FINAL REPORT

Project Title: **An integrated view of the American Monsoon Systems: observations, models and probabilistic forecasts**

Award NA10OAR4310170

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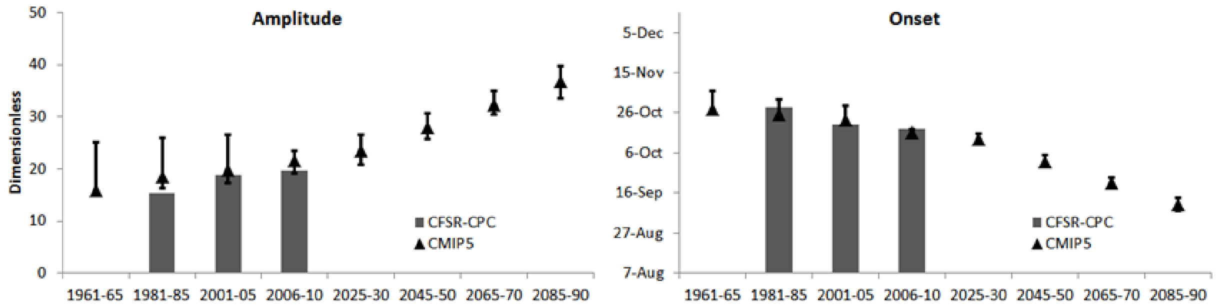
Period: Year 5 (08/01/2010-07/31/2015)

1. Results and Accomplishments

This project focuses on the possible associations between the monsoons in the Americas. Specifically, the objectives of the project are to: 1) develop indices for a unified approach to monitor and forecast the variability of the monsoon systems in the Americas, 2) investigate the associations between the two monsoon systems and the importance of atmosphere-ocean variations on intraseasonal-to-interannual (ISI) time scales in explaining these linkages, 3) examine the degree to which simulations from the Coupled Model Intercomparison Project (CMIP-3 and CMIP-5) realistically represent the associations between the monsoons in the Americas, and 4) use Climate Forecast System (CFS) model outputs (reforecasts and operational) to develop probabilistic forecasts of the American Monsoon Systems on subseasonal to seasonal lead times. Identify sources of potential predictability of the AMS on ISI time scales. The following highlights some of the accomplishments obtained during this project.

Jones, C., and L. M. V. Carvalho, 2013: Climate change in the South American Monsoon System: present and CMIP5 projections. *Journal of Climate, 26, 6660-6678*.

The South American monsoon system (SAMS) is the most important climatic feature in South America. This study focuses on the large-scale characteristics of the SAMS: seasonal amplitudes, onset and demise dates, and durations. Changes in the SAMS are investigated with the gridded precipitation, Climate Forecast System Reanalysis (CFSR), and the fifth phase of the Coupled Model Intercomparison Project (CMIP5) simulations for two scenarios [“historical” and high-emission representative concentration pathways (rcp8.5)]. Qualitative comparisons with a previous study indicate that some CMIP5 models have significantly improved their representation of the SAMS relative to their CMIP3 versions. Some models exhibit persistent deficiencies in simulating the SAMS. CMIP5 model simulations for the historical experiment show signals of climate change in South America. While the observational data show trends, the period used is too short for final conclusions concerning climate change. Future changes in the SAMS are analyzed with six CMIP5 model simulations of the rcp8.5 high-emission scenario. Most of the simulations show significant increases in seasonal amplitudes, early onsets, late demises, and durations of the SAMS. The simulations for this scenario project a 30% increase in the amplitude from the current level by 2045–50. In addition, the rcp8.5 scenario projects an ensemble mean decrease of 14 days in the onset and 17-day increase in the demise date of the SAMS by 2045–50. The results additionally indicate lack of spatial agreement in model projections of changes in total wet-season precipitation over South America during 2070–2100. The most consistent



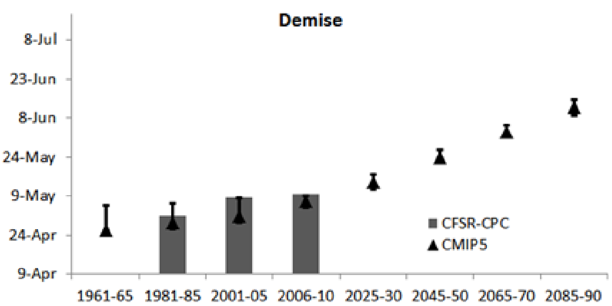


Figure 1. Decadal changes in the SAMS (top) amplitude, (middle) onset, and (bottom) demise dates. Gray bars show changes obtained from CPCU/CFSR. Triangles indicate ensemble means of CMIP5 simulations for the historical (1961–2005) and rcp8.5 (2006–90) experiments. Tips of the vertical lines show minimum and maximum values. Changes are estimated in 5-yr periods (horizontal axis). Number of CMIP5 models used were 10 (historical) and 6 (rcp8.5) (Jones and Carvalho 2013).

CMIP5 projections analyzed here are the increase in the total monsoon precipitation over southern Brazil, Uruguay, and northern Argentina

Carvalho, L. M. V., and C. Jones, 2013: CMIP5 simulations of low-level tropospheric temperature and moisture over tropical Americas. *Journal of Climate,* 26, 6257-6286.

Global warming has been linked to systematic changes in North and South America's climates and may severely impact the North and South American Monsoon systems (NAMS and SAMS, respectively). This study examines interannual-to-decadal variations and changes in the low-troposphere (850hPa) temperature (T850) and specific humidity (Q850) and relationships with daily precipitation over the tropical Americas using NCEP/NCAR and CFSR reanalyses and fifth phase of the Coupled Model Intercomparison Project (CMIP5) simulations for two scenarios: "historic" and high emission representative concentration pathways "RCP8.5". Trends in the magnitude and area of the 85th percentiles were distinctly examined over North America (NA) and South America (SA) during the peak of the respective monsoon season. The historic simulations (1951-2005) and the two reanalyses agree well and indicate that significant warming has occurred over tropical SA with a remarkable increase in the area and magnitude of the 85th percentile in the last decade (1996-2005). The RCP8.5 CMIP5 ensemble mean projects an increase in the T850 85th percentile of about 2.5^{o}C (2.8^{o}C) by 2050 and 4.8^{o}C (5.5^{o}C) over SA (NA) by 2095 relative to 1955. The area of SA (NA) with T850 ≥ the 85th percentile is projected to increase from ~10% (15%) in 1955 to ~58% (~33%) by 2050 and ~80% (~50%) by 2095. The respective increase in the 85th percentile of Q850 is about 3g/kg over SAMS and NAMS by 2095. CMIP5 models project variable changes in daily precipitation over tropical Americas. The most consistent is increased rainfall in the intertropical convergence zone in DJF and JJA and decreased precipitation over NAMS in JJA

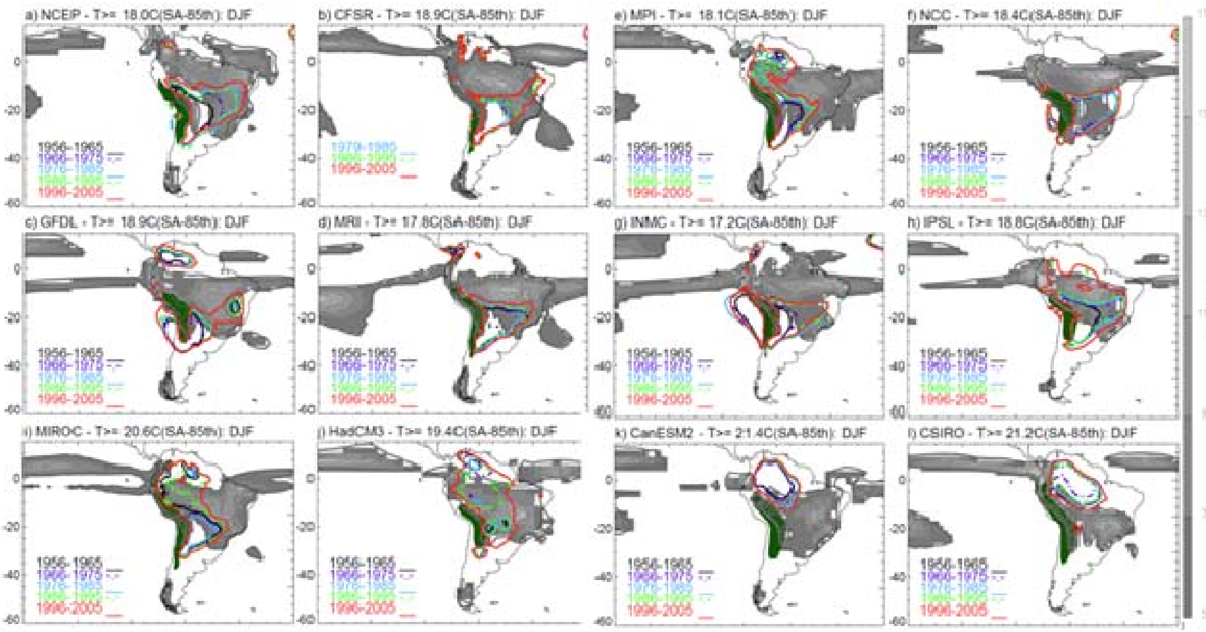


Figure 2. Decadal variation of the T850 85th percentile (T850p85) during DJF (colored lines) and mean daily precipitation above 5mm day-1 (gray shades) for the historic simulations (1951-2005). Values of the T850p85 were calculated over SA (see Table-2) and are indicated at the top of each frame (oC): a) NCEP/NCAR, b) CFSR, c) GFDL-ESM2M, d) MRI-CGCM3, e) MPI-ESM-LR, f) NorESM1-M, g) INM-CM4, h) IPSL-CM5A-LR, i) MIROC4h, j) HadCM3, k) CanESM2, l) CSIRO-Mk3.6.0. For NCEP/NCAR (a) and all CMIP5 models, averages were taken in the following decades: 1956-1965 (black solid line); 1966-1975 (dark blue dashed line); 1976-1985 (light blue solid line); 1986-1995 (light green dashed line); 1996-2005 (red solid line). Decadal averages for CSFR (b) were obtained for the periods 1979-1985 (black solid line), 1986-1995 (blue dashed line), 1996-2005 (red solid line). The dark green shade indicates topography above 1500m and the gray shade color bar indicates mean daily precipitation rate (mm/day) calculated for the entire historic period of the simulations (1951-2005).

Carvalho, L. M. V., and I. F. A. Cavalcanti, 2015: The South American Monsoons System (SAMS). The Monsoons and Climate Change: Observations and Modelling, L. M. V. Carvalho, and C. Jones, Eds., Springer, (In Press).

This book originated from the conference session entitled “The global monsoons and climate change: observations, models and projections” held at the Fall Meeting of the American Geophysical Union (AGU) in 2012 in San Francisco, California. A significant portion of the material presented here includes results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulations, which contributed to the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC) finalized in 2013. Thus, the main goal of this book is to provide a concise and timely assessment of the monsoons and climate change.

The book has 11 chapters. Chapter 1 introduces the main motivations for the book. A global view of the monsoons and its change is presented in Chapter 2. Chapters 3 and 4 discuss the Asian Monsoon variability and the projected changes in the 21st Century. Chapter 5 covers the Australian summer monsoon and potential changes. The monsoon systems in South America and North America are discussed in Chapters 6 and 7, respectively. Connections between the North American and South American monsoon systems are discussed in Chapter 8. Chapter 9 explores the seasonal variation of the Indo-Pacific monsoon circulation and interactions with the climate of East Africa. Since all monsoon systems exhibit significant variability on intraseasonal time scales, Chapter 10 discusses future changes in the Madden-Julian Oscillation (MJO). Lastly, Chapter 11 analyzes the importance of the monsoon systems on glaciers over the central Andes and Himalaya.

Carvalho and Cavalcanti (2015) reviews differences in mean precipitation in the RCP8.5 scenario (2075-2100) and the historical period (1980-2005) (Fig. 3). The most dramatic differences are observed over the Amazon, in the Atlantic ITCZ and oceanic SACZ. The ensemble difference indicates minimal precipitation change over the central Amazon (less than 5%) and 10-20% increases over the La Plata Basin, southern Peru, Colombia and northeast Brazil (Fig. 3a). In contrast, a reduction of about 40% of DJF rainfall is projected over northern South America and Chile. The difference in humidity flux between the two periods shows an increase of moisture flux over the Amazon and toward southeastern South America in the future climate and consistent with the precipitation increase in that region. This suggests that the intensity of the SALLJ may be significantly altered as the planet continues to warm (Fig. 3b). However, the relationships between global warming and the mechanisms of the SALLJ have not been studied in depth and this proposal seeks to fill this gap in the current knowledge of climate change in the SAMS.

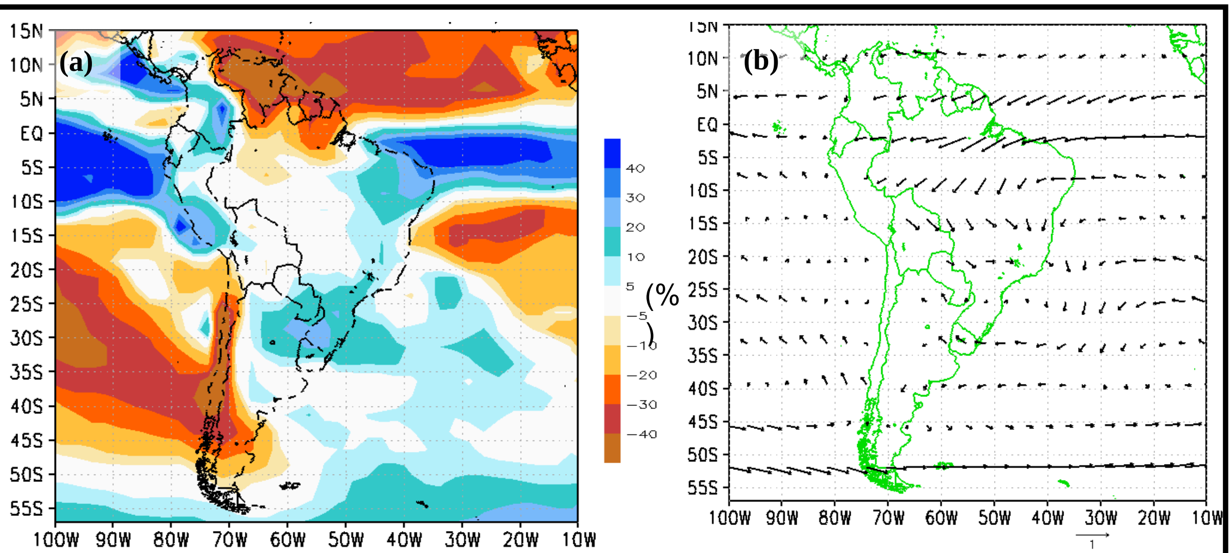


Figure 3. Difference between RCP8.5 (2075 to 2100) scenario and historical simulation (1980 to 2005) in DJF, a) precipitation difference (%) (b) Difference in moisture flux at 850 hPa. Five CMIP models were used (*After Carvalho and Cavalcanti 2015*).

2. Publications

Books

Carvalho, L. M. V., and C. Jones, 2015: *The Monsoons and Climate Change: Observations and Modelling.* Springer, expected in November 2015.

Silva Dias, M. A. F, and Carvalho L. M. V., 2014: The South American Monsoon System, in The Global Monsoon System: Research and Forecast, 2nd Edition, WMO.

Silva Dias, M. A. F., A. C. T. Sena , J. Dias**,** L. M. V. Carvalho**,** E. D. Freitas, P. L. Silva Dias, 2013: Historic and future evolution of extreme daily precipitation in São Paulo (In Portuguese: Evolucao Historica e futura dos extremos de chuva diaria em Sao Paulo). In INCLINE: Ciencia das Mudancas Climaticas e sua Inter-disciplinaridade.(in Portuguese)

Refereed journal articles

Alvarez, M. S., C. S. Vera, G. N. Kiladis, and B. Liebmann, 2015: Influence of the Madden Julian Oscillation on precipitation and surface air temperature in South America. Climate Dynamics, doi:10.1007/s00382-015-2581-6.

Bombardi, R., L. M. V. Carvalho, C. Jones, and M. S. Reboita, 2013: Precipitation over eastern South America and the south Atlantic sea surface temperature during neutral ENSO periods. *Climate Dynamics*, **42**, 1553-1568 DOI 10.1007/s00382-013-1832-7

Bombardi, R., L. M. V. Carvalho, and C. Jones, 2013: Simulating the influence of the South Atlantic dipole on the South Atlantic Convergence Zone during neutral ENSO. *Theoretical and Applied Climatology* DOI 10.1007/s00704-013-1056-0.

Bombardi, R., L. M. V. Carvalho, C. Jones, and M. S. Reboita, 2013: Precipitation over eastern South America and the south Atlantic sea surface temperature during neutral ENSO periods. *Climate Dynamics* DOI 10.1007/s00382-013-1832-7

Carvalho, L. M. V., C. Jones, and B. Liebmann, 2015: An integrated view of the American Monsoons. *Journal of Climate*, (in preparation).

Carvalho, L. M. V., and Jones, C., 2013: CMIP5 simulations of low-level tropospheric temperature and moisture over tropical Americas. *Journal of Climate, **26**,* 6257-6286. doi: http://dx.doi.org/10.1175/JCLI-D-12-00532.1

Carvalho, L. M. V., Jones, C**.,** A. N. Posadas, R. Quiroz, B. Bookhagen, and B. Liebmann, 2012: Precipitation characteristics of the South Monsoon System derived from multiple data sets. *Journal of Climate, 25,* 4600-4620

Cati E. A. Valadão P. S. Lucio, R. R. Chaves, L. M. V. Carvalho, 2015: MJO Modulation of Station Rainfall in the Semiarid Seridó, Northeast Brazil. *Atmos. and Climate Sci.*, **5**, 408-417.

Fu, R., L. Yin, W. Li, P. A. Arias, L. Huang, K. Fernandes, R. E. Dickinson, B. Liebmann, R. Fisher, and R. Myneni, 2013: The increase in dry season length over southern Amazonia in recent decades, its causes, and implications for climate projection. *Proc. Nat. Accad. Sci. U. S. A*., PNAS: 1302584110v1-201302584.

Heidinger, H. A., L. M. V. Carvalho, C. Jones, A. Posadas, R. Quiroz: Evaluating trends in total and extreme rainfall over Central and Southern Peruvian Andes. Theoretical and Applied Climatology (in preparation). Paper with student.

Heidinger, H. A., C. Jones, L. M. V. Carvalho, R. Quiroz, A. Posadas: Regional model simulation of daily rainfall over Central and Southern Peruvian Andes with the WRF model. *Theoretical and Applied Climatology* (in preparation). Paper with student.

Jones, C., and L. M. V. Carvalho, 2013: Climate change in the South American Monsoon System: present climate and CMIP5 projections. *Journal of Climate, **26,** 66*60-6678 doi: http://dx.doi.org/10.1175/JCLI-D-12-00412.1

Jones, C**.,** L. M. V. Carvalho, and B. Liebmann, 2012: Forecast skill of the South American Monsoon System. *Journal of Climate **25**,* 1883-1889.

Oliveira, F. N. M., L. M. V. Carvalho and T. Ambrizzi: A New Climatology for Southern Hemisphere blockings and the combined effect of ENSO and SAM phases. *Int. J. Climatology*, DOI: 10.1002/joc.3795

Pedron, I. T. M. A. F. Silva Dias, S. P. Dias, L. M. V. Carvalho, E. D. Freitas, 2015: Trends, variability, and oscillations in extreme precipitation in Curitiba, Southern Brazil, *Int. J. Climatology* (in revision).

Posadas, A., L. A. Duffaut Espinosa, C. Yarleque, M. Carbajal, H. Heidinger, L. Carvalho, C. Jones, and R. Quiroz, 2015: Spatial Random Downscaling of Rainfall Signals in Andean Heterogeneous Terrain. *Nonlinear Processes in Geophysics*, 22, 383–402.

Tomaziello, A. C. N., L. M. V. Carvalho and A. D. W. Gandu, 2015: Intraseasonal variability of the Atlantic Intertropical Convergence Zone during austral summer and winter. *Climate Dynamics*, (in revision). Paper with student.

Valadão, C. ,L. M. V. Carvalho, P. S. Lucio and R. R. Chaves, 2015: Impacts of the Madden-Julian Oscillation on Intraseasonal Precipitation over Northeast Brazil. *Int. J. Climatology* (in revision). Paper with student.

Zilli, M. T., L. M. V. Carvalho, B. Liebmann, and M. A. F. Silva Dias, 2015: a comprehensive analysis of trends in extreme precipitation over southeastern coast of Brazil. *Int. J. Climatology* (in revision). Paper with student.

3. Highlights of Accomplishments

- ✓ New book with 11 chapters discussing the most recent and up to date observational and modeling results on Global Monsoons and Climate Change was edited and is currently in the process of publication by Springer. This book presents an overview of all monsoon systems and projected climate change. A special chapter is dedicated to discuss the most recent studies on connections between the North and South American Monsoons. We also include a comprehensive review on how climate changes in the monsoon regions have impacted glaciers such as the ones in the Andes and the impacts of the MJO in monsoon systems.
- ✓ A new book chapter discussing the South American Monsoon System variability with a major focus on mesoscale systems was elaborated and reviewed during this period (in The Global Monsoon System: Research and Forecast, 2nd Edition, WMO).
- ✓ We examined tropical-extratropical interactions and inter-hemispheric transfer of momentum and energy associated with the enhancement and weakening of convection in the Atlantic ITCZ on intraseasonal time-scales.

- ✓ We investigated extreme precipitation trends in several regions in South America using raingauge stations such as south and southeastern Brazil and the Peruvian Andes. These studies were motivated by our previous research developed in this project. Two articles addressing these issues were submitted and one is currently in preparation.
- ✓ We performed 15 years regional modeling simulations using WRF at 15 km with focus on the Peruvian Andes to investigate the role of variations in the South American Monsoon in modulating extreme precipitation in the region.
- ✓ We have developed a statistical downscaling method using multifractal methodology using TRMM daily data (~28 km) to downscale rainfall over the Peruvian Andes on horizontal scales of about 1km
- ✓ We investigated the influence of the MJO on precipitation in different regions of South America including Northeast Brazil (a semi-arid region) and Southeastern South America (SESA).
- ✓ Ph.D. Thesis completed and supported by this award: R. Bombardi, 2013: The role of variations in the Atlantic Sea Surface Temperature on the climate of eastern South America. Dept. Geography, UCSB.

5. PIs Contact Information

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