Department of Commerce
Research Performance Progress Report (RPPR)

1. Federal Agency: National Oceanic and Atmospheric Administration – Office of Oceanic and Atmospheric Research

2. Federal Grant Award Number: NA16OAR4310064

3. Project Title: Forecasting North Pacific Blocking and Atmospheric River Probabilities: Sensitivity to Model Physics and the MJO

4-5. Project/Grant Period (Start Date, End Date): 07/01/2016 - 06/30/2021

6-10. Project Director/Principal Investigator (PD/PI) Names, Titles, and Contact Information (email address and phone number):

CSU PI:
Elizabeth A. Barnes
Associate Professor
eabarnes@colostate.edu
970-491-8206

CSU Co-PI:
Eric Maloney
Professor
emaloney@atmos.colostate.edu
970-286-9410

11-15. Recipient Authorizing Official's Name, Title, and Contact Information (email address and phone number):
Bill Moseley, Senior Research Administrator Office of Sponsored Programs
2002 Campus Delivery
Fort Collins, CO 80523-2002
Phone: 970-491-1541
bill.moseley@colostate.edu

20-23. Recipient Organization (name, address, DUNS, EIN):
Colorado State University
601 South Howes St.
Fort Collins, CO 80521-2807
EIN 84-6000545
DUNS 785979618

16. Submission Date: September 2015
17. Current Reporting Period (start date, end date): 07/01/2016 - 06/30/2021
18. Report Frequency (annual, semi-annual, quarterly): annual
19. Final Annual Report? (yes or no): YES

SECTION 1. ACCOMPLISHMENTS

24. What were the major goals and objectives of this project?

The overarching aim of this work was to quantify the extent to which east Pacific blocking and atmospheric river probabilities could be skillfully forecast at lead times of multiple weeks through their dynamical link with the Madden-Julian Oscillation (MJO). The MJO is characterized by 30-90 day timescales and through its teleconnections to midlatitudes is a key climate phenomena for skillful S2S prediction. While this work ultimately addressed multiple key questions outlined by the NOAA S2S Prediction Task Force, the work predominantly addressed the Task Force key question (from the Task Force summary document from Year 1): How do tropical/extratropical and stratosphere/troposphere connections influence S2S prediction? While this work focused mostly on the MJO as a predictor, we expect the general framing and approach utilized here to be applicable for S2S prediction based on other climate indices as well.

The work can be summarized by four main scientific goals:

A. Quantification of the predictability and prediction skill of North Pacific blocking and atmospheric river probabilities through knowledge of the MJO.
B. Assessment of the sensitivity of forecast skill to MJO skill and model setup: model physics, model resolution and forecast lead time.
C. Deliver a database of extreme events (i.e. atmospheric rivers and blocking) from the reanalysis and hindcast models
D. Deliver statistical forecast models of extremes (i.e. atmospheric rivers and blocking)

We also had primary goals related to leadership of the MAPP S2S Task Force:

E. provide scientific leadership to the Task Force (PI Barnes is the Lead of the Task Force) by leading scientific papers, reports and special collections, organizing meetings and meeting sessions, leading teleconferences, facilitating collaboration across the Task Force.
F. linking to international efforts on advancing S2S prediction

25. What was accomplished under these goals?
(links to goals and activities denoted in brackets)

- [A,B,C,D] Publication of 23 peer-reviewed journal articles (See # 29)
- [F] The International Conference on Subseasonal-to-Decadal Meeting (Sept. 2018, Boulder CO) was attended by PI Barnes, Cory Baggett and Kai-Chih Tseng, all supported by this project.
- [E,F] PI Barnes helped organize the International Conference on Subseasonal-to-Decadal Meeting (Sept. 2018, Boulder CO).
- [E,F] PI Barnes and the other Task Force leads organized and facilitated monthly telecons across the Task Force from 2016-2020. These telecons focused on science

results and discussions of reports and special issues with the entire Task Force. Telecons averaged 25-50 participants per call.

- [E,F] Organization of Journal of Geophysical Research/Geophysical Research Letters Special Collection on S2S Prediction and publication of collection summary
- [E] Final NOAA Technical Report on the S2S Task Force was completed and published (report led by PI Barnes).
    - https://cpo.noaa.gov/Portals/0/OAR_CPO_MAPP_S2S%20Task%20Force.pdf?ver=2021-06-03-104446-203
- [E,F] PI Barnes was on the organizing committee for the NCAR ASP S2S Summer School that was held July 2021. Planning took place between 2020 and 2021.
- [E,F] Created an internal wiki that was used by the Task Force, providing resources for obtaining processed data, raw model output, overview presentations, etc.
- [E,F] Organization of a one-day NOAA MAPP S2S Kickoff Meeting at Columbia University's Lamont-Doherty Earth Observatory on Dec. 5, 2016; the event was very successful with participants representing all but one funded project; immediate actions stemming from the workshop have led to further development of the Task Force Wiki and a two-page summary document of the Task Force goals and scientific linkages; representatives from international S2S efforts were also present
- [E,F] PI Barnes flew to Washington D.C. to present about the MAPP S2S Task Force at a science and media event at NOAA Science days in June 2017.
- [E,F] Creation of a two-page summary document of the Task Force's driving questions and a schematic depicting how the different projects connect with each other; this document was used for both external communication of Task Force efforts but also to inform Task Force members of possible avenues for collaboration.
    - https://cpo.noaa.gov/Portals/0/Docs/MAPP/TaskForces/S2S%20Prediction/MAPP_S2S__2page_Summary.pdf
- [F] Many presentations on the results of this project were given at the following conferences/workshops: AMS 2019, AGU 2018, Climate Diagnostics and Prediction Workshop 2018, MAPP S2S Webinars, Western States Water Council (San Diego, CA), S2S/S2D Meeting (Boulder, CO). This includes a presentation on Task Force efforts by PI Barnes at the MAPP S2S Webinar held Feb. 21, 2018 with 100+ in attendance.

26. What opportunities for training and professional development has the project provided?

- Funded graduate students and postdocs to do research and go to scientific conferences to meet/connect with others in the community.
- PI Barnes was on the organizing committee for the NCAR ASP S2S Summer School that was held July 2021. Planning took place between 2020 and 2021. The summer school was open to graduate students and postdocs interested in S2S topics. The summer school featured lectures from domestic and international experts on the fundamental processes leading to S2S predictability such as the Madden-Julian Oscillation, sudden stratospheric warmings, and interactions with the land and cryosphere. Barnes gave a talk on machine learning with S2S prediction and participated in a debate. The co-PI

Maloney participated in the summer school by giving a lecture, technical science presentation, and by participating in a debate.

27. How were the results disseminated to the communities of interest?
Peer-reviewed publications, press stories, talks at conferences, department seminars by the PI and Co-PI.

28. What do you plan to do during the next reporting period to accomplish the goals and objectives?
None.

SECTION 2. PRODUCTS

29. Publications, conferences papers, and presentations

Published Reports

- NOAA MAPP S2S Task Force Final Report, Barnes et al. (2021), doi: 10.25923/795y-kn9, https://cpo.noaa.gov/Portals/0/OAR_CPO_MAPP_S2S%20Task%20Force.pdf?ver=2021-06-03-104446-203

Publications over the reporting period
In total, this project led to 23 peer-reviewed journal articles.

- Hsiao, Wei-Ting, Eric D. Maloney, and Elizabeth A. Barnes, 2020: Investigating Recent Changes in MJO Precipitation and Circulation in Multiple Reanalyses. Geophysical Research Letters, https://doi.org/10.1029/2020GL090139.
- Mariotti, Annarita, Elizabeth A. Barnes, Edmund Kar-Man Chang, Andrea Lang, Paul A. Dirmeyer, Kathy Pegion, Daniel Barrie, and Cory Baggett, 2019: Bridging the Weather-to-Climate Prediction Gap. EOS, https://doi.org/10.1029/2019EO115819.
- Baggett, Cory F. , Kyle M. Nardi, Samuel J. Childs, Samantha N. Zito, Elizabeth A. Barnes, Eric D. Maloney, 2018: Skillful 5 Week Forecasts of Tornado and Hail Activity. Journal of Geophysical Research: Atmospheres.
- Tseng, Kai-Chih, Eric Maloney and Elizabeth Barnes, 2018: The consistency of MJO teleconnection patterns: an explanation using linear Rossby wave theory. Journal of Climate, https://doi.org/10.1175/JCLI-D-18-0211.1.
- Baggett, C. F., E. A. Barnes, E. D. Maloney, and B. D. Mundhenk, 2017: Advancing atmospheric river forecasts into subseasonal-to-seasonal time scales. Geophys. Res. Lett., 44, 2017GL074434.
- Henderson, S. A., and E. D. Maloney, 2018: The impact of the Madden-Julian Oscillation on high-latitude winter blocking during El Niño-Southern oscillation events. J. Climate, 31, 5293–5318.

- Mundhenk, B. D., E. A. Barnes, E. D. Maloney, and C. F. Baggett, 2018: Skillful empirical subseasonal prediction of landfalling atmospheric river activity using the Madden–Julian oscillation and quasi-biennial oscillation. npj Climate and Atmospheric Science, 1, 7.
- Tseng, K.-C., E. A. Barnes, and E. D. Maloney, 2018: Prediction of the Midlatitude Response to Strong Madden-Julian Oscillation Events on S2S Time Scales. Geophys. Res. Lett., 45, 2017GL075734.
- Mariotti, Annarita; Cory Baggett; Elizabeth Barnes; Emily Becker; Amy Butler; Dan C Collins; Paul A Dirmeyer; Laura Ferranti; Nathaniel C. Johnson; Jeanine Jones; Ben P. Kirtman; Andrea L. Lang; Andrea Molod; Matt Newman; Andrew W. Robertson; Siegfried Schubert; Duane E. Waliser, 2019: Windows of Opportunity for Skillful Forecasts S2S and Beyond, BAMS.
- Lang, Andrea, Kathleen Pegion and Elizabeth A. Barnes, 2020: Bridging Weather and Climate: Subseasonal-to-Seasonal (S2S) Prediction, Journal of Geophysical Research - Atmospheres, doi: https://doi.org/10.1029/2019JD031833.
- Tseng, Kai-Chih, Elizabeth. A. Barnes and Eric D. Maloney, 2020: The importance of past MJO activity in determining the future state of the midlatitude circulation, Journal of Climate, https://doi.org/10.1175/JCLI-D-19-0512.1
- Jenney, Andrea, Kyle Nardi, Elizabeth Barnes, and David Randall, 2019: The Seasonality and Regionality of MJO Impacts on North American Temperature, Geophysical Research Letters, https://doi.org/10.1029/2019GL083950.
- Gonzales, K., D. Swain, K. Nardi, E. A. Barnes, and N. Diffenbaugh, 2019: Recent warming of landfalling atmospheric rivers along the west coast of the United States, Journal of Geophysical Research: Atmospheres, 10.1029/2018JD029860
- Anderson, G. Brooke, Elizabeth A. Barnes, Francesca Dominici, and Michelle Bell, 2019: The future of climate epidemiology: Examples of key opportunities for advancing research on climate and health in the context of climate change, American Journal of Epidemiology, https://doi.org/10.1093/aje/kwz034.
- Jenney, Andrea., D. Randall, E. Barnes: Quantifying regional sensitivities to periodic events, 2019: Application to the MJO. Journal of Geophysical Research: Atmospheres, https://doi.org/10.1029/2018JD029457.
- Stone, Kane, S. Solomon, D. Kinnison, C. Baggett and E. Barnes, 2019: Prediction of Northern Hemisphere regional surface temperatures using stratospheric ozone information, https://doi.org/10.1029/2018JD029626.
- Tseng, Kai-Chih, Eric D. Maloney and Elizabeth. A. Barnes, 2020: The consistency of MJO teleconnection patterns on interannual timescales, Journal of Climate.
- McGraw, M.C., C. F. Baggett, C. Liu, and B.D. Mundhenk, 2019: Changes in Arctic moisture transport over the North Pacific associated with sea ice loss, Climate Dynamics, https://doi.org/10.1007/s00382-019-05011-9.
- Nardi, Kyle M., Cory F. Baggett, Elizabeth A. Barnes, Eric D. Maloney, Daniel S. Harnos, and Laura M. Ciasto, 2020: Skillful all-season S2S prediction of U.S. precipitation using the MJO and QBO, Weather and Forecasting, doi:10.1175/WAF-D-19-0232.1.
- Toms, B. A., E. A. Barnes, E. D. Maloney, and S. C. van den Heever, 2020: The Global Teleconnection Signature of the Madden-Julian Oscillation and its Modulation by the

Quasi-Biennial Oscillation, Journal of Geophysical Research: Atmospheres, doi.org/10.1029/2020JD032653.
- Tseng, Kai-Chih, Nathaniel Johnson, Eric Maloney, Elizabeth A. Barnes and Sarah B. Kapnick, 2021: Mapping Large-scale Climate Variability to Hydrological Extremes: An Application of the Linear Inverse Model to Subseasonal-to-Seasonal prediction, Journal of Climate, https://doi.org/10.1175/JCLI-D-20-0502.1
- Mayer, Kirsten J. and Elizabeth A. Barnes: Subseasonal Midlatitude Prediction Skill Following QBO-MJO Activity, Weather and Climate Dynamics, https://www.weather-clim-dynam.net/1/247/2020/.
- Wang, J., H. Kim, D. Kim, S. A. Henderson, C. Stan, and E. D. Maloney, 2020: MJO teleconnections over the PNA region in climate models. Part II: Impacts of the MJO and basic state. J. Climate, 33, 5081–5101.

Conference Presentations
Nothing to report.

30. Technologies or techniques
Nothing to report.

31. Inventions, patent applications, and/or licenses
Nothing to report.

32. Other products
- **[D] Web Application:**
    - We developed a web application for visualizing predictions of weather anomalies at S2S leads using our empirical model based on the MJO, QBO, and ENSO. Weather variables include: precipitation, atmospheric rivers, integrated water vapor transport and surface temperature. The we application can be accessed here: http://barnes.atmos.colostate.edu/S2SPredictionModel/

SECTION 3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

33. What individuals have worked on this project?
Dr. Elizabeth Barnes, Dr. Eric Maloney, Kai-Chih Tseng (graduate student), Dr. Cory Baggett (research scientist), Wei-Ting Hsiao (graduate student), Kirsten Mayer (graduate student), Marie McGraw (graduate student)

34. Has there been a chance in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
No.

35. What other organizations have been involved as partners?
None other than those on the initial grant.

36. Have other collaborators or contacts been involved?
No.

SECTION 4. IMPACT

37. What was the impact on the development of the principal discipline(s) of the project?
This work has shown great promise in forecasts of opportunity using the MJO and the QBO states, and how these opportunities may be changing over the observational record.

38. What was the impact on other disciplines?
The major impact of this work on other disciplines is showing the utility of forecasts of opportunity for the prediction of severe weather (i.e. hail, tornadoes, atmospheric rivers).

39. What was the impact on the development of human resources?
Nothing to report.

40. What was the impact on teaching or educational experiences?
Nothing to report.

41. What was the impact on physical, institutional, and information resources that form infrastructure?
Nothing to report.

42. What was the impact on technology transfer?
Nothing to report.

43. What was the impact on society beyond science and technology?
This work is moving toward skillful forecasts of extreme weather multiple weeks in advance. This will benefit society as a whole, saving lives and reducing detrimental economic impacts.

44. What percentage of the award's budget was spent in foreign countries?
None.

SECTION 5. CHANGES/PROBLEMS

45. Changes in approach and reasons for change.
Nothing to report.

46. Actual or anticipated problems or delays and actions or plans to resolve them.
Nothing to report.

47. Changes that had a significant impact on expenditures

Nothing to report.

48. Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents.
Nothing to report.

49. Change of primary performance site location from that originally proposed
Nothing to report.

SECTION 6. SPECIAL REPORTING REQUIREMENTS

SECTION 7. BUDGETARY INFORMATION
Nothing to report.

SECTION 8. PROJECT OUTCOMES

50. What were the outcomes of the award?
While see accomplishments and products are provided in the above sections, major results from this project include the demonstration of significant skill at lead times of 2-5 weeks for extreme weather events (hail, tornadoes, atmospheric rivers) using empirical prediction models based on climate phenomena including the MJO, QBO and ENSO. For example, Baggett et al. (2018) demonstrates that an empirical prediction scheme based solely on the MJO phase and lead time exhibits significant Heidke Skill Scores for predicting tornado and hail events over the U.S. Plains in springtime (the time of most severe weather). Our analysis shows that the MJO (through its propagation) is indeed the reason for this enhanced skill. Using the MJO as a predictor, skillful weekly forecasts of severe weather with lead times of 2–5 weeks can be realized. See Baggett et al. (2018) for the original figure and more details.

In addition to demonstrating skill at S2S leads with empirical models, multiple other studies under this project explored the dynamical reasons for the observed behaviour of MJO teleconnections. Specifically, this work showed that some MJO phases exhibit more robust teleconnections than others that translate to forecasts of opportunity, and that this can be largely explained by the location and behaviour of the subtropical Rossby wave source. MJO phases with Rossby wave sources that resemble an east-west dipole spanning the Pacific jet produce more robust teleconnections.

As this work strongly focused on identifying and exploiting “forecasts of opportunity”, additional contributions of this project include multiple publications specifically describing and outlining the potential utility of these forecasts of opportunity for S2S prediction, and how this approach differs from the more typical approach taken for short term forecasts. We additionally developed a web application for visualizing these forecasts of opportunity of weather anomalies, and their skill, at S2S leads using our empirical model based on the MJO, QBO and ENSO.

END OF REPORT TO UPLOAD TO NOAA'S GRANTS PAGE

The following page will be submitted as a single page PDF.