(SubX) Developing a Real-Time Multi-Model Sub-Seasonal Predictive Capability
Progress Report

1. General Information

Project Title: (SubX) Developing a Real-Time Multi-Model Sub-Seasonal Predictive Capability
PI/co-PI names and institutions:

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Report Year: Final Report: 07/01/2016 - 06/30/2019
Grant #: NA16OAR4310141

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

Coordination Activities

- Collecting and Serving Data: Re-forecasts and real-time
- Baseline Verification
- Multi-model Evaluations and Combinations
- Communications

Production of Environment Canada Re-forecasts and Forecasts

3. Results and accomplishments

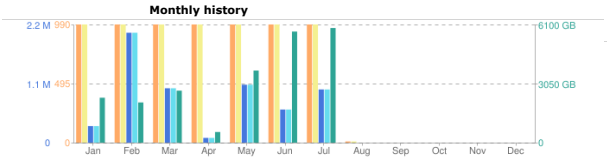
The SubX project had a formal CTB review on August 19th, 2019. The review report prepared by the review panel from that assessment is expected to be completed and forwarded to the appropriate program management team very soon.

a) Production & Dissemination of re-forecasts

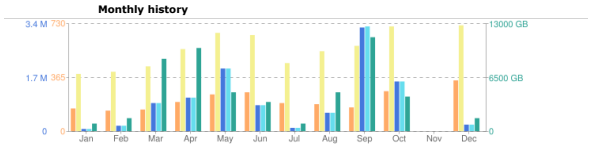
SubX provides a publicly available database of seventeen years of historical re-forecasts (1999-2015). All groups have provided re-forecasts for the 1999-2015 period with the exception of ECCC-GEM (1999-2014) (ECCC-GEM runs its re-forecasts on the fly as part of their operational practice and will fill in 2015 at a later date) and most have provided additional re-forecasts to fill the gap between the end of the SubX re-forecast period and beginning of the real-time forecasts in July 2017. Additionally, ECCC began providing re-forecasts and real-time forecasts from their new model in Sep 2018.

The SubX database is archived in IRI Data Library (http://iridl.ldeo.columbia.edu/SOURCES/.Models/.SubX/) where they are made publicly available as datasets that can be visualized, downloaded, and included in computations within the IRIDL interface. IRIDL staff also respond to user requests for assistance in

accessing or using the data. The SubX database at the IRIDL currently contains 18TB of data. Since the beginning of 2018, 72TB of SubX was downloaded, with over 11,000 visits to the data (Figure 1). Real time forecasts usually become available for download within a day or two. In addition to the model forecast and reforecast fields, the ROMI MJO indices are also updated in real time.



Month	Unique visitors	Number of visits	Pages	Hits	Bandwidth
Jan 2019	346	782	343,683	344,839	2200.48 GB
Feb 2019	326	859	2,157,416	2,157,867	1966.71 GB
Mar 2019	349	988	1,061,431	1,062,968	2580.01 GB
Apr 2019	353	759	92,022	94,023	565.29 GB
May 2019	315	808	1,130,738	1,131,745	3539.17 GB
Jun 2019	275	767	648,333	649,250	5445.44 GB
Jul 2019	340	828	1,044,519	1,046,017	5628.79 GB
Aug 2019	1	1	1	1	11.19 MB
Sep 2019	0	0	0	0	0
Oct 2019	0	0	0	0	0
Nov 2019	0	0	0	0	0
Dec 2019	0	0	0	0	0
Total	2,305	5,792	6,478,143	6,486,710	21925.89 GB



Month	Unique visitors	Number of visits	Pages	Hits	Bandwidth
Jan 2018	156	394	96,924	98,937	942.55 GB
Feb 2018	147	410	198,121	202,771	1578.94 GB
Mar 2018	155	448	938,004	939,517	8760.12 GB
Apr 2018	204	568	1,104,055	1,105,523	10123.53 GB
May 2018	255	679	2,032,587	2,033,616	4783.12 GB
Jun 2018	270	659	854,136	855,454	3622.15 GB
Jul 2018	195	469	111,658	113,891	960.19 GB
Aug 2018	192	553	612,345	613,218	4809.17 GB
Sep 2018	170	585	3,394,948	3,395,800	11444.45 GB
Oct 2018	278	718	1,632,084	1,634,240	4186.76 GB
Nov 2018	1	1	1	1	8.70 MB
Dec 2018	354	728	239,767	240,374	1577.83 GB
Total	2,377	6,212	11,214,630	11,233,342	52788.83 GB

Figure 1: IRIDL SubX Database statistics for 2018-present.

b) Weekly Real-time Forecasts

The SubX participating modeling centers have produced new forecasts each week since July 2017. These are provided to the NOAA Climate Prediction Center (CPC) as dynamical guidance for their official week 3-4 temperature outlook and experimental week 3-4 precipitation outlook, issued every Friday. The CPC outlooks show regions of increased probability of above-normal or below-normal temperature and precipitation, and regions where the probabilities of above or below normal are equally likely (i.e. 50/50 chance). Using guidance from the realtime SubX forecasts for 2m temperature, precipitation, and 500hPa geopotential heights as well as other tools, NCEP/CPC forecasters produce the official maps for week 3-4 outlooks.

We have evaluated the skill of the SubX real-time 2m temperature forecasts produced from July 2017 - Dec 2018. Overall the real-time forecasts have similar skill to the re-forecasts (Figure 2). The real-time forecasts are also substantially more skillful over the continental US than the re-forecasts. Skill is expected to vary from year to year, depending on the presence or absence of major modes of climate variation, land surface conditions, and other factors. The sources of the higher skill over the continental

US during this period remain to be identified, but could come from the trend, ENSO, or other sources.

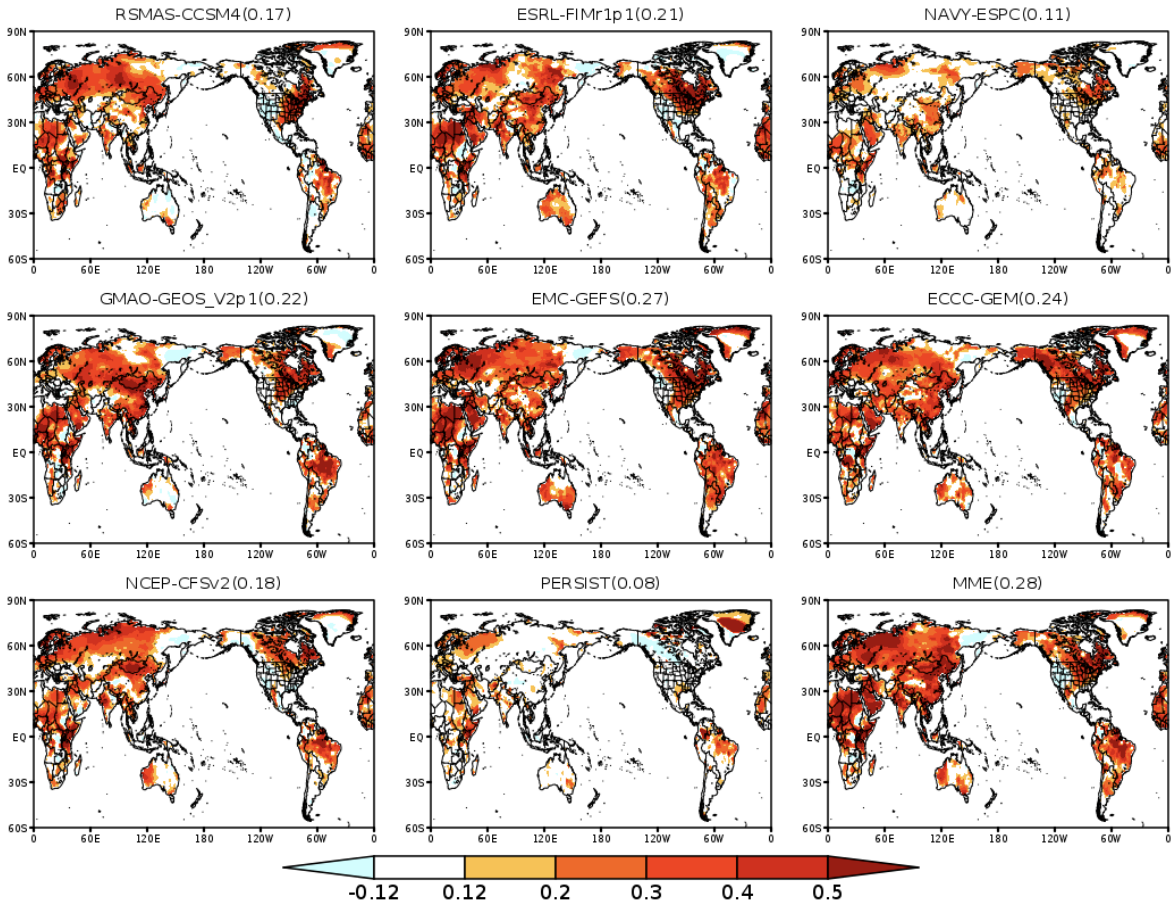


Figure 2 SubX real-time 3-week (average of forecast days 15-21) forecast skill for 2m Temperature over the period Jul 2017-Dec 2018. Numbers in parenthesis indicate the average ACC value over all land points in the domain.

The over-all forecast skill assessment is provided comprehensively in Pegion et al. (2019). Here we show a couple of plots that are noteworthy highlights. In particular, Fig. 3 shows the anomaly correlation for T2m and precipitation for week 3-4 forecasts initialized in the winter and summer. As expected the skill is better in winter than summer and better for T2m than for precipitation.

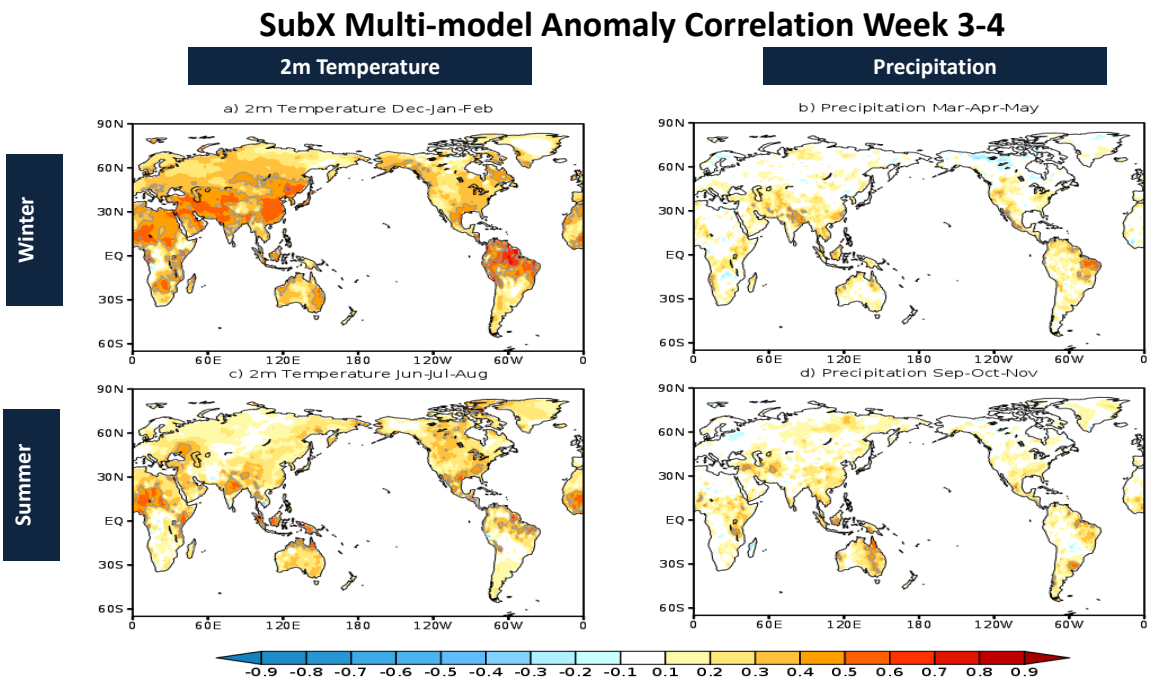


Figure 3: Anomaly correlation coefficient for week 3-4 forecasts of T2m and precipitation initialized during the winter and summer. Forecast years are 1999-2016.

c) Real-time Prediction of Hazardous and Extreme Events}

Disaster preparedness and emergency management is one sector for which prediction of hazardous and extreme weather on S2S timescales is of particular interest. As an example of how SubX real-time forecasts can potentially provide information useful to this sector, Figure 4 shows precipitation forecasts associated with Hurricane Michael for the SubX real-time forecasts. These forecasts were issued on Sep 20, 2018, prior to the formation of Michael, and were valid for the two week period of Oct 6-19. All SubX models indicated the potential for precipitation anomalies in this period in excess of 50mm over the two week period along a line stretching from southwest to northeast across Florida at 3-weeks lead time. Tropical storm Michael formed on Oct 7 and made landfall as a hurricane along the Florida panhandle on Oct 10. The storm tracked across the panhandle and through the southeastern US, delivering heavy rainfall. Although the actual track is not accurately predicted at this lead-time, the forecast for a potential tropical cyclone and associated enhanced precipitation during this period is useful information, potentially helping emergency managers to plan and aid organizations to stage supplies in anticipation of a disaster. A similar early picture was provided by SubX for Hurricane Harvey. SubX models forecasted anomalously high precipitation over the week spanning August 24-31 in Texas and Louisiana at 3-4 week lead times (not shown). Case studies such as these add to our understanding of the prediction and predictability of extreme events, especially in the context of a database designed for operational considerations.

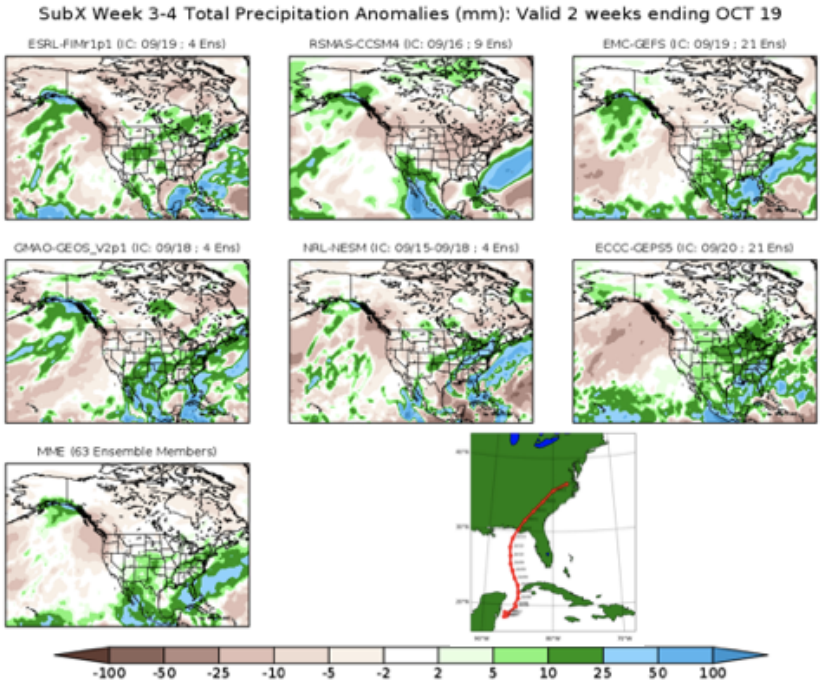


Figure 4 SubX real-time forecasts for total precipitation anomalies (mm) for the 2-week period of Oct 6-19 issued on Sep 17, 2019. The observed track of Hurricane Michael from from Oct 7-12 is shown in the bottom right panel. Hurricane track data are from the initial tropical cyclone position (i.e. TC Vitals) obtained from the National Hurricane Center.

d) Baseline Verification, Model Comparison, and Multi-model Skill

The SubX team has evaluated deterministic and probabilistic skill of individual models and the multi-model ensemble for 2m temperature, and precipitation for week 3-4 forecasts. The full suite of maps for all months/seasons are available on the SubX website (http://cola.gmu.edu/kpegion/subx/skill/skill.html). For both 2m temperature and precipitation, the MME provides benefit over any single model for all seasons (not shown, but available in the submitted BAMS paper available at http://cola.gmu.edu/kpegion/subx/docs/SubXBAMSRevision.pdf).

The skill of SubX re-forecasts is also assessed in terms of their pattern structure. A question of particular interest is whether the multi-model mean has significantly more skill than an individual model. This question is addressed using the random walk test of \cite{dt_randomwalk}. For each 2-week mean hindcast, the pattern correlation with respect to observations over U.S. and Canada is computed. The random walk score is a function of time that starts at zero and, for each hindcast, goes up one unit if the multi-model mean has a larger pattern correlation than the model being compared, otherwise the score goes down one unit. The score is tallied for each SubX model separately. The resulting random walk scores for week 3-4 2m-temperature and precipitation are shown in Figure 5. As seen in the figure, the score is positive for each model by the end of the period, indicating that the multi-model mean has larger pattern correlation more frequently than any single model. Moreover, the score is statistically significant at

the 5\% level in all cases except one, namely the CFSv2 hindcasts of 2m-temperature (although the score still is positive). These results demonstrate that the multi-model mean predicts the anomaly pattern for temperature and precipitation more skillfully, more frequently, than any individual model, and this frequency is statistically significant in almost all cases considered.

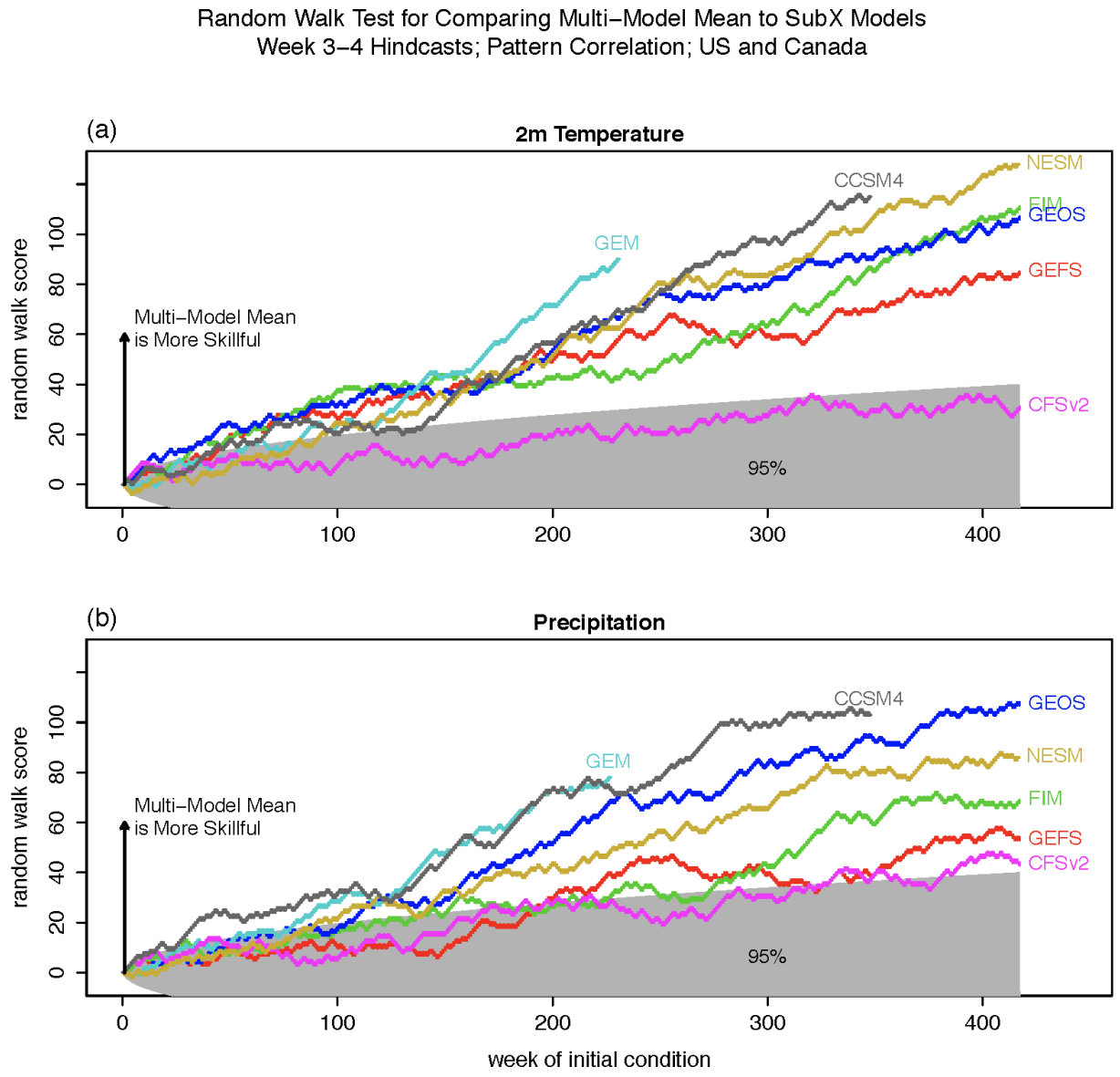


Figure 5 Results of performing the random walk test for comparing the multi-model mean to individual model hindcasts of week 3-4 temperature (a) and precipitation (b). The x-axis refers to the week of the initial condition, but the corresponding date may differ across models because of verification gaps. The shaded region indicates the 95% probability range in which the random walk would lie if a given model were equally as skillful as the multi-model mean. In particular, a random walk that goes above the

shaded region indicates that the multi-model mean has a higher pattern correlation more frequently (at the 5% level) than the model being compared.

e) SubX Research

The SubX Project has created 3 working groups to perform more focused research and model evaluation efforts. The groups are as follows:

- Verification - Climatology, bias corrections, deterministic and probabilistic verification, multi-model combinations.

  This working group has produced climatologies, evaluating model biases, and a range of deterministic and probabilistic skill scores which will be presented in a more comprehensive paper than possible in BAMS (paper in prep). This group is also evaluating the skill of the individual SubX MME versus the skill of various MMEs with different model combinations using the random walk methodology described above and a paper on these combinations is anticipated.

- MJO - Skill, process-based evaluation, impacts, providing MJO indices to the SubX at the IRIDL

  This working group has provided a basic evaluation of MJO re-forecast skill using RMM and ROMI indices and provided these indices to the IRIDL. They have also evaluated the MJO propagation, processes and biases in the SubX models and compared to the S2S models. A paper titled “MJO Propagation Processes and Mean Biases in the SubX and S2S Reforecasts” is in preparation.

- NAO - Skill, impacts, MJO-NAO, NAO-SST, providing NAO indices to the SubX database at the IRIDL

  This group has evaluated the skill of Pacific-North American pattern (PNA) and the North Atlantic Oscillation (NAO) in the extended winter season (November to March) in the SubX models. The Northern Hemisphere teleconnection associated with the Madden-Julian Oscillation (MJO) is also evaluated for the SubX models. A paper titled “Subseasonal Forecast Skill of the PNA and NAO in boreal winter by the Sub-seasonal Experiment (SubX) Models” is in preparation.

f) Communications: Conference Calls, Website, Google Drive, Github

The SubX website (http://cola.gmu.edu/kpegion/subx/) provides information about the project, details on models and their configuration, how to access data, real-time forecast maps, and model evaluation. Real-time forecast maps are posted and users can also view previous forecasts (http://cola.gmu.edu/kpegion/subx/forecasts/forecasts.html). Additionally an interactive forecast viewer is available for the most recent forecasts (http://wxmaps.org/subx_custom.php). Model evaluation of skill and bias are also

posted on the website (http://cola.gmu.edu/kpegion/subx/skill/forecasts.html). Data documentation and codes for downloading and processing the SubX data are also made available.

The IRI produces a SubX Real Time Precipitation Probability Forecast Maproom
The IRI has been issuing calibrated global probabilistic forecasts of biweekly precipitation based on SubX in real time since August 2018. The forecasts are issued every Friday, based on the output from 3 SubX models, CFSv2, GEFS, and ESRL-FIM which are all initialized on Wednesdays. The forecasts are presented in a maproom in tercile format, showing the probability of the dominant tercile category in a similar fashion to IRI's seasonal forecasts: (http://iridl.ldeo.columbia.edu/maproom/Global/ForecastsS2S/precip_subx.html?S=0000%2026%20Apr%202019)

The SubX team holds semi-monthly conference calls that began in Sep 2016. Additionally, the individual SubX working groups also hold conference calls, maintains a Google Drive folder for collaboration and coordination between team members, and provides codes for downloading and processing the SubX data from the IRIDL.

g) SubX Presentations

The SubX team have given 20+ presentations over the last year of the project, including:

1. Achuthavarier, D, R. Koster, S. Schubert, J. Marshak and A. Molod, 2019: MJO Teleconnection Signals and Prediction Skill in the NASA GEOS Subseasonal Reforecasts, Topics in Atmospheric and Oceanic Sciences, School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY. (Oral)

2. Achuthavarier, D., R. Koster, S. Schubert, J. Marshak and A. Molod, 2018: MJO Teleconnection Signals in the NASA GEOS-5 Subseasonal Reforecasts, Subseasonal to Seasonal Prediction of Weather and Climate, Washington D.C., Amer. Geophy. Union Fall Meeting. (Oral)

3. Achuthavarier, D., R. Koster, J. Marshak, S. Schubert and A. Molod, 2018: prediction skill of the MJO teleconnection signals in the NASA GEOS-5 subseasonal reforecasts, Second International Conference on Subseasonal to Seasonal Prediction, Boulder, CO. World Climate Research Program. (Poster)

4. Achuthavarier, D., R. Koster, J. Marshak, S. Schubert and A. Molod, 2018: Prediction and predictability of the Madden Julian Oscillation in the NASA GEOS-5 seasonal-to-subseasonal system, Sixth Symposium on Prediction of the Madden-Julian Oscillation: Processes, Prediction and Impact, Austin, TX, Amer. Meteor. Soc. (Poster)

5. DelSole, T., “Recent Developments in Forecast Quality Assessment", 2018 Second International Conference on Seasonal to Decadal Prediction (S2D), Boulder CO, September 19, 2018.

6. Kim, H., Matthew A. Janiga, Deepthi Achuthavarier, Kathy Pegion, "Process-based MJO hindcast evaluation in SubX", International Conference on Subseasonal to Decadal Prediction (S2D)”, NCAR, Boulder, CO, USA, September 14-22, 2018

7. Kim, H., "Process-based MJO hindcast evaluation in S2S and SubX models", Intraseasonal oscillations and extended-range prediction workshop, Taiwan, 10/18/2018

8. Kim, H., Matthew A. Janiga, Deepthi Achuthavarier, Kathy Pegion, "Process-based MJO evaluation in SubX and S2S hindcasts", AGU Fall 2018

9. L’Heureux, M. and M. K. Tippett, Skill of California Precipitation on S2S timescales, AGU Fall Meeting, Washington, D.C., Dec 10-14, 2018.

10. Pegion, K., Bridging the Gap between Weather and Climate Prediction using Multi-model Ensembles, University of Colorado, Boulder, CO, Feb 2019

11. Pegion, K., The Subseasonal Experiment (SubX), Dynamics Group Meeting/CSU, Fort Collins, CO Nov 2018

12. Pegion, K., The Subseasonal Experiment (SubX), NCAR/CGD Seminar, Boulder, CO, Nov 2018

13. Pegion, K., The Subseasonal Experiment (SubX), NOAA/ESRL/GSD Seminar, Boulder, CO, Oct 2018

14. Pegion, K., The Subseasonal Experiment (SubX), NOAA/Climate Diagnostic and Prediction Workshop, Santa Barbara, CA, Oct 2018

15. Pegion, K., The Subseasonal Experiment (SubX), Second International Conference on Subseasonal to Seasonal Prediction (S2S), Boulder, CO, Sep 2018

16. Pegion, K., Metrics for S2S: Examples from SubX, National Earth System Prediction Capability Workshop on Metrics, Postprocessing, and Products for Subseasonal to Seasonal Timeframes, College Park, MD, Feb 2018

17. Pegion, K., The Subseasonal Experiment, NOAA/ESRL, Boulder, CO, Jan 2018

18. Robertson, A.W., N. Vigaud, J. Yuan, M. Tippett, D. Collins, 2018: Calibrated Multi-model Probabilistic Sub-seasonal Forecasts Based on SubX and S2S Models. AGU Fall Meeting, Dec 12, 2018.

19. Robertson, A.W, 2018: “Connecting Climate, Weather, and Water: Status, Challenges, and Needs for Subseasonal-to-Seasonal Forecasting for Water Use and

Management", National Academy Of Sciences, Washington DC, November 30, 2018. Keynote Speaker.

20. Sun. S. and K. Pegion, Real-time Subseasonal Forecast with SubX, American Meteorological Society, Annual Meeting, Pheonix, AZ, Jan 2019.

21. Zhu, Yuejian, Wei Li1, Eric Sinsky, Hong Guan, Xiaqiong Zhou and Bing Fu, 2019: An Assessment of Predictability and Prediction of NCEP GEFS for Subseasonal Forecast. S2S workshop, Reading, UK.

22. Zhu, Y., W Li, E Sinsky, H Guan, X Zhou and B Fu, 2018: An Investigation of Prediction and Predictability of NCEP Global Ensemble Forecast System (GEFS). Science and Technology Infusion Climate Bulletin, NOAA's National Weather Service, 43rd NOAA Annual Climate Diagnostics and Prediction Workshop

4. Highlights of Accomplishments

- Complete re-forecast database, including climatologies
- Weekly Real-time forecasts
- Comprehensive skill evaluation of 2m temperature and precipitation
- MJO and NAO Skill evaluation
- Submitted BAMS paper

5. Transitions to Operations/Applications

SubX real-time forecasts are used as guidance to CPC's week 3-4 forecasts.

6. Estimate of current technical readiness level of work

RL 6/7: SubX has been tested in a real-time environment. Evaluation of re-forecast and real-time forecast skill shows capability to make skillful subseasonal predictions and a potential to benefit operational predictions for week 3-4.

7. Publications from the Project

1. Achuthavarier, D, R. Koster, S. Schubert, J. Marshak and A. Molod, 2019: MJO Teleconnection Signals and Prediction Skill in the NASA GEOS Subseasonal Reforecasts.

2. Diro, G. T., and H. Lin, 2019: Subseasonal forecast skill of snow water equivalent and its link to surface air temperature in three SubX models. Weather and Forecasting, under review.

3. Guan H, Y Zhu, E Sinsky, W Li, X Zhou, D Hou, C Melhauser, R Wobus, 2018: Systematic Error Analysis and Calibration of 2-m Temperature for the NCEP GEFS Reforecast of Subseasonal Experiment (SubX) Project. *Weather Forecasting*, 34, 361-376

4. Janiga, M. A., J Schreck, C., III, Ridout, J. A., Flatau, M., Barton, N. P., Metzger, E. J., & Reynolds, C. A. (2018). Subseasonal Forecasts of Convectively Coupled Equatorial Waves and the MJO: Activity and Predictive Skill. *Monthly Weather Review*, *146*(8), 2337–2360. http://doi.org/10.1175/MWR-D-17-0261.1

5. Kim, H., Matthew A. Janiga, Kathy Pegion, Deepthi Achuthavarier: MJO Propagation Processes and Mean Biases in the SubX and S2S Reforecasts, JGR-atmos (in preparation)

6. Li, W, Y Zhu, X Zhou, D Hou, E Sinsky, C Melhauser, M Peña, H Guan, R Wobus, 2018: Evaluating the MJO Prediction skill from Different Configurations of NCEP GEFS Extended Forecast. *Climate Dynamics*, 52, 4923–4936

7. Pegion, K. and Co-authors, 2019: The Subseasonal Experiment (SubX): A multi-model subseasonal prediction experiment, *under revision*

8. Poan, E., and H. Lin, 2019: Subseasonal Forecast Skill of the PNA and NAO in boreal winter by the Sub-seasonal Experiment (SubX) Models. In preparation.

9. Sun, S., Benjamin W. Green, Rainer Bleck, and Stanley G. Benjamin. (2018) Subseasonal Forecasting with an Icosahedral, Vertically Quasi-Lagrangian Coupled Model. Part II: Probabilistic and Deterministic Forecast Skill. *Monthly Weather Review* **146**:5, 1619-1639.

10. Sun, S., Rainer Bleck, Stanley G. Benjamin, Benjamin W. Green, and Georg A. Grell. (2018) Subseasonal Forecasting with an Icosahedral, Vertically Quasi-Lagrangian Coupled Model. Part I: Model Overview and Evaluation of Systematic Errors. *Monthly Weather Review* **146**:5, 1601-1617.

11. Tippett, M. K. and W. J. Koshak. A baseline for the predictability of U.S. cloud-to-ground lightning. Geophys. Res. Lett., 45, 10,719–10,728, 2018. doi:10.1029/2018GL079750.

12. Zhu Y, X Zhou, M Peña, W Li, C Melhauser, D Hou, 2017: Impact of sea surface temperature forcing on weeks 3 & 4 prediction skill in the NCEP global ensemble forecasting system. *Weather Forecast*, 32:2159–2174

13. Zhu, Y, X Zhou, W Li, D Hou, C Melhauser, E Sinsky, M Pena, B Fu, H Guan, W Kolczynsk, 2018: Toward the improvement of sub-seasonal prediction in the NCEP Global Ensemble Forecast System (GEFS). *J. Geophys. Res. Atmos.*, 123, 6732–6745

14. Zhu, Y. W Li, X Zhou and D Hou, 2018: Stochastic Representation of NCEP GEFS to Improve Sub-seasonal Forecast. Book chapter.

15. IRI media story from Oct 2017 mentions SubX: https://iri.columbia.edu/news/iri-data-library-hosts-new-experimental-forecasts/

8. High Performance Computing Use
GMU- None

9. PI Contact Information
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10. Budget for Coming Year
No cost extension has been requested through June 30, 2019 for GMU PIs Pegion and DelSole to complete papers/analysis in preparation.

11. Future Work
- BAMS Paper published
  Pegion, K. and Co-authors, 2019: The Subseasonal Experiment (SubX): A multi-model subseasonal prediction experiment, in press
- A more comprehensive assessment of skill for individual models and more details and evaluation for constructing and evaluating the skill of a MME than was possible in a BAMS paper, including: model mean biases, seasonal evaluation of skill for 2m temperature, precipitation, 500 hPa height by week, evaluation of MME relative to CFSv2 using random walk method of DelSole and Tippett, comparison of skill with the WWRP/WCRP S2S models, and evaluation of a various models combinations to SubX MME skill. These activities are already in progress, but need additional time to be completed and papers submitted.
- Completion and submission of papers currently in preparation.