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Alexander Mitchell
University at Albany, SUNY

**Identifying Sources of Large-Scale Variability Linked to Forecasted Track Errors of Tropical Cyclone Marie (2020)**

Tropical cyclone (TC) Marie, which underwent rapid intensification and reached peak intensity by 1200 UTC 2 Oct 2020, was the strongest TC of the season in the eastern North Pacific (EPAC). Leading up to TC Marie's peak intensity, the deterministic operational GFS run initialized at 0000 UTC 2 October 2020 inaccurately indicated that TC Marie would follow a rare recurving track and make landfall in California due to the presence of a deep EPAC trough in the medium-range forecast. This GFS forecast scenario was preceded by an observed amplified Rossby wave train (RWT) that was associated with recurving western North Pacific (WPAC) TCs Dolphin and Kujira. Downstream development (DBD) across the North Pacific basin observed at 0000 UTC 28 September 2020 was first initiated by the recurvature and extratropical transition of WPAC TC Dolphin that produced localized ridge amplification and jet streak intensification. Subsequently, divergent outflow aloft from TC Kujira enhanced a pre-existing WPAC ridge on 0000 UTC 30 September 2020.

The result of the further amplification of the pre-exisitng upper-level Rossby wave pattern was originally induced by TC Dolphin and continued DBD. TC Kujira tracked as a remnant low into the Central Pacific before phasing and interacting with a downstream upper-level trough along the West Coast at 0000 UTC 3 October 2020. The aforementioned observed EPAC trough was depicted as a much deeper and more equatorward centered feature in the operational GFS forecast from (add date and time), thereby steering TC Marie poleward well past 30°N as opposed to taking the storm on a westward track towards Hawaii as shown in observations. It is hypothesized that the handling of the downstream features and dynamical processes associated with the recurvature of TCs Dolphin and Kujira, respectively, in the operational GFS throughout the seven-day period produced a deeper West Coast trough that would have falsely steered TC Marie poleward near the northwest coast of Baja California.

Prior to TC Marie reaching peak intensity, a notable track bifurcation was depicted for this storm in the 30-member GFS ensemble (GEFS) medium-range forecasts that were initialized at 0000 UTC 2 October 2020. Approximately half of the 30 GEFS members depicted a bifurcated TC track scenario similar to the operational GFS, in which TC Marie tracked north-northeastward toward California, suggesting the possibility of a rare West Coast landfall poleward of 35°N. In contrast, a smaller, second cluster of members maintained a solution consistent with the observed track and intensity towards Hawaii. The discrepancy between both of these GEFS forecast cluster solutions motivates a predictability investigation to assess the dynamic processes and environmental conditions that contributed to the observed track bifurcation and the GEFS forecast uncertainty. We will compare the structure and evolution of the large-scale flow between both aforementioned GEFS clusters to better understand the dynamical processes that governed TC Marie's forecast track bifurcation.

Bosong Zhang
Princeton University/GFDL

**Impacts of Radiative Interactions on Tropical Cyclones, Convective Organization, and Extreme Precipitation Simulated in a ~50 km Resolution GCM**

A ∼50 km resolution atmospheric general circulation model (GCM) is used to investigate how radiative interactions affect tropical cyclones (TCs), the spatial organization of convection, and extreme precipitation. Mechanism-denial experiments are performed in which synoptic-scale radiative interactions are suppressed by overwriting the model-generated atmospheric radiative cooling rates with its monthly varying climatological values. When synoptic-scale radiative interactions are suppressed, i) the global TC frequency is significantly reduced, indicating that radiative interactions are a critical component of TC development under realistic boundary conditions. In addition, TC genesis shifts toward coastal regions, whereas TC lysis locations stay almost unchanged; together the distance between genesis and lysis is shortened, reducing TC duration. ii) tropical convection becomes less aggregated, which is associated with a decrease in the frequency of extreme precipitation events. These results highlight the role of radiative interactions in modulating different aspects of weather extremes.

Catherine L. Stauffer
Florida State University

**The Influence of Changes in Cloud and Aggregation Properties on Cloud Feedbacks in the Radiative-Convective Equilibrium Model Intercomparison Project**

Clouds have long been understood to be one of the highest sources of error and uncertainty in the estimation of climate sensitivity. Radiative-Convective Equilibrium (RCE) simulations, an idealization of the tropical climate, are frequently used to study the changes in cloud properties with warming SST, to varying conclusions. The RCE Model Intercomparison Project (RCEMIP) provides the opportunity to bridge the gap between studies by standardizing the initialization of the RCE state for use in both high resolution cloud resolving models (CRM) and global climate models (GCM) as well as input by global cloud resolving models (GCRM) and large eddy simulations (LES). These simulations are run at three different SSTs (295 K, 300 K, and 305 K) and contain two different domain sizes: RCE_small, which resists the self-aggregation of convection, and RCE_large, in which the convection spontaneously organizes.

RCEMIP finds that, in agreement with the literature, anvil clouds rise in altitude and slightly increase in temperature. RCEMIP also finds anvil cloud fraction to decrease with warming SST for two-thirds of the models. In addition to verifying existing hypotheses for the anvil cloud response to warming SST, RCEMIP found that mid-level clouds robustly decrease with warming SST while collapsing to a common temperature profile. Using a method for collapsing profiles of atmospheric variables to a single representative value as applied to a diagnostic scaling for the prediction of mid-level cloud fraction, we analyze the controls of mid-level cloud fraction. This metric proved to be decently representative of the system as it accurately captures the degree of decrease in mid-level cloud fraction when compared to the full, respective 1D profiles.

We also exploit the diversity of the RCEMIP suite to study the influence of changing clouds and organization properties on the cloud feedback and its decomposition for the models with explicit convection using a couple of commonly used methods for cloud feedback studies. Both rely on the use of offline RRTMG calculations of heating rate profiles and top of atmosphere radiation properties using perturbed profiles of cloud fraction to create cloud radiative kernels. These are then used to compute a corrected cloud feedback that can be used to decompose the total feedback into common components such as the Planck effect, water vapor effect, as well as cloud effects. Similarly, we use an offline approximate to the ISCCP simulator to decompose the cloud feedbacks into impacts due to cloud top pressure and optical thickness properties. This allows for the study of the influence of different cloud feedbacks on the climate sensitivity as represented by the RCEMIP suite, which has previously been shown to not be influenced by the changing properties of the convection or a state's aggregation status. The influence of organized convection and its changes with warming on the cloud feedbacks is studied by comparing the kernel-corrected cloud feedbacks and their decompositions in the RCE_small simulations to those in the RCE_large simulations.

Chia-Ying Lee, Adam H. Sobel, Suzana J. Camargo, and Michael K. Tippett
Columbia University

**Tropical cyclone hazard/risk modeling**

Inclusion of climate change in tropical cyclone risk assessment is challenging: the climate models used for climate projection either simulate TCs poorly, or are too expensive to simulate the very long periods of time necessary to fully sample the distribution of extremes, or both; while typical catastrophe models, as used in the insurance industry, are not climate-sensitive, being based strictly on historical data. One way of overcoming these challenges is to use a statistical-dynamical downscaling tropical cyclone model, an approach that was pioneered by Dr. Emanuel in the early 2000s. This method generates synthetic tropical cyclones conditioned on large-scale climate, which then can be simulated by earth system models for future climate projection applications. In this presentation, I will (1) present our work on the development of the Columbia HAZard model (CHAZ), a statistical-dynamical downscaling tropical cyclone model we developed, inspired by Dr. Emanuel's work; (2) show examples of how CHAZ is used for understanding climate change impacts to TC activity and for assessing regional risk for private sector companies and humanitarian NGOs; and (3) discuss some of the difficulties that arise in this work. These include (a) the need to account for and explain uncertainty; and (b) the tension between bias correction, which is needed for realism and reliability in the recent historical climate, and the model freedom necessary to account for the effects of anthropogenic climate change.

Chih-Chi Hu
Colorado State University

**Ensemble Sensitivity Analysis of Tropical Cyclone Intensification Rate during the Development Stage**

Ensemble sensitivity analysis based on convective-permitting ensemble simulations is used to understand the processes associated with tropical cyclone (TC) intensification under idealized conditions. Partial correlations between different variables and the future TC intensification rate, with the effect of intensity removed, are used to identify the sensitive factors. It is found that the equivalent potential temperature (θe) in the region from the radius of maximum wind (RMW) to 3 times the RMW below 2 km (hereafter, the sensitive region) has the largest correlation (over 0.7) with 2.5-h intensity change. It is found that higher θe in the sensitive region is associated with not only a stronger updraft but also an inward shift of vertical motion in the mid- to upper eyewall. This suggests that higher θe just outside the RMW is favorable to TC intensification not only because of the larger amount of the heating, but also due to the heating location that is closer to the center. Verification experiments justify that higher θe around the RMW to 3 times the RMW is favorable to TC intensification, while higher θe away from 5 times the RMW is shown to be unfavorable for TC intensification. We also verify our results based on a newly developed causality framework, which shows that θe in the sensitive region is a more important driver to short-term intensification rate, compared to other dynamical variables (e.g., boundary layer inflow).

Dazhi Xi
Princeton University

**Sequential Tropical Cyclone Hazards in US East and Gulf Coast**

Sequential tropical cyclone (TC) hazards can pose great risks to coastal US, but the climate change impact on sequential TC hazards has not been investigated. Using both historical observations and a physics-based TC hazard assessment framework, we show that the chances of sequential TC hazards have increased in the past decades for some US locations and will continue to increase in the projected (SSP5 8.5) future conditions. The return period of two hazard producing TCs impacting US East and Gulf coast within 15 days will decrease by -80% to -94% (-60% to -76%) if sea level rise (SLR) is (not) considered. This increase of sequential hazardous TCs is induced by both SLR and TC climatology change, with SLR having the dominate effect that caused ~80% of landfalling TCs to be hazard-producing in the future. Increase of rainfall hazard is the main TC climatology factor that increases sequential TC hazard risks.

Evan Jones
Department of Earth, Ocean and Atmospheric Science, The Florida State University

**Factors Affecting the Development of Frontal Boundaries During the Extratropical Transition of Tropical Cyclones**

As tropical cyclones (TCs) undergo extratropical transition (ET), a hallmark indicator of the completion of this process is the development of distinct frontal boundaries separating the resulting air masses across the developed extratropical cyclone. The resulting locations of the fronts have long been assumed based on the Norwegian and Shapiro-Keyser conceptual models for extratropical cyclone structure. The development and strength of the resulting frontal boundaries has previously been contextualized based on case studies in isolated oceanic basins (such as the North Atlantic and Western Pacific, where ET preferentially occurs), but a global and comprehensive analysis of their exact positioning and strength based on different paths through the cyclone phase space (CPS) has not been undertaken to date. Thus, a global contextualization of how frontal boundaries develop as ET progresses, as well as how this is influenced by ocean surface conditions, is presented here.

We consider the development and strength of cold, warm, and stationary fronts based on both the onset and completion of ET within the CPS. During ET, we find that fronts preferentially form for storms that first become asymmetric and maintain their warm core structure. We also determine that SSTs are colder on average for storms that lose their warm core structure prior to becoming asymmetric. We then utilize an objective frontal diagnostic to identify fronts according to the local 900-hPa temperature gradient and local relative vorticity. Composites of frontal frequency are computed relative to poleward direction, storm motion vector, and deep layer environmental wind shear vector at both the onset and completion of ET. There appears to be a preferred orientation for frontal development that we hypothesize is related to surface conditions, such as baroclinicity. This orientation changes based on basin, and the dependence to the ocean surface conditions, such as the orientation and strength of western boundary currents, is also discussed. Results indicate that forcing based on the strength of the lower-level baroclinicity could result in a different evolution for how the fronts develop as TCs undergo ET.

Funing Li
Purdue University

**Roughening Amazon suppresses South American tornado potential**

North America is the global hotspot for tornadoes, which is typically ascribed to elevated terrain to the West and a source of warm moist air towards the equator. South America has a similar geographic setup, though, yet observations indicate that it produces substantially fewer tornadoes though similar severe thunderstorm activity. Here we show that the roughness of the Amazon surface strongly suppresses tornadoes over central South America relative to a smooth ocean surface equatorward of North America. We use real-Earth global climate model (GCM) experiments with the Amazon surface flattened and smoothed to be ocean-like to show that Amazon roughness strongly reduces the 0-1-km storm relative helicity, which indicates a reduced potential to develop near-ground rotation, while the ingredients for severe thunderstorms (CAPE and bulk shear) remain relatively constant. We then use idealized GCM experiments with a simple continent at midlatitudes and north-south oriented mountains range to the west to show that roughening the tropical surface equatorward of the continent, which is upstream of the low-level flow, reproduces this same result. Moreover, taller mountains (analogous to the Andes versus the Rocky Mountains) act to enhance tornado potential, but this response is fully offset by a roughened upstream surface. These results demonstrate for the first time how the roughness of landmasses can directly impact the geography of hazardous weather on Earth.

Jacob Carstens
Florida State University

**Tropical Cyclones, Equatorial Waves, and Convective Self-Aggregation in Idealized Beta-Plane Simulations**

High-resolution modeling reveals a tendency for deep convection to spontaneously self-aggregate from radiative-convective equilibrium. Self-aggregated convection takes different forms in non-rotating versus rotating environments, ranging from non-rotating bands to tropical cyclones (TCs). Cloud-resolving f-plane simulations show that the relative roles of the mechanisms influencing self-aggregation gradually change with background rotation. This study represents a continuation of that work, building toward more Earth-like model configurations by employing a series of large (~10000 km) cloud-resolving β-plane simulations with fixed, uniform sea surface temperature and uniform insolation. These are developed to allow TCs, non-rotating aggregated convection, and potential equatorial wave activity to co-exist in one space, allowing a robust examination of the role that planetary rotation has in convective behavior.

After a spinup period, numerous TCs first emerge in parts of the domain under the strongest rotation. Numerous TCs co-exist, generally remaining poleward of latitudes analogous to 10-15° on real Earth with little latitudinal preference in TC genesis. Vortex tracking analysis reveals that TCs generally feature an initial vorticity maximum between 1.5-5 km above the surface, before vorticity is eventually generated closer to the surface. They tend to intensify quickly and maintain hurricane strength, unless located near the northern or southern boundary or another TC. In contrast, the weakly-rotating equatorial portion of the domain is characterized by a drier mean state with no TC activity. Aggregated convection primarily emerges as eastward-propagating disturbances resembling convectively-coupled Kelvin waves. Similar to f-plane simulations, these results suggest a fundamental transition in the regime of self-aggregation, including feedback strengths as diagnosed by the frozen moist static energy variance budget, from weakly to strongly rotating environments.

James Hlywiak and David S. Nolan
University of Miami

**On the futility of geoengineering tropical cyclones through ocean cooling**

Proposals to use technology to cool sea surface temperatures have received attention for the potential application of weakening a tropical cyclone ahead of landfall. First, application of an ocean-mixing aware maximum potential intensity theory finds that artificial ocean cooling could drastically weaken tropical cyclones over high sea surface temperature, deep mixed layer environments, especially for fast translation speeds. In contrast, realistic mesoscale numerical simulations reveal that massive regions of artificial cooling could weaken a TC two days before landfall by 15% but only under the most ideal atmospheric and oceanic conditions. Thus, the fundamental theory provides an unreachable upper-bound that is only attainable via unlimited resources. Capital would likely be better spent on endeavors such as improved forecasting and near-shore infrastructure.

Jayesh Phadtare
University of Notre Dame

**Stagnation of weak cyclonic systems along an orographic range**

During the winter monsoon season, cyclonic systems form and organize over the eastern equatorial Indian Ocean and subsequently propagate northwestwards to make landfall. The stronger vortices with high tangential wind speeds move over the Indian peninsula causing damages related to the winds and flooding due to the downpour as well as storm surge. Weak vortices, on the other hand, tend to stagnate over the Indian east coast. Winds in these vortices have moderate strength (10-15 m/s). But they have a high degree of convective organization which hovers over the coast for 2-3 days producing serious rainfall accumulations locally. The most extreme rainfall events at the coastal locations can be associated with these weak cyclonic vortices. These vortices look innocuous on the weather maps, and predicting their behavior along the coast can be challenging. With the help of a few case studies, I suggest that a simple Froude number criterion can be a good predictor of their stagnation; this hits at the orographic blocking of the vortices by the Eastern Ghats mountain range over the coast. A further investigation of the complex interaction between these cyclonic systems and topography is needed for better forecasting of extreme rainfall events along the coast.

Jhordanne Jones
Purdue University

**Simulated Response in the Westward Extent of the Pacific Subtropical High to SST forcings in the CESM2 Global Climate Model**

The variability of the summertime subtropical highs, large regions of subsidence centered between 30°-40°N, have previously been linked to the tracks of landfalling tropical cyclones. An enhanced subtropical high is extended further west resulting in a shift of tropical cyclone tracks to the west and increased chance of landfalls. A weakened subtropical high retreats further east resulting in eastward shifts in storm tracks. However, the strong intraseasonal variations in the subtropical highs make prediction of storm tracks and steering flow difficult. Previous studies have indicated that local ocean-atmosphere coupling is instrumental in maintaining and enhancing the subtropical highs. In this study, we use the NCAR Community Atmosphere Model version 6 to examine the response of month-to-month subtropical high variability to simulations of local sea surface temperature changes. We further assess whether local sea surface temperature variability increases the predictability of large-scale steering flow through modulation of the subtropical highs.

Jie Chen
Princeton University

**A Theoretical Model for Predicting the Tropical Cyclone Wind Field in Response to Idealized Landfalls**

The hazardous weather and the tremendous impact brought by post-landfall tropical cyclones depend not only on the storm intensity but also on the wind field structure and overall size. A simple model that can provide a first-order prediction of inland storm wind fields with limited information is essential for preventing hazards dispatching public resources. This work tests the existing theoretical wind field model and the storm natural radial length scale against idealized landfall experiments. In these simplified landfalls, the surface beneath a mature f-plane axisymmetric storm is dried and roughened individually or simultaneously with various combinations. The theoretical structural model captures the response of the low-level wind field to different types of idealized landfalls. The storm natural length scale, estimated by the ratio of time-dependent intensity to the Coriolis parameter in this work, can generally predict the response of the storm gale wind radii to inland surface forcings but exhibits different responses to each type of idealized landfall experiment. Finally, combining the above results with the previously-reformed Emanuel intensification solution, a theoretical model that can reproduce the wind field response to idealized landfalls is formed. Results indicate the potential of using theoretical models with simplified assumptions for predicting TC inland wind fields and impacts.

Jonathan Lin
MIT

**Tropospheric Influence on Stratospheric Tropical Upwelling**

While it is generally accepted that the stratospheric Brewer-Dobson circulation is a wave-driven phenomenon, there are some characteristics of stratospheric tropical upwelling that remain poorly understood. Solutions to steady forcing in a simple linear model that couples a convecting troposphere with a passive stratosphere are used to investigate tropospheric influence on stratospheric tropical upwelling. It is shown that sea surface temperature (SST) forcing can drive tropical upwelling in the absence of wave-drag, though wave-drag is necessary to induce an equator-to-pole circulation. Under an equatorially-centered SST forcing, the linear response is akin to a tropopause anticyclonic potential vorticity anomaly, i.e. a warm troposphere and a cold stratosphere. The combined effect of the annual cycle, off-equatorial heating, and wave-drag on the stratospheric circulation are also explored. It is shown that tropospheric forcing of stratospheric tropical upwelling explains observations of 1) strong anti-correlations between SST and tropopause temperature, 2) a minimum (and sometimes downwelling) in stratospheric upwelling on the equator, and 3) the maximum in stratospheric upwelling in the summer hemisphere. Limits on the extent of downward control in the tropical lower stratosphere are discussed.

Josef Schrottle, Nili Harnik, Jai Sukhatme, and Suhas DL
Tel Aviv University

**Turbulence and equatorial waves in moist and dry shallow-water flow, excited through mesoscale stochastic forcing**

Observed space-time spectra of tropical brightness temperatures (Wheeler-Kiladis diagrams) show peaks along the linear dispersion relation for linear tropical waves, embedded in a red-noise background. We examine the ability of turbulent interactions to excite both the red-noise background and the linear waves, in a moist shallow-water spherical model, stochastically forced at the mesoscales.

Separately forcing the vorticity, divergent, height or moisture fields, we study the dependence of the formation of an upscale energy cascade on the variable forced, and on the existence of moisture. When vorticity is forced, a clear -5/3 upscale energy cascade develops from the mesoscale to the Rossby deformation scale. This upscale cascade is fails to be excited when divergence is forced. Forcing the height field is able to excite a weak upscale cascade, more strongly so in the presence of moisture, and forcing moisture excites an upscale cascade very efficiently, likely due to the memory introduced to the system by the moist interactions. Unlike for vorticity forcing, however, the upscale cascade of moisture-forced anomalies depends on the Coriolis force exciting vorticity in the flow, thus it disappears when there is no planetary rotation.

We also examine the aggregation of moisture in the vorticity-forced runs, and find that horizontal advection results in an upscale cascade of moisture anomalies. In all, these experiments demonstrate that the vortical and divergent wind are inextricably linked with the evolving moisture field, and that large-scale equatorial waves co-exist with synoptic-scale moist turbulence.

Kuan-Yu Lu
Purdue University

**The vortex Rhines scale strongly limits tropical cyclone size**

Recent work found evidence using aquaplanet experiments that tropical cyclone (TC) size on Earth is limited by the Rhines scale, which depends on the planetary vorticity gradient, β. This study aims to examine how the Rhines scale limits the size of an individual TC. First, this study re-express the traditional Rhines scale as a Rhines speed to characterize how the effect of β varies with radius in a vortex whose wind profile is known. With this framework, this study define the vortex Rhines scale, which is the transition radius that divides the vortex into a vortex-dominant region at smaller radii, where the axisymmetric circulation is steady, and a wave-dominant region at larger radii, where the circulation stimulates planetary Rossby waves and dissipates. Experiments are performed using a simple barotropic model on a β-plane initialized with a TC-like axisymmetric vortex defined using a recently-developed theoretical TC wind profile model. β and initial vortex size are each systematically varied to investigate the detailed responses of the TC-like vortex to β. Results show that the vortex shrinks towards an equilibrium size that closely follows the vortex Rhines scale. A larger initial vortex relative to its vortex Rhines scale will shrink faster. The shrinking timescale is well-described by the vortex Rhines timescale, which is defined as the overturning timescale of the circulation at the vortex Rhines scale and is shown to be directly related to the Rossby wave group velocity.

Lingwei Meng
Princeton University

**Non-local Controls on Tropical Cyclogenesis: A Trajectory-based Genesis Potential Index**

Tropical cyclone genesis (TCG) is a continuously evolving process initiated by convective TC precursors (or "seeds") and influenced by environmental conditions both local and non-local along the seed-to-TC trajectory. Genesis potential indices (GPIs) have previously been constructed to evaluate the TCG frequency using local environmental variables. Currently, the effects of non-local environments on TCG remain elusive and are not included in any GPI.\\In this study, we first investigate the local environmental factors that are most influential on seed genesis and TC genesis, respectively, over the Eastern North Pacific (ENP) and North Atlantic (NA). A sequential feature selection algorithm (SFS) applied to 20 candidate variables identifies the upward motion as the dominant factor regulating the seed genesis over both basins, and the vertical wind shear (heating condition) as the leading factor favoring TCG in the ENP (the NA).

We now propose trajectory-based GPIs (traj-GPIs), which aim to link the TCG frequency to the environmental conditions from the seed genesis points. Our approach is to construct spatial filters using observed trajectory densities, and to merge adjacent non-local environments into each grid by convolving between the filters and the original environments. SFS is again used to identify the dominant filtered factors, followed by the Poisson regression to produce the “traj-GPIs”. We find that the combination of seed activity driven mainly by upward motion and maturation controlled primarily by vertical wind shear (heating) is now captured simultaneously. Traj-GPIs provide a more accurate reproduction of spatiotemporal variations than the original GPIs.

Lizzie Wallace
Rice University

**Resolving long-term variations in North Atlantic tropical cyclone activity using paleohurricane proxy networks**

Our knowledge of the climate influence on tropical cyclone variability on decadal or longer timescales is limited by a short and biased observational record. Sedimentary archives of past hurricanes can extend the observations of tropical cyclones back thousands of years. These reconstructions demonstrate that there were large centennial-scale shifts in regional hurricane activity over the past few thousand years, with critical implications for the risk of a local hurricane landfall. However, these records are subject to biases – capturing only close-moving intense storms at varying resolutions. Given these biases, it is difficult to assess whether variability in paleohurricane records is related to climate variability or just random clustering of events under a stationary climate. Here, we devise two pseudo proxy networks drawing from the full suite of published paleohurricane studies in the North Atlantic. We run a large set of synthetic storms forced with the CESM Last Millennium Ensemble and MPI-ESM-P climate as boundary conditions through each pseudo network to assess the theoretical skill of paleohurricane proxies at capturing low frequency variability in North Atlantic basin-wide and intrabasin tropical cyclones. We find that basin-wide and paleohurricane compiled tropical cyclone counts are significantly correlated with one another for the past millennium on annual to multi-decadal timescales. Our findings lend support for the use of paleohurricane records to infer long-term basin-wide tropical cyclone frequency. However, current paleohurricane proxy networks predominantly capture storms moving in the Caribbean/Gulf of Mexico. We can improve our estimates of past Atlantic hurricanes in future work by adding more sites from the U.S. Southeast.

Martin Velez Pardo
MIT

**Organized convection and dry tropical cyclones in simulations of simple convective setups**

Under the current climate conditions on Earth, tropical cyclones are powered primarily by the exchange of latent heat between the ocean surface and the overlying air. Inspired by theory of mature tropical cyclones as thermodynamic engines, however, recent modeling work has provided solid evidence that tropical cyclones could form and persist under conditions where latent surface heat exchange is totally suppressed, provided instead that the sensible heat flux is strong enough. The formation of such "dry hurricanes" allows the use of simple models of dry convection to probe the relationship between surface enthalpy fluxes, convective organization, and cyclone development, structure and intensity. We use direct numerical simulations of rotating Rayleigh-Bénard convection to analyze the properties of organized convection and dry-hurricane-like structures that form in such idealized setups, with a focus on the role of thermal boundary conditions on the top and bottom of the domain. We find that parameter regimes characterized by weak rotation and at least moderate levels of turbulence (that is, with convective Rossby numbers around O(1) and flux Rayleigh numbers of O(10^9) and greater), and sufficiently large domain aspect ratios, give rise to organized convection for some configurations of the thermal boundary conditions, but not for others. Furthermore, for a subset of these thermal boundary conditions, the convective organization takes the form of persistent vortices that exhibit the same essential properties of the dry tropical cyclones found in more realistic atmospheric models: a warm core, high levels of axisymmetry, a strong azimuthal circulation, and a substantially larger size than the most unstable modes in rotating Rayleigh-Bénard convection with boundaries at fixed temperatures. The results lead us to hypothesize that both up-down asymmetry of thermal boundary conditions, and a direct flow dependence of the heat exchange at at least one boundary, are key for the persistence of dry tropical cyclones.

Collaborators: Timothy W. Cronin

Matthieu Kohl
MIT

**Diabatic Rossby Vortices - Extratropical Cyclones with Strong Latent Heating**

Past research has identified a special class of midlatitude storm, dubbed the Diabatic Rossby Vortex (DRV), which derives its energy from latent heating rather than baroclinic effects, and as such goes beyond the traditional understanding of midlatitude storm formation. DRVs have been implicated in extreme and poorly predicted forms of cyclogenesis along the east coast of the US and the west coast of Europe with significant damage to property and human life. Recently, it has been shown that in idealized simulations of moist baroclinic instability on a sphere, the most unstable mode transitions from a periodic wave to an isolated DRV in sufficiently warm climates. The emergence of the DRV as the fastest growing mode of moist baroclinic instability points to the profound modifying influence that latent heating has on the structure of fast growing disturbances in a warming climate.

While theories exist for the growth rate and length scale of dry baroclinic waves (Charney 1947, Eady 1949, Philipps 1954) and moist baroclinic waves (Emanuel et. al. 1987), there currently is no theory for the growth rate and length scale of DRVs or the wave-vortex transition observed at higher temperatures in moist baroclinic instability simulations. Building on the pioneering study by Emanuel et. al. 1987, we introduce a minimal moist two-layer quasigeostrophic model with tilted boundaries in which the most unstable mode is a DRV, and we derive growth rates and length scales for this DRV mode analytically. In the limit of a convectively-neutral stratification, the length scale of ascent of the DRV is the same as that of a periodic moist baroclinic wave, but the growth rate of the DRV is 54% faster. We explain the isolated structure of the DRV using a simple potential vorticity (PV) argument, and we create a phase diagram for when the most unstable solution is a periodic wave versus a DRV, with the DRV emerging when the moist static stability and meridional PV gradients are weak. Finally, we compare the structure of the DRV mode to DRV storms found in reanalysis and to a DRV storm in a warm-climate simulation.

Nathanael Wong
Harvard University

**The inherent instability of the Weak Temperature Gradient Approximation**

The weak-temperature gradient approximation has been a popular method used to couple convection in limited-area domain simulations to the large-scale climatology. In this study, we investigate the sensitivity of models initiated with homogeneous surface conditions to different weak-temperature gradient implementation methods and strengths, and perturbations to the reference states. As long as the reference profile of temperature and water-vapour that is coupled with the model using the weak temperature gradient is close to radiative-convective equilibrium, multiple equilibrium states can simply be generated from small perturbations of the initial profile of temperature and humidity. Furthermore, we see that this bifurcation of model states into wet and dry regimes can occur not just in simulations with interactive radiation schemes such as RRTM, but also in simulations with static radiation and where the bulk-surface fluxes are fixed. This indicates that the coupling of convection to the large-scale climatology via the weak-temperature gradient approximation is inherently unstable, and the perturbations that result from this instability are then be further exploited by radiative feedback processes.

Peter Sousounis
Verisk

**Using Dynamically Based Projections to Estimate Future Hurricane Losses from Climate Change**

Catastrophe models are used worldwide by the insurance industry, banks, investors, and local governments to quantify risk from extreme weather events. These models by default focus on the risk for the current climate but all interested parties express growing desire for such models to reflect the risk on longer time scales. Hurricanes in the U.S. occur infrequently but are the single largest contributing weather phenomenon to annual average insured loss. Future climate views of hurricane activity are constrained by current coarse resolution in general circulation model (GCM) output. Emanuel has developed a downscaling technique that evolves tropical cyclone activity in a dynamically consistent way from large scale environmental conditions from GCMs that is more trustworthy. We use output from this technique (described in numerous articles by Emanuel from 2008-2021) to create a stochastic view of how economic and insured losses may change for a variety of future time horizons and shared socio-economic pathways (climate scenarios). A variety of loss metrics are obtained besides annual average losses, including losses at select exceedance probabilities. Losses are most sensitive to projected changes in major category storms as well as changes in regional landfall frequencies.

Sarah Weidman
Harvard EPS

**Modification of the OMI for MJO characterization**

Characterization of the phase and amplitude of the Madden-Julian oscillation (MJO) has been shown in observations to be relevant to predicting weather in North America on a subseasonal timescale. One of the standard methods used to characterize the state of the MJO is using the OMI, an index based on the spatial pattern of 30-96 day eastward filtered OLR. The set of EOFs used to calculate the OMI in observations exhibits oscillations on the order of 20-30 days, which could confound the characterization of the MJO propagation throughout the year. These high-frequency oscillations are more pronounced when using model data and datasets with shorter timespans, and are compounded by issues with continuity and degeneracy of the EOFs. We propose a simple fix to the OMI that involves rotating the EOFs to minimize negligible oscillations while retaining the spatial pattern described by the EOFs. This rotation method is simple to implement as a postprocessing step of the current OMI calculation and cleanly reduces the spurious oscillations and degeneracy issues seen in the standard method. Improvements in characterization of the MJO will facilitate analysis of the MJO using model data and data with shorter timespans, and allow for more robust analysis of the teleconnections arising from the state of the MJO.

Sydney Sroka
MIT

**Trends in Maximum Potential Intensity**

Since 1980, hurricanes have inflicted more damage in the US than any other weather-related hazard, and their destructive potential is expected to increase with climate change. The environment through which a hurricane travels modulates its intensity, and so it is critical to accurately forecast the meteorological features that influence hurricanes. This poster will primarily focus on how IBM's PAIRS can be used to study Maximum Potential Intensity (MPI), which is the theoretical maximum intensity a hurricane could exhibit in a given environment. The MPI can be used to forecast rapid changes in hurricane intensity for specific storms, and can provide insight into long-term trends in overall intensity.

Timothy Merlis
Princeton University

**The Sensitivity of Idealized GCM Simulations of Tropical Cyclones to Radiation**

Radiation is a critical aspect of the climate system that influences tropical circulations and is coupled to the circulations through clouds and water vapor. Tropical cyclones (TCs) are one of the most distinctive tropical circulations, and they are usually thought of as being energetically driven by the turbulent surface flux of latent energy (evaporation). Recently, it has been suggested that flow-dependent aspects of radiative transfer can accelerate the spin-up of TCs. Here, I examine the sensitivity of atmospheric general circulation model (GCM) simulations with uniform thermal forcing to changes in radiation. The tropospheric-mean cooling rate is one important control on the number and intensity of TCs in this model configuration. The flow-dependence of radiation on clouds and water vapor is also assessed. Finally, the vertical structure of the radiative cooling is another potentially important aspect of radiation in determining TC statistics. The aim of this systematic investigation of radiation's influence on TCs is to elucidate new robust mechanisms of the large-scale climate on these destructive extreme events.

Tsung-Lin Hsieh
Princeton University

**Radiative cooling suppresses tropical cyclone frequency through large-scale seeding propensity**

Tropical cyclone (TC) frequency depends on a set of large-scale environmental variables. The complex response of these variables to warming often obscures understanding of TC projection. Here we investigate how TC frequency is influenced by the large-scale radiation pattern, which is an important climate change signature. In atmospheric model simulations with uniform surface warming, we prescribe two radiative heating/cooling anomaly patterns that differ mostly over the Western Pacific while holding other settings identical. The simulation prescribed with radiative heating anomaly generates more TCs and seeds than that prescribed with radiative cooling anomaly over the Western Pacific. The results are explained using a downscaling formula, known as the seed propensity index, combined with the gross moist stability theory. The prescribed radiation modifies large-scale vertical velocity to maintain column energy balance. Large-scale vertical velocity is associated with the frequency of convection aggregates, which modulates the frequency of seeds and TCs. The effects of large-scale radiation control on TC frequency and small-scale surface flux feedback are summarized by the seed propensity index.

Tsung-Yung Lee
Department of Earth, Ocean and Atmospheric Science, Florida State University

**Using the CloudSat Tropical Cyclone Overpass Dataset to Investigate Tropical Cyclone-Radiation Interactions**

Understanding the development of tropical cyclones (TCs) has been one of the most challenging tasks in improving TC forecasts. In numerical simulations, radiative feedbacks have been considered as one of the factors that contribute to convective organization and TC development. The cloud-infrared radiation feedback warms the mid-troposphere in the inner core of TCs relative to clear-sky cooling in the environment. This radial gradient of warming from infrared radiation can induce a transverse circulation and support moistening in the inner core, favoring TC development. Whether or not real-world TCs develop via similar processes of cloud-radiative feedback is worthy of investigation.

The CloudSat TC (CSTC) overpass dataset is used to investigate the cloud-radiative feedbacks from an observational perspective. Composites in radius-height and precipitable water (PW)-height diagrams for all overpasses are conducted to demonstrate general features of thermodynamic, cloud and radiative structure in TCs. The composites are categorized by 24-h intensification rate of each overpass which is evaluated from the International Best Track Archive for Climate Stewardship (IBTrACS) database. In addition, only weak TCs (with the maximum surface sustained wind weaker than 42 m s-1) and overpasses prior to each TC reaching its lifetime maximum intensity for the first time are included. This focuses on the early development stage. The intensification rate composite includes 758 TC cases, 2,638 overpasses and 3,762,186 satellite footprints in total. The categorization of TC intensification rate includes neutral, intensifying, fast-intensifying, and rapid-intensifying groups.

Radius-height composites show that the CSTC overpasses capture significantly greater amount of cloud ice within 200-km of the TC center with a gradual decrease in magnitude with radius. This radial gradient of cloud ice water content leads to the decrease (increase) in magnitude of both infrared cooling and shortwave warming in the middle and lower troposphere (above the cloud top) within 200-km radius. Anomalous net radiative warming in the inner core in the mid-troposphere favors the development of the transverse circulation of TC. The contribution from cloud-radiative forcing dominates the net radiative warming anomaly in the inner core, while the clear-sky effect provides a cooling anomaly in the mid-troposphere in the inner core with its magnitude an order smaller than the cloud-radiative forcing. Although the contribution from the shortwave radiative flux supports an inner-core cooling anomaly in mid-troposphere, the net inner-core warming anomaly in mid-troposphere mainly comes from the longwave radiative flux via the cloud-radiative forcing.

PW-height composites demonstrates that bins with greater PW are accompanied by greater frozen moist static energy, radar reflectivity, ice water content, specific humidity and relative humidity below 16-km height compared to the bins with lower PW. The net radiative fluxes also display greater mid-level warming effect in the greater PW bins which is mainly contributed by the cloud-longwave effect. These results support the moist-dry difference between the TC inner core and outer area. Whether this moist-dry difference can lead to the difference in the net radiative flux divergence is worthy of further investigation.

Tyler Leicht
University at Albany, SUNY

**Dynamics and Evolution of the Longest-Lasting Persistent Ridge Regime over Western North America**

A persistent hemispheric upper-level flow pattern, linked to the longest-lasting ridge regime over western North America in 70 years, resulted in anomalous surface weather of much of the Northern Hemisphere in winter 1980–1981. While this work started by identifying the month-long ridge regime over western North America, further investigation suggested the NH flow pattern had remarkable persistence throughout late December 1980 and January 1981. Wagner (1981) and Taubensee (1981) states that the US experienced record cold in the east and record warmth in the west, while record dry was widespread in January 1981 due to a stable wavenumber-3 upper-tropospheric flow pattern for both December and January. This presentation will detail the surface impacts of the aforementioned persistent NH flow pattern as well as the dynamic and thermodynamic drivers for the formation and maintenance of this regime.

Before persistent regime onset over the North Pacific (NPAC) basin, a strong 1048-hPa surface high near the Bering Strait helped to shift and extend a pre-existing storm track from the east coast of Asia toward the coast of western North America. Several storms within this storm track began to rapidly deepen as a quasi-stationary ridge built over the Western US around 21 December. Subsequently, this ridge built northward into Canada and became quasi-stationary. The strong surface high over the Bering Strait slowly retrogressed into eastern Siberia, merged with a smaller-scale ridge, and prevented cyclones from tracking through the Bering Strait. Cold-air advection behind developing cyclones in the western Pacific helped to maintain a broad trough across the NPAC, an extended and equatorward-shifted jet stream, and an accompanying zone of enhanced baroclinicity. This persistent flow pattern remained quasi-stationary for approximately three weeks and enabled repeated cold air surges into central and eastern US during much of January. A pattern change occurred on 21 January 1981, when cyclogenesis in the jet exit region over the eastern Pacific led to a new ridge near 150W and no longer reinforced the previously persistent ridge over western North America. As a result of this cyclone, strong diffluence in that same jet exit region favored progressive flow and an end to the downstream stable regime by the end of January 1981.

Zachary Johnson
Purdue University

**Statistical framework for western North Pacific tropical cyclone landfall risk through modulation of the western Pacific subtropical high and ENSO**

Seasonal predictions of tropical cyclone (TC) landfalls are challenging because seasonal landfall count not only depends on the number and spatial distribution of TC genesis, but also whether those TCs are steered toward land or not. Past studies have separately examined genesis and landfall as a function of large-scale ocean and atmospheric environmental conditions. Here, we introduce a practical statistical framework for estimating the seasonal count of TC landfalls as the product of a Poisson model for seasonal TC genesis and a logistic model for landfall probability. We compute spatial variations in TC landfall and genesis by decomposing TC activity in the western North Pacific (WNP) basin into 10x10 degree bins, then identify coherent regions where the El Niño-Southern Oscillation (ENSO) and the western extent of the Pacific subtropical high (WPSH) have significant influences on seasonal landfall count. Our framework shows that ENSO and the WPSH are weakly related to basin-wide landfalls but strongly related to regional genesis and landfall probability. ENSO modulates the zonal distribution of TC genesis, consistent with past work, whereas the WPSH modulates the meridional distribution of landfall probability due to variations in steering flow associated with the Pacific subtropical high. These spatial patterns result in four coherent sub-regions of the WNP basin that define seasonal landfall variations: landfall count increases in the southwestern WNP during a positive WPSH and La Niña, the south-central WNP during a positive WPSH and El Niño, the eastern WNP during a negative WPSH and El Niño, and the northern WNP during a negative WPSH and La Niña.