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The Dynamics and Variability of the South American Low-Level Jet

A dissertation submitted in partial satisfaction
of the requirements for the degree

Doctor of Philosophy
in
Geography

by

Tessa L. Montini

Committee in charge:

Professor Charles Jones, Chair
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March 2022

The Dissertation of Tessa L. Montini is approved.

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January 2022

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Tessa L. Montini

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Tessa L. Montini

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Abstract

The Dynamics and Variability of the South American Low-Level Jet

by

Tessa L. Montini

The South American low-level jet (SALLJ) east of the Andes plays an important role in transporting moisture from the Amazon Basin towards the subtropics, influencing the development of convection and precipitation over the La Plata Basin. This research presents a comprehensive analysis of the spatial and temporal variability of the SALLJ across multiple time scales. A new algorithm is introduced for detecting low-level jet events based on seasonal-percentile thresholds of wind speed and wind shear. The algorithm was applied to ERA-Interim reanalysis data to develop a 38-year dataset of SALLJ days (1979-2016). Although the SALLJ occurs year round, seasonal composites show that moisture transport associated with the jet is largest during austral summer. Trends in the SALLJ were analyzed over the climatological period and revealed an intensification of the northwesterly moisture flux over the SALLJ region in recent decades. The second part of this research examines the large-scale atmospheric influences that modulate the strength and direction of the SALLJ and consequently, influence local precipitation regimes. By applying principal component analysis and k-means clustering to atmospheric fields associated with SALLJ days, we identified four distinct subtypes of SALLJ events. Composites of SALLJ types revealed noticeable differences in the exit region of the jet and the location and intensity of precipitation. In part, these differences may be influenced by the behavior of barotropic wave trains as they cross over the Andes from the extratropical Pacific. To explore the potential predictability of the SALLJ, we investigated the influence of global climate variability on the strength

and frequency of SALLJ events. On interannual time scales, the warm phase of the El Niño Southern Oscillation was found to enhance the strength and frequency of the SALLJ. On subseasonal scales, significant relationships were found between the frequency of SALLJ subtypes and certain phases of the Madden Julian Oscillation. This information provides valuable insight that can be used to improve weather forecasts and subseasonal-to-seasonal climate predictions over South America.

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Chapter 1

Introduction

Subtropical South America is susceptible to some of the deepest and most extreme convective storms in the world (Zipser et al., [2006](#)). Oftentimes, individual convective cells conglomerate into large, organized Mesoscale Convective Systems (MCS) that produce significant rainfall and severe weather over the densely-populated La Plata Basin (LPB) (Durkee et al., [2009](#)). MCSs that bring heavy precipitation to urbanized areas may lead to disastrous flooding and landslides.

One of the most important atmospheric influences on the development of MCSs and extreme precipitation over the LPB is the South American Low-Level Jet (SALLJ). Located east of the Andes Mountains, the SALLJ transports substantial heat and moisture to the subtropics, creating a favorable environment for convective development (Marengo et al., [2004](#); Salio et al., [2007](#); Vera et al., [2006a](#)). The spatiotemporal variability of the SALLJ is likely modulated by a combination of synoptic-scale and boundary-layer mechanisms. Large-scale dynamics that may influence SALLJ include the intensity of the equatorial Atlantic easterly winds, the strength and position of the South Atlantic subtropical high-pressure cell (Marengo et al., [2004](#); Vera et al., [2006a](#)), and the flow of upper-level westerlies across the Andes (i.e., the subtropical jet stream;

Wang and Fu, 2004).

Several studies have shown robust changes in large-scale circulation over South America in recent decades, including the expansion of the Hadley circulation and poleward shift of the subtropical jet stream (Adam et al., 2014; Hu & Fu, 2007). On interannual time scales, the variability of large-scale circulation over South America is strongly linked to the El Niño Southern Oscillation (Grimm, 2011). It is likely that variations in large-scale dynamics impact the characteristics of the SALLJ and subsequently, influence the distribution and intensity of MCSs and precipitation over the LPB. However, a detailed understanding of the mechanisms by which these changes take place is currently incomplete.

The main objective of this research is to investigate linkages between the spatiotemporal variability of the SALLJ, large-scale atmospheric dynamics, and precipitation over subtropical South America. Understanding the mechanisms that influence SALLJ variability in the present climate is crucial to better predict future changes in regional precipitation regimes.

1.1 La Plata Basin

The two largest watersheds in South America are the tropical Amazon Basin and the subtropical La Plata Basin. The La Plata Basin (LPB) is located east of the Andes Mountain range between 20°S and 40°S latitude (Figure 1.1). The densely populated LPB covers areas of five countries – Argentina, Bolivia, Brazil, Paraguay, and Uruguay – and produces approximately 70% of their combined gross national products. The main economic sectors of the LPB are agriculture and hydropower production (Popescu et al., 2012), which are simultaneously dependent on and vulnerable to extreme precipitation events. Furthermore, large urbanized areas in this region rely on sufficient

rainfall to meet their water resource demands. Although a large portion of the region's total precipitation is produced by MCSs (Velasco & Fritsch, 1987), heavy rainfall events have also caused disastrous flooding and debris flows resulting in numerous injuries, fatalities, and damages to crops and property (Doss-Gollin et al., 2018). Therefore, variability in precipitation and extreme events over the LPB has wide-ranging socioeconomic consequences.

1.2 Climate dynamics of South America

Seasonal variability of circulation and precipitation over the continent is closely linked to the annual cycle of the South American Monsoon System (SAMS), which is active from October through March. The onset of SAMS is characterized by a reversal of trade winds onto the continent and enhanced convection and precipitation over the Amazon Basin (Vera et al., 2006b; Zhou & Lau, 2001).

During austral summer (December–February), the main upper-level circulation features over South America include a large anticyclonic circulation over Bolivia (known as the “Bolivian High”) and a trough over the coast of northeastern Brazil (Figure 1.2a). The establishment of the Bolivian High is related to seasonal surface heating over land and maintained by the deep convection and the release of latent heat over the Amazon (Lenters & Cook, 1997). Near the surface, the Bolivian High is coupled with a quasi-stationary low-pressure over Bolivia and Paraguay known as the “Chaco Low”. A strengthening of the Chaco Low over Bolivia and Paraguay enhances the land-ocean pressure gradient, which drives the northeasterly trade winds further south, increasing the advection of warm, moist tropical air over the continent (Vera et al., 2006b; Zhou & Lau, 1998). After crossing the Amazon, these low-level winds are channeled poleward by the Andes Mountains. Intensification of the low-level northerly flow on the east-



Figure 1.1: Map of topography (color shading), national boundaries (black), and South America's two largest watersheds: the Amazon Basin (yellow) and La Plata Basin (red).

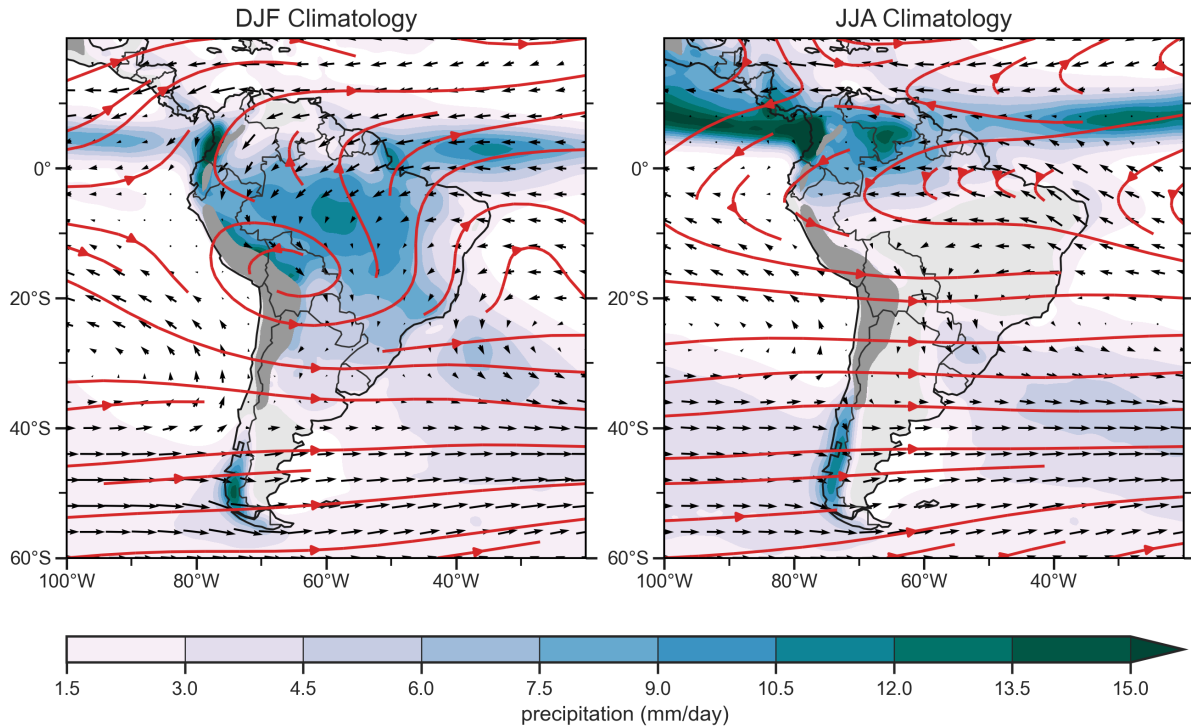


Figure 1.2: Climatological wind vectors at 850 hPa (*black vectors*), streamlines at 250 hPa (*red*), and precipitation (*color shading*) over South America based on ERA5 reanalysis (1979-2016) for austral summer (*left*) and winter (*right*).

ern slopes of the Andes is known the South American low-level jet (SALLJ) (Marengo et al., 2004; Vera et al., 2006a). The SALLJ transports considerable amounts of moisture to the subtropical La Plata Basin throughout the year and consequently influences precipitation (Berbery & Barros, 2002).

Another prominent feature of SAMS is the South Atlantic Convergence Zone (SACZ). The SACZ is an elongated band of convection that extends southeast from the Amazon towards the South Atlantic Ocean (Carvalho et al., 2004; Kodama, 1993). A well-documented dipole pattern has been observed between the SACZ and the SALLJ, where an active SALLJ is associated with a weak SACZ and vice versa (Nogués-Paegle & Mo, 1997). During SALLJ events, precipitation is enhanced over southeastern South America (SESA) and suppressed over the SACZ region. Conversely, the active phase of the

SACZ is associated with enhanced precipitation over eastern Brazil and suppressed precipitation over SESA. The dipole pattern is also influenced by the strength and position of the South Atlantic subtropical high (SASH), where an intensification of the SASH over the continent advects moisture towards SESA and reinforces the northerly flow associated with the SALLJ (Vera et al., 2006b).

The demise of SAMS in autumn is associated with a more intermittent Chaco low and the disappearance of the Bolivian High. During austral winter, upper-level westerlies dominate as the subtropical jet stream shifts farther north (Figure 1.2b). The western branch of the South Atlantic subtropical high-pressure cell extends further over the continent, influencing low-level circulation during the dry season.

1.2.1 Climate variability

Interannual climate variability over South America is closely related to the phase of the El Niño/Southern Oscillation (ENSO) (Grimm, 2011; Grimm et al., 2000). Throughout most of the austral warm season, El Niño conditions are generally associated with below average precipitation over northern South America and above average precipitation over SESA (Grimm, 2003). Nearly opposite rainfall anomalies are observed during La Niña years.

During an El Niño episode, anomalous convection in the central and eastern Pacific displace the descending branch of the Walker cell east over northern South America, resulting in enhanced subsidence and below average rainfall in this region (Ambrizzi et al., 2004). Over subtropical South America, enhanced rainfall is attributed to the propagation of Rossby wave-train from over the South Pacific (Grimm, 2011; Grimm & Ambrizzi, 2009). The wave train strengthens the upper-level subtropical jet stream over SESA, which reinforces convection on the lee side of the Andes through cyclonic

vorticity advection. At low-levels, this pattern is associated with an intensification of the South Atlantic subtropical high-pressure cell, which enhances the zonal pressure gradient over SESA and strengthens the northerly advection of warm, moist air to this region (Grimm & Zilli, 2009). The impact of ENSO over subtropical SA is largest during austral spring, when Rossby-wave propagation towards SA is strongest and the PSA-wave structure is most defined (Grimm & Tedeschi, 2009).

1.3 SALLJ and MCS precipitation

The South American low-level jet (SALLJ) plays an important role in the regional climate and hydrological cycle (Berbery & Barros, 2002; Zanin & Satyamurty, 2020). Located to the east of the Andes Mountains, the SALLJ represents an intensification of the northerly flow that extends from the southwestern Amazon into southern Brazil and northern Argentina. Maximum wind speeds associated with the jet are observed over Bolivia and Paraguay around 1-2 km above the surface. Observations and reanalysis have identified the wind maximum near the 850-hPa level. The jet experiences strong diurnal variations and typically exhibits a nocturnal maximum around 0600 UTC (2:00 AM Bolivia local time) (Marengo et al., 2004; Vera et al., 2006a). Although the SALLJ occurs year-round, the poleward moisture transport associated with the jet is greatest during the warm season (Marengo et al., 2004; Nascimento et al., 2016).

Much of the rainfall over subtropical South America is produced by large mesoscale precipitation systems, known as Mesoscale Convective Complexes (MCCs) (Durkee et al., 2009). MCCs are a subtype of mesoscale convective systems characterized by their large size, longevity, and nearly circular cloud shields (Velasco & Fritsch, 1987). Compared to other types of mesoscale convective systems, the structure and evolution of MCCs is more dependent on the synoptic-scale environment. Large-scale features

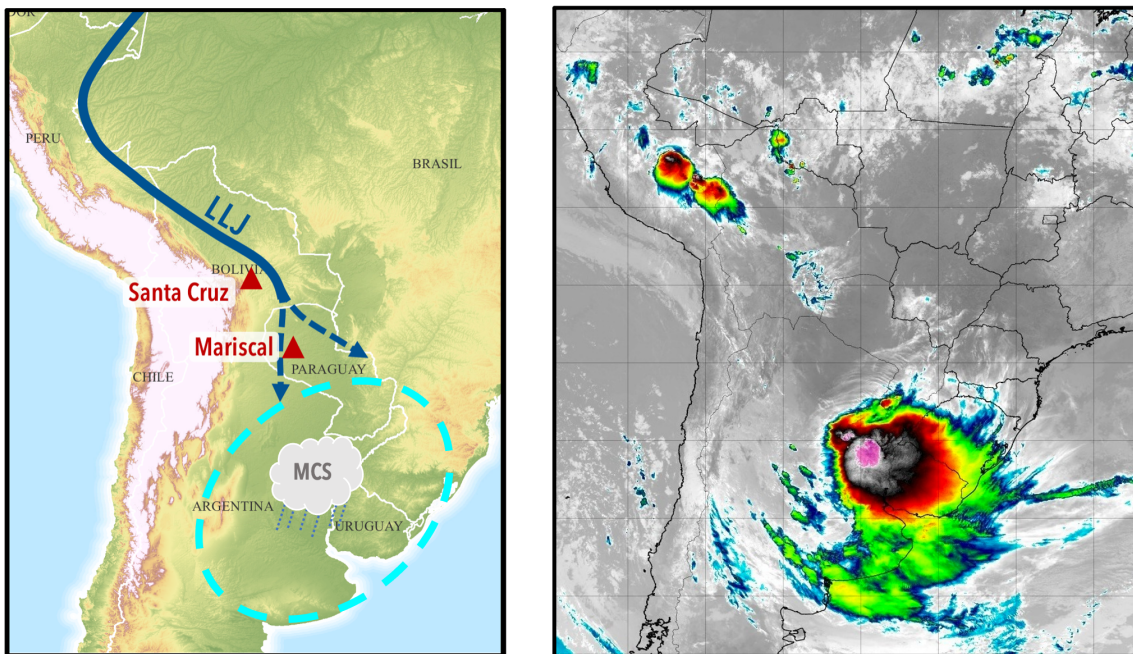


Figure 1.3: (a) Schematic of the SALLJ (*blue arrow*) with locations used for identifying jet events (*red triangles*). The light blue dashed circle indicates the exit region of the SALLJ over SESA. (b) GOES satellite imagery of a Mesoscale Convective Complex over northern Argentina associated with a strong SALLJ on 12 November 2018 at 0600 UTC.

that promote the development of MCCs include low-level convergence generated by a strong low-level jet and divergence associated with an upper-level jet stream (Salio et al., 2007). MCCs commonly develop on the leading edge of a synoptic cold front, where a low-level jet supplies the storm with moist, conditionally unstable inflow (Markowski & Richardson, 2011).

Subtropical SA is a favorable region for development of large, long-lived MCCs (Velasco & Fritsch, 1987; Zipser et al., 2006). The highest concentration of MCCs is found east of the Andes between 20° S and 30° S, with the highest frequency observed in December-February (Durkee & Mote, 2010). Synoptic-scale patterns that favor MCC development over subtropical SA include an active SALLJ, the deepening of low-pressure over northern Argentina, and the propagation of a cold front over southern SA (Salio et al., 2007). The Northwestern Argentinian Low (NAL) is a thermal-orographic low that arises from surface heating and subsidence on the lee side of Andes (Seluchi et al., 2003). A deepening of the NAL may reinforce the meridional component of the SALLJ and consequently, increase the transport of warm, moist air further south. The ample supply of heat and moisture at low-levels causes the atmosphere to become even more unstable by increasing the convective available potential energy. As a result, maximum low-level convergence occurs ahead of the cold front at the exit region of the SALLJ (Salio et al., 2007).

The mean position of upper-level circulation features relative to the exit region of the SALLJ helps explain the large occurrence of MCCs over subtropical SA (Salio et al., 2007). The positioning of the subtropical jet stream may enhance tropospheric instability and reinforce convective development at the exit region of the SALLJ. The SALLJ is dynamically coupled with upper-level jet streaks through meridional ageostrophic circulations (Uccellini, 1980). In the Southern Hemisphere, enhanced convection is associated with the left entrance or right exit regions of an upper-level jet streak. Di-

vergence at the left entrance of an upper-level jet streak east of the Andes reinforces low-level convergence and upward motion at the exit region of the SALLJ. Similarly, a jet streak upwind of the Andes may strengthen low-level poleward flow by coupling with the SALLJ at its right exit region (Saulo et al., 2007). These dynamical mechanisms are further explained in Appendix A.

Convective development over subtropical SA is also enhanced by the passing of a mid-level shortwave trough with a cyclonic vorticity maximum. In this case, cyclonic vorticity advection reinforces upward motion and subsequently, convective development downstream of the trough's axis (Wang & Fu, 2004).

1.4 Dissertation objectives

This research seeks to advance the scientific understanding of the mechanisms that modulate the spatiotemporal variability of the South American Low-Level Jet. Specifically, we investigate relationships between the SALLJ, large-scale climate dynamics, and precipitation over subtropical South America in recent decades. The objectives of this dissertation are as follows:

1. Develop a robust climatology of SALLJ events between 1979-2016 and provide an overview of the jet's seasonal variability, relationship with ENSO, and long-term trends (Chapter 2).
2. Categorize warm-season SALLJ days into subtypes and identify the synoptic-scale circulation features that influence the exit region of the jet and the development of precipitation over the LPB (Chapter 3).
3. Investigate the relationships between SALLJ variability and large-scale atmospheric dynamics on intraseasonal-to-interannual time scales (Chapter 3).

The content of Chapter 2 is the result of a collaboration with Charles Jones¹ and Leila Carvalho¹. This work was previously published in the *Journal of Geophysical Research: Atmospheres* on 3 January 2019 and can be accessed at: <https://doi.org/10.1029/2018JD029634>. The full article is reproduced here with permission of the authors.

¹UC Santa Barbara; Earth Research Institute

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

Abbreviation	Definition
CFSR	Climate Forecast System Reanalysis
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Nino Southern Oscillation
ERA-I	ECMWF Interim Reanalysis
ERA5	ECMWF Reanalysis v5
IVT	Vertically integrated water vapor transport
JRA-55	Japanese 55-year Reanalysis
LLJ	Low-level jet
LPB	La Plata Basin
MA	Mariscal Estigarribia, Paraguay
MCC	Mesoscale convective complex
MCS	Mesoscale convective system
MERRA-2	Modern-Era Retrospective Analysis for Research & Applications
MJO	Madden Julian Oscillation
MSLP	Mean sea-level pressure
NAL	Northwestern Argentinian Low
NCEP R2	National Centers for Enviromental Predication Reanalysis II
PC	Principal Component
PCA	Principal Components Analysis
SA	South America
SACZ	South Atlantic Convergence Zone
SALLJ	South American Low-Level Jet
SALLJEX	South American Low-Level Jet Experiment
SAMS	South American Monsoon System
SASH	South Atlantic Subtropical High
SC	Santa Cruz de la Sierra, Bolivia
SESA	Southeastern South America
SST	Sea-surface temperature

References

- Adam, O., Schneider, T., & Harnik, N. (2014). Role of changes in mean temperatures versus temperature gradients in the recent widening of the hadley circulation. *Journal of Climate*, 27(19), 7450–7461.
- Ambrizzi, T., Souza, E. B. d., & Pulwarty, R. S. (2004). The hadley and walker regional circulations and associated enso impacts on south american seasonal rainfall. *The hadley circulation: Present, past and future* (pp. 203–235). Springer.
- Berbery, E. H., & Barros, V. R. (2002). The hydrologic cycle of the La Plata basin in South America. *Journal of Hydrometeorology*. [https://doi.org/10.1175/1525-7541\(2002\)003<0630:THCOTL>2.0.CO;2](https://doi.org/10.1175/1525-7541(2002)003<0630:THCOTL>2.0.CO;2)
- Carvalho, L. M., Jones, C., & Liebmann, B. (2004). The south atlantic convergence zone: Intensity, form, persistence, and relationships with intraseasonal to inter-annual activity and extreme rainfall. *Journal of Climate*, 17(1), 88–108.
- Doss-Gollin, J., Muñoz, Á. G., Mason, S. J., & Pastén, M. (2018). Heavy rainfall in paraguay during the 2015/16 austral summer: Causes and subseasonal-to-seasonal predictive skill. *Journal of Climate*, 31(17), 6669–6685.
- Durkee, J. D., & Mote, T. L. (2010). A climatology of warm-season mesoscale convective complexes in subtropical South America. *International Journal of Climatology*, 30(3). <https://doi.org/10.1002/joc.1893>
- Durkee, J. D., Mote, T. L., & Shepherd, J. M. (2009). The contribution of mesoscale convective complexes to rainfall across subtropical South America. *Journal of Climate*, 22(17). <https://doi.org/10.1175/2009JCLI2858.1>
- Grimm, A. M. (2003). The El Nino impact on the summer monsoon in Brazil: Regional processes versus remote influences. *Journal of Climate*, 16(2), 263–280.
- Grimm, A. M. (2011). Interannual climate variability in South America: impacts on seasonal precipitation, extreme events, and possible effects of climate change. *Stochastic Environmental Research and Risk Assessment*, 25(4), 537–554. <https://doi.org/DOI10.1007/s00477-010-0420-1>
- Grimm, A. M., Barros, V. R., & Doyle, M. E. (2000). Climate variability in southern South America associated with El Nino and La Nina events. *Journal of Climate*, 13(1), 35–58.
- Grimm, A. M., & Ambrizzi, T. (2009). Teleconnections into south america from the tropics and extratropics on interannual and intraseasonal timescales. *Past climate variability in south america and surrounding regions* (pp. 159–191). Springer.

- Grimm, A. M., & Tedeschi, R. G. (2009). ENSO and extreme rainfall events in South America. *Journal of Climate*, 22(7), 1589–1609. <https://doi.org/10.1175/2008JCLI2429.1>
- Grimm, A. M., & Zilli, M. T. (2009). Interannual Variability and Seasonal Evolution of Summer Monsoon Rainfall in South America. *Journal of Climate*, 22(9), 2257–2275. <https://doi.org/10.1175/2008jcli2345.1>
- Hu, Y., & Fu, Q. (2007). Observed poleward expansion of the Hadley circulation since 1979. *Atmospheric Chemistry and Physics*, 7(19), 5229–5236. <https://doi.org/10.5194/acp-7-5229-2007>
- Kodama, Y.-M. (1993). Large-scale common features of sub-tropical convergence zones (the baiu frontal zone, the spcz, and the sacz) part ii: Conditions of the circulations for generating the stczs. *Journal of the Meteorological Society of Japan. Ser. II*, 71(5), 581–610.
- Lenters, J., & Cook, K. H. (1997). On the origin of the bolivian high and related circulation features of the south american climate. *Journal of the Atmospheric Sciences*, 54(5), 656–678.
- Marengo, J. A., Soares, W. R., Saulo, C., & Nicolini, M. (2004). Climatology of the low-level jet east of the Andes as derived from the NCEP-NCAR reanalyses: Characteristics and temporal variability. *Journal of Climate*, 17(12), 2261–2280. [https://doi.org/10.1175/1520-0442\(2004\)017<2261:COTLJE>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<2261:COTLJE>2.0.CO;2)
- Markowski, P., & Richardson, Y. (2011). *Mesoscale meteorology in midlatitudes* (Vol. 2). John Wiley & Sons.
- Nascimento, M. G., Herdies, D. L., & De Souza, D. O. (2016). The south American water balance: The influence of low-level jets. *Journal of Climate*, 29(4), 1429–1449. <https://doi.org/10.1175/JCLI-D-15-0065.1>
- Nogués-Paegle, J., & Mo, K. C. (1997). Alternating wet and dry conditions over south america during summer. *Monthly Weather Review*, 125(2), 279–291.
- Popescu, I., Brandimarte, L., Perera, M., & Peviani, M. (2012). Assessing residual hydropower potential of the la plata basin accounting for future user demands. *Hydrology and Earth System Sciences*, 16(8), 2813–2823.
- Salio, P., Nicolini, M., & Zipser, E. J. (2007). Mesoscale convective systems over southeastern South America and their relationship with the South American low-level jet. *Monthly Weather Review*, 135(4), 1290–1309. <https://doi.org/10.1175/MWR3305.1>
- Saulo, C., Ruiz, J., & Skabar, Y. G. (2007). Synergism between the low-level jet and organized convection at its exit region. *Monthly Weather Review*, 135(4), 1310–1326.

- Seluchi, M. E., Saulo, A. C., Nicolini, M., & Satyamurty, P. (2003). The northwestern argentinean low: A study of two typical events. *Monthly Weather Review*, 131(10), 2361–2378.
- Uccellini, L. W. (1980). On the role of upper tropospheric jet streaks and leeside cyclogenesis in the development of low-level jets in the great plains. *Monthly Weather Review*, 108(10), 1689–1696.
- Velasco, I., & Fritsch, J. M. (1987). Mesoscale convective complexes in the americas. *Journal of Geophysical Research: Atmospheres*, 92(D8), 9591–9613.
- Vera, C., Baez, J., Douglas, M., Emmanuel, C. B., Marengo, J., Meitin, J., Nicolini, M., Nogues-Paegle, J., Paegle, J., Penalba, O., Salio, P., Saulo, C., Silva Dias, M. A., Silva Dias, P., & Zipser, E. (2006a). The South American low-level jet experiment. *Bulletin of the American Meteorological Society*, 87(1), 63–77. <https://doi.org/10.1175/BAMS-87-1-63>
- Vera, C., Higgins, W., Amador, J., Ambrizzi, T., Garreaud, R., Gochis, D., Gutzler, D., Lettenmaier, D., Marengo, J., Mechoso, C., et al. (2006b). Toward a unified view of the american monsoon systems. *Journal of climate*, 19(20), 4977–5000.
- Wang, H., & Fu, R. (2004). Influence of Cross-Andes Flow on the South American Low-Level Jet. *Journal of Climate*, 17(6), 1247–1262. [https://doi.org/10.1175/1520-0442\(2004\)017<1247:IOCFOT>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<1247:IOCFOT>2.0.CO;2)
- Zanin, P. R., & Satyamurty, P. (2020). Hydrological processes interconnecting the two largest watersheds of south america from multi-decadal to inter-annual time scales: A critical review. *International Journal of Climatology*, 40(9), 4006–4038.
- Zhou, J., & Lau, K. (1998). Does a monsoon climate exist over south america? *Journal of climate*, 11(5), 1020–1040.
- Zhou, J., & Lau, K. (2001). Principal modes of interannual and decadal variability of summer rainfall over South America. *International Journal of Climatology*, 21(13), 1623–1644.
- Zipser, E. J., Cecil, D. J., Liu, C., Nesbitt, S. W., & Yorty, D. P. (2006). Where are the most: Intense thunderstorms on Earth? *Bulletin of the American Meteorological Society*, 87(8). <https://doi.org/10.1175/BAMS-87-8-1057>

Chapter 2

The South American Low-Level Jet: a new climatology, variability, and changes

Abstract

The South American low-level jet (SALLJ) east of the Andes plays an important role in regional weather and hydrology by transporting large amounts of moisture from the Amazon to the subtropics. A new methodology is introduced for detecting SALLJ events based on seasonal-percentile thresholds of wind speed and wind shear. Direct comparisons are made between new and conventional fixed-threshold methods. Identification of SALLJ events is compared between five different reanalysis products and validated against available radiosonde observations. A new climatology of the SALLJ is presented for one particular reanalysis during a 38-year period (1979-2016). Based on this new definition, the present study analyzes the spatiotemporal variability of the SALLJ on seasonal and interannual time-scales, as well as trends in the jet over re-

cent decades. Results show that the interannual variability of the jet's strength and frequency are significantly modulated by the El Niño Southern Oscillation, especially during spring. Trends in the vertically integrated moisture transport during SALLJ days reveal significant increases in the northwesterly moisture flux associated with the jet towards southern Brazil in spring, summer, and fall. These changes likely contribute to the increase in precipitation and extreme precipitation events observed over southeastern South America in recent decades.

2.1 Introduction

The South American low-level jet (SALLJ) east of the Andes (Marengo et al., 2002; Nascimento et al., 2016; Oliveira et al., 2018; Vera et al., 2006) transports substantial amounts of moisture from the Amazon to the subtropics, influencing the development of deep convection and precipitation over the La Plata Basin (LPB). The densely populated LPB is the continent's second largest drainage basin, but arguably the most important in terms of its socio-economic significance. The basin covers areas of five countries - Argentina, Bolivia, Brazil, Paraguay, and Uruguay - and produces approximately 70% of their combined gross national products. The economy of the LPB is primarily based on agriculture and hydropower production, which are both dependent on and vulnerable to extreme precipitation events. Much of the available water vapor for precipitation in this region is supplied by the SALLJ (Berbery & Barros, 2002; Nascimento et al., 2016), which creates the necessary conditions for the formation and sustenance of large, long-lived Mesoscale Convective Systems (MCSs) (Salio et al., 2007; Zipser et al., 2004). MCSs often intensify over the LPB, causing disastrous flooding and debris flows that are responsible for numerous injuries, fatalities, and damages to crops and property. Due to the considerable socio-economic implications, a further

understanding of the mechanisms that control extreme precipitation and deep convection over subtropical South America has motivated much of the research regarding the SALLJ.

In general, the SALLJ represents a strengthening of the low-level northerly flow along the eastern slopes of the Andes that reaches maximum intensities over Bolivia and northern Paraguay (Marengo et al., 2004; Vera et al., 2006). The shallow vertical structure of the jet is confirmed by direct observations and gridded reanalysis, which identify the wind speed maximum near the 850-hPa level (Marengo et al., 2002; Salio et al., 2002). The jet experiences strong diurnal variations and a nocturnal maximum around 0600 UTC (2:00 AM Bolivia local time). Although the SALLJ occurs throughout the year, the spatial and temporal characteristics of the jet vary between seasons (Marengo et al., 2004; Wang & Fu, 2004).

Early studies of the SALLJ date back to the 1980s, although the sparse network of observations and low-resolution reanalysis prevented an adequate spatiotemporal characterization of the SALLJ. Significant progress was achieved during the South American Low-Level Jet Experiment (SALLJEX) during 15 November 2002–15 February 2003 (Cattle, 2004). In-situ measurements made during the SALLJEX field campaign aimed at providing a more complete temporal and spatial description of the jet (Vera et al., 2006). Because long-term radiosonde network over this region is rare, most studies of the SALLJ heavily rely on reanalysis data and numerical models. The first climatology of the SALLJ was developed by Marengo et al. (2004) based on NCEP/NCAR reanalysis for 1950-2000. Their study presents a robust characterization of circulation and moisture fields associated with SALLJ events during the warm and cold seasons. Their findings show that moisture transport associated with the jet is greater during summer (seasons are always referred to austral seasons), when the SALLJ is influenced by warm, moisture-rich air masses from tropical South America. To our knowledge,

Marengo et al. (2004) is the only comprehensive climatological analysis of the spatial and temporal variability of the SALLJ. However, some limitations of Marengo et al. (2004) include the utilization of the first-generation NCEP/NCAR reanalysis, which has coarse horizontal resolution (2.5° lat/lon), an old data assimilation system, uncoupled first-guess model and uncertainties related to the pre-satellite data era. Additionally, that study identifies the SALLJ with fixed wind speed and shear thresholds, which are shown here to introduce seasonal biases in the identification of the SALLJ.

In the past decade, new reanalysis datasets have become available that are derived from state-of-the-art numerical models and advanced data assimilation schemes at higher vertical and horizontal resolutions. Given the importance of reanalysis data in SALLJ studies, it is crucial to understand the uncertainties and reliability of these datasets in representing the SALLJ.

Previous studies (Marengo et al., 2002; Marengo et al., 2004; Nascimento et al., 2016) have identified SALLJ events by applying the Bonner criteria to reanalysis data. The Bonner criteria for identifying low-level jet events are as follows: (1) northerly winds (850 hPa) with speeds ≥ 12 m/s, (2) vertical wind shear between 850 and 700 hPa ≥ 6 m/s, (3) meridional component larger than the zonal component, and (4) meridional winds from the north. The Bonner (1968) wind speed and wind shear thresholds were determined from seasonal, diurnal, and geographical distributions of wind maxima over the United States Great Plains. Although the thresholds of wind speeds and wind shear above have been widely used in previous studies of the SALLJ, we contend that these fixed thresholds introduce biases in the identification of SALLJ events because significant seasonal variations in winds exist in South America.

This study has several objectives. First, the paper introduces a new method to identify SALLJ events that accounts for the seasonal variations of winds in South America; comparisons between the new and fixed-thresholds methods are also presented.

Second, the identification of SALLJ events is also compared in five different reanalysis products. A new climatology of the SALLJ during 1979-2016 is presented for one particular reanalysis. Additionally, this study investigates interannual variations in the SALLJ and relationships with El Niño/Southern Oscillation (ENSO), and identify changes in the intensity and frequency of the SALLJ in recent decades. The paper is organized as follows. Data sets and identification of SALLJ events are presented in section 2.2. Section 2.3 compares vertical wind profiles of SALLJ events in five different reanalysis and radiosondes released during the SALLJEX. Section 2.4 compares the conventional fixed-thresholds and new methods to identify the SALLJ. Seasonal and interannual variability of the SALLJ are discussed in sections 2.5 and 2.6. Changes in the SALLJ are presented in section 2.7; section 2.8 provides a summary and conclusions.

2.2 Data

An upper-air observing network was temporarily implemented over Bolivia and Paraguay as part of SALLJEX to help reduce large voids in observational data that exist over the SALLJ region (Vera et al., 2006). During the SALLJEX field campaign (January–February 2003), radiosondes were launched twice daily at locations along the core of the jet. This study uses the wind profiles from radiosondes launched over Bolivia and Paraguay at 0600 UTC (2 a.m. local time), which is the time of day when the jet typically reaches its maximum intensity. The two locations are shown in Figure 2.1.

This study uses 6-hourly and daily reanalysis data to characterize the SALLJ and atmospheric conditions during the period 1979–2016 (38 years). Low-level jet events are identified from 6-hourly zonal and meridional winds at 850 and 700 hPa. Daily reanalysis is used to characterize synoptic-scale circulation and moisture transport fields

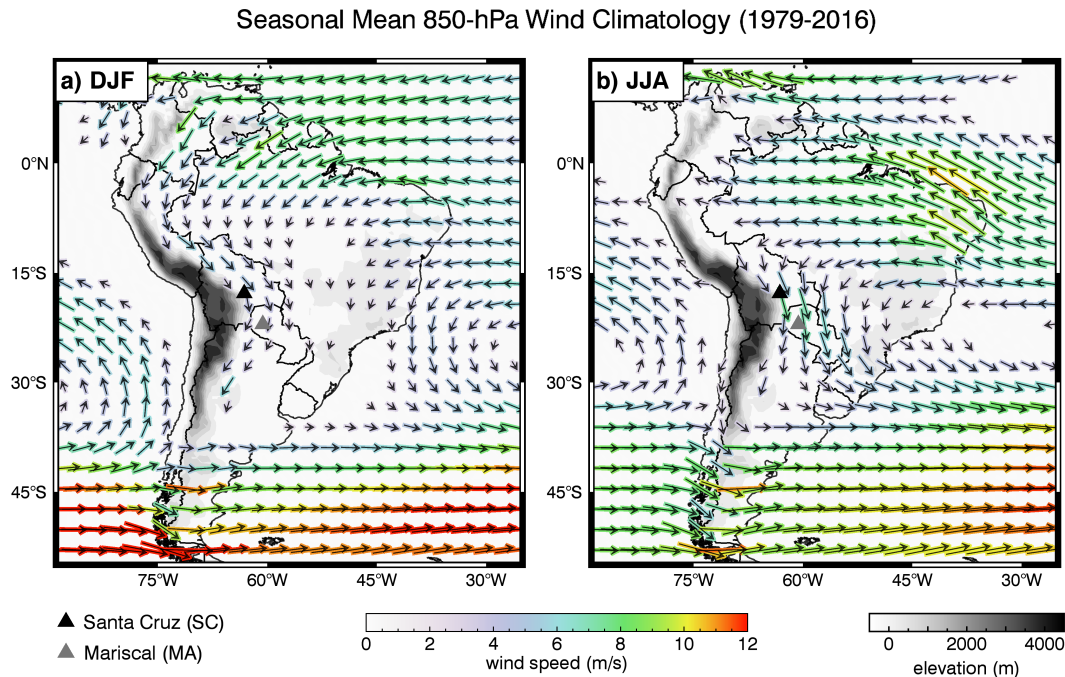


Figure 2.1: Climatological winds at 850 hPa for (a) summer and (b) winter based on ERA-I for 1979–2016. Wind vector plotting begins at 2.5 m/s; colors represent the wind magnitude. Triangles mark the locations used to identify SALLJ events: Santa Cruz de la Sierra, Bolivia (*black*) and Mariscal Estigarribia, Paraguay (*grey*). Grey shading represents topography (m).

during SALLJ days. Daily fields include 850-hPa winds, 200-hPa geopotential height (H200), and vertically integrated water vapor transport (IVT) between surface and 300 hPa. It is worth noting that only two standard pressure levels are used to identify the SALLJ. This is done so that the results of this study can be compared to previous climatological studies of the SALLJ. However, a caveat is that the pressure level where the SALLJ reaches maximum speeds may not necessarily correspond to 850 hPa. Since modern reanalyses are currently available with high vertical resolution, future improvements should take full advantage of additional vertical levels to specifically characterize the pressure level where the SALLJ reaches maximum intensity and its variability.

To minimize uncertainties, the analysis is repeated for five separate reanalyses and results are compared against available observations. This is important because although reanalyses are produced from virtually the same original data sets (e.g., station data, radiosondes, satellite data etc.), there are substantial differences in their data quality control, data assimilation systems, model physics, and spatial and vertical resolution. The five reanalysis datasets used in this study include Climate Forecast System Reanalysis (CFSR; Saha et al., 2014), European Center for Medium-range Weather Forecasts (ERA Interim; Dee et al., 2011), Modern-Era Retrospective Analysis for Research and Applications (MERRA-2; Rienecker et al., 2011), Japanese 55-year Reanalysis (JRA-55; Kobayashi et al., 2015), and National Centers for Environmental Prediction Reanalysis-DOE AMIP II (NCEP R2; Kanamitsu et al., 2002). Modern, high resolution (ranging from $0.5\text{--}0.7^\circ$ lat/lon) are CFSR, ERA-I, and MERRA-2. JRA-55 also uses the new data assimilation system; however, it has a lower horizontal resolution (1.25° lat/lon) than the other three modern reanalyses. To examine the effects of improved data assimilation and increased spatial resolution on representing the SALLJ, the first generation NCEP R2 is included for comparison (Supporting Information Table S1).

SALLJ events are identified at two locations along the main stream of the jet: Santa Cruz de la Sierra, Bolivia (17.8° S, 63.2° W) and Mariscal Estigarribia, Paraguay (22.0° S, 60.6° W). The locations of Santa Cruz and Mariscal (hereafter referred to as SC and MA) are shown in Figure 2.1. Both sites are part of the radiosonde network used during SALLJEX, which allows some comparison between reanalysis and upper-air observations in an otherwise data-sparse region. Time series of wind speed (850 hPa) and wind shear (850–700 hPa) are calculated from 6-hourly zonal and meridional winds at SC and MA. Individual wind components are generally averaged over four grid boxes closest to each location. However, due to the coarser horizontal resolution of JRA-55,

wind components are only obtained for single grid boxes at each location.

Figures 2.2 and 2.3 show seasonal frequency distributions of wind speed and wind shear, respectively, at SC and MA based on CFSR, ERA-I, JRA-55, and MERRA-2 re-analyses. The fixed Bonner thresholds of wind speed and wind shear are drawn for comparison (red horizontal lines in Figures 2.2 and 2.3). Several limitations of applying the fixed Bonner thresholds to the SALLJ are worth noticing. First, wind speed distributions at both SC and MA exhibit a pronounced seasonal cycle, with peak wind speeds occurring during austral winter. Because wind speeds are larger during winter than in other seasons, the statistics of SALLJ occurrences based on fixed thresholds creates seasonal biases in SALLJ frequencies. Second, the Bonner wind shear threshold exceeds the 90th percentile of wind shear at both SC and MA in most datasets and seasons. This shows that the Bonner wind shear threshold of >6 m/s is too high for the SALLJ.

Because of the substantial seasonal variability in wind speed and shear, it seems unlikely that a single wind speed or wind shear threshold would be suitable for identifying SALLJ events throughout the year. Therefore, this study uses the 75th percentiles of wind speed and wind shear to define local and seasonal thresholds of SALLJ occurrences. The 75th percentile thresholds are computed separately for each location, season, and reanalysis.

Thus, the proposed new criteria for identifying SALLJ events are as follows: (1) wind speed at 850 hPa exceeding the 75th seasonal percentile, (2) wind shear between 850 and 700 hPa exceeding the 75th seasonal percentile, and (3) wind direction at 850 hPa between 292.5° and 45° (i.e., NW to NE). An SALLJ day is identified when the criteria are simultaneously satisfied for at least one of the sub-daily times (00, 06, 12, or 18 UTC). For each reanalysis, time series of SALLJ days are computed at SC and MA by applying the seasonal thresholds of wind speed and wind shear to the 6-hourly

wind data. To demonstrate the advantages of using seasonal percentiles as opposed to fixed thresholds, a second set of SALLJ time series are computed by applying the conventional Bonner criteria (i.e., fixed-thresholds) to the exact same 6-hourly wind data at SC and MA.

2.3 Validation of reanalysis data

The description of the SALLJ by reanalysis is validated against radiosonde observations from the SALLJEX field campaign. Vertical profiles of wind speed at 06 UTC (2:00 a.m. Bolivian local time) are averaged over all days during which an SALLJ event is identified according to the new criteria and radiosonde data is available at SC and MA. To evaluate how well reanalyses are able to represent the structure and intensity of the SALLJ, the mean absolute error (MAE) is computed over pairs of observed and reanalysis wind speeds at 850 and 700 hPa (i.e., the pressure levels used in identifying the SALLJ). The general conclusion is that very large MAEs are noted for NCEP-R2 and, to some degree, for JRA-55. CFSR, ERA-I and MERRA-2 show similar order of MAE magnitudes; ERA-I outperforms the other two reanalyses (Table S2).

Figure 2.4 shows that the vertical profile and intensity of the SALLJ based on modern reanalyses are generally consistent with radiosonde observations at both locations. Above 2,000 m (3,000 m at MA), all reanalysis data sets demonstrate a negative bias in wind speed. Among the four reanalyses, ERA-I has the smallest error at levels used to identify the SALLJ (within 1.6–2.2 m/s at SC). CFSR and MERRA-2 perform slightly better at MA, with errors of 2.5 m/s at 850 hPa and 2.4 m/s at 700 hPa, respectively. However, errors based on ERA-I at MA are within 0.1–0.2 m/s of CFSR and MERRA-2 errors.

ERA-I, CFSR, and MERRA-2 demonstrate substantial improvements over NCEP R2

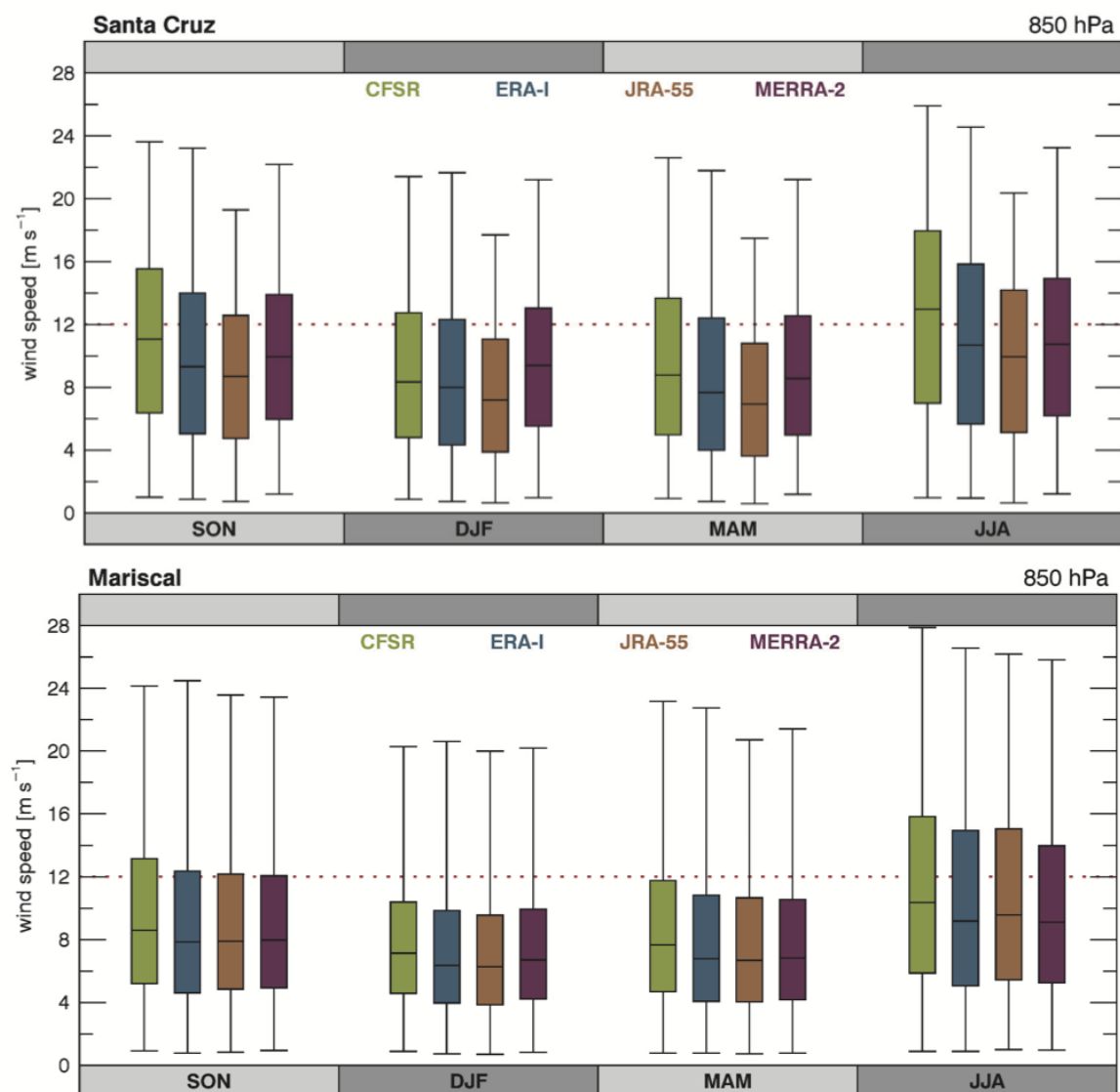


Figure 2.2: Seasonal frequency distributions of 850-hPa wind speed (m/s) at Santa Cruz de la Sierra (*top*) and Mariscal Estigarribia (*bottom*) based on 6-hourly reanalysis for 1979–2016. Colored boxes represent the interquartile range from CFSR (green), ERA-I (blue), JRA-55 (orange), and MERRA-2 (purple) reanalysis. Tops of colored boxes correspond to the seasonal 75th percentiles of wind speed, which used as thresholds to identify SALLJ events. Red dashed lines show the traditional Bonner criterion of wind speed >12 m/s.

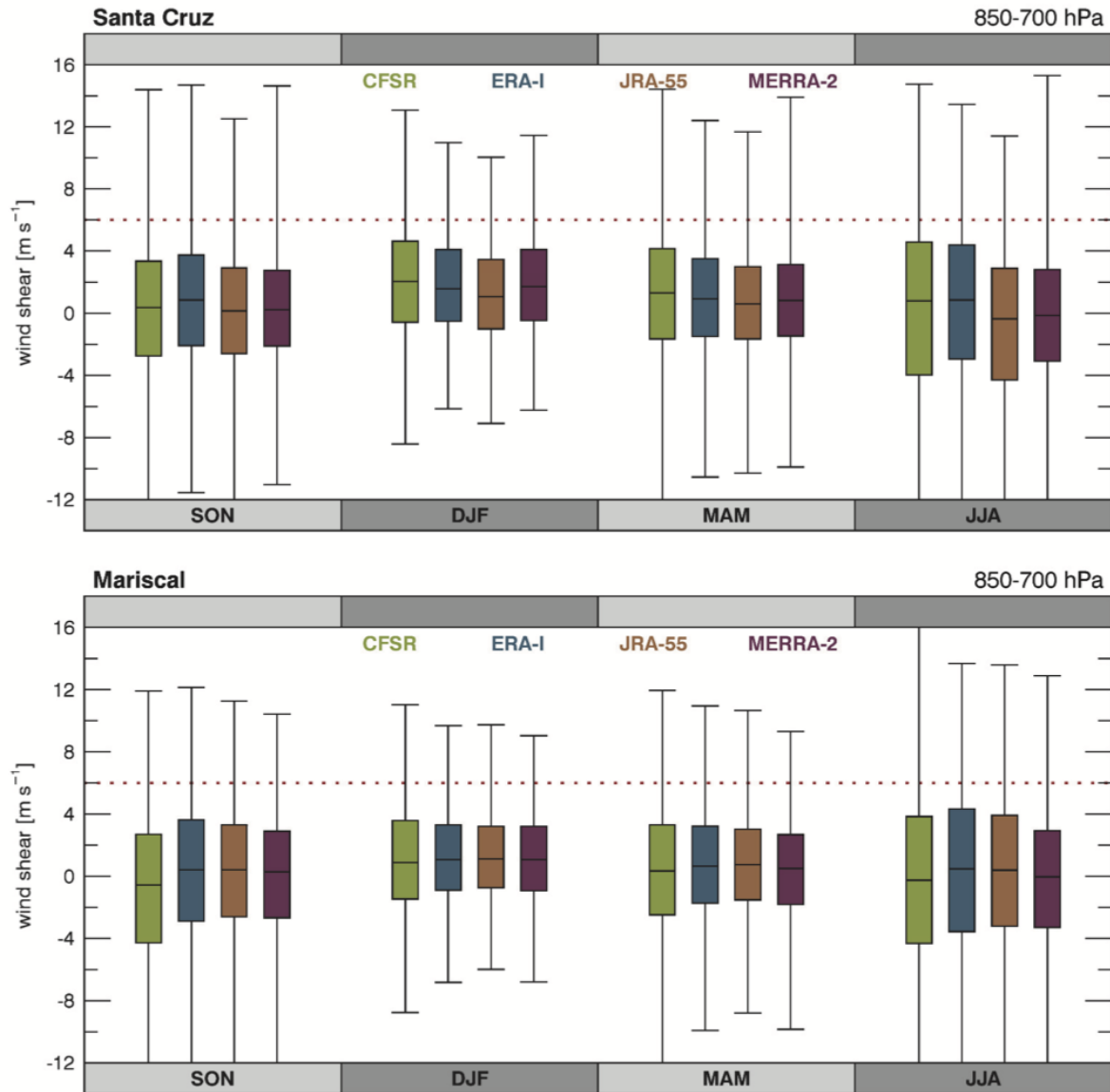


Figure 2.3: Same as in Figure 2.2, but for wind shear (m/s) between 850 and 700 hPa. Red dashed lines show the traditional Bonner criterion of wind shear > 6 m/s.

in representing the SALLJ. NCEP R2 is unable to represent the jet's peak intensity, especially at Santa Cruz. NCEP R2 is a first-generation reanalysis that has a much coarser resolution (2.5° lat/lon), fewer vertical levels, and an older data assimilation system compared to the other reanalyses examined here. JRA-55 uses an improved data assimilation system (4DVAR) and demonstrates significant improvements over NCEP R2; however, it does not capture the peak intensity of the jet as well as the other modern reanalyses. The negative bias in JRA-55 is also demonstrated in the seasonal frequency distributions of wind speed (Figures 2.2 and 2.3) and is likely due to the coarser horizontal resolution (1.25°) compared to CFSR, ERA-Interim, and MERRA-2.

Considering that the spatial density and frequency of upper-air observations have not increased over the SALLJ region over the years, these results suggest that higher resolution and modern data assimilation systems improve the skill of reanalyses in representing the structure and intensity of the SALLJ. Based on the five reanalyses examined here, we found that ERA-I, MERRA-2, and CFSR are able to simulate the vertical structure and intensity of the SALLJ fairly well at both SC and MA; however, ERA-I is overall the most accurate at levels used to identify the SALLJ. Therefore, the ERA-I reanalysis is used for the remaining analysis.

2.4 Frequency of SALLJ and comparison with fixed-threshold Bonner Criterion

Based on the new criteria and ERA-I reanalysis, SALLJ events are identified in 23% of days at SC and 25% of days at MA during 1979–2016. This is equivalent to 3,143 and 3,468 SALLJ days at SC and MA, respectively. However, time series of SALLJ days at SC and MA are not mutually independent from one another, since roughly two-thirds

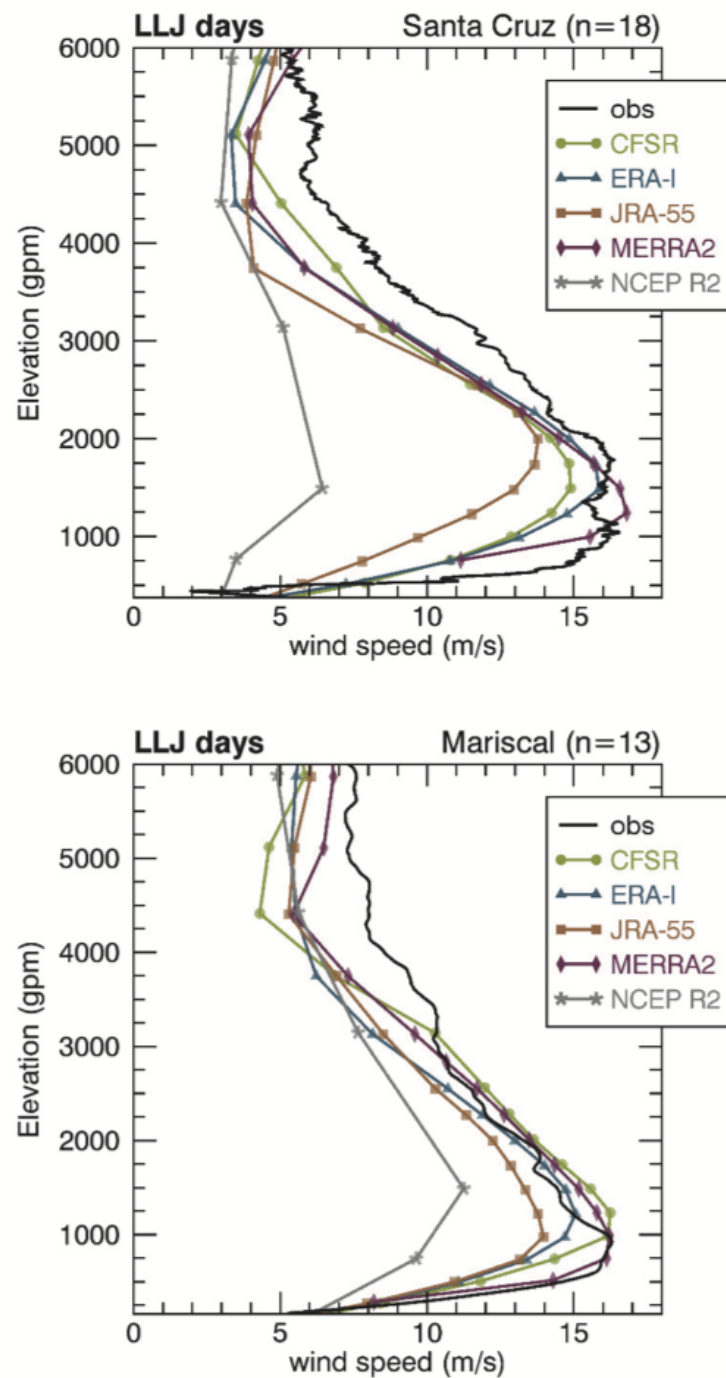


Figure 2.4: Vertical profiles of mean wind speed (m/s) at 06 UTC near Santa Cruz (*top*) and Mariscal (*bottom*). Profiles are averaged over all SALLJ days identified during the SALLEX field campaign for which observations are available. Radiosonde profiles are in black and reanalysis profiles are colored according to the legend.

of the SALLJ days at SC are also identified at MA and vice-versa. During 15% of all days analyzed (2,141 days total), the jet is identified at both SC and MA. An additional time series of SALLJ days is computed for events that occur at both locations, which are hereafter referred to as SC/MA days. The SC/MA jet events are generally stronger than events detected at SC and MA alone.

To compare the new methodology against the conventional fixed-thresholds Bonner method, the Bonner criteria are also applied to ERA-I reanalysis for 1979-2016. Based on the Bonner criteria, SALLJ events are only detected in 15% and 16% of days at SC and MA (1,088 and 1,204 days, respectively). Therefore, the new criteria identify approximately 1.5 times more SALLJ days than the Bonner criteria over all days analyzed. Discrepancies in SALLJ frequency between the new and Bonner criteria are illustrated in Figure 2.5. Compared to the new criteria, the conventional Bonner criteria underestimates the number of SALLJ days in every month. The largest differences in SALLJ frequency between the two methods are observed in summer at MA (Figure 2.5b) during which 2.2 times more SALLJ days are identified by the new criteria compared to the conventional. At SC, the largest difference is observed during autumn, with 2 times more SALLJ days identified by the new criteria. The new and conventional Bonner criteria climatologies are most similar during winter, which is in accordance with the higher wind speeds and wind shear observed during winter at SC and MA (Figures 2.2 and 2.3).

2.5 Seasonal Variability

The seasonal variability of circulation and precipitation over South America is closely linked to the annual cycle of the South American Monsoon System (SAMS). The peak of SAMS occurs during summer and is characterized by increased convection and pre-

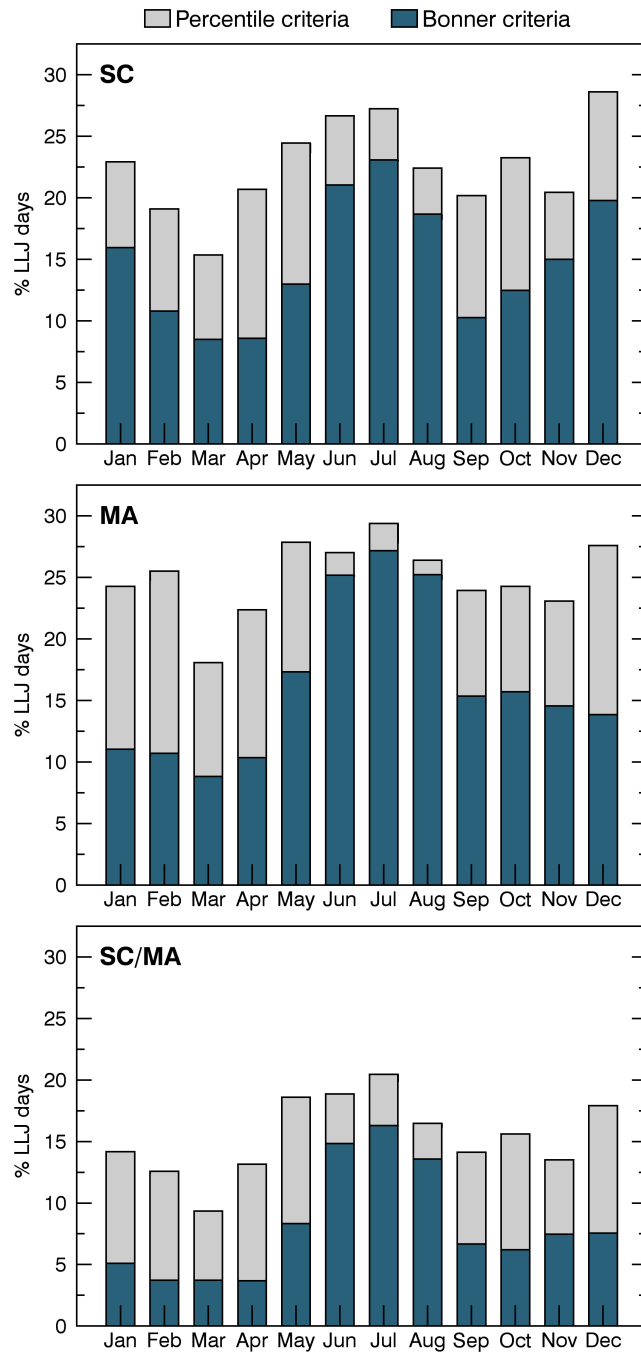


Figure 2.5: Monthly frequency of SALLJ days identified at Santa Cruz (*top*), Mariscal (*middle*), and both locations simultaneously (*bottom*) based on ERA-I for 1979–2016. The light grey bars indicate the number of SALLJ days identified by the new criteria. The dark blue bars indicate the number of SALLJ days identified by the conventional Bonner criteria.

precipitation over the Amazon Basin. Diabatic heating due to deep convection over the Amazon enhances the land-ocean pressure gradient and strengthens the thermal circulation over the continent. This drives equatorial easterlies further south and increases the advection of warm, moist air over the Amazon (Figure 2.1a). Subtropical features tend to dominate circulation patterns over South America during winter, as the upper-level subtropical jet shifts further north and the South Atlantic subtropical high pressure extends westward over the continent.

Figure 2.6 shows seasonal composites of IVT for SALLJ days that are identified at SC/MA based on the new criteria and ERA-I reanalysis. SALLJ composites are characterized by enhanced northerly moisture transport east of the Andes from the Amazon to the LPB (i.e., southern Brazil and northern Argentina), which reaches a maximum near the border of Bolivia and Paraguay. Although the SALLJ transports moisture to southeastern South America year-round, there are some important seasonal differences in the strength and configuration of the moisture transport field. During spring and summer, the moisture flux associated with the jet is more frequently influenced by the northeasterly trade winds, which carry moisture-rich air masses from equatorial Atlantic across the Amazon. The tropical air is eventually channeled south/southeast by the Andes, thus forming the SALLJ. During fall and winter, the northeasterly trade winds weaken and tropical air masses are less likely to penetrate into the SALLJ region. Instead, the jet is more influenced by the intensification of the South Atlantic subtropical high, as its western branch drives moisture directly into the SALLJ. The fall and winter composites also depict the equatorward shift of the upper-level westerlies, which influence a ridge-trough pattern across the Andes that reinforces low-level northerly flow as described by Wang and Fu (2004). The year-round northwest-southeast orientation with its exit region directed towards coastal southern Brazil is related to surface cyclogenesis east of the central Andes (Gan & Rao, 1991), and the SALLJ sustains pre-

frontal systems in these occasions (Salio et al., 2002; Salio et al., 2007). Although wind speeds over the SALLJ region are typically highest during winter (Figure 2.2), the composites show that the moisture flux associated with the jet is largest during spring and summer, owing to the higher moisture content of the tropical air masses.

Seasonal composites of IVT are also computed for SALLJ days identified by the conventional Bonner criteria. Difference maps of new minus conventional methods composites are presented in Figure 2.7 to highlight any significant differences in the jet's intensity or spatial configuration between the two methods. In all seasons, positive IVT anomalies are observed over northern Argentina indicating stronger northerly moisture flux in the new SALLJ composite. This result suggests that the conventional Bonner criteria are insufficient for identifying northerly SALLJ events that penetrate into Argentina. This is evident during spring and summer (Figure 2.7a-b) when negative IVT anomalies over southern Brazil and much of the SALLJ region indicate that the Bonner criteria is detecting the strongest jet events. Thus, the conventional Bonner criteria only identify the portion of SALLJ events with a strong, westerly moisture flux directed towards southern Brazil. In addition to nearly all the SALLJ days identified by the conventional Bonner criteria, the new criteria capture events with a wider range of the jet's intensity (moderate jet events) and SALLJ events that penetrate into Argentina.

In summary, the new criteria capture a wider range of the jet's spatiotemporal variability as opposed to the conventional Bonner method. These results demonstrate the improvements that can be made in SALLJ studies by using percentile-based criteria for identifying jet events and a modern reanalysis dataset. Here, we have only presented the new climatology (and comparison to the Bonner method) based on ERA-I reanalysis. However, similar results and conclusions are obtained using CFSR and MERRA-2 reanalyses (not shown). Some applications of the new SALLJ climatology are explored in the following sections.

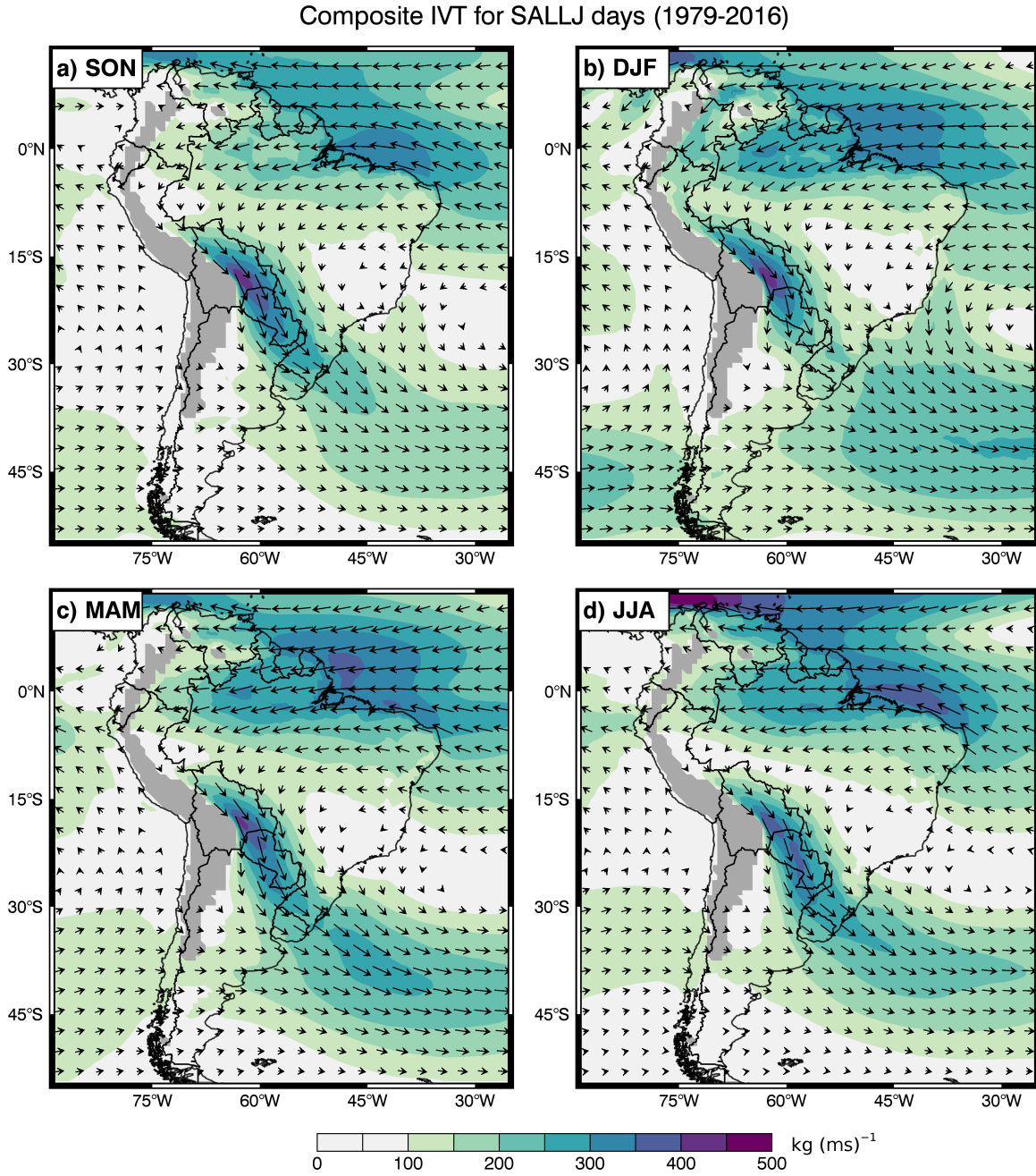


Figure 2.6: Seasonal composites of integrated vapor transport (IVT, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) for SALLJ days identified at SC/MA based on ERA-I for 1979–2016. Gray shading indicates topography above 1500 m.

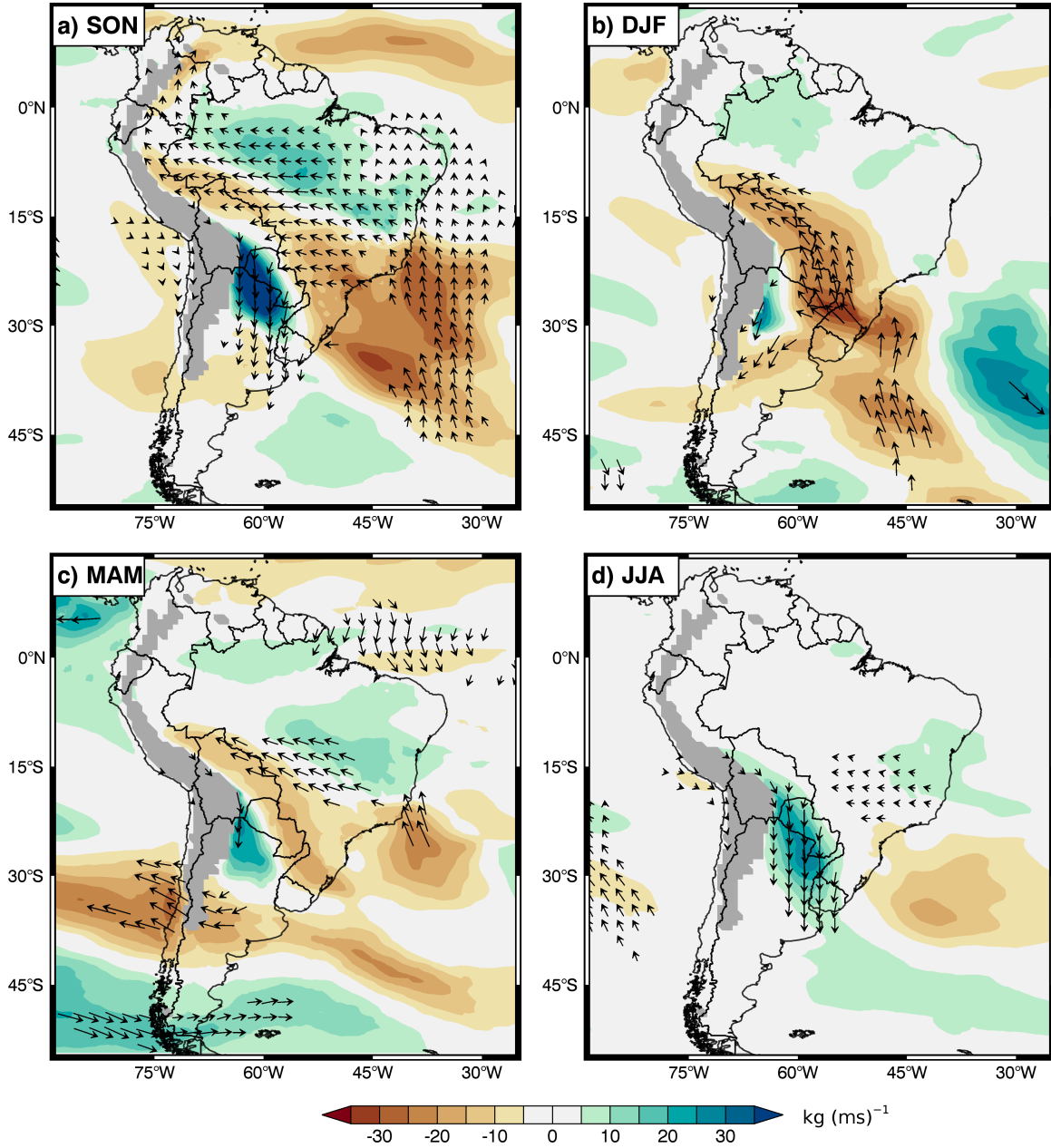


Figure 2.7: Composite differences of integrated vapor transport (IVT, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) between SALLJ days identified by new criteria and SALLJ days identified by conventional Bonner criteria based on ERA-I for 1979–2016. Only IVT vectors that show statistically significant differences at the 5% level are plotted.

2.6 Interannual variability

On interannual timescales, ENSO is the main source of variability in precipitation and circulation over South America. Many studies have shown that during El Niño events, precipitation is suppressed over central-eastern Brazil and enhanced over southeastern South America (southern Brazil, Uruguay, and northern Argentina), while opposite anomalies are observed during La Niña events (Grimm, 2003, 2011; Grimm et al., 2000; Paegle & Mo, 2002). The subtropical rainfall anomalies during El Niño are related to a stronger SALLJ and enhanced poleward moisture transport to southeastern South America (Zhou & Lau, 2001). ENSO influence on the SALLJ is exerted through a combination of tropical and extratropical teleconnections. Tropical mechanisms involve perturbations to the Walker and Hadley circulations, while extratropical forcings manifest through Rossby wave trains over southern South America that originates over the eastern Pacific (Grimm, 2003).

Although there has been substantial research on ENSO and precipitation variability over South America, only a few studies have directly investigated the link between ENSO and the SALLJ. For example, Ferreira et al. (2003) and Marengo et al. (2004) demonstrated that the SALLJ was stronger and more frequent during summer of the 1998 El Niño than during summer of the 1999 La Niña, which contributed to twice as much summer rainfall during 1998 over subtropical South America compared to 1999. Silva et al. (2009) investigated the influence of ENSO on SALLJ events during summer using NCEP/NCAR reanalysis for 1976–2004. They concluded that the spatiotemporal variability of the SALLJ related to ENSO is influenced by the intensity of the northeasterly trade winds and the Subtropical Jet, which are in turn modulated by the phase and position of the upper-level wave train. Although previous studies of the SALLJ and ENSO have almost exclusively focused on the summer season, impacts of ENSO over

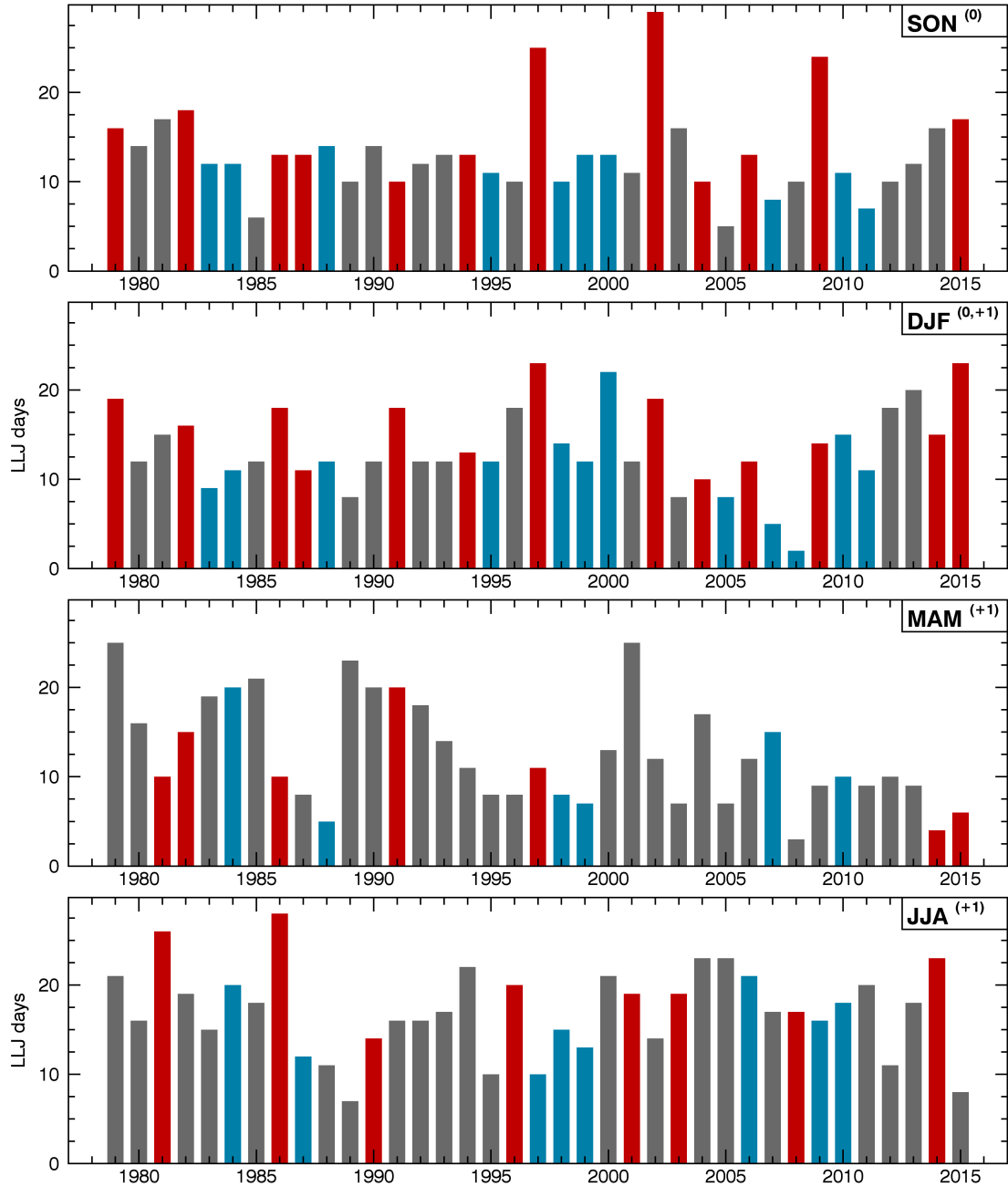


Figure 2.8: Number of SALLJ days per year identified at SC/MA during each season based on ERA interim reanalysis. The colored bars correspond to El Niño (*red*), La Niña (*blue*), and neutral (*grey*) conditions, as determined by the Oceanic Niño Index.

Table 2.1: Differences in the proportion of SALLJ days between ENSO and neutral seasons

% SALLJ days	Location	SON	DJF	MAM	JJA
El Niño–neutral	SC	+6.6 [†]	+7.2 [†]	−2.3	+6.0 [†]
	MA	+5.4 [†]	+4.2*	−3.2	+4.9*
La Niña–neutral	SC	−1.3	−2.4	−6.0 [†]	+0.7
	MA	−2.0	−3.5	−3.2	−1.9

Note. Z scores are used to test for significant differences between two proportions.

*Statistically significant at the 5% significance level.

[†]Statistically significant at the 1% significance level.

South America are in fact larger during spring and autumn, especially in the subtropics (Grimm, 2011).

Making use of the new SALLJ climatology presented here, we investigate the influence of ENSO on the strength, frequency, and position of the SALLJ during all four seasons. Seasons are classified as El Niño, La Niña, or neutral according to the Oceanic Niño Index (ONI, 3-month running mean of SST anomalies in the Niño 3.4 region). ENSO events are identified when the ONI exceeds $\pm 0.5^\circ \text{C}$ for at least five consecutive overlapping months. The categorization of ENSO events and the interannual variability of SALLJ days are depicted in Figure 2.8 for each season over the period 1979–2016.

To identify variations in SALLJ frequency related to ENSO, seasonal proportions of SALLJ days are computed for El Niño, La Niña, and neutral conditions during 1979–2016. The null hypothesis of El Niño (La Niña) and neutral frequencies being equal is evaluated using a z test at the 5% significance level. Significant differences in Table 2.1 indicate that SALLJ days are more frequent during winter, spring, and summer of El Niño years than during that of neutral years. However, differences related to El Niño conditions are not significant during fall. On the other hand, SALLJ days are significantly less frequent during fall of La Niña years, whereas no significant differences for La Niña are observed in winter, spring, and summer. Notice that SALLJ frequency at

both locations increases (decreases) during El Niño (La Niña) events, but ENSO-related changes in frequency are larger at SC than at MA.

To investigate impacts of ENSO on the strength and position of the SALLJ, we compare seasonal averages of moisture and circulation fields between SALLJ days during El Niño (La Niña) with SALLJ days during neutral conditions. Difference composites of IVT patterns are shown in Figures 2.9 and 2.11 for El Niño and La Niña, whereas Figures 2.10 and 2.12 similarly show composite differences of geopotential height at 200 hPa. In spring of El Niño years, enhanced moisture transport is observed over the SALLJ region and into southern Brazil (Figure 2.9a). Enhanced moisture transport towards SESA is associated with an anticyclonic circulation anomaly over central-eastern Brazil, which is produced by subsidence related to the descending branch of the Walker circulation cell (Grimm & Tedeschi, 2009). At upper levels, a prominent wave train resembling a Pacific South America (PSA) pattern extends from the South Pacific to subtropical SA (Figure 2.10a). The upper level wave train is associated with an anticyclonic anomaly over eastern Brazil and the subtropical Atlantic and a cyclonic anomaly over southwestern South America and the Pacific. The pair of cyclonic/anticyclonic anomalies strengthen the subtropical jet stream over southeastern South America, providing dynamical support for ascending motion and reinforcing the SALLJ through secondary ageostrophic circulations.

During summer of El Niño events, ENSO teleconnections weaken over South America as the upper-level wave train breaks down (Figure 2.10b). Although stronger northeasterly trade winds are observed over northern Brazil, no significant changes in moisture transport patterns are detected over the SALLJ region (Figure 2.9b). Negative moisture flux anomalies over parts of southern Brazil are associated with a cyclonic circulation anomaly over central-eastern Brazil (Figure 2.9b). According to Grimm and Zilli (2009), reversal of the circulation anomaly over central-eastern Brazil between

EN – Neutral IVT composites for SALLJ days (1979-2016)

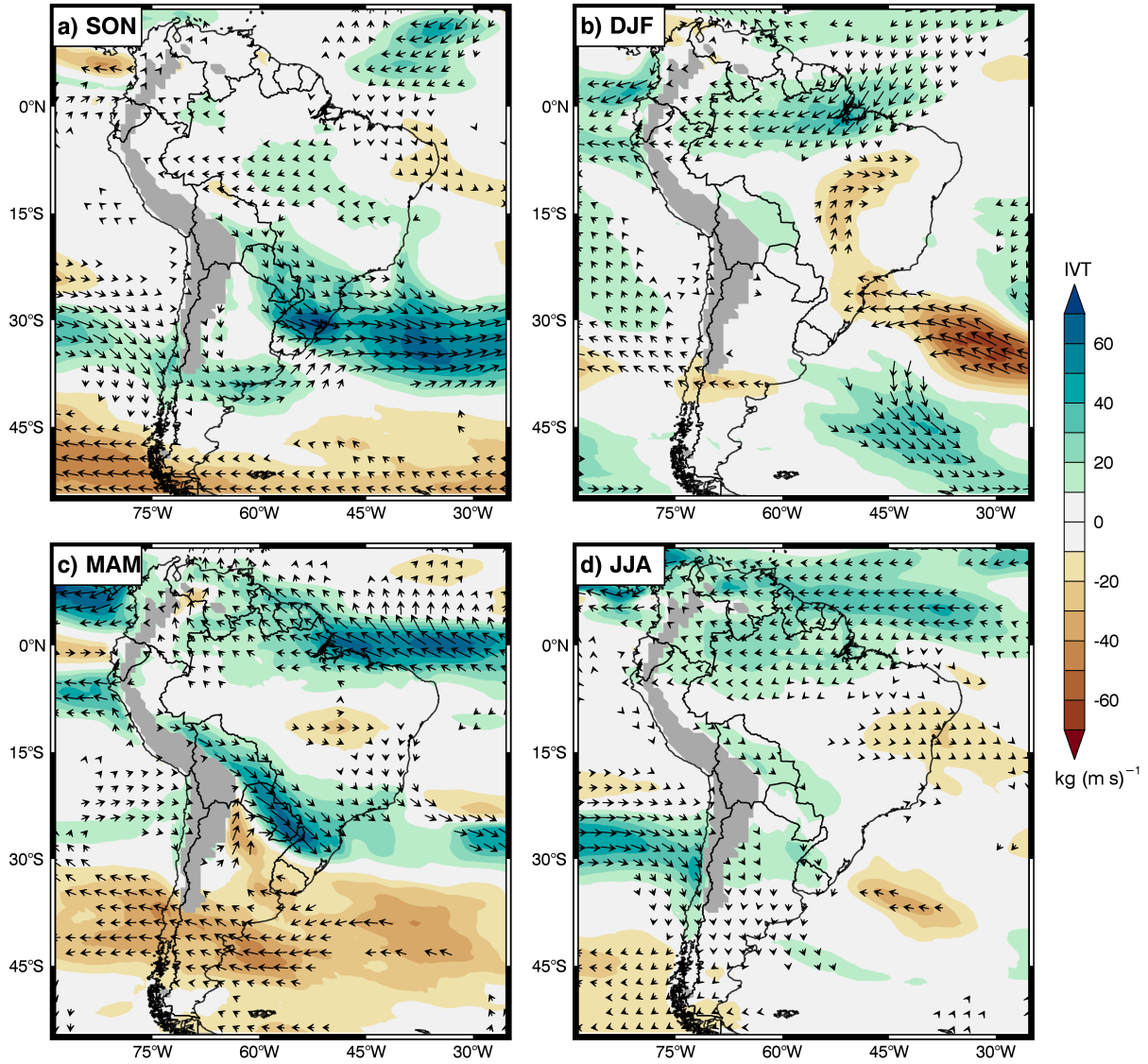


Figure 2.9: Composite differences of integrated vapor transport ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) between SALLJ days in El Niño and neutral conditions based on ERA-I for 1979–2016. Only differences in integrated vapor transport vectors that are statistically significant at the 5% level are plotted.

EN – Neutral 200-hPa composites for SALLJ days (1979-2016)

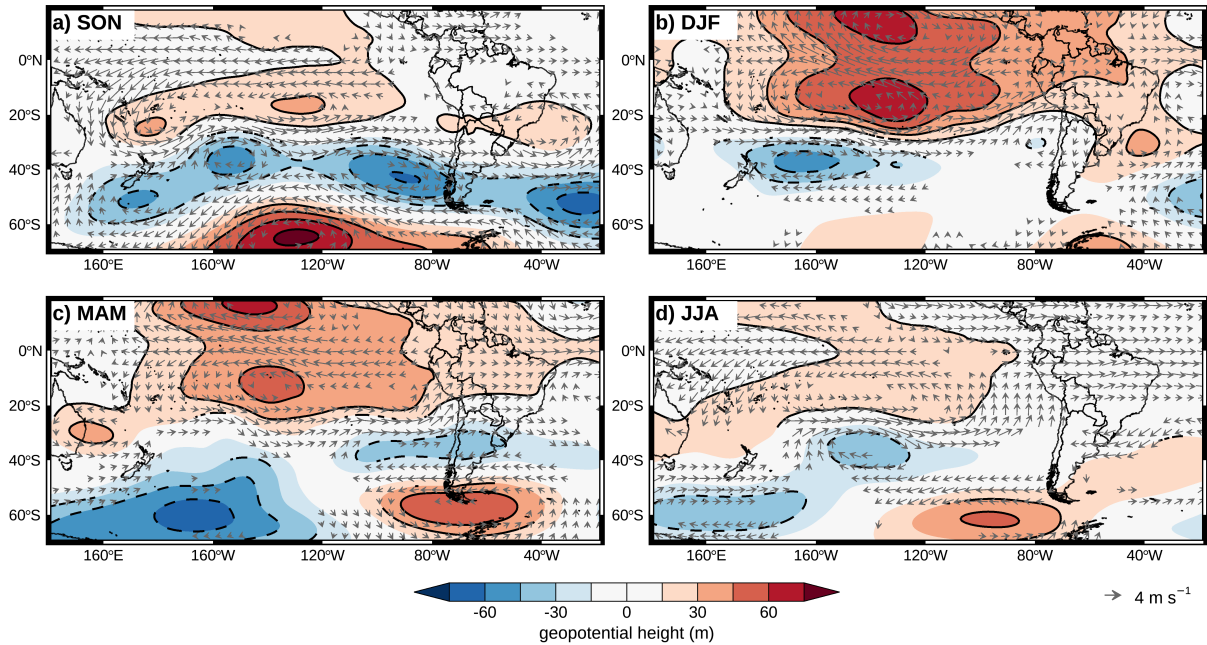


Figure 2.10: Composite differences of 200-hPa geopotential height (m) and wind vectors (m/s) between SALLJ days in El Niño and neutral conditions based on ERA-I (1979–2016). Contours indicate differences are statistically significant at the 5% level.

spring and summer is locally forced from surface-atmosphere feedback mechanisms triggered by the spring El Niño anomalies.

ENSO influences reappear again in autumn, with enhanced moisture flux over the SALLJ region. As seen in Figure 2.9c, positive IVT anomalies indicate enhanced moisture transport over Bolivia and Paraguay and over southern Brazil, while negative IVT anomalies south of the Paraguay border indicate decreased moisture flux into northern Argentina. These patterns are associated with an upper-level cyclonic anomaly over Argentina and anticyclonic anomalies over northern and southern SA (Figure 2.10c). During winter (Figure 2.9d), few significant differences are observed over SALLJ region; the largest difference over tropical SA is stronger easterly trade winds.

Difference composites of IVT and 200-hPa geopotential height are also computed between SALLJ days in La Niña and neutral conditions. During La Niña events, negative

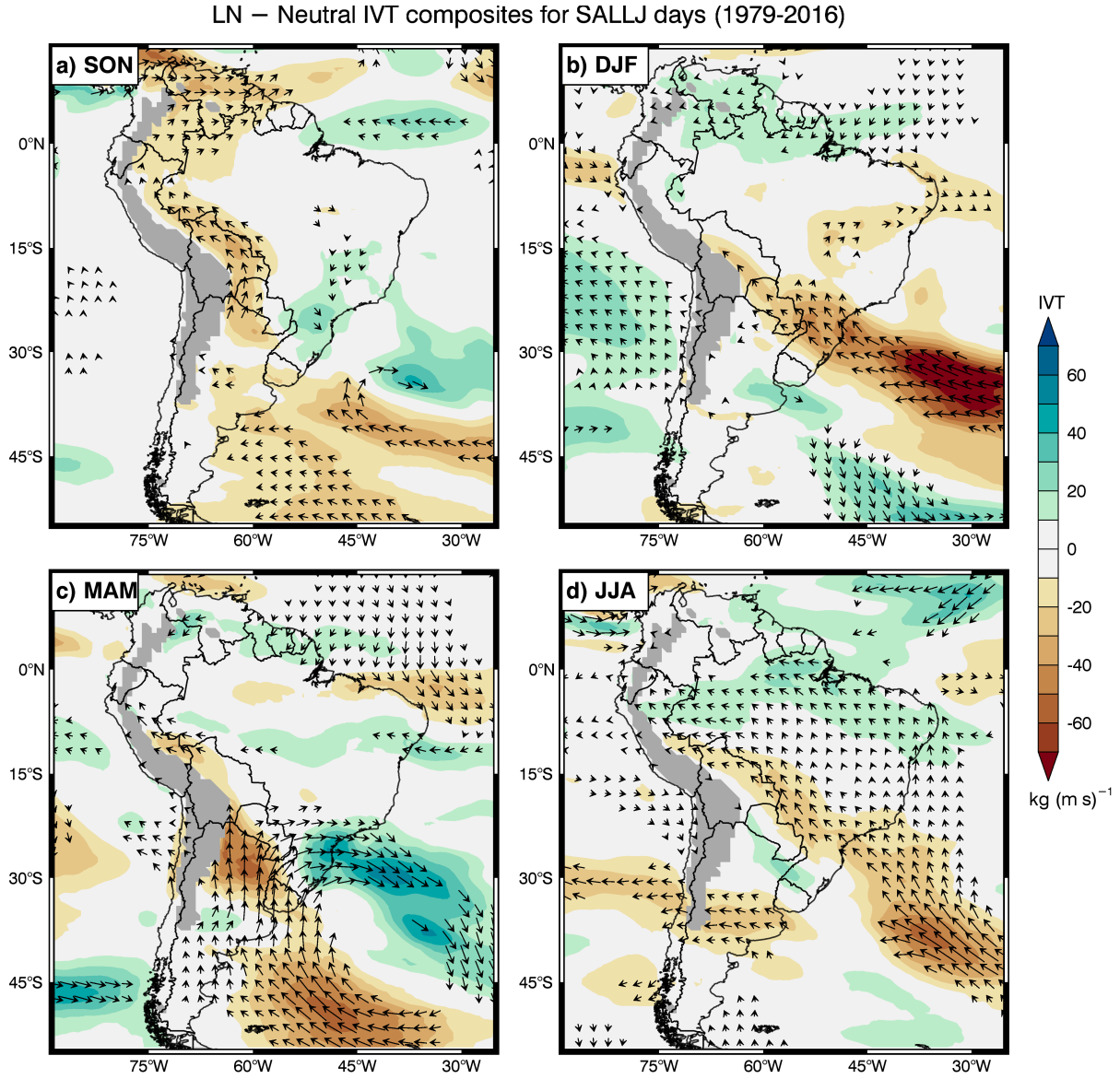


Figure 2.11: Same as in Figure 2.9 but for composite differences of integrated vapor transport (IVT, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) between SALLJ days in La Niña and neutral conditions.

LN – Neutral 200-hPa composites for SALLJ days (1979-2016)

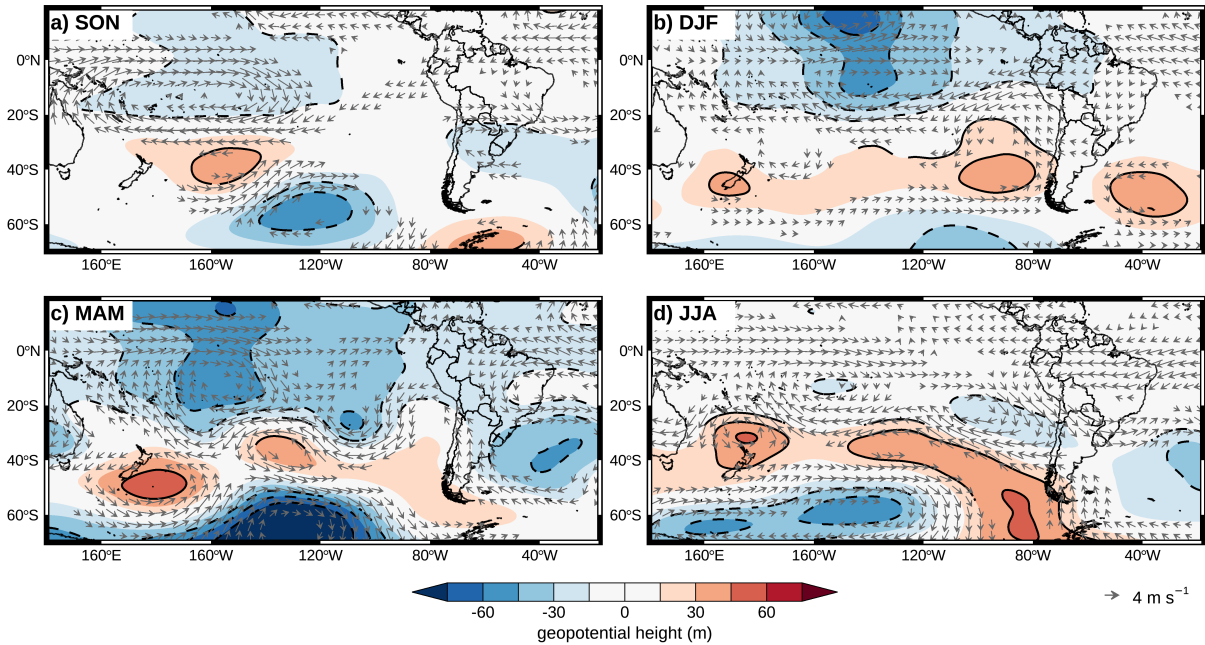


Figure 2.12: Same as in Figure 2.10 but for composite differences in 200-hPa geopotential height (m) and wind vectors (m/s) between SALLJ days in La Niña and neutral conditions.

IVT anomalies over Bolivia indicate a weakening of moisture transport associated with the SALLJ (Figure 2.11). Decreased moisture transport over Bolivia, Paraguay, and southern Brazil is also observed during summer; however, there is no clear pattern at upper levels. Differences in autumn include a cyclonic anomaly over the South Atlantic and anticyclonic anomaly off the southwestern tip over SA over the South Pacific. The cyclonic anomaly over the South Atlantic is prominent at low-levels (Figure 2.11c) and seems to be associated with increased moisture transport towards southeastern Brazil.

2.7 Trends in the SALLJ

South America has significantly warmed in recent decades, with greater warming occurring over tropical regions and adjacent oceans compared to the subtropics (Car-

valho & Jones, 2013; de Barros Soares et al., 2017). These changes can alter land-ocean temperature gradients and consequently affect regional circulation and moisture transport patterns. Observational studies have shown significant increases in precipitation over southeastern Brazil and the LPB (Barros et al., 2008; Liebmann et al., 2004; Zilli et al., 2017) that are consistent with climate model projections for the end of the 21st century (Díaz & Vera, 2017; Jones & Carvalho, 2013; Seth et al., 2010). Increased precipitation over southeastern South America is associated with enhanced poleward moisture transport from the Amazon to the subtropics, which suggests that precipitation trends in this region may be related to changes in the SALLJ. Several studies have examined future changes in the jet based on climate projections of warming scenarios for the end of the 21st century (Seth et al., 2010; Soares & Marengo, 2009). The role of natural variability is also important. For instance, Jones and Carvalho (2018) showed that negative phases of the Atlantic Multidecadal Oscillation (AMO) enhances decadal-to-multidecadal activity in the SALLJ and, consequently, favors enhances precipitation over the LPB. Here, we investigate changes in the SALLJ in the present climate using the newly derived SALLJ climatology.

To characterize changes in the SALLJ, we analyze seasonal trends in jet's frequency, intensity, and moisture transport fields over the last several decades. The nonparametric Mann-Kendall test is used to identify significant trends, while Sen's slope is used to estimate trend magnitude. These tests are applied to the 38-year SALLJ climatology based on ERA-I reanalysis for 1979–2016. To assess uncertainties in the observed changes, the same trend analysis was repeated using CFSR and MERRA-2 reanalyses (not shown) and support the same conclusions based on ERA-I data.

Seasonal trends in SALLJ frequency at SC and MA are listed in Table 2.2. Applying the Mann-Kendall test reveals a significant negative trend in SALLJ frequency during autumn, with a decrease of 16 SALLJ days at MA over the 38-year period (i.e., -0.4

Table 2.2: Seasonal trends in SALLJ frequency and intensity based on ERA-I (1979–2016)

Trend	Location	SON	DJF	MAM	JJA	Units
Frequency	SC	0.0	+0.1	−0.3*	+0.1	days/year
	MA	0.0	−0.1	−0.4 [†] *	−0.2	
Wind speed	SC	+0.012	+0.035*	+0.018	−0.011	$\text{m} \cdot \text{s}^{-1} \cdot \text{year}^{-1}$
	MA	+0.018	+0.017	−0.032	−0.006	
Zonal wind	SC	+0.018*	+0.032 [†]	+0.030*	−0.001	$\text{m} \cdot \text{s}^{-1} \cdot \text{year}^{-1}$
	MA	0.010	+0.014	−0.009	−0.011	
Meridional wind	SC	−0.009	+0.009	−0.003	−0.010	$\text{m} \cdot \text{s}^{-1} \cdot \text{year}^{-1}$
	MA	−0.002	+0.014	−0.044*	−0.014	

Note. Winds represent seasonal averages of SALLJ days at 850 hPa.

Trends are determined with Sen’s slope estimate and the significance of Mann-Kendall test.

*Statistically significant at the 1% significance level.

[†]Statistically significant at the 5% significance level.

days per year; 95% confidence interval: $-0.70, -0.25$). This trend is slightly weaker at SC, with a decrease of approximately 10 SALLJ days (-0.3 days per year, 95% confidence interval: $-0.52, 0.00$). The decreasing trend in fall frequency is also significant in CFSR and MERRA-2 reanalyses. During summer, a significant negative trend in SALLJ frequency is detected at MA in CSFR and MERRA-2 (not shown); however, this trend is not significant in ERA-I.

The intensity of the SALLJ is characterized by the seasonal average 850-hPa wind speed during low-level jet days at SC or MA. A significant positive trend is identified during summer at SC, with an increase in wind speed of 1.3 m/s over the 38 years based on ERA-I reanalysis ($+0.035$, 95% confidence interval: $+0.003, +0.065$). This trend is also significant in CFSR (not shown). No significant trends in wind speed are detected at MA in any season. Trend analysis of the zonal and meridional wind components separately reveals a significant increase in the zonal wind component during spring, summer, and fall. In the zonal wind component in SC, the trends and 95% confidence

intervals are: SON $+0.018$ ($+0.001, +0.003$), DJF $+0.032$ ($+0.017, +0.053$), and MAM $+0.030$ ($+0.007, +0.056$). Significant positive trends in the zonal wind are also detected in CSFR and MERRA-2 (not shown). On the other hand, trends in the meridional wind component are less significant and inconsistent among reanalyses. During autumn, a significant decreasing trend in the meridional wind speed is detected using ERA-I (MA: -0.044 , 95% confidence interval $-0.078, -0.010$), but this trend is not significant in either CFSR or MERRA-2. Therefore, changes in the wind speed of the jet in recent decades are mainly due to an intensification of the westerly wind.

To characterize changes in large-scale circulation and moisture transport associated with the SALLJ, we identify trends in vertically integrated moisture flux fields during low-level jet days. Figure 2.13 depicts trends in the seasonal average IVT during SALLJ days computed at each grid box using ERA-I reanalysis. Positive trends over Bolivia and Paraguay indicate a strengthening of the northwesterly moisture flux associated with the jet in spring, summer, and fall (Figures 2.13a-c), whereas no significant trends over the SALLJ region are detected during winter. During spring, enhanced moisture transport east of the Andes is associated with an anticyclonic anomaly over central Brazil and an increase in the easterly moisture flux across the Amazon (Figure 2.13a). These patterns intensify during summer, when changes over the SALLJ region are largest compared to other seasons. Figure 2.13b shows substantial increases in the northeasterly moisture flux over tropical South America from the equatorial Atlantic during summer. The moisture flux is channeled south by the Andes, contributing to an increase in IVT over the SALLJ region of approximately $30 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$ per decade (Figure 2.13b). The anticyclonic circulation anomaly strengthens over central-eastern Brazil in summer, which helps direct the enhanced moisture flux associated with the jet towards southeastern Brazil. Additionally, this anomaly is associated with decreased northerly moisture transport over northeastern Brazil.

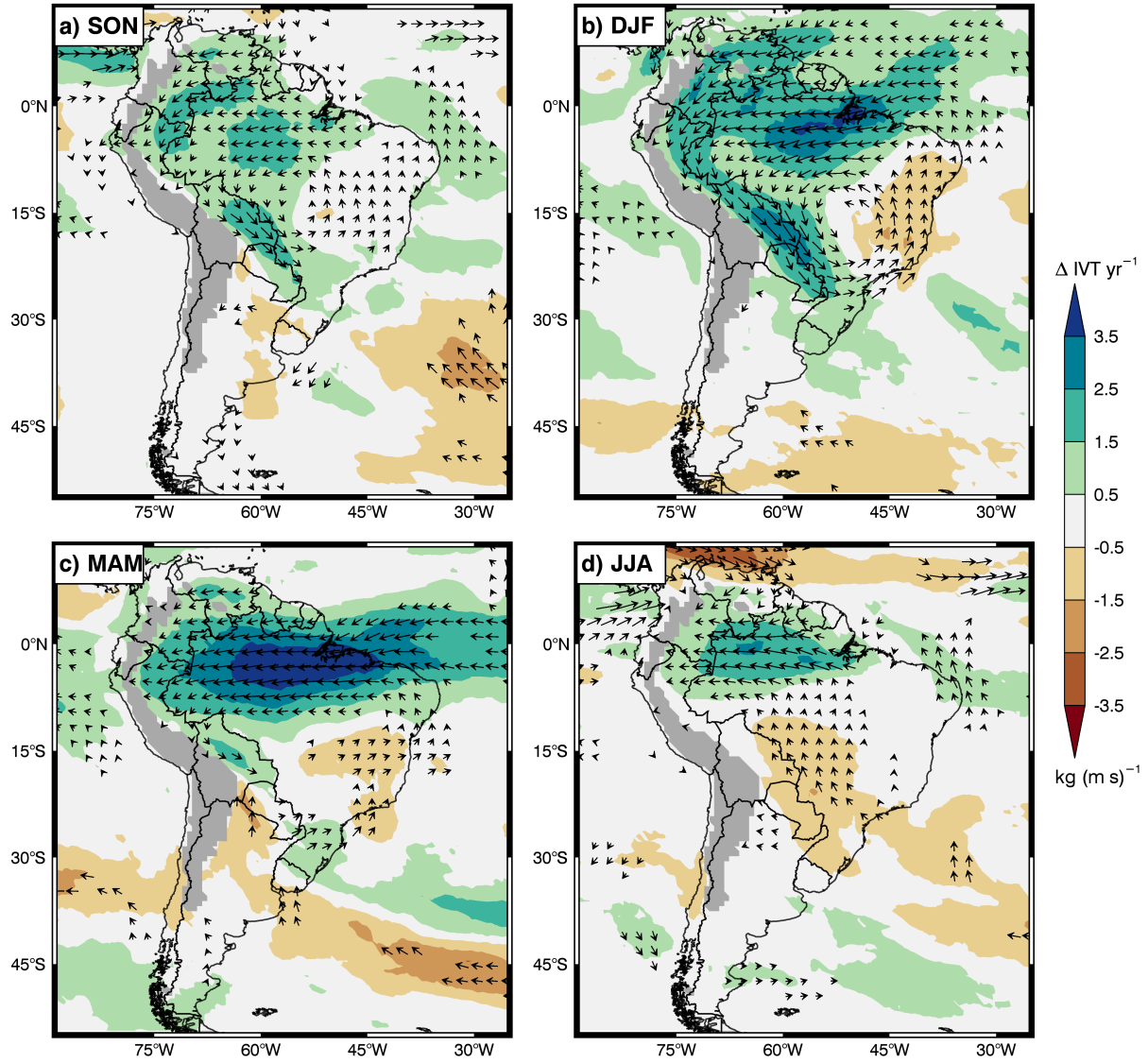


Figure 2.13: Seasonal trends in integrated vapor transport (IVT, $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) per year for SALLJ days identified at SC/MA based on ERA-I for 1979–2016. IVT vectors are only plotted where trends are statistically significant at the 5% level.

During autumn, large positive trends over tropical South America indicate substantial increases in the easterly moisture flux across the Amazon from the equatorial Atlantic (Figure 2.13c). At the same time, trends over the SALLJ region and the anticyclonic anomaly over Brazil are both weaker compared to those in spring and summer. Negative trends over northern Argentina indicate a decrease in moisture flux to that region. This suggests that northerly jet events that penetrate into Argentina are becoming weaker or less frequent, which agrees with the decrease in SALLJ frequency observed at MA during autumn. On the other hand, positive trends over southern Brazil indicate an increase in the strength and/or frequency of northwesterly jet events directed toward that region. Dry, southerly anomalies over northern Argentina may indicate an increase in cold fronts over that region during SALLJ days, which would help deflect the jet towards southern Brazil and facilitate convection along the frontal boundary.

Overall, greater moisture transport by the SALLJ is related to an anticyclonic circulation anomaly over Brazil and the intensification of the northeasterly moisture flux across the Amazon. The latter may be partially explained by significant warming over tropical South America (Carvalho & Jones, 2013), which affects land-ocean temperature gradients and alters the monsoonal circulation over the continent. The observed warming also increases the moisture capacity of the lower troposphere according to Clausius-Clapeyron relation. Thus, increased moisture availability over the Amazon leads to a higher moisture content of air masses that feed directly into the SALLJ. Additionally, the role of decadal-to-multidecadal variations associated with the AMO (Jones & Carvalho, 2018) needs to be further investigated to explain these trends.

On the other hand, the anticyclonic circulation anomaly over central-eastern Brazil is consistent with simulations of DJF climate presented by Junquas et al. (2013) based on projected SST changes. Their study shows that positive precipitation trends over SESA are influenced by the longitudinal component of global SST changes, which is

characterized by stronger warming in the equatorial Indian and western Pacific oceans as compared to the rest of the equatorial band. The zonally asymmetric pattern of SST anomalies triggers Rossby wave trains extending throughout the South Pacific to South America that induce an anticyclonic anomaly over central-eastern Brazil and a cyclonic anomaly over the southern tip of South America. These large-scale circulation patterns favor moisture transport towards southeastern South America; therefore, increased wave train activity could explain the strengthening of the SALLJ.

Our results are also consistent with changes in summer circulation patterns over South America reported by Zilli et al. (2019). Although they do not specifically analyze the SALLJ, their study demonstrates enhanced low-level flow east of the Andes and decreased flow over northeastern Brazil. They relate these decadal changes to a poleward shift of the South Atlantic Convergence Zone associated with the southwestward expansion of the South Atlantic subtropical high. The pattern of enhanced low-level northerly flow east of the Andes is also consistent with climate projections for the end of the 21st century by Seth et al. (2010). They show that the poleward expansion of the South Atlantic subtropical high increases the zonal pressure gradient over subtropical South America, which strengthens low-level northerly flow east of the Andes and its associated moisture transport from the tropics to southeastern South America.

2.8 Summary and conclusions

A 38-year climatology of SALLJ events is presented based on ERA-I reanalysis (1979–2016) and a new set of criteria for identifying low-level jet events. This study applies the new climatology to examine the spatiotemporal variability of the SALLJ on seasonal and interannual time scales and analyze trends in the jet over recent decades. A new method uses the 75th percentiles of wind speed and wind shear to define lo-

cal and seasonal thresholds of jet occurrences. According to this approach, an SALLJ event is identified whenever the wind speed at 850 hPa and wind shear between 850 and 700 hPa both exceed the 75th percentile of their respective seasonal climatology. Based on the new criteria and ERA-I reanalysis, SALLJ events are detected in 23% of days at Santa Cruz, Bolivia and 25% of days at Mariscal Estigarribia, Paraguay during 1979–2016. Additionally, it is worth noticing that users interested in using the new method proposed here can use the results presented in Tables S3 and S4, which show the seasonal 75th percentile thresholds of wind speed (850 hPa) and wind shear (i.e., difference wind speed 850 hPa minus 700 hPa) for different reanalyses. Users can select a given reanalysis product, the corresponding thresholds, and apply the modified Bonner criteria discussed in section 2.2.

Direct comparisons are made between the new criteria and the conventional Bonner method, which applies fixed thresholds of wind speed and wind shear to identify low-level jets. The revised criteria account for the seasonality of winds over South America. As a result, the new method identifies 1.5 times more SALLJ days than the conventional Bonner method, which only detects a subset of strong SALLJ events. Limitations of using the Bonner method for LLJ detection over South America are also demonstrated by Oliveira et al. (2018), whose study examines the sensitivity of LLJ detection to the height of the layer used to identify jet events. By extending the layer height, they are also able to produce a larger sample of LLJ events. It is worth noticing that Oliveira et al. (2018) is interested in a broader application of LLJ detection that includes all low-level wind maxima across the LPB, whereas the present study is specifically focused on the SALLJ east of the Andes. Additionally, we identify the SALLJ at standard pressure levels rather than employing a criterion for height in meters above sea level.

The description of the SALLJ by reanalysis is validated against radiosonde observations from the SALLJEX experiment. Based on the five reanalyses examined in this

study, we found that the vertical structure and intensity of the jet in ERA-I, MERRA-2, and CFSR are the most consistent with radiosonde observations and demonstrate substantial improvements from older/coarser reanalyses. Wind speeds at 850 and 700 hPa based on ERA-I are within 1-2 m/s of observations during low-level jet days. Therefore, results are primarily presented for ERA-I reanalysis because it is the most accurate at levels used to identify the SALLJ.

Seasonal composites of vertically integrated moisture transport during SALLJ days show that the northwesterly moisture flux towards the LPB is strongest during summer and weakest during winter. The seasonal variability of the moisture flux associated with the jet is related to the moisture content of air masses that feed into the SALLJ region, rather than the jet's wind speed. During summer, jet events are more influenced by the penetration of the northeasterly trade winds across the Amazon, whereas the South Atlantic subtropical high and the upper-level subtropical jet stream are more likely to influence jet events during the fall and winter. These results support the description of large-scale circulation and moisture transport patterns presented in previous studies of the SALLJ (Marengo et al., 2004; Nascimento et al., 2016; Wang & Fu, 2004).

On interannual timescales, the strength and frequency of the SALLJ is modulated by ENSO. The SALLJ is stronger and more frequent during El Niño episodes, whereas La Niña episodes are associated with weaker and less frequent SALLJ days. ENSO influence on the SALLJ is largest during the spring of El Niño events and during autumn of La Niña events. During spring of an El Niño episode, enhanced northwesterly moisture transport is observed over the SALLJ region towards southern Brazil. This contributes to the enhanced precipitation anomalies over southeastern South America observed during El Niño (Grimm, 2011; Grimm et al., 2000). Difference composites suggest that the stronger SALLJ is remotely influenced by an upper-level wave train, which establishes a pair of cyclonic/anticyclonic anomalies over South America that strengthen the

Subtropical Jet across the Andes and reinforces the SALLJ.

Trend analysis of SALLJ characteristics reveals significant changes in the strength and spatiotemporal variability of the jet in recent decades. Results indicate that the mean wind speed of the SALLJ is increasing during summer, while the frequency of jet events is decreasing during fall. The changes in wind speed primarily represent a strengthening of the zonal wind component, since changes in the meridional wind component are relatively weak and insignificant. Trends in vertically integrated moisture transport over South America indicate significant increases in the northwesterly moisture flux towards southern Brazil during SALLJ days in spring, summer, and fall. The strengthening of the moisture flux associated with the jet is related to the intensification of moisture transport across the Amazon and an anticyclonic circulation anomaly over central-eastern Brazil. In summary, these results suggest that SALLJ events have become stronger and more westerly in recent decades. This is consistent with climate model projections by Soares and Marengo (2009) and Seth et al. (2010), which predict a stronger SALLJ and increased moisture flux towards SESA under future warming scenarios.

Identification of the physical mechanisms responsible for the observed changes in the SALLJ is beyond the scope of this study. However, possible mechanisms include the southwestward expansion of the South Atlantic subtropical high pressure (Li et al., 2013; Zilli et al., 2019); the poleward displacement of the Subtropical Jet (Hu & Fu, 2007); changes in land-ocean thermal gradients due to extensive warming of tropical regions. The poleward displacement of subtropical circulation features is related to a broadening of the Hadley cell circulation due to tropospheric warming (Chen et al., 2014). Recent changes in the SALLJ are also influenced by decadal-to-multidecadal changes in AMO. A more detailed analysis of SALLJ changes and the associated mechanisms is necessary to determine the relative influence of anthropogenic climate change

versus natural climate variability.

Finally, changes in the strength and variability of the SALLJ may significantly impact the hydrological cycle of the LPB. The increase in moisture transport by the SALLJ implies an increase in moisture convergence over southern Brazil, which may explain positive precipitation trends observed over that region in recent decades. These changes may also explain the increase in extreme precipitation events, due the larger amount of moisture available to fuel large, long-lived convective systems. The authors are currently investigating the sensitivity of MCSs and extreme precipitation over the LPB to changes in the SALLJ and results will be presented elsewhere.

Acknowledgements

The CFSR, ERA-I, JRA-55 and NCEP/DOE reanalyses were downloaded from the Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, Boulder, CO [available online at <https://rda.ucar.edu>]. The MERRA-2 reanalysis was downloaded from <https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>. Radiosonde data during the SALLJEX was downloaded from the UCAR Earth Observing Laboratory [https://www.eol.ucar.edu/field_projects/salljex]. The authors greatly appreciate the data availability and service provided by these institutions.

References

- Barros, V. R., Doyle, M. E., & Camilloni, I. A. (2008). Precipitation trends in southeastern South America: relationship with ENSO phases and with low-level circulation. *Theoretical and Applied Climatology*, 93(1-2), 19–33. <https://doi.org/DOI10.1007/s00704-007-0329-x>

- Berbery, E. H., & Barros, V. R. (2002). The hydrologic cycle of the La Plata basin in South America. *Journal of Hydrometeorology*. [https://doi.org/10.1175/1525-7541\(2002\)003<0630:THCOTL>2.0.CO;2](https://doi.org/10.1175/1525-7541(2002)003<0630:THCOTL>2.0.CO;2)
- Bonner, W. D. (1968). Climatology of the Low Level Jet. *Monthly Weather Review*, 96(12), 833–850. [https://doi.org/10.1175/1520-0493\(1968\)096<0833:COTLLJ>2.0.CO;2](https://doi.org/10.1175/1520-0493(1968)096<0833:COTLLJ>2.0.CO;2)
- Carvalho, L. M. V., & Jones, C. (2013). CMIP5 Simulations of Low-Level Tropospheric Temperature and Moisture over the Tropical Americas. *Journal of Climate*, 26(17), 6257–6286. <https://doi.org/10.1175/JCLI-D-12-00532.1>
- Cattle, H. (Ed.). (2004). *Clivar exchanges no. 29. south american low level jet experiment salljex* (tech. rep.). Southampton, UK, International CLIVAR Project Office. <http://nora.nerc.ac.uk/id/eprint/119310/>
- Chen, S., Wei, K., Chen, W., & Song, L. (2014). Regional changes in the annual mean hadley circulation in recent decades. *Journal of Geophysical Research*, 119(13), 7815–7832. <https://doi.org/10.1002/2014JD021540>
- de Barros Soares, D., Lee, H., Loikith, P. C., Barkhordarian, A., & Mechoso, C. R. (2017). Can significant trends be detected in surface air temperature and precipitation over South America in recent decades? *International Journal of Climatology*, 37(3), 1483–1493. <https://doi.org/10.1002/joc.4792>
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., ... Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553–597. <https://doi.org/10.1002/qj.828>
- Díaz, L. B., & Vera, C. S. (2017). Austral summer precipitation interannual variability and trends over Southeastern South America in CMIP5 models. *International Journal of Climatology*, 37(March), 681–695. <https://doi.org/10.1002/joc.5031>
- Ferreira, R. N., Rickenbach, T. M., Herdies, D. L., & Carvalho, L. M. V. (2003). Variability of South American convective cloud systems and tropospheric circulation during January-March 1998 and 1999. *Monthly Weather Review*, 131(5), 961–973. [https://doi.org/10.1175/1520-0493\(2003\)131<0961:Vosacc>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<0961:Vosacc>2.0.CO;2)
- Gan, M. A., & Rao, V. B. (1991). Surface cyclogenesis over South America. *Monthly Weather Review*, 119(5), 1293–1302. [https://doi.org/10.1175/1520-0493\(1991\)119<1293:SCOSA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1991)119<1293:SCOSA>2.0.CO;2)
- Grimm, A. M. (2003). The El Nino impact on the summer monsoon in Brazil: Regional processes versus remote influences. *Journal of Climate*, 16(2), 263–280.

- Grimm, A. M. (2011). Interannual climate variability in South America: impacts on seasonal precipitation, extreme events, and possible effects of climate change. *Stochastic Environmental Research and Risk Assessment*, 25(4), 537–554. <https://doi.org/DOI10.1007/s00477-010-0420-1>
- Grimm, A. M., Barros, V. R., & Doyle, M. E. (2000). Climate variability in southern South America associated with El Nino and La Nina events. *Journal of Climate*, 13(1), 35–58.
- Grimm, A. M., & Tedeschi, R. G. (2009). ENSO and extreme rainfall events in South America. *Journal of Climate*, 22(7), 1589–1609. <https://doi.org/10.1175/2008JCLI2429.1>
- Grimm, A. M., & Zilli, M. T. (2009). Interannual Variability and Seasonal Evolution of Summer Monsoon Rainfall in South America. *Journal of Climate*, 22(9), 2257–2275. <https://doi.org/10.1175/2008jcli2345.1>
- Hu, Y., & Fu, Q. (2007). Observed poleward expansion of the Hadley circulation since 1979. *Atmospheric Chemistry and Physics*, 7(19), 5229–5236. <https://doi.org/10.5194/acp-7-5229-2007>
- Jones, C., & Carvalho, L. M. (2013). Climate change in the South American monsoon system: Present climate and CMIP5 projections. *Journal of Climate*, 26(17), 6660–6678. <https://doi.org/10.1175/JCLI-D-12-00412.1>
- Jones, C., & Carvalho, L. M. (2018). The influence of the Atlantic multidecadal oscillation on the eastern Andes low-level jet and precipitation in South America. *npj Climate and Atmospheric Science*, 1(1), 40. <https://doi.org/10.1038/s41612-018-0050-8>
- Junquas, C., Vera, C. S., Li, L., & Le Treut, H. (2013). Impact of projected SST changes on summer rainfall in southeastern South America. *Climate Dynamics*, 40(7-8), 1569–1589. <https://doi.org/10.1007/s00382-013-1695-y>
- Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J. J., Fiorino, M., & Potter, G. L. (2002). NCEP–DOE AMIP-II Reanalysis (R-2). *Bulletin of the American Meteorological Society*, 83(11), 1631–1643. [https://doi.org/10.1175/bams-83-11-1631\(2002\)083<1631:nar>2.3.co;2](https://doi.org/10.1175/bams-83-11-1631(2002)083<1631:nar>2.3.co;2)
- Kobayashi, S., Ota, Y., Harada, Y., Ebata, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K., & Kiyotoshi, T. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. *Journal of the Meteorological Society of Japan*, 93(1), 5–48. <https://doi.org/10.2151/jmsj.2015-001>
- Li, W., Li, L., Ting, M., Deng, Y., Kushnir, Y., Liu, Y., Lu, Y., Wang, C., & Zhang, P. (2013). Intensification of the Southern Hemisphere summertime subtropical an-

- tycyclones in a warming climate. *Geophysical Research Letters*, 40(22), 5959–5964. <https://doi.org/10.1002/2013GL058124>
- Liebmann, B., Vera, C. S., Carvalho, L. M. V., Camilloni, I. A., Hoerling, M. P., Allured, D., Barros, V. R., Baez, J., & Bidegain, M. (2004). An observed trend in central South American precipitation. *Journal of Climate*, 17(22), 4357–4367.
- Marengo, J. A., Douglas, M. W., & Silva Dias, P. L. (2002). The South American low-level jet east of the Andes during the 1999 LBA-TRMM and LBA-WET AMC campaign. *Journal of Geophysical Research: Atmospheres*, 107(D20), LBA 47-1-LBA 47-11. <https://doi.org/https://doi.org/10.1029/2001JD001188>
- Marengo, J. A., Soares, W. R., Saulo, C., & Nicolini, M. (2004). Climatology of the low-level jet east of the Andes as derived from the NCEP-NCAR reanalyses: Characteristics and temporal variability. *Journal of Climate*, 17(12), 2261–2280. [https://doi.org/10.1175/1520-0442\(2004\)017<2261:COTLJE>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<2261:COTLJE>2.0.CO;2)
- Nascimento, M. G., Herdies, D. L., & De Souza, D. O. (2016). The south American water balance: The influence of low-level jets. *Journal of Climate*, 29(4), 1429–1449. <https://doi.org/10.1175/JCLI-D-15-0065.1>
- Oliveira, M. I., Nascimento, E. L., & Kannenberg, C. (2018). A new look at the identification of low-level jets in South America. *Monthly Weather Review*, 146(7), 2315–2334. <https://doi.org/10.1175/MWR-D-17-0237.1>
- Paegle, J. N., & Mo, K. C. (2002). Linkages between Summer Rainfall Variability over South America and Sea Surface Temperature Anomalies. *Journal of Climate*, 15(12), 1389–1407. [https://doi.org/10.1175/1520-0442\(2002\)015<1389:LBSRVO>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1389:LBSRVO>2.0.CO;2)
- Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M. G., Schubert, S. D., Takacs, L., Kim, G. K., Bloom, S., Chen, J., Collins, D., Conaty, A., Da Silva, A., Gu, W., Joiner, J., Koster, R. D., Lucchesi, R., . . . Woollen, J. (2011). MERRA: NASA's modern-era retrospective analysis for research and applications. *Journal of Climate*, 24(14), 3624–3648. <https://doi.org/10.1175/JCLI-D-11-00015.1>
- Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H.-y., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., & Becker, E. (2014). The NCEP Climate Forecast System Version 2. *Journal of Climate*, 27(6), 2185–2208. <https://doi.org/10.1175/JCLI-D-12-00823.1>
- Salio, P., Nicolini, M., & Saulo, A. C. (2002). Chaco low-level jet events characterization during the austral summer season. *Journal of Geophysical Research Atmospheres*, 107(24), XLXIII–XLXIV. <https://doi.org/10.1029/2001JD001315>

- Salio, P., Nicolini, M., & Zipser, E. J. (2007). Mesoscale convective systems over southeastern South America and their relationship with the South American low-level jet. *Monthly Weather Review*, 135(4), 1290–1309. <https://doi.org/10.1175/MWR3305.1>
- Seth, A., Rojas, M., & Rauscher, S. A. (2010). CMIP3 projected changes in the annual cycle of the South American Monsoon. *Climatic Change*, 98(3-4), 331–357.
- Silva, G. A. M., Ambrizzi, T., & Marengo, J. A. (2009). Observational evidences on the modulation of the South American Low Level Jet east of the Andes according the ENSO variability. *Annales Geophysicae*, 27(2), 645–657. <https://doi.org/10.5194/angeo-27-645-2009>
- Soares, W. R., & Marengo, J. A. (2009). Assessments of moisture fluxes east of the Andes in South America in a global warming scenario. *International Journal of Climatology*, 29(10), 1395–1414. <https://doi.org/10.1002/joc.1800>
- Vera, C., Baez, J., Douglas, M., Emmanuel, C. B., Marengo, J., Meitin, J., Nicolini, M., Nogues-Paegle, J., Paegle, J., Penalba, O., Salio, P., Saulo, C., Silva Dias, M. A., Silva Dias, P., & Zipser, E. (2006). The South American low-level jet experiment. *Bulletin of the American Meteorological Society*, 87(1), 63–77. <https://doi.org/10.1175/BAMS-87-1-63>
- Wang, H., & Fu, R. (2004). Influence of Cross-Andes Flow on the South American Low-Level Jet. *Journal of Climate*, 17(6), 1247–1262. [https://doi.org/10.1175/1520-0442\(2004\)017<1247:IOCFOT>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<1247:IOCFOT>2.0.CO;2)
- Zhou, J., & Lau, K. (2001). Principal modes of interannual and decadal variability of summer rainfall over South America. *International Journal of Climatology*, 21(13), 1623–1644.
- Zilli, M. T., Carvalho, L. M., Liebmann, B., & Silva Dias, M. A. (2017). A comprehensive analysis of trends in extreme precipitation over southeastern coast of Brazil. *International Journal of Climatology*, 37(5), 2269–2279. <https://doi.org/10.1002/joc.4840>
- Zilli, M. T., Carvalho, L. M., & Lintner, B. R. (2019). The poleward shift of South Atlantic Convergence Zone in recent decades. *Climate Dynamics*, 52(5-6), 2545–2563. <https://doi.org/10.1007/s00382-018-4277-1>
- Zipser, E., Salio, P., & Nicolini, M. (2004). Mesoscale convective systems activity during SALLJEX and the relationship with SALLJ events. *CLIVAR exchanges*, 9(1), 14–18.

Chapter 3

Synoptic variability of warm-season SALLJ events

3.1 Introduction

Precipitation over subtropical South America is mainly produced by large, mesoscale convective systems, especially during austral spring and summer (Durkee et al., [2009](#); Velasco & Fritsch, [1987](#)). It is well-known that the development of organized convection and precipitation in this part of the continent is associated with the exit region of the South American low-level jet (SALLJ) (Salio et al., [2007](#); Saulo et al., [2007](#)). Located east of the Andes Mountains, the SALLJ is a northerly flow that transports heat and moisture from the Amazon Basin towards the subtropics. The strength and direction of moisture transport may vary substantially between SALLJ events, and as a result, the exit region of the jet varies from central Argentina to Paraguay to southern Brazil. Therefore, regional precipitation is influenced by the SALLJ, which is in turn modulated by synoptic systems and climate variability across multiple time-scales.

At seasonal time scales, the El Niño Southern Oscillation (ENSO) dominates pre-

precipitation and convection variability over SESA. During El Niño events, a low-level anticyclonic anomaly over central Brazil enhances the northerly flow associated with the SALLJ, which favors the development of MCSs and above-average precipitation over SESA (Grimm, 2003; Grimm & Tedeschi, 2009). On subseasonal time-scales, the Madden Julian Oscillation (MJO) influences precipitation and convection variability over South America through a tropical disturbance that propagates eastward from the Indian Ocean (Jones et al., 2004).

This study employs an objective pattern classification method to identify and categorize different types of SALLJ days. This method involves performing a principal components analysis of SALLJ days, followed by a cluster analysis on the leading components. Previous studies have applied this methodology, which is sometimes referred to as *weather typing*, to a variety of weather phenomena and regions (e.g., Mercer et al., 2012; Michelangeli et al., 1995; Peters and Schumacher, 2014).

The goal of this chapter is to develop a more robust understanding of synoptic circulation patterns that modulate the frequency and location of the SALLJ, and consequently influence precipitation over SESA. To highlight the key patterns of variability among low-level jet events, this study applies PCA and clustering analysis to large-scale atmospheric fields associated with warm-season SALLJ days. This procedure identifies a set of daily circulation regimes (also known as *synoptic types*) that are associated with SALLJ days. Next, we investigate the relationships between the synoptic types of SALLJ days and large-scale climate variability, such as ENSO and MJO. This determination has important implications for subseasonal to seasonal climate predictability.

The organization of this chapter is as follows. An overview of the various datasets used in this analysis is provided in section 3.2. A description of the statistical methods used to objectively categorize SALLJ days into synoptic subtypes is outlined in section 3.3. Frequency, duration, and transition probabilities between synoptic types of SALLJ

days are discussed in section 3.4. Section 3.5 presents composites of SALLJ types in order to better diagnose the specific features that drive variability in the exit region of the jet and determine the location of convection and precipitation. Relationships between the SALLJ types and modes of large-scale climate variability are investigated in sections 3.6 and 3.7. Summary and conclusions are presented in section 3.8.

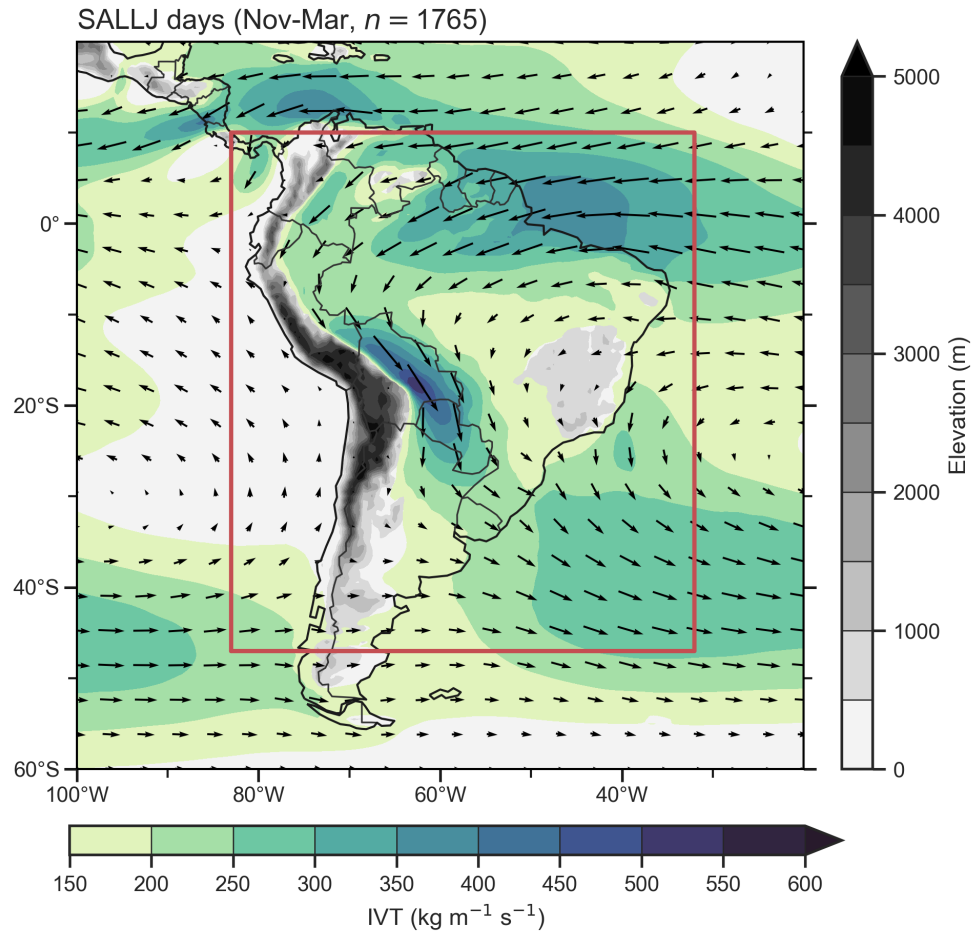


Figure 3.1: Average vertically integrated vapor transport (IVT) vectors and IVT magnitude (color shading) of SALLJ days in November-March during 1979-2016 ($n = 1,765$ days). The red box marks the spatial domain used for Principal Components Analysis. Grey shading represents topography in meters above sea level.

3.2 Datasets

A dataset of SALLJ days was presented in Chapter 2 based on ERA Interim reanalysis (Dee et al., 2011) for the period 1979-2016. Because subtropical convective systems and precipitation develop with greater frequency on SALLJ days during austral spring and summer (Salio et al., 2007), this chapter focuses only on warm-season (November–March) SALLJ occurrences. A total of 1,765 SALLJ days occurred over the 37-year period from 01-November 1979 to 31-March 2016. This sample of warm-season SALLJ days was used in the PCA and cluster analysis.

Daily atmospheric fields were obtained from ERA5 Reanalysis (Hersbach et al., 2020) at a spatial resolution of $0.5^\circ \times 0.5^\circ$ latitude/longitude. The primary variable used to represent the SALLJ was vertically integrated water vapor transport (IVT). Both zonal and meridional IVT components were included in the PCA. Additional atmospheric variables were used to create composites of SALLJ types, including mean sea-level pressure, winds at 850- and 250-hPa, geopotential height at 850- and 250-hPa, and 1000–500 hPa thickness. Precipitation data was obtained from hourly ERA5 total precipitation at 0.25° spatial resolution, and total daily precipitation was computed by summing over the hourly data each day. Anomalies were calculated relative to the long-term seasonal mean from November 1979 to March 2016.

Climate indices of ENSO and MJO were also used in this analysis. MJO events were identified using the methodology in (Jones, 2009). This index is similar to the eight-phase convention of the real-time multivariate MJO index of (Wheeler & Hendon, 2004); however, the primary difference is that the Jones (2009) index uses bandpass filtered anomalies. ENSO variability was defined based on the Oceanic Niño index (ONI), which is calculated by averaging sea surface temperature for the Niño 3.4 region and applying a 3-month running mean. Phases of ENSO are classified by monthly

ONI values greater than 0.5 (El Niño), less than -0.5 (La Niña), and between -0.5 and 0.5 (neutral). Data were retrieved from the National Oceanic and Atmospheric Administration’s Climate Prediction Center website¹.

3.3 Cluster analysis

3.3.1 Methodology

To classify the synoptic circulation regimes of SALLJ days, PCA was applied to zonal and meridional IVT fields over the domain shown in Figure 3.1 (i.e., 10°N to 47°S and 82°W to 32°W). Prior to PCA, the gridded IVT data was standardized by removing the long-term mean and dividing by the standard deviation. The data was also spatially weighted by the square-root of the cosine of latitude.

Cluster analysis was performed in the subspace defined by the leading principal components (PCs). Cluster analysis is used to group data points according to their similarity, in such a way that minimizes differences among data points within a cluster, while maximizing the differences between data points in separate clusters. In this study, clustering is performed on the PC loadings matrix so that SALLJ days with similar loadings (i.e., spatial patterns) on the leading PCs are grouped together.

We used the non-hierarchical k -means method with Euclidean distance for our cluster analysis (Wilks, 2011). K-means is an iterative algorithm that reassigns data points (i.e., SALLJ days) to a predefined number of clusters (k) in such a way that minimizes the *intragroup distance*, which is defined as the sum of squared distances between each cluster member and the corresponding cluster mean (Wilks, 2011). Because the number of clusters (k) within our data is unknown in advance, intragroup distance is

¹https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

tracked over a range of k and the optimal number of clusters (k_i) is selected when the change in intragroup distance (between k_i and k_{i+1}) becomes inconsequential.

Therefore, k -means objectively groups together SALLJ days in a way that minimizes differences between SALLJ days within a cluster and maximizes differences between SALLJ days in one cluster to another. This means that SALLJ days with similar synoptic patterns will be grouped together. We refer to the resulting clusters as "synoptic subtypes" of SALLJ days. To further analyze these atmospheric regimes, composites are computed by averaging over the SALLJ days belonging to each subtype.

3.3.2 Results

We performed PCA on the standardized data matrix that retained 75% of the total variance in the leading 22 PCs. Of these components, the first four PCs passed the North et al. (1982) test for separation of eigenvalues and accounted for 12.8%, 11.2%, 8.6%, and 5.5% of the total variance, respectively. Starting with the fifth PC, sampling errors became greater than the separation between adjacent eigenvalues; therefore, it is unlikely that the structures of these trailing components ($\geq$ PC 5) would be significant (North et al., 1982; Wilks, 2011). As such, only the first four PCs were retained for cluster analysis.

The k -means clustering algorithm was applied to the matrix of 4 PC loadings x 1,765 SALLJ days. Each loading represents the relationship between the original IVT field of an SALLJ day and the spatial pattern of one of the four leading components shown in Figure 3.2. For example, SALLJ days that load positively (negatively) on PC 1 are associated with a cyclonic (anticyclonic) anomaly around 40°S, 45°W, which corresponds to southerly (northerly) flow over northern Argentina and westerly (easterly) flow over southern Brazil (Figure 3.2a).

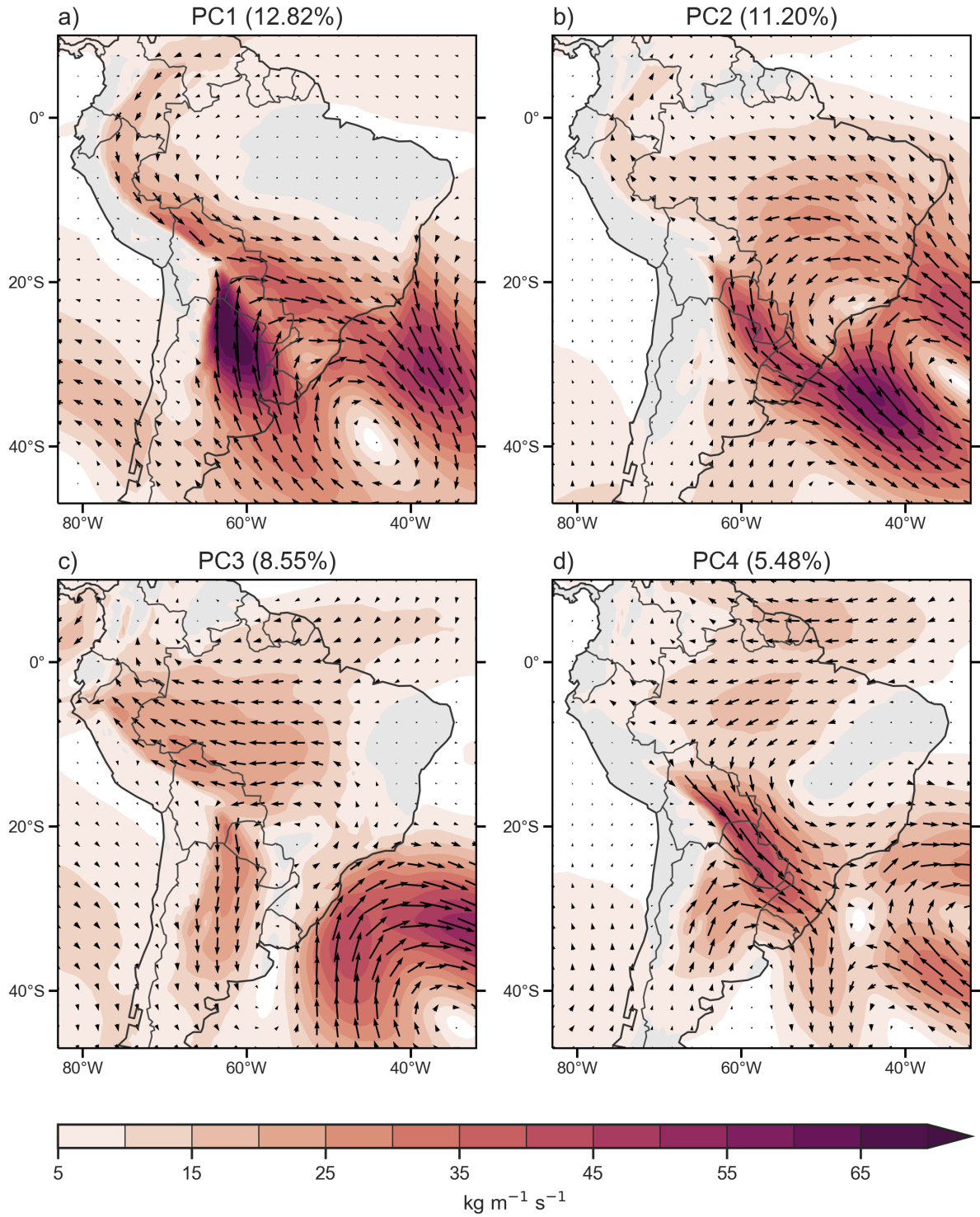


Figure 3.2: Scores of the four leading principal components (PCs) corresponding to IVT anomalies of SALLJ days during November–March (1979–2016). Percent of the total variance explained by each PC is indicated at the top of each map.

By performing k-means for a range of k ($k = 2, \dots, k = 10$), a minimum decrease in the intragroup distance was observed at $k = 4$, which was determined to be the optimal number of clusters. We also found that this number of clusters was appropriate from a physical standpoint, as the resulting composites represented four distinct synoptic patterns. Therefore, we identified four subtypes of SALLJ events, which are hereafter referred to as SALLJ types 1-4.

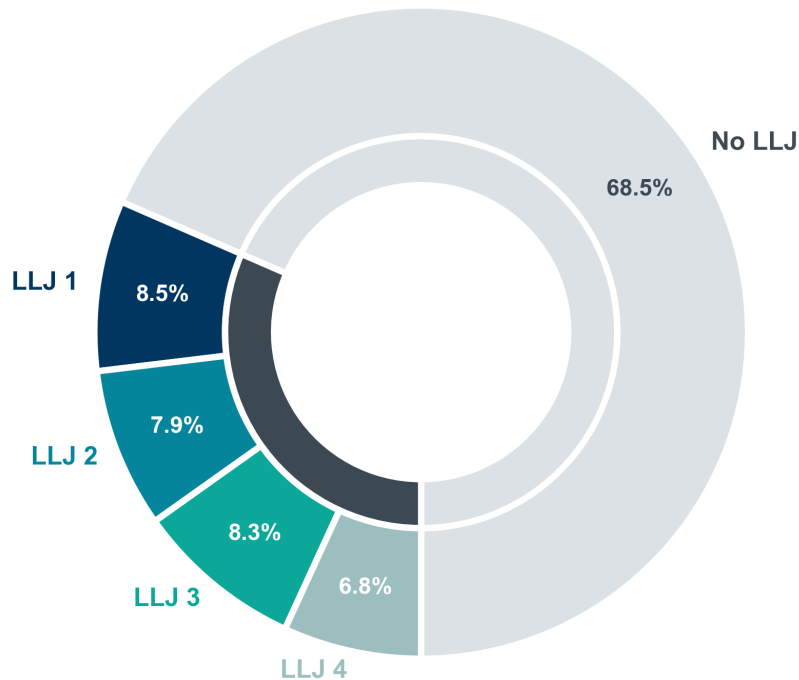


Figure 3.3: Percent frequency of SALLJ subtypes and non-SALLJ days during November–March (1979–2016).

3.4 Classification of SALLJ types

The frequency of each SALLJ type during NDJFM is presented in Figure 3.3. Overall, the distribution of SALLJ days was fairly equal between the four subtypes. The most common SALLJ occurrence was type 1, which accounted for 8.5% of all NDJFM days.

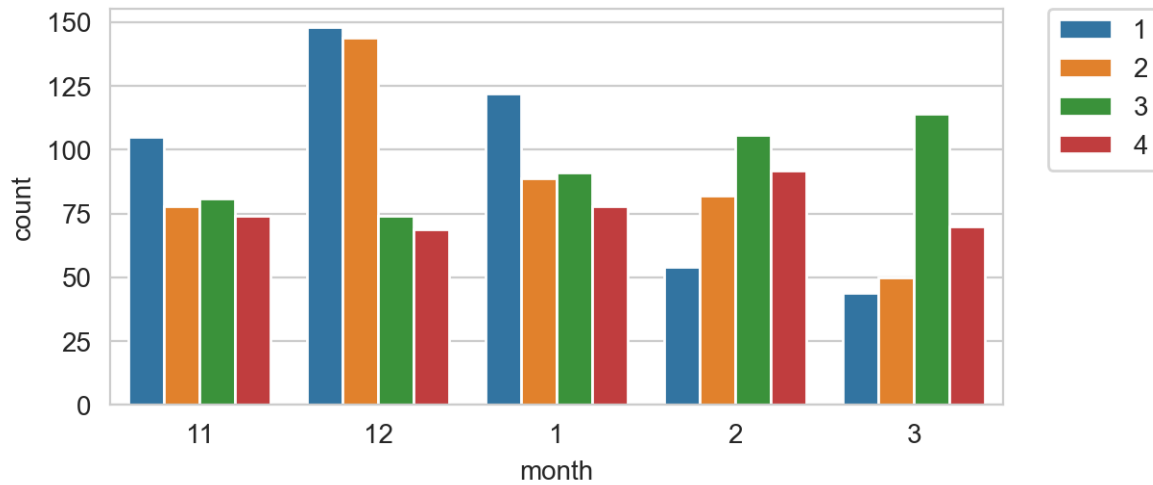


Figure 3.4: Monthly distribution of SALLJ days (1979-2016) by synoptic type: SALLJ 1 (blue), SALLJ 2 (orange), SALLJ 3 (green), and SALLJ 4 (red).

On the other hand, SALLJ 4 occurred on only 6.8% of all NDJFM days, making it slightly less frequent than the other SALLJ types.

3.4.1 Monthly frequencies

The monthly distribution of SALLJ days varies between the four synoptic types. Figure 3.4 shows that SALLJ 1, and to a lesser extent SALLJ 2, are more frequent at the beginning of the warm season (Nov-Jan), whereas SALLJ 3 and SALLJ 4 are more frequent later in the season (Feb-Mar). The maximum number of SALLJ 1 and SALLJ 2 days occur in December, with a total of 148 and 144 days respectively. This is approximately twice the amount of SALLJ 3 and 4 days that occur during the same month. The decreasing frequency of SALLJ 1 and 2 days in late summer is simultaneous with an increase in the frequency of SALLJ 3 and 4 days. The monthly distributions of SALLJ 4 and SALLJ 3 show peak occurrence in February and March, respectively.

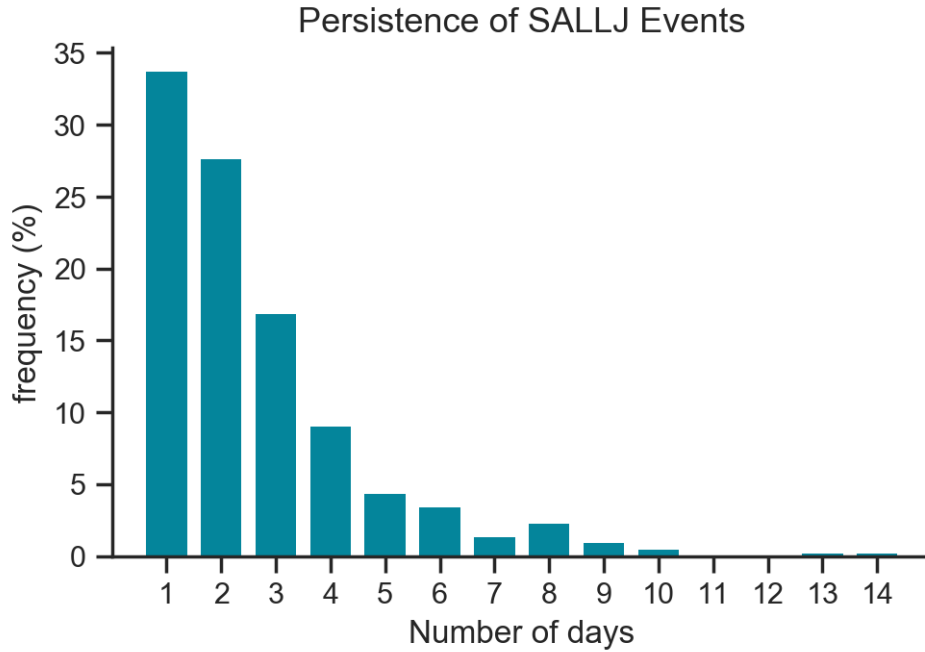


Figure 3.5: Typical duration (in days) of SALLJ events.

3.4.2 Duration and transition probabilities

Figure 3.5 shows the typical duration (in days) of SALLJ events. Approximately 33% of SALLJ occurrences are single-day events, while nearly two-thirds of SALLJ occurrences persist for two or more consecutive days. The average duration of an SALLJ event is 2.5 days. As shown in Figure 3.5, the duration of most SALLJ events ranges between 1 and 4 days, with only 12% of SALLJ events persisting for more than 5 days.

Daily-transition probabilities are used to analyze the temporal evolution of SALLJ events and identify preferred sequences of SALLJ types. The set of SALLJ subtypes represents the available states (1-4) of the system during SALLJ events. An additional state (0) is included to represent non-SALLJ days. Therefore, we can analyze the sequencing of SALLJ subtypes by estimating the daily transition probabilities between synoptic states. For a first order Markov chain, the state of the system at the next time step ($t + 1$) depends only on its state at the current time step (t). Therefore, transition

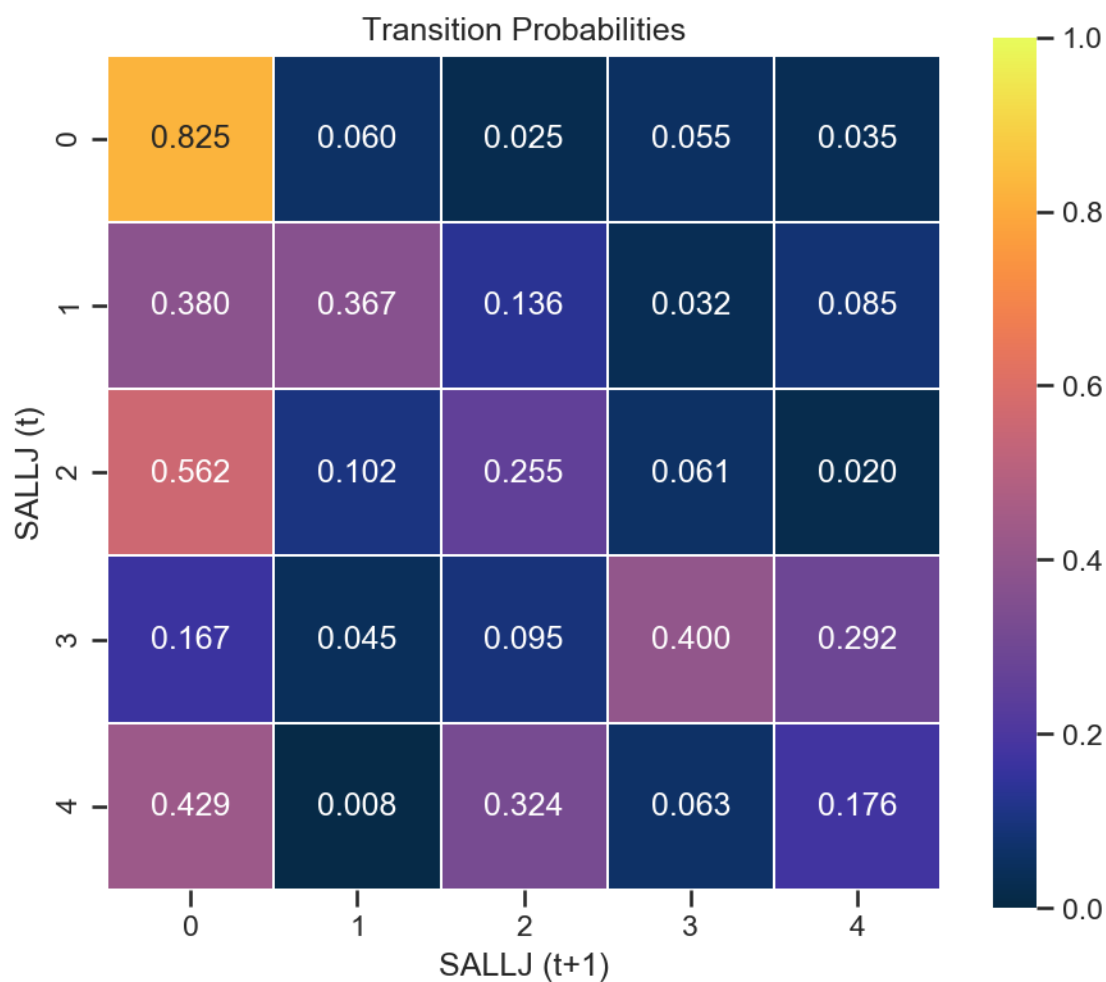


Figure 3.6: Matrix of daily transition probabilities between an initial SALLJ type (vertical axis) and the SALLJ type of the following day (horizontal axis). Type “0” represents days without an SALLJ occurrence. Brighter (darker) colors correspond to higher (lower) probabilities.

probabilities are simply the conditional probability for the state at $t + 1$ given the state at t (Wilks, 2011).

The matrix of daily transition probabilities between SALLJ types is presented in Figure 3.6. Elements of this matrix represent the conditional probabilities of transition from an initial SALLJ type (*vertical axis*) to another SALLJ type the following day (*horizontal axis*). The top row of the matrix represents the probabilities of transitioning from a non-SALLJ day (represented as type “0”) to one of the four SALLJ types. The diagonal of the transition probabilities matrix demonstrate the persistence of each SALLJ type.

Due to the persistence of non-SALLJ days (type 0), the likelihood of transitioning from type 0 to types 1-4 appears low. However, relative transition probabilities reveal that a non-SALLJ day is most likely to transition to SALLJ 1 (34%) or SALLJ 3 (40%). This indicates that SALLJ events are more likely to begin as Type 1 or 3. SALLJ type 1 is most likely to remain in its current state (37%), meaning that the following day will also be type 1, or transition back to a non-SALLJ day (38%). There is also a small probability of transitioning from SALLJ 1 $\rightarrow$ 2 (13.6%).

On the other hand, SALLJ 3 is most likely to persist as type 3 (40%) or transition to SALLJ 4 (29%). Following this sequence, SALLJ 4 is most likely to transition back to a non-LLJ day (43%) or to SALLJ 2 (32%), and SALLJ 2 is most likely to transition back to a non-LLJ day (56%). Therefore, SALLJ events are most likely to begin as either type 1 or 3, while types 2 and 4 are more likely to occur at the end of an SALLJ event. Additionally, SALLJ 3 is the least likely to transition back to a non-SALLJ day (17%). These results suggest a combined sequence of SALLJ 3 $\rightarrow$ 4 $\rightarrow$ 2. In the following sections, we demonstrate that this SALLJ sequence (3 $\rightarrow$ 4 $\rightarrow$ 2) is associated with the northeastward propagation of Rossby waves as they cross the Andes from the extratropical Pacific.

3.5 Synoptic composites of SALLJ types

3.5.1 SALLJ Type 1

SALLJ 1 days are more frequent in the early summer season. Nearly 80% of all SALLJ 1 days occur between the months of November and January. The IVT composite of SALLJ 1 days shows northwesterly moisture transport over Bolivia and the exit region of the jet is located over Paraguay (Figure 3.7a). Compared to the other SALLJ types, the SALLJ 1 is more zonal and does not extend in the subtropical portion of the LPB. Furthermore, the IVT composite of SALLJ 1 reveals strong northerly moisture transport along the eastern slopes of tropical Andes between (Figure 3.7a).

The upper-level composite of SALLJ 1 days (Figure 3.10a) shows a relatively flat, weak jet stream over subtropical South America. Unlike the other types of SALLJ days, upper-level jet streaks are not present. At low levels, Figure 3.8a shows a thermal low-pressure center located just east of the Andes near 20° S. Cyclonic flow around the surface low strengthens the northwesterly SALLJ and warm air advection over Bolivia and Paraguay.

The precipitation composite shows a broad region of moderate rainfall over Brazil, with an area of light rainfall extending into subtropical SA (Figure 3.11a). Precipitation develops behind the leading edge of the warm and moist air advection associated with the SALLJ. Notably, enhanced precipitation is also evident in the region of the South Atlantic Convergence Zone (SACZ) – a quasi-stationary NW-SE oriented band of convection that extends from the Amazon to the South Atlantic (Carvalho et al., 2004). The SACZ is only active during summer months and is known to exhibit a classic dipole relationship with the SALLJ and subtropical precipitation (i.e., when the SACZ is active, convection is suppressed over the La Plata Basin and vice versa). Therefore, SALLJ 1

could represent a transitional phase to or from an active SACZ.

3.5.2 SALLJ Type 2

The IVT composite of SALLJ 2 days shows a northwesterly SALLJ that extends from western Bolivia to southern Brazil (Figure 3.7b). For SALLJ 2, the exit region of the jet is located over the Triple Border region of Argentina, Brazil, and Paraguay. Although the core of the SALLJ is located over Bolivia, Figure 3.7b shows a secondary area of moisture convergence over the South Atlantic near 35°S, 35°W.

As shown in Figure 3.10b, there is an upper-level trough east of subtropical South America with an axis around 50°W. The trough is associated with an upper-level jet streak over the South Atlantic. Notably, the left entrance of the jet streak is located over the La Plata Basin, just south of the Triple Border region. In the Southern Hemisphere, the left entrance region of a jet streak is associated with upper-level divergence and low-level convergence. This provides enhanced dynamical support for convection in this region. Further explanation of the dynamical mechanism that couples the SALLJ and upper-level jet streaks is provided in Appendix A.

The composites of mean sea-level pressure reveals a deep low-level trough with its axis near 40°W (Figure 3.8b). As shown in Figure 3.8b, this trough is associated with an extratropical low-pressure center over the South Atlantic. Furthermore, Figure 3.8b shows warm air advection that extends from Bolivia towards southern Brazil and the South Atlantic along the axis of the SALLJ. At the same time, cold air advection dominates over southern and central Argentina. The composite of thickness anomalies reveals strong thermal contrasts over the subtropics, which mark the location of frontal boundaries (Figure 3.9b).

Figure 3.11b shows a precipitation maximum over the Triple Border region. This

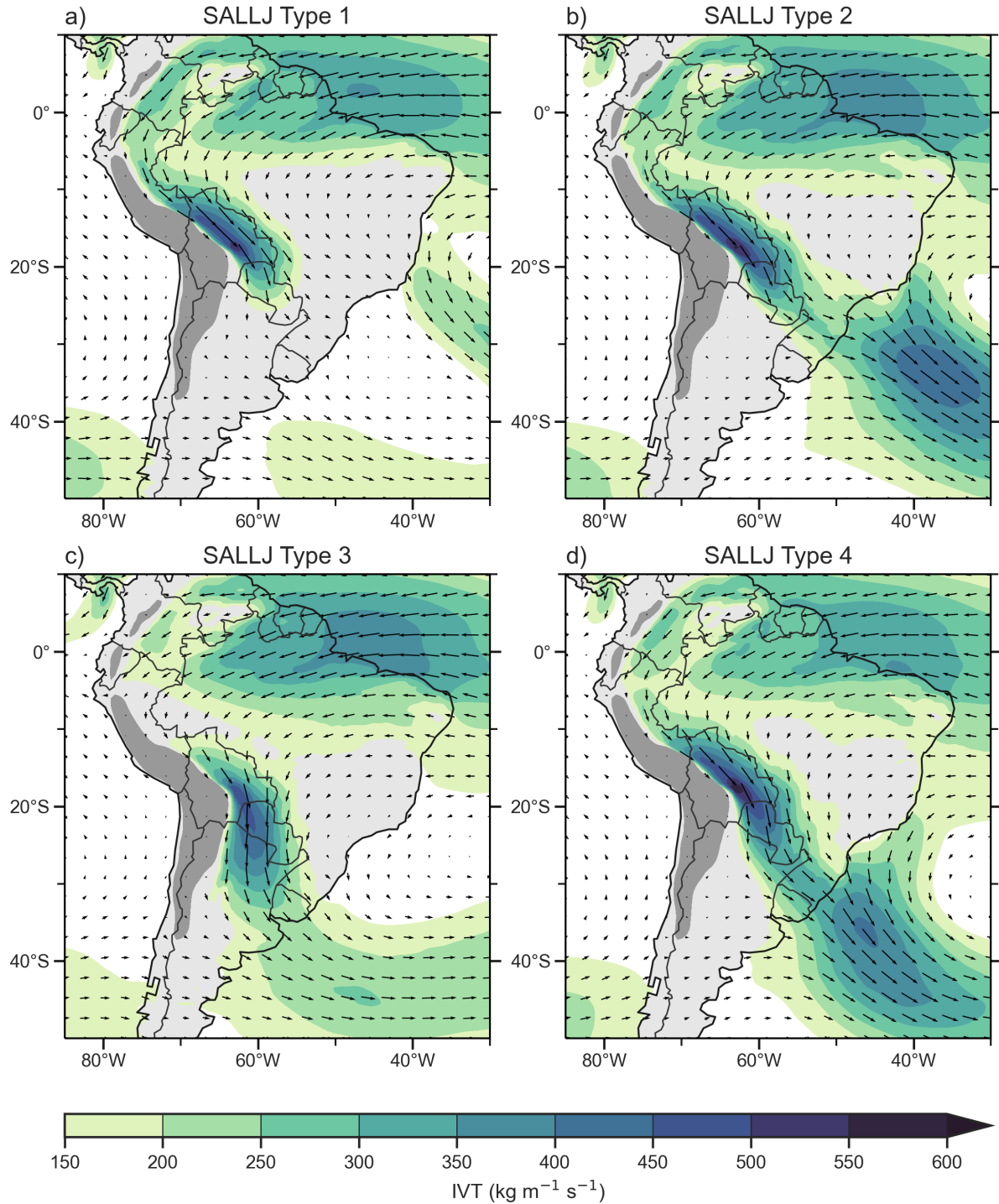


Figure 3.7: Composites of vertically integrated vapor transport (IVT) vectors and IVT magnitude ($\text{kg m}^{-1} \text{s}^{-1}$) for each SALLJ type. Color shading of IVT magnitude begins at the $200 \text{ kg m}^{-1} \text{s}^{-1}$ contour. Dark gray shading indicates topography above 1,500 m.

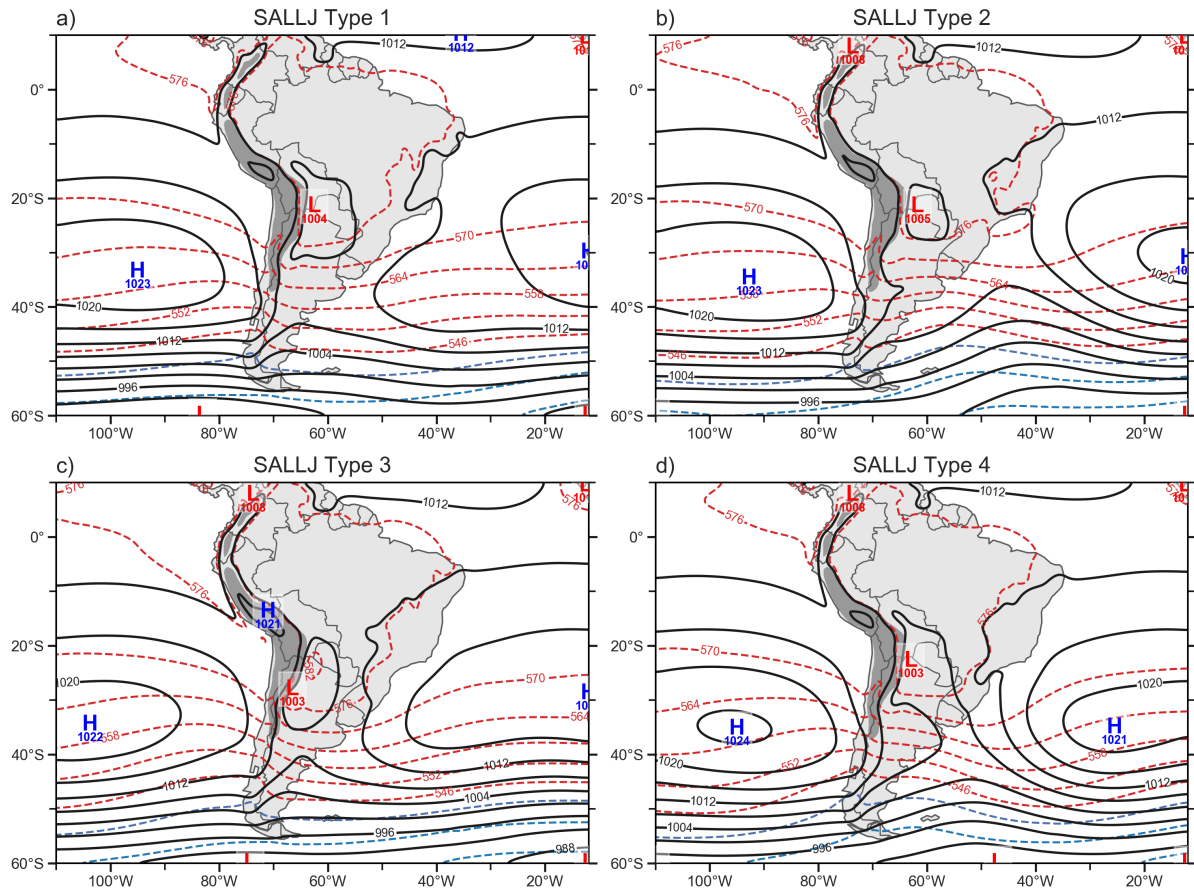


Figure 3.8: Composites of mean sea-level pressure (MSLP; black contours; hPa) and 1000-500 hPa thickness (red/blue dashed contours; $\text{m} \cdot 10^{-1}$) for each SALLJ type. High and low pressure centers are marked with the letters 'H' and 'L', respectively. Red (light blue) thickness contours represent areas of warmer (colder) air in the lower atmosphere. The dark-blue dashed line represents the 540-thickness contour (5,400 meters thick), which is approximately the point where precipitation changes from rain to snow. Dark gray shading indicates topography above 1,500 m.

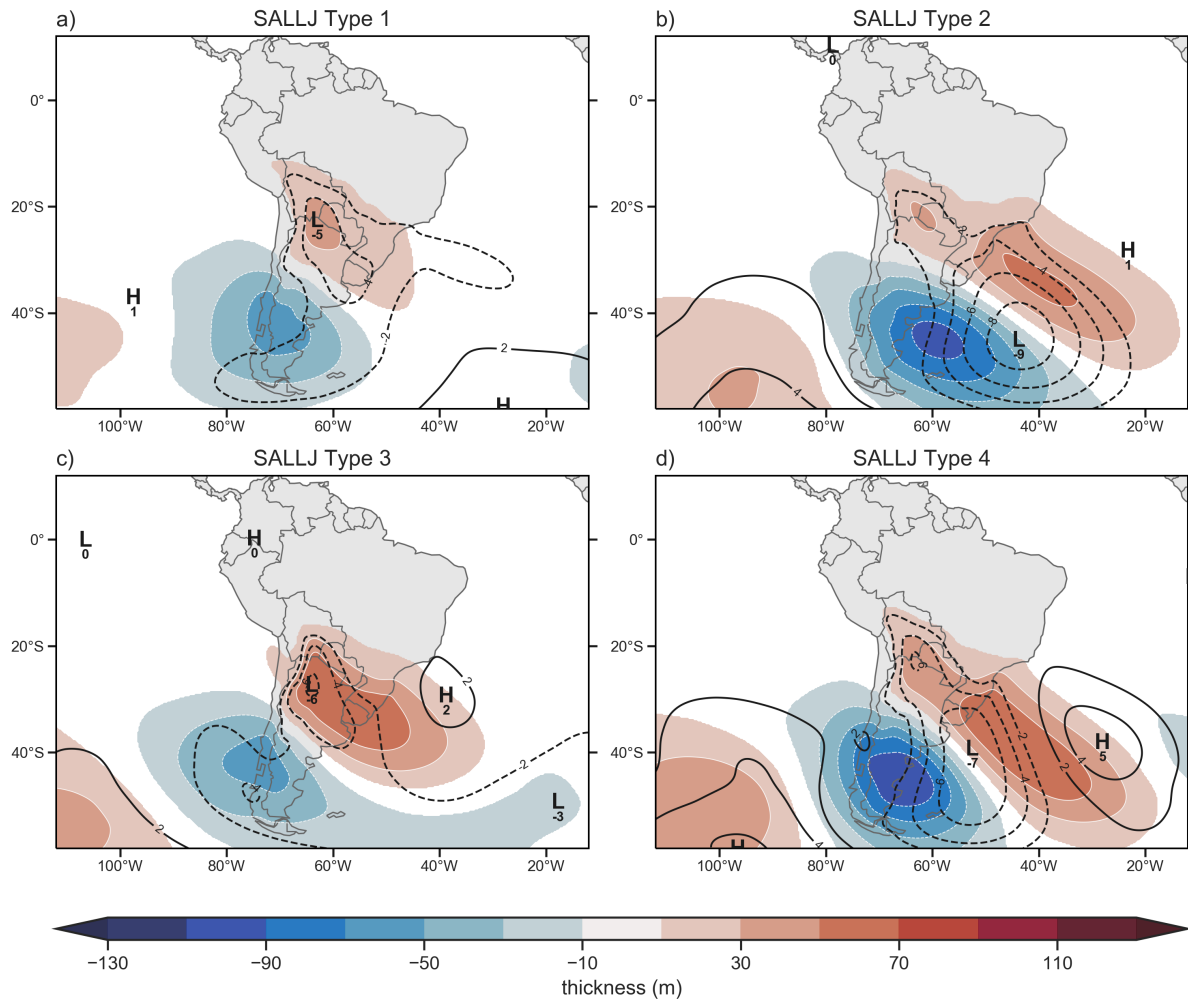


Figure 3.9: Composites of MSLP anomalies and 1000-500 hPa thickness anomalies for each SALLJ type. Red (blue) shading indicates positive (negative) thickness anomalies, which represent areas of warmer (colder) air in the lower atmosphere. Black solid (dashed) lines indicate positive (negative) MSLP anomalies. High and low pressure centers are marked with the letters 'H' and 'L', respectively.

precipitation is likely fueled by an influx of warm, humid, unstable air by the SALLJ. Convection is located on the leading edge of the cold front and is likely strengthened by the presence of the upper-level jet streak. A second, weaker precipitation maximum is located over the South Atlantic behind the warm front. Meanwhile, cold air advection inhibits convection over southern SA (Figure 3.9b).

3.5.3 SALLJ Type 3

SALLJ type 3 is characterized by strong, northerly moisture transport from Bolivia into central Argentina. As shown in Figure 3.7c, SALLJ 3 has the greatest meridional extension, with an exit region located south of 30°S over Argentina and Uruguay. The poleward elongation of SALLJ type 3 is driven by the transient deepening of the northwestern Argentinian low (NAL). Located on the eastern slopes of the Andes near 30°S (Figure 3.8c), the deepening of the thermal-orographic NAL is primarily driven by surface heating and subsidence of upper-level flow as it crosses the Andes (Seluchi et al., 2003). Additionally, Figures 3.8c and 3.9c show that the western branch of the South Atlantic subtropical high is strengthened over the continent. This enhances the east-west pressure gradient and reinforces northerly flow over the La Plata Basin.

An upper-level trough is located upstream of the Andes around 80°W (Figure 3.10c). This is associated with an upper-level jet streak centered at 45°S, 50°W. The anticyclonic flank of the jet streak is located over central Argentina and Uruguay. At low levels, a weak polar trough is present over the southern tip of South America (Figure 3.8c). Maps of thickness anomalies (Figure 3.9c) show that warm air advection dominates over La Plata Basin during a type 3 event.

Figure 3.11c shows a large precipitation maximum located in central Argentina around 32°S, 62°W. The circular shape of the rainfall maximum and subtropical loca-

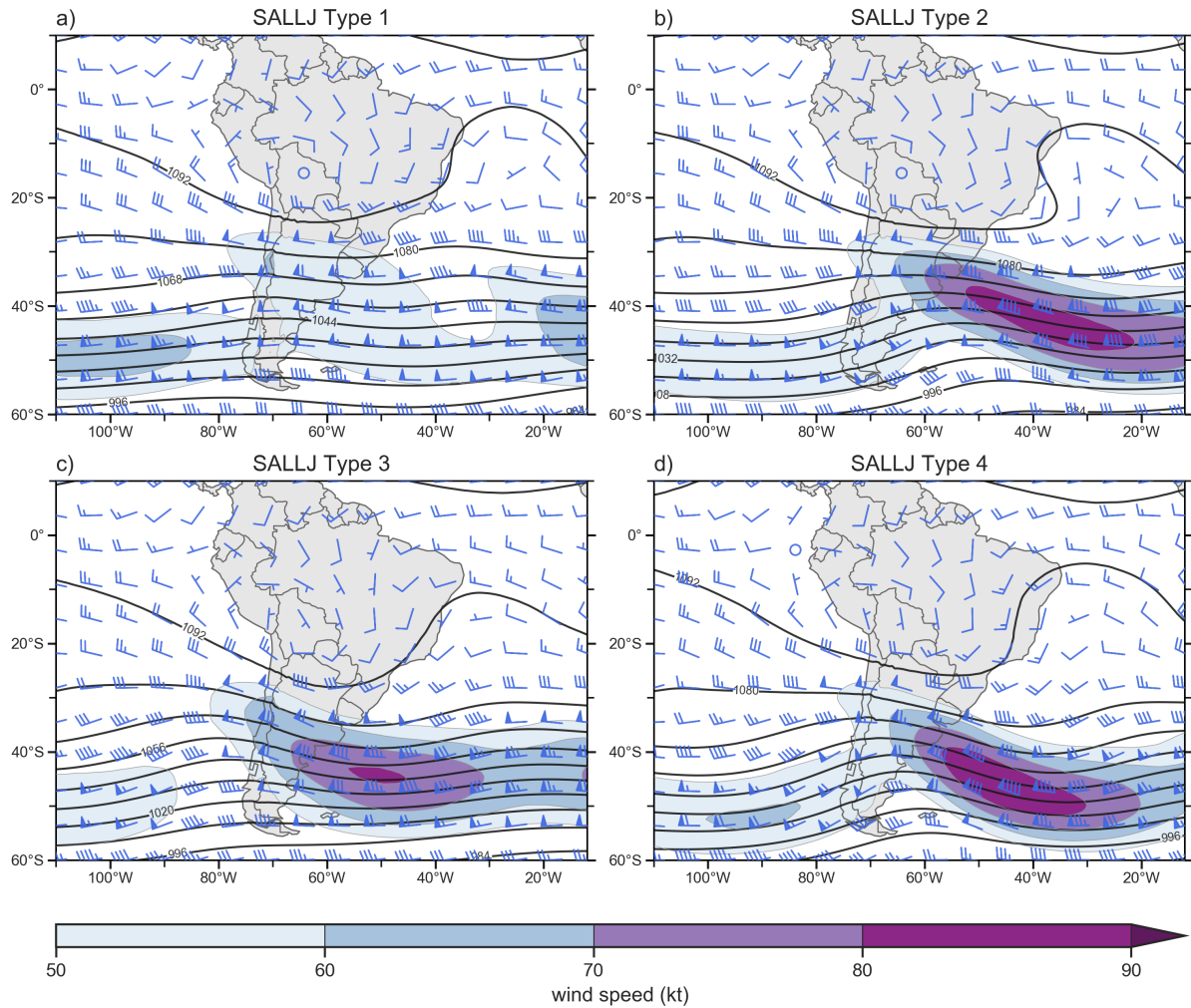


Figure 3.10: Composites of 250-hPa geopotential height (black contours; $\text{m} \times 10^{-1}$), isotachs (purple shading; knots), and wind barbs for each SALLJ type. Isotachs begin at 50 knots in order to better identify upper-level jet streaks.

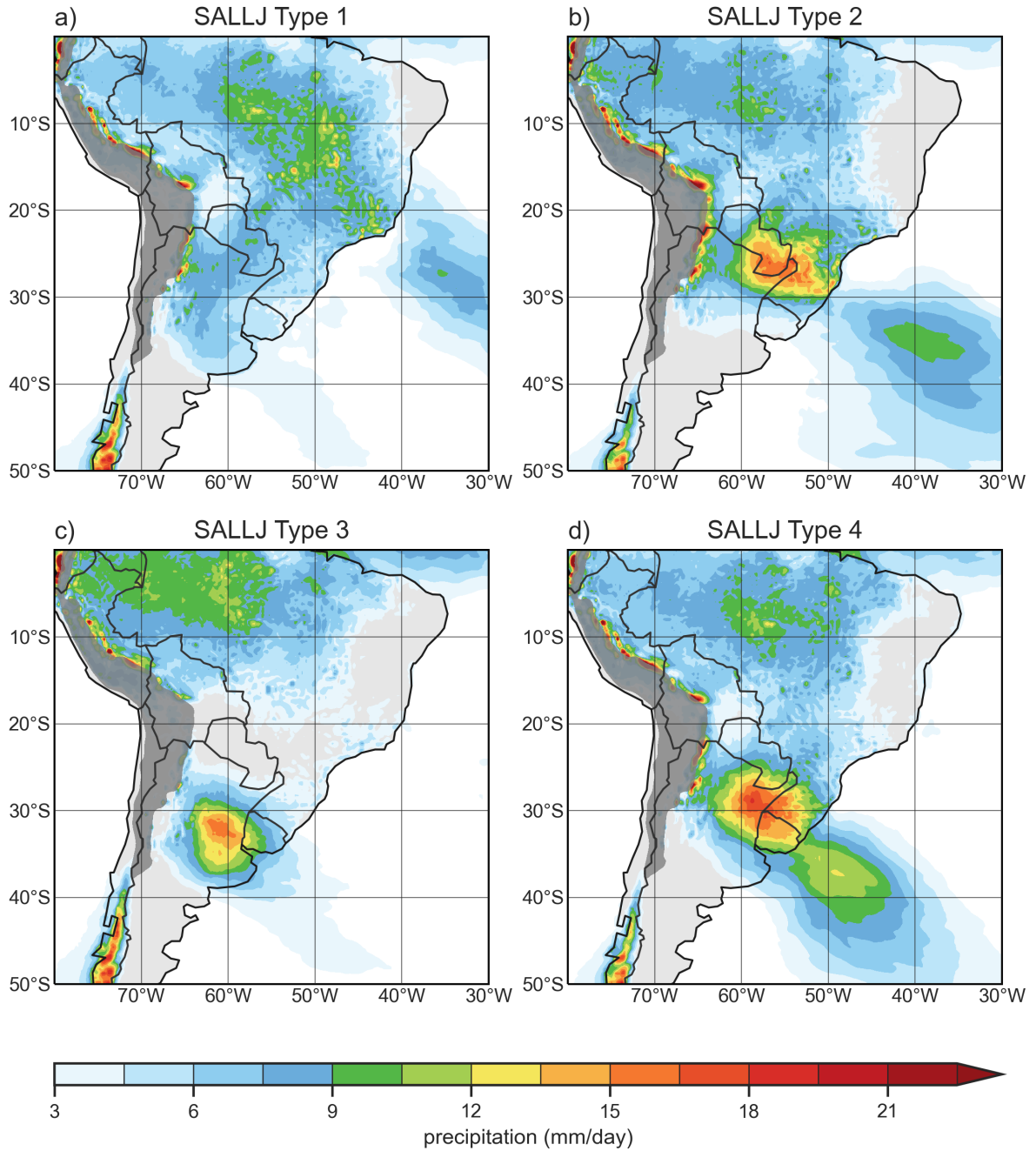


Figure 3.11: Composites of daily accumulated precipitation (mm day⁻¹) for each SALLJ type. The gray shading indicates topography above 1,500 m.

tion suggests that SALLJ 3 events are associated with the development of Mesoscale Convective Complexes (Durkee & Mote, 2010; Velasco & Fritsch, 1987). This type of storm is fueled by the propagation of a cold front from southern Argentina and the convergence of the warm, moist air at the exit region of the SALLJ. Deep convection is sustained by upper-level divergence associated with the left entrance region of the upper-level jet streak .

3.5.4 SALLJ Type 4

SALLJ type 4 resembles an intermediate phase between SALLJ 3 and SALLJ 2. The IVT composite (Figure 3.7d) shows northwesterly moisture transport over Bolivia, which becomes more northerly south of 20°S. During an SALLJ 4 event, the exit region of the jet is located over southern Brazil/northern Uruguay. Similar to SALLJ 2, a second area of moisture convergence is evident over the South Atlantic ocean.

An upper-level trough is present just east of the Andes, with an axis around 65°W (Figure 3.10d). The trough is associated with a strong upper-level jet streak, with the left-entrance region over Uruguay. Mean-sea level pressure anomalies reveal a midlatitude cyclone located just off the east coast of South America (Figure 3.9d). Thickness anomalies reveal areas of strong baroclinicity over central Argentina and the South Atlantic (indicative of cold and warm frontal boundaries, respectively).

Figure 3.11d shows a large, circular precipitation maximum located over northwestern Argentina and Uruguay. The intensity and size of the precipitation maximum is greater than during any other type of SALLJ day. Similar to the precipitation associated with SALLJ 3, the large, circular shape suggests a mature MCC (Velasco & Fritsch, 1987). The MCC is located on the leading edge of the cold front, while a secondary precipitation maximum is located over the South Atlantic and is likely associated with

the passage of a warm front.

3.6 Remote forcing

Figure 3.12 shows the large-scale evolution of upper-level circulation anomalies for the days proceeding and concurrent with the four types of SALLJ events. There is evidence of a midlatitude wave train over the South Pacific three days prior to an SALLJ type 2, 3, or 4 day (Figures 3.12c,e,d). The wave train approaches South America from the west, then turns northeastward after crossing the Andes. For each of these SALLJ types (2-4), the upstream centers of the wave train are stronger and possess more barotropical features in the days proceeding the actual SALLJ event. However, these features change to baroclinic as the wave passes over the Andes mountains. According to Vera et al. (2002), the main structure of midlatitude waves changes as they cross the Andes from the South Pacific Ocean. These changes involve the decoupling of upper and lower level anomalies on the lee side of the mountains, with the low-level anomalies turning abruptly towards the equator and upper-level anomalies continuing eastward. This produces a more favorable baroclinic structure and intensifies the low-level cyclone over the subtropics (Vera et al., 2002).

As shown in Figure 3.12 (d,f,h), a pair of cyclonic/anticyclonic anomalies strengthen over the continent on the actual the day of SALLJ type 2, 3, and 4 events. Meanwhile, the upstream wave centers weaken on the day of the SALLJ event. A similar evolution of circulation anomalies was presented by Liebmann et al. (2004) for the days leading up to heavy rainfall events in the exit region of the SALLJ. However, instead of comparing the circulation features proceeding an active SALLJ to those of an active SACZ (Liebmann et al., 2004), our study focuses on identifying differences in circulation anomalies between the four types of SALLJ events.

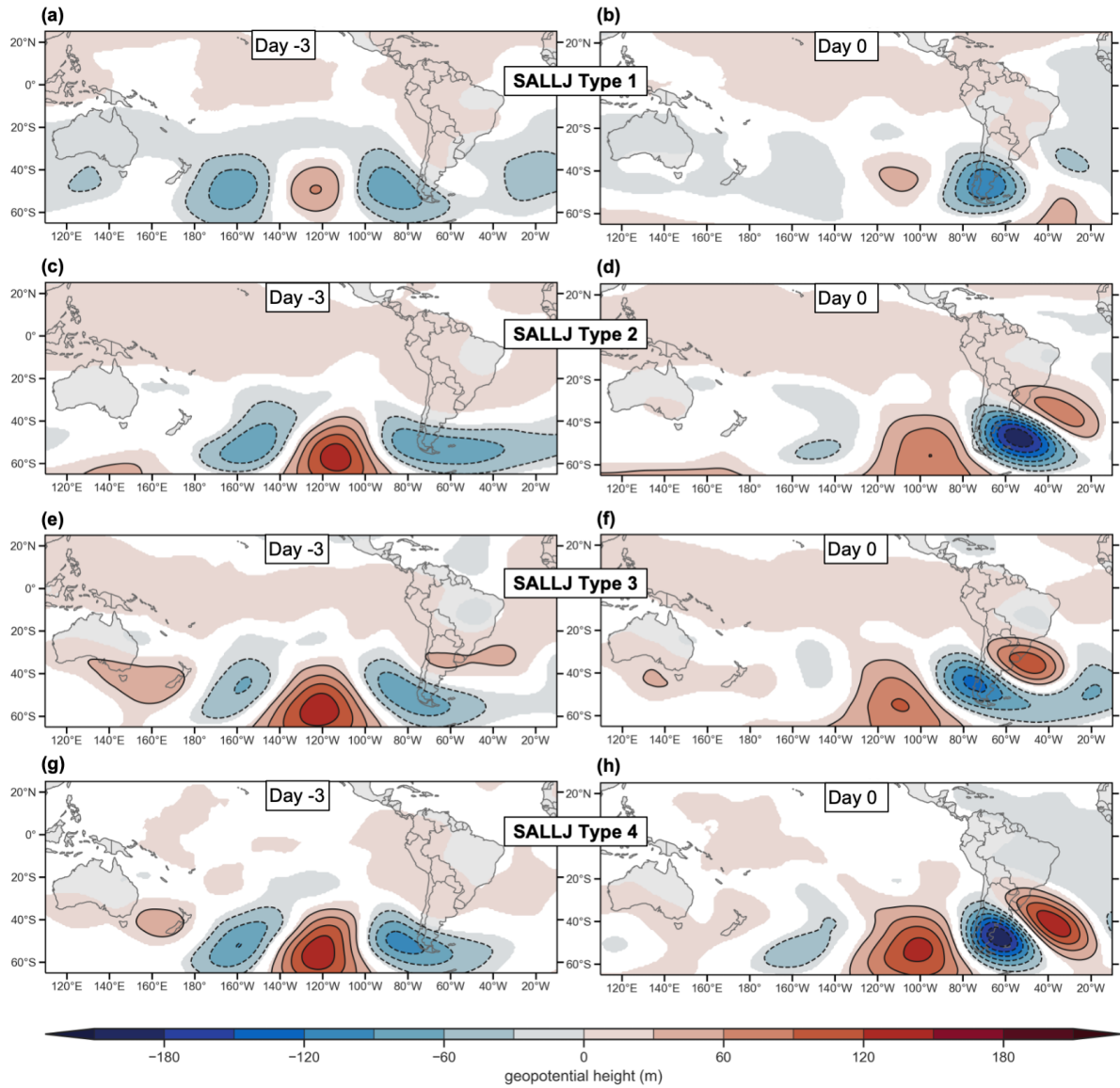


Figure 3.12: Composites of 250-hPa geopotential height anomalies three days prior to an SALLJ event (*left column*) and on the day of the SALLJ event (*right column*).

Based on Figure 3.12, the main difference between SALLJ types 2, 3, and 4 is the location of the upper level cyclonic/anticyclonic anomaly pair over the continent with respect to the Andes. For example, on the day of an SALLJ type 3 event, the center of the cyclonic anomaly is located just west of the Andes while the anticyclonic anomaly is located over southeastern South America (Figure 3.12f). On the day of an SALLJ type 4 event, the upper-level cyclonic anomaly is located just east of the Andes over the tip of South America (Figure 3.12h) and on the day of an SALLJ type 2 event, it's located just east of the continent over the South Atlantic (Figure 3.12d). The eastward progression of the upper-level cyclonic anomaly follows the preferred sequencing of SALLJ events discussed in the previous section from SALLJ 3 $\rightarrow$ 4 $\rightarrow$ 2. These results suggest that the wave train strengthens the upper-level subtropical jet over South America, which modulates the exit region of the SALLJ and in turn, the location of convection and precipitation.

Unlike SALLJ types 2-4, there is no evidence of a midlatitude wave train on the day of an SALLJ type 1 event (Figure 3.12b). Three days prior to an SALLJ 1 event, a weak wave train is observed over the South Pacific (Figure 3.12a), but it nearly dissipates by the day of the SALLJ event. The only remnant of the wave train on the day of an SALLJ 1 event is an upper-level cyclonic anomaly over the southern tip of South America (Figure 3.12b). However, unlike the other types of SALLJ events, there is no anticyclonic anomaly over southeastern South America or the South Atlantic. This is in agreement with the weaker upper-level subtropical jet, as well as lighter precipitation on SALLJ 1 days.

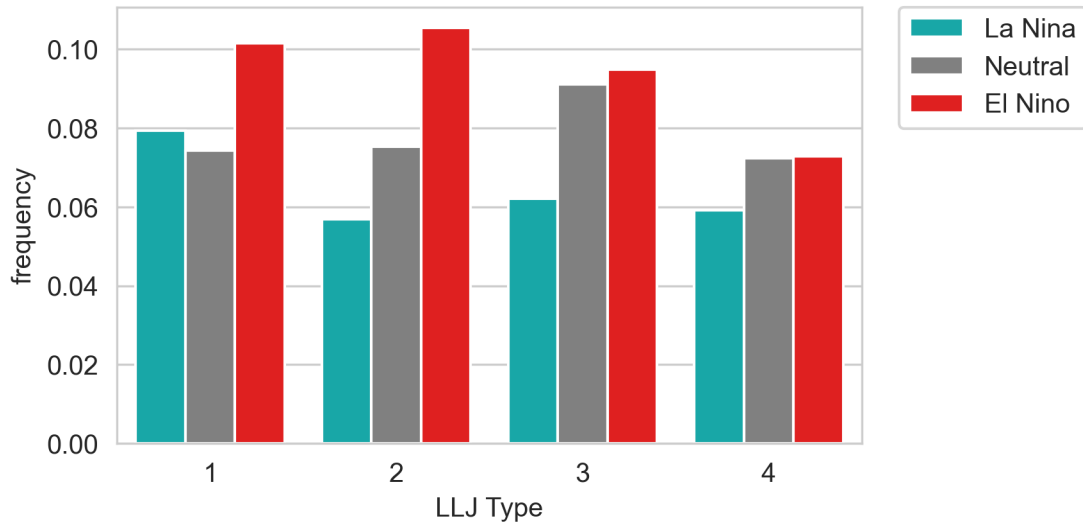


Figure 3.13: Relative frequencies of each SALLJ type during the warm (red bars), cold (blue bars), and neutral (grey bars) phases of ENSO (November-March, 1979-2016).

3.7 Subseasonal-to-seasonal variability

This section investigates the effect of large-scale climate drivers on the frequency of occurrence of SALLJ types. On seasonal time scales, we explore the effects the ENSO and on subseasonal time scales we explore the effects of the MJO. Despite their variability at different time scales, the occurrence of ENSO and MJO often overlaps. For example, the seasonal signal from ENSO may be enhanced or weakened when it occurs simultaneously with the MJO. Therefore, it is important to analyze both the individual and the combined effects of ENSO and MJO phases on the frequency of SALLJ types.

The relative frequency of each SALLJ type is shown for the warm, cold, and neutral phases of ENSO in Figure 3.13. Evidently, all four types of SALLJ days occur more frequently during El Niño and less frequently during La Niña. This is in agreement with our findings on the relationship between ENSO and SALLJ frequency presented in Chapter 2. Here, we apply the same significance testing for the difference in proportions of SALLJ days between El Niño/La Niña and neutral phases to the individual

SALLJ types (z -score, $\alpha = 0.05$). As a result, the proportions of SALLJ 1 and SALLJ 2 days are significantly greater during El Niño than during neutral conditions. Meanwhile, SALLJ types 2 and 3 are significantly less frequent during La Niña compared to neutral conditions. Overall, the frequency of SALLJ 2 varies the greatest with ENSO, whereas SALLJ 4 exhibits the least ENSO-related variability.

Figure 3.14 shows anomalous frequencies of SALLJ types for the active (1-8) and inactive (0) phases of MJO. For each MJO phase, anomalies are computed by comparing the relative frequency of a given SALLJ type to its mean seasonal frequency over the climatological period (NDJFM, 1979-2016). Figure 3.14 shows that both SALLJ 3 and SALLJ 4 occur more frequently during MJO phase 5, when convection is enhanced over Indonesia. On the other hand, SALLJ type 1 occurs more frequently during MJO phase 3, which is associated with enhanced convection over the Indian Ocean. The occurrence of SALLJ 2 favors MJO phases 3 and 6. This makes sense in terms of the daily sequencing patterns of SALLJ events discussed in section 3.4, as SALLJ 2 is most likely to follow SALLJ 1 ($1 \rightarrow 2$) or SALLJ 4 ($3 \rightarrow 4 \rightarrow 2$). In general, SALLJ days are less frequent during MJO phases 1 and 8, when convection is suppressed over Indonesia.

Next, we examined the combined effect of ENSO and MJO phases on the occurrence of SALLJ types. Figure 3.15 shows that during El Niño conditions, SALLJ 1 occurs more frequently during MJO phase 3, while SALLJ 3 occurs more frequently during MJO phases 5 and 6. Figure 3.15 shows that SALLJ 2 occurs more frequently during El Niño for nearly all phases of MJO, which supports the strong relationship between ENSO and the frequency of SALLJ 2 events discussed at the beginning of this section. Lastly, SALLJ 4 occurs more frequently during MJO phases 2 and 5 in El Niño years, but is less frequent during MJO phase 7 + El Niño.

During La Niña conditions, SALLJ events are less frequent in nearly all MJO phases.

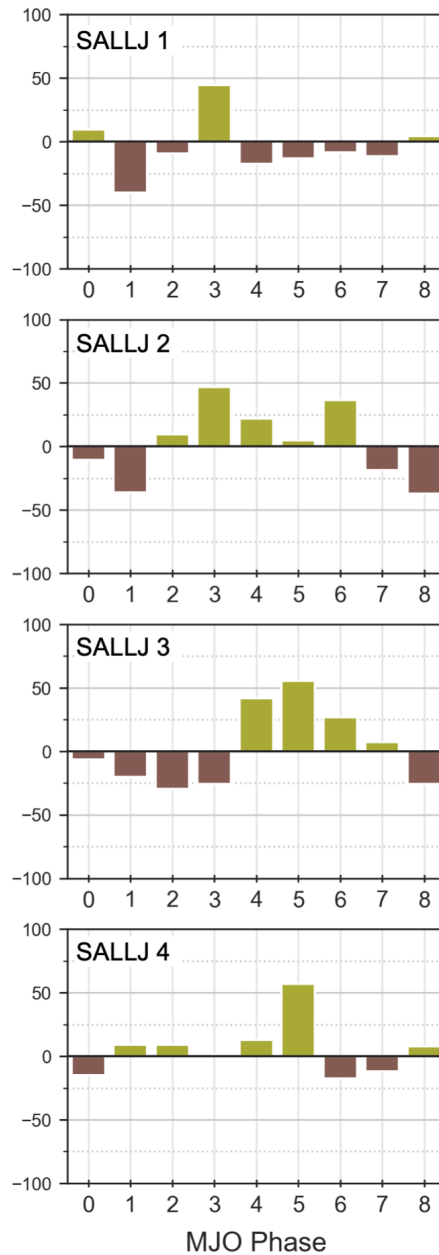


Figure 3.14: Anomalous frequencies of each SALLJ type for each phase of MJO. A value of 100% indicates that the given SALLJ type occurs twice as frequently compared to its climatological mean; -100% indicates no occurrence of the given SALLJ type; 0% indicates no determinable effect on SALLJ frequency (i.e., SALLJ frequency is equal to its climatological mean).

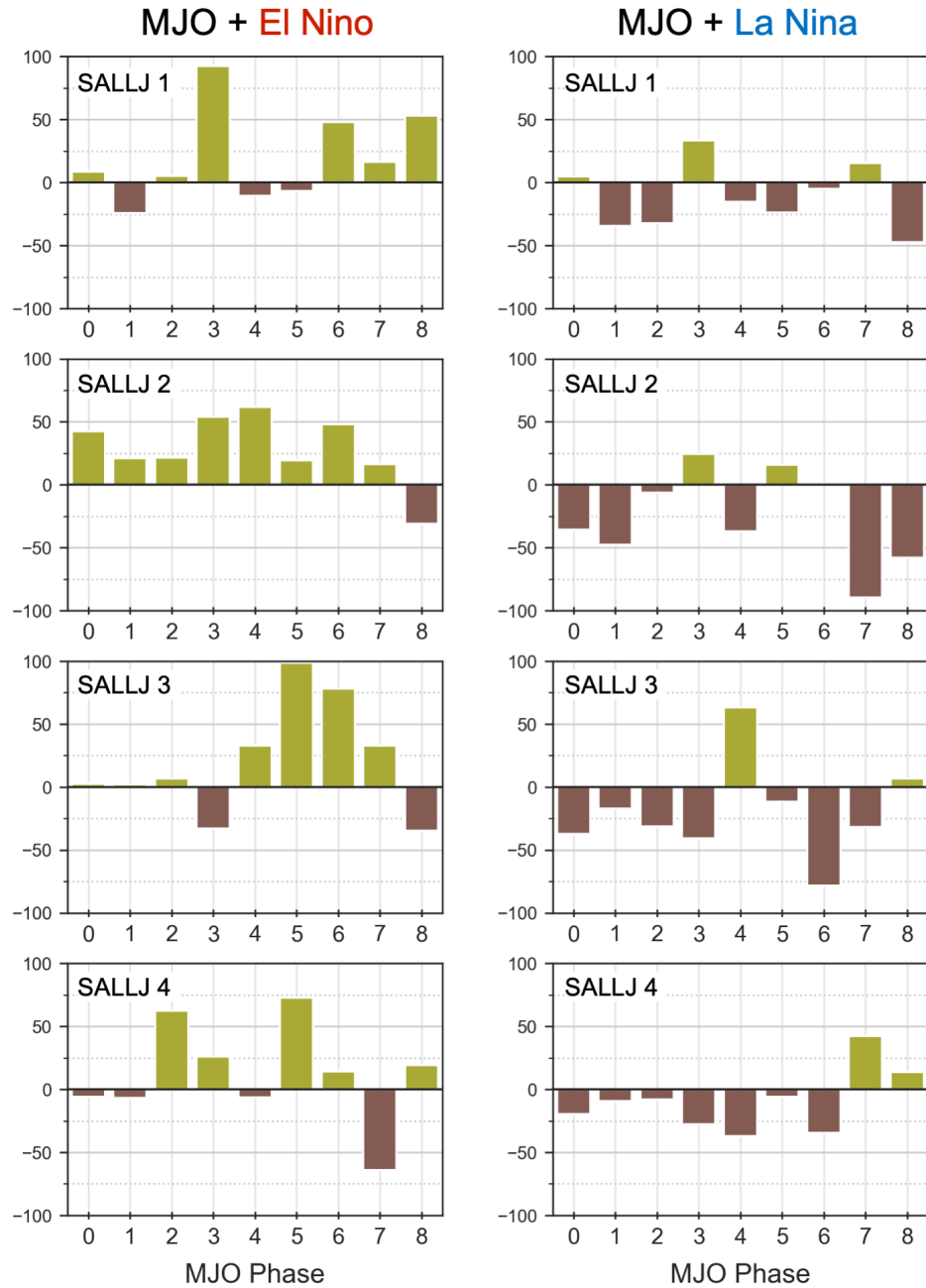


Figure 3.15: Same as in Figure 3.14, but the anomalous frequency of SALLJ types for each phase of MJO is computed during El Niño (*left column*) and La Niña (*right column*) events.

Figure 3.15 shows that the frequency of SALLJ 2 events is greatly suppressed by the combined effect of La Niña and MJO phases 7 and 8. Similarly, the combination of La Niña + MJO phase 6 reduces the frequency of SALLJ 3. However, SALLJ 3 days are actually more frequent during La Niña + MJO phase 4. In this case, the MJO signal dominates the background signal from ENSO.

3.8 Summary

This chapter examines synoptic circulation regimes that modulate the intensity and position of the SALLJ, and explores sources of variability on subseasonal to seasonal time scales. The framework of a weather typing analysis was used to identify a set of four distinct circulation patterns from 1,765 warm-season SALLJ days (November–March, 1979–2016). Principal components analysis was applied to the moisture transport fields of the SALLJ days and k-means clustering was performed in the subspace defined by the leading EOFs. The clustering algorithm objectively categorizes SALLJ days into four distinct subtypes, which are referred to as SALLJ types 1–4.

Separate composites of SALLJ types revealed both similarities and differences in the circulation and precipitation fields. Most notable are the differences between SALLJ 1 and SALLJ 3. During an SALLJ type 1 event, the moisture flux associated with the jet is more zonal and is restricted to tropical latitudes over Bolivia and Paraguay; additionally, the light, widespread precipitation suggests that SALLJ 1 events are not likely associated with the formation of a large MCS. This finding is also supported by the absence of a cold front and weak support at upper levels. On the other hand, the meridional component of low-level flow dominates on SALLJ 3 days, when the low-level moisture flux penetrates farthest south into Argentina. During an SALLJ 3 day, the influx of warm, moist air interacts with a frontal boundary to initiate cyclogenesis,

forming an MCS and precipitation maximum over central Argentina. As the frontal system pushes northeastward on the following day, the MCS and precipitation strengthen over northeastern Argentina and Uruguay (SALLJ 4), and may even advance as far northward as Paraguay and southern Brazil (SALLJ 2).

Our analysis of the persistence and transitions of SALLJ types demonstrated the preferred sequencing of SALLJ types from $3 \rightarrow 4 \rightarrow 2$, which is consistent with the northeastward migration of an extratropical cyclone and baroclinic front from southern South America. These findings are also consistent with the passage of a midlatitude Rossby wave train and the evolution of its associated circulation anomalies in the days proceeding a SALLJ 2-4 events. Another sequence of SALLJ types identified by the transition matrix is $1 \rightarrow 2$, which suggests a strengthening of a zonally-oriented SALLJ event. In this case, heavy precipitation over Paraguay/southern Brazil develops on the second day or later of an SALLJ event, consistent with the transition to SALLJ type 2.

Several aspects of the resulting SALLJ types (and the composites generated therein) are noteworthy within the context of past studies of the types of SALLJ events. Specifically, Salio et al. (2002) differentiated between SALLJ events that penetrate south of 25°S – i.e., "Chaco Jet Events" vs "Non-Chaco Jet Events". It should be noted that SALLJ 3 and SALLJ 1 have similar characteristics to Chaco Jet Events and Non-Chaco Events, respectively. However, this study presents two additional SALLJ archetypes, SALLJ 2 and SALLJ 4, which represent intermediate patterns of the zonal and meridional extreme cases. Differences in the location and intensity of precipitation associated with SALLJ 2 and SALLJ 4 days highlights the importance of identifying all four SALLJ types.

To explore the variability of SALLJ types, we analyzed the relationship between large-scale climate drivers and the frequency of SALLJ types. Our results shows that the year to year occurrence of SALLJ types is influenced by ENSO, where the warm phase of ENSO increases the frequency of all SALLJ types. Furthermore, we found that

ENSO has the greatest impact on the frequency of SALLJ 2, which is characterized by northwesterly moisture flux towards southern Brazil. This result is in agreement with moisture flux anomalies of SALLJ events during El Niño events from Chapter 2, which showed enhanced northwesterly moisture transport towards southern Brazil during SON and MAM.

On subseasonal time scales, the frequency of SALLJ types is influenced by MJO. Unlike the uniform response of SALLJ frequency to ENSO, there are notable differences among SALLJ types and their relationship with phases of MJO. Specifically, phase 5 of MJO is associated with an increased frequency of northerly jet events (SALLJ 3 and 4), while phase 3 of MJO is more conducive to zonally-oriented jet events (SALLJ 1 and 2). In general, the effects of MJO on SALLJ frequency are enhanced during the warm phase of ENSO. The combination of MJO phase 5 + El Niño is particularly favorable to SALLJ 3 and 4 activity. This information has important implications for subseasonal to seasonal predictions of precipitation over SESA.

For example, a study by Doss-Gollin et al. (2018) examined the regional climate drivers of the persistent and heavy rainfall events in summer 2015/16 that led to severe flooding of the Paraguay River and displaced approximately 170,000 people in Paraguay, Argentina, and southern Brazil. They found that these devastating events were associated with enhanced SALLJ activity, a strong El Niño, and an active MJO in phases 4-5. Furthermore, they suggest that the simultaneous use of seasonal and sub-seasonal predictions of heavy rainfall could have provided decision makers with useful information about the start of these flooding events two to four weeks in advance.

Physically, large-scale climate drivers such as ENSO and MJO modulate the occurrence of SALLJ types through the passage of circulation anomalies associated with extratropical Rossby wave trains, which originate from anomalous heat sources in the tropical Pacific (Grimm & Ambrizzi, 2009). Liebmann et al. (2004) showed that the

location of precipitation is determined by the phase of the wave train as it crosses the Andes. Similarly, the results of this analysis demonstrate that the phase of the wave crossing the Andes modulates the type of SALLJ event, which ultimately helps determine the exit region of the jet and subsequently, the location and intensity of convection and precipitation.

References

- Carvalho, L. M., Jones, C., & Liebmann, B. (2004). The south atlantic convergence zone: Intensity, form, persistence, and relationships with intraseasonal to interannual activity and extreme rainfall. *Journal of Climate*, 17(1), 88–108.
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., ... Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553–597. <https://doi.org/10.1002/qj.828>
- Doss-Gollin, J., Muñoz, Á. G., Mason, S. J., & Pastén, M. (2018). Heavy rainfall in paraguay during the 2015/16 austral summer: Causes and subseasonal-to-seasonal predictive skill. *Journal of Climate*, 31(17), 6669–6685.
- Durkee, J. D., & Mote, T. L. (2010). A climatology of warm-season mesoscale convective complexes in subtropical South America. *International Journal of Climatology*, 30(3). <https://doi.org/10.1002/joc.1893>
- Durkee, J. D., Mote, T. L., & Shepherd, J. M. (2009). The contribution of mesoscale convective complexes to rainfall across subtropical South America. *Journal of Climate*, 22(17). <https://doi.org/10.1175/2009JCLI2858.1>
- Grimm, A. M. (2003). The El Nino impact on the summer monsoon in Brazil: Regional processes versus remote influences. *Journal of Climate*, 16(2), 263–280.
- Grimm, A. M., & Ambrizzi, T. (2009). Teleconnections into south america from the tropics and extratropics on interannual and intraseasonal timescales. *Past climate variability in south america and surrounding regions* (pp. 159–191). Springer.
- Grimm, A. M., & Tedeschi, R. G. (2009). ENSO and extreme rainfall events in South America. *Journal of Climate*, 22(7), 1589–1609. <https://doi.org/10.1175/2008JCLI2429.1>

- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., et al. (2020). The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049.
- Jones, C. (2009). A homogeneous stochastic model of the madden–julian oscillation. *Journal of Climate*, 22(12), 3270–3288.
- Jones, C., Waliser, D. E., Lau, K., & Stern, W. (2004). Global occurrences of extreme precipitation and the madden–julian oscillation: Observations and predictability. *Journal of Climate*, 17(23), 4575–4589.
- Liebmann, B., Kiladis, G. N., Vera, C. S., Saulo, A. C., & Carvalho, L. M. (2004). Sub-seasonal variations of rainfall in south america in the vicinity of the low-level jet east of the andes and comparison to those in the south atlantic convergence zone. *Journal of climate*, 17(19), 3829–3842.
- Mercer, A. E., Shafer, C. M., Doswell III, C. A., Leslie, L. M., & Richman, M. B. (2012). Synoptic composites of tornadic and nontornadic outbreaks. *Monthly Weather Review*, 140(8), 2590–2608.
- Michelangeli, P.-A., Vautard, R., & Legras, B. (1995). Weather regimes: Recurrence and quasi stationarity. *Journal of the atmospheric sciences*, 52(8), 1237–1256.
- North, G. R., Bell, T. L., Cahalan, R. F., & Moeng, F. J. (1982). Sampling errors in the estimation of empirical orthogonal functions. *Monthly weather review*, 110(7), 699–706.
- Peters, J. M., & Schumacher, R. S. (2014). Objective categorization of heavy-rain-producing mcs synoptic types by rotated principal component analysis. *Monthly Weather Review*, 142(5), 1716–1737.
- Salio, P., Nicolini, M., & Saulo, A. C. (2002). Chaco low-level jet events characterization during the austral summer season. *Journal of Geophysical Research Atmospheres*, 107(24), XLXIII–XLXIV. <https://doi.org/10.1029/2001JD001315>
- Salio, P., Nicolini, M., & Zipser, E. J. (2007). Mesoscale convective systems over south-eastern South America and their relationship with the South American low-level jet. *Monthly Weather Review*, 135(4), 1290–1309. <https://doi.org/10.1175/MWR3305.1>
- Saulo, C., Ruiz, J., & Skabar, Y. G. (2007). Synergism between the low-level jet and organized convection at its exit region. *Monthly Weather Review*, 135(4), 1310–1326.
- Seluchi, M. E., Saulo, A. C., Nicolini, M., & Satyamurty, P. (2003). The northwestern argentinean low: A study of two typical events. *Monthly Weather Review*, 131(10), 2361–2378.

- Velasco, I., & Fritsch, J. M. (1987). Mesoscale convective complexes in the americas. *Journal of Geophysical Research: Atmospheres*, 92(D8), 9591–9613.
- Vera, C. S., Vigliarolo, P. K., & Berbery, E. H. (2002). Cold season synoptic-scale waves over subtropical south america. *Monthly Weather Review*, 130(3), 684–699.
- Wheeler, M. C., & Hendon, H. H. (2004). An all-season real-time multivariate mjo index: Development of an index for monitoring and prediction. *Monthly weather review*, 132(8), 1917–1932.
- Wilks, D. S. (2011). *Statistical methods in the atmospheric sciences* (Vol. 100). Academic press.

Chapter 4

Conclusions

4.1 Summary

The South American low-level jet (SALLJ) transports substantial amounts of moisture from the Amazon to the subtropics, where it influences the development of deep convection and precipitation over the densely-populated La Plata Basin. This dissertation provides a detailed analysis of the spatial and temporal variability of the SALLJ, with the aim of identifying large-scale atmospheric patterns that modulate the jet and consequently influence regional precipitation regimes. The information provided in previous chapters focuses on the following objectives:

1. Develop a 38-year climatology of SALLJ events (1979-2016) based on an improved algorithm for identifying low-level jet events and ERA-Interim reanalysis (Chapter 2).
2. Characterize the seasonal and interannual variability of the SALLJ and identify long-term trends in the jet's frequency, intensity, and moisture transport patterns over the climatological period of 1979-2016 (Chapter 2).

3. Categorize warm-season SALLJ days into four distinct synoptic types, and examine the large-scale circulation features that modulate the jet and consequently precipitation over southeastern SA (Chapter 3).
4. Investigate the relationships between the frequency of occurrence of SALLJ types and large-scale climate drivers at subseasonal and interannual time scales (Chapter 3).

4.2 Key results

Chapter 2 presents a new dataset of SALLJ days based on ERA-I reanalysis (1979-2016) and a novel algorithm for identifying SALLJ events. The new method uses the 75th percentiles of wind speed and wind shear to define local and seasonal thresholds of jet occurrences. According to this approach, an SALLJ event is identified whenever the wind speed at 850 hPa and wind shear between 850 and 700 hPa both exceed the 75th percentile of their respective seasonal climatology.

The new climatology of SALLJ days is used to examine the temporal and spatial variability of the jet on seasonal and interannual time scales and to investigate trends in jet frequency and intensity over the 38-year period of analysis. Despite higher wind speeds and greater frequency of SALLJ during winter, seasonal composites of SALLJ days show that the northwesterly moisture flux towards southeastern SA is strongest during austral summer. During summer, the SALLJ is supplied by moisture from the tropical North Atlantic which is carried across the continent by the trade winds and supplemented with evapotranspiration from over the Amazon. Evapotranspiration over the Amazon continues to supply the SALLJ during the winter, which is also influenced by moisture from the subtropical South Atlantic.

Due to the significant relationship between the SALLJ and MCSs/precipitation during the warm season, the third chapter of this dissertation focuses only on SALLJ events that occur between November-March (1979-2016). We used PCA and clustering analysis to identify a set of four distinct circulation patterns from 1,765 warm-season SALLJ days, which are referred to as SALLJ types. SALLJ type 1 is characterized by zonal moisture transport over Bolivia and Paraguay; SALLJ 2 is characterized by northwesterly moisture transport towards Paraguay and southern Brazil; SALLJ 3 is characterized by northerly moisture into central Argentina; and SALLJ 4 is characterized by northwesterly moisture transport towards northeastern Argentina and Uruguay.

SALLJ types 2-4 are associated with an extratropical cyclone, a baroclinic front, an upper-level jet streak, and heavy precipitation likely associated with a mesoscale convective system. Our analysis of the persistence and transitions of SALLJ types suggests the preferred sequence of SALLJ types from $3 \rightarrow 4 \rightarrow 2$, which is consistent with the migration of a baroclinic system from southern South America towards the subtropics. These findings are also consistent with the passage of a midlatitude Rossby wave train and the evolution of its associated circulation anomalies in the days proceeding a SALLJ 2-4 events.

On interannual timescales, the strength and frequency of the SALLJ is modulated by ENSO, especially during SON and MAM. SALLJ days are stronger (weaker) and more (less) frequent during El Niño (La Niña) as compared to neutral conditions. During El Niño events, circulation anomalies strengthen the upper-level subtropical jet, which enhances low-level northwesterly flow in the SALLJ region. Enhanced moisture transport by the jet contributes to the above-average precipitation anomalies over southeastern South America observed during El Niño (Grimm, 2011; Grimm et al., 2000).

On subseasonal time scales, the frequency of SALLJ types is influenced by MJO. Specifically, phase 5 of MJO is associated with an increased frequency of northerly jet

events (SALLJ 3 and 4), while phase 3 of MJO is more conducive to zonally-oriented jet events (SALLJ 1 and 2). In general, the effects of MJO on SALLJ frequency are enhanced during the warm phase of ENSO. The combination of MJO phase 5 + El Nino is particularly favorable to SALLJ 3 and 4 activity. This information has important implications for subseasonal to seasonal predictions of precipitation.

Trends in vertically integrated moisture transport over South America indicate significant increases in the northwesterly moisture flux towards southern Brazil during SALLJ days in spring, summer, and fall. The strengthening of the moisture flux associated with the jet is related to the intensification of moisture transport across the Amazon and an anticyclonic circulation anomaly over central-eastern Brazil.

Improvement of subseasonal-to-interannual climate prediction relies on our understanding of recurrent weather patterns and the identification of specific climate drivers responsible for their frequency of occurrence, persistence, or transition. Therefore, results of this research can be used to improve weather forecasts and subseasonal-to-seasonal climate predictions over southeastern South America. Furthermore, the information provided here has useful applications in water resource management and natural disaster monitoring. This is especially important in the context of global warming, as an intensification of the hydrological cycle is foreseen in the future. It is crucial to understand the dynamics and variability of the SALLJ in the current climate in order to understand and interpret future changes in the SALLJ.

4.3 Suggestions for future work

This dissertation provides valuable insight and motivation to improve and develop tools for regional monitoring and predictability of the SALLJ and precipitation over southeastern SA. Towards that end, future and ongoing research efforts regarding the

SALLJ include the following:

1. Examine the influence of additional large-scale climate patterns on SALLJ variability, such as the Southern Annular Mode (SAM) or persistent SST anomalies in the Atlantic and/or Pacific. Similar to the combined analysis of ENSO/MJO phases on SALLJ frequency, future analysis of additional climate drivers should examine the combined effects of multiple climate drivers simultaneously.
2. Develop a probabilistic forecast model of the SALLJ based on the potential predictors analyzed in Chapter 3, which may include the phases of ENSO and MJO, monthly frequency, and transition probabilities.
3. Investigate the relationship between the SALLJ and extreme precipitation events, with the goal of identifying the types and sequences of SALLJ events that may trigger heavy flooding or other severe weather events.

Appendix A

Supplementary Material

Dynamical coupling of the SALLJ and upper-level jet

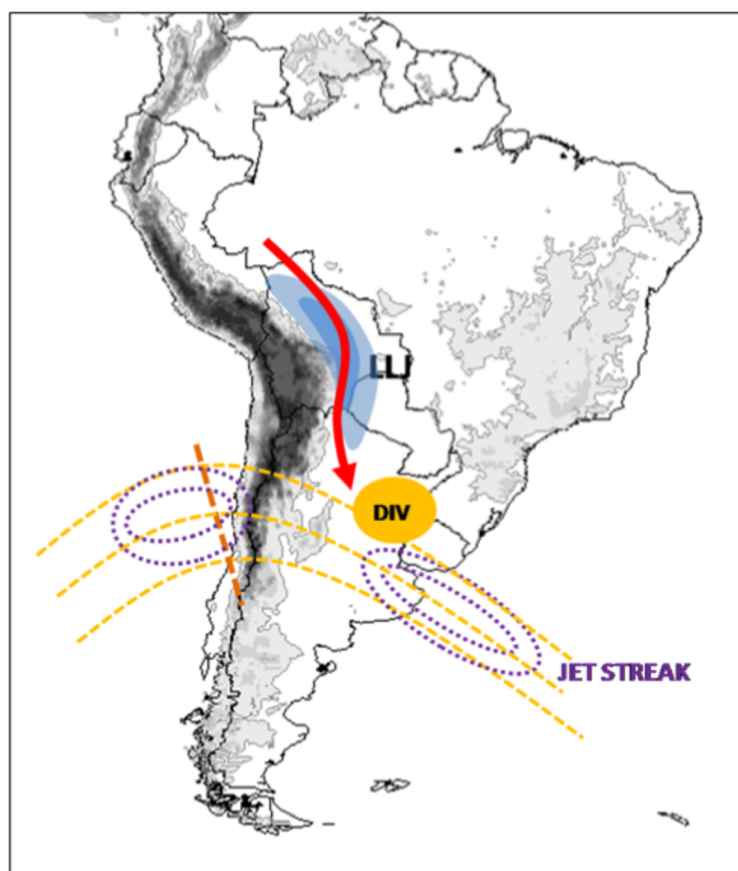


Figure A.1: Schematic of the SALLJ and the upper-level jet stream over subtropical South America. Upper-level divergence (DIV) at the left entrance region of a upper-level jet streak over southeastern SA enhances low-level convergence at the exit region of the SALLJ. This figure is adapted from <http://www.eumetrain.org/>.

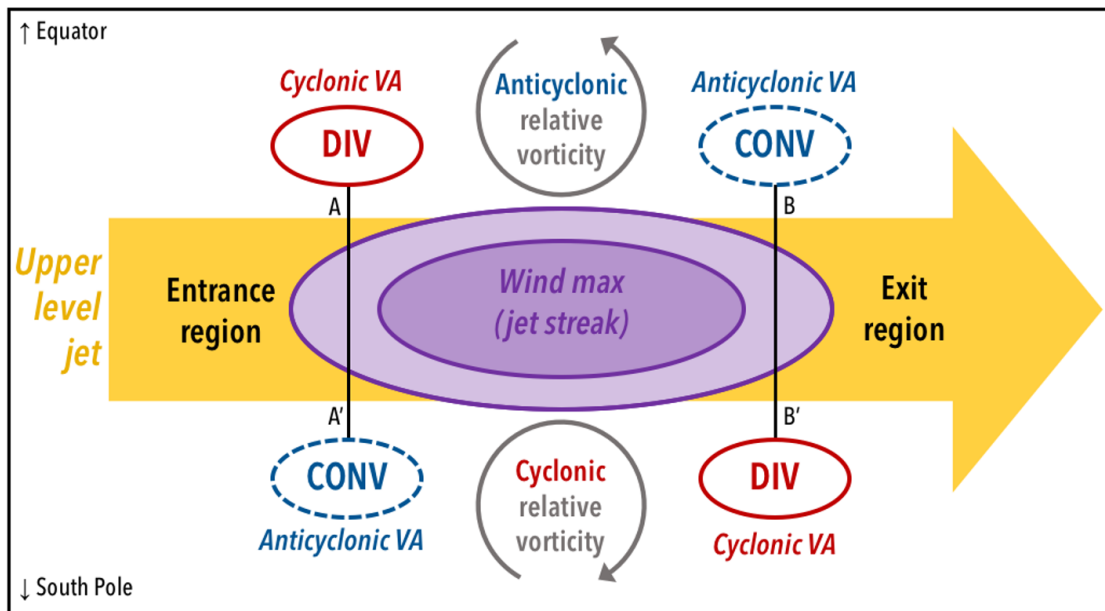


Figure A.2: Vorticity advection associated with an upper-level jet streak in the Southern Hemisphere. Due to strong horizontal wind shear, areas of cyclonic (anticyclonic) relative vorticity form on the poleward (equatorward) side of a jet streak, which represent an absolute vorticity maximum (minimum). Note that absolute vorticity is negative in the Southern Hemisphere. Regions of cyclonic vorticity advection (VA; red circles) are associated with upper-level divergence (DIV) and low-level convergence, which creates upward vertical motion and supports convective development. Therefore, enhanced convection is found at the left entrance and right exit regions of an upper-level jet streak (Saulo et al., 2007; Uccellini, 1980). Note that "left" and "right" refer to the equatorward and poleward sides of the jet streak, respectively.

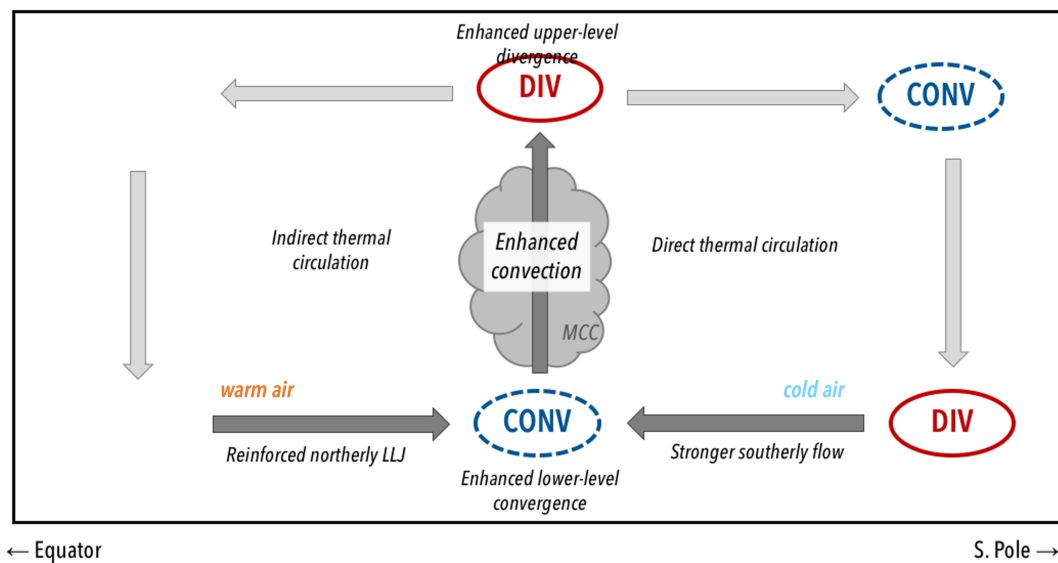


Figure A.3: Vertical cross section of meridional ageostrophic circulations associated with an acceleration of an upper-level jet streak in the Southern Hemisphere. Cross sections show the indirect and direct thermal circulation cells generated at the left entrance and right exit regions of the jet streak. The low-level meridional branch of an indirect (direct) thermal cell strengthens low-level northerly (southerly) flow. Therefore, an indirect cell located to the north of convection reinforces the advection of warm, moist air into the region via the northerly SALLJ (Saulo et al., 2007; Uccellini, 1980).

References

- Saulo, C., Ruiz, J., & Skabar, Y. G. (2007). Synergism between the low-level jet and organized convection at its exit region. *Monthly Weather Review*, 135(4), 1310–1326.
- Uccellini, L. W. (1980). On the role of upper tropospheric jet streaks and leeside cyclogenesis in the development of low-level jets in the great plains. *Monthly Weather Review*, 108(10), 1689–1696.