Final Report:
The relationship of tropical cyclones to MJO and ENSO in the S2S database

1. General Information

Project Title: *The relationship of tropical cyclones to MJO and ENSO in the S2S database*
PI/co-PI names and institutions:

- Suzana J. Camargo (PI), Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY
- Adam Sobel (co-PI), Lamont-Doherty Earth Observatory, Department of Applied Physics and Applied Mathematics, Department of Earth and Environmental Sciences, Columbia University, New York, NY
- Chia-Ying Lee (co-PI), Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY
- Frédéric Vitart (collaborator), European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

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2. Main goals of the project, as outlined in the funded proposal

- Track tropical cyclones (TCs) in the S2S models. Our dataset of TC tracks will be available to the scientific community at the end of this project.
- Analyze how well the S2S models simulate the climatology of TCs globally and regionally, considering, TC frequency, genesis, intensity, location, tracks and seasonality.
- Determine the skill of the S2S models in reproducing the ENSO-TC modulation, by analyzing the models' simulations of ENSO, their relationships between ENSO and TCs, and the models' ENSO teleconnections.
- Determine the skill of the S2S models in simulating the MJO-TC relationship. We will analyze the models' MJO and MJO-TC modulation.
- Study the dependence of the S2S models' TC climatology, ENSO-TC and MJO-TC relationships to model configuration, including model horizontal resolution, ensemble size, model physics, coupling method and lead time, by analyzing variations in these parameters across the ensemble of opportunity.

3. Results and accomplishments

During the period of this grant, we did a in depth assessment of the skill of the S2S dataset models in forecasting tropical cyclones TCs in subseasonal time-scales. We also analyzed the skill of the ECMWF monthly hindcasts in forecasting North Atlantic hurricanes. We contributed to multiple publications on S2S time-scales and led the Ninth International Workshop on Tropical Cyclones (IWTC-9) report on tropical cyclones in subseasonal time-scales, a meeting organized by the World Meteorological Organization.

Chia-Ying Lee is the PI (Camargo is co-PI) of a new NASA grant which will investigate the skill of the NASA-GEOS model in forecasting TCs in subseasonal time-scales and will examine the sensitivity of various aspects of the model configuration to improve the model skill.

1. **TC Genesis in the S2S models:**
   The first comprehensive analysis of TC skill in forecasting TC genesis in the different basis for the S2S multi-model dataset appeared in Weather and Forecasting in 2018, in a manuscript led by Chia-Ying Lee (Lee et al. 2018). Here is the abstract of the manuscript, describing the main results:
   Subseasonal probabilistic prediction of tropical cyclone (TC) genesis is investigated here using models from the Seasonal to Subseasonal (S2S) Prediction dataset. Forecasts are produced for basin-wide TC occurrence at weekly temporal resolution. Forecast skill is measured using the Brier skill score relative to a seasonal climatology that varies monthly through the TC season. Skill depends on models' characteristics, lead time, and ensemble prediction design. Most models show skill for week 1 (days 1–7), the period when initialization is important. Among the six S2S models examined here, the European Centre for Medium-Range Weather Forecasts (ECMWF) model has the best performance, with skill in the Atlantic, western North Pacific, eastern North Pacific, and South Pacific at week 2. Similarly, the Australian Bureau of Meteorology (BoM) model is skillful in the western North Pacific, South Pacific, and across northern Australia at week 2. The Madden–Julian oscillation (MJO) modulates observed TC genesis, and there is a relationship, across models and lead times, between models' skill scores and their ability to accurately represent the MJO and the MJO–TC relation. Additionally, a model's TC climatology also influences its performance in subseasonal prediction. The dependence of the skill score on the simulated climatology, MJO, and MJO–TC relationship, however, varies from one basin to another. Skill scores increase with the ensemble size, as found in previous weather and seasonal prediction studies.

2. **TC Occurrence and Intensity in the S2S models:**
   The second manuscript from this grant continued the analysis analyzing now TC occurrence and intensity. As part of our analysis we proposed the use of a different calibration method for TC occurrence, instead of the one being used in previous study, which we showed had issues. The second manuscript also appeared in Weather in Forecasting and was led by Chia-Ying Lee (Lee et al. 2020). Below is the abstract of the manuscript:

   Probabilistic tropical cyclone (TC) occurrence, at lead times of week 1–4, in the Subseasonal to Seasonal (S2S) dataset are examined here. Forecasts are defined over 158 in latitude 3 208 in longitude regions, and the prediction skill is measured using the Brier skill score with reference to climatological reference forecasts. Two types of reference forecasts are used: a seasonally constant one and a seasonally varying one, with the latter used for forecasts of anomalies from the seasonal climatology. Models from the European Centre for Medium-Range Weather Forecasts (ECMWF), Australian Bureau of Meteorology, and Météo-France/Centre National de Recherche Météorologiques have skill in predicting TC occurrence four weeks in advance. In contrast, only the ECMWF model is skillful in predicting the anomaly of TC occurrence beyond one week. Errors in genesis prediction largely limit models' skill in predicting TC occurrence. Three calibration techniques, removing the mean genesis and occurrence forecast biases, and a linear regression method, are explored here. The linear regression method performs the best and guarantees a higher skill score when applied to the in-sample dataset. However, when applied to the out-of-sample data, especially in areas where the TC sample size is small, it may reduce the models' prediction skill. Generally speaking, the S2S models are more skillful in predicting TC occurrence during favorable Madden–Julian oscillation phases. Last, we also report accumulated cyclone energy predictions skill using the ranked probability skill score.

3. **North Atlantic TC characteristics in the ECMWF Monthly Forecasting System:**
   The third manuscript focused on the North Atlantic TCs in the ECMWF Monthly Forecasts and performed a comprehensive analysis of their characteristics, the relationship with the large-scale environment and various climate modes. This manuscript was led by Camargo and currently

appears as “early online” at Monthly Weather Review (Camargo et al. 2021). The abstract is below:

In this paper we analyze Atlantic hurricane activity in the European Centre for Medium-Range Weather Forecasts (ECMWF) Monthly hindcasts for the period 1998–2017. The main climatological characteristics of Atlantic tropical cyclone (TC) activity are considered at different lead times and across the entire ECMWF ensemble using three diagnostic variables: the number of tropical cyclones, the number of hurricanes, and the accumulated cyclone energy. The impacts of changing horizontal resolution and stochastic parametrization are clear in these diagnostic variables. The model skill scores for the number of tropical cyclones and Accumulated Cyclone Energy by lead time are also computed. Using cluster analysis, we compare the characteristics of the forecast TC tracks with observations. While four of the ECMWF clusters have similar characteristics to observed ones, one of the ECMWF clusters does not have a corresponding one in observations. We consider the predictability of each of these clusters, as well the modulation of their frequency by climate modes, such as the El Niño-Southern Oscillation and the Madden Julian Oscillation, taking advantage of the very large sample size TC datasets in these hindcasts.

4. Review of TCs on subseasonal time-scales

Camargo was invited to lead a group of scientists to summarize the progress in understanding and forecasting TCs in subseasonal time-scales at the Ninth International Workshop on Tropical Cyclones (IWTC-9), a meeting organized by the World Meteorological Organization every 4 years. They wrote a report, which was later published at the journal Tropical Cyclone Research and Review (Camargo et al. 2019). Here is the abstract of the review paper:

Here we discuss recent progress in understanding tropical cyclone (TC) subseasonal variability and its prediction. There has been a concerted effort to understand the sources of predictability at subseasonal time-scales, and this effort has continued to make progress in recent years. Besides the Madden-Julian Oscillation (MJO), other modes of variability affect TCs at these time-scales, in particular various equatorial waves. Additionally, TC activity is also modulated by extratropical processes via Rossby wave breaking. There has also been progress in the ability of models to simulate the MJO and its modulation of TC activity. Community efforts have created multi-model ensemble datasets, which have made it possible to evaluate the forecast skill of the MJO and TCs on subseasonal time-scales in multiple forecasting systems. While there is positive skill in some cases, there is strong dependence on the ensemble system considered, the basin examined, and whether the storms have extratropical influences or not. Furthermore, the definition of skill differs among studies. Forecasting centers are currently issuing subseasonal TC forecasts using various techniques (statistical, statistical-dynamical and dynamical). There is also a strong interest in the private sector for forecasts with 3-4 weeks lead time.

5. Review of S2S and TCs:

In collaboration with Andrew Robertson and Frédéric Vitart, Camargo wrote one of the invited review papers for the AGU Grand Challenges Centennial Collection on S2S prediction, with a focus on tropical cyclones (Robertson et al. 2020). The abstract of the review paper is:

Demands are growing rapidly in the operational prediction and applications communities for forecasts that fill the gap between daily weather forecasts and seasonal climate outlooks. Recent scientific advances have identified sources of predictability on this time range, and modeling advances are leading to better forecasts. However, much remains to be done to further improve their skill and to develop new climate service forecast products to help countries and sectorial decision makers better manage weather risks and extremes and to adapt to climate change. This

paper reviews the history and describes the main challenges and opportunities for the modeling and forecast-applications communities to improve subseasonal to seasonal (S2S) forecasts and products, along with current developments catalyzed by the World Weather Research Programme and World Climate Research Programme's joint Sub-Seasonal to Seasonal Prediction Project. The case of tropical cyclones is highlighted as an illustrative example of the points discussed.

4. Highlights of Accomplishments

- Comprehensive analysis of the current state-of-the art models in forecasting tropical cyclones in subseasonal time-scales.
- Analysis of the main characteristics of North Atlantic TCs subseasonal forecasts in the ECMWF Monthly Forecasting System.
- Contribution to multiple review papers on S2S.
- Organization of S2S workshop at Lamont-Doherty Earth Observatory, Columbia University.

5. Transitions to Applications

None

6. Publications from the Project:

1. Main Publications:

- Camargo, S.J., F. Vitart, C.-Y. Lee, and M.K. Tippett, 2021. Skill, predictability, and cluster analysis of Atlantic hurricanes in the ECMWF monthly forecasts. *Monthly Weather Review*, in press, doi: 10.1175/MWR-D-21-0075.1.
- Camargo, S.J., J. Camp, R.L. Elsberry, P.A. Gregory, P.J. Klotzbach, C.J. Schreck, A.H. Sobel, M.J. Ventrice, F. Vitart, Z. Wang, M.C. Wheeler, M. Yamaguchi, and R. Zhan, 2019. Tropical cyclone prediction on subseasonal time-scales. *Tropical Cyclone Research and Review*, 8, 150-165, doi:10.1016/j.tcrr.2019.10.004.
- Lee, C.-Y., S.J. Camargo, F. Vitart, A.H. Sobel, J. Camp, S. Wang, M.K. Tippett, and Q. Yang, 2020. Subseasonal predictions of tropical cyclone occurrence and ACE in the S2S dataset. *Weather and Forecasting*, 35, 921-938, doi: 10.1175/WAF-D-19-0217.1.
  Lee, C.-Y., S.J. Camargo, F. Vitart, A.H. Sobel, and M.K. Tippett, 2018. Sub-seasonal tropical cyclone genesis prediction and MJO in the S2S dataset. Weather and Forecasting, 33, 967-988, doi: 10.1175/WAF-D-17-0165.1.
- Robertson, A.W., F. Vitart, and S.J. Camargo, 2020. Sub-seasonal to seasonal prediction of weather to climate with application to tropical cyclones. *Journal of Geophysical Research - Atmospheres*, 125, e2018JD029375, doi: 10.1029/2018JD029375.
- Robertson, A., S.J. Camargo, A. Sobel, F. Vitart, and S. Wang, 2018. Summary of workshop on sub-seasonal to seasonal predictability of extreme weather and climate. *npj Clim. Atmos. Sci.,* 1, 8, doi: 10.1038/s41612-017-0009-1.

2. Additional Publications with contributions from the PI during this project:

- Camargo, S. J., 2021. Tropical Cyclones, Western North Pacific Basin, in "State of the Climate in 2020", Bulletin of the American Meteorological Society, 02 (8), S236-S240, doi: 10.1175/BAMS-D-21-0080.1.

- Camargo, S. J., 2020. Tropical Cyclones, Western North Pacific Basin, in "State of the Climate in 2019", Bulletin of the American Meteorological Society, 101 (8), S214-S219.
- Camargo, S. J., 2019. Tropical Cyclones, Western North Pacific Basin, in "State of the Climate in 2018", J. Blunden, and D.S. Arndt (editors), Bulletin of the American Meteorological Society, 100 (9), S124-S127.
- Bell, S.S., S.S. Chand, S.J. Camargo, K.J. Tory, C. Turville, and H. Ye, 2019. Western North Pacific tropical cyclone tracks in CMIP5 models: Statistical assessment using a model-independent detection and tracking scheme. *Journal of Climate*, **32**, 7191–7208, doi: 10.1175/JCLI-D-18-0785-1.
- Bieli, M., A.H. Sobel, S.J. Camargo, H. Murakami, and G.A. Vecchi, 2020a. Application of the cyclone phase space to extratropical transition in a global climate model. Journal of Advances in Modeling Earth Systems, 12, e2019MS001878, doi: 10.1029/2019MS001878.
- Bieli, M., A.H. Sobel, S.J. Camargo, and M.K. Tippett, 2020. A statistical model to predict the extratropical transition of tropical cyclones. *Weather and Forecasting*, **35**, 451-466, doi: 10.1175/WAF-D-19-0045.1.
- Boudreault, M., L.-P. Caron, and S.J. Camargo, 2017: Reanalysis of climate influences on Atlantic tropical cyclone activity using cluster analysis. *J. Geophys. Res.*, 122, 4258-4280, doi: 10.1002/2016JD026103.
- Camargo, S. J., 2018. Tropical Cyclones, Western North Pacific Basin, in "State of the Climate in 2017", G. Hartfield, J. Blunden, and D.S. Arndt (editors), Bulletin of the American Meteorological Society, 99 (8), S120-S124.
- Camargo, S. J., 2017. Tropical Cyclones, Western North Pacific Basin, in "State of the Climate in 2016", J. Blunden and D.S. Arndt (editors), Bulletin of the American Meteorological Society, 98 (8), S114-S118.
- Camargo, S.J., 2016. Tropical Cyclones, Western North Pacific Basin, in "State of the Climate in 2015", J. Blunden and D.S. Arndt (editors), Bulletin of the American Meteorological Society, 97 (8), S110-S113.
- Camargo, S.J., and L.M. Polvani, 2019. Little evidence of reduced global tropical cyclone activity following recent volcanic eruptions. npj Climate and Atmospheric Science, 2, 14, doi: 10.1038/s41612-019-0070-z.
- Domeisen, D.I.V., et al. (including S. J. Camargo), 2021. Advances in the subseasonal prediction of extreme events. Bulletin of the American Meteorological Society, submitted May (2021), currently in review.
- Gualtieri, L., S.J. Camargo, S. Pascale, F.M.E. Pons, and G. Ekström, 2018. The persistent signature of tropical cyclones in ambient seismic noise. *Earth Planet. Sci. Lett.,* 484, 287-294, doi: 10.1016/j.epsl.2017.12.026.
- Hassanzadeh, C.-Y. Lee, E. Nabizadeh, S.J. Camargo, D. Ma, and L. Yeung, 2020. Effects of climate change on the movement of future landfalling Texas tropical cyclones, Nature Communications, 11, 3319.
- Patricola, C.M., S.J. Camargo, P.J. Klotzbach, R. Saravanan, and P. Chang, 2018. The influence of ENSO flavors on western North Pacific tropical cyclone activity. *J. Climate,* **31**, 5395-5416, doi: 10.1175/JCLI-D-17-0678.1.
- Pausata, F.S.R., and S.J. Camargo, 2019. Tropical cyclone activity affected by volcanically induced ITCZ shifts. *Proc. Nat. Acad. Sci.*, early online, doi: 10.1073/pnas.1900777116.

- Seth, A., A. Giannini, M. Rojas, S.A. Rauscher, S. Bordoni, D. Singh, and S.J. Camargo, 2019. Monsoon responses to climate changes - Connecting past, present, and future. *Curr. Clim. Change Rep.,* early online, doi:10.1007/s40641-019-00125-y.
- Shen, Y., Y. Sun, S.J. Camargo, and Z. Zhong, 2018. A quantitative method to evaluate tropical cyclone tracks in climate models. *J. Atmos. Oceanic Technol.,* 35, 1807-1818, doi: 10.1175/JTECH-D-18-0056.1.
- Ting, M., J.P. Kossin, S.J. Camargo, and C. Li, 2019. Past and future hurricane intensity change along the U.S. East coast. Scientific Reports, 9, 7795, doi: 10.1038/s41598-019-44252-w.
- Touma, D., S. Stevenson, S.J. Camargo, D.E. Horton, and N.S. Diffenbaugh, 2019. Variations in the intensity and spatial extent of tropical cyclone precipitation. Geophysical Research Letters, 46, 13992-14002, doi: 10.1029/2019GL083452.
- Trenary, L., T. DelSole, S.J. Camargo, and M.K. Tippett, 2019. Are mid-20th century forced changes in North Atlantic hurricane potential intensity detectable*? Geophysical Review Letters*, **46**, 3378-3386, doi:10.1029/2018GL081725. EOS Research Spotlight: Role of humans in past hurricane potential intensity is unclear, Eos, 100, doi: 10.1029/2019EO125003, Link, June (2019).

7. PI Contact Information

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8. Budget for Coming Year:

Project ended in July 2021.

9. Future Work

Publication of Domeisen et al. 2021, currently in review.