U.S. Global Change Research Program

The Ninth U.S. Climate Modeling Summit Report

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Summary

The Ninth U.S. Climate Modeling Summit (USCMS) was held in a hybrid format at NOAA's Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. The Summit consisted of a 1.5-day Topical Workshop, "*The oceans' role on air–sea coupled climate interactions*," held April 24-25, 2023 (Appendix A), and a Summit Meeting held April 25-26, 2023 (Appendix B). The Workshop engaged scientists, primarily from modeling centers and national laboratories, working on coupled ocean–atmosphere interactions and related areas. The USCMS, involving core members (see Appendix C) and the U.S. Global Change Research Program's (USGCRP) Interagency Group on Integrative Modeling (IGIM) managers, continued to be an opportunity for high-level modeling discussions to enhance coordination and collaborations across the centers. As in past years, the Summit Meeting was dedicated to the progress made at the modeling centers, with other updates since the 2022 meeting and discussions on various ongoing efforts and emerging opportunities and challenges. The meeting concluded with planning coordinated activities among the modeling centers for the upcoming year, including the 10th USCMS.

Background on the U.S. Climate Modeling Summit and Workshops

To improve the coordination and communication of national climate modeling goals and objectives, the USGCRP's IGIM has been convening an annual USCMS since 2015. The Summit brings together representatives from the U.S. climate model development centers and operational climate and weather prediction programs. Specifically, two representatives—one lead and one additional delegate—from each of the following groups are invited to participate in the Summit: NOAA National Weather Service (NWS) National Centers for Environmental Prediction (NCEP) and Environmental Modeling Center (EMC); NOAA Geophysical Fluid Dynamics Laboratory (GFDL); NASA Goddard Institute for Space Studies (GISS); NASA Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System (GEOS); NSF National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM); and DOE Energy Exascale Earth System Model (E3SM). As envisioned by the IGIM, the high-level USCMS objectives include:

1. Developing a shared understanding of modeling groups' directions and implementation strategies
2. Identifying opportunities for enhanced coordination and synergy among modeling groups
3. Identifying outreach opportunities to user communities

Starting in 2017, a topical workshop has also been organized under the auspices of the USCMS and in conjunction with the annual meeting. These workshops serve as a venue for focused scientific and technical information exchange on a high-priority modeling-related topic identified by the modeling centers together with the IGIM, and they may include invitees from the broader community.

Workshop Agenda

The Ninth USCMS explored the state of modeling of the ocean's role in coupled tropical–subtropical air–sea interactions on subseasonal to multidecadal timescales, with foci on representation of processes and predictability of extremes:

1. Climate variability, in particular relating to the generation of extremes such as tropical and extratropical storm intensification and atmospheric rivers
2. Multidecadal sea surface warming patterns, pattern effects, preconditioning for extremes, and associated model uncertainties
3. Biases in modeling modes of variability potentially related to representation of air–sea interactions
4. Advances in modeling ocean, and air–sea boundary interactions to address these biases

Throughout the workshop, participants were challenged to identify current observational and modeling gaps limiting understanding of predictability and prediction. The full workshop agenda is provided as Appendix A.

Session 1: Coupled tropical-subtropical air–sea interactions on subseasonal to multidecadal timescales

Session 1 included 5 presentations on coupled tropical–subtropical air–sea interactions on subseasonal to multidecadal timescales, focused on sea surface warming patterns and effects and associated model uncertainties:

1. **Essential elements for modeling MJO teleconnections and their impacts** (Stephanie Henderson) showed that Madden–Julian Oscillation (MJO) biases in mean state negatively affect MJO teleconnections even if the East/West ratio is correct.
2. **Tropical Pacific variability and air–sea interactions across timescales** (Andrew Wittenberg) illustrated that El Niño–Southern Oscillation (ENSO) zonal asymmetry is still very difficult to represent in models contributing to the 6th phase of the Coupled Model Intercomparison Project (CMIP6), but that those underestimating ENSO activity tend to increase under climate warming while those with active ENSO maintain the same or decline, and use of model analogs for prediction shows encouraging skill.
3. **Analyzing CESM and E3SM solutions with a focus on modes of variability, extremes, etc**. (John Fasullo) gave an overview of the Climate Model Assessment Tool (CMAT) diagnostics package and stressed that robust assessment of the Inter decadal Pacific Oscillation in CMIP6 models remains undermined by internal variability.
4. **Seasonal-to-decadal variability, predictability, and change of North Pacific air–sea interactions** (Youngji Joh) illustrated up to 5-year skill in Kuroshio Extension Sea Surface Height (SSH) with a coarse model, but that resolution of 10-25 km is needed to represent the air–sea interaction impact on the atmospheres and that downstream KE response on longer (decadal) increasing over the last few decades.
5. **Subseasonal to seasonal timescale modes of climate variability represented in the coupled GEOS model and their predictions** (Young-Kwon Lim) explained how representing the evolution of the Moist Static Energy budget correctly is critical for the eastward propagation of the MJO and showed that their model has significant prediction skill out 30 days.

The second part of Session 1 focused on biases in modeling modes of variability potentially related to representations of air–sea interactions:

1. **Subseasonal to seasonal ocean forecasts in UFS-based global coupled modeling system** (Sulagna Ray) pointed out the relatively high Sea Surface Temperature (SST) skill in tropical and Northeast Pacific and used ocean diagnostics to investigate mean state biases of excess cloud cover/equatorial cold SST bias, sea surface salinity (SSH) bias in the eastern equatorial region, and Northeast Pacific – SST warm bias. A major emphasis was that at week 3&4, anomaly forecasts still suffer from too warm equatorial SST anomaly in the 2015/16 El Niño, weak response to strong Westerly Wind Events, and weak oceanic teleconnections along the U.S. West coast.
2. **S2S Coupled Modeling and evaluation focusing on NOAA/EMC coupled Unified Forecast System (UFS)** (Lydia Stefanova) highlighted improved anomaly correlations (AC) in tropical SST and precipitation but low AC for week 3&4 CONUS precipitation, improved climatology/biases, and coupled UFS representation of tropical cyclones (TC) but with underestimated intensity.
3. **Gulf Stream interactions with North Atlantic storm track** (Justin Small) highlighted the role of smoothing SST in Atmospheric Model Intercomparison Project (AMIP) experiments demonstrating that the representation of the SST gradient is important to represent the Eady growth rate, heat flux, and wintertime precipitation. He stressed that using daily data in forcing the atmosphere or ocean is important to identify sources of feedbacks.
4. **Including impacts of altimetry and sea-surface salinity data assimilation for ENSO prediction** (Eric Hackert) demonstrated that because satellites measure only the first centimeter, rain events must be translated with a Rain Impact Model (RIM) simulator into the first model layer (5 m). Adding satellite Sea Surface Salinity (SSS) into their Subseasonal to Seasonal model in this manner increases equatorial Mixed Layer Depth (MLD) and slows the propagation of Kelvin waves.

Session 2: The role of air–sea interactions in extreme events

Session 2 began with 3 presentations focusing on local-regional air–sea interactions associated with extremes such as tropical and extratropical storm intensification and atmospheric rivers:

1. **The influence of ocean coupling on future projections of tropical cyclones** (Chris Patricola) noted that a collection of tropical cyclone projections put tracks far to the south of present day, illustrating SST biases as important drivers of tropical cyclone (TC) errors and advocating for improved ENSO prediction for improved TC predictions.
2. **Atmospheric rivers across timescales. Seasonal prediction of atmospheric rivers (AR) and multidecadal projection of changes in atmospheric rivers** (Nat Johnson) showed AR predictability in California and Alaska, little in the Pacific Northwest and Canada.
3. **Aspects of air–sea interactions, including oceanic heat uptake, ARs, etc.** (Dan Fu) showed that the CESM High Resolution model (HR) does a great job at CONUS winter precipitation extremes due to good representation of the cyclonic weather patterns bringing moisture from the Southwest over the ocean to the Northeast over land. HR also gives much better decadal prediction than the low-resolution version.

Session 2 continued with 4 presentations on preconditioning for extremes by modes of variability, SST warming patterns, and long-term trends:

1. **The role of tropical air–sea interactions in modulating North Pacific stationary-transient eddy interaction and North American climate extremes** (Mingyu Park) showed that the wintertime North Pacific wave interference changes the occurrence of North American climate extremes and that in a warming climate, tropical convection associated wave interference shifts toward the central equatorial Pacific. With responses dependent on the mean state, and improved interactions having been found when reducing the equatorial tropical Pacific SST bias by prescribing the surface flux adjustment, he argued that techniques such as 'flux adjustments' would be useful to reduce the current gaps.
2. **Seasonal prediction of extreme heat and cold events over North America** (Liwei Jia) showed that external forcing, the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), central Pacific El Niño, soil moisture give predictability of North American summer heat extremes. She described how climate change, central Pacific SST anomalies, and snow anomalies in mid-to-high latitudes contribute to the prediction skill of North American winter cold extremes. She argued that to improve prediction of temperature extremes, it is important for models to well-represent the connections between predictability drivers and extremes; better observations and DA also support attribution, and reconstructing forecasts with predictable modes also improves forecast skill.
3. **Enhanced US hurricane risk under global warming: the role of tropical SST warming patterns** (Karthik Balaguru) used a computationally efficient Risk Analysis Framework for Tropical cyclones (RAFT) driven by 8 CMIP6 models to generate 50000 TC tracks each for historical and future (800K total) conditions, and found that increased cyclone frequency along the Gulf and lower East Coast in the future is attributable to changes in steering flow induced by diabatic heating changes associated with an El Niño-like warming pattern.
4. **Influences of surface-atmosphere interactions in the propagation of MJO and implications for landfalling atmospheric rivers (AR)** (Samson Hagos) described an interpretive framework whereby different MJO phases modulate the background moisture transport in North Pacific, with eastward transport during phases 6-7 favoring AR landfall in the western United States.

Session 3 included 5 presentations on advances in modeling ocean and air–sea boundary interactions to address large scale biases:

1. **AirSeaFluxCode: Open-source software for calculating turbulent air–sea fluxes from meteorological parameters** (Stavroula Biri) highlighted that comparison of flux schemes is now a capability, showing up to 15W m-2 differences between schemes, and illustrating uncertainty at both low and high wind speeds and the importance of consistent salinity/humidity.
2. **The impact of a wave-dependent surface flux parameterization on the mean wave climate and MJO** (Steven Brus) showed results from Wavewatch III, where adding waves to E3SM improves MJO through momentum flux into the ocean from wave dissipation. Regional NCAR Latent heat flux and zonal wind flux biases are dramatically improved.
3. **Modular Ocean Model version 6 (MOM6) related development on air–sea interactions** (Brandon Reichl) showed that adding better representation of the diurnal cycle in mixed-layer depth to address the "steppy" zonal equatorial structure in CM4 using comparison of Large Eddy Simulation (LES) heat fluxes.

4. **Skin-temperature assimilation and ocean-atmosphere interaction** (Santha Akella) showed that there can be a large difference between skin temperature (2 mm) and the first layer of the model (2-10 m). They are modeling skin temperature as a function of heat fluxes in both atmosphere only and S2S coupled mode and would like to resolve the microlayer with Arbitrary Lagrangian Eulerian Method (ALE) in MOM6.
5. **Report back from the March 2023 US CLIVAR Mesoscale and Frontal-Scale Air–Sea Interactions Workshop report** (Justin Small and Brandon Reichl). They argued for future missions (satellite and in situ) targeting collocated multivariable datasets at high resolution that can constrain fluxes and modes of variability (e.g., S-MODE, Butterfly, ODYSEA), continued emphasis on data sharing and data accessibility, support for forward high-resolution and data assimilation to make sense of the complex observations and assigning causality and assessing impact on weather and climate, and extended analysis after observations are carried out such as analysis/modeling/theory teams (e.g. Climate Process Teams) to maximize the benefit of observational campaigns and numerical experiments, and called members of this U.S. Air–Sea Flux community to get involved in CMIP7, the follow-on to HighResMIP, Flux Adjusted Forcing Model Intercomparison Project (FAFMIP), and other flux-related cooperative modeling endeavors and U.S. modeling center activities.

Workshop Discussion on Air–Sea Observations

Two sets of breakout groups were conducted. The first set of breakout groups focused on priority advances in incorporating existing observations and recommendations for new observations on ocean and air–sea boundary interactions to improve representation of extremes.

What is the state of the science?

Model representation of coupled air–sea interactions and their associated phenomena have improved considerably over the last decade. Tropical cyclones are now regularly represented in high-resolution regional and global models as are ENSO and MJO. In the Atlantic region, recent focus has been on capturing the strength of decadal variability towards decadal predictability. Atmosphere teleconnections are also a major theme driven by air–sea interaction and how these relate to the statistics of events with inter-basin connections between Pacific–Atlantic shown to be synchronized through storm tracks. In particular, representation of MJO and stationary wave-transient wave interactions that give rise to extremes such as tropical cyclones are particularly active foci. Additional foci have been on processes that produce extremes like severe storms, atmospheric fronts, and atmospheric rivers, and on the air–sea interactions driving the Gulf stream and Kuroshio separation bias and their subsequent impact on storm track, and the impacts of bulk formulations on behavior in high winds and its role on tropical cyclone intensity.

What are the gaps in understanding?

One of the largest modeling challenges in confident projections of future climate variability and change is capturing historical changes in the equatorial Pacific zonal SST gradient and its relationship to representation of ENSO processes, regression feedback, and overall strength. There is the question of whether we have the right observations; that to improve physics as we increase model resolution, we need to increase resolution of observations; and that we are limited by the lack of collocated observations, simultaneous observations of state variables used to measure fluxes, e.g., albedo and emissivity. Gaps in understanding also include bulk flux formulae under strong winds as well as in the quiescent state where these parameterizations diverge. One question is whether the physics parametrizations will hold up as they go to higher resolution and be able to capture precipitation means (relieving biases) and extremes, as well as determining the factors behind success or failure and causes of improvements.

WHAT OBSERVATIONAL AND MODELING CAPACITIES NEED TO BE ADVANCED TO ADDRESS THE GAPS?

1. **Representation of ocean weather**: Current limits in high-performance computing have resulted in coupled models that are only beginning to represent the eddies, fronts, jets, and boundary currents that drive variability in air–sea interactions. Until this "ocean weather" is represented explicitly in coupled models—requiring resolution on the order of 10 km or better— this primary structure in air–sea interactions will be missing.
2. **Advancement of satellite system**: There are several studies out that used remote sensing data to look at sea spray under high wind conditions (e.g., Ricciardulli, L., & Wentz, F. J., 2015; Bourassa et al., 2019). As we are able to rely more heavily on satellites for mapping, moorings provide detailed data for parameterization modeling, since previous data were so sparse. However, the West Pacific lost a lot of moorings, which leads to gaps in measurements, especially in cloudy and rainy regimes that satellites can't see.
3. **Reanalysis simulations**: Realistic estimates of uncertainties of reanalysis information would be highly valuable, particularly considering the inhomogeneous nature of the record the further back one goes in time. (e.g., 20th century reanalysis relies heavily on sea level pressure records).
4. **Process level**: A comprehensive assessment is needed on the impacts of bulk formulations on tropical cyclone intensity, exchange coefficient behavior in high winds, and recommendations for next generation model implementation. These efforts rely on the availability of flux observations at high wind speed. Saildrones and gliders are particularly useful for taking these kinds of measurements.
5. **More constraints**: Wake temperatures, sea salt, and outgoing longwave radiation provide multiple constraints beyond SST and wave field alone. Adding salt flux to air–sea flux codes would make air–sea flux codes more coherent. Process level understanding of air–sea interactions at high wind conditions can be advanced with simultaneous observation of convection, SST, and fluxes. There is a need for better statistics of observations for modeling applications both for characterizing uncertainty to prevent overfitting and in support of higher frequency of coupling in models.

WHAT SHOULD MODELING CENTERS ADDRESS?

1. **Atmospheric reanalysis forcing requirements for ocean-only experiments:** The recent CMIP6 Ocean Model Intercomparison Project (OMIP) exposed many deficiencies in current ocean-only experimental design. Refinement of atmospheric reanalysis with historical ocean measurements is necessary to constrain their energy and water budgets and make them more useful for improving understanding of air–sea interactions and fast-responding aspects of the system, such as equatorial upwelling. Other important objectives are documentation of reanalysis' uncertainties and reducing uncertainty in satellite observations (e.g., salinity) for use as constraints in ocean models (adjusted reanalysis products). Leaders

of the next phase of the OMIP at NCAR, GFDL, and the academic community are currently preparing an atmospheric forcing for the ocean to address the imbalance in precipitation used in constraining global models.

2. **Coupling of air–sea boundary layers:** Reducing uncertainty in air–sea fluxes requires comparing existing process observations with regional high resolution coupled models. Machine learning-based parameterization schemes have the potential to include the impact of precipitation on salinity, mixed layer, etc. There is currently little direct data of fluxes, and the data collected have not been synthesized into a harmonized collection for comparison with models. Support for a data archival of process observations including an inventory of past and on-going of field campaigns around the world and their associated data in a format to facilitate model comparison and evaluation could help scientists identify underlying commonalities. More emphasis on direct covariance and inertial-dissipation methods in future observational campaigns could also help address this challenge. These efforts could be done in partnership with the Observing of Air–Sea Interactions Strategy (OASIS; airseaobs.org) program.
3. **Comprehensive inclusion of wave interactions:** Wave processes in both the ocean and atmospheric boundary layers and at the interface are currently not represented in the coupled models commonly run for predictions and projections but have demonstrated effects on ocean mixing (particularly in the Southern Ocean) and teleconnections such as MJO. There are many useful applications of wave models in ESMs even beyond the climate interactions discussed above, including providing information for navigation, offshore oil platforms, ports, wind/wave energy, surfers etc.
4. **Hierarchy of modeling**: There is a need to balance the desire for high resolution to avoid parameterization with the practical considerations for forecasting. One approach is to use high- resolution (eddying) simulations to tune coarse resolution and compare net fluxes from low-res model with high-res model to match fluxes in the long term. Establishing robust physical diagnostics is critical for this. Necessary model experiments include both general sensitivity experiments at a variety of time and space scales capable of capturing emergent phenomena and targeted perturbation physics experiments (e.g., fluxes under high winds) to compare model sensitivity to the different bulk flux formulae options available. Parameters in bulk formulae should also be explored by comparison with high-resolution models and proposed observations database in item 2 above.
5. **Climate Process Teams and process study:** The need for continued emphasis on Climate Process Teams is recognized as well as the need for small process-oriented field campaigns combined with modeling experiments. Several relevant "bite size" projects, such as Observation System Simulation Experiments, have been proposed through the NASA MAP ocean call, Year Maritime Continent, and UN Ocean Decade.

Workshop Discussion on Air–Sea Modeling

The second set of breakout groups focused on priority advances in modeling ocean, and air–sea boundary interactions to improve representation of extremes.

What is the state of the science?

Wave models currently but are not practical for regular use in climate applications due to their slowness, expense, and lack of adequate parallelization. Similarly challenging to representing air–sea interactions is the divergence of bulk formula for low and high wind speeds. While various Large Eddy Simulation (LES) efforts have provided process level boundary layer constraints, coupled climate models have made slow, incremental progress with the recalcitrant near-surface biases in clouds, winds, and SST, particularly the cold tongue bias in the equatorial Pacific and Southern Ocean warm bias. There is growing confidence that the mismatch between the simulated and observed tropical SST trend pattern reflects a systematic bias in the current generation of climate models (Seager et al., 2022, J. Clim.). This particular SST trend pattern has important impacts on the simulation of extremes, including tropical cyclones and North American hydroclimate and temperature extremes. Model ability to represent extreme events, such as atmospheric rivers and tropical cyclones, has improved, at least partially attributed to higher resolution. Biases in upper ocean stratification have been linked to precipitation biases in the tropics.

What are the gaps in the understanding?

While constraints on the open ocean mean, seasonal, and interannual state exist, better constraints on fluxes in heterogeneous and extreme environments (and scale awareness) and representation of coastal ocean processes from short time scales (diurnal scales) to long time scales (centennial) are necessary. To complete observationally based local budgets of heat and freshwater, observations should be combined with process models (e.g., through LES) and enthalpy fluxes instead of the standard use of global fixes to correct for lack of heat-conserving treatment of water precipitation at different temperatures than what is was evaporated. With respect to climate model development, more explicit guidance and tools for formally evaluating the costs versus benefits for investing in improving model resolution versus improving physics versus increasing the number of ensemble members would be extremely helpful, even as difficult trade-offs to evaluate for each choice exist, and the decision of where best to invest resources will depend on the application. There is a need to define best practices for assessing models with existing satellite data–for example, the presentation on Rain Impact Model (RIM)-corrected sea surface salinity provided an example of where post-processing of satellite products is necessary to resolve the distinction between the thin surface skin that the satellite observes and the multi-meter scale of the explicit vertical model resolution. Whether to focus on tuning to long-term observational trends where the forced response has emerged remains an open question, particularly with respect to tuning models at high resolution because of the required additional computational power. A common theme has emerged that extremes often involve the interaction between modes of variability, and it is an open question of whether this interaction represents linear superposition versus nonlinear interactions.

What observations and modeling capacity need to be advanced to address the gaps?

There is an ongoing need for communication between the modeling and observational communities to establish where targeted field campaigns would be beneficial for constraining models such as hurricanes and atmospheric rivers as extreme test cases for our existing air–sea flux parameterizations. Also critical is establishing the necessary parameters to measure. Of particular value to modelers are closed budgets, and multi-variable observations will be important to facilitate analysis of models/model hierarchies.

In the context of data assimilation (DA), improved use of scatterometers in coupled analysis/reanalysis systems is required (e.g., assimilating backscatter rather than winds), as there are currently 30% differences amongst scatterometer estimates of the wind speed in key regions.

DA systems want the wind speed, but a coupled DA system could potentially utilize the surface flux directly if scattering were considered as a direct model DA target. There are several relevant parameters/variables to model and observe to verify/falsify our models from observations including not only surface winds, but also skin temperature, and salinity where some observables are robustly measured in some regions/conditions but not in others. There needs to be more dialogue among reanalysis community and attention paid to these key regions. Huge uncertainties remain in high latitudes (marginal ice zone), particularly in ice packs.

While implementation of parameterization packages (such as the Community Ocean Vertical Mixing (CVMix) project and AirSeaFluxCode) in current models might add computational burdens that prevent their practical application in prediction and projections, application during model development and testing would promote comparability and attribution of model differences. These packages also facilitate modeling groups and parameterization developers to work together to 1) increase the relevant functionality and 2) constrain the parameterizations with observations. Using LES/ high-res simulations and observations as benchmarks is a promising avenue of research. AI-assisted emulators and machine learning techniques may also be advanced to bridge low-resolution simulations to extremes at high resolutions.

For addressing noted mismatches between observed and simulated trends relevant for extremes, perturbed physics and perturbed parameter experiments were identified as priorities, where the expectation is to identify subsets of ensemble members that match observations better than other members and to tease out mechanisms based on ensemble diversity. Given the slow advance in high-resolution global model experimentation, implementation of regional coupled nesting experiments could be beneficial for the simulation of extremes.

Given the demonstrated importance of satellite-derived energy balance through the Clouds and the Earth's Radiant Energy System (CERES) project and similar projects focusing on precipitation, there is a need to identify to NOAA and NASA where continuity of satellite observations is most critical. The launches of PACE (Plankton, Aerosol, Cloud, Ocean Ecosystem) and SWOT (Surface Water and Ocean Topography) satellite products will provide high-resolution biological (e.g., phytoplankton blooms) and altimetry data to aid our evaluation of high-resolution modeling, including for coastal sea level variability.

WHAT SHOULD MODELING CENTERS ADDRESS?

Explicit incorporation of wave interactions has been shown to have important implications for the representation of regional and temporal variability in both atmospheric and ocean boundary layer interactions; air–sea fluxes of radiation, heat, and water; and variability/teleconnections patterns and represent a key application of models in both the prediction and projection contexts for coastal and ship vulnerability assessment. However, a major long-term challenge in comprehensively modeling air–sea interactions in the climate context has been the high computational cost and lack of scalability of existing wave model codes. The development of a single community wave model/code appropriate for climate applications could facilitate a broad set of improvements in model fidelity and applicability. We propose a cooperative effort across all US Climate Modeling Centers delivering wave models for climate applications for emerging computational technologies:

Wave Architecture for Variable Environments in Climate Research with Emerging Software Technology (WAVECREST).

Another potential point of coordination between modeling centers could be through initialized predictions from seasonal to decadal timescales towards advancing identification and understanding of fast-developing biases. These coordinated experiments among interested centers could include initialization experiments at both short (weather) timescales and seasonal to decadal timescales to look at issues such as the signal-to-noise paradox in forecasting the seasonal impact of the North Atlantic Oscillation.

Cooperative efforts for parameterization toolkits like CVMIX that allow centers to standardize implementations and compare sensitivities are powerful ways of stepping the community forward. A synthesis effort of existing observations is needed to assess the climate implications of uncertainty associated with the diversity in behavior for low wind speeds in bulk parameterizations that each collapse to different theoretical considerations at the limit of zero wind speed. The presentation on RIM-corrected sea surface salinity provided an example of where post-processing of satellite products is necessary. Indirects method of modeling to see if formulae work well. Adding salt flux to air–sea flux codes would make air–sea flux codes more comprehensive and consistent. Overall, the modeling centers stress the need for centralized data access from observational campaigns to facilitate such model comparison.

The modeling centers should consider collaborating on test cases/high-resolution simulations used to verify the air–sea flux/boundary layer/etc. parameterizations – potentially through US CLIVAR. Cases should be prioritized based on how well we know the solution and forcing and can determine important diagnostics/budgets to guide our model development, including LES based on observational constraints/field campaigns of the ocean boundary layer, such as TPOS field experiments with moorings/satellites/gliders/etc. to constrain test cases. Observations in high-flux regions like Labrador sea with systems that can measure as many relevant variables as possible would be most helpful.

Summit Meeting

Summary of Activities Since the Previous U.S. Climate Modeling Summit

Progress was reported from three projects that were initiated at previous USCMS meetings, including:

The world-avoided mini-Model Intercomparison Project (mini-MIP): Vaishali Naik presented on the impacts of the Clean Air Act on air quality and climate. This project, initiated by Jean-François Lamarque (formerly NCAR) and currently led by Vaishali Naik, developed emission scenarios for the United States had the Clean Air Act not been implemented in 1970, resulting in increased pollutant emissions, with impacts on air quality and climate. Simulations performed by NCAR (CESM2), DOE (E3SM), NASA GISS (modelE), and NOAA GFDL (ESM4) were analyzed. Preliminary results showed significant impacts of US emissions trajectories on global surface ozone concentrations and particulate pollution. A manuscript is in preparation.

CERESMIP: Susanne Bauer presented on this international model intercomparison to answer the question, "What is driving the changes in Earth's Energy Imbalance?" by comparing CERES observations from 2003 to present with an updated AMIP simulations from 2003-2022 with prescribed SST and ScenarioMIP forcings post-2014. The experimental protocol has been submitted as Schmidt et al. "CERESMIP: A climate modeling protocol to investigate recent trends in the Earth's energy imbalance". Front. Clim., submitted.

Outcome of 2021 Workshop on Earth system predictability: Gokhan Danabasoglu gave an update on the inter-center project to answer the question, "Is Better Representation of Modes of Variability Related to Reduced Biases and Better Simulations of Extreme Events in US Climate Models?" through an initial discussion of the available analysis. For example, pattern correlations calculated by the NCAR Climate Variability Diagnostics Package for Large Ensembles (CVDP-LE) diagnostic package were shown for each mode of variability simulated by CESM, E3SM, GFDL, and GISS models.

Outcome of 2022 workshop on water cycle and water security: Ruby Leung provided a brief update on a proposal developed by Isla Simpson (NCAR) to investigate the discrepancy between the observed and model simulated historical trends in near-surface water vapor trends, which has important implications for model projections for hydroclimate, wildfires, and temperature extremes. The proposal was submitted to the NOAA Modeling, Analysis, Predictions and Projections (MAPP) Program, and if selected for funding, other centers (e.g., GFDL, DOE) will request funding from the agencies to participate by running the proposed numerical experiments using different models to test various hypotheses on the discrepant trends.

Outcome of 2023 workshop: John Dunne summarized the 2023 workshop, "The oceans' role on air–sea coupled climate interactions," described above.

Modeling Center Reports: The six modeling centers provided updates, including a summary of center activities related to modeling weather and climate extremes, followed by Q&A and some discussions on topics such as stakeholder engagement.

The day concluded with a Climate/Earth system reanalysis presentation and discussion led by Steve Pawson, focusing on provision of new and improved data products as part of NASA's MERRA3 effort. Steve noted various opportunities for involvement by other agencies, such as defining output needs, multi-agency approaches to data distribution, and HPC.

Digital Twins

Summary of NASEM Digital Twins Workshop: Ruby Leung presented a brief summary of the key takeaways from the workshop, noting the lack of an agreed upon definition of digital twin—although there are general agreements that a digital twin includes the physical system, the digital system, and a bi-directional connection between the two for the purpose of supporting decision-making—and that uncertainty quantification is an important aspect of digital twins. She also highlighted challenges and opportunities related to digital twins, as noted by the presenters at the workshop.

WCRP *Digital Earths Lighthouse Activity*: Andrew Gettelman presented on the breadth of activities in "Digital Earth" towards "Digital Twins" being sponsored by WCRP as a Lighthouse activity, including the science and technical challenges associated with km-scale modeling and access to the high-resolution inputs and results. He also discussed the opportunities to leverage high-resolution satellite data, high- performance computing, and multi-sector models; collaborate with the regional modeling and regional hydroclimate communities; and learn from established mesoscale model developers with more extensive experience in km-scale modeling.

Digital Twin Priorities, Activities, Visions, Challenges, Opportunities, and Collaborations: the Modeling Center Representatives Panel presented ongoing/planned activities related to digital twins at their centers, which include ultra-high-resolution modeling, different uses of AI/ML in climate modeling, and data assimilation. The panel discussed some challenges related to digital twins, emphasizing that both complexity and resolution are needed to produce a digital twin of Earth and the importance of understanding what high-resolution models are getting right or not. There is an opportunity for the modeling centers to collaborate on analysis of existing high-resolution runs, such as those from HighResMIP and DYAMOND. The panel also discussed the need for co-production of climate information and opportunities for using digital twins to support decision-making, including use of data analytics for making high-resolution model results useful for decision-making.

Data

Panel Discussion on Data Access, Sharing, and Management: Implications of the Nelson Memo, Big Data Challenges, and Current and Future Considerations relevant to all the agencies and centers were discussed.

This session included four presenters representing different agencies: David Considine (NASA), Aparna Radhakrishnan (NOAA), Forrest Hoffman and Casey Burleyson (DOE), and Raleigh Martin (NSF). David briefly discussed NASA's approach to sharing data, such as satellite data and reanalysis data.

Aparna Radhakrishnan discussed several aspects towards FAIR data, including data access and discoverability, data licensing, data usability, and data storage, highlighting the need to strengthen internal and external collaborations, leverage new technology and advance computing capability, and increase ability to access and use Earth system data.

Forrest Hoffman introduced the Next Generation Earth System Grid Federation (ESGF), which is an international consortium and a globally distributed peer-to-peer network of data servers using a common set of protocols and interfaces to archive and distribute climate and Earth system model output and related input, observational, and reanalysis data. He also introduced a new consortium project in the USA (ESGF2-US) to develop new data discovery tools and data interfaces, server-side computing, and user computing.

Casey Burleyson introduced the multi-sector dynamics (MSD) community MSD-LIVE platform which facilitates open science by tackling the foundational elements of the open science pyramid, the top of which addresses the policy for data sharing. MSD-LIVE is a cloud-based data and code management system and advanced computing platform that enables researchers to document and archive their data; run their models and analysis tools; and share data, software, and multi-model workflows.

Raleigh Martin introduced some NSF Foundation-wide efforts on open science, including Public Access Repository (PAR), a new program (FAIROS RCNs) supporting Research Coordination Networks (RCNs) that advance FAIR principles and open science (OS) practices, and a consensus study on "Reproducibility and Replicability in Science." He also discussed Geosciences specific efforts and investments, including EarthCube, AI2ES, LEAP, and Derecho (new NCAR Supercomputer), as well as new opportunities through the Geosciences Open Science Ecosystem solicitation and the Advancing Research in the Geosciences Using Artificial Intelligence (AI) and Machine Learning (ML).

Updates and Discussions on U.S. and International Activities

CMIP: John Dunne has been named CMIP co-chair along with Helene Hewitt (UKMO). A CMIP International Project office has been established with Eleanor O'Rourke as Director and two staff. Seven CMIP7 Task Teams have been stood up: Data access (Robert Pincus and Atef Ben-Nasser), Data citation (Martina Stockhause and Sasha Ames), Data Request (Martin Juckes and Chloe Mackallah), Forcings (Paul Durack and Vaishali Naik), Model benchmarking (Birgit Hassler and Forrest Hoffman), Model documentation (David Hassell and Guillaume Levavasseur), Strategic ensemble design (Ben Sanderson and Isla Simpson). Current thinking on the definition of CMIP7 is to split into a limited set of DECK, historical, Scenario and supporting "fast track" experiments targeted for IPCC, and a longer timescale development of Science-based MIPs, with a planning paper submitted by the end of calendar 2023. The distinction between CMIP6+ and CMIP7 is still under discussion.

Modeling Center Support for the National Climate Assessment (NCA): Allison Crimmins described the NCA's biggest challenges in the use of climate model information from downscaling as: 1) the timing issue that NCA always seems to be between MIPs, 2) funding issue (statistically downscaled data provided by the LOCA2 group and STAR group – opportunistic versus planned), 3) need to better capture projection past 2100 as mandated "100 years out,, and 4) the biggest issue is that regions outside of CONUS feel left out. Dan Barrie noted the synchrony that the next NCA (NCA6) is likely to come out about the same time as the next IPCC assessment report (AR7). Framing ideas: 1) NCA is a convenient organizing principle that could be better leveraged as a stakeholder group for high-resolution coupled modeling. 2) While the impacts community thinks they want the highest resolution data, there is a potential for climate centers to provide insight on the value or lack thereof for downscaling. In the near term in the absence of dedicated funding, the objective would be for NCA to informally coordinate timing of simulations and analysis.

GPEX and International Year of Precipitation: Jin Huang provided an update on the Global Precipitation EXperiment (GPEX) which will be a cross-WCRP initiative focused on the WCRP Years of Precipitation (YoP) and associated activities before and after. The GPEX/YoP will include coordinated global field campaigns, with an emphasis on different storm types for different seasons (atmospheric rivers in winter, springtime mesoscale convective systems, summer monsoons, and tropical cyclones in the fall), gridded data evaluation and analysis, km-scale modeling, process understanding, prediction of extreme precipitation events, and changes in precipitation seasonality.

Planning for the 10th U.S. Climate Modeling Summit

For the 2024 meeting (the 10th USCMS), the group agreed that John Dunne (GFDL) and Vijay Tallapragada (EMC) would co-chair the meeting. The meeting is anticipated to be a hybrid event with its location TBD. An expressed desire is to have the meeting earlier in the year, perhaps in early spring, returning to the timeline of the earlier USCMS meetings. On the topic of next year's workshop, several topics were discussed including climate model biases, coupled data assimilation, climate tipping points, cascading extreme events, and climate and air quality. After some discussions, the group decided that next year's topic will be on "*Coupled Data Assimilation – establishing the need and viability across components*." More detailed ideas will be discussed among the co-chairs, in coordination with the modeling centers and the IGIM, over the several months.

Other next steps: Danabasoglu will send out an invitation for a meeting to discuss potential collaborations among the centers on understanding why extreme precipitation in southeast U.S. winter is improved from low to high resolution while other features (such as summer extreme precipitation in the central US) are not improved by increasing resolution. There is an opportunity to use existing simulations (such as HighResMIP and the DYAMOND runs) and downscaled simulations from regional models (connected to NCA needs).

Appendix A: Workshop Agenda

USCMS9 Topical Workshop on
The oceans' role on air – sea coupled climate interactions
24-25 April 2023 (All times are EDT)

Charge to all speakers with providing a concluding statement on "Observational and modeling gaps limiting understanding of predictability and prediction"

24 April 2023 (Monday; virtual connection meet.google.com/htm-itgy-yrc)
09:00 Gary Geernaert (USGCRP/DOE; **In person**): Welcome and Background
09:10 John Dunne (GFDL; **In person**): Workshop objectives and outcomes

Session 1: Coupled tropical-subtropical air–sea interactions on subseasonal to multi decadal time scales

a) Climate variability on subseasonal to multidecadal timescales, sea surface warming patterns and effects, and associated model uncertainties

Chair: Ruby Leung; Rapporteur: Liwei Jia

9:15 Stephanie Henderson (University of Wisconsin; **In person**) – Essential elements for modeling MJO teleconnections and their impacts
9:30 Andrew Wittenberg (GFDL; **In person**) - Tropical Pacific variability and air–sea interactions across timescales
9:45 John Fasullo (NCAR; **In person**) - Analyzing CESM and E3SM solutions with a focus on modes of variability, extremes, etc.
10:00 Youngji Joh (NOAA/GFDL; **In person**) - Seasonal-to-decadal variability, predictability, and change of North Pacific air–sea interactions
10:15 Young-Kwon Lim (NASA/GMAO and GESTAR-2; **In person**) – Subseasonal to seasonal timescale modes of climate variability represented in the coupled GEOS model and their predictions

10:30 General Discussion
10:45 Break

b) Biases in modeling modes of variability potentially related to representations of air-sea interactions

Chair: Dave Bader; Rapporteur: Andrew Wittenberg

11:00 Sulagna Ray (NOAA/EMC; **In person**) - Subseasonal to seasonal ocean forecasts in UFS-based global coupled modeling system
11:15 Lydia Stefanova (NOAA EMC; **Virtual**) - S2S Coupled Modeling and evaluation focusing on NOAA/EMC coupled Unified Forecast System (UFS)
11:30 Justin Small (NCAR; **In person**) - Gulf Stream interactions with North Atlantic storm track
11:45 Eric Hackert (NASA/GMAO; **Virtual**) Including impacts of altimetry and sea-surface salinity data assimilation for ENSO prediction
12:00 General Discussion
12:30 Catered Lunch

Session 2: The role of air–sea interactions in extreme events

Chair: John Dunne; Rapporteur: Youngji Joh

a) Local-regional air–sea interactions associated with extremes such as tropical and extratropical storm intensification and atmospheric rivers

13:30 Chris Patricola (Iowa State; **Virtual**) –The Influence of Ocean Coupling on Future Projections of Tropical Cyclones .
13:45 Nat Johnson (NOAA/GFDL; **In person**) - Atmospheric rivers across timescales. Seasonal prediction of atmospheric rivers and multidecadal projection of changes in atmospheric rivers.
14:00 Dan Fu (TAMU; **In person**) Aspects of air - sea interactions, including oceanic heat uptake, ARs, etc.

b) Preconditioning for extremes by modes of variability, SST warming patterns and long-term trends

14:45 Mingyu Park (NOAA/GFDL; **Virtual**) - The role of tropical air–sea interactions in modulating North Pacific stationary-transient eddy interaction and North American climate extremes
15:00 Liwei Jia (NOAA/GFDL; **In person**) - Seasonal prediction of extreme heat and cold events over North America
15:15 Karthik Balaguru (DOE/PNNL; **In person**) Enhanced US hurricane risk under global warming: the role of tropical SST warming patterns
15:30 Samson Hagos (DOE/PNNL; **In person**) – Influences of surface-atmosphere interactions in the propagation of MJO and implications for landfalling atmospheric rivers
15:45 Charge to Breakout group discussion on priority advances in incorporating existing observations and recommendations for new observations on ocean, and air–sea boundary interactions to improve representation of extremes followed by Break

1. What is the state of the science?
2. What are the gaps in the understanding?
3. What observational and modeling capabilities need to be advanced to address the gaps?
4. What topics can the modeling centers work on synergistically to address the gaps and enhance understanding

Group 1 (Smagorinsky Room): Bauer, Johnson
Group 2 (Rm 217; meet.google.com/rdt-utgg-vcj): Leung, Park
Group 3 (Rm 317; meet.google.com/jzy-eydh-bkj): Putman, Hagos
17:15 Report-Back from Breakouts
17:30 Adjourn for the day

Dinner on your own

25 April 2023 (Tuesday; virtual connection: meet.google.com/cbc-mpnd-eyf**)**

Session 3: Advances in modeling ocean, and air–sea boundary interactions to address large scale biases

Chair: Gokhan Danabasoglu; Rapporteur: Sulagna Ray

9:00 Stavroula Biri (NOC, UK; **Virtual**) - AirSeaFluxCode: Open-source software for calculating turbulent air–sea fluxes from meteorological parameters
9:15 Steven Brus (DOE/ANL; **In person**) The impact of a wave-dependent surface flux parameterization on the mean wave climate and MJO
9:30 Brandon Reichl (NOAA/GFDL; I**n person**) - MOM6-related development on air–sea interactions
9:45 Santha Akella (NASA/GMAO; I**n person**) skin-temperature assimilation and ocean-atmosphere interaction)
10:00 Justin Small, Brandon Reichl, and others - Report-back on the March, 2023 US CLIVAR Mesoscale and Frontal-Scale Air–Sea Interactions Workshop report

10:15 General discussion

10:30 Charge to Breakout group discussion on priority advances in modeling ocean, and air–sea boundary interactions to improve representation of extremes followed by Break:

1. What is the state of the science?
2. What are the gaps in the understanding?
3. What observational and modeling capabilities need to be advanced to address the gaps?
4. What topics can the modeling centers work on synergistically to address the gaps and enhance understanding

Group 1 (Smagorinsky Room;): Ramaswamy, Small
Group 2 (Rm 217; meet.google.com/fdx-adgp-duo): Pawson, Reichl
Group 3 (Rm 317; meet.google.com/tdf-fxwz-npo): Bader, Brus
12:00 Report-Back from Breakouts
12:15 General discussion
12:30 Adjourn the workshop

Appendix B: Summit Agenda

Ninth United States Climate Modeling Summit

April 25th – 26th 2023 (All times are EDT)

Day 1 (Tuesday, April 25th 2023):

Virtual Connection: meet.google.com/akq-xzpz-xoe

1:30 – 2:30 Updates on previous/ongoing USCMS activities, milestones, and timelines.

1:30 – 1:45 Vaishali Naik: World Avoided.

1:45 – 2:00 Susanne Bauer and V Ramaswamy: CERESMIP.

2:00 – 2:10 Gokhan Danabasoglu: Outcome of 2021 Workshop on Earth system. predictability

2:10 – 2:15 Ruby Leung: Outcome of 2022 workshop on water cycle and water security.

2:15 – 2:30 John Dunne: Summary of 2023 workshop.

2:30 – 3:30 Modeling center update including summary of center activities related to modeling weather and climate extremes (Part 1).

2:30 – 2:50 Ruby Leung: E3SM

2:50 – 3:10 V Ramaswamy: GFDL

3:10 – 3:30 Gavin Schmidt: GISS

3:30 – 4:00 Break

4:00 – 5:00 Modeling center update including summary of center activities related to modeling weather and climate extremes continued (Part 2).

4:00 – 4:20 Steve Pawson: GSFC

4:20 – 4:40 Gokhan Danabasoglu: NCAR

4:40 – 5:00 Vijay Tallapragada: NCEP

5:00 – 5:30 Steven Pawson: Climate/Earth system reanalysis presentation and discussion

End of Day 1

Group Dinner: Palace of Asia (116 Flock Road, Hamilton Township, NJ 08619)

Day 2 (Wednesday, April 26th, 2023):

Virtual Connection: meet.google.com/wee-obfb-cde

8:30 – 10:00 Discussion on digital twins

8:30 – 8:45 Ruby Leung: Summary of NASEM Digital Twin Workshop.

8:45 – 9:00 Andrew Gettelman: WCRP Digital Earths Lighthouse Activity

9:00 – 10:00 Modeling Center Representatives: Panel Discussion on Digital Twin Priorities, Activities, Visions, Challenges, Opportunities, and Collaborations

Questions: Why DT, how is DT relevant to your agency's priorities, what's your vision on DT? What is being done at your centers? What are the challenges? What are the opportunities? What collaborative efforts may help achieve your goals on DT?

10:00 – 10:30: Break

10:30 – 11:15: Panel Discussion on Data Access, Sharing, and Management. Nelson Memo, Big Data Challenges, and Current and Future Considerations.

- Questions to be addressed by the presentations: what type of big data challenges are you facing, how have you been addressing those challenges, and how to address remaining gaps

- Questions to be addressed at the panel discussion: reflect on what we’ve heard, identify gaps and challenges that are common to the agencies, discuss opportunities for collaborations/coordination

10:30 – 10:38 David Considine: NASA.

10:38 – 10:46 Aparna Radhakrishnan: NOAA

10:46 – 10:54 Forrest Hoffman, Casey Burleyson: DOE (ESGF and MSDLIVE)

10:54 – 11:02 Raleigh Martin: NSF

11:02 – 11:15 General Discussion

11:15 – 12:00 Updates and Discussions on US and International Activities

11:15 – 12:00 John Dunne: CMIP.

12:00 – 12:15 Allison Crimmins, Dan Barrie: Modeling Center Support for NCA

12:15 – 12:25 Jin Huang: GPEX and International Year of Precipitation

12:25 – 12:30 General Discussion

12:00 – 12:30 John Dunne, Ruby Leung: Topics and Summit Items for 2024

End of Meeting

Appendix C: Climate Modeling Center Representatives

Dave Bader (DOE LLNL)
Susanne Bauer (NASA GISS)
Gokhan Danabasoglu (NSF NCAR)
John Dunne (NOAA OAR/GFDL)
Brian Gross (NOAA NWS/NCEP/EMC)
Dave Lawrence (NSF NCAR)
L. Ruby Leung (DOE PNNL)
Steven Pawson (NASA GMAO)
Bill Putman (NASA GMAO)
V. Ramaswamy (NOAA OAR/GFDL)
Gavin Schmidt (NASA GISS)
Vijay Tallapragada (NOAA NWS/NCEP/EMC)

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