Synoptic to Intraseasonal Scale Interactions

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Much Earth system variability manifests as transfers of energy, momentum, and mass between processes occurring on an extremely broad range of temporal and spatial scales. Yet interactions between the synoptic, intraseasonal, and interannual scales set some of the most prominent patterns of variability of the atmosphere, the upper ocean, and the land surface.

For example, moisture transport by synoptic-scale atmospheric rivers sets the seasonal mean surface hydrology of much subtropical land and is in turn modulated by the months-long eastward propagation of moisture anomalies across the Indo-Pacific Oceans associated with the Madden-Julian Oscillation (MJO; Madden and Julian, 1971). Interannual variations of seasonal-mean, planetary-scale winds induced by the El Niño-Southern Oscillation (ENSO) alter the MJO and the hydrodynamically unstable basic state out of which monsoon depressions and easterly waves emerge; the MJO and synoptic-scale westerly wind bursts in turn alter the initiation and evolution of ENSO events. The existence of such interactions has been known for decades, yet only now are numerical methods and computational resources available to enable more accurate simulation of these interactions down to the synoptic scale, thus enabling a new era in the study of the eddy-mean flow interactions that dominate the hydrological cycle. For example, a horizontal grid spacing of around 25 km in global atmospheric models is beginning to represent many convectively coupled atmospheric vortices and waves, blocking events, atmospheric rivers, and other weather phenomena. The coming decade is thus an opportune time to address longstanding questions of eddy-mean flow interactions across this range of scales.

Grand Challenge Question: *How do synoptic-scale disturbances and intraseasonal modes of variability emerge from—and feed back onto—the seasonal mean land-atmosphere-ocean-ice state, and how will these interactions evolve in a changing climate?*

Implicit in this challenge is the question of how synoptic to intraseasonal variability, and its relationship with the seasonal mean background state, will evolve as climate changes. Here we set our sights on new sources of predictability and novel understanding that will enable us to project secular changes in synoptic-scale and intraseasonal variability.

A key component of synoptic to intraseasonal scale predictability is serial clustering of extreme events. This has both implications for societal impacts but also links to important large-scale atmospheric states and predictability. Understanding the geospatial variability in event clustering (e.g. the occurrence of windstorms and/or windstroms coupled with surface icing) will aid both .

Expertise across existing projects within RGMA offers a unique opportunity to advance our understanding of synoptic to intraseasonal scale interactions by organizing research across the following science questions:

- How does synoptic to intraseasonal variability shape (and feed back on) the background mean state? How do changes in Earth system drivers impact this variability?
- What are the modes of atmospheric variability that have yet to be tapped for extending the forecast beyond the typical weather range? For those already identified, what are the mechanisms of the added predictability?
- What are the first-order dynamic and thermodynamic constraints on the subseasonal to seasonal evolution and poleward reach of monsoons, which control climate over nearly all low-latitude land, including the southwestern US?
- What are the foundational building blocks for the MJO? What is the origin of MJO predictability and how does this manifest as predictability for subtropical to mid-latitude extremes?
- To what extent can sea ice melt be considered a forcing for midlatitude variability and extremes in the context of the coupled Earth system?
- What are the respective roles of polar and extra-polar forcings in driving changes at high latitudes?
- How do land surface processes interact with synoptic and intraseasonal atmospheric disturbances?

Description of Current Challenges and Research in RGMA

Existing lines of research in the RGMA portfolio address a wide range of topics on synoptic to interannual variability.

Modes of Subseasonal Variability: Internal modes of variability are the result of deterministic dynamics and feedbacks from constituent processes and hence of unique predictability beyond the typical weather range; external climate forcings often drive the climate by projecting on these internal modes. Considerable activities are centered around understanding the formation mechanisms of poorly understood modes (e.g., the MJO and the Baroclinic Annular Mode [BAM]; Thompson and Barnes, 2014) through phenomenon-focused diagnostics and hypothesis-driven modeling. Activities also focus on understanding the possible influence of these modes on tropical and subtropical extremes, such as tropical cyclones (TCs) and atmospheric rivers (ARs).

Detection and Statistical Characterization: Effort is also ongoing to statistically characterize daily-to-seasonal precipitation variability and detect the change of hydrological extremes in the past and future under climate change. A good example is the Atmospheric River Tracking Method Intercomparison Project (ARTMIP; Shields et al., 2018) for ARs that characterizes uncertainty in AR science associated with uncertainty in the tracking methods.

Monsoons: Recognizing that monsoons are multi-scale phenomena involving interactions across a wide range of scales from the convective (1 km) to the planetary (10^4 km), and also recognizing that large uncertainties exist in projections of future monsoon rainfall, effort has focused on fundamental dynamic and thermodynamic constraints on the seasonal evolution of tropical precipitation, as well as on the sensitivity of synoptic disturbance genesis and intensification to the background seasonal mean state.

Polar-Extra-polar Interactions: There has been considerable interest in the scales between synoptic to decadal on two themes: i) High- or variable-resolution modeling for capturing the fine-structured processes of the polar climate system itself and polar-extra-polar interactions; ii) identifying/understanding the robust impacts of Arctic sea ice melt on midlatitude weather and extremes and the associated teleconnection mechanisms through development of metrics and hierarchical modeling.

Research Gaps and Future Directions

The search for fundamental understanding remains—and should remain—the central driving force for research within RGMA, especially for subjects such as the MJO, BAM, TCs, ARs, etc. For example, gaps in understanding of the fundamental formation and propagation mechanisms of the MJO hamper advances in simulation of the MJO by the model development community, initialization of the MJO by the numerical weather and subseasonal prediction communities, and projection of long-term changes in MJO activity by the climate change community. This lack of understanding is rooted in the multi-scale, multi-component nature of these phenomena. Process-based approaches are still valuable in this regard: e.g., process/feedback/component denial experiments that leverage the modeling hierarchies developed within RGMA. Understanding of the energy and enstrophy cascades may give insights into the limit of prediction of certain phenomena (e.g., mesoscale convective systems).

There are two general research approaches that, when combined with existing expertise and investments within RGMA, are most likely to advance fundamental understanding leading to predictive understanding of the Earth system: holistic modeling and analysis approaches that emphasize inter-scale, inter-component, tropics-to-extratropics, and polar-extra-polar interactions; and statistically oriented analyses that are explicitly merged with physical principle-based diagnostic approaches (e.g., physics-guided machine learning approaches). The following research directions will advance our ability to understand synoptic to intraseasonal interactions in the Earth system.

Short Term (3-5 years) Research Goals

- Determine where, when, and for what applications high resolution is necessary to accurately represent synoptic and intraseasonal modes, and their interactions, in Earth system models; attention should especially be focused on attribution of bias in low-resolution simulations to unresolved processes and to bias in large-scale boundary conditions and forcings.

- Develop new statistically advanced and computationally efficient analysis frameworks to understand and assess the fidelity of cross-scale interactions in upcoming exascale Earth system simulations; these frameworks should explicitly be designed to digest exabytes of data and should leverage existing RGMA investments in statistics and machine learning to enable new scientific understanding.
- Improve the synergistic use of high-resolution remote sensing data, modern ensemble atmosphere-ocean reanalyses, and operational atmospheric state estimates (e.g. from numerical weather prediction) to create process-based diagnostics of synoptic-scale and intraseasonal phenomena. Emphasize use of ensembles to characterize uncertainty, as well as novel estimates of atmospheric state tendencies due to radiation, latent heating, surface drag, and other subgrid-scale processes typically parameterized in global Earth system models.
- Systematically characterize the causal relationship between synoptic-scale disturbances, intraseasonal modes of variability, and extreme events.
- Develop model hierarchies to assess the sensitivity of synoptic-scale and intraseasonal phenomena to the seasonal-mean background state. E.g., combine regional cloud-resolving models that employ imposed lateral boundary conditions with global model ensembles, land- or ice-surface models, or atmosphere-ocean state estimates; Bayesian frameworks and data assimilation techniques may be useful here.
- Expand the use of *in situ* data, especially from ARM facilities and other BER platforms, in the assessment of synoptic-scale and intraseasonal phenomena in global models; employ direct observations of surface fluxes of radiation, water, and heat to expand understanding of the role of these fluxes in synoptic-scale and intraseasonal variability.

Long Term (10 years) Research Goals

- Understand the physical processes responsible for interactions between synoptic-scale disturbances, intraseasonal modes, and the seasonal-mean background state by addressing questions of how and where hydrodynamic instability of the background state causes synoptic variability, how upscale momentum and energy transfers allow the ensemble of synoptic variability to influence the seasonal mean, and how intraseasonal modes (e.g. the MJO) undergo two-way interactions with the seasonal mean state and with the ensemble of synoptic disturbances.
- Understand how the above cross-scale interactions set regional Earth system variability and teleconnections and how they affect predictability and prediction of the long-term statistics of synoptic and intraseasonal variability.
- Create new projections, and better constrain existing projections, for the response of synoptic-scale and intraseasonal phenomena to warming, with specific focus on implications for regional hydrologic change over land.

- Develop simple models—conceptual, statistical, and theoretical—that augment and validate future projections of synoptic-scale and intraseasonal variability made by exascale Earth system models. Empirically constrained, physically motivated simple models provide a way to confirm and expand on results from much more complex Earth system models.

References

Madden, R. A., & Julian, P. R. (1971). Detection of a 40–50 Day Oscillation in the Zonal Wind in the Tropical Pacific. *Journal of the Atmospheric Sciences*, *28*, 702–708. https://doi.org/10.1175/1520-0469(1971)028<0702:doadoi>2.0.co;2

Shields, C. A., Rutz, J. J., Leung, L. Y., Martin Ralph, F., Wehner, M., Kawzenuk, B., … Nguyen, P. (2018). Atmospheric River Tracking Method Intercomparison Project (ARTMIP): Project goals and experimental design. *Geoscientific Model Development*, *11*, 2455–2474. https://doi.org/10.5194/gmd-11-2455-2018

Thompson, D. W. J., & Barnes, E. A. (2014). Periodic variability in the large-scale Southern Hemisphere atmospheric circulation. *Science*, *343*, 641–645. https://doi.org/10.1126/science.1247660