold PDO phases shift the large-scale circulation, altering moisture convergence zones and pushing extreme precipitation closer to the western Amazon (Rojas et al., 2022; Garreaud et al., 2003). Despite these recognized teleconnections,

a critical gap remains in quantifying exactly how these interacting oceanic forcings uniquely regulate the duration, frequency, and specific spatial propagation of the distinct Central (SALLJ), Northern, and Andes LLJ types over multi-decadal timescales.

C. Downstream Impacts on Precipitation

The LLJ transports substantial amounts of heat and moisture from the Atlantic Ocean and Amazon region to the subtropics of South America throughout the year (Berbery and Barros 2002; Marengo et al., 2004; Nascimento et al., 2016; Jones 2019). From 1902 to 2020, precipitation in the LPB in southern South America (SESA) demonstrated a notable 27% increase during the austral summer season (DJF) (Varuolo-Clarke et al., 2022). The SALLJ influences the occurrence of deep moist convection and heavy precipitation associated with the Mesoscale Convective Systems (MCSs) in SESA due to a combination of low-tropospheric air ascent in its exit region or mountain ranges, and upper-level capping inversion inhibiting convection (Romatschke and Houze 2013; Rasmussen et al. 2016; Salio et al. 2007). In the subtropical regions of South America, particularly the LPB, MCSs are responsible for 60% to 90% of summertime precipitation and represent some of the most intense convective storms globally (Velasco & Fritsch, 1987; Gilmour et al., 2026).

The Amazon is one of the three main centers of action of deep convection around the tropical belt and a major moisture source for other parts of South America. Marengo et al. (2004) found that the SALLJ brings tropical maritime air (cold season) and tropical moist air (warm season) from the Amazon to southern Brazil

and northern Argentina. By transporting moisture originating in the equatorial Atlantic and evaporation from the Amazon to extratropical latitudes in the LPB, the SALLJ is a principal mechanism supplying water vapor to precipitation. Low-level convergence in the SALLJ exit region can induce uplift and instability for convection. During the 1997-1998 spring-summer season, Saulo et al. (2000) found that the LPB had a net convergence of moisture flux in both seasons with a southward flux that strongly correlated with the SALLJ. During the Chaco Jet events (central SALLJ), the flux of moisture and low to mid-level convergence is about 10 times more intense than the mean during the austral summer season (1979-1993) over southeastern South America (Salio et al., 2002). On monthly scales, Nascimento et al. (2016) observed that moisture convergence during the SALLJs accounts for 48% of the monthly mean rainfall.

Historically, accurately representing these systems has been a significant challenge for coarse-resolution global climate models, which rely on parameterized convection and often introduce regional precipitation biases. However, the advent of high-resolution, convection-permitting models (CPMs), such as the Weather Research and Forecasting (WRF) model operating at kilometer-scale grid spacings, allows for the explicit resolution of convective updrafts without parameterization (Prein et al., 2024). By analyzing CPM simulations alongside satellite-based tracking algorithms, it is now possible to definitively quantify how variations in LLJ intensity dictate the spatial patterns, initiation frequency, and precipitation intensity of MCSs east of the Andes.

D. Future Projections in a Warming Climate

As global temperatures rise, the thermodynamic capacity of the atmosphere to hold moisture increases, fundamentally altering the hydrologic cycle and introducing new risks to regional stability. Predicting how the complex interactions between LLJs and MCSs will respond to anthropogenic climate change is paramount for water resource management and disaster mitigation. Multi-decadal convection-permitting climate simulations over South America under high-emission scenarios (e.g., RCP8.5) project significant shifts in regional precipitation regimes (Kahana et al., 2024).

In the Amazon Basin, models project an intensification of the dry season, lengthened dry spells, and a potential reduction in the terrestrial moisture pool available for transport by the LLJs (Kahana et al., 2024). Despite mean drying in certain tropical regions, the subtropics, including southeastern Brazil and the LPB, are projected to experience a robust increase in precipitation intensity and the frequency of extreme events. High-resolution projections indicate that the convective cores of future MCSs will produce significantly higher maximum precipitation rates, driven by altered atmospheric instability and moisture availability (Gilmour et al., 2026). Consequently, utilizing convection-permitting models to project the future state of LLJs and MCSs bridges the critical gap between large-scale climate change and localized extreme weather impacts in South America.

E. Dissertation Objectives

The primary objective of this dissertation is to investigate the multiscale dynamical interactions governing South America's hydroclimate pipeline from the

large-scale oceanic forcings that dictate moisture transport to the mesoscale storm environments they generate, and to project how this coupled system will evolve under anthropogenic climate warming. By bridging the gap between historical synoptic variability and future high-resolution climate projections, this research aims to advance our predictive understanding of extreme precipitation events across the continent.

To achieve this overarching goal, the research is driven by three specific objectives, which are addressed sequentially in the subsequent chapters:

1. To examine the influence of large-scale oceanic teleconnections on the activity of the LLJ and precipitation in South America during austral summers (Chapter 1).

Despite the known importance of the South American Low-Level Jet (SALLJ), its regional variations remain under-examined over multi-decadal timescales. This objective seeks to isolate the distinct Central, Northern, and Andes LLJ types and evaluate how the interactive phases of the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) govern their frequency, duration, and downstream precipitation patterns.

2. To determine the thermodynamic and kinematic impacts of LLJ variability on the characteristics of Mesoscale Convective Systems (MCSs) east of the Andes (Chapter 2).

Building upon the synoptic frameworks established in Chapter 1, this objective transitions to the mesoscale to investigate the direct atmospheric response to LLJ-driven MCSs. Utilizing kilometer-scale, convection-permitting regional climate models (CPRCMs) coupled with advanced storm-tracking algorithms, this research

aims to quantify how changes in specific LLJ types affect the initiation frequency, size, duration, and precipitation rates of downstream MCSs in the La Plata Basin and western Amazon.

3. To project the future evolution of the LLJ-MCS coupled system under anthropogenic climate warming scenarios (Chapter 3).

As global temperatures rise, the fundamental components of South America's hydrologic cycle will be altered. Because coarse-resolution models cannot accurately resolve mesoscale storm dynamics, this final objective employs multi-decadal convection-permitting climate projections to assess future vulnerabilities. The goal is to determine how warming-induced changes to atmospheric instability and regional moisture pools will alter LLJ behavior, and subsequently, how these shifts will impact the intensity and frequency of extreme, MCS-driven precipitation events across the continent.

This dissertation fundamentally advances our understanding of South America's hydroclimate by bridging the critical gap between large-scale oceanic teleconnections (ENSO and PDO) and the localized, extreme precipitation produced by Mesoscale Convective Systems (MCSs). By utilizing high-resolution, convection-permitting regional climate models, this research explicitly resolves storm-scale physics, significantly reducing uncertainties in historical analyses and future projections of extreme weather in a warming world. Beyond its scientific contributions, the findings provide actionable, highly localized risk assessments crucial for societal resilience; predicting the future behavior of low-level jet-driven rainfall is essential for optimizing agricultural security in the globally vital La Plata Basin, updating

infrastructure to mitigate intensifying flood disasters, and equipping regional policymakers with the precise data needed for effective climate adaptation strategies.

Table 1.1. List of abbreviations and acronyms used throughout this dissertation

ABBREVIATION	DEFINITION
AMO	Atlantic Multidecadal Oscillation
CESM2	Community Earth System Model 2
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CIN	convective inhibition
DJF	December - February
ENSO	El Niño Southern Oscillation
ERA5	fifth-generation European Centre for Medium-Range Weather Forecasting atmospheric reanalysis
GCM	General circulation model
IMERG	Integrated Multi-satellite Retrievals for GPM
IVT	Vertically integrated water vapor transport
LENS2	CESM2 Large Ensemble
LLJ	Low-Level Jet
LPB	La Plata Basin
MCS	Mesoscale Convective System
NCAR	National Center for Atmospheric Research
NDJFM	November – March
NLLJ	Nocturnal low-level jet
PDF	Probability density function
PDO	Pacific Decadal Oscillation
PDV	Pacific Decadal Variability
PGW	Pseudo-Global Warming
PSA	Pacific–South American

RKW	Rotunno-Klemp-Weisman theory
SA	South America
SAAG	South America Affinity Group
SACZ	South Atlantic Convergence Zone
SALLJ	South American Low-Level Jet
SALLJEX	South American Low-Level Jet Experiment
SAM	South American Monsoon
SAO	South Atlantic Ocean
SASH	South Atlantic Subtropical High
SESA	Southeastern South America
SST	Sea surface temperatures
TOBAC	Tracking and Object-Based Analysis of Clouds
TRMM	Tropical Rainfall Measuring Mission
U200	Zonal winds (200-hPa)
UTC	Coordinated Universal Time
V850	Meridional winds (850-hPa)
VPD	Vapor pressure deficit
WRF	Weather Research and Forecasting Model
Z200	Geopotential height (200-hPa)

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II. Pacific decadal oscillation and ENSO forcings of northerly low-level jets in South America

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Charles Jones, Leila M. V. Carvalho, Lulin Xue, Changhai Liu & Qinghua Ding

Abstract

The hydrological cycle in South America during austral summer, including extreme precipitation and floods, is significantly influenced by northerly low-level jets (LLJs) along the eastern Andes. These synoptic weather events have been associated with three different types of LLJs (Central, Northern, and Andes) and are sensitive to remote large-scale forcings. This study investigates how tropical forcings related to El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) regulate the duration and frequency of each LLJ type and their impacts on extreme precipitation. Our analysis reveals that ENSO and PDO are important in driving the variability of LLJs over the past 65 years. Specifically, the Central LLJ type is more prevalent during El Niño and Warm/Neutral PDO phases, leading to heightened extreme precipitation in southern South America. Conversely, La Niña years during Cold PDO phases tend to favor the Northern and Andes LLJs, which are associated with increased precipitation extremes in the western Amazon and southeastern South America. Central and Andes LLJs tend to persist longer during these favored conditions, causing more pronounced precipitation events in the areas under their influence. This study enhances our understanding of the influence of

large-scale atmospheric forcings on the regional precipitation dynamics in South America.

A. Introduction

Low-level jets (LLJs) are highly efficient in transporting heat, moisture, and momentum due to their strong intensity and the availability of abundant lower-atmosphere moisture. Originating from local-to-regional boundary layer processes, LLJs typically peak at nighttime and are observed across diverse climates (Bonnor 1968; Stull 1988). They usually feature a horizontal extension ranging over hundreds to thousands of kilometers, influenced by topographic features and atmospheric pressure gradients. Vertically, they exhibit a pronounced wind speed maximum near the 850 hPa level, which facilitates enhanced moisture transport, particularly during nocturnal stable conditions (Stensrud 1996; Marengo et al., 2004; Montini et al., 2019). In addition, LLJs are not only influenced by synoptic-to-large-scale atmospheric circulation patterns in their local area but also by remote forcing mechanisms (Silva and Ambrizzi 2006; Jones and Carvalho 2018; Reboita et al., 2021; Builes-Jaramillo et al., 2022). Despite recent advancements, we still lack a comprehensive understanding of their local and remote forcing mechanisms and related impacts on precipitation beyond the synoptic time scale. Here, for brevity, we refer to nocturnal northerly low-level jets along the eastern Andes, which is the most essential feature of LLJs over South America, as simply LLJs.

In South America, three types of LLJs along the eastern Andes have been identified (Jones et al., 2023). The Central type, also known as the South American low-level Jet (SALLJ), is located along the eastern slopes of the central Andes

(Bolivia, Paraguay, northern Argentina), playing a vital role in precipitation and often triggering heavy rainfall and mesoscale convective systems (MCSs) in southeastern South America (Berbery and Barros 2002; Marengo et al., 2004; Salio et al., 2007; Romatschke and Houze 2013; Rasmussen and Houze 2016; Nascimento et al., 2016; Jones 2019; Jones et al., 2023). The Northern type, also known as Orinoco LLJ, is found in the northern Andes (northeastern Peru, Colombia, Venezuela) and brings Atlantic moisture inland, enhancing rainfall in the northern Andes and western Amazon (Builes-Jaramillo et al. 2022; Espinoza et al. 2020; Jiménez-Sánchez et al. 2020; Jones 2019; Jones et al., 2023; Martinez et al. 2022; Mu et al., 2023; Torrealba & Amador 2010). In addition, Jones et al. (2023) identified the Andes (simultaneous occurrence in northern and central Andes), and Peru (short-lived and less frequent) types.

The interaction between upper-level wave trains and the subtropical jet has significant implications for the activity of the LLJ. The upper-level Rossby wave trains, often initiated by large-scale atmospheric phenomena such as the El Niño/Southern Oscillation (ENSO), propagate along the subtropical jet, modifying LLJ strength and position. During El Niño phases, these wave trains often strengthen the subtropical jet by amplifying zonal wind speeds and creating positive 200 hPa geopotential height anomalies, which enhance the meridional pressure gradient, driving stronger Central LLJ events (Wang & Fu 2004). Remote forcings from the equatorial Pacific on intraseasonal-to-interannual time scales influence the variability and evolution of LLJs (Jones et al., 2023). On interannual time scales, for instance, ENSO plays an important role in linking LLJs and precipitation in South America. El Niño years increase the frequency and duration of Central LLJ events,

which, in turn, extend the duration of precipitation events in South American subtropical region (SESA). In contrast, La Niña years favor an increase of Northern LLJ events and their duration, leading to greater persistence of precipitation in the central Andes and southwestern Amazon.

Other modes of low-frequency variability such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) also have a significant impact on climate variability in South America (e.g. Silva et al., 2009; Grimm & Saboia 2015; Grimm et al., 2016; Carvalho and Cavalcanti, 2016; Kayano et al. 2018; Jones et al., 2023). The PDO, for example, has been shown to influence the South American climate by modulating rainfall variability, which can lead to extreme climate conditions such as floods and multi-year droughts (Reboita et al., 2021; Grimm & Saboia 2015). During the warm phase of the PDO, southeastern South America experiences positive precipitation anomalies, whereas negative precipitation anomalies occur in northern South America. In the cold PDO phase, the pattern reverses (Andreoli & Kayano 2005; Dong & Dai 2015; Silva et al., 2020). In addition, the warm and cold phases of the PDO can enhance the El Niño and La Niña phases and amplify their teleconnections (Maher et al., 2022). During the warm phases of PDO and El Niño, there is an intensification of warm water conditions in the tropical Pacific, leading to further weakening of the trade winds and more extreme wet-dry conditions across various regions of the globe (Wang et al., 2014; Lee et al., 2019). The AMO-negative phase can strengthen and displace the South Atlantic Convergence Zone, shifting its precipitation band further south. This displacement could enhance the Andes LLJs, particularly those directed toward southeastern Brazil, due to increased moisture transport and favorable large-scale

atmospheric circulation patterns. However, during this phase, Central LLJ activity is often weakened, which may be attributed to changes in the meridional pressure gradient and altered moisture pathways that favor the Andes region (Jones & Carvalho 2018; Reboita et al., 2021).

While previous studies have investigated how ENSO modifies the variability of LLJs in South America (Marengo et al., 2004; Montini et al., 2019; Builes-Jaramillo et al., 2022; Jones et al., 2023), the relationships among ENSO, PDO, and LLJs have not been fully studied and understood. The main objective of this study is to decipher the role of large-scale modes on the variability of LLJs and precipitation extremes in South America on interannual-to-decadal time scales. Specifically, building upon Jones et al. (2023), this study aims to investigate the importance of the joint variability of ENSO and PDO in controlling the activity of the LLJ and precipitation in South America during austral summers. We use 65 years of reanalysis to characterize the LLJ variability and large-scale teleconnections associated with ENSO and PDO. Since the typical period of the AMO spans several decades, and only one complete cycle has been observed over the past 65 years, we do not examine its impacts. A particular emphasis is placed on the linkages among ENSO-PDO, LLJ activity in the northern and central Andes, and extreme precipitation across South America. Decadal changes in precipitation in South America are also assessed with a combination of reanalysis and observed gridded precipitation.

B. Methods

The European Centre for Medium-Range Weather Forecasts reanalysis v5 (ERA5) (Hersbach et al., 2020) (available from 1940 to 2023) was used to identify LLJs, climatology, variability, and large-scale forcings. ERA5 was used with $0.25^\circ \times 0.25^\circ$ latitude/longitude resolution during austral summers (December 1st–Feb 28, 1957–2022) (DJF). Variables used include u-velocity, v-velocity at 850-hPa and 700-hPa pressure levels, geopotential height at 200-hPa, and precipitation. Precipitation was used with daily resolution and all other variables at the hourly resolution. We found a discontinuity in ERA5 data in representing the frequency and intensity of all LLJ types from 1940 to 1956 and, therefore, the analysis excluded data prior to November 1957 (see examples in Supplementary Fig. 2.5). LLJ definition was based on: (a) nighttime (23-09 UTC) wind speed (850-hPa) greater than the 75th percentile of the monthly frequency distribution; (b) wind shear between 850-hPa and 700-hPa greater than the 75th percentile; and (c) spatial extent is identified by contiguous regions of wind speeds greater than 10 m s^{-1} . The detailed LLJ identification method is described in Jones et al. (2023). The Northern LLJ occurs along the eastern Andes from Venezuela to Peru, while the Central LLJ occurs in Bolivia and Paraguay. The Andes LLJ occurs simultaneously in the northern and central Andes. The Peru LLJ type occurs primarily in central eastern Peru and is characterized by its short-lived nature and small spatial extent. The Peru-type LLJ, being the least frequent, was not included in this study. LLJ frequency refers to the total days of LLJ occurrence for each year from December to February, and the LLJ intensity refers to the mean wind speed (850-hPa) in the LLJ

spatial extent where the wind speed is greater than 10 m s^{-1} . Figure 2.1 shows the annual summertime time series of frequency and intensity as well as linear trends for each type. Trends are based on Mann–Kendall tests statistically significant at 95% confidence.

ENSO classification was based on the Climate Prediction Center, National Centers for Environmental Prediction (<https://origin.cpc.ncep.noaa.gov/>) from 1957 to 2022. The Pacific Decadal Oscillation (PDO) index data was obtained from the National Centers for Environmental Information (NCEI) (<https://www.ncei.noaa.gov/access/monitoring/pdo/>) and covered the period from December 1957 to February 2022. The mean (μ) and standard deviation (σ) of the PDO index for the December to February period were calculated. A classification function was developed to categorize the PDO index values into three phases: Warm, Cold, and Neutral. The criteria were based on the mean and standard deviation of the PDO index, using a 0.5 standard deviation threshold: Warm Phase: $\text{PDO} > \mu + 0.5\sigma$; Cold Phase: $\text{PDO} < \mu - 0.5\sigma$; and Neutral Phase: $\mu - 0.5\sigma \leq \text{PDO} \leq \mu + 0.5\sigma$. The dominant phase for each season year was determined by identifying the phase with the highest count within that season. To discriminate the joint effects of PDO and ENSO phases on the types of LLJ, they are combined for eight joint phases, including EN+ Warm PDO, EN+Cold PDO, EN+Neutral PDO, LN+Warm PDO, LN+ Cold PDO, LN+Neutral PDO, Neutral ENSO+ Warm PDO, Neutral ENSO+ Cold PDO. For each pair of phase combinations, we constructed a contingency table and performed a Two-Tailed Z-test to compare the LLJ occurrences. The proportions of occurrences were calculated for each combination, and the difference in these proportions between the two combinations was

computed. A P value threshold of 0.05 was used to determine significance, with P values below this threshold indicating significant differences.

To focus on the extratropic Rossby wave trains affecting South America (Yang et al., 2018), daily ERA5 200-hPa geopotential height was filtered to retain variations between 2.5 and 30 days and eastward propagating 1–15 zonal wavenumbers (Figs. 2.6–2.8). To show circulation anomalies during LLJs, the annual cycle was removed from the time series of U and V at 850-hPa and 200-hPa by subtracting the climatology determined with the first two harmonics. Basic states comparison (Fig. 2.9) uses the V850 anomalies during El Niño and La Niña combined with Warm, Cold, and Neutral PDO phases during DJF. Anomalies statistical significance is based on two-sample t test at 95% confidence level.

Daily precipitation data over South America were obtained from the ERA5 precipitation (0.25°, 1957–2023), CPC Global Unified Gauge-Based Analysis of Daily Precipitation (0.5°, 1979–2023) (Chen et al., 2008), and the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2015).

Supplementary Fig. 2.4 presents the aggregated precipitation data for the South American subtropical region (SESA). It is derived by first summing the daily precipitation amounts over the DJF season and then calculating the average of these sums across the SESA region. While all three precipitation datasets have inherent biases, ERA5 and CPC show trends opposite to those reported in the literature over the SESA region (Supplementary Fig. 2.4), we based our results on CHIRPS data at 0.05° resolution from 1981 to 2022. Extreme precipitation events were defined as the 95th percentile of daily precipitation. To show the LLJ influence on precipitation extremes, we defined the frequency of LLJ precipitation extremes anomaly as:

Anomaly_{LLJ precipitation extremes} =

$$\left(\frac{\#LLJ \text{ extremes events}}{\#LLJ \text{ precipitation events}} \right) \times 100\% - \left(\frac{\#No_LLJ \text{ extremes events}}{\#No_LLJ \text{ precipitation events}} \right) \times 100\%$$

In this equation, “#” denotes the number of events, and LLJ refers to the type of jet (Central, Northern, and Andes). Given that the number of LLJ events is only a subset of all precipitation events, we computed the anomaly as the difference between the ratio of LLJ extreme events and the ratio of non-LLJ extreme events. The resulting precipitation extremes anomaly is then multiplied by 100 and expressed as a percentage.

C. Results

C.1 Trends in LLJ intensity and frequency

The following analysis focuses on LLJs occurring in the northern and central parts of the Andes Mountains (see “Methods”) during austral summers (DJF). Fig. 2.1 shows the wind climatology at 850-hPa and the spatial extents of the Central, Northern, and Andes types. Note that in any given LLJ type day, the LLJ may not extend through all the spatial domain regions simultaneously (Fig. 2.1). During austral summers (1957–2022), the Northern and Central types account for 20% and 34.7% of the total LLJ cases, respectively. Moreover, consistent with Jones et al. (2023), the Andes type has the highest frequency (44.4%). The Peru LLJ type (0.9% frequency) identified in Jones et al. (2023) is excluded from this study since its frequency is much less than the other types. The three major LLJ types (Northern, Central, and Andes) account for 99% of all 4946 LLJ cases.

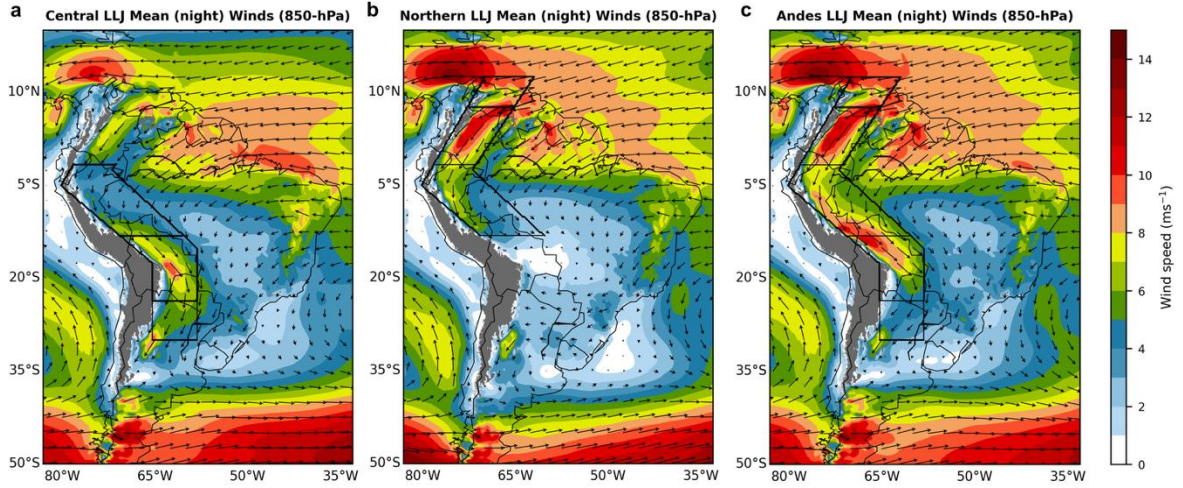


Figure 2.1. Composites of Mean DJF Nighttime Winds (850-hPa) and spatial domains for (a) Central, (b) Northern, and (c) Andes LLJ types in South America. The color shading indicates wind speed in meters per second with arrows depicting the direction and relative magnitude of the winds. Nighttime corresponds to 23-09 UTC (19:00-05:00 Bolivia local time). Black boxes show the spatial domain masks to identify LLJs.

The variability of the LLJ types during austral summer is shown in Fig. 2.2a and indicates that the Andes type is most frequent from December to February, with the Northern type being the least for all 3 months. The trends shown in Fig. 2.2 reflect changes in the frequency and intensity of LLJs over the 65-year period of the study. The observed trends provide a contextual background to understand the modulation of LLJ activity by ENSO and PDO phases. While we show trends in LLJ types (Fig. 2.2), we did not analyze trends in ENSO or PDO phases themselves, so any potential shifts in their frequency were not examined in this study. By identifying these trends, we can better interpret how ENSO and PDO influence LLJ behavior within the broader context of changing climatic conditions. Positive trends

in frequency are statistically significant for the Northern and Andes types, but Central LLJs display a significant negative trend (Fig. 2.2b–d). Interestingly, the Northern LLJ type also shows a positive significant trend in wind speeds (850-hPa) (Fig. 2.2e). These results suggest that the frequency and intensity of LLJs in the northern Andes have both increased in the last 65 years, which is consistent with Jones (2019).

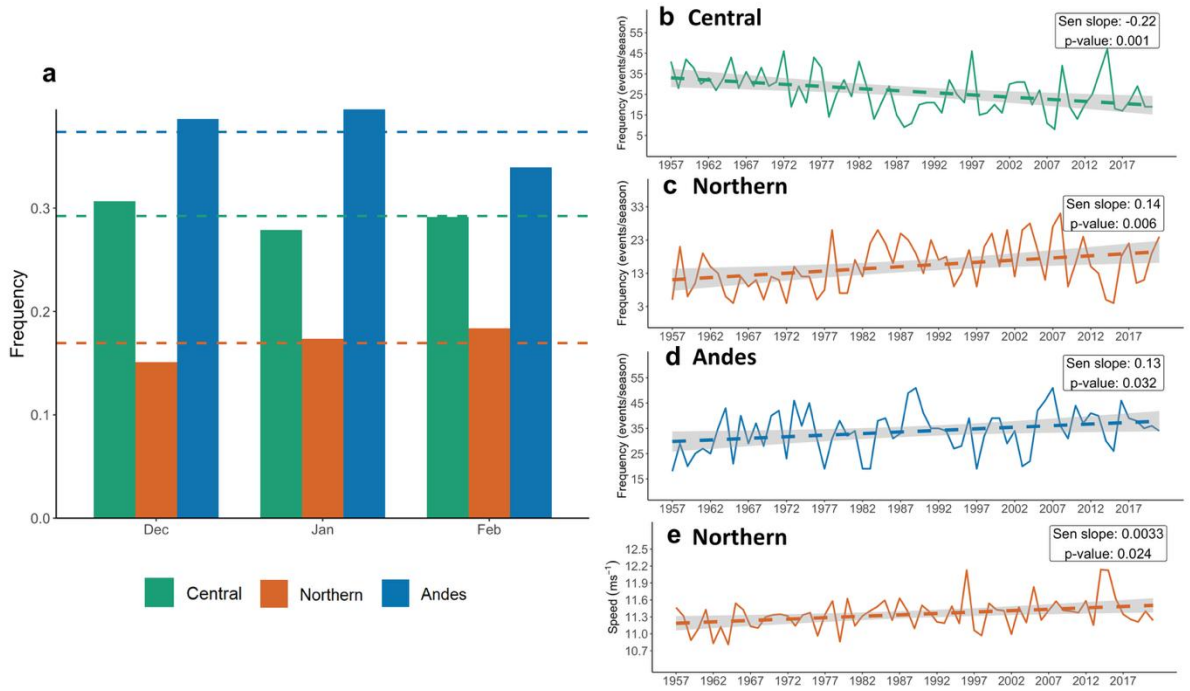


Figure 2.2. Frequency and Wind Speed Trends of Austral Summer LLJs. (a) Bars represent monthly mean frequencies of three LLJ types. Dashed lines indicate the mean frequency of the LLJ types across all months. Time series of LLJ frequency for Central (b), Northern (c), and Andes (d) types from 1957-2022. (e) Time series of LLJ wind speeds for the Northern type from 1957-2022. Dashed lines show trends with grey shading representing confidence intervals. The statistical significance of the trends, determined using Mann-Kendall tests, is shown in the insets. Monthly

LLJ frequency is calculated by dividing the number of LLJ days by the total number of days in each month.

C.2 The role of large-scale remote forcings

To examine the role of large-scale forcings connected with trends in frequency and intensity of the LLJ, we employ the National Oceanic and Atmospheric Administration (NOAA) ENSO and PDO seasonal indices along with ERA5 reanalysis. As the warm and cold phases of the PDO can enhance El Niño and La Niña episodes, respectively, and thus amplify their effects (Newman et al., 2016; Lee et al., 2019), we examined the in-phase and out-of-phase ENSO-PDO combinations. The relatively long data records and large number of LLJ cases facilitate an investigation of interannual-to-decadal large-scale forcings on the LLJs and give rise to more robust conclusions.

The variability of LLJs on interannual-to-decadal time scales is shown in Fig. 2.3, where the temporal distributions of the three LLJ types are color-coded according to warm (red), neutral (gray), and cold (blue) phases of ENSO and PDO to illustrate the joint impacts of ENSO and PDO. Note that there is only 1 year of El Niño+Cold cases, and this combination is not discussed further. For the Central LLJ, the highest frequency is observed during El Niño+Warm PDO, where 459 events were recorded, accounting for 48.3% of the total LLJ events for that ENSO-PDO joint phase (Fig. 2.3d). In contrast, the lowest frequency for the Central LLJ occurs during La Niña+Cold with 229 events. The Northern LLJ displays a different pattern, with the highest frequency during La Niña+Cold, recording 260 events (Fig. 2.3e). The Andes LLJ, on the other hand, shows its highest frequency during La Niña+Cold

phases, with 531 events, representing 52.1% of the total for that joint phase (Fig. 2.3f). The lowest frequency of the Andes LLJ is during El Niño+Warm PDO, which is 37% of the total for that joint phase.

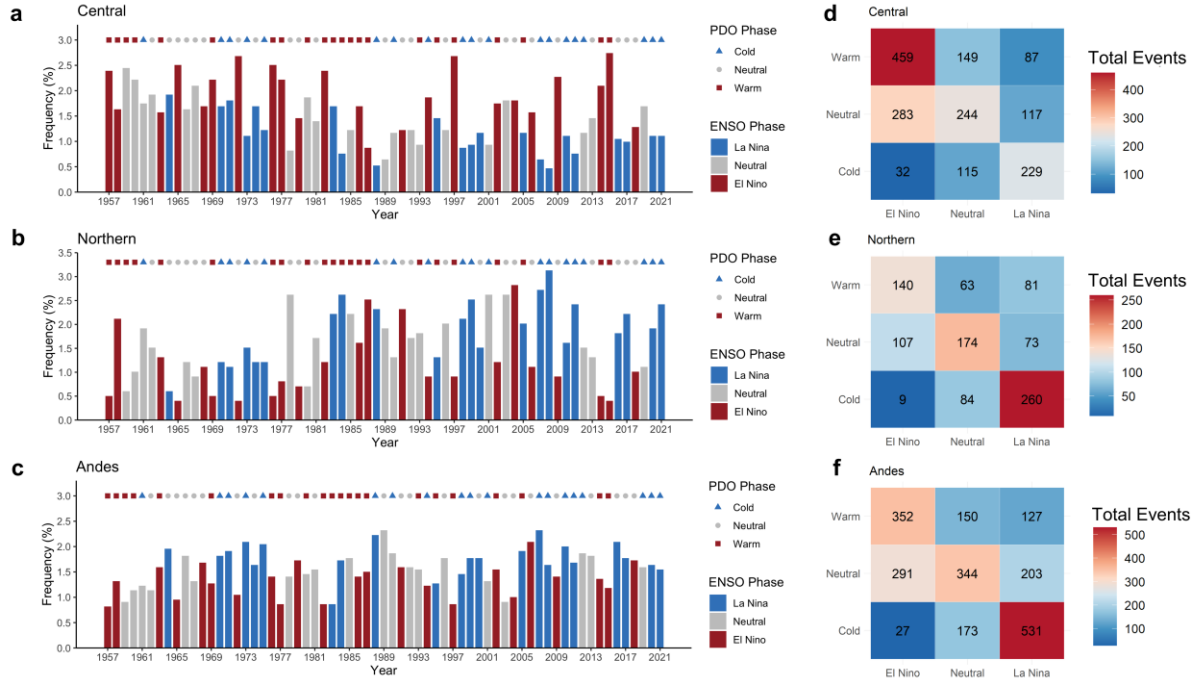


Figure 2.3. LLJ frequencies during ENSO and PDO phases. Annual frequencies (%) (DJF) of (a) Central, (b) Northern, and (c) Andes LLJ types during warm, neutral, and cold ENSO-PDO phases, and total events (days) for (d) Central, (e) Northern, and (f) Andes across all ENSO-PDO combinations. Frequency ratios in (a-c) are represented in red bars for El Niño, blue bars for La Niña, and grey bars for neutral phases. LLJ frequency ratios are calculated by dividing the number of LLJ days in each DJF season by the total LLJ days from 1957 to 2022. Red squares correspond to warm PDO, grey circles to neutral PDO, and blue triangles to cold PDO phases.

Overall, the analysis reveals distinct patterns in the frequencies of Central, Northern, and Andes LLJs during different ENSO-PDO phases. The Central LLJ shows a strong dominance during El Niño conditions, particularly when coupled with a warm PDO, while the Northern LLJ exhibits higher frequency during La Niña and cold conditions, with reduced occurrences during El Niño. The Andes LLJ exhibits a clear preference for La Niña phases, especially when combined with cold PDO, highlighting the variability in the behavior of these LLJs in response to large-scale climatic oscillations.

Figure 2.4 displays heatmaps of differences in proportions of LLJ occurrences (Central, Northern, and Andes) for various joint ENSO-PDO phases. For the Central LLJ, there are significantly higher occurrences of events during the El Niño+Warm/El Niño +Neutral compared to La Niña+Cold, La Niña +Warm, La Niña +Neutral, Neutral+Cold, and Neutral+Neutral, as indicated by the red color and asterisks (Fig. 2.4a). However, El Niño+Warm has a statistically higher frequency than both El Niño+Neutral and Neutral+Warm. Additionally, El Niño+Neutral is not higher than Neutral+Warm. The Central type also has significantly lower occurrences during the La Niña+Cold compared to all other phase combinations. This suggests that the La Niña +Cold is less favorable for the occurrence of Central LLJ compared to other phases, particularly those involving El Niño or neutral ENSO with varying PDO phases. The Northern LLJ shows a contrasting pattern with a predominance of red cells, showing statistically significant higher occurrences for La Niña+Cold/Warm compared to El Niño+Neutral/Warm, La Niña+Neutral, and Neutral+Warm (Fig. 2.4b). For the Andes type, La Niña+Cold exhibits higher occurrences compared to El Niño+Neutral/Warm, La Niña +Warm,

and Neutral+Warm/Neutral, as indicated by the red cells and asterisks. In addition, La Niña+Neutral also shows significant differences but lacks Neutral+Neutral, but both La Niña+Cold and Neutral PDO are statistically more frequent than La Niña+Warm.

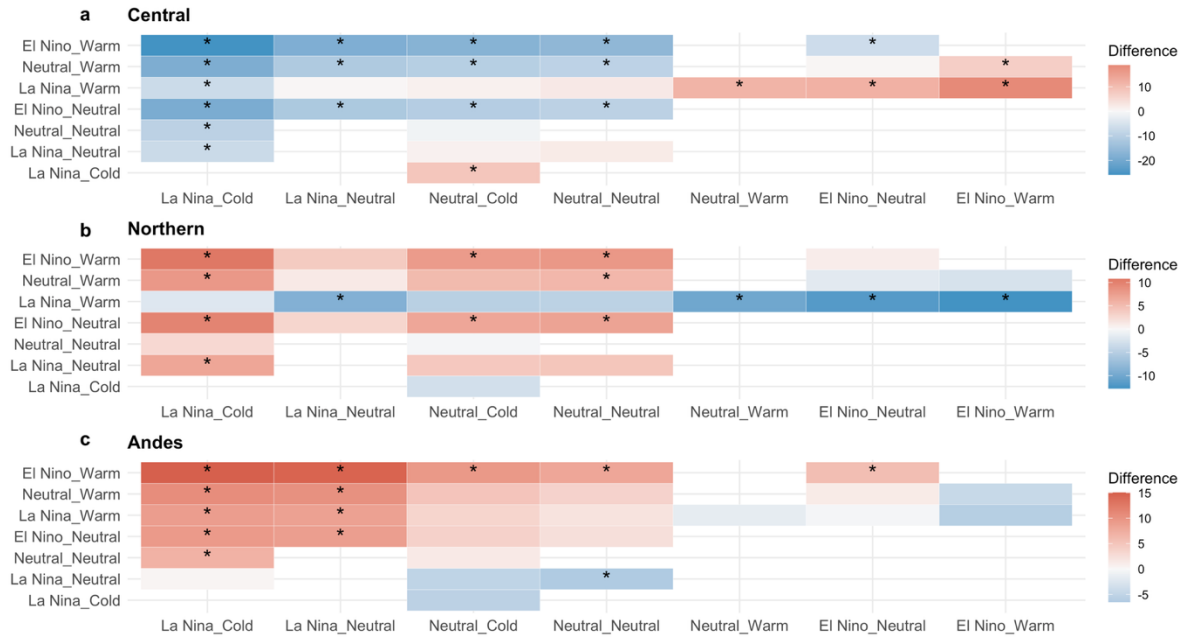


Figure 2.4. Heatmaps of differences in LLJ occurrences during ENSO-PDO phase combinations. Heatmaps display the differences in percentages of events in the (a) Central, (b) Northern, and (c) Andes LLJs for various combinations of ENSO and PDO phases. The x-axis and y-axis represent different phase combinations, with colors indicating the magnitude and direction of the differences in occurrences: blue signifies that the occurrence is lower for the phase combination on the x-axis compared to the phase combination on the y-axis, while red signifies higher occurrences for the phase combination on the x-axis compared to the phase combination on the y-axis. Asterisks (*) denote statistically significant differences determined using two-tailed Z-tests ($p < 0.05$).

Figure 2.5 illustrates the distribution of persistence for different LLJ types (Central, Northern, Andes) during various combinations of ENSO and PDO phases. The violin plots summarize the data distribution, with embedded boxplots highlighting the median and interquartile range, and outliers marked as black dots. For the Central type, the majority of the values cluster around lower persistence days, with occasional outliers indicating longer persistence of events (Fig. 2.5a). Notably, the El Niño+Warm exhibits more persistent LLJs, as indicated by the higher medians and the presence of several outliers reaching above 10 days. However, Neutral+Neutral and Neutral+Warm also exhibit long Central LLJ persistence. The Northern type shows relatively low variability across the different ENSO and PDO phases (Fig. 2.5b). The persistence values are generally lower, with fewer outliers compared to the Central and Andes types. This indicates that none of the phase combinations result in significantly higher persistence for Northern LLJs. For the Andes type, while several phase combinations, such as La Niña+Neutral and Neutral+Neutral, show comparable median persistence, the La Niña + Cold phase stands out with the highest number of outliers (Fig. 2.5c). Our findings suggest that the changes in frequency and persistence are more pronounced under the different ENSO and PDO phases. However, the mean wind speed, used as a proxy for LLJ intensity, did not show a clear pattern of variation in relation to these phases, and those results are not included here.

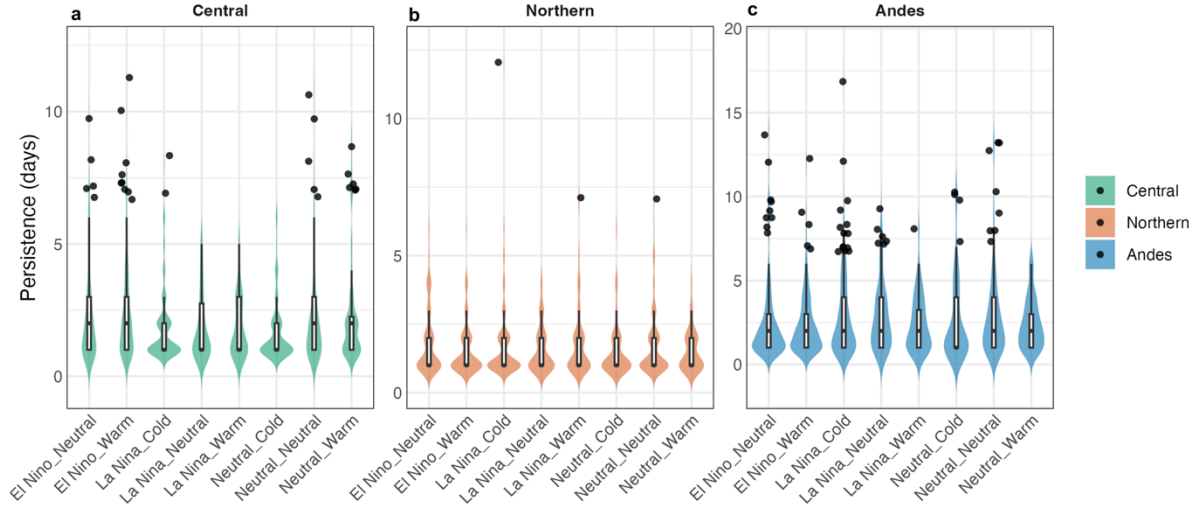


Figure 2.5. Persistence of LLJs across different ENSO and PDO phases. The violin plots show the distribution of persistence (in days) for each ENSO-PDO combination, with (a) Central, (b) Northern, and (c) Andes types represented by different colors. The boxplots inside the violins show the median and interquartile range, while the black dots represent outliers. The violin plot includes areas slightly below zero due to kernel density estimation smoothing, although no actual data values fall below zero.

To further examine large-scale atmospheric circulation patterns, Figs. 2.6–2.8 show composites of meridional winds (850-hPa, V850), zonal winds (200-hPa, U200), and geopotential height (200-hPa, Z200) anomalies during the favored phases of ENSO and PDO combinations for each LLJ type. For the Central LLJ, during El Niño+PDO phases (Figs. 2.6a, b and S2.2a), V850 anomalies generally display southerly components over northern South America and northerly components over southern South America, which may reduce the formation of Northern LLJs. The upper-level Z200 anomalies show a wave train pattern extending from the Pacific into South America, potentially modulating the

subtropical jet stream. Positive U200 wind anomalies are observed crossing the central Andes and interacting with positive/negative Z200 anomalies in subtropical South America during El Niño+Warm/Neutral PDO, possibly enhancing the subtropical jet. During La Niña, the upper-level conditions typically feature stronger zonal flows with positive anomalies over the central Pacific, which may stabilize the atmosphere and reduce convective activity, potentially reducing the Central LLJ occurrences (Fig. 2.6g, h). However, during La Niña+Warm PDO (Fig. 2.6c), V850 anomalies show strong northerly winds over central South America, indicating that individual LLJ events may be more intense during this phase. Despite these wind anomalies, the overall frequency of Central LLJ events tends to be higher during El Niño + Warm PDO phases.

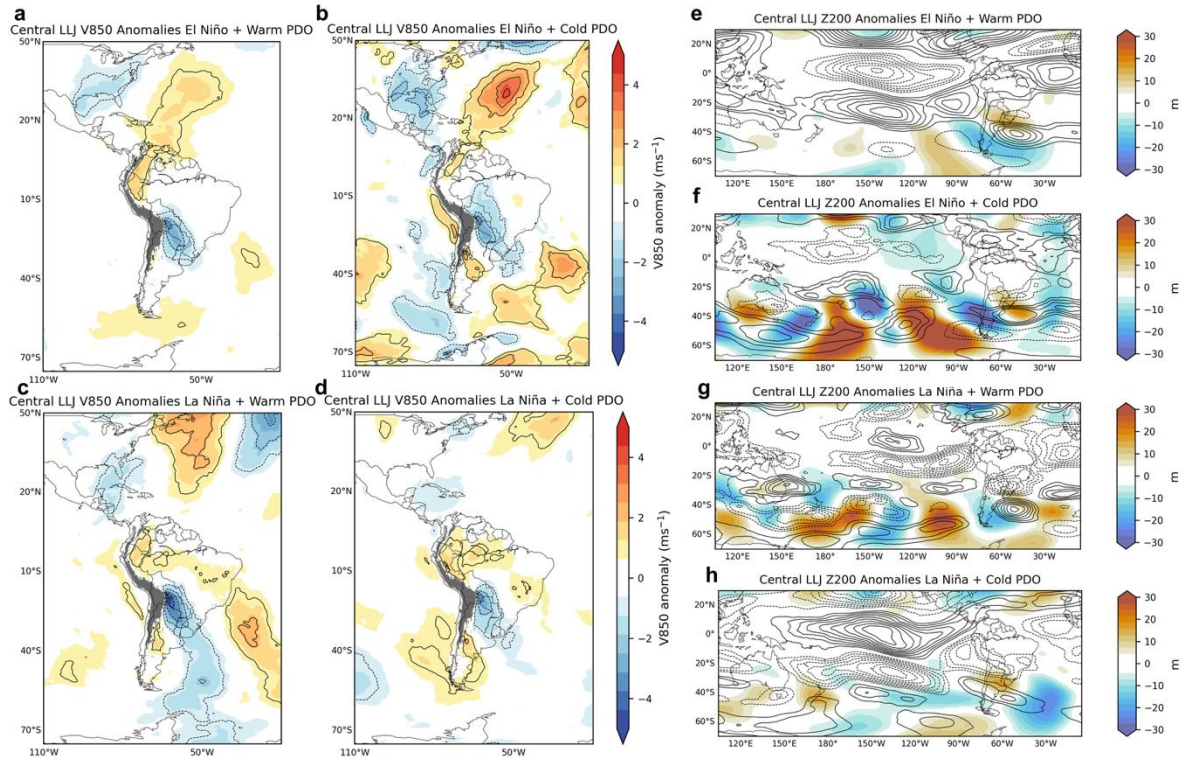


Figure 2.6. Composites of austral summer low-level (850-hPa) meridional winds and upper-level anomalies during Central LLJ and ENSO-PDO phases. The

left column shows 850-hPa meridional wind (V850) anomalies (m s^{-1}) during Central LLJ and (a) El Niño plus Warm PDO, (b) El Niño plus Cold PDO, (c) La Niña plus Warm PDO and (d) La Niña plus Cold PDO phases. The right column shows 200-hPa geopotential height (m) (Z200) and 200-hPa zonal wind (U200) anomalies during the Central LLJ type and (e) El Niño plus Warm PDO, (f) El Niño plus Cold PDO, (g) La Niña plus Warm PDO and (h) La Niña plus Cold PDO phases. Z200 anomalies are shown in colors. Positive (negative) U200 anomalies are shown in solid (dashed) contours (1 m s^{-1} interval), with zero contour omitted. Anomalies are statistically significant at a 95% confidence level.

For the Northern LLJ, V850 wind anomalies show extended southerly components over central South America during Warm PDO phases (Fig. 2.7a, c). This configuration indicates stronger southward wind flow, which might influence the typical northward transport of moist air associated with the South American Monsoon System (SAMS). La Niña combined with Cold PDO phases (Fig. 2.7c, d) tends to show northerly wind anomalies over northern South America, which could strengthen the southward flow. The upper-level anomalies are marked by negative anomalies over the central Andes which may weaken the subtropical jet and suppress the occurrence of the Central type (Fig. 2.7g, h). During La Niña, the Andes type has negative V850 anomalies in the North Atlantic and flows along the eastern slopes of the northern and central Andes (Fig. 2.8c, d). In the upper levels (Fig. 2.8e–h), the zonal propagation of Z200 anomalies seems to have less influence on the subtropical jet, though La Niña+Warm PDO favors northerly winds, potentially supporting Andes LLJ formation (Fig. 2.8c). The La Niña+Cold PDO combination also reinforces northerly wind patterns, particularly in the northern Andes domain.

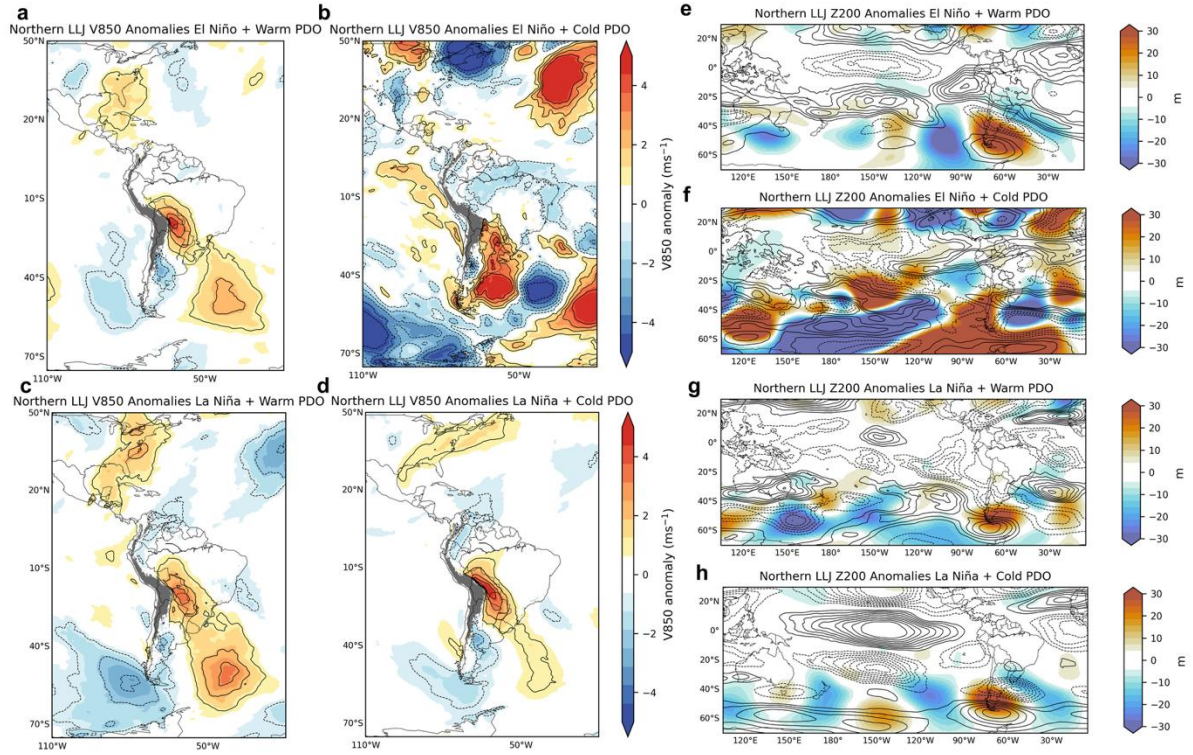


Figure 2.7. Composites of austral summer low-level (850-hPa) meridional winds and upper-level anomalies during Northern LLJ and ENSO-PDO phases. The left column shows 850-hPa meridional wind (V850) anomalies (m s^{-1}) during Northern LLJ and (a) El Niño plus Warm PDO, (b) El Niño plus Cold PDO, (c) La Niña plus Warm PDO and (d) La Niña plus Cold PDO phases. The right column shows 200-hPa geopotential height (m) (Z200) and 200-hPa zonal wind (U200) anomalies during the Northern LLJ type and ENSO plus PDO phases. Z200 anomalies are shown in colors. Positive (negative) U200 anomalies are shown in solid (dashed) contours (1 m s^{-1} interval), with zero contour omitted. Anomalies are statistically significant at a 95% confidence level.

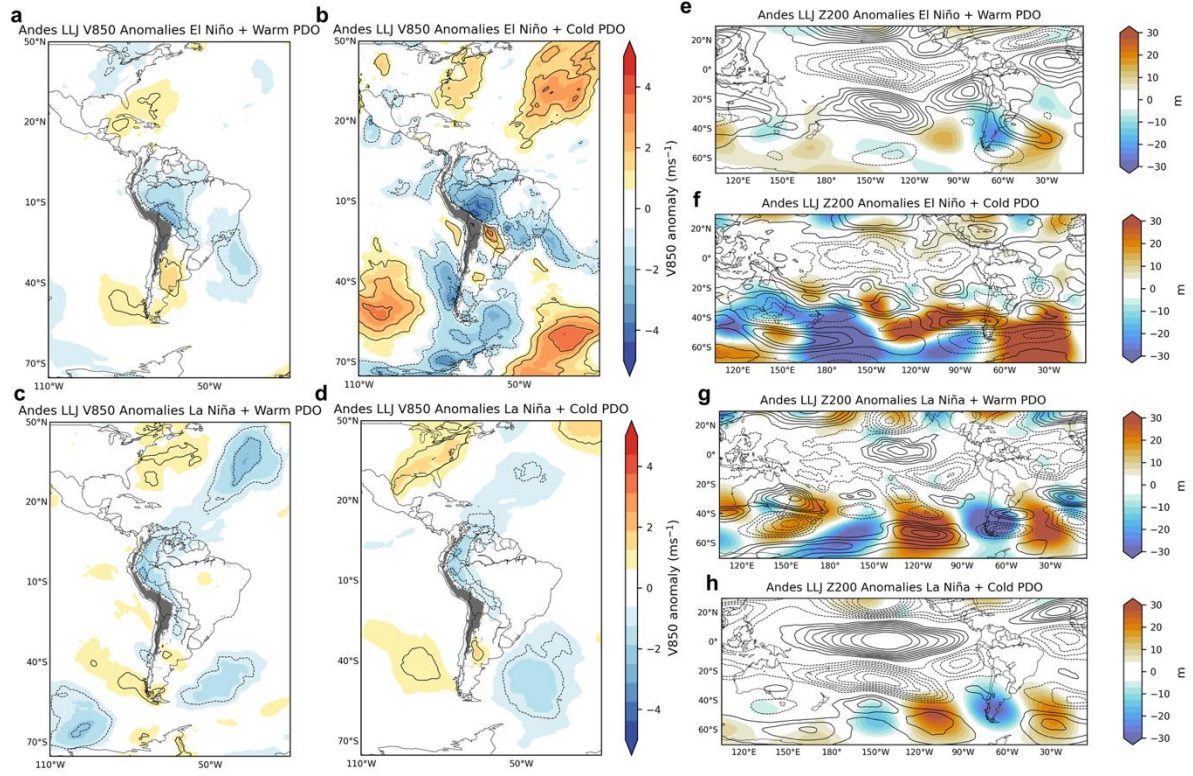


Figure 2.8. Composites of austral summer low-level (850-hPa) meridional winds and upper-level anomalies during Andes LLJ and ENSO-PDO phases. The left column shows 850-hPa meridional wind (V850) anomalies (m s^{-1}) during Andes LLJ and (a) El Niño plus Warm PDO, (b) El Niño plus Cold PDO, (c) La Niña plus Warm PDO and (d) La Niña plus Cold PDO phases. The right column shows 200-hPa geopotential height (m) (Z200) and 200-hPa zonal wind (U200) anomalies during the Andes LLJ type and ENSO plus PDO phases. Z200 anomalies are shown in colors. Positive (negative) U200 anomalies are shown in solid (dashed) contours (1 m s^{-1} interval), with zero contour omitted. Anomalies are statistically significant at a 95% confidence level.

It has been demonstrated that ENSO modifies the mean atmospheric state and, thus, rainfall and temperature variability in South America (e.g. Yang et al.,

2018; Cai et al., 2020; Gamelin et al., 2020; Kayano et al., 2022). Additional understanding is gained by compositing low-level meridional winds under different combinations of ENSO-PDO phases to examine their in-phase and out-of-phase contributions to changes in the low-level meridional circulation (Fig. 2.9). Note that composites are calculated by averaging V850 anomalies during all days in the respective PDO and ENSO phases regardless of the occurrence of LLJs.

During the El Niño+Warm PDO phase, the V850 anomalies enhance northerly winds over the central Andes, promoting the formation of the Central LLJ type (Fig. 2.9a). When La Niña coincides with Warm PDO, the V850 anomalies show enhanced northerly winds over the northern Andes (Fig. 2.9b). The differences in composites (Fig. 2.9c, d) suggest that the in-phase component, i.e., El Niño minus La Niña (Fig. 2.9c), dominates the out-of-phase component, i.e., El Niño plus La Niña Warm PDO phases (Fig. 2.9d). The El Niño+Cold PDO phase is less favorable for any specific LLJ type, creating a complex and variable atmospheric environment (Fig. 2.9e). The Cold PDO tends to moderate the typical El Niño effects, leading to less pronounced atmospheric stability and moisture transport (Newman et al., 2003). In contrast, changes in the mean atmospheric state during La Niña years occurring in Cold PDO phases favor the occurrence of the Northern and Andes types (Fig. 2.9f). The differences in composites (Fig. 2.9g, h) also indicate that the linear component dominates. Furthermore, ENSO teleconnections in low-level circulation appear to be stronger over South America during the Cold PDO. During La Niña plus Cold PDO phases, the differences in the anticyclonic activity in the North Atlantic Ocean (Fig. 2.9b, f) and the waveguides in the Southern Hemisphere are enhanced (Fig. 2.9c, g), creating more favorable conditions for the Northern and Andes LLJs.

When the PDO is neutral during El Niño conditions, enhanced northerly winds over the central Andes continue to support the Central LLJ (Fig. 2.9i). Similarly, during La Niña+Neutral PDO, the V850 anomalies continue to show northerly winds over the northern Andes, but it is weaker compared to the La Niña+Cold PDO phase. Comparing these phases, El Niño phases, especially when combined with a warm PDO, consistently favor the Central LLJ in the central Andes. La Niña phases, particularly with a cold PDO, enhance northerly winds, favoring the Northern and Andes LLJs. Neutral PDO phases moderate these effects, maintaining the influence of ENSO-driven patterns on LLJ formation.

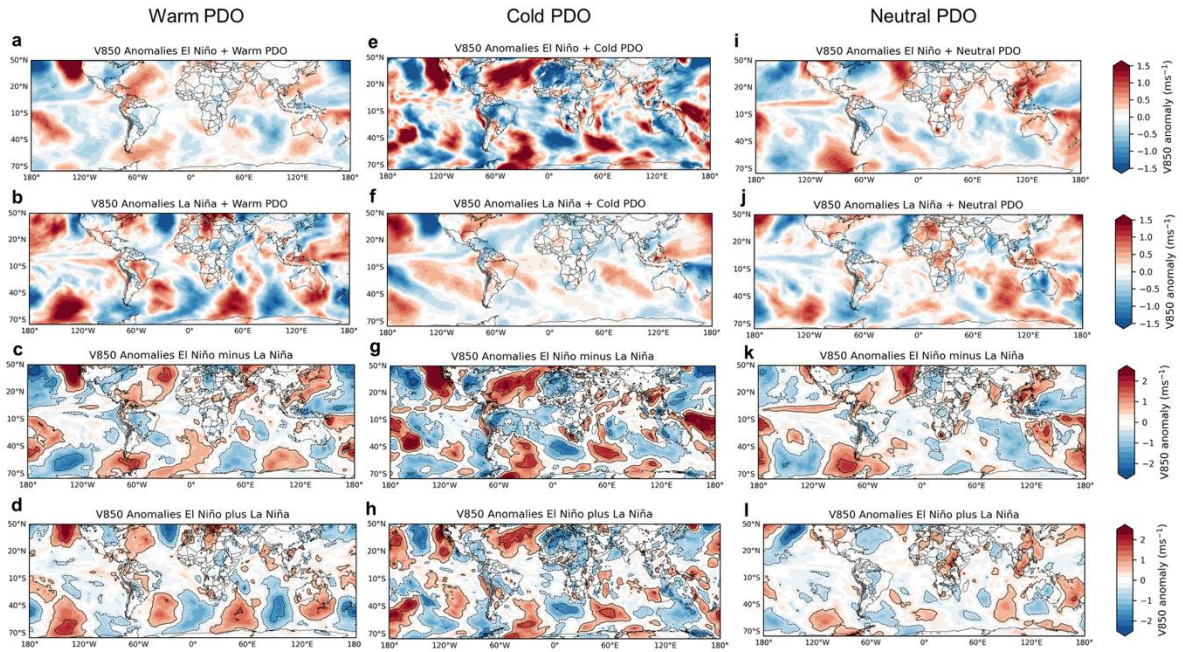


Figure 2.9. Composites of 850-hPa meridional wind (V850) anomalies (m s^{-1}). The left column shows composites of V850 anomalies during Warm PDO and (a) El Niño and (b) La Niña phases. The middle column shows composites of V850 anomalies during Cold PDO and (e) El Niño and (f) La Niña phases. The right column shows composites of V850 anomalies during Cold PDO and (i) El Niño and

(j) La Niña phases. Panels (c, g, k) and (d, h, l) show La Niña minus El Niño composites (linear component), and La Niña plus El Niño composites (non-linear component), respectively. Solid (dashed) contours in the linear (c, g) and non-linear (d, h) panels indicate positive (negative) anomalies statistically significant at a 95% confidence level. The contour interval is 1 ms^{-1} .

C.2 Precipitation extremes during LLJ types

Moisture transport by LLJs is critical in modulating precipitation variability in South America as well as the formation and maintenance of MCS (e.g. Berbery & Barros 2002; Salio et al., 2007; Nascimento et al., 2016; Rasmussen & Houze 2016). For the Northern LLJ, La Niña years favor longer precipitation events than El Niño years. In contrast, El Niño years favor persistence with longer duration than in La Niña years during Central types (Jones et al., 2023). The previous results indicate that the Central type is more likely to occur during El Niño+Warm/Neutral PDO, while the occurrence of the Northern type is favored by La Niña+Cold/Warm PDO phases. Therefore, the specific purpose is to investigate how the combination of ENSO-PDO phases influences the frequency of extreme precipitation events in South America, particularly through their modulation of LLJ behavior. We hypothesize that these climate oscillations not only impact the occurrence of LLJ types but also directly influence the frequency of extreme precipitation.

The importance of LLJs in modulating precipitation variability is further investigated by calculating precipitation extreme anomalies in the SESA and western Amazon Basin (black boxes in Fig. 2.10). During Central LLJs, positive precipitation extreme anomalies are spatially coherent in the SESA region (Fig. 2.10a), consistent

with the influence of the Central type on MCS formation (Salio et al., 2007). In contrast, during Northern LLJs (Fig. 2.10b), a large area of precipitation extreme anomalies extends over the Amazon Basin and western Brazil. While there are small pockets of precipitation extremes in the SESA domain, there is a clear reduction of extremes. Precipitation extreme anomalies during Andes types (Fig. 2.10c) show positive anomalies over parts of the Amazon Basin, Central Brazil, and SESA. To examine the relationship between extreme precipitation and LLJs, Fig. 2.10d shows scatterplots of the frequency of precipitation extreme anomalies and LLJs frequency. The relationships are separated by Central, Northern, and Andes types and show positive correlations, especially for the Northern LLJ type and precipitation extremes in the northwestern Amazon. Lastly, Fig. 2.10e shows the seasonal frequency of precipitation extreme anomalies during 1981–2021 associated with each LLJ type. An increase in precipitation extremes over the western Amazon is related to the increase in the Northern LLJ activity (compare Fig. 2.2).

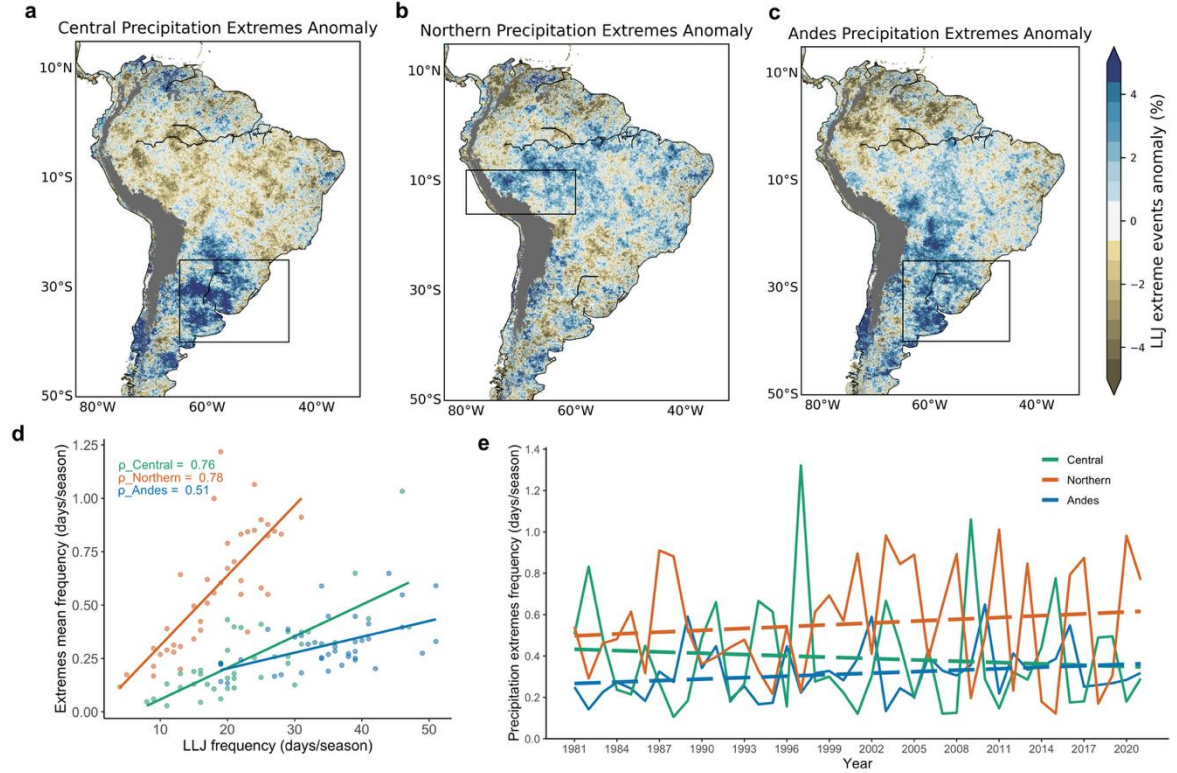


Figure 2.10. Precipitation extreme anomalies during LLJ types. Daily DJF precipitation extreme anomalies (%) during (a) Central, (b) Northern, and (c) Andes LLJs. Black boxes in (a, b, c) are located downstream from the respective exit regions of the three LLJ types. (d) Correlation (ρ) between the frequency of Central (green), Northern (orange), and Andes (blue) LLJ types and frequency of precipitation extremes (days/season) from 1981 to 2021. (e) Time series of frequency of precipitation extremes (days/season) for each LLJ type. The dashed line shows trends of precipitation extremes for each LLJ type.

Figure 2.11 shows the seasonal frequency of extreme precipitation events across different types (Central, Northern, and Andes) under varying combinations of the ENSO-PDO. Due to the small sample size for the El Niño+Cold and Neutral+Warm during the CHIRPS periods, these combinations are not shown in the

plot. For the Central Andes, the occurrence of extreme precipitation events is most frequent during El Niño phases, particularly when the PDO is neutral or warm (Fig. 2.11a). The Central LLJ positive influence on precipitation is evident from the higher median frequencies of extreme events during El Niño+Warm/Neutral phases. In the Northern Andes, extreme precipitation events are favored during La Niña phases, especially when combined with a Cold PDO (Fig. 2.11b). During La Niña plus Cold PDO phases, the meridional circulation is enhanced along the eastern Andes, strengthening the Northern LLJ and leading to increased precipitation extremes in the exit region. The Andes type shows a complex relationship with extreme precipitation (Fig. 2.11c). These events are not favored by any single ENSO-PDO phase combination strongly but exhibit variability depending on the interactions between the phases.

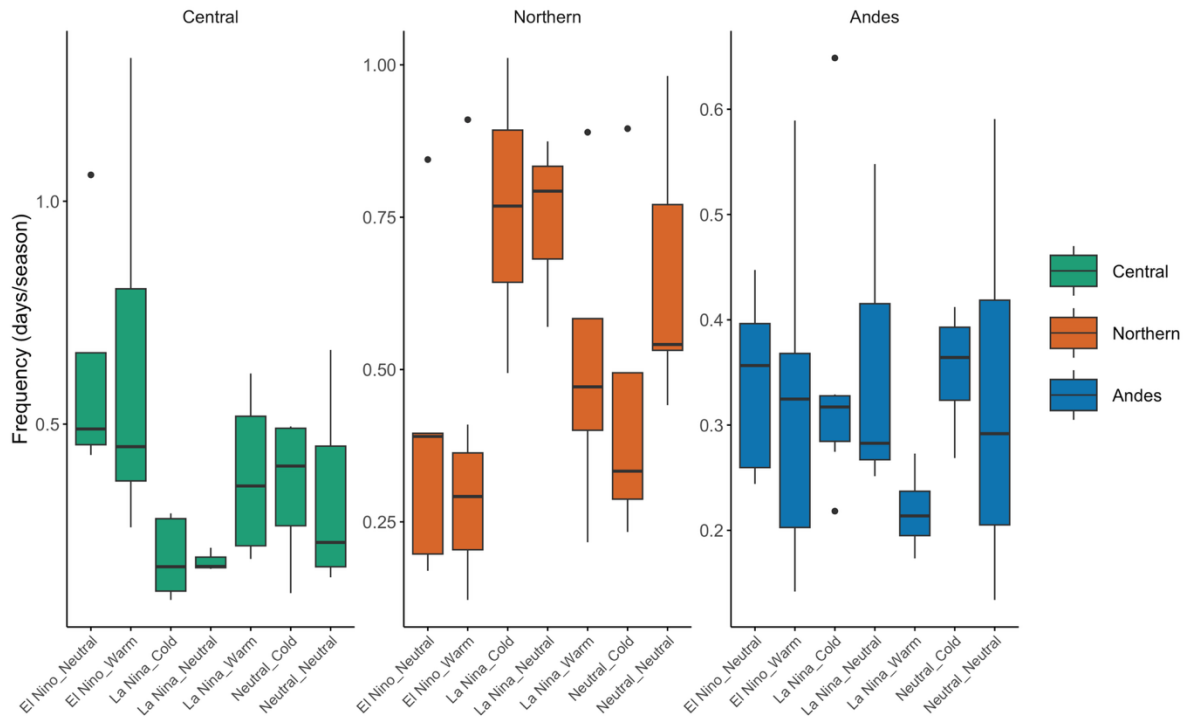


Figure 2.11. Seasonal frequency of extreme precipitation events of LLJs during ENSO-PDO phases. The box plots represent the distribution of frequencies during different phases of the ENSO and PDO from 1981 to 2021. El Niño plus Cold PDO is excluded due to insufficient samples during this period. The green, orange, and blue colors correspond to the (a) Central, (b) Northern, and (c) Andes LLJs, respectively. The central line within each box plot indicates the median frequency, while the edges of the box mark the interquartile range (IQR). Whiskers extend to the $1.5 \times \text{IQR}$, and outliers are represented by individual points.

D. Discussion

This study uses 65 years of ERA5 reanalysis to investigate the variability of LLJs along the eastern Andes on interannual-to-decadal scales. The research focuses on the joint variability of ENSO and PDO phases and their influence in controlling the activity of LLJs in the northern and central Andes. The results reveal distinct patterns in LLJ behavior contingent on ENSO and PDO phases, demonstrating the complex interactions between these large-scale forcings and LLJ dynamics. El Niño years during Warm and Neutral PDO phases were found to favor high frequency and persistence of the Central LLJ type while inhibiting the formation of LLJs in the northern Andes. Conversely, La Niña years during Cold PDO phases enhance the frequency and persistence of the Northern and Andes LLJ types and suppress the Central LLJ type. The influence of out-of-phase ENSO and PDO combinations on LLJs is notably weaker, highlighting the critical role of phase synchronization in modulating LLJ activity.

The frequency and intensity of the Northern LLJ type show positive trends in the sixty-five years of ERA5 reanalysis. In contrast, the Central type shows a statistically significant negative trend in the frequency of occurrence but not in its intensity. While the frequency of the Andes type also shows a positive increase, the increase in its intensity is not statistically significant. The increase in frequency and intensity of LLJs in the northern Andes is consistent with Jones (2019), who used a different methodology of LLJs identification and found similar positive trends. The temporal distributions of LLJ types differentiated by ENSO and PDO phases (Fig. 2.3) show a higher number of joint occurrences of La Niña and Cold PDO phases since the early 2000s than in the preceding period. These conditions favor the activity of the Northern type and suppress the occurrence of the Central LLJ. Jones found negative trends in wind shear anomalies over the central Andes, which, therefore, create less favorable conditions for the Central LLJ type (Jones 2019).

LLJs transport significant amounts of warm and moist air from the equatorial Atlantic and Amazon Basin and, consequently, supply the moisture for the formation of MCSs (Salio et al., 2007; Romatschke & Houze 2013; Rasmussen & Houze 2016). This study contextualizes the findings within broader precipitation extreme variability across South America. In summary, the Central LLJ is most active and promotes extreme precipitation during El Niño phases with a Warm or Neutral PDO. The Northern LLJ is favored during La Niña phases with a Cold PDO, leading to increased precipitation extremes in the northern Andes regions. The Andes LLJ, representing simultaneous occurrences of LLJs in both central and northern Andes, is influenced by La Niña phases, especially with a Cold PDO, contributing to extreme precipitation events across a broader area. These findings align with the

understanding that ENSO and PDO phases modulate LLJ activity and extreme precipitation patterns in South America.

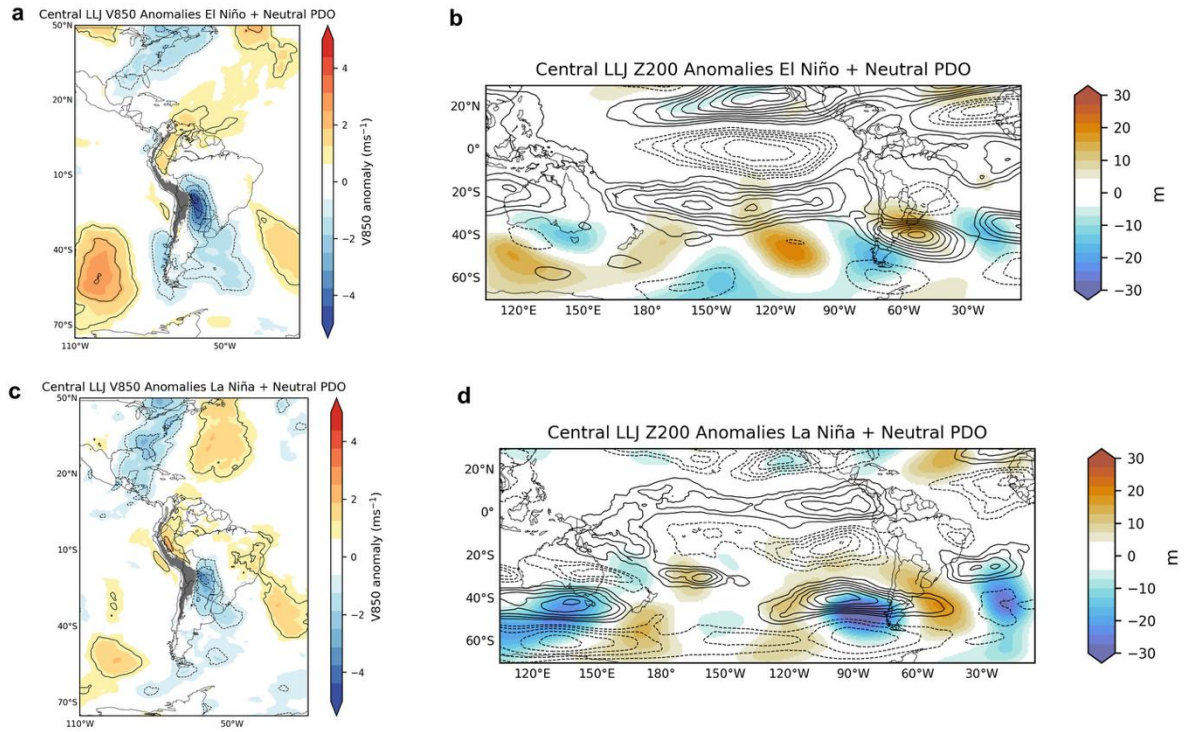
Zhang et al. (2016) reported a noticeable multidecadal positive moistening trend during the twentieth century over southeastern South America, followed by a decadal negative trend in rainfall starting around 2000. They concluded that the decrease in decadal rainfall is primarily attributed to the observed strengthening of the Pacific trade winds, which is likely associated with natural Pacific decadal variability (Zhang et al., 2016). While earlier studies (Liebmann et al., 2004; Varuolo-Clarke et al., 2022) identified positive precipitation trends in southern Brazil of SESA, our analysis using ERA5 and CPC data shows no significant positive precipitation trends in SESA from 1957 to 2022 (Supplementary Fig. 2.4). In addition, the CHIRPS dataset reveals no significant trends in extreme events during Central and Andes LLJ types over the past 40 years. Both Central and Andes LLJs influence precipitation in the SESA region, but their contributions and trends differ. The Central LLJ, with a significant decreasing trend in frequency, is less frequent during recent decades, corresponding to fewer El Niño events during Warm/Neutral PDO phases. Conversely, the Andes LLJ shows a significant increasing trend in frequency, primarily driven by La Niña phases with Cold PDO, contributing more to recent extreme precipitation events. However, Andes LLJs exhibit low correlations with SESA precipitation extremes (0.51, Fig. 2.10d), indicating that while they play roles in modulating precipitation, other factors also contribute to precipitation variability in the region.

Changes in the activity of LLJs in the northern and central Andes can be viewed as resulting from changes in large-scale atmospheric circulation on

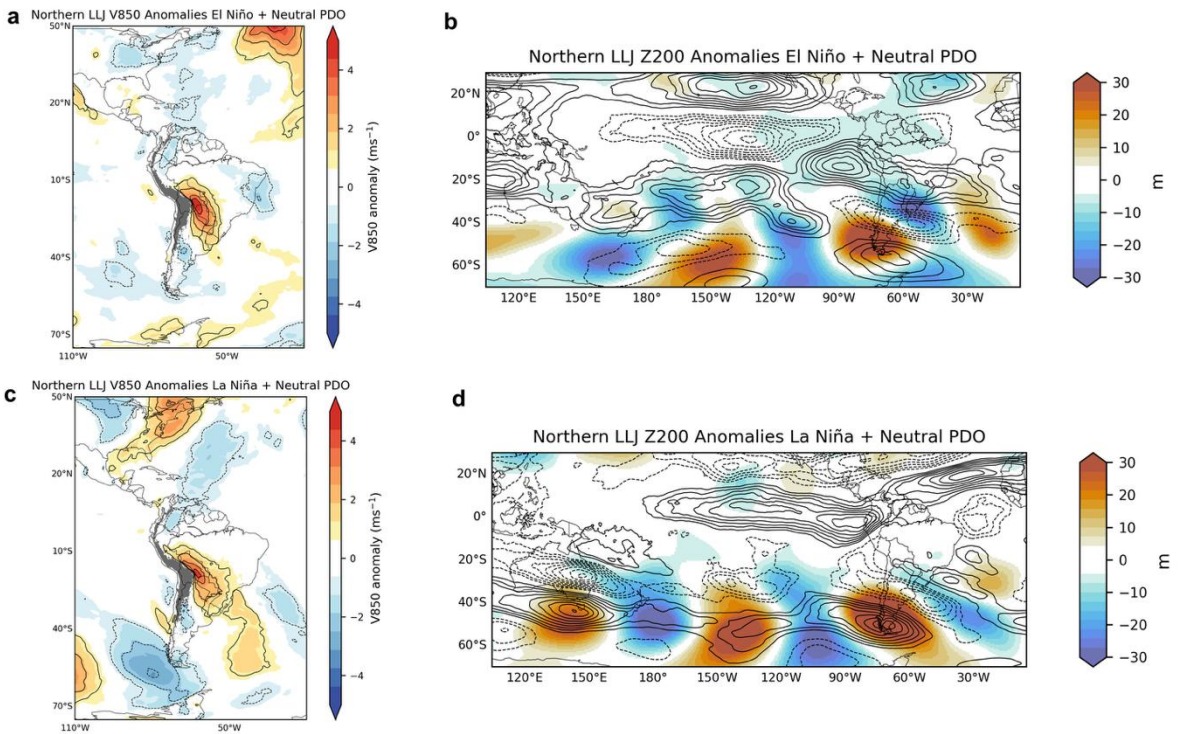
interannual-to-decadal time scales. During El Niño events, the warming of the central and eastern Pacific leads to a weakening of the Walker circulation, characterized by weaker trade winds and an eastward shift of the convection zone (Lee et al., 2019; Bayr et al., 2020; Silva et al., 2020; Heede & Fedorov 2023). This alteration in atmospheric circulation results in anomalous westerly winds at lower levels and the strengthening of the subtropical jet, disrupting the typical easterly flow and enhancing the formation of the Central LLJ (Gill 1980; Silva et al., 2009; Yun et al., 2021). In contrast, during La Niña events, cooler SSTs in the central and eastern Pacific strengthen the Walker circulation, enhancing the easterly trade winds (Li et al., 2015; Zhang et al., 2016; Takahashi & Watanabe 2016; Han & Zheng 2023). These enhanced easterlies can extend into the northern and eastern Andes, promoting the formation of the Northern LLJ. In addition, the Cold PDO phase, characterized by cooler sea surface temperatures (SST) in the North Pacific, can reinforce La Niña conditions by further enhancing the trade winds and altering the subtropical jet (Hoerling et al., 1997; Silva et al., 2009). This explanation is consistent with the changes in the mean atmospheric state during La Niña years in Cold PDO phases (Fig. 2.9f), which favor an increase in the activity of the Northern and Andes LLJs.

Some studies indicated that the cooling trends observed in the tropical Pacific might be largely attributed to internal climate variability mechanisms, notably the Pacific Decadal Variability (PDV), as opposed to a direct result of anthropogenic factors. Moreover, it is anticipated that this cooling will eventually stabilize at a neutral state before transitioning into a period of warming (Hoerling et al., 1997; Zhang et al., 2016). If this transitioning scenario materializes to more frequent El

Niño years occurring during Warm/Neutral PDO phases, our analysis indicates a potential intensification of the Central LLJ type, while simultaneously reducing the activity of the Northern and Andes LLJs. These changes are likely to exacerbate strengthened precipitation variability in South America, leading to more frequent extreme rainfall events in SESA and inducing drier conditions within the southwestern Amazon Basin. To fully comprehend these complex interactions, there is a pressing need to investigate deeper into the connections between large-scale atmospheric forcings, the behavior of LLJs, and precipitation variability in South America. Assessing the fidelity of global climate models in representing these processes is a critical next step. It is essential to improve climate models to more accurately simulate the observed relationships and, thus, enhance predictive capabilities and mitigation strategies.

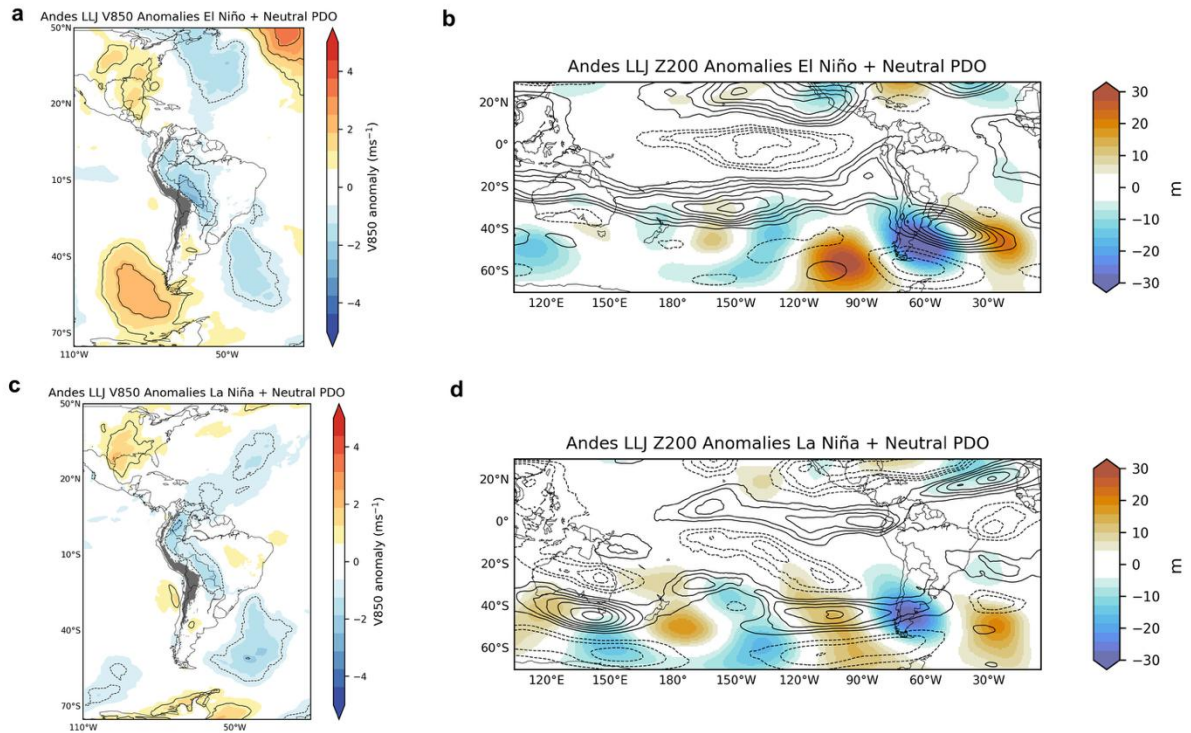


Supplementary Figure 2.1. Composites of austral summer meridional winds (850-hPa) and upper-level anomalies during Central LLJ and ENSO-Neutral PDO phases. The left column shows 850-hPa meridional wind (V850) anomalies (m s^{-1}) during Central LLJ and (a) El Niño plus Neutral PDO and (c) La Niña plus Neutral PDO phases. The right column shows 200-hPa geopotential height (m) (Z200) and 200-hPa zonal wind (U200) anomalies during the respective LLJ type and ENSO plus Neutral PDO phases. Z200 anomalies are shown in colors. Positive (negative) U200 anomalies are shown in solid (dashed) contours (1 m s^{-1} interval), with zero contour omitted. Anomalies are statistically significant at a 95% confidence level.



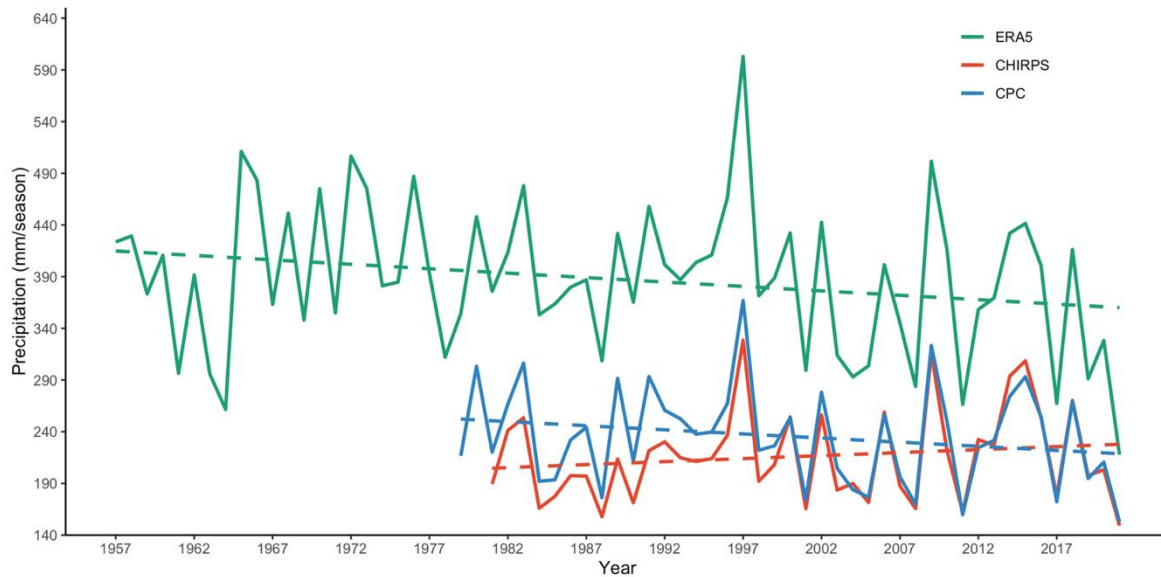
Supplementary Figure 2.2. Composites of austral summer meridional winds (850-hPa) and upper-level anomalies during Northern LLJ and ENSO-Neutral PDO phases. The left column shows 850-hPa meridional wind (V850) anomalies (m s^{-1})

during Northern LLJ and (a) El Niño plus Neutral PDO and (c) La Niña plus Neutral PDO phases. The right column shows 200-hPa geopotential height (m) (Z200) and 200-hPa zonal wind (U200) anomalies during the respective LLJ type and ENSO plus Neutral PDO phases. Z200 anomalies are shown in colors. Positive (negative) U200 anomalies are shown in solid (dashed) contours (1 m s⁻¹ interval), with zero contour omitted. Anomalies are statistically significant at a 95% confidence level.

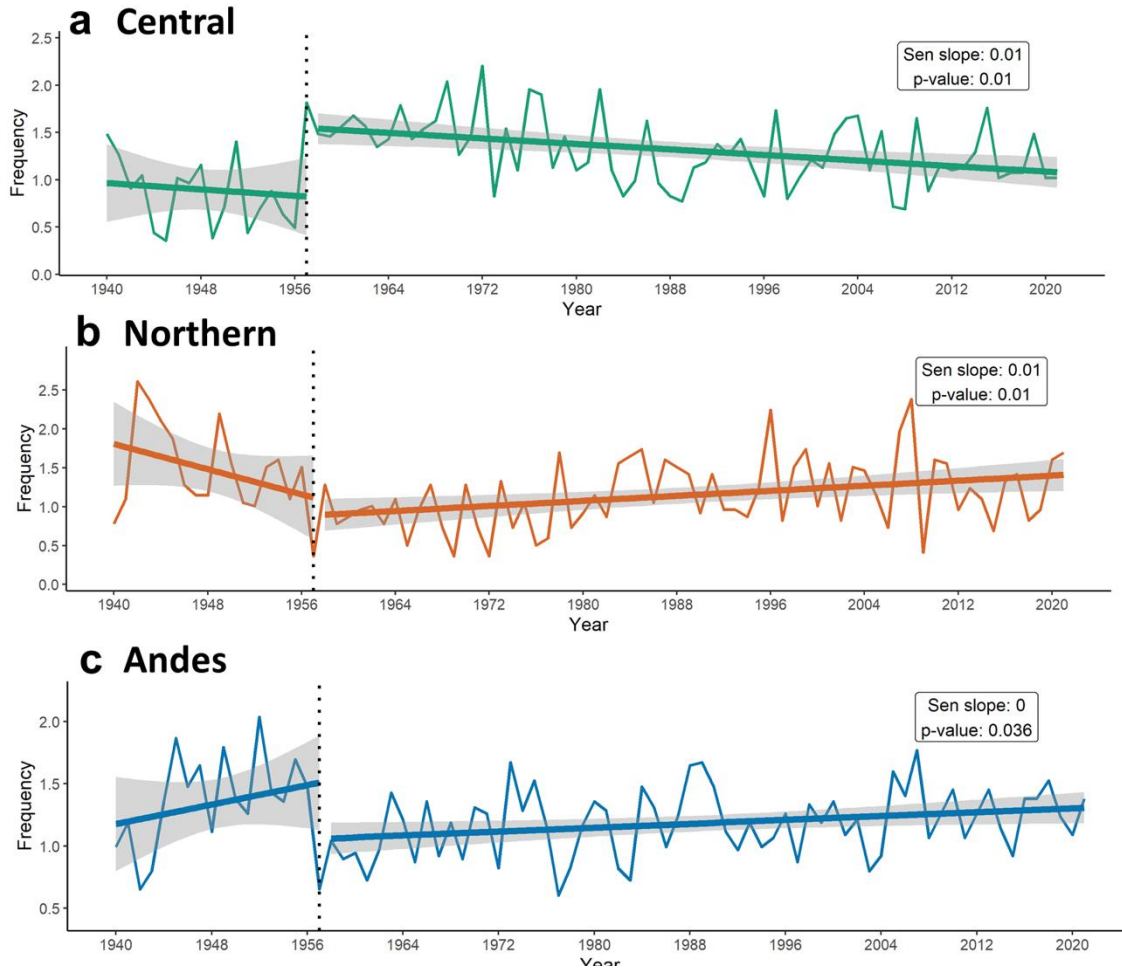


Supplementary Figure 2.3. Composites of austral summer meridional winds (850-hPa) and upper-level anomalies during Andes LLJ and ENSO-Neutral PDO phases. The left column shows 850-hPa meridional wind (V850) anomalies (m s⁻¹) during Andes LLJ and (a) El Niño plus Neutral PDO and (c) La Niña plus Neutral PDO phases. The right column shows 200-hPa geopotential height (m) (Z200) and 200-hPa zonal wind (U200) anomalies during the respective LLJ type and ENSO plus Neutral PDO phases. Z200 anomalies are shown in colors. Positive (negative)

U200 anomalies are shown in solid (dashed) contours (1 m s^{-1} interval), with zero contour omitted. Anomalies are statistically significant at a 95% confidence level.



Supplementary Figure 2.4. SESA wet season (DJF) precipitation from 1957 to 2021 from ERA5, CHIRPS and CPC daily data.



Supplementary Figure 2.5. Discontinuity in the frequency of Austral Summer for LLJs. Time series of LLJ frequency for Central (b), Northern (c), and Andes (d) types from 1940-2022. The vertical dashed line at 1957 highlights the discontinuity. Solid lines show trend lines, with grey shading representing the confidence intervals. Statistical significance of the trends, determined using Mann-Kendall tests, is shown in the insets. Monthly LLJ frequency is calculated by dividing the number of LLJ days by the total number of days in each month.

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III. Impacts of Northerly Low-Level Jets on Mesoscale Convective Systems East of the Andes

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Charles Jones, Leila M. V. Carvalho, Julia Kukulies, Andreas F. Prein, Lulin Xue
& Changhai Liu

Abstract

Low-level jets (LLJs) play a critical role in moisture transport, vertical motion enhancement, and orographic lifting, frequently leading to deep, organized convection formation in South America. This study examines the impacts of three types of LLJs (Central, Northern, and Andes) on Mesoscale Convective Systems (MCSs), using a 4 km horizontal grid spacing Weather Research and Forecasting (WRF) model simulation and satellite-based data. The Central and Andes LLJ types facilitate significant moisture flux convergence over the La Plata Basin (LPB), contributing to intense MCS activity and heavy precipitation. In contrast, the Northern LLJ type, operating over the eastern slopes of the northern Andes, exerts a weaker impact on MCS development over the Amazon Basin, leading to more scattered convection. Stronger LLJs support larger, longer-lived MCSs with higher mean precipitation in jet exit regions. El Niño Southern Oscillation modulates these relationships, with El Niño increasing MCS size and duration in the Central LLJ region, while La Niña enhances MCS frequency in the Andes and Northern LLJ regions. The WRF model captures many of these dynamics but produces higher extreme MCS mean precipitation than IMERG. These findings highlight the

importance of LLJ variability in modulating MCSs and suggest that future LLJ changes could alter the hydroclimate and extreme weather patterns in the region. This study underscores the utility of km-scale models in representing the complex interactions of LLJs and MCSs, making them a promising tool to improve our understanding of these interactions and to assess the potential impacts of climate change on water resources and extreme weather in South America.

A. Introduction

Mesoscale Convective Systems (MCSs) are large, organized clusters of thunderstorms that can span several hundred kilometers and persist for several hours to a day, often leading to significant rainfall, strong winds, hail, or even tornadoes (Houze, 2014). Some of the most intense convective systems on Earth are found east of the Andes in southeastern South America (SESA), which frequently evolve into large and organized MCSs (Liu & Zipser, 2015; E. J. Zipser et al., 2006). In South America, the common precipitation features identified by multiple MCS tracking algorithms include large MCS sizes, with cloud shields typically exceeding 40,000 km² at their peak. These systems last at least 4 hr and produce large rainfall volumes that contribute notably to total regional precipitation (Prein et al., 2024). On average, the South American MCSs are roughly 60% larger than those found in the continental United States (Velasco & Fritsch, 1987), contributing up to 95% of climatological warm-season rain in the La Plata Basin (LPB) (Feng et al., 2021; Nesbitt et al., 2006; Prein et al., 2023; Rasmussen & Houze, 2016). The LPB is the second-largest water basin in South America, covering areas of Argentina, Bolivia, Brazil, Paraguay, and Uruguay. It also has the largest population density and the

most agriculturally productive region on the continent (Cavalcanti et al., 2015). Therefore, MCSs that bring heavy precipitation can significantly impact agriculture, hydroelectric power, water resources, and socioeconomic activities in the LPB (Carvalho & Jones, 2013; Cavalcanti et al., 2015; Marengo et al., 2012).

Low-level jets (LLJs), located on the eastern slopes of the Andes in South America, transport substantial amounts of warm and moist air from the Amazon region to the LPB throughout the year but are most frequent during the austral summer (Jones, 2019; Jones et al., 2023; Marengo et al., 2004; Nascimento et al., 2016). The variability of the LLJ is likely driven by a combination of synoptic-scale and boundary-layer mechanisms. When the thermal-orographic North Argentine Low deepens and interacts with the South Atlantic subtropical high, the strengthening in pressure gradients increases the northerly flow, resulting in the penetration of the LLJ to latitudes south of 25°S (Marengo et al., 2004; Nicolini & Saulo, 2000; Salio et al., 2002).

The LLJ exhibits variability on multiple time scales. On interannual time scales, changes in large-scale circulation over South America are strongly linked to the El Niño Southern Oscillation (ENSO), during which a low-level anticyclonic anomaly influences the LLJ northerly flow (Grimm, 2003; Grimm & Tedeschi, 2009; Mu et al., 2024). Furthermore, extratropical Rossby wave trains emanating from the Pacific appear to have an important dynamical forcing to the jet (Jones et al., 2023; Liebmann et al., 2004), and the Atlantic Multidecadal Oscillation (AMO) notably affects the LLJ's decadal-to-multidecadal variability (Jones & Carvalho, 2018). The LLJ critically influences the development of MCSs at its exit region in the LPB (Nascimento et al., 2016; Salio et al., 2007; E. Zipser et al., 2004). Low-level

moisture transported from the tropics to the subtropics can ascend into the free troposphere due to the decelerating leading edge of the flow. The resulting strong low-level convergence couples with upper-level divergence at the exit region of the LLJ through ageostrophic circulation, initiating and sustaining moist convection, and the strong convection in turn accelerates the LLJ, favoring the development of deeper and better-organized MCSs in the region (Salio et al., 2007; Saulo et al., 2007; Uccellini, 1980). However, despite extensive research on LLJ structure and its role in moisture transport, few studies have systematically quantified how different LLJ types (e.g., Central, Northern, Andes) influence MCS characteristics such as frequency, size, duration, and precipitation intensity. Moreover, the modulation of these LLJ-MCS relationships by interannual variability, particularly ENSO, remains poorly understood.

This study contributes to a deeper understanding of the relationships between LLJ characteristics and the development of MCSs. The specific questions investigated are: (a) How does the intensity of the LLJ affect the size, duration, and frequency of MCS? (b) How much do MCSs contribute to total precipitation for different types of LLJs? (c) How well does the Weather Research and Forecasting (WRF) model simulate the LLJ and its influence on the development of MCSs? (d) How does ENSO influence the interannual variability of the frequency, size, and duration of MCS? This paper is organized as follows: Section 2 describes the data and analysis methods. The results are presented and discussed in Section 3. The summary and conclusions are in Section 4.

B. Materials and Methods

B.1 Data

This study focuses on the austral summers (1 November–31 March 2000–2020) (NDJFM) and uses half-hourly precipitation from the Integrated Multi-satellite Retrievals for GPM (IMERG) Vo6B (Huffman, Stocker, et al., 2019) on a 0.1° grid. IMERG is a merged satellite gridded precipitation product that combines observations from a network of partner satellites in the GPM constellation (Huffman, Bolvin, & Nelkin, 2019; Huffman, Bolvin, Braithwaite, et al., 2019; Huffman, Stocker, et al., 2019). For varying user requirements for latency and accuracy, IMERG includes three runs: Early, Late, and Final. The gauge-adjusted estimates from the IMERG Vo6B Final runs are used in this study. NCEP/CPC L3 Half Hourly 4 km Global Merged IR V1 (GPM MergIR), a gridded data set of infrared brightness temperatures combined from different sensors of geostationary satellites, is also employed (Janowiak et al., 2017). Both IMERG and NCEP/CPC are used in this study to identify and track MCS deep convective clouds. The brightness temperature data is regridded to match the IMERG 0.1° grid using conservative regridding in the Earth System Modeling Framework (ESMF) software (Collins et al., 2005), and both are used at an hourly resolution for tracking, which is sufficient for large and long-lasting convective storms (Feng et al., 2019).

The hourly fifth-generation European Centre for Medium-Range Weather Forecasting atmospheric reanalysis (ERA5) on a 0.25° grid (Hersbach et al., 2020) is used for one LLJ index that will be explained in the next section.

The study also includes a 4-km horizontal grid spacing Weather Research and Forecasting (WRF) simulation covering the entire South America produced by the South America Affinity Group (SAAG) from 2000 to 2020 (Dominguez et al., 2024; Liu et al., 2022; Rasmussen et al., 2022). This data set is used for comparison and analysis of the LLJ-MCS dynamics. For the MCS tracking, the WRF variables are also regridded to the IMERG grid to ensure a consistent comparison with the observational data, following the same procedure as in Prein et al. (2024). The 4-km WRF simulation provides a high-resolution, convection-permitting data set that explicitly resolves mesoscale features like MCSs without relying on deep convection parameterizations. With 61 vertical levels and driven by ERA5 reanalysis data, the simulation captures detailed atmospheric dynamics, including moisture transport, orographic lifting, and vertical velocity, which are key to understanding LLJ-MCS interactions. The WRF model is configured with advanced parameterizations to improve precipitation and land-atmosphere interactions (Dominguez et al., 2024), using the Thompson microphysics scheme (Thompson et al., 2008) for detailed cloud and precipitation processes, the Noah-MP land surface model (Niu et al., 2011) with the shallow groundwater module (Miguez-Macho et al., 2007) for improved surface water and energy exchanges, and the Yonsei University (YSU) planetary boundary layer scheme (Hong et al., 2006) for boundary layer processes. Radiative transfer is handled by the RRTMG radiation scheme (Iacono et al., 2008), which enhances shortwave and longwave flux calculations.

B.2 LLJ Definition and Intensity Classification

Early studies of South American low-level jets commonly applied the Bonner criteria (Bonner, 1968), originally developed for the U.S. Great Plains (e.g., Marengo et al., 2004; Nascimento et al., 2016). This study identifies LLJ using the percentile-based methodology proposed by Montini et al. (2019) and expanded by Jones et al. (2023), with separate adaptations for the ERA5 reanalysis and WRF model outputs. For each data set, a LLJ event is defined when the nighttime 850-hPa wind speed and the vertical wind shear between 850 and 700 hPa exceed the corresponding 75th percentiles of their monthly distributions. To ensure spatial coherence, LLJs must be embedded within a contiguous region of 850-hPa wind speeds (CRWS) exceeding 10 m/s. As in previous work, we analyze three LLJ types: the Central LLJ (over Bolivia and Paraguay), the Northern LLJ (along the eastern Andes from Venezuela to Peru), and the Andes LLJ, characterized by simultaneous jet activity in both the northern and central Andes (Figure 3.1). Exit regions are defined as rectangular boxes centered on the climatological jet exit locations identified in Mu et al. (2024). To enable direct comparisons, the Central and Andes LLJs share the same exit region over SESA, where both jets contribute to enhanced convection. In contrast, the Northern LLJ exit region is smaller and confined to the southwestern Amazon, consistent with the limited spatial extent and influence of this jet type.

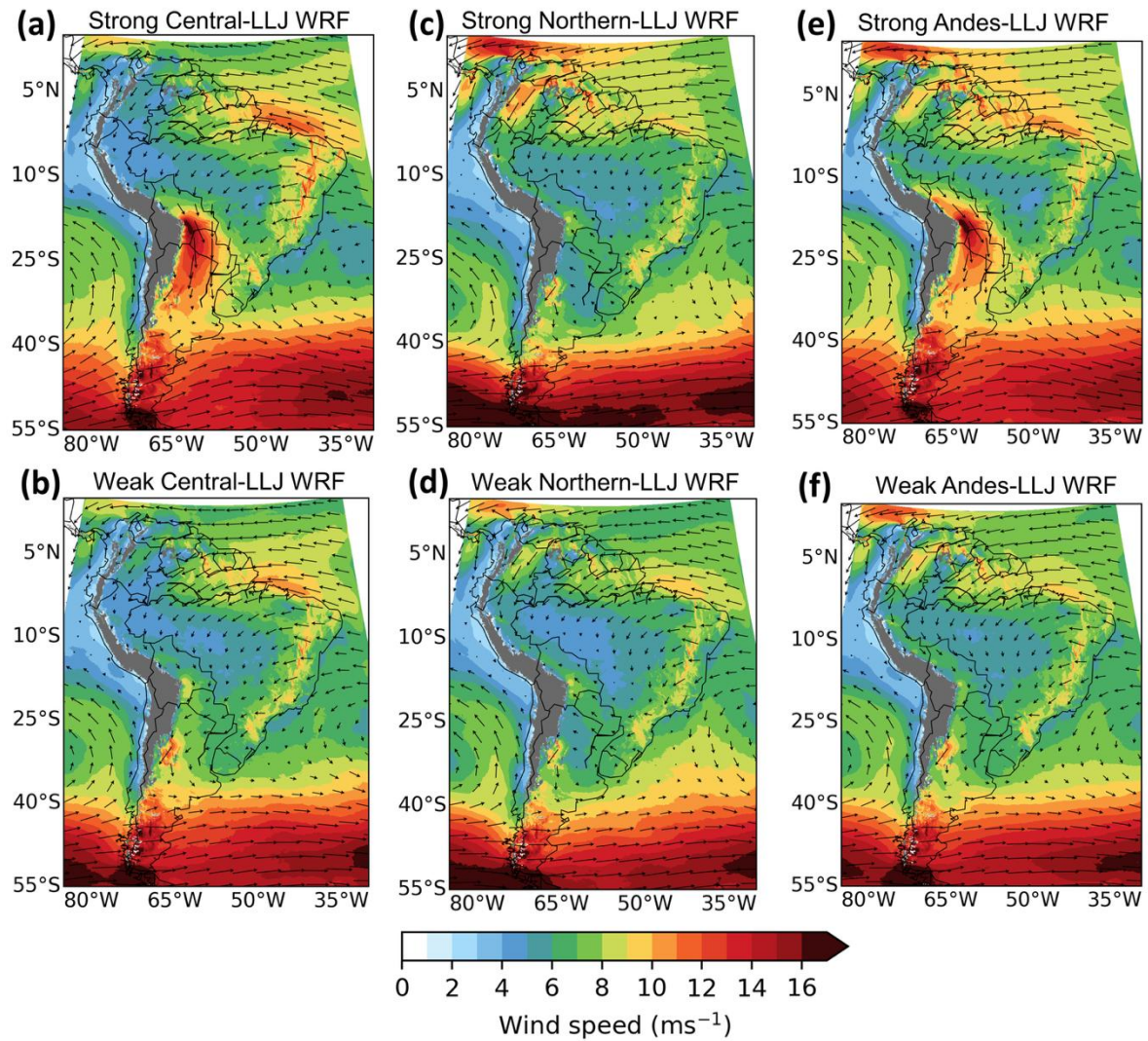


Figure 3.1. WRF 850-hPa wind climatology of each LLJ type and intensity from 2000 to 2020. Strong types for (a) Central LLJ, (c) Northern LLJ, and (e) Andes LLJ. Weak types for (b) Central LLJ, (d) Northern LLJ, and (f) Andes LLJ. All figures show 850-hPa wind speeds in shading and directions in vectors.

Given the disparity in spatial resolution between ERA5 (0.25°) and the convection-permitting WRF simulation (4 km), different spatial criteria are applied for each data set. For ERA5, additional requirements include a minimum of 5 grid points in the CRWS and at least 5 grid points within the CRWS satisfying the LLJ

wind and shear thresholds. For WRF, these thresholds are scaled to finer resolution, requiring a minimum of 1,500 total CRWS grid points and 1,500 LLJ grid points within that CRWS. This larger minimum size, compared to the 5-gridpoint minimum used for ERA5 (0.25°), reflects the much finer WRF resolution. Sensitivity tests with thresholds of 40, 200, 1,600, and 2,500 cells showed that lower thresholds allowed numerous small, isolated wind patches that hindered reliable classification into Central, Northern, and Andes types. The 1,500-cell criterion effectively filters these spurious features and yields contiguous, physically coherent LLJ regions suitable for classification. The LLJ intensity for each type is determined based on the CRWS wind speed: strong LLJs are defined as those with wind speeds exceeding the 75th percentile, while weak LLJs have wind speeds below the 25th percentile of all events (Figure 3.2). Figure 3.2 shows WRF overall reproduces the general wind-speed distribution across all LLJ types but exhibits a modest high-bias in wind speed relative to ERA5. The median jet-core wind speeds in WRF are higher by approximately 0.5–1.0 m/s for the Central and Andes LLJs, while the Northern LLJ distribution is comparable between the two data sets. For each LLJ type (Central, Northern, Andes, Peru, and No-LLJ), we compare the WRF classification to the ERA5-based classification on a daily basis (Figure 3.3). Accuracy is calculated as the ratio of correctly classified LLJ days (true positives + true negatives) to the total number of days. The F1-score is calculated as the harmonic mean of precision and recall, that is, $F1 = 2 \times (\text{precision} \times \text{recall}) / (\text{precision} + \text{recall})$, where precision is the number of correctly classified LLJ days divided by all WRF-classified LLJ days, and recall is the number of correctly classified LLJ days divided by all ERA5-classified LLJ days for that type.

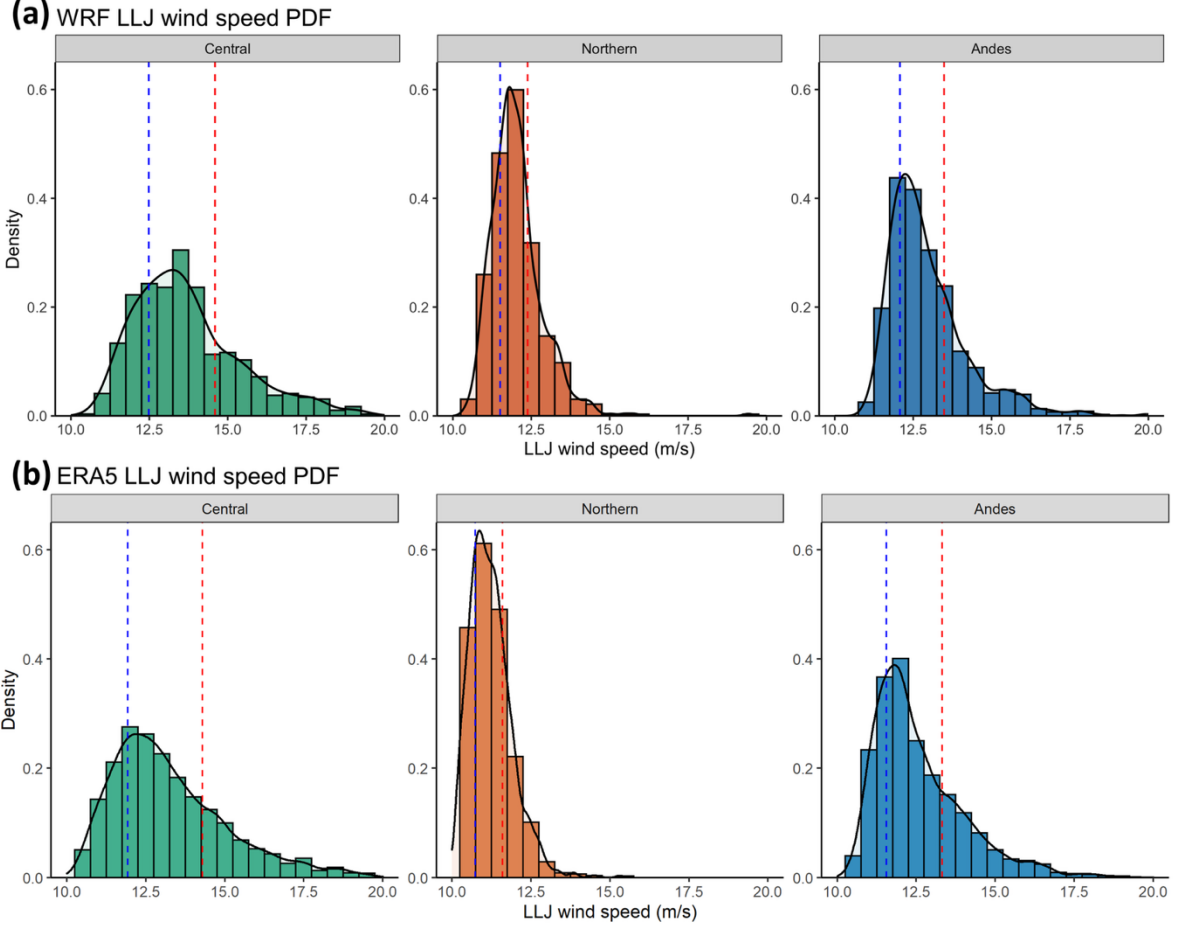


Figure 3.2. Probability density functions (PDF) of LLJ wind speed (m/s) for three different types (Central, Northern, and Andes) from 2000 to 2020 for (a) WRF, and (b) ERA5. The histograms represent the distribution of LLJ wind speeds, with a kernel density estimation overlaid in black. The dashed blue and red vertical lines indicate the 25th and 75th percentile of wind speed.

B.3 MCS Definition and Tracking

The MCS tracking is based on the Tracking and Object-Based Analysis of Clouds (tobac) algorithm (Heikenfeld et al., 2019; Sokolowsky et al., 2024), which identifies and tracks individual MCSs in a Lagrangian framework, allowing for the

analysis of the MCS lifecycle evolution. While *tobac* is a variable-agnostic tracking library that works with any gridded input data, we use both infrared brightness temperatures (T_b) and precipitation to detect cloud features. We define an MCS when the detected cloud features meet the following criteria: (a) there must be a continuous area with $T_b \leq 241$ K measuring at least 40,000 km² and lasting for at least four consecutive hours; (b) maximum hourly precipitation under the ≤ 241 K T_b area must be larger than 10 mm/hr for at least four consecutive hours; (c) hourly precipitation volume must exceed 20,000 km² mm/h (e.g., 100 km $\times$ 100 km $\times$ 2 mm/hr) at least once in the lifetime of the MCS; (d) minimum T_b must be < 225 K during the MCS lifetime to account for overshooting tops. These criteria are the same as those used in an MCS tracking intercomparison based on the same WRF simulations over South America presented in Prein et al. (2024). We applied the MCS tracking algorithm to both the observational data (gridded IR and GPM IMERG rain rates) and the 4 km WRF simulation. With this approach, we analyzed precipitation characteristics such as total amount and peak timing in each MCS life cycle associated with different LLJs. The MCS peak size is calculated by multiplying the grid cell area and the number of cells for the detected cloud shield at the maximum area during the lifetime. The MCS mean precipitation is the mean rain rate underneath the 241K-cloud shield considering only rain rate > 10 mm/hr.

In the following analysis, the ERA5-based LLJ index is treated as an observational proxy and is applied to the IMERG-based MCS tracking results. The WRF-derived LLJ index is used exclusively with the WRF-based MCS tracking. This distinction is necessary because the wind structures in reanalysis and convection-permitting simulations differ substantially in spatial scale and intensity, and

applying a uniform LLJ definition across data sets would misrepresent jet occurrence and characteristics. By deriving LLJ indices natively within each data set, we ensure a consistent and internally valid association between jet activity and MCS behavior. For temporal matching, we assume that the LLJ identified between 23:00 and 09:00 UTC (typically when nocturnal LLJs peak) contributes to the environmental conditions that influence convective initiation later that same day.

C. Results

C.1 LLJ and MCS Characteristics

Figure 3.3 evaluates the WRF model's ability to reproduce the observed LLJs classifications over South America during the austral summer months. The model performs best for the Andes LLJ category, correctly identifying 81.6% of observed events. In contrast, Central and Northern LLJ classifications are more ambiguous: 45.4% of observed Central LLJs and 39.2% of observed Northern LLJs are misclassified as Andes events, respectively. The No-LLJ category exhibits lower fidelity, with only 28.9% correctly classified, and 30.4% of these events misclassified as Northern LLJs (Figure 3.3a). Overall, the model tends to overestimate Andes LLJs while underestimating Central and No-LLJ categories (Figure 3.3b).

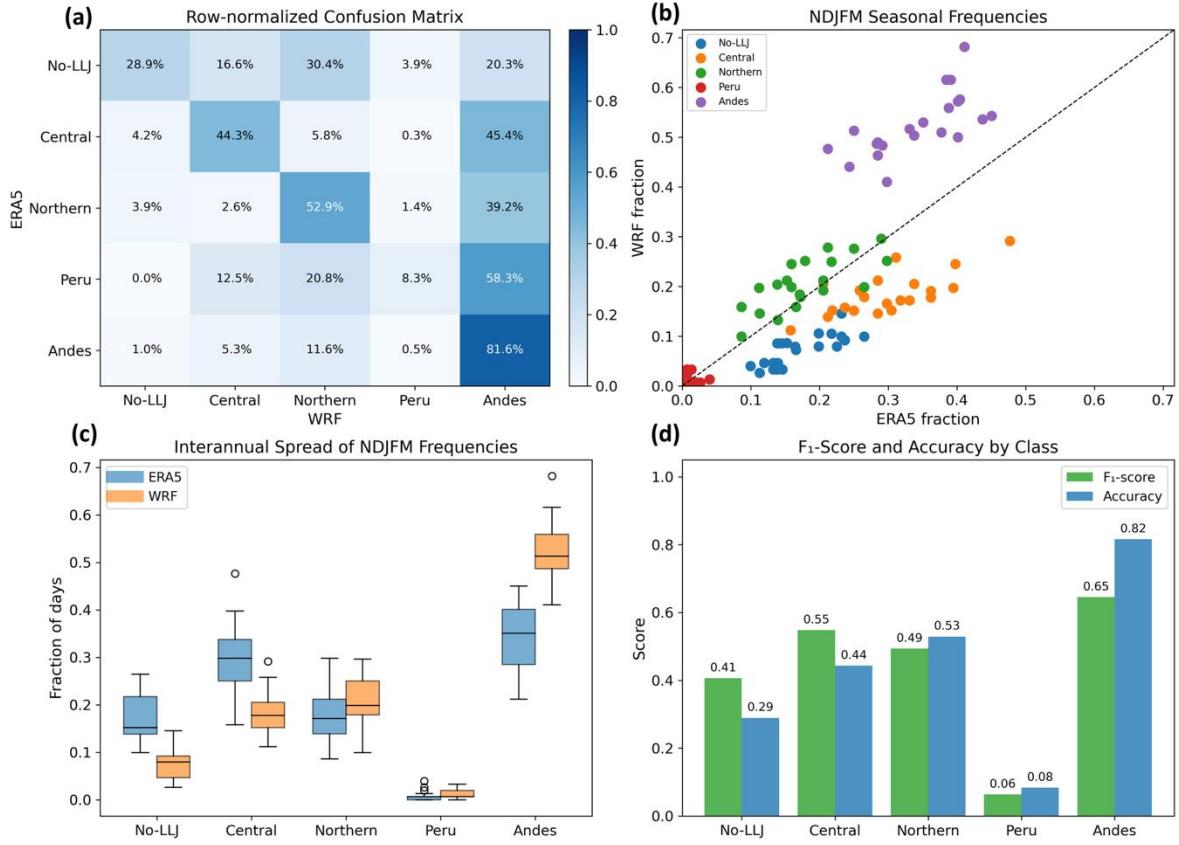


Figure 3.3. Evaluation of WRF-simulated LLJ classifications (WRF) against ERA5-based observations (ERA5) over South America during the austral summer (NDJFM). (a) Row-normalized confusion matrix between ERA5 (rows) and WRF (columns) LLJ types. (b) Seasonal mean LLJ frequencies from the WRF versus ERA5, and the dashed line is the 1:1 line. (c) Boxplots showing the interannual distribution (2000–2020) of seasonal LLJ frequencies (fraction of days per season) for each type in ERA5 (blue) and WRF (orange). (d) F1-score and accuracy for each LLJ class based on categorical agreement.

Regarding interannual variability, WRF simulates a more persistent Andes LLJ regime and fails to fully capture year-to-year variability in weaker or less spatially extensive jets, such as the Central and No-LLJ categories (Figure 3.3c).

Other classes, particularly Peru LLJ, exhibit very low F1-scores and accuracy, indicating strong disagreement with ERA5 (Figure 3.3d). These discrepancies are, in part, attributable to the design of the SAAG-WRF simulation, which does not employ spectral nudging. As a result, the internal dynamics of the model are free to evolve without large-scale constraints above the boundary layer. While this setup allows the WRF model to simulate mesoscale features such as MCSs more realistically, it can also lead to deviations in the simulated large-scale circulation, such as the strength and position of LLJs, compared to reanalysis products like ERA5. This inherent divergence may contribute to the overrepresentation of Andes LLJs and the reduced classification skill for other LLJ types.

Anomalies in MCS initiation frequency for each LLJ type are calculated as the difference in initiation frequency between LLJ and No-LLJ days (Figure 3.4). The top row (a, c, e, g, i, k) displays anomalies derived from IMERG satellite observations using the ERA5-derived LLJ index, while the bottom row (b, d, f, h, j, l) presents anomalies from WRF simulations using the WRF-derived LLJ index. Overall, weak LLJ cases exert a less pronounced influence on MCS initiation compared to strong LLJ cases. Strong Central LLJ conditions significantly enhance MCS initiation over southeastern South America while suppressing convective initiation across large portions of the Amazon Basin (Figures 3.4c and 3.4d). The WRF simulation reproduces this spatial pattern but exhibits less coherent suppression in the Amazon compared to IMERG observations (Figures 3.4b and 3.4d). Northern LLJs show near neutral or negative anomalies in the exit region in the southwestern Amazon (Figures 3.4g and 3.4h). In contrast, strong Andes LLJs are associated with pronounced positive anomalies in MCS initiation, particularly over southeastern

South America (Figures 3.4k and 3.4l). This enhancement is consistently captured in both IMERG and WRF, though WRF slightly underestimates the anomaly magnitude and extent compared to observations.

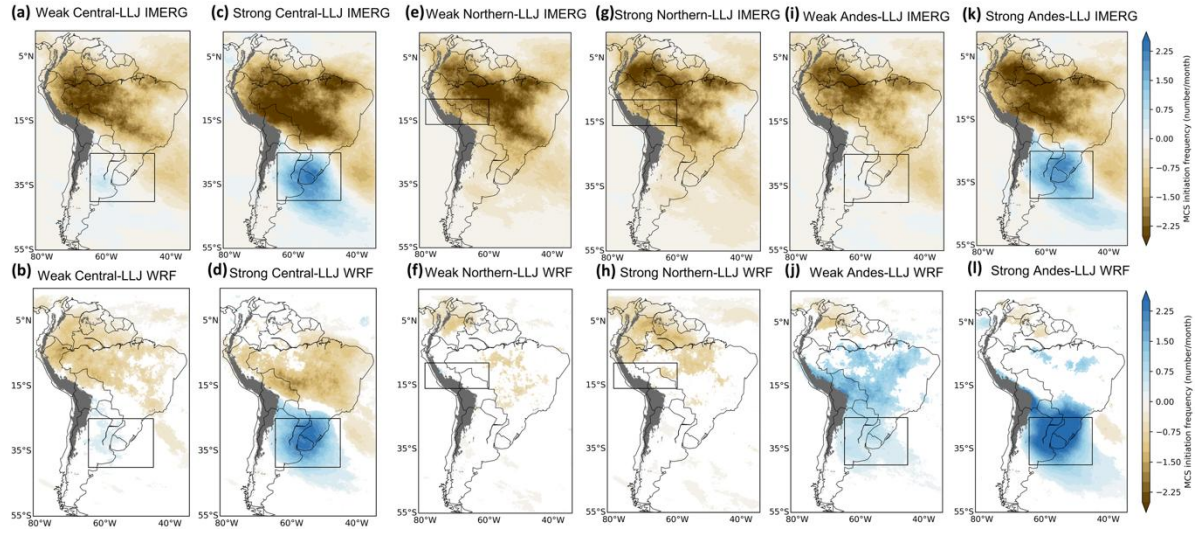


Figure 3.4. Composites of MCS mean monthly initiation frequency anomalies based on IMERG with the ERA5 LLJ index (top row), the WRF (bottom row) with the WRF LLJ index from 2000 to 2020, for (a–d) the Central LLJ, (e–h) Northern LLJ, and (i–l) Andes LLJ. The box indicated the exit region for each LLJ type. Only anomalies statistically significant at a 95% confidence level are shown.

Weak Central LLJs also induce modest but discernible increases in MCS initiations within their respective exit regions in both IMERG and WRF (Figures 3.4a and 3.4b). Weak Andes LLJs show modest enhancements in MCS initiation only in the WRF simulation (Figure 3.4j). Conversely, weak Northern LLJ events show negligible or slightly negative influences on convective initiation, reinforcing their comparatively limited influence of the Northern LLJ relative to the Central and Andes LLJs. Interestingly, suppression of MCS initiation in upstream regions, such as the western Amazon during Central LLJ events, is likely driven by the

displacement of low-level moisture convergence toward the jet exit region. This spatial shift reduces convective triggering upstream, as convergence, instability, and moisture flux are redirected toward southeastern South America. These patterns are consistent with previous studies showing that LLJs reorganize the regional moisture budget and vertical motion fields, enhancing convection downstream while inhibiting it upstream (Marengo et al., 2004; Salio et al., 2007).

Figure 3.5 displays box plots for three key MCS characteristics (duration, size, and precipitation rate) under varying LLJ types and their respective weak and strong intensities. The statistics for these characteristics are extracted for each MCS whose centroid (latitude, longitude) falls within the box boundaries in Figure 3.4. Both IMERG observations and WRF simulations indicate longer MCS durations during strong LLJ events compared to weak events, with statistically significant differences particularly for the Andes LLJ ($p < 0.001$ in IMERG and WRF) and Central LLJ ($p < 0.01$ in WRF only) regimes (Figures 3.5a and 3.5b). Similarly, strong LLJ conditions lead to significantly larger MCSs in both the Central and Andes regions ($p < 0.001$ for IMERG and WRF; Figures 3.5c and 3.5d). Additionally, strong Central and Andes LLJ events are associated with significantly higher median precipitation rates (exceeding 10 mm/hr) compared to weak LLJs for IMERG (Figures 3.5e and 3.5f). These results confirm that LLJ intensity plays a crucial role in shaping the characteristics of MCSs. Stronger LLJs, particularly the Andes and Central LLJs, are consistently associated with longer-lived, larger, and more intense convective systems. This finding aligns with previous research characterizing the South American LLJ (SALLJ) as a conduit for transporting heat and moisture from the Amazon basin, thereby fueling downstream convective activity (Salio et al., 2007).

WRF-simulated precipitation rates show a more complex relationship with LLJ strength than IMERG. While IMERG generally indicates stronger precipitation under strong LLJs, WRF displays weaker contrasts and, for some LLJ types, slightly higher median precipitation rates for weak LLJs (Figures 3.5f and 3.6d). This difference may reflect sampling variations when applying the WRF-based LLJ index, sensitivities of MCS rain statistics to the TOBAC tracker and thresholds (Prein et al., 2024), and possible WRF microphysics biases that enhance stratiform rain during weaker low-level inflow (Zhang et al., 2021). WRF tend to produce higher mean precipitation rates compared to IMERG, particularly for Northern LLJ cases in the Amazon. This pattern aligns with recent high-resolution convection-permitting studies over South America (Prein et al., 2024; Rehbein et al., 2024; Zhang et al., 2021), which also report that WRF consistently produces more intense rainfall than IMERG. In addition, IMERG's reliance on infrared (IR)-based precipitation estimates in regions with sparse microwave coverage introduces uncertainties that could further amplify discrepancies between observations and simulations.

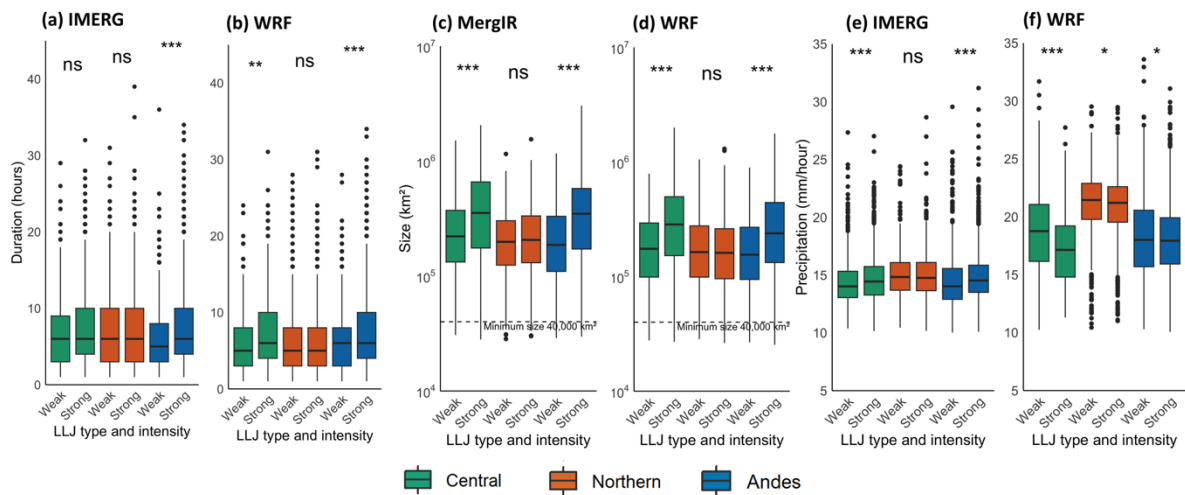


Figure 3.5. Observed (IMERG and GPM MergIR) and simulated (WRF) MCS characteristics for three LLJ types: Central, Northern, and Andes, under weak and strong LLJ conditions. Displayed are the distributions of MCS (a, b) duration (hours); (c, d) mean lifetime size (km²); and (e, f) 10 mm mean precipitation rate (mm/hour). Precipitation statistics only consider precipitation rates larger than 10 mm/hr. Statistical significance of differences between weak and strong LLJ conditions is indicated at the top of each pair of boxplots ($p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***), while “ns” denotes non-significant differences), based on the Kolmogorov-Smirnov test. The box width represents the interquartile range, with the median indicated by a horizontal line within the box. Whiskers extend to the minimum or maximum data points, or 1.5 times the interquartile range, whichever is smaller. Results are based on the LLJ exit region boxes in Figure 3.4.

C.2 MCS Diurnal Cycles and Precipitation Contribution

Figure 3.6 shows IMERG and WRF hourly frequency of MCS initiation and associated precipitation rates for different LLJ types (Central, Northern, Andes) under weak and strong intensities. A pronounced diurnal cycle is evident, with MCS initiation consistently peaking between approximately 3:00 p.m. and 6:00 p.m. local Bolivia Time (BOT; 19:00–22:00 UTC). The afternoon peak is likely driven primarily by daytime surface heating and the associated increase in boundary layer instability, which favors convective initiation. Nocturnal LLJ intensification (approximately 8:00 p.m. - 2:00 a.m. BOT), as documented by Montini et al. (2019), may precondition the atmosphere by enhancing overnight moisture supply and thus

contribute to the early-morning precipitation peak, but we did not explicitly examine the diurnal variation of moisture transport.

However, the Andes and Central LLJs exhibit more pronounced increases in initiation frequency under strong conditions, especially in WRF simulations (Figure 3.6c). In contrast, the Northern LLJ appears less sensitive to LLJ intensity in terms of MCS initiation frequency (Figures 3.6a and 3.6c). IMERG and WRF mean precipitation rates (Figures 3.6b and 3.6d) differ both in magnitude and timing (note the different y-axis scales). Additionally, WRF simulates substantially higher rainfall intensities ($\sim 14\text{--}22$ mm/hr) compared to IMERG ($\sim 10\text{--}16$ mm/hr), especially during strong LLJ events. IMERG observations indicated that strong LLJ conditions lead to enhanced MCS precipitation during peak hours, a feature not captured in WRF simulations. This discrepancy highlights potential limitations in WRF's representation of convective rainfall timing and intensity, particularly under strong jet regimes.

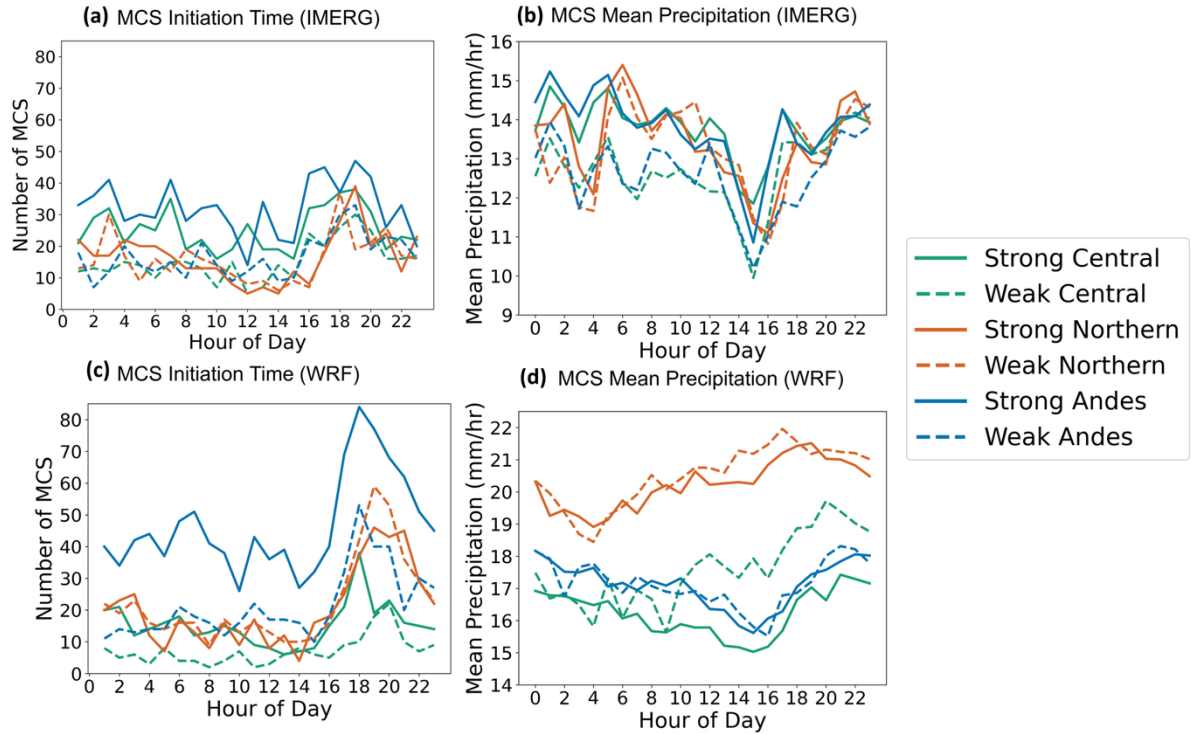


Figure 3.6. MCS initiation and precipitation diurnal cycles (UTC time) based on observations (top row) and simulations (bottom row) for three LLJ types: Central (green), Northern (orange), and Andes (blue), under weak (dashed lines) and strong (solid lines) LLJ conditions. The MCS mean hourly initiation counts (number of MCS/hour) and 10 mm mean precipitation rate (mm/hour) are displayed. Precipitation statistics only consider precipitation rates larger than 10 mm/hr.

Results are based on the LLJ exit region boxes in Figure 3.4.

The relationship between LLJs and MCS-driven rainfall varies geographically, with different LLJ regimes producing distinct precipitation patterns across South America. For the Central LLJ, the highest fractions of MCS precipitation from IMERG are concentrated over southeastern South America, particularly in northern Argentina, southern Brazil, and Paraguay (Figure 3.7a). In these areas, more than 60% of the total warm-season precipitation is associated with MCS activity. The

WRF simulation reproduces this southeast-South-American maximum but underrepresents its relative importance: less than 50% of the total precipitation can be attributed to the MCS (Figure 3.7d). For the Northern LLJ, IMERG indicates >50% MCS contribution across the southwestern Amazon (Figure 3.7b). WRF reproduces the general spatial pattern but underestimates the maximum fractions by roughly 10% (Figure 3.7e), consistent with the model's tendency to produce smaller, less-organized systems in that jet regime. In the case of Andes LLJs, which are characterized by the simultaneous jet maxima in both the northern and central Andes, IMERG attributes 50%–70% of rainfall to MCSs across a broad zonal band extending from the southern Amazon through Paraguay into the upper La Plata Basin (Figure 3.7c). WRF successfully reproduces this zonal band and even extends the 50% isohyet northeastward into the western Amazon (Figure 3.7f), though peak fractions remain roughly 10% lower than IMERG. While WRF captures total precipitation reasonably well, it tends to underestimate the total MCS-related precipitation in some areas compared to IMERG, consistent with previous analyses (Prein et al., 2024).

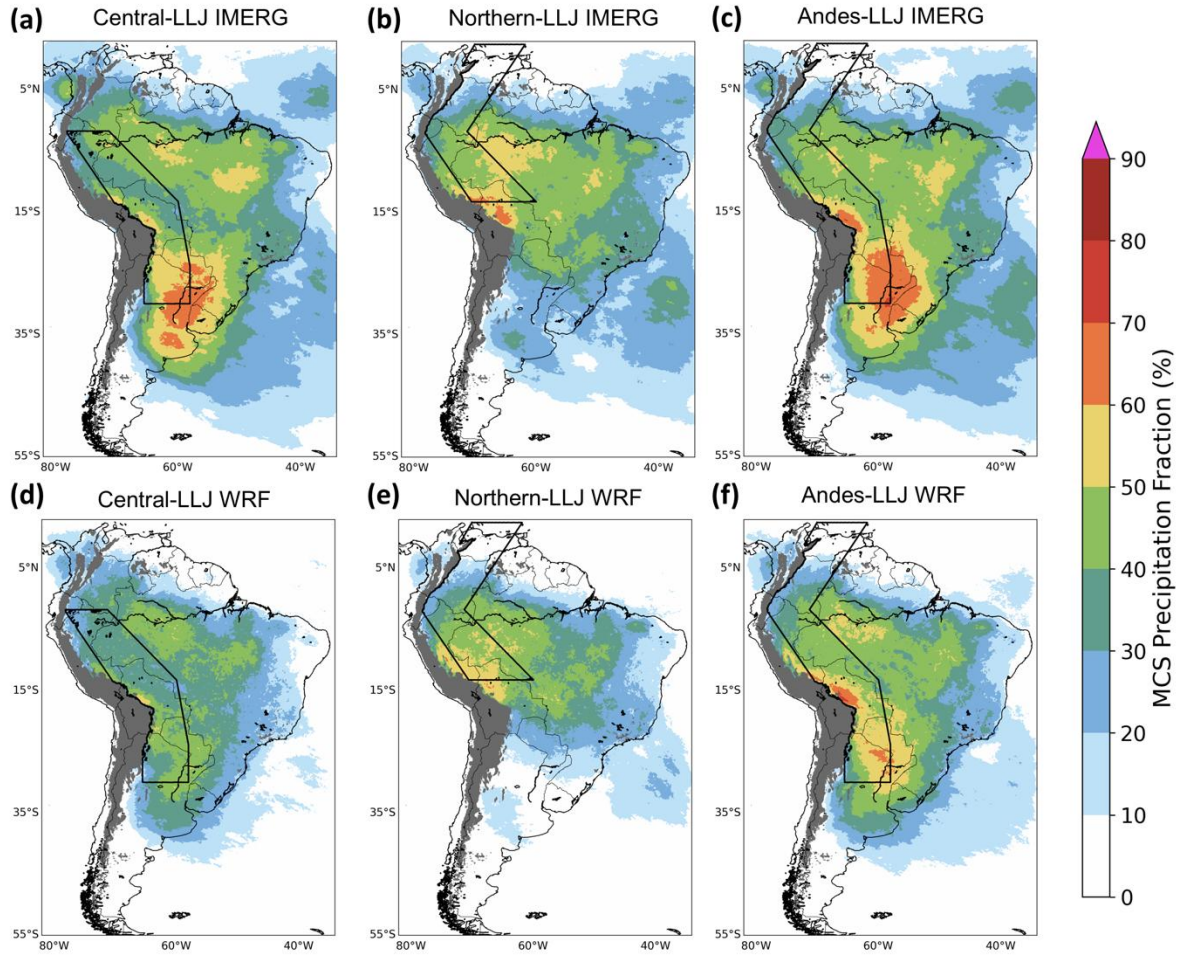


Figure 3.7. Fraction of MCS precipitation to total precipitation based on observations (top row), simulations (bottom row) for (a, d) Central LLJ, (b, e) Northern LLJ, and (c, f) Andes LLJ. The black box outlines the corresponding LLJ regions.

These results highlight the importance of LLJs in organizing MCSs and their contribution to total precipitation across South America, particularly within the La Plata Basin. Both IMERG and WRF indicate that MCSs dominate the total precipitation in the southeastern part of the continent, especially under Central and Andes LLJ conditions. In these regions, MCS-driven precipitation often exceeds

60%, underscoring the role of LLJs in fostering large, long-lived convective systems that account for most of the regional rainfall (Monaghan et al., 2010; da Rocha et al., 2024).

C.3 MCS Interannual Variability and ENSO

This section examines the interannual variability of MCS characteristics across different LLJ regions and explores the influences of ENSO on MCS activity. Figure 3.8 illustrates yearly fluctuations in MCS initiation frequency, duration, and size for the Central, Northern, and Andes LLJs, based on IMERG, MergIR, and WRF from 2000 to 2020. Significant interannual variability in MCS initiation frequency is observed across all LLJ exit regions, with the Andes LLJ exhibiting the highest average MCS initiations (Figures 3.8a–8c). The WRF simulation (green) captures both the amplitude and phasing of fluctuations downstream of the Central ($r = 0.80$) and Northern LLJs ($r = 0.70$) and reasonably reproduces the broad peaks and troughs associated with the Andes LLJ ($r = 0.52$). Nevertheless, WRF systematically over-produces storms in the Northern and Andes exit regions, an expression of the moist bias previously documented for this model over the southwestern Amazon and SESA (Rehbein et al., 2024). MCS duration also exhibits significant interannual variability in both data sets (Figures 3.8d–8f). However, discrepancies are evident, particularly in the Central and Northern LLJs, where correlations are weak or absent. This suggests that while WRF simulations may capture environmental controls on storm maintenance under strong jets, but they lack skill in reproducing year-to-year variations in MCS duration downstream of the Central or Northern LLJs. Both IMERG and WRF indicate that the largest systems preferentially form in

the SESA exit region, often exceeding 3×10^5 km² in area, and their inter-annual variability is reasonably captured in the Central ($r = 0.66$) and Andes ($r = 0.82$) LLJs (Figures 3.8g and 8i). By contrast, WRF markedly underestimates MCS sizes in the Northern LLJ region, reinforcing the weak organizational influence of the jet on convection in the Amazon, in agreement with previous km-scale modeling studies over South America (Prein et al., 2024; Zhang et al., 2021).

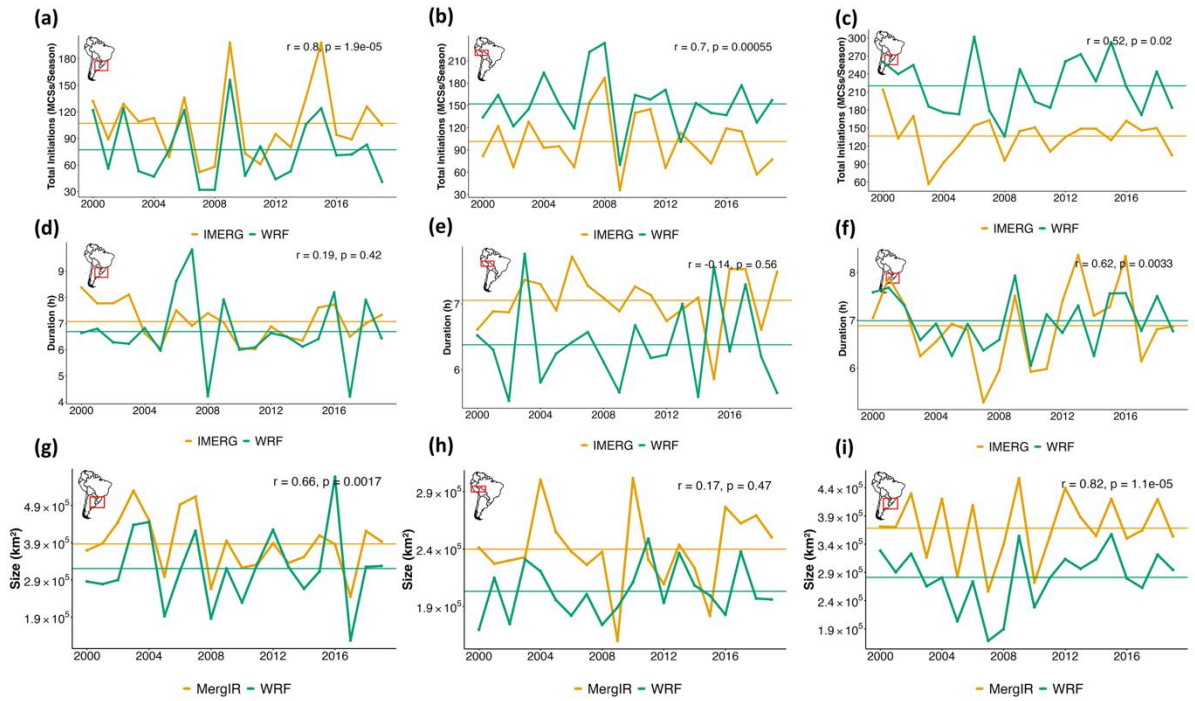


Figure 3.8. Interannual variability of MCS characteristics for each LLJ exit region based on IMERG, GPM MergIR, and WRF from 2000 to 2020. The first column (a, d, g) represents the Central LLJ region, the second column (b, e, h) represents the Northern LLJ region, and the third column (c, f, i) represents the Andes LLJ region. Panels (a–c) show the total number of MCS initiations per warm season, panels (d–f) display the mean MCS duration (hours), and panels (g–i) illustrate the mean MCS size (km²) for each season. Solid horizontal lines indicate

long-term means. Orange lines denote satellite-based IMERG (or MergIR for size), green lines denote WRF. Pearson correlation coefficients (r) and p -values test the IMERG-WRF agreement.

Figure 3.9 compares observations and WRF simulations to address two related questions: (a) how ENSO phases modulate the frequency of the three LLJs and (b) how MCS initiation rates and the corresponding exit regions respond to each phase. Based on ERA5, Central LLJs occur most frequently in El Niño years (380 cases) and least in La Niña, whereas Andes and Northern LLJs peak in La Niña and decline toward El Niño (Figure 3.9a). WRF reproduces these phase-dependent shifts, albeit with a systematic over-count of Andes events. However, both data sets agree on the ENSO response: El Niño favors Central LLJ, and La Niña favors Andes and Northern LLJs (Figure 3.9c), in agreement with Mu et al. (2024). IMERG observations show that the Central LLJ exit region experiences a highly significant ($p < 0.01$) increase in seasonal MCS initiations during El Niño, mirroring the LLJ frequency spike. Conversely, Northern-LLJ MCS initiations are significantly greater in La Niña years ($p < 0.01$), consistent with more frequent Northern jets, while Andes-LLJ initiations display no phase-dependent signal, suggesting compensating

influences from the two overlapping jets (Figure 3.9b).

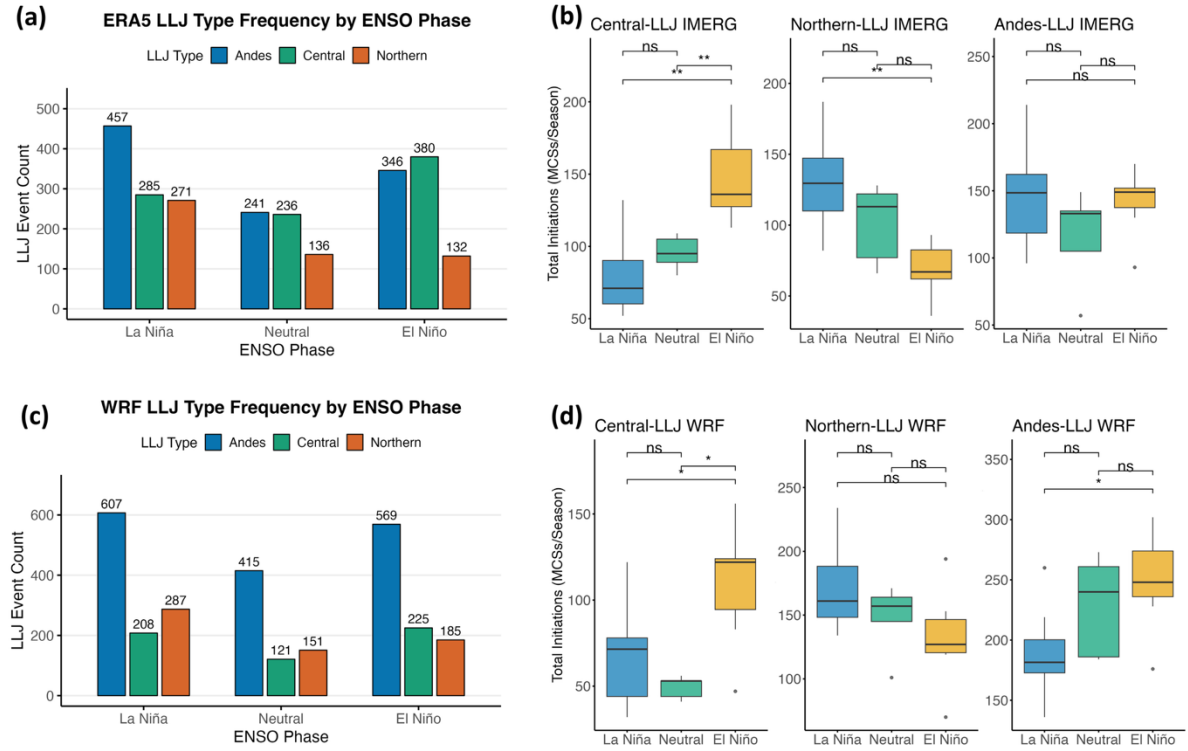


Figure 3.9. ENSO phase modulation of LLJ occurrence and the associated number of warm-season MCS initiations from 2000 to 2020. (a) Bar-plot of ERA5-derived LLJ event counts; (b) Box-and-whisker plots of IMERG MCS initiations per season stratified by ENSO phase for the three LLJ regions; horizontal brackets show pair-wise Kolmogorov-Smirnov tests; (c) Same as (a) but for the WRF-simulated LLJ index (used with WRF-tracked MCSs); (d) Same as (b) but for WRF MCS initiations. Central, Northern and Andes regions correspond to the LLJ exit-boxes in Figure 3.4. Statistical significance of ENSO-phase contrasts is indicated above each bracket: $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***), while “ns” denotes non-significant differences.

WRF shows a robust El Niño enhancement for Central LLJ MCSs ($p < 0.05$), a non-significant ENSO effect in the Northern exit region, and opposite changes in the Andes LLJs (Figure 3.9d). The model's stronger absolute counts reflect the known high bias in km-scale simulations (Rehbein et al., 2024), but the phase relationships agree with IMERG well.

These results highlight the regional differences in how ENSO modulates MCS characteristics, with El Niño primarily affecting MCSs in the Central LLJs, while La Niña boosts MCS activity in the Andes and Northern LLJ region. El Niño-related strengthening of the subtropical jet and low-level northerlies over the La Plata basin leads to more Central LLJs and, therefore, more organized convection within SESA (Salio et al., 2007). Furthermore, WRF reproduces the sign and rank of the ENSO signals but overestimates overall Andes LLJ frequency and, consequently, MCS initiations, in agreement with the positive bias reported by Prein et al. (2024). Conversely, the model's muted ENSO modulation of Northern-sector MCS size and duration is in line with Rehbein et al. (2024), who showed that convection-permitting models struggle to grow large, long-lived systems over the north-western Amazon owing to premature stratiform–convective transitions.

D. Conclusions

This study investigates MCS characteristics in both observational data and WRF climate simulations during different LLJ types in South America. Building on the LLJ definition of Jones et al. (2023), there is evidence in both observations and simulations that the longest-lived and most intense MCSs occur when the LLJs are strong. Moreover, MCSs associated with the Central LLJ also exhibit relatively long

durations and large sizes. In contrast, the Northern LLJ generates shorter-lived, smaller MCSs with lower mean precipitation, indicating a predominant influence of local convective processes with less organized convection and weaker moisture flux convergence in the Amazon Basin (Ruiz-Vásquez et al., 2024). These differences in MCS characteristics are related to the differing strengths, positions, and orographic influences of each LLJ type, all of which affect moisture flux convergence, vertical ascent, and precipitation (Mu et al., 2024; Nascimento et al., 2016). Before interpreting LLJ–MCS interactions in the WRF simulation, it is important to acknowledge that WRF shows notable deviations in LLJ characteristics when compared to ERA5 reanalysis. While the model captures the occurrence of Andes LLJs with relatively high fidelity, it tends to overestimate their frequency and misclassifies a significant fraction of Central and Northern LLJs. These biases stem partly from the boundary-forced WRF simulation without spectral nudging, allowing circulation patterns to evolve independently from reanalysis and potentially altering jet strength, spatial extent, and vertical structure.

Despite these limitations, our results demonstrate that convection-permitting WRF simulations reproduce many key aspects of MCS behavior observed in satellite products. The model captures spatial patterns of MCS initiation and precipitation, particularly the enhanced activity in southeastern South America under Andes and Central LLJ regimes. Simulations accurately reproduce the diurnal cycle of MCSs, with afternoon initiation followed by nocturnal peaks in precipitation, broadly consistent with IMERG. However, discrepancies remain: WRF produces higher extreme rainfall than IMERG, especially during strong LLJ events. This overestimation may be due to biases in the model's convective dynamics (e.g.,

stronger updrafts and microphysical feedback), whereas IMERG is known to underestimate intense convective rainfall due to reliance on infrared-based retrievals and limited microwave coverage in complex terrain (Prein et al., 2024; Zhang et al., 2021).

The biases in MCS characteristics documented here may be partly linked to systematic differences in simulated LLJ frequency and intensity. WRF tends to overestimate Andes LLJ events while underestimating Central and Northern LLJs, which can shift MCS statistics toward larger, longer-lived systems. The higher rainfall intensities found in WRF may reflect stronger simulated convective updrafts and enhanced moisture convergence, consistent with other convection-permitting studies in South America (Rehbein et al., 2024; Zhang et al., 2021). Furthermore, it is important to acknowledge that the identification and characterization of MCSs may depend on the tracking algorithm employed. In this study, we used the TOBAC tracker, which applies feature-based detection and lifetime constraints based on infrared brightness temperature fields and precipitation thresholds. As noted in Prein et al. (2024), different trackers, especially those with contrasting definitions of system initiation, splitting/merging treatment, or spatial-temporal smoothing, can lead to variations in MCS frequency, size, and duration statistics, but the differences between model and observations should still be consistent when the same method is used. Despite these uncertainties, the combination of WRF and satellite data provides a robust framework to evaluate LLJ-driven MCS climatology.

The response of MCS activity to ENSO variability further underscores the importance of LLJ modulation. During El Niño events, the Central LLJ becomes more frequent, facilitating the transport of moisture from the Amazon Basin toward

the subtropics of South America (Jones, 2019; Mu et al., 2024). This strengthened Central LLJ and associated upper-level jet streams provide sustained moisture and dynamic support, leading to more frequent, longer-lasting, and more extensive convective systems in southeastern South America. La Niña events strengthen the Northern LLJ, enhancing moisture advection into the Amazon Basin and the northern Andes (Mu et al., 2024). This moisture transport is associated with an increase in MCS frequency in these areas. Interestingly, the Andes LLJ, which represents the overlap of the Central and Northern LLJs, shows enhanced MCS activity during El Niño in WRF simulations, likely driven by the strengthened Central LLJ influence. Furthermore, while ENSO strongly modulates South American LLJ occurrence and strength (Grimm, 2003; Grimm & Tedeschi, 2009; Mu et al., 2024), a longer simulation period is needed to fully capture the range of ENSO variability and to assess its influence on LLJ–MCS interactions with greater confidence. Spectral nudging would mainly force the simulation toward the reanalysis fields and could mask the model's intrinsic ability to reproduce these teleconnections, whereas we aim to evaluate whether the convection-permitting model can simulate these relationships on its own.

The strong link between LLJ dynamics and MCS activity has important implications for both weather forecasting and climate modeling. Accurate representations of LLJ behaviors in numerical weather prediction models is crucial for predicting extreme weather events, such as heavy rainfall and flooding, which are often driven by MCSs (Martinez et al., 2024; Prein et al., 2023). In the context of climate change, understanding how LLJs may evolve under warming scenarios is critical. Our results reveal that shifts in wind patterns, moisture availability, and jet

intensities could significantly alter the frequency and intensity of MCSs, potentially increasing the risk of extreme precipitation events across South America. As climate change continues to shape regional weather patterns, LLJ-MCS interactions will remain a key area of study for predicting extreme weather and managing climate impacts (Hodnebrog et al., 2022; Li et al., 2022; Yun et al., 2021).

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IV. Convection-Permitting Projections of Low-Level Jets and Mesoscale Convective Systems in South America

*This work is submitted to the *Journal of Geophysical Research: Atmospheres* with the below co-authors:

Charles Jones, Leila M. V. Carvalho, Julia Kukulies, Andreas F. Prein, Lulin Xue & Changhai Liu

Abstract

Anthropogenic warming is expected to substantially modify the hydroclimate of South America, a region in which low-level jets (LLJs) and mesoscale convective systems (MCSs) are key components of moisture transport and precipitation. However, the responses of these systems to future climate change, including the relative roles of thermodynamic and dynamic forcing, remain poorly understood. Using convection-permitting model projections under a climate warming of approximately 3 °C above preindustrial levels, this study examines future changes in the characteristics of LLJs and MCSs. The results reveal a widespread thermodynamic intensification of precipitation, with maximum rainfall rates surging at magnitudes consistent with thermodynamic expectations. However, the structural evolution of MCSs exhibits a sharp dynamic bifurcation between the tropics and subtropics. In Southeastern South America, the strengthening of the background northerly flow enhances vertical wind shear during Central and Andes LLJ events. This kinematic support facilitates the upscale growth of MCSs into larger, longer-

lived complexes, elevating the potential for high-volume hydrometeorological extremes. Conversely, the projected circulation anomaly across the western Amazon weakens the Northern LLJs, reducing the dynamic organization of historical squall lines and favoring a transition toward widespread, thermodynamically driven, loosely organized convective clusters. These regional shifts are consistent with a stationary Rossby wave train resembling the Pacific-South American pattern, which enhances meridional moisture transport into the subtropics. These findings highlight a transition toward a complex hydrometeorological hazard profile, in which future extremes are defined not merely by total rainfall, but by regime-specific changes in storm morphology, duration, and peak intensity.

A. Introduction

Low-Level Jets (LLJs) and Mesoscale Convective Systems (MCSs) are coupled components that are fundamental to the hydroclimate of South America. The LLJ acts as a narrow, persistent northerly flow along the eastern foothills of the Andes, transporting warm, moist air toward subtropical latitudes (Marengo et al., 2004; Vera et al., 2006; Montini et al., 2019). Early studies established the LLJ as a dominant mechanism for moisture transport, modulating precipitation patterns and extreme rainfall events across the La Plata Basin and southeastern South America (SESA) (Insel et al., 2010; Saulo & Skabar, 2007). Intensive observations from the SALLJEX field campaign further documented the jet's vertical structure, diurnal variability, and role in convective initiation, highlighting the strong interaction between jet dynamics, orography, and deep convection (Vera et al., 2006; Rasmussen & Houze, 2011). More recent analyses have revealed multiple jet types,

including Northern, Andes, and Central LLJs characterized by distinct locations, durations, intensities, and relationships to synoptic-scale systems (Jones et al., 2023; Mu et al., 2024). Collectively, these studies depict the LLJ as a dynamically robust yet variable circulation feature, whose structure strongly influences warm-season precipitation and extreme weather across the South American continent.

Additionally, these LLJs exhibit substantial low-frequency variability driven by large-scale ocean-atmosphere coupled patterns. ENSO-induced shifts in the Walker circulation modify baroclinicity, moisture transport, and jet strength (Grimm & Tedeschi, 2009; Carvalho et al., 2004; Jones et al., 2023), while the Atlantic Multidecadal (AMO) and Pacific Decadal Oscillations (PDO) further modulate LLJ frequency and preferred location on decadal to multidecadal timescales (Jones and Carvalho 2018; Mu et al., 2024). These teleconnections influence both the occurrence of LLJ events and their associated extreme rainfall distributions. In addition, land–atmosphere feedbacks, such as Amazon deforestation and widespread increases in dry-season vapor pressure deficit (VPD), affect regional moisture availability and alter the environmental conditions through which the jet transports moisture. Observational and modeling studies show rapidly increasing VPD trends driven jointly by greenhouse forcing and land-use change (Mu et al., 2025a; Williams et al., 2015), with important implications for moisture recycling and jet–convection coupling. Despite progress in understanding these drivers, projections of future LLJ structural changes remain uncertain because most analyses rely on coarse-resolution models that cannot accurately represent jet–terrain interactions or convective feedbacks.

South America hosts some of the most intense convective storms on Earth. Satellite-based analyses using the Tropical Rainfall Measuring Mission (TRMM) and infrared tracking methods identify southeastern South America as a global hotspot of tall, ice-rich convective cores, extreme rainfall rates, and long-lived MCSs (Zipser et al., 2006; Rasmussen & Houze, 2011). MCSs in this region contribute disproportionately to warm-season rainfall totals and flood-producing events, playing a central role in agriculture, hydropower, and water-resource reliability (Nicolini et al., 2002; Salio et al., 2007). Their formation and longevity are strongly influenced by environmental factors, including enhanced low-level wind shear, abundant moisture, and intense convergence, all of which are directly tied to LLJ strength and spatial organization (Rasmussen & Houze, 2016; Durkee et al., 2009). The eastern Andean foothills serve as a key trigger zone, where orographically forced ascent and LLJ-driven moisture convergence initiate deep convection that subsequently evolves into expansive MCSs propagating southeastward into the La Plata Basin (Nesbitt et al., 2006; Gamelin et al. 2022). However, despite their importance, global and traditional regional climate models poorly represent South American convection. Deep convection parameterizations fail to capture realistic storm morphology, underestimate MCS frequency, distort diurnal cycles, and misrepresent extreme rainfall intensities (Prein et al., 2015; Kawazoe & Gutowski, 2013). Over mountainous regions and along the steep eastern Andes, these biases are magnified because coarse models cannot resolve the sharp topographic gradients that organize MCS initiation or the narrow jet regions that shape moisture flux (Solman, 2013). Consequently, coarse-resolution models may produce correct regional rainfall statistics for the wrong physical reasons, masking misrepresented

convective processes and mischaracterizing extreme-event changes (Kendon et al., 2017).

Convection-permitting models (CPMs) represent a major advance in addressing these limitations. By explicitly resolving deep convection, CPMs accurately capture MCS structure, cold-pool dynamics, orographic precipitation, and sub-daily rainfall extremes (Prein et al., 2013; Ban et al., 2015). Across Europe, North America, and Africa, CPM simulations show substantial improvements in representing extreme precipitation and often reveal stronger intensification of hourly rainfall extremes under warming than models with parameterized convection predict (Kendon et al., 2014; Prein et al., 2017; Berthou et al., 2019). CPMs also reproduce realistic diurnal convection cycles and mesoscale organization, both of which are critical for diagnosing LLJ–MCS coupling under climate change (Liu et al., 2017, Prein et al., 2024).

For South America, convection-permitting modeling has only recently begun to emerge, offering new opportunities to investigate regional LLJ–MCS interactions. Building on this progress, the South America Affinity Group (SAAG) CPM dataset provides the first continental-scale convection-permitting climate simulations for the region, demonstrating improved representation of storm initiation along the Andes, realistic MCS diurnal cycles, and more accurate extreme rainfall climatologies (Dominguez et al., 2024). Yet, despite these advances, no study has systematically examined how LLJs and MCSs jointly respond to anthropogenic warming using convection-permitting simulations across the full continental domain. Existing CPM work has predominantly focused on either model evaluation (e.g., Rehbein et al. 2024; Prein et al. 2024) or regional precipitation changes, without explicitly

quantifying future shifts in LLJ intensity, jet-type frequency, MCS size and longevity, or alterations in coupling pathways. This knowledge gap is especially consequential given the rapid hydroclimatic transformation underway in South America. Rising temperatures, associated increases in atmospheric moisture demand, reflected in higher vapor pressure deficit and concurrent changes in moisture recycling and atmospheric dynamics, all have the potential to alter the environments that support LLJs and MCSs (Marengo et al., 2018; Williams et al., 2021; Mu et al., 2025a). These processes may modify jet strength and nocturnal enhancement, orographic triggering, and convective organization, yet their interacting effects cannot be reliably inferred from coarse-resolution models.

In this study, we address these gaps by using a suite of convection-permitting (4 km) WRF pseudo-global-warming simulations spanning continental South America. We present the first integrated assessment of how anthropogenic warming alters (1) LLJ structure, frequency, and spatial pathways; (2) MCS characteristics, including initiation, size, duration, and precipitation; and (3) the basic state change that drives extreme precipitation across the Andes foothills, Amazon Basin, and La Plata Basin. By explicitly resolving deep convection and jet–terrain interactions, these simulations offer a process-based perspective on future hydroclimatic risk in one of the world’s most convectively active and socioeconomically vulnerable regions.

B. Materials and Methods

B.1 Data and Model Simulation

This study uses output from two sets of 22-year convection-permitting Weather Research and Forecasting (WRF) simulations conducted over a continental-scale domain encompassing South America at 4 km horizontal grid spacing: a historical climate simulation and a future climate simulation representing late-century conditions under approximately 3°C of global warming above preindustrial levels (Liu et al., 2026; Dominguez et al., 2024). The historical simulation downscales ERA5 reanalysis data for the period 2000–2021, aiming to reproduce recent climatological characteristics. The future climate simulation downscales the late-century South American climate projected by the CESM2 Large Ensemble (LENS2) under the SSP3-7.0 radiative forcing scenario using the Pseudo-Global Warming (PGW) approach. Specifically, the model forcing is derived by imposing the LENS2-projected climate change signal for 2060–2080 relative to 2000–2020 onto the reanalysis-based forcing from the historical simulation. In essence, the boundary conditions in the PGW simulation represent the mean climatological conditions of the future period projected by GCMs while retaining the synoptic variability of the ERA5 reanalysis. Further details on the simulations, including model configuration, evaluation of the historical run, and an overview of the PGW-based future simulation, are provided in Liu et al. (2026).

The two climate simulations use identical model configurations and share similar synoptic variability at the lateral boundaries, allowing a direct comparison of mesoscale processes between present-day and future climates, the latter

characterized by a systematically warmer and moister atmosphere and altered large-scale flow imposed through PGW perturbations. The 4-km grid-spacing eliminates the need for parameterized deep convection and improves the representation of terrain and land-surface heterogeneity, facilitating the explicit representation of MCSs, LLJs, and their interactions with the complex Andean topography. All physical variables required for MCS tracking and LLJ diagnostics are extracted directly from the model output at hourly temporal resolution. To contextualize the large-scale basic state changes driving regional anomalies, we additionally utilize the LENS2, consisting of 100 members at 1-degree spatial resolution.

B.2 LLJ and MCS definition

LLJs are identified using the percentile-based methodology of Jones et al. (2023) and Mu et al. (2025b), applied consistently to both the Historical and PGW simulations. An LLJ event is defined for a given day when the nighttime (23:00–09:00 UTC) 850-hPa wind speed exceeds its monthly 75th percentile, and the 850–700-hPa vertical wind shear simultaneously exceeds its monthly 75th percentile. To ensure spatial coherence, the event must occur within a Contiguous Region of Wind Speeds (CRWS) where the 850-hPa wind speed exceeds 10 ms⁻¹. Following the classification established in Jones et al. (2023), LLJs are categorized into three types, Central, Northern, and Andes, based on the location of their jet cores along the eastern Andean slopes (Figure 4.1). Jet exit regions are defined using fixed geographic boxes enabling direct spatial comparison between the Historical and PGW climates, following Mu et al. (2025b). LLJ intensity is determined based on the maximum wind speed within the CRWS. Strong LLJs are defined as events with

CRWS wind speeds exceeding the 75th percentile, while weak LLJs are those falling below the 25th percentile of the distribution (Figure 4.2b). Percentiles from the historical simulation are also used for PGW simulations.

MCSs are identified and tracked using the Tracking and Object-Based Analysis of Clouds (tobac) algorithm (Heikenfeld et al., 2019; Sokolowsky et al., 2024), which detects and follows convective systems in a Lagrangian framework. Although tobac is variable-agnostic, we apply it to both infrared brightness temperature (T_b) and precipitation fields from the WRF simulations. An MCS is defined when a tracked cloud object meets the following criteria: (1) a contiguous cloud shield with $T_b \leq 241$ K exceeding 40,000 km² and lasting at least 4 hours; (2) maximum hourly precipitation beneath the ≤ 241 K cloud shield of at least 10 mm hr⁻¹ for a minimum of consecutive hours; (3) at least one hour with precipitation volume exceeding 20,000 km² mm hr⁻¹; (4) a minimum $T_b < 225$ K at any time during its lifetime, indicating deep convection and overshooting tops. These thresholds follow the MCS tracking intercomparison for the same WRF domain described in Prein et al. (2024) and Feng et al. (2025) and have been successfully implemented for the historical simulations of this study, as evaluated against satellite observations in Mu et al. (2025b). The algorithm is applied identically to the Historical and PGW WRF simulations. For each MCS, we compute standardized characteristics, including duration, maximum cloud-shield area, and mean rainfall beneath the ≤ 241 K cloud shield.

C. Results and Discussions

C.1 Projected Shifts in Low-Level Jet Intensity and Frequency

The PGW projection reveals a distinct latitudinal contrast in the LLJ response (Figure 4.1). While the jet core region along the subtropical Andes (15°S - 25°S) exhibits robust intensification, the tropical segment (0 - 10°S) shows a widespread reduction in wind speed. Specifically, the Central and Andes LLJ types (Figures 4.1a and 1c) are characterized by significant positive wind speed changes ranging from $+1.0$ to $+2.0 \text{ m s}^{-1}$ within the jet core. This strengthening is spatially coherent and statistically significant, indicating a systematic intensification of the northerly flow. In contrast, the Northern LLJ type exhibits predominantly neutral-to-negative anomalies within its defined domain (Figure 4.1b). The blue shading inside the Northern LLJ boundary indicates a weakening of the climatological northerly winds along the eastern slopes of the northern Andes.

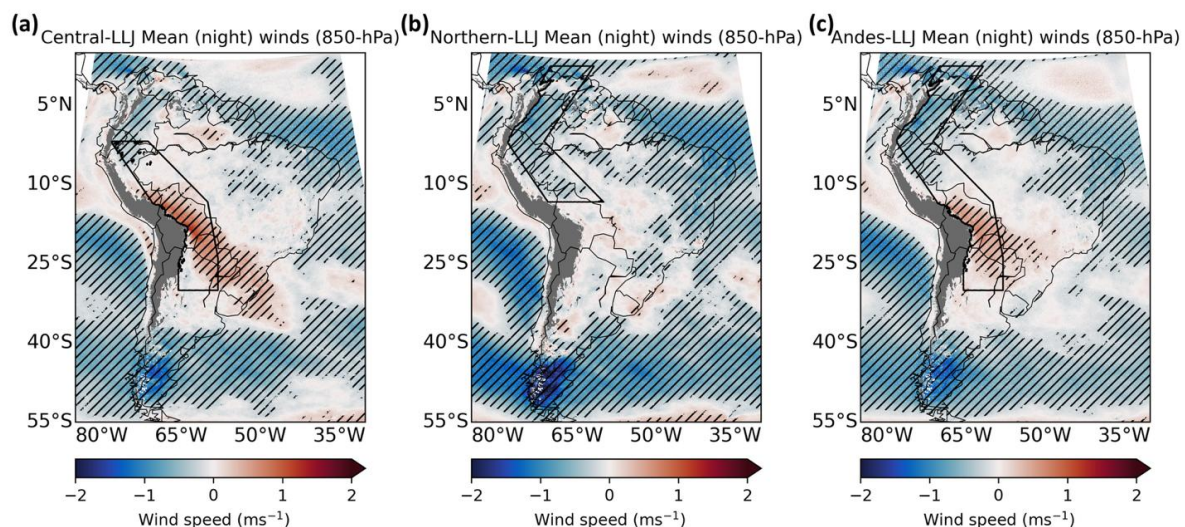


Figure 4.1. Projected changes in 850-hPa wind speed conditioned on the occurrence of each LLJ type. Maps display mean wind speed anomalies calculated as

the PGW simulation minus the Historical simulation during (a) Central LLJ, (b) Northern LLJ, and (c) Andes LLJ events. Shading indicates the magnitude of wind speed change (ms^{-1}), with red indicating strengthening and blue indicating weakening of the flow. Black polygons outline the spatial domains of each LLJ type. Hatched areas indicate regions where the differences are statistically significant at the 95% confidence level.

The Central LLJ exhibits a robust transition from weak/moderate to strong events, with the frequency of weak and moderate events decreasing and strong events (wind speeds exceeding the historical 75th percentile) increasing by approximately 5% (Figure 4.2a). This intensification corroborates the probability density functions (PDFs), which shows a rightward shift in the future distribution relative to the historical baseline, indicating a significantly higher likelihood of extreme wind speeds exceeding 15 m s^{-1} (Figure 4.2b). In contrast, the Northern LLJ shows a systematic weakening. The frequency of moderate events decreases by nearly 20%, accompanied by an increase in weak events (Figure 4.2a). The PDF for the Northern LLJ narrows and shifts toward lower velocities, signaling a suppression of the organized northerly flow (Figure 4.2b). The Andes LLJ displays a unique polarization, with both weak and strong events increasing at the expense of moderate events (Figure 4.2).

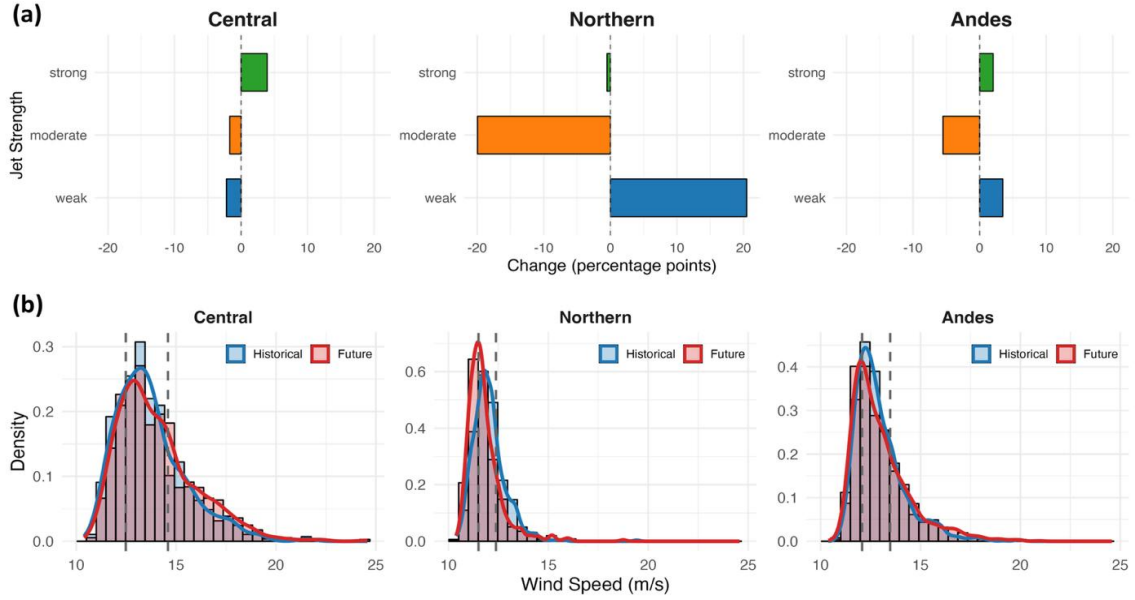


Figure 4.2. Projected shifts in LLJ intensity and wind speed distributions. (a) Change in the frequency (%) of weak (blue), moderate (orange), and strong (green) intensity events for the Andes, Central, and Northern LLJ types in the PGW simulation relative to the Historical baseline. Positive values indicate an increase in frequency under a future climate conditions. (b) Probability density functions (curves) and histograms (bars) of jet core wind speeds (m s^{-1}) for the Central, Northern, and Andes LLJs. Blue represents the Historical simulation, and red represents the PGW simulation. Vertical dashed lines indicate the climatological 25th and 75th percentile thresholds used to define the weak and strong intensity categories, respectively.

This tropical weakening is consistent with the thermodynamically driven slowing of the Hadley and Walker circulations, where a rapid increase in atmospheric water vapor necessitates a deceleration of convective overturning to maintain mass balance (Vecchi & Soden, 2007; Ma et al., 2018). Simultaneously, the strengthening of the LLJ in the subtropics (Central/Andes types) is indicative of a

poleward expansion of the Hadley cell, which redistributes kinetic energy away from the deep tropics (Hu et al., 2018). Together, these structural changes suggest that under warming conditions, the transport of Amazonian moisture toward the La Plata Basin will become more efficient and energetic, while the weakening of the Northern jet implies reduced moisture convergence in the northwestern Amazon. The intensification of the Central and Andes LLJs is particularly critical for severe weather, as these jets enhance low-level moisture transport, erode convective inhibition, and promote the organization of long-lived convective storms (Salio et al., 2007). The shift toward strong LLJ events in the Central and Andes regimes implies that, when present, the jet enhances low-level shear and moisture flux convergence (Dominguez et al., 2024). This raises a critical question: Does this kinematic intensification of the jet translate directly into more frequent or intense downstream MCSs? In the following section, we address this by explicitly quantifying the changes in MCS initiation, size, duration, and precipitation associated with these altered jet regimes.

C.2 Regime Shift in Convective Organization

The projected changes in MCS initiation frequency are spatially sensitive to LLJ type and intensity (Figure 4.3). Under strong Central LLJ (Figure 4.3d), MCS triggering intensifies across the La Plata Basin in SESA. Red shading indicates an increase in initiation frequency of up to 3 events per month, particularly concentrated along the eastern slopes of the Andes and the plains of northern Argentina. This subtropical intensification aligns directly with the increased kinematic forcing of the jet: enhanced northerly advection of Amazonian moisture

lowers convective inhibition (CIN) (Jones et al., 2023), while the jet's exit region provides the necessary low-level convergence and vertical wind shear for rapid upscale growth (Salio et al., 2007). However, significant increases in initiation are also observed in the eastern Amazon and western Colombia, areas dynamically removed from the Central Jet's primary influence. This suggests that future Central LLJs are characterized not just by strong winds, but by a broadly more favorable thermodynamic environment across the continent. In these tropical zones, the increase is likely driven by ubiquitous thermodynamic destabilization associated with the warming background state, rather than direct kinematic support from the jet itself. Thus, while the jet mechanically drives the excess storms in SESA, it acts as a proxy for a widespread convectively active environment in the tropics.

The Northern LLJ also demonstrates a dependence of organized convective activity on jet strength, but with MCS initiation frequency increasing during weak jet events and decreasing during strong jet events (Figure 4.3b, e), opposite to the behavior identified for the Central LLJ. This suppression of organized convection during traditionally favorable strong jet periods aligns with the distinct seasonality of the PGW forcing. While trade wind projections vary throughout the year, the weakening is most pronounced during the peak monsoon month of January, which is the critical period for Amazonian convection (Liu et al., 2026). Strong future Northern LLJ events are associated with distinct negative anomalies across the northwestern Amazon, suggesting a reduction in the efficacy of the jet to organize convection in this region (Mu et al., 2025b), likely attributed to weakened jet intensity (Figure 4.2b). This regime shift mirrors the slowing of the Walker circulation and the weakening of the tropical trade winds during the austral summer,

which limits the background kinematic support necessary for organizing long-lived Amazonian systems (Vecchi et al., 2006; Sierra et al., 2015).

The Andes LLJ exhibits a unique polarization in convective response. In the future climate, weak Andes LLJ events are associated with a broad decrease in MCS initiation along the Andean foothills (Figure 4.3c). For strong Andes LLJs, initiation is markedly enhanced near the Sierras de Córdoba (SDC) in central Argentina, a known focal point for terrain-focused upscale growth (Rasmussen & Houze, 2016). Stronger future jets in this region enhance the interaction between the northerly flow and complex topography, creating localized zones of intense lift and shear that favor the rapid transition of supercells to MCSs (Mulholland et al., 2019). This result suggests increased contrasts in the future hydroclimate of the Andean foothills: convective initiation will be suppressed under weak LLJ while intensified outbreaks and organized storms will be triggered when the LLJ is strong.

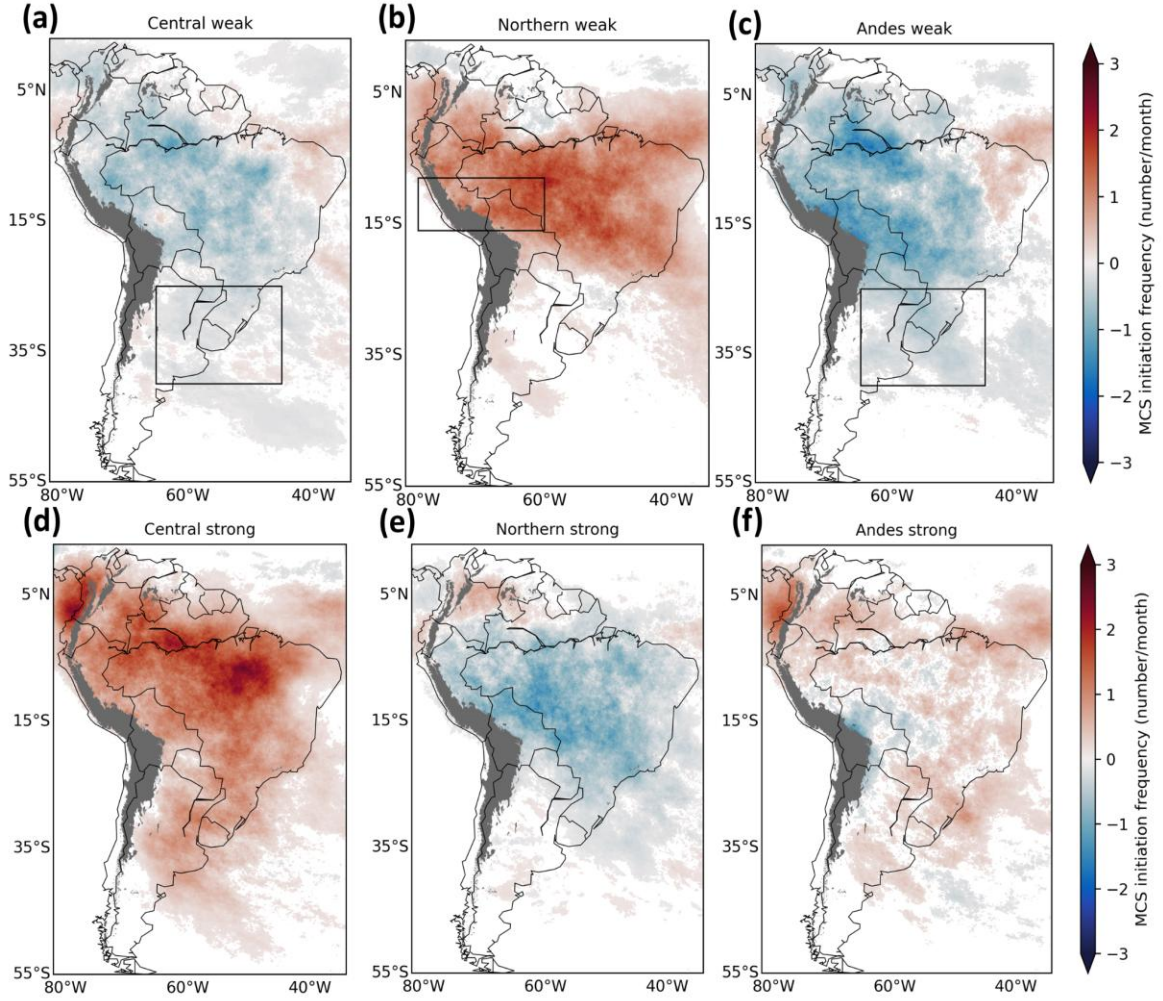


Figure 4.3. Spatial changes in MCS initiation frequency under different LLJ types. Panels display the projected change in MCS initiation frequency (events month⁻¹) in the PGW simulation relative to the Historical baseline, stratified by jet intensity and type. The top row (a–c) corresponds to weak jet events, and the bottom row (d–f) to strong jet events for the (a, d) Central, (b, e) Northern, and (c, f) Andes LLJ types. Red shading indicates regions with increased MCS initiation, while blue shading indicates decreased initiation. Only areas where the differences are statistically significant at the 95% confidence level are shown. Boxes indicate the exit region for each LLJ type.

Figure 4.4 shows the projected changes in total monthly precipitation and MCS precipitation. Climatologically, these regions typically exhibit a precipitation dipole: periods of active SACZ convection are associated with a suppression of the LLJ and reduced rainfall in SESA, while strong LLJ events favor SESA precipitation at the expense of the SACZ (Nogués-Paegle & Mo, 1997; Doyle & Barros, 2002; Salio et al., 2007). However, the PGW mean field (Figure 4.4c) shows robust wetting in both regions. In SESA, positive anomalies exceed +50 mm month⁻¹, consistent with previous projections of increased frequency in the positive phase of this dipole (Junquas et al., 2013). Concurrently, the SACZ region also exhibits significant wetting. This generalized intensification suggests that thermodynamic forcing dominates the climatological mean, as the background increase in specific humidity enhances rainfall rates in whichever phase of the dipole is active (Seth et al., 2010; Kendon et al., 2017).

In the historical baseline (Figure 4.4d), the most intense MCSs are concentrated in SESA, coincident with the exit region of the Central LLJ. Under PGW (Figure 4.4e), this region exhibits a robust increase in intensity, with positive anomalies of +2 to +5 mm (Figure 4.4f). This indicates that future subtropical storms will not only be more frequent (as shown in Figure 4.3) but will also yield significantly higher precipitation totals per event. In the western Amazon, while the weakening of the Northern LLJ suppresses the organization of frequent squall lines, the storms that do initiate are thermodynamically charged, producing heavier rainfall rates than their historical counterparts. The evolving contribution of MCS to the regional water budget is illustrated by the MCS precipitation contribution maps (Figure 4.4d–f). Historically, MCSs have accounted for a substantial fraction (40–

70%) of total rainfall across both the Amazon and La Plata basins (Figure 4.4d). This contribution generally increases under future climate conditions (Figure 4.4e), although the magnitude of the change is region dependent. In SESA, the contribution of MCSs to total rainfall increases by +5% to +15% (Figure 4.4f), indicating that the projected wetting in this region is partly driven by an intensification of organized convection.

The environment, primed by the stronger LLJ, favors the rapid upscale growth of storms into large, flood-producing MCSs, making them the dominant hydrometeorological agent in the future subtropical climate. In the western Amazon, total rainfall decreases, yet the fractional contribution from MCSs increases (Figure 4.4c, f). This pattern indicates a fundamental regime shift from frequent, localized convection to more episodic, organized convection. We postulate that the physiological response of the rainforest to warming (reduced evapotranspiration) induces a drier, warmer boundary layer that stabilizes the column, suppressing the widespread, disorganized thunderstorms that historically provide much of the daily rainfall (Kooperman et al., 2018). As a result, the rainfall that does occur is almost exclusively produced by larger MCSs that have sufficient dynamic forcing to overcome this inhibition (Viscardi et al., 2024). Thus, the western Amazon transitions to a regime of longer dry spells punctuated by intense organized events, maintaining a high MCS fraction despite a reduced total water budget.

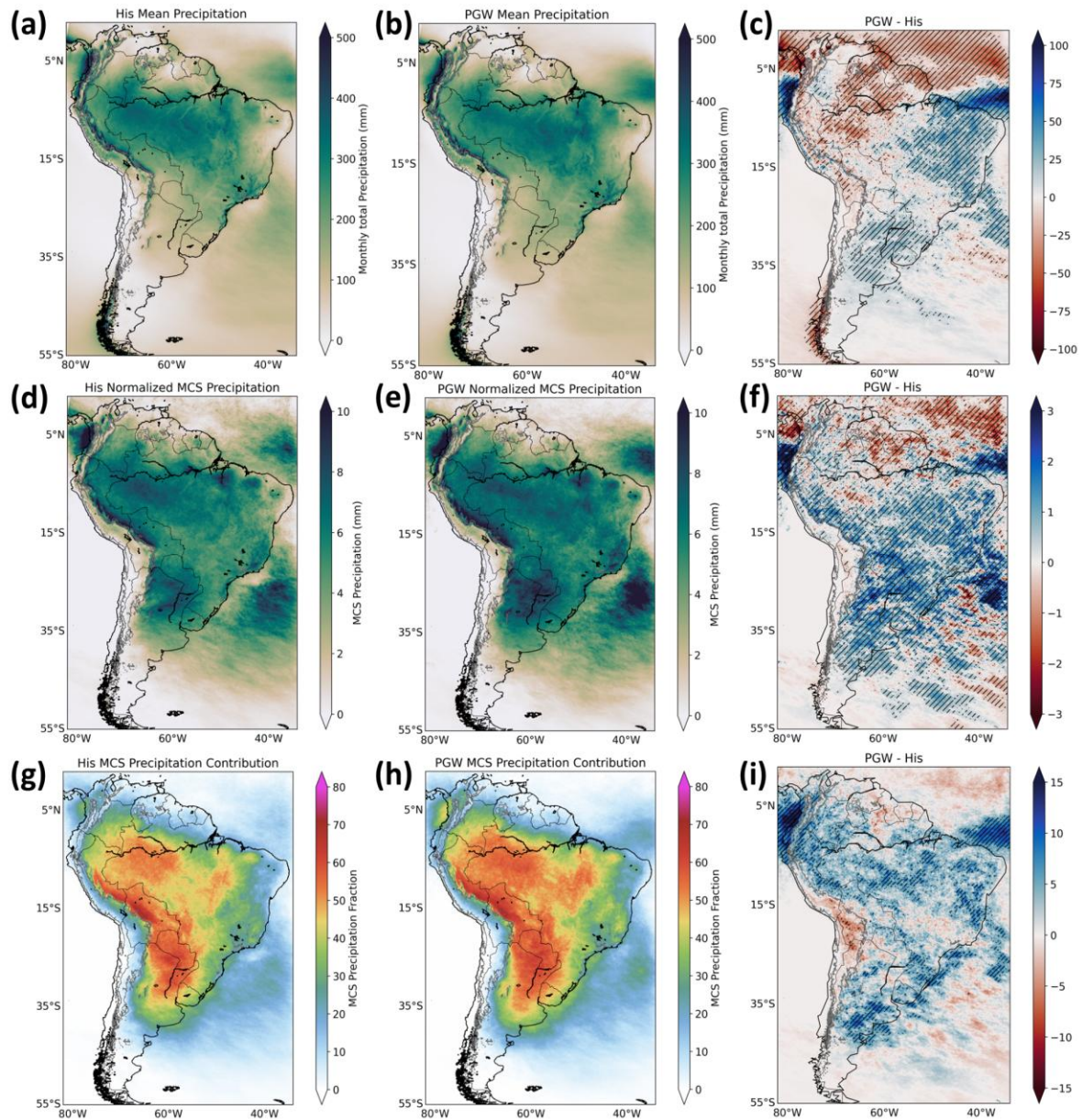


Figure 4.4. Projected changes in mean total precipitation, MCS precipitation intensity, and relative contribution. (a) Historical and (b) PGW mean monthly total precipitation (mm month⁻¹). (c) Projected change in mean monthly precipitation (PGW minus Historical). (d) Historical and (e) PGW mean MCS precipitation intensity (calculated as total accumulated MCS precipitation divided by MCS frequency). (f) Projected change in mean MCS precipitation intensity. (g) Historical

and (h) PGW spatial distribution of the MCS precipitation contribution (fraction of total rainfall attributed to MCSs, %). (i) Projected change in the MCS precipitation contribution (percentage points). In the difference maps (c), (f), and (i), hatched regions indicate areas where the changes are statistically significant at the 95% confidence level.

C.3 Changes in MCS Characteristics

MCS characteristics are computed for all systems with centroids located within the box boundaries indicated in Figure 4.3. Figure 4.5 shows an upward shift in the density distribution of mean precipitation intensity for both strong and weak Central LLJ, with the upper tails extending toward higher rainfall rates in the future climate. This trend is quantified in the quantile difference plot (Figure 4.5e), which shows positive anomalies across nearly the entire distribution (5th to 95th percentiles). Notably, the magnitude of the intensity increase is larger for MCSs associated with weak jet events than for those associated with strong jet events. For Central LLJ, the mean precipitation intensity increases monotonically with the quantile, reaching a maximum enhancement of approximately $+0.4 \text{ mm h}^{-1}$ at the 95th percentile ($\sim 10\%$ increase). However, the maximum precipitation intensity reveals a critical dependency on dynamic support (Figure 4.5b, f). MCSs associated with strong LLJ events show a robust increase in maximum precipitation (Figure 4.5f). MCSs occurring during weak LLJ events show a reduction or stagnation in peak intensity (Figure 4.5f), despite their increasing mean intensity. This divergence implies that while weak Central LLJ storms become wetter on average due to

thermodynamic water loading, they lack the dynamic organization to sustain the extreme updrafts required for peak intensities.

In contrast to precipitation intensity, the projected changes in MCS peak size (Figure 4.5c, g) exhibit a sharp bifurcation depending on the jet intensity. For strong LLJ, there is a distinct trend toward larger systems, particularly in the upper quantiles. The changes fluctuate near zero for smaller systems (below the 50th percentile) but rise sharply for extreme events, with the 75th–95th percentiles showing size increases of approximately +25,000 to +50,000 km² (~10% increase). Conversely, MCSs occurring during weak LLJ show a systematic reduction in spatial extent. The shifts in MCS duration (Figure 4.5d, h) mirror the intensity-dependent divergence observed in MCS size. Under strong LLJs, MCSs exhibit a consistent increase in longevity across the majority of the distribution, with a median increase of approximately +0.5 (~7% longer) and peaks approaching +1.0 hours in the upper quantiles. By contrast, MCSs forming under weak LLJ are projected to have shorter lifecycles in the PGW scenario (Figure 4.5h). While the lower quantiles show modest reductions (approximately -0.3 hours), the decrease becomes more pronounced for the longest-lived storms (above the 75th percentile), with durations declining by up to 1.0 hour (a decrease of ~10–15%). Collectively, these metrics depict a future where MCSs associated with strong Central LLJ become larger and longer-lasting, while MCSs under weak LLJ become more compact and ephemeral, despite both becoming more intense.

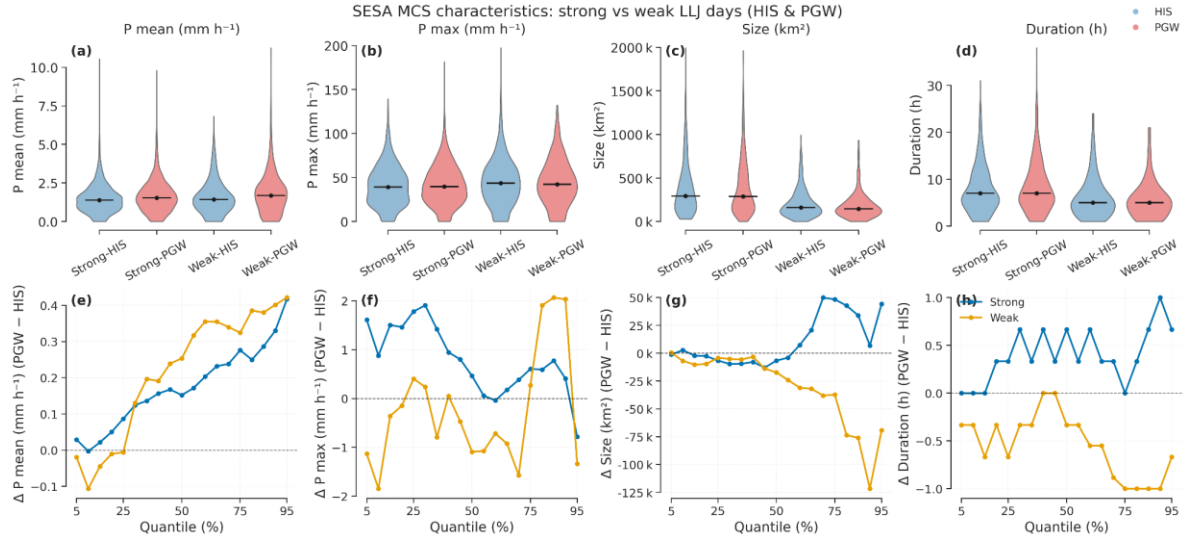


Figure 4.5. Projected changes in MCS characteristics in SESA conditioned on Central LLJ. The top row displays violin plots of the distributions for (a) mean precipitation intensity (mm h^{-1}), (b) maximum precipitation intensity (mm h^{-1}), (c) MCS peak size (km^2), and (d) duration for Historical (blue) and PGW (red) simulations, stratified by Strong and Weak jet events. Black dots and horizontal lines within the violins represent the median values. The bottom row shows the changes in the quantile distributions for (e) mean precipitation intensity, (f) maximum precipitation, (g) MCS peak size, and (h) duration. In these panels, blue lines represent the projected shift during strong jet events, while yellow lines represent the shift during weak jet events across the 5th to 95th percentiles.

The analysis of Amazonian MCSs during Northern LLJ reveals an intensification of rainfall density for both strong and weak LLJs in the PGW simulation (Figure 4.6a). This is quantitatively confirmed in Figure 4.6e, where precipitation anomalies are predominantly positive. For weak Northern LLJ events, the intensity enhancement is consistent across the entire distribution, rising steadily

from $+0.05 \text{ mm h}^{-1}$ at the 5th percentile to roughly $+0.45 \text{ mm h}^{-1}$ ($\sim 11\%$ increase) at the 95th percentile. For strong Northern LLJ events, the response is slightly more non-linear as it begins below zero for the lowest quantiles but accelerates rapidly in the upper tail, exhibiting the largest overall intensification of nearly $+0.6 \text{ mm h}^{-1}$ ($\sim 15\%$ increase) for the most extreme events. Under strong Northern LLJ (Figure 4.6f), maximum precipitation increases by $+0.5$ to $+2.0 \text{ mm h}^{-1}$ ($\sim 3\text{--}4\%$ increase), suggesting that despite the suppression of system size, the convective cores that do form are thermodynamically invigorated. Conversely, under weak Northern LLJ (Figure 4.6f), maximum precipitation exhibits a significant decrease of -1.0 to -3.0 mm h^{-1} ($\sim 5\%$ reduction). This implies that while weak Northern LLJ storms become larger and wetter on average and the reduced dynamic forcing limits the strength of the most intense updrafts, preventing them from reaching historical peak intensities.

Weak Northern LLJ events are also associated with a systematic increase in MCS size. Conversely, strong Northern LLJ events (Figure 4.6g) generally result in smaller systems for most of the distribution (5th to 75th percentiles), with decreases ranging from $-5,000$ to $-20,000 \text{ km}^2$ ($\sim 10\text{--}13\%$ reduction). A reversal to growth occurs only at the extreme upper tail ($>80\text{th}$ percentile), where the very largest systems under strong jet conditions show significant expansion, with increases of $+60,000$ to $+80,000 \text{ km}^2$ ($\sim 13\%$ expansion). Under weak Northern LLJ conditions (Figure 4.6h), MCSs are projected to last longer, with duration increasing by $+0.5$ to $+1.5$ hours ($\sim 10\text{--}20\%$ longer) across the distribution. In contrast, under Strong Northern LLJ conditions, MCSs exhibit a marked reduction in duration (Figure 4.6h).

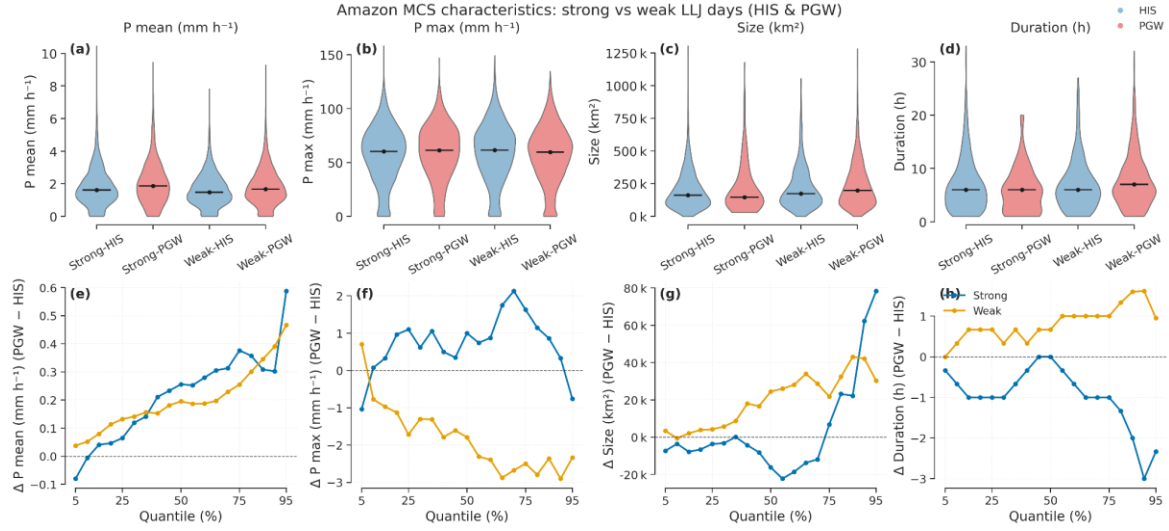


Figure 4.6. Projected changes in MCS characteristics in the western Amazon conditioned on Northern LLJ. The top row displays violin plots of the distributions for (a) mean precipitation intensity (mm h^{-1}), (b) maximum precipitation intensity (mm h^{-1}), (c) MCS peak size (km^2), and (d) duration for Historical (blue) and PGW (red) simulations, stratified by Strong and Weak jet events. Black dots and horizontal lines within the violins represent the median values. The bottom row shows the changes in the quantile distributions for (e) mean precipitation intensity, (f) maximum precipitation, (g) MCS peak size, and (h) duration. In these panels, blue lines represent the projected shift during strong jet events, while yellow lines represent the shift during weak jet events across the 5th to 95th percentiles.

For the Andes LLJ, while the probability density distributions for both strong and weak events shift toward higher mean precipitation in the PGW simulation (Figure 4.7a), the quantile analysis (Figure 4.7e) uncovers a much stronger signal for the weak LLJ. For weak Andes LLJ events, mean precipitation intensity surges dramatically, with anomalies rising from $+0.2 \text{ mm h}^{-1}$ in the lower tail to over $+1.2 \text{ mm h}^{-1}$ (an increase of $\sim 30\text{--}40\%$ relative to the baseline) in the upper quantiles. In

contrast, Strong Andes LLJ events show a more moderate, linear increase, reaching approximately $+0.6 \text{ mm h}^{-1}$ ($\sim 15\%$ increase) at the 95th percentile. Unlike the Central LLJ, the weak Andes LLJ regime exhibits the most explosive increase in peak rainfall rates. While strong jet events show a steady enhancement of $+1.5$ to $+2.5 \text{ mm h}^{-1}$ ($\sim 4\text{--}5\%$), weak jet events (Figure 4.7f) exhibit a sharp, non-linear surge, with anomalies peaking at $+4.5 \text{ mm h}^{-1}$ (an increase of $\sim 10\%$) near the median and remaining robustly high across the upper tail. This suggests that in the absence of strong shear, Andes-region storms evolve into violent, thermodynamically driven pulse systems that produce extreme instantaneous rainfall rates despite their smaller size.

The analysis of MCS size indicates that under strong Andes LLJ, there is a robust shift toward upscale growth (Figure 4.7g), with size anomalies consistently positive, ranging from $+25,000 \text{ km}^2$ in the median range to a peak of roughly $+100,000 \text{ km}^2$ (an expansion of $\sim 12\text{--}15\%$) near the 85th percentile. Conversely, weak LLJs are associated with a systematic shrinking of convective systems (Figure 4.7g), with sizes decreasing by $10,000$ to $50,000 \text{ km}^2$ (a contraction of $\sim 10\text{--}20\%$). Similarly, MCSs associated with the strong Andes LLJ are projected to persist longer in the future climate (Figure 4.7h). The increase is particularly notable in the upper-middle quantiles (50th to 80th percentiles), where duration increases by $+0.5$ to $+1.0$ hours ($\sim 15\%$ longer). In contrast, MCSs forming under weak Andes LLJs exhibit predominantly negative changes and degrade rapidly for the longest-lived events, reaching reductions of approximately -1.0 to -1.4 hours (a decrease of $\sim 20\%$) for systems above the 75th percentile (Figure 4.7h).

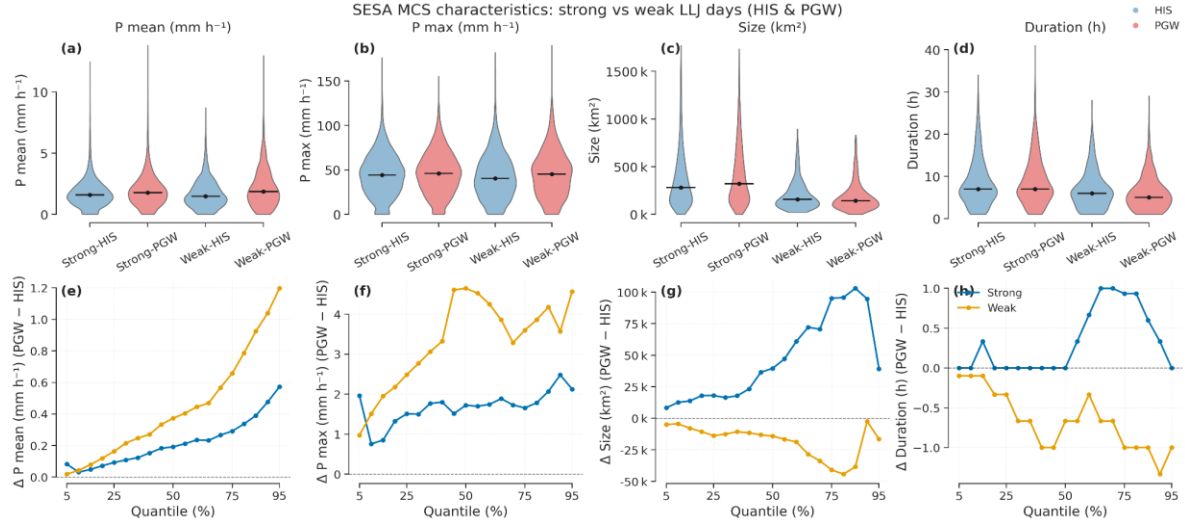


Figure 4.7. Projected changes in MCS characteristics in SESA conditioned on Andes LLJ. The top row displays violin plots of the distributions for (a) mean precipitation intensity (mm h^{-1}), (b) maximum precipitation intensity (mm h^{-1}), (c) MCS peak size (km^2), and (d) duration for Historical (blue) and PGW (red) simulations, stratified by Strong and Weak jet events. Black dots and horizontal lines within the violins represent the median values. The bottom row shows the changes in the quantile distributions for (e) mean precipitation intensity, (f) maximum precipitation, (g) MCS peak size, and (h) duration. In these panels, blue lines represent the projected shift during strong jet events, while yellow lines represent the shift during weak jet events across the 5th to 95th percentiles.

The intensification of MCS precipitation across all LLJ types (Figures 4.5–4.7) highlights the dominance of thermodynamic forcing in a warming climate, though a distinction must be made between mean and extreme rainfall rates. While changes in mean precipitation are often energetically constrained to rates lower than thermodynamic expectations (Held & Soden, 2006), the maximum precipitation intensity exhibits a response primarily governed by the Clausius-Clapeyron (C-C)

relationship. This relationship dictates that the moisture-holding capacity of the atmosphere increases by approximately 7% per degree of warming (Emori & Brown, 2005; Prein et al., 2017). As the atmosphere warms, the enhanced availability of specific humidity leads to greater moisture flux convergence into convective updrafts, resulting in higher instantaneous rainfall rates even when the kinematic background is weak (Seager et al., 2010).

Notably, the results indicate that weak jet environments experience a proportionally larger surge in peak intensity, particularly during the Andes (Figure 4.7f) and Central (Figure 4.5f) LLJ regimes. In the historical climate, weak-shear environments typically support convection of limited severity. However, future warming is projected to significantly increase Convective Available Potential Energy (CAPE) across South America (Romps, 2016). In the absence of strong shear during weak LLJ events, storm intensity becomes primarily controlled by this enhanced instability rather than dynamic organization. As a result, future storms, while potentially less organized or shorter-lived, may become explosively intense through the release of extreme CAPE. This effectively narrows the intensity gap between dynamically organized and unorganized convection, a phenomenon increasingly observed in convection-permitting projections (Schumacher & Rasmussen, 2020).

In the western Amazon, the intensification of convection is primarily fueled by the thermodynamic component (Marengo et al., 2009). The observed expansion of MCSs under weak Northern LLJ conditions likely reflects the aggregation of widespread, thermodynamically driven convection into loosely organized clusters. In this regime, the elevated background moisture of the PGW state facilitates the merger of scattered cells into extensive stratiform shields, resulting in larger total

cloud areas despite the lack of strong kinematic organization (Seager et al., 2010; Anselmo et al., 2020). The finding that strong Northern LLJs produce smaller systems implies a dynamic constraint. Strong low-level winds in the Amazon are typically associated with rapidly propagating squall lines (Cohen et al., 1995). Under PGW conditions, the enhanced shear in these rare strong-jet events favors a linear convective mode, narrow, intense, and fast-moving over the sprawling, quasi-stationary clusters observed in weak-shear environments. Furthermore, the surrounding environment during strong trade wind phases often features mid-level drying or subsidence, which can evaporate the trailing stratiform region and limit the spatial extent of the system, even while the leading convective line remains violently intense.

The projection that strong LLJ events lead to larger, longer-lived MCS (Figures 4.5e/f, 4.7e/f) aligns with the Rotunno-Klemp-Weisman (RKW) theory of cold pool balance (Rotunno et al., 1988; Weisman & Rotunno, 2004). Although originally developed for idealized squall lines, RKW theory posits that optimal storm organization occurs when low-level environmental shear balances the circulation induced by the storm's cold pool, promoting deep, upright ascent along the gust front. In this context, an intensified LLJ enhances low-level shear and moisture transport, facilitating sustained lifting and the maintenance of organized convective systems. This kinematic support favors the development of extensive stratiform precipitation regions and prolongs system lifetimes, consistent with previous observational and modeling studies linking strong LLJs to large, long-lived MCSs and widespread heavy rainfall (Salio et al., 2007; Mulholland et al., 2019).

Conversely, the reduction in MCS size and duration under weak-LLJ conditions suggests a breakdown of this organizational mechanism. When low-level shear is insufficient to balance cold-pool propagation, convective updrafts are more easily undercut or tilted upshear, limiting sustained lifting and inhibiting the aggregation of convective cells into larger complexes. However, while these weak-shear systems are structurally disorganized, they are not benign. As shown in the maximum precipitation analysis (Figure 4.7f), these MCSs produce some of the most extreme instantaneous rainfall rates in the future climate. This suggests that in the absence of dynamic organization, convection enters a pulse regime driven purely by extreme thermodynamic instability (CAPE), resulting in storms that are spatially compact and ephemeral, yet explosively intense (Mulholland et al., 2021). Together, these results point to a future convective regime between large, organized super-systems (driven by shear) and violent, disorganized pulse storms (driven by thermodynamics).

C.4 Potential changes in large-scale forcing

The mean state circulation changes in the high-resolution PGW simulation (Figures 4.8a–b) show a distinct latitudinal dipole that reinforces the convective shifts documented in previous sections. In the subtropics (15°S – 35°S), the difference map for 850-hPa meridional wind shows a coherent band of significant negative anomalies (Figure 4.8b), indicating a robust intensification of the climatological northerlies channeling moisture into the La Plata Basin (SESA). This kinematic strengthening is accompanied by widespread positive wind speed anomalies in the continental interior (red shading in Figure 4.8a), effectively shifting the mean

climate closer to the strong LLJ threshold of the historical period. This enhanced background flow provides the necessary shear to balance cold pools, creating an optimal environment for the intense MCSs discussed in Figure 4.5 (Mulholland et al., 2019). Conversely, in the deep tropics (0° – 10° S), positive meridional wind anomalies (Figure 4.8b) and negative wind speed anomalies (blue in Figure 4.8a) indicate a weakening of the trade winds and the Northern LLJ. This slowing of the tropical circulation, consistent with the dynamical response to Walker circulation deceleration (Vecchi et al., 2006; Ma et al., 2018), limits the kinematic support for Amazonian squall lines, explaining the shift toward pulse convection observed in Figure 4.6.

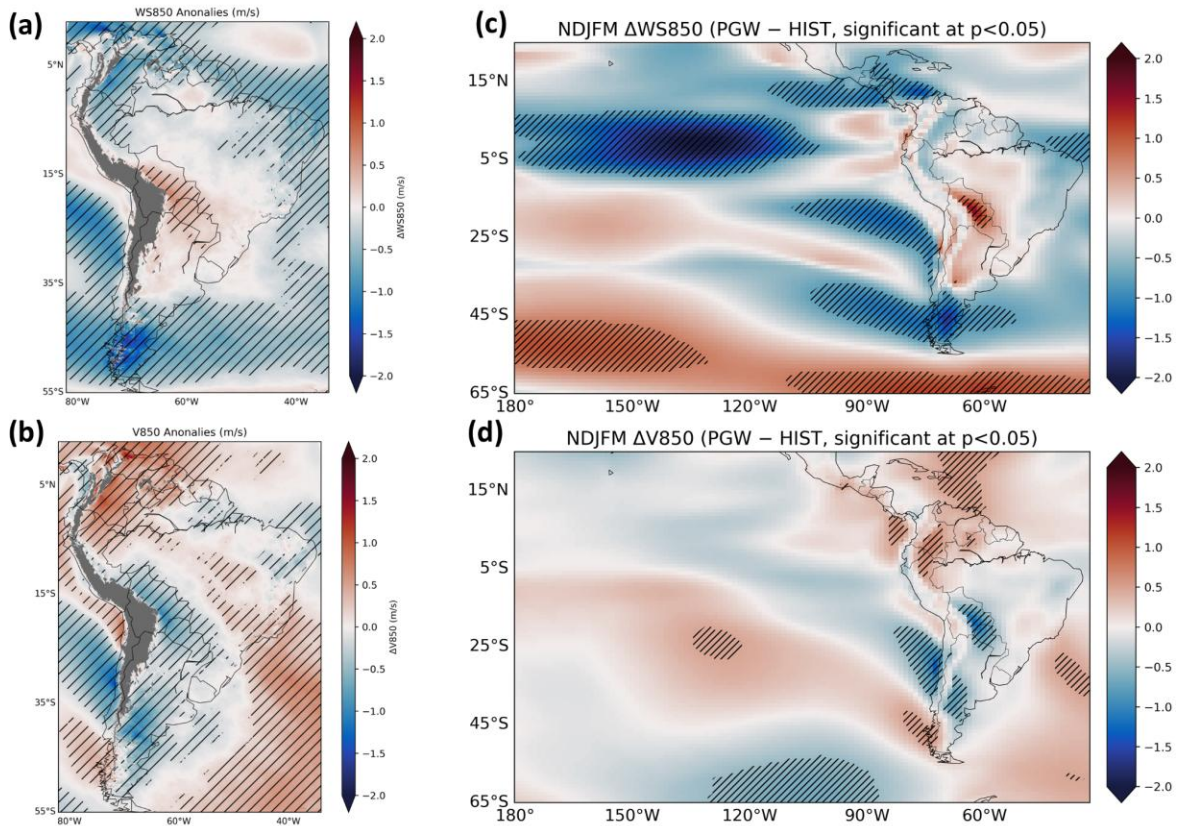


Figure 4.8. Projected large-scale circulation changes (2060–2080 relative to 2000–2020) in the mean state derived from WRF and the CESM2 Large Ensemble

(LENS2). (a) WRF PGW minus Historical mean difference for 850-hPa wind speed (m s^{-1}) and (b) 850-hPa meridional wind (V , m s^{-1}) over the WRF domain. (c) LENS2 mean difference (PGW minus Historical) for 850-hPa wind speed (m s^{-1}) and (d) 850-hPa meridional wind (V , m s^{-1}) over the broader Pacific-South American domain. In panels (b) and (d), blue colors indicate anomalous southward flow (strengthened northerlies), while red colors indicate anomalous northward flow. Hatched regions in all panels denote areas where the projected changes are statistically significant at the 95% confidence level.

This regional strengthening of the subtropical LLJ is not an isolated feature but is dynamically coupled to a broader, global-scale stationary wave train captured by the LENS2 (Figures 4.8c–d). The 850-hPa meridional wind anomalies reveal a distinct wave pattern extending from the tropical Pacific, across the Southern Ocean, and curving into South America (Figure 4.8d), resembling the positive phase of the Pacific–South American (PSA) teleconnection pattern (Irving & Simmonds, 2016). This wave train positions an anomalous cyclonic circulation west of the Andes and reinforces anticyclonic flow over the South Atlantic, a configuration that steepens the regional pressure gradient and acts as a dynamic accelerant for the Central and Andes LLJs (Junquas et al., 2012). Furthermore, this pattern is consistent with the projected poleward expansion of the Hadley cell, which shifts the subtropical dry zones and associated jet streams southward (Lu et al., 2007; Hu et al., 2013).

D. Conclusions

This study demonstrates that, within a PGW framework, the hydroclimate of South America exhibits regime-dependent responses to climate warming, with

changes emerging in dynamical components even when climate change is imposed solely through thermodynamic perturbations. Thermodynamically, MCSs across all regimes from the western Amazon to the La Plata Basin are projected to produce higher rain rates. This intensification agrees with thermodynamic expectations, where a warmer atmosphere supports higher specific humidity and moisture flux convergence, strongly governing the increase in extreme instantaneous rainfall rates regardless of the kinematic background (Emori & Brown, 2005; Seager et al., 2010). However, the structural evolution of these storms (size and duration) is distinct from this thermodynamic signal, appearing to be driven primarily by regional dynamic changes in the LLJ regimes. This results in a future where storm severity increases everywhere, but storm morphology diverges sharply between the tropics and subtropics (Mulholland et al., 2019).

In SESA, the robust strengthening of the Central and Andes LLJs creates an environment favorable for upscale convective growth. The intensified basic state (Figure 4.8) lowers the barrier for strong LLJ events, providing the critical low-level vertical wind shear needed to balance cold pools according to the RKW theory (Weisman & Rotunno, 2004). This kinematic support allows future MCSs to organize into larger, longer-lived systems capable of sustaining heavy stratiform rainfall over vast areas (Salio et al., 2007). Conversely, under weak LLJ conditions, the lack of shear limits this organization, resulting in MCSs that are structurally smaller but explosively intense due to enhanced CAPE (Romps, 2016). The western Amazon Basin experiences a weakening of the climatological northerly flow, which decreases the frequency of dynamically organized strong LLJ events. Consequently, future western Amazonian convection transitions toward a regime dominated by

weak LLJ characteristics with widespread, semi-organized convective clusters. While these thermodynamically driven MCSs are larger and longer-lived due to stratiform expansion, they lack the dynamic organization of historical squall lines, explaining the shift away from linear convective modes despite the increase in atmospheric moisture content (Seager et al., 2010; Thome & Magnusdottir, 2020).

These regional changes appear to be partly associated with a robust shift in the planetary-scale circulation imposed through the lateral boundary conditions. The projected strengthening of the Central and Andes LLJs is consistent with a stationary Rossby wave train in the Southern Hemisphere mid-latitudes (approximately 40°S–60°S), resembling the Pacific-South American (PSA) teleconnection pattern (Irving & Simmonds, 2016). In the PGW framework, this large-scale forcing manifests as an anomalous cyclonic circulation west of the Andes and a reinforced South Atlantic Subtropical High (SASH). Because these features are present in the mean-state delta derived from the global model, they effectively steepen the zonal pressure gradient across the continent within the regional simulation. This imposed background state acts as a dynamic driver that accelerates the geostrophic component of the LLJ, thereby potentially reinforcing the Central and Andes jet types (Patterson et al., 2021).

Collectively, these shifts imply a transition toward a complex, bimodal hydrometeorological hazard profile for South America. In the subtropics of SESA, the projected increase in storm size and duration creates a meteorological setup conducive to high-volume accumulation events. While the translation of this rainfall into riverine flooding depends on complex, non-linear hydrological processes such as antecedent soil moisture and basin geometry, the shift toward larger, longer-lived

MCSs significantly raises the potential for saturating major catchments. Conversely, the Andes foothills and urban centers may face an elevated threat from rapid surface runoff driven by the explosive intensification of short-duration storms. Adaptation strategies must therefore account not just for changes in total rainfall, but for these regime-dependent shifts in storm structure and intensity, which define the atmospheric boundary conditions for future hydrological extremes.

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V. Conclusions

A. Summary

The primary objective of this dissertation is to investigate the multiscale dynamical interactions governing South America's hydroclimate, from the large-scale remote forcings that dictate moisture transport down to the mesoscale storm environments they generate, and to project how this coupled system will evolve under anthropogenic climate warming. By bridging the gap between historical synoptic variability and future high-resolution climate projections, this research advances our predictive understanding of extreme precipitation events across the continent.

Chapter 1 established the foundational synoptic framework by investigating the variability of distinct northerly LLJs, specifically the Central, Northern, and Andes types, driven by coupled oceanic teleconnections. The research demonstrated that constructive phase interactions between the ENSO and the PDO dynamically dictate regional precipitation. Coincident warm PDO and El Niño phases heavily favor the Central LLJ, driving intense moisture flux and extreme precipitation into the subtropics. Conversely, cold phases suppress the Central branch and shift moisture convergence toward the western Amazon.

Transitioning from the synoptic scale to the mesoscale, Chapter 2 quantified the downstream thermodynamic and kinematic impacts of these distinct LLJs on deep convection. Utilizing kilometer-scale, convection-permitting WRF simulations and satellite-based feature-tracking, the research explicitly linked LLJ intensity to the MCSs. The findings indicated that enhanced Central and Andes LLJs significantly

increase the initiation frequency, spatial extent, duration, and peak precipitation rates of MCSs across the La Plata Basin. Furthermore, high-resolution models confirm that the presence of the LLJ distinctly modifies the convective environment, significantly amplifying moisture profiles and instability necessary for upscale storm growth.

Chapter 3 projected the future evolution of this coupled atmospheric system under a ~ 3 °C warming scenario. Utilizing a Pseudo-Global Warming (PGW) framework, multi-decadal convection-permitting projections revealed a widespread thermodynamic intensification of precipitation, characterized by a sharp dynamic bifurcation in storm structural evolution. In the subtropics, strengthened background northerly flow enhanced vertical wind shear, facilitating the upscale growth of larger, longer-lived MCSs. Conversely, weakened Northern LLJs over the western Amazon shifted historical squall lines toward loosely organized convective clusters.

B. Overarching Conclusions

Collectively, the findings of this dissertation represent a critical advancement in our understanding of South America's hydrometeorological hazard profile, proving that regional extreme precipitation cannot be understood or predicted through isolated spatial scales. By bridging planetary-scale remote teleconnections with explicitly resolved, storm-scale physics, this research establishes a unified multiscale dynamical framework for the coupled LLJ and MCS systems.

A primary overarching conclusion of this work is the indispensable necessity of dynamical downscaling via convection-permitting regional climate models

(CPRCMs) for South American hydroclimate research. Coarse-resolution Global Climate Models (GCMs), such as those in the CMIP6 ensemble, could potentially misrepresent the diurnal cycle, peak intensity, and spatial organization of MCSs because they rely heavily on convective parameterizations. By explicitly resolving convective updrafts without parameterization, this dissertation effectively closed the critical scale gap. The results show that capturing the severe kinematic gradients, specifically the low-level wind generated by the Central and Andes LLJs, is critical for accurately simulating the upscale growth and longevity of intense convective clusters in the La Plata Basin.

Furthermore, the future projections detailed in this dissertation introduce a critical reconceptualization of climate change impacts in the region. Traditionally, future precipitation extremes are assumed to scale directly with the Clausius-Clapeyron relationship, wherein a warmer atmosphere simply holds and drops more water. However, this research demonstrates a sharp dynamic bifurcation that overrides simple thermodynamic scaling. While the entire continent experiences a thermodynamic intensification of moisture capacity, the structural evolution of future storms is entirely dictated by shifting wind domains. In the subtropics, enhanced northerly flow couples with heightened thermodynamics to create deeply organized, long-lived "super-MCSs." Conversely, over the western Amazon, a projected weakening of the Northern LLJ weakens storms of the wind shear necessary for organization, reducing historical squall lines to loosely organized, pulse-like convective clusters. Therefore, this dissertation concludes that future extreme weather risk assessments should transition from focusing solely on total

precipitation accumulation to evaluating regime-specific, dynamically driven changes in storm morphology and peak instantaneous rainfall rates.

C. Future Work

While this dissertation provides a comprehensive analysis of the coupled LLJ-MCS system under historical and warmed climates, the South American climate system is subjected to multiple overlapping anthropogenic and natural stressors. Several critical avenues remain open for future investigation:

1. Competing Oceanic and Sub-Seasonal Drivers

This research successfully isolated the constructive and destructive phase interactions of the ENSO and PDO. However, the South American hydroclimate is also strongly modulated by sub-seasonal transient forcings, such as the Madden-Julian Oscillation (MJO), and long-term Atlantic basin anomalies, such as the Atlantic Multidecadal Oscillation (AMO). The MJO is known to heavily influence the active and break phases of the South American Monsoon System (SAMS), causing intra-seasonal pulsing of the LLJ. Future research must leverage multidecadal, high-resolution datasets to investigate how MJO-driven sub-seasonal anomalies destructively or constructively interfere with the established ENSO/PDO base states to trigger highly anomalous LLJ transport events.

2. Anthropogenic Land-Use and Land-Cover Change (LULCC)

The future projections utilizing the Pseudo-Global Warming (PGW) framework in this dissertation primarily evaluated thermodynamic and kinematic changes driven by greenhouse-gas concentrations. However, the Amazon Basin is undergoing rapid deforestation and land-use modifications, pushing the biome dangerously close to a

hydrological "tipping point". Because a massive fraction of the moisture transported by the Central LLJ originates from forest evapotranspiration, widespread deforestation threatens to fundamentally sever the moisture pipeline feeding the La Plata Basin. Future high-resolution modeling efforts must couple CPRCMs with dynamic vegetation models to quantify how the synergistic effects of localized deforestation and global greenhouse-gas warming will independently and jointly alter the strength of northerly LLJs and the subsequent frequency of subtropical MCSs.

3. Fully Coupled Hydrological and Impact Modeling

Finally, translating atmospheric variables into actionable societal impacts requires coupling these meteorological projections with surface hydrology. The extreme precipitation rates generated by the future MCSs projected in this dissertation will fundamentally alter streamflow, flash-flood frequencies, and agricultural runoff. Future work should couple the meteorological outputs of these WRF simulations directly into distributed hydrological models (such as WRF-Hydro). Simulating river routing and overland flow across the Paraná and Uruguay river basins under these new, dynamic MCS regimes will provide water resource managers and agricultural stakeholders with the precise, localized inundation projections required to adapt to a rapidly warming world.