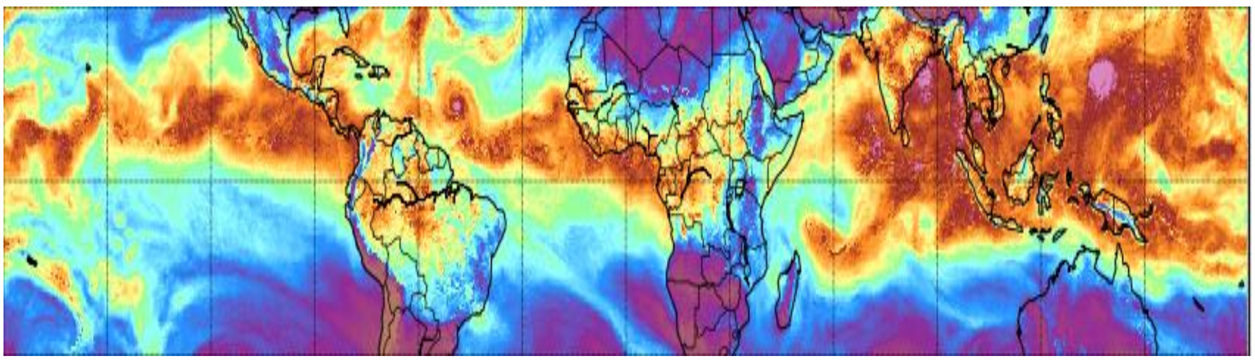
10th Northeast Tropical Workshop
Program



University at Albany, ETEC Building
5–7 June 2023

Schedule

Monday June 5		Affiliation	Title
8:50-9:00	**Opening remarks**		
9:00-10:15	**TCs & Climate I**	*Chair: Suzana Camargo*	
	Kevin Reed	Stony Brook University	Using a model hierarchy to advance understanding of climate change impacts on hurricanes
	Tsung-Lin Hsieh	Princeton University	Large-scale radiation response to global warming influences tropical cyclone frequency
	Hiro Murakami	NOAA-GFDL	Substantial global influence of anthropogenic aerosols on tropical cyclones over the past 40 years
	Kerry Emanuel	MIT	Effects of Climate Change on TC freshwater flooding
	Jorge Luis Garcia Franco	Lamont-Doherty Earth Observatory, Columbia University	Subseasonal prediction of tropical cyclone precipitation
10:15-10:30	**Break**		
10:30-11:30	**Discussion 1**		
11:30-13:00	**Lunch**		
13:00-14:00	**TCs & Climate II**	*Chair: Adam Sobel*	
	Gabriel Vecchi	Princeton University	Connecting past and future hurricane activity changes
	Gabriel Rios	Princeton University	What would a climate without tropical cyclones look like? A preliminary analysis of WISHE suppression on TCs and climate
	Shuai Wang	Princeton University / GFDL-NOAA	Anthropogenic forcing changes coastal tropical cyclone frequency
	Colin Zarzycki	Penn State University	Is it possible? Stakeholder-informed synthetic hurricane storylines in a 3km Earth system model
14:00-14:45	**Discussion 2**		
14:45-15:15	**Break and photo**		
15:15-16:15	**Tropical General Circ.**	*Chair: Kerry Emanuel*	
	Baoqiang Xiang (virtual)	NOAA-GFDL, UCAR	Predictions of Boreal Summer Intraseasonal Oscillation in GFDL SPEAR model
	Levi Silvers	Stony Brook University	Decomposing the large-scale tropical circulation across a hierarchy of CESM model configurations
	Chenggong Wang	Princeton University	Diagnose the factors contribute to the intermodel spread of climate feedbacks
	Ilai Guendelman	Princeton University	The response of tropical precipitation and circulation to warming in a global storm resolving model
16:15-17:00	**Discussion 3**		
17:00-18:30	**Reception (cash bar) and Poster Session**		

	Wenchang Yang	Princeton University	How does global mean precipitation respond to radiative forcings?
	Jonathan Lin	Lamont-Doherty Earth Observatory, Columbia University	Tropospheric Influence on Stratospheric Upwelling
	Alex Gonzalez	Woods Hole Oceanographic Institution	Dynamical importance of the trade wind inversion in suppressing the southeast Pacific ITCZ
	Crizzia Mielle De Castro	University at Albany	Upper tropospheric circulation associated with Kelvin waves propagating through the MJO
	Dazhi Xi	Princeton University	Statistical Downscaling Projections of North Atlantic Tropical Cyclone Activity: Uncertainties Inherent from Large-Scale Climate Simulations
	Indrani Ganguly	Iowa State University	Investigating double-ITCZ biases in climate models: Role of daily-resolved air-sea interactions
	Melissa Piper	University at Albany	A Climatology of Tropical Cyclone Interactions with Deformation Steering Flows in the Atlantic Ocean
	Sofia Menemenlis	Princeton University	Convection-permitting ensemble simulations of extreme rainfall: A case study of Hurricane Ida's aftermath
	Nathalie Rivera Torres	University at Albany	Investigating the downshear reformation of Sally (2020) using ensemble simulations

18:30-20:00 **Dinner**

Tuesday June 6

9:00-10:15 **ENSO & MJO** *Chair: Tim Cronin*

	Adam Sobel	Columbia	Near-term tropical cyclone risk and coupled Earth system model biases
	Suzana J. Camargo	Lamont-Doherty Earth Observatory, Columbia University	ENSO diversity and Projections of ENSO-Tropical Cyclone relationship
	Maya Chung	Princeton University	The influence of sea surface salinity variability on the equatorial Pacific mean state and extreme ENSO events
	Paul Roundy	University at Albany	How Advection Influences the Phase Speed of the MJO
	Sarah Weidman	Harvard	Potential predictability of the MJO in SPCAM

10:15-10:30 **Break**
10:30-11:30 **Discussion 4**
11:30-13:00 **Lunch**

13:00-14:15	**Convection & Tropical Dynamics**	*Chair: Alex Gonzalez*	
	Martin Velez-Pardo	MIT	Contrasting two perspectives on deep atmospheric convection: low-level convergence vs. column energetics
	Isabelle Bunge	Columbia University	SST-Induced Boundary Layer Convergence Variability in Relation to Precipitation
	Patrick Orenstein	Columbia University	Efficiency of convective cold pool production by rainfall moderated by column saturation
	Nathanael Wong	Harvard	Bridging the Gap between Implementing and Understanding the Different Implementations of the Weak Temperature Gradient Approximation in Cloud Resolving Models
	Zhiming Kuang	Harvard	Linear time-invariant models of a large cumulus ensemble
14:15-15:15	**Discussion 5**		
15:15-15:30	**Break**		

15:30-16:30	**TC Genesis & Midlat. Interactions**	*Chair: Kristen Corbosiero*	
	Lingwei Meng	Princeton University	Non-local Controls on Tropical Cyclogenesis: A Trajectory-based Genesis Potential Index
	Xingchao Chen	Penn State University	Role of diurnal gravity waves in MCS initiation and Tropical Cyclogenesis over the Bay of Bengal
	Alex Mitchell	University at Albany	Intraseasonal Variability of Recurving EPAC Tropical Cyclones
	Erica Bower	Stony Brook University	Exploring Extratropical Transition and Associated Precipitation in Climate Simulations and Operational Forecast Models
16:30-17:15	**Discussion 6**		

Wednesday June 7

9:00-10:00	**TC Structure & Intensity I**	*Chair: Jonathan Lin*	
	Jacob Carstens	Penn State University	Asymmetric Tropical Cyclone Structures and Processes in Reanalyses and Climate Models
	Chau Lam Yu	University at Albany	Tilt-following boundary layer asymmetries of tropical cyclones in moderately sheared environment
	Timothy Cronin	MIT	An analytic model for Tropical cyclone outer winds
	Kun Gao (virtual)	Princeton University, NOAA-GFDL	Improving hurricane track prediction in high-resolution models
10:00-10:45	**Discussion 7**		

10:45-11:00	**Break**		
11:00-12:00	**TC Structure & Intensity II**	*Chair: Jake Carstens*	
	Minghao Zhou	University at Albany	Inertial Instability and the Development of Outflow Channel in Modeled Tropical Cyclones
	Jannetta Richardson	University at Albany	Impact of Cloud-Radiation Processes on Tropical Cyclone Development in Sheared Environments
	Jeremiah Piersante	University at Albany	Decomposing Forcing Mechanisms and Impacts of Simulated Diurnal Pulses
	Kristen Corbosiero	University at Albany	Global Characteristics of "On-the-Clock" and "Off-the-Clock" Tropical Cyclone Diurnal Pulses
12:00-12:45	**Discussion 8 and closing remarks**		
12:45-14:00	**Lunch**		

Attendee List

Name	Affiliation	Attendance
Adam Sobel	Columbia University	In-person
Patrick Orenstein	Columbia University	In-person
Isabelle Bunge	Columbia University	In-person
Zhiming Kuang	Harvard	In-person
Sarah Weidman	Harvard	In-person
Nathanael Wong	Harvard	In-person
Indrani Ganguly	Iowa State University	In-person
Jonathan Lin	Lamont-Doherty Earth Observatory, Columbia University	In-person
Jorge Luis Garcia Franco	Lamont-Doherty Earth Observatory, Columbia University	In-person
Suzana Camargo	Lamont-Doherty Earth Observatory, Columbia University	In-person
Kerry Emanuel	MIT	In-person
Martin Velez-Pardo	MIT	In-person
Tim Cronin	MIT	In-person
Steve Garner	NOAA-GFDL	In-person
Thomas Knutson	NOAA-GFDL	Virtual
Hiro Murakami	NOAA-GFDL	In-person
Baoqiang Xiang	NOAA-GFDL, UCAR	Virtual
Colin Zarzycki	Penn State University	In-person
Jake Carstens	Penn State University	In-person
Xingchao Chen	Penn State University	In-person
Chenggong Wang	Princeton University	In-person
Dazhi Xi	Princeton University	In-person
Gabriel Rios	Princeton University	In-person
Gabriel Vecchi	Princeton University	In-person
Ilai Guendelman	Princeton University	In-person
Lingwei Meng	Princeton University	In-person
Maya Chung	Princeton University	In-person
Sofia Menemenlis	Princeton University	In-person
Tsung-Lin Hsieh	Princeton University	In-person
Wenchang Yang	Princeton University	In-person
Shuai Wang	Princeton University, GFDL	In-person
Kun Gao	Princeton University, GFDL	Virtual
Michael Dickinson	RenaissanceRe Risk Sciences	Virtual
Erica Bower	Stony Brook University	In-person
Kevin Reed	Stony Brook University	In-person
Levi Silvers	Stony Brook University	In-person
Crizzia Mielle De Castro	University at Albany	In-person
Kyle Ahern	University at Albany	Virtual
Alex Mitchell	University at Albany	In-person

Brian Tang	University at Albany	In-person
Chau Lam Yu	University at Albany	In-person
Jannetta Richardson	University at Albany	In-person
Kristen Corbosiero	University at Albany	In-person
Melissa Piper	University at Albany	In-person
Nathalie Rivera Torres	University at Albany	In-person
Paul Roundy	University at Albany	In-person
Minghao Zhou	University at Albany	In-person
Jeremiah Piersante	University at Albany	In-person
Daiwei Wang	Verisk	Virtual
Suz Tolwinski-Ward	Verisk	Virtual
Wesley Terwey	Verisk	Virtual
Sylvie Lorsolo	Verisk	Virtual
Eric Uhlhorn	Verisk	Virtual
Alex Gonzalez	Woods Hole Oceanographic Institution	In-person
Dan Kirk-Davidoff	Electric Power Research Institute	In-person

Abstracts and Supplementary Material

Using a model hierarchy to advance understanding of climate change impacts on hurricanes

Kevin Reed
Stony Brook University

The use of idealized model configurations has had a long history in the understanding of the atmosphere. As global atmospheric models become more complex (i.e., higher resolution, improved parameterizations, higher-order dynamics packages), the use of these models for exploring change and decadal variations in tropical cyclones remains vital. Hierarchies of reduced complexity configurations within the Community Atmosphere Model (CAM) have been constructed and used to understand physical processes and explore model sensitivities at reduced computational expense. Clouds, circulations, and rainfall in the tropics play an important role in Earth's climate, and idealized model configurations can be useful to explore the response of tropical climate to warming, including tropical cyclones. This work uses CAM in the Radiative Convective Equilibrium (RCE) Model Intercomparison Project (RCEMIP), the Atmospheric Model Intercomparison Project (AMIP) and short-term weather-hindcast configurations to estimate how tropical cyclone precipitation is impacted by increasing sea surface temperature (SST) due to climate change. Across the hierarchy we calculate a 5-10% increase in storm precipitation per K increase in SST depending on the precipitation metric. We find that for extreme tropical cyclone precipitation, SST and the resulting tropical cyclone intensity increases dominate the per K increase. By comparing these results to observed changes in storms over the historical record, this work helps to improve our understanding of how changes and variations in SST impact tropical cyclones.

Large-scale radiation response to global warming influences tropical cyclone frequency

Tsung-Lin Hsieh, Gabriel Vecchi, Wenchang Yang, Bosong Zhang, Chenggong Wang
Princeton University

Ming Zhao
NOAA/Geophysical Fluid Dynamics Laboratory

Brian Soden
University of Miami

Atmospheric radiative feedbacks and tropical cyclone (TC) frequency response to climate change are among the most challenging factors to predict using global climate models. In this study, we present a physical mechanism that connects these two variables through a combination of atmospheric column energy budgets and a newly developed TC seed propensity index. We test our theoretical hypothesis through model experiments with prescribed radiative heating rates and sea surface temperatures. Given two atmospheric models with opposite TC frequency response to warming, we interchange their radiative heating rate anomalies. In the Western North Pacific where the model responses are the most distinct, the radiative heating anomalies from one model flip the sign of TC response in the other model, as expected by theory. The results highlight the impact of large-scale radiation patterns on TC frequency.

Substantial global influence of anthropogenic aerosols on tropical cyclones over the past 40 years

Hiro Murakami
NOAA-GFDL

Over the past 40 years, anthropogenic aerosols have been substantially decreasing in Europe and the United States owing to pollution control measures, whereas they have increased in South and East Asia because of the economic and industrial growth in these regions. However, it is not yet clear how the changes in anthropogenic aerosols have altered global tropical cyclone (TC) activity. In this study, we reveal that the decreases in aerosols over Europe and the United States have contributed to significant decreases in TCs over the Southern Hemisphere as well as increases in TCs over the North Atlantic, whereas the increases in aerosols in South and East Asia have exerted substantial decreases in TCs over the western North Pacific. These results suggest that how society controls future emissions of anthropogenic aerosols will exert a substantial impact on the world's TC activity.

Supplementary Material

Effects of Climate Change on TC freshwater flooding

Kerry Emanuel
MIT

Freshwater flooding is the dominate source of casualties in tropical cyclones and a major contributor to damage. Most and perhaps all projections indicate increased TC flooding as the climate continues to warm. In this talk I will present forward projections of TC storm total rainfall at the county level in the U.S. and deconvolve the changes in rainfall into contributions from changing frequency, intensity, environmental water vapor, and translation speed.

Subseasonal prediction of tropical cyclone precipitation

Jorge Luis Garcia Franco, Chia-Ying Lee, Suzana Camargo, Michael Tippett, Daehyun Kim, Andrea Molod, Young-Kwon Lim
Lamont-Doherty Earth Observatory, Columbia University. University of Washington. Global Modeling and Assimilation Office, Goddard Space Flight Center, NASA, Greenbelt, MD, USA. University of Maryland, Baltimore County, Baltimore, MD, USA

This presentation will show the climatology and prediction skill tropical cyclone precipitation (TCP) in the S2S models. Firstly, key biases in the models such as in the spatial distribution of TCP, total P and the fraction TCP/P are introduced. Then, the origins of TCP biases are decomposed into contributions from frequency biases and precipitation structure biases. Results show frequency biases are the dominant contribution to TCP biases. Briefly, model skill is assessed by analyzing occurrence and TCP skill through the Brier Skill Score and the Ranked Probability Skill Score. Occurrence forecasts are skillful up to several weeks, but TCP forecasts are not skillful beyond a few days. After calibration, most models are able to predict TC occurrence at weeks 2-3 lead times. The skill of calibrated TCP forecasts is basin and model-dependent. Finally, a discussion is given on the implications of climatological biases and low skill in predicting TCP from these models onto subseasonal predictions of total precipitation, commonly used by weather centers for long-range prediction.

Supplementary Material

Connecting past and future hurricane activity changes

Gabriel Vecchi
Princeton University

Through a series of targeted dynamical and statistical modeling experiments, and analysis of observed data, we explore the mechanisms driving historical tropical cyclone changes. We further compare historical changes to projected changes, and explore the extent to which the mechanisms that are most influential in the evolution of projected future hurricane activity changes are evident/dominant in historical changes in hurricanes. We find that historical century-scale changes in tropical cyclone activity can differ profoundly from future changes, and that the dominant drivers of past tropical cyclone activity can differ substantially from those in projected activity - unless one targets specific parameters and historical time periods. This may leave us in an uncomfortable position where observations may not be sufficient to constrain future projections directly, though we will discuss (and attempt) possible ways forward.

What would a climate without tropical cyclones look like? A preliminary analysis of WISHE suppression on TCs and climate

Gabriel Rios [1, 2], Wenchang Yang [2, 3], Bosong Zhang [1], Gabriel Vecchi [2, 3], Brian Soden [4]

Do tropical cyclones (TCs) play a significant role in global climate? TCs contribute to the meridional transport of energy, modulation of precipitation in the tropics and subtropics, and may impact the large-scale atmospheric circulation. Despite their relevance in climate, a unified theory of their formation and their impacts on climate remains elusive. To address this, we attempt to eliminate TC activity in global climate models (GCMs) to explore mechanisms required for cyclogenesis and evaluate the associated impacts on global climate. To eliminate TC activity, we suppress the wind-induced surface heat exchange (WISHE) feedback, which we assume to be critical to TC intensification, in GCM model runs. We then evaluate impacts of TC suppression on climate by comparing results with results from control experiments to identify differences in heat, momentum, and moisture. Preliminary results show that although suppressing WISHE reduces hurricane-strength TC frequency by over 90%, hurricane-strength TCs still form in GCMs, with properties similar to those in control runs. This indicates that suppression of additional mechanisms is required to fully eliminate TC activity, suggesting that WISHE is necessary but insufficient for TC intensification. With regards to impacts on climate, model output shows that TC suppression results in lower annually-averaged temperatures and specific humidities in the upper troposphere, with increasing differences towards higher latitudes.

Affiliations

1. Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey
2. Department of Geosciences, Princeton University, Princeton, New Jersey
3. High Meadows Environmental Institute, Princeton University, Princeton, New Jersey
4. Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Miami, Florida

Anthropogenic forcing changes coastal tropical cyclone frequency

Shuai Wang
Princeton University, GFDL

It remains a mystery if and how anthropogenic climate change has altered the global tropical cyclone (TC) activities, mainly due to short reliable TC observations and substantial climate internal variabilities. In this study we show with large-ensemble TC-permitting simulations that the observed changes in global coastal TC frequency since 1980 were caused by anthropogenic greenhouse gases (GHG) and/or aerosols. The observed increases in TC frequency near the US Atlantic coast and Hawaii are likely related to the aerosol and GHG effects, respectively. The observed decrease in the South China Sea could be associated with GHG emissions alone, whereas the observed increase near Japan and Korea would be related to the aerosol and GHG combined effects. These changes are explained by the responses of large-scale environmental conditions to anthropogenic forcing. We find that two kinds of anthropogenic warming are related. First, the anomalous lower-tropospheric warming at midlatitudes under the aerosol and/or GHG effect alters the subtropical jets over the North Atlantic, western North Pacific, and Northeast Asia. Second, the equatorial central Pacific warming under the GHG effect simulates a classical Gill-type circulation pattern in the northern tropical Pacific. These large-scale circulation changes modify the TC genesis and steering conditions, contributing to the observed increases in TC frequency in the global coastal regions as identified above. Our findings suggest the substantial influence of anthropogenic forcing on TC frequency over the heavily populated coastal regions worldwide.

Is it possible? Stakeholder-informed synthetic hurricane storylines in a 3km Earth system model

Colin Zarzycki, Corrine DeCiampa
Penn State University

We discuss using global Earth system model simulations of short, high-resolution, "storylines" to evaluate and communicate climate risk and potential changes in their associated hazards in the future. In particular, we focus on gray swan tropical cyclones (physically plausible, but historically unrealized events extracted from multi-decadal climate ensembles). We discuss scientific insights gained from these simulations, the strengths and limitations of this approach, and the potential benefits of using them to communicate with stakeholders and the general public.

Predictions of Boreal Summer Intraseasonal Oscillation in GFDL SPEAR model

Baoqiang Xiang
NOAA-GFDL, UCAR

The prediction of boreal summer intraseasonal oscillation (BSISO) is examined based on 20 years' (2000-2019)) hindcast experiments using the GFDL SPEAR model. The overall skillful prediction of BSISO reaches out to 22 days measured by Lee et al. (2013) index. By separating individual BSISO into two clusters, it is revealed that the canonical BSISO (CB) has higher prediction skill (28 days) than the northward dipole-type BSISO (DB, 23 days). The SPEAR model has demonstrated its ability in predicting the initial development of both type of BSISO even with a lead time of 20 days, while DB has a more repaid decay after its peak phase over the Indian Ocean and the model is struggling in predicting this, partially accounting for their contrasting prediction skills. For CB, the cases with lower prediction skill are related to its weaker amplitude and also the rapid decay of the titled (the second EOF in Lee et al. 2013) mode after its peak convection over the Indian Ocean. Meanwhile, the prediction of individual CB during early summer (May-July) tends to be more challenging and case-dependent than those in later summer (August-October).

Decomposing the large-scale tropical circulation across a hierarchy of CESM model configurations

Levi Silvers
Stony Brook University

The large-scale overturning tropical circulations are intertwined with multiple cloud types including deep convection, cirrus anvil clouds, and low-level stratus cloud decks. Meridionally (zonally) oriented overturning circulations are often described in the context of the Hadley (Walker) circulation. In this work we partition the horizontal divergent wind field into two independent and orthogonal circulations, our Hadley and Walker circulations. We then dynamically sample the results of the decomposition and use the cloud radiative effect to calculate the cloud characteristics for the Hadley and Walker circulations. With the goal of connecting idealized tropical models such as radiative convective equilibrium (RCE) to CMIP6-era global climate models we use the community earth system model (CESM) framework with this method to analyze a wide range of model configurations including global RCE, mock-Walker, aquaplanet, amip, historical, and piControl simulations.

Diagnose the factors contribute to the intermodel spread of climate feedbacks

Chenggong Wang
Princeton University

The intermodel spread of climate feedbacks is large in current generation of climate models. It has also been found that the sea surface temperature (SST) warming patterns strongly regulated the climate feedback in historical period. In this study, we design a series of experiments quantify how much the SST (both the warming pattern and the base climatology) contributes to the intermodel spread of climate feedbacks. We use two high-resolution GFDL climate models, HiRAM and AM2.5, to run the fixed-SST experiment with the warming patterns from the 4xCO2 experiment by different CMIP6 model. HiRAM is a high climate sensitivity model with strong positive cloud feedback while the AM2.5 has low climate sensitivity with weak cloud feedback. We found different SST warming patterns cannot explain the intermodel difference in cloud feedback and climate sensitivity. Our results suggest the major source of the uncertainty in climate sensitivity is the AGCM (potentially the convection/cloud scheme).

The response of tropical precipitation and circulation to warming in a global storm resolving model

Ilai Guendelman
Princeton University

Investigating double-ITCZ biases in climate models: Role of daily-resolved air-sea interactions

[a]Indrani Ganguly, [b]Alex O. Gonzalez, [c]Richard Neale
[a]Iowa State University, [b]Woods Hole Oceanographic Institution, [c]NCAR

Over the east Pacific during February-April the Intertropical Convergence Zone (ITCZ) varies spatially on daily to weekly time scales. Climate models continue to struggle to mitigate long standing biases in the ITCZ over this region. While atmosphere-only models have relatively weak-biases, coupled climate models exacerbate the biases through air-sea feedback mechanisms. Our recent results using observational (TRMM) and reanalysis (ERA5) data showed that the distribution of sea surface temperature (SST) anomalies and latent heat flux anomalies follow the classic wind-evaporation-SST (WES) positive feedback mechanism during daily to weekly spatial variability of the ITCZ. However, a mechanism embracing the effect of SST anomalies on vertical stratification and momentum mixing acts in parallel, giving rise to a negative wind-evaporation-SST (WES) feedback.
In this study, we compare daily precipitation from NCAR Community Atmosphere Model 6 (CAM6) to TRMM and IMERG. During January through May, CAM6 produces less than the observed precipitation in the northern hemisphere, while producing similar or slightly more than the observed precipitation in the southern hemisphere. We run a series of atmosphere-only simulations to test the positive WES feedback mechanism using data from prescribed SST AMIP simulations during these months.
We hypothesize that the atmospheric and oceanic variables associated with the positive WES feedback mechanism are too strong or those associated with the negative WES feedback mechanism are too weak when there is an ITCZ in the southern hemisphere or both of these WES feedbacks are happening simultaneously, which contributes to the climate models producing a double ITCZ bias.

Supplementary Material

Dynamical importance of the trade wind inversion in suppressing the southeast Pacific ITCZ

Alex O. Gonzalez[1,2], Indrani Ganguly[2], Marissa Osterloh[2], and Gregory V. Cesana[3]
[1]Woods Hole Oceanographic Institution
[2]Iowa State University
[3]Columbia University

Sea surface temperature (SST) gradients are a primary driver of low-level wind convergence associated with the Inter-Tropical Convergence Zone (ITCZ) through their hydrostatic relationship to the surface pressure force (PGF). To what extent temperature gradients above the surface have an effect on ITCZ convergence through their modulation of the surface PGF is not well understood, which could be important in tropical regions with a strong trade wind inversion (TWI), such as the east Pacific Ocean. In this study, we show evidence of a dynamical link between the TWI and east Pacific ITCZ in a series of simulations using an idealized boundary layer model (SBLM). SBLM simulations using the full, surface to 850 hPa, virtual temperature profile produce a realistic northern hemisphere ITCZ. However, SST-only simulations tend to produce excessive equatorial cold tongue-driven divergence and off-equatorial convergence, a double ITCZ-like structure. Subsequent SBLM simulations and investigations of virtual temperature gradients at different pressure levels highlight the importance of temperature gradients weakening with height everywhere, especially from the equator to 15 degrees south, where there is anomalous divergence south of the equator due to an elevated cold anomaly and anomalous convergence on the equator due to an elevated warm anomaly both associated with the TWI and stratocumulus clouds. Thus, the TWI and stratocumulus clouds can help enable a more northern hemisphere dominant ITCZ. In this way, we provide evidence of a dynamical link between double ITCZs and low clouds, which both are problematic in present-day Earth System Models.

Supplementary Material

Tropospheric Influence on Stratospheric Upwelling

Jonathan Lin
Lamont-Doherty Earth Observatory, Columbia University

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 we believe remain poorly understood. In this work we show that the troposphere can influence upwelling in the stratosphere, using simple theory and idealized modeling. The response of the stratosphere to a steady geopotential forcing is considered in two separate theoretical models. Solutions to the linearized quasi-geostrophic potential vorticity equations are first used to show that the vertical length scale of a tropopause geopotential anomaly is initially shallow, but significantly increased by diabatic heating from radiative relaxation. This process is deemed as geostrophic adjustment of the stratosphere to tropospheric forcing, since it depends on the horizontal length scale of the tropospheric disturbance. A previously developed, coupled troposphere-stratosphere model is introduced and modified to further understand how tropospheric geopotential forcing can induce upwelling in the stratosphere. Solutions to steady, zonally-symmetric sea-surface-temperature forcings in the linear β-plane model show that the upwards stratospheric penetration of the thermally induced tropopause geopotential anomaly is controlled by a non-dimensional parameter that depends on the ratio between the time scale of wave-drag to that of radiation. It is also shown that the horizontal scale of the tropopause geopotential anomaly modulates the vertical scale of the anomaly. When Earth-like non-dimensional parameters are used, the theoretical model predicts stratospheric temperature anomalies around two times larger in magnitude than those in the boundary layer, approximately in line with observational data. The results are argued to show that wave-drag alone may not suffice to explain certain observed features of the lower stratosphere, foremost of which is the anti-correlation between sea-surface temperature and lower stratospheric temperature.

Supplementary Material

Convection-permitting ensemble simulations of extreme rainfall: a case study of Hurricane Ida's aftermath

Sofia Menemenlis [1], Gabriel Vecchi [1], Kun Gao [2]
[1] Princeton University [2] NOAA Geophysical Fluid Dynamics Laboratory

The extratropical aftermath of Hurricane Ida (2021) produced record-breaking hourly-scale rainfall and flooding in the Northeastern United States. We perform retrospective ensemble forecasts of the event using GFDL's T-SHiELD model, which features a ~3-km resolution North Atlantic nest. T-SHiELD skillfully reproduces the large-scale patterns of rainfall at multi-day lead times. Observed maximum rainfall accumulations fall within the range of a large ensemble spread, and the locations of heaviest rainfall vary widely between ensemble members. We analyze emergent differences in environmental variables that predict the simulated ensemble spread in rainfall rates. Statistical relationships between precipitation rates and TC track, moisture convergence, CAPE, and wind shear point to the different weather phenomena controlling precipitation at different scales. The results inform hypotheses about how rainfall from similar events might be expected to scale with global warming.

Upper tropospheric circulation associated with Kelvin waves propagating through the MJO

Crizzia Mielle De Castro and Paul Roundy
University at Albany

This study investigates the spatial and temporal evolution of upper tropospheric dynamics associated with a Kelvin wave propagating through the Madden-Julian oscillation's (MJO) active convection. To examine upper tropospheric dynamics, this study looks at 20-day time-lagged composites of outgoing longwave radiation (OLR) with 200 mb geopotential height, 200 mb winds, 300 mb specific humidity, and 200 mb temperature anomalies. Only days with the real-time multivariate MJO (RMM) index at phase 3, and strong Kelvin waves passing through (1) 80^{o}E, and (2) 110^{o}E were considered. Monte Carlo experiments determined the time and location of the statistically significant effects of the Kelvin wave. This study found that the Kelvin wave propagating with the MJO appears as a small strong OLR signal embedded within a larger weaker OLR signal. In the upper troposphere, a low geopotential height coincided with easterlies west of the Kelvin wave, and vice versa to the east. The Kelvin wave passing through 110^{o}E moistened and warmed the west upper troposphere much earlier than the Kelvin wave passing through 80^{o}E. The tilted vertical structure of the Kelvin wave manifested in the shifted statistically significant time and locations of the composites. To better observe this tilt, future work will look at other pressure levels, particularly the lower and middle troposphere.

Supplementary Material

A Climatology of Tropical Cyclone Interactions with Deformation Steering Flows in the Atlantic Ocean

Melissa Piper, Alex Mitchell, Kristen Corbosiero, and Ryan Torn
University at Albany

Tropical cyclones (TCs) in large-scale deformation steering flows (DSFs) have been shown in previous case studies to be associated with large position errors and track uncertainty. Errors in the steering flow surrounding the center of a TC reveal which side of the axis of contraction the TC would move to and, thus, the future position of the storm. In this study, a climatology of TC interactions with DSFs is developed in order to quantify the total deformation of the environmental steering flow during the lifetime of all TCs over the North Atlantic from 2010–2021. The frequency in which TCs interact with deformation zones and the characteristics of the upper percentile of DSF zones in proximity to TCs will be analyzed. The environmental steering flow is calculated at 00 and 12 UTC for each day a storm remains a TC using the ECMWF fifth generation reanalysis dataset (ERA-5) on a 1 degree grid. The total DSF is calculated using the optimal steering flow for a TC described in the methods of Galarneau and Davis (2013) and averaged within 500 km of the TC position at each time step. TCs that interacted with DSFs are identified using a threshold value, which will serve as a procedure for extracting characteristic DSF patterns. Additionally, the steering flow regimes associated with the upper percentile of deformation values will be examined to identify potential sources of TC track forecast errors that are associated with a TC's interaction with the DSF patterns.

Investigating the downshear reformation of Sally (2020) using ensemble simulations

Nathalie Rivera Torres
University at Albany

Statistical Downscaling Projections of North Atlantic Tropical Cyclone Activity: Uncertainties Inherent from Large-Scale Climate Simulations

Dazhi Xi
Princeton University

North Atlantic tropical cyclone (TC) activities under high-emission scenario are projected using a statistical synthetic storm model coupled with nine CMIP6 climate models. The ensemble projection shows by the end of the 21st century, the annual frequency of TCs generated in the basin will drop from 15.91 to 12.16, and TC activities will be shift poleward and coast-ward. The mean lifetime maximum intensity will increase from 66.50 knots to 75.04 knots. Large uncertainties in TC frequency and intensity projections are found between the nine CMIP6 climate models. It is found that the uncertainty in the projection of wind shear change is the leading reason for the uncertainty in TC climatology projection, dominating the uncertainties in the projection of thermodynamic parameters. The uncertainty in the projection of wind shear change may be related to the different projections of horizontal gradient of vertically integrated temperature. Informed by the uncertainty analysis, a statistical tool is developed to estimate the TC activities in a climate model before downscaling is performed.

How does global mean precipitation respond to radiative forcings?

Wenchang Yang
Princeton University

Global mean precipitation responds to external radiative forcings (e.g. double CO_2) both directly and indirectly through change of surface temperature. It is crucial to disentangle these two impacts in order to understand the net response. Here we conduct idealized AGCM experiments in which we either uniformly increase global sea surface temperature by 2K while keep CO_2 constant or double CO_2 but keep sea surface temperature fixed, and apply the estimated precipitation sensitivity in these idealized experiments to explain precipitation anomaly time series in double CO_2 experiment in coupled climate models. The results suggest that insights from the idealized AGCM experiments are valuable and can help build a framework to understand precipitation response to radiative forcings in coupled models.

Near-term tropical cyclone risk and coupled Earth system model biases

Adam Sobel
Columbia University

Most current climate models predict that the equatorial Pacific will evolve under greenhouse gas-induced warming to a more El Niño like state over the next several decades, with a reduced zonal sea surface temperature gradient and weakened atmospheric Walker circulation. Yet observations over the last 50 years show the opposite trend, towards a more La Niña-like state. Recent research provides evidence that the discrepancy cannot be dismissed as due to internal variability, but rather that the models are incorrectly simulating the equatorial Pacific response to greenhouse gas warming. This implies that projections of regional tropical cyclone activity may be incorrect as well, perhaps even in the direction of change, in ways that can be understood by analogy to historical El Niño and La Niña events: the north Pacific tropical cyclone projections will be too active, north Atlantic ones not active enough, for example. Other perils, including severe convective storms and droughts, will also be projected erroneously, in similarly predictable ways. While it can be argued that these errors are transient, such that the models' responses to greenhouse gases may be correct in equilibrium, the transient response is relevant for climate adaptation in the next several decades. Given the urgency of understanding regional patterns of climate risk in the near term, and the difficulty of eliminating the model biases that cause the problem, it would be desirable to develop alternative projections that are consistent with recent observed trends, even if such projections cannot currently be produced using entirely free-running coupled ocean-atmosphere models.

ENSO diversity and Projections of ENSO-Tropical Cyclone relationship

Suzana J. Camargo
Lamont-Doherty Earth Observatory, Columbia University

We will discuss how the ability of the CMIP6 models in reproducing ENSO diversity and variability influences their projections of the ENSO-Tropical Cyclone relationship in the 21C using large-scale environmental fields associated with TC activity.

The influence of sea surface salinity variability on the equatorial Pacific mean state and extreme ENSO events

Maya Chung
Princeton University

This study investigates the influence of sea surface salinity (SSS) variability on the equatorial Pacific mean state and El Niño-Southern Oscillation (ENSO). A multi-century simulation from a coupled atmosphere-ocean model with fully interactive salinity (control, CTRL) is compared to the same model but with SSS restored to the CTRL seasonally-varying climatology (fixed-SSS). The CTRL experiment produces about 2.5 times the number of extreme El Niño and La Niña events compared to fixed-SSS. The western equatorial Pacific (WEqP) mean-state salinity stratification is stronger in CTRL, with greater salinity at depth. Ensemble experiments reveal that this stratification difference establishes during the first few weeks of SSS nudging and persists thereafter. The enhanced WEqP subsurface salinity in CTRL is the result of the CTRL model's ability to produce saltier, denser waters at the surface during periods of mixed layer deepening, such as those associated with wind bursts and enhanced evaporative cooling, which then enter the subsurface as the mixed layer deepens. These results imply that correctly simulating the mean salinity stratification in the WEqP requires accurate simulation of the covariability of SSS and sub-seasonal mixed layer deepening. We further hypothesize that sub-seasonal salinity variability can strengthen the mean state of the WEqP salinity barrier layer, which may increase the likelihood of developing extreme ENSO events by trapping heat and momentum in the surface ocean. Monitoring local sub-seasonal salinity variability and stratification may therefore be useful for simulating the tropical Pacific mean state and predicting ENSO.

How Advection Influences the Phase Speed of the MJO

Paul Roundy
University at Albany

A robust linear regression algorithm is applied to estimate the effects of advection by the upper tropospheric wind on the eastward phase speed of zonal wind anomalies associated with the Madden Julian Oscillation (MJO) in the upper troposphere. Results show that the slowest MJO events are more strongly advected westward, and that the dominant signals leading to their phase speed are generated by Kelvin wave eastward propagation reduced by advection by easterly wind background flow.

Potential predictability of the MJO in SPCAM

Sarah Weidman
Harvard

The Madden-Julian oscillation (MJO) is a promising avenue towards improving sub-seasonal weather forecasts in the tropics and at midlatitudes through MJO teleconnections. Current weather forecast models struggle to simulate and predict the MJO for a variety of reasons, including imperfect convective parameterizations, mean state issues, and poorly specified initial conditions. Several studies have used a “perfect model” approach that reveals how long a model can predict its own MJO as a way to inform a potential predictability limit of real forecasts. We perform a similar perfect predictability experiment using a version of super-parameterized CAM (SPCAM), since SPCAM has been shown to simulate a reasonable MJO. Initial conditions for the perturbed forecast runs are generated by adding a second “silent” cloud resolving component to the control simulation that independently calculates convective-scale processes without sending input back to the GCM scale. The silent cloud resolving component initializes the forecast runs in the prefect model experiments, representing uncertainty on the convective scale but perfect knowledge of the large scale. We find a predictability of the MJO in SPCAM of 35-40 days in boreal winter using a single ensemble member forecast.

Contrasting two perspectives on deep atmospheric convection: low-level convergence vs. column energetics

Martin Velez-Pardo
MIT

Two influential perspectives view atmospheric convection in the tropics through substantially different lenses: One, stemming from the analysis by Lindzen and Nigam (1987), argues that deep convection over tropical oceans is governed by low-level wind convergence induced by sea-surface temperature gradients. The other, represented by the work of Neelin and Held (1987), approaches it as resulting from the variations in atmospheric column energy, which drive differential vertical motions. While not inherently contradictory, both frameworks emphasize different mechanisms that lead to convection and precipitation in the tropics. However, due to the coupling between mechanical and column-energetic effects, the conditions under which each perspective is adequate remain largely unclear.
In this work, we propose a method to study the effects of column energetics and low-level convergence on tropical precipitation and convection using cloud-resolving simulations of an all-ocean domain in radiative-convective equilibrium (RCE). We perform three kinds of simulations: one where we define an area of anomalous sea-surface temperature, to test the effects of locally enhanced SST on rainfall; another where we keep the SST homogeneous but introduce a steady, vertically and horizontally localized heating source at different heights to probe the sensitivity of precipitation to column energetic enhancements at different levels in the atmosphere, and a third one where we also keep SST uniform, but create purely mechanically forced convergence in the boundary layer with limited horizontal extent, to study the sensitivity of rainfall to low-level convergence in the absence of a thermodynamic forcing. Our results so far show that, at horizontal scales between 10 and 100km, precipitation is highly sensitive to thermal forcings at low levels (800 to 1000 hPa), but much less so to forcings in the free troposphere (200 to 700 hPa). Furthermore, the normalized gross moist stability associated with low-level thermal forcings is systematically lower than that of simulations with varying SST anomalies, suggesting that regions with comparable column energetics can exhibit significant differences in precipitation, depending on the location and the type of the energy source in the column. We will discuss these and other findings based on our setups.

SST-Induced Boundary Layer Convergence Variability in Relation to Precipitation

Isabelle Bunge
Columbia University

The Intertropical Convergence Zone (ITZC) is a near-equatorial band of deep, precipitating convection which makes up the ascending branch of the tropical Hadley cell. To understand the fundamental mechanisms driving convection in the ITCZ, simple models have been used to study the causal relationship between many proposed forcings and convection. In work using a mixed-layer model, it was established that deep convection, and thus precipitation, can be viewed in part as a consequence of low-level convergence in the planetary boundary layer (PBL) (Back and Bretherton, 2009a, 2009b). Lindzen and Nigam (1987) developed a theory for the relationship between PBL convergence and underlying sea surface temperature (SST) field. Using a linear mixed layer model, in which the PBL pressure gradient is fully a function of SST and has no free-tropospheric component, they can approximate low-level wind fields from knowledge of SST only. In the EP, where there exists a large meridional SST gradient due to oceanic circulation patterns, this SST-induced low-level wind component has been found to play a critical role in driving convection. However, this component of the PBL convergence does not tell the whole story of precipitation in the EP. Since the large meridional SST gradient varies only slowly in time, it can be thought of as providing a nearly constant forcing to precipitation in the EP. But ITCZ precipitation itself is highly variable. What additional factors drive synoptic scale variability in rainfall?

For precipitation events of varying magnitudes and durations, given a slowly changing SST field, convection can be forced by a pressure gradient that has a highly variable free-tropospheric component (related to synoptic scale transients) and a quasi-steady boundary layer component (due to SST gradients) that is independent of rainfall. This research seeks to confirm this hypothesis in the EP and establish the relationship between SST and free-tropospheric driven components of the boundary layer winds and precipitation.

ERA5 products are employed in conjunction with TRMM 3B42 precipitation products to study variations in the pressure structures in and above the PBL to confirm that a part of the low-level pressure and convergence is driven by SST, independent of precipitation. The spatial and temporal variability of temperature and geopotential in the EP are examined to validate the steadiness of the SST-gradient driven component in the boundary layer. Then, using TRMM products to define precipitation events of varying spatial domains and intensities, reanalysis geopotential is broken down into components defined by contributions from the SST and by contributions from above the boundary layer and studied as composites for differing precipitation event.

Results show that for varying degrees of precipitation, the SST-driven component of the surface geopotential remains rather stable, and that increases in precipitation are related to increasing geopotential gradients that are imprinted from the free-troposphere on the PBL. Overall, it appears that the low-level convergence forcing described by Lindzen and Nigam (1987) has a steady effect on convection and seems to be an external forcing to precipitation, while the synoptic scale variations in rainfall are related to transient waves and local changes to temperature and geopotential fields above the PBL.

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Efficiency of convective cold pool production by rainfall moderated by column saturation

Patrick Orenstein
Columbia University

Intense storms generate downdrafts through latent cooling from the evaporation of falling rain which create small regions of anomalously stable air at the surface termed cold pools. Previous studies of cold pools have mostly covered relatively small areas or used idealized simulations. The work presented here uses a recently published global data set of cold pools identified in satellite observations of ocean surface winds. Combining this data set with observations of rainfall and column relative humidity (CRH), we find that while cold pool frequency and size generally scale with precipitation, the efficiency with which rainfall generates cold pools is modulated strongly by CRH. Less rain can evaporate in air with higher CRH, decreasing the production of downdrafts and their resulting cold pools. This has implications for the representation of cold pools in climate models, where the accurate simulation of convective precipitation has been a persistent source of uncertainty.

Bridging the Gap between Implementing and Understanding the Different Implementations of the Weak Temperature Gradient Approximation in Cloud Resolving Models

Nathanael Wong, Zhiming Kuang
Harvard

The weak-temperature gradient (WTG) approximation has been a popular method used to couple convection in limited-area domain simulations to large-scale dynamics in the tropics. Two major implementations that use the WTG approximation have gained popular use over the past two decades - the Temperature Gradient Relaxation (TGR) implementation and the Damped Gravity Wave (DGW) implementation. Our comparison of these different WTG implementations in an idealised framework result in different model behaviour, with implications on the nature of convective self-aggregation in similarly idealised setups. A further investigation shows that the different model behaviour is caused by the different treatment of the baroclinic modes by the different WTG implementations. More specifically, we hypothesise that the ratio of the strengths of the baroclinic modes is important in determining if multiple-equilibria states are obtained under different WTG implementations. By varying the strengths of these two baroclinic modes, we use the Gross Moist Stability framework to understand the major difference between two major WTG schemes and therefore bridge the gap between them.

Linear time-invariant models of a large cumulus ensemble

Zhiming Kuang
Harvard

Linear time-invariant state-space models of a large ensemble of cumulus convection simulated by a convective-system-resolving model in radiative-convective equilibrium are obtained using methods in system identification, extending steady-state linear response functions used in past studies. The identified models provide accurate descriptions of the transfer function, the noise model, and behavior of convection when coupled with two-dimensional gravity waves. A novel approach is developed to turn the state space model into an interpretable form, which is then used to demonstrate the importance of convective memory and to examine its nature. Implications to current efforts to parameterize cumulus convection with machine learning are discussed.

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

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Princeton University

Tropical cyclone (TC) genesis is initiated by convective precursors or "seeds" and influenced by environmental conditions along the seed-to-TC trajectories. Genesis Potential Indices (GPIs) provide a simple way to evaluate TC genesis likelihood from environmental conditions, but have two limitations that may introduce prediction bias. First, the globally fixed GPIs fail to represent inter-basin differences in the relationship between environments and genesis. Second, existing GPIs are only functions of local environmental conditions, whereas non-local factors may have a significant impact. We address the first limitation by constructing basin- and timescale-specific GPIs (local-GPIs) over the Eastern North Pacific (ENP) and North Atlantic (NA) using Poisson regression. A sequential feature selection algorithm (SFS) identifies vertical wind shear and a heating condition as leading factors controlling TC genesis in the ENP and the NA, respectively. However, only a slight improvement in prediction is achieved, motivating us to tackle the second limitation with a novel trajectory-based GPI (traj-GPI). We merge adjacent non-local environments into each grid point based on observed seed trajectory densities. The seed activity, driven mainly by upward motion, and the transition to TCs, controlled primarily by vertical wind shear or heating conditions, are captured simultaneously in the traj-GPI, yielding a more accurate prediction than the original GPIs. This study illustrates the importance of seed activity in predicting TC genesis and identifies key environmental factors that influence the process of TC genesis at different stages.

Role of diurnal gravity waves in MCS initiation and Tropical Cyclogenesis over the Bay of Bengal

Xingchao Chen
Penn State University

Previous observational studies have indicated that mesoscale convective systems (MCSs) are responsible for the majority of summer precipitation over the Bay of Bengal (BoB), yet their initiation and organization remain poorly understood. Using 20 years of satellite observations and MCS tracking, we found that the majority of MCSs responsible for summer precipitation over the BoB are initiated from the coastal or open ocean regions, rather than inland areas. Diurnal MCSs frequently initiated near the coastlines are due to land-sea breezes, while early morning MCSs initiated over the open ocean are strongly influenced by diurnal radiative forcings. Our findings also highlight clear propagating signals of diurnal MCS initiation from the west and north coastlines of the BoB towards the central BoB region. Reanalysis data indicates a strong association between the offshore propagating signal and diurnal wind and temperature perturbations. Using a linear model, we found that the offshore propagating MCS initiation signal is generated by diurnal gravity waves emitted from coastal regions, which are in turn caused by diurnal variations in the land-sea sensible-heat difference and the latent heating of coastal convective systems. The diurnal gravity waves can be strongly influenced by the background monsoonal flow and vertical wind shear. Additionally, we found that the diurnal gravity waves may also play a crucial role in modulating tropical cyclogenesis over the BoB. Using a high-resolution regional reanalysis, we demonstrated that the diurnal gravity waves radiated from inland afternoon convection modulated the MCSs that preceded the formation of tropical cyclone (TC) Mora (2017) by modulating the offshore stability and relative humidity.

Intraseasonal Variability of Recurving EPAC Tropical Cyclones

Alex Mitchell
University at Albany

The eastern North Pacific (EPAC) exhibits the highest density of tropical cyclogenesis among all tropical cyclone (TC) basins. Climatologically, upper-level easterlies at the southern edge of an EPAC subtropical anticyclone centered over Mexico steer a majority of developed EPAC TCs along the North American coastline before tracking westward. A subset of EPAC TCs, however, have been observed to move poleward or recurve inland due to the influence of EPAC troughs and an eastward displaced EPAC subtropical anticyclone that imposes southerly flow over EPAC TCs. The aforementioned EPAC troughs have been linked to upper-tropospheric anticyclonic Rossby wave breaking (AWB) associated with the development of upstream extratropical cyclones and recurving western North Pacific TCs that undergo extratropical transition commonly exhibited in early autumn. Therefore, the purpose of this study is to investigate the dominant large-scale patterns that are conducive for AWB across the North Pacific that can lead to the formation of downstream EPAC troughs that interact with recurving EPAC TCs.

EPAC TCs observed from 1979–2021 during the autumn will be identified using 6-h best-track data compiled by the NHC (HURDAT2). EPAC TCs that undergo recurvature will be extracted from HURDAT2 using the methods detailed in Archambault et al. (2013). Self-organizing maps (SOMs) will be used to objectively classify the associated upper-level patterns at the onset of each TC recurvature using the potential temperature on the dynamic tropopause surface and 500-hPa geopotential height fields derived from global reanalysis datasets (i.e., the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR)). Recurvature-relative composite analyses of the large-scale flow pattern for each SOM node will be constructed to identify the large-scale flow patterns and Rossby wave breaking events across the NPAC that lead to recurving EPAC TCs.

Exploring Extratropical Transition and Associated Precipitation in Climate Simulations and Operational Forecast Models

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Tropical cyclones (TCs) can still have devastating impacts after completing the process of extratropical transition (ET) and becoming post-tropical cyclones (PTCs). PTCs can produce heavy rainfall which can lead to widespread inland flooding, making the forecasting of these events critical to preventing the loss of life and property. However, less attention has been focused on PTCs and the associated rainfall by the research and operational community and has instead centered on forecasting the impacts of storms of tropical nature in present and future climates. This study addresses the representation of PTCs in three HighResMIP models and performs the verification of two different operational models' abilities to forecast the occurrence of ET, as well as the associated rainfall. PTCs and their precipitation are under-represented in the HighResMIP climate simulations despite improvements in the models' ability to simulate TCs. The global operational model assessed, the Global Forecast System (GFS), is a better predictor of the occurrence of ET than the regional model analyzed, the Hurricane Analysis and Forecast System (HAFS). HAFS, on the other hand, tends to have lower track errors when compared to GFS. This work offers a first step in exploring ET and PTC precipitation in each of these five models.

Asymmetric Tropical Cyclone Structures and Processes in Reanalyses and Climate Models

Jacob Carstens
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While tropical cyclones (TCs) are axisymmetric vortices to first order, they often exhibit noteworthy structural asymmetries. These largely result from a response to environmental vertical wind shear, which modulates the TC's circulation, convection, and precipitation in a wavenumber-one pattern. Prior work has leveraged aircraft and radar observations, along with idealized modeling, to better understand the TC-wind shear relationship and its consequences for TC hazards. Concurrently, computational advances have allowed reanalyses and global climate models (GCMs) to more realistically represent TC structure, intensity, and climatology.

Obstacles remain, however, particularly in climate modeling for TCs. Small-scale processes remain unresolved, and simulation of TCs depends strongly on model characteristics such as the dynamical core, resolution, physical parameterizations, and in the case of reanalyses, data assimilation techniques. In addition, prior work in this area has largely considered TCs axisymmetrically, neglecting structural asymmetries and the effects of wind shear. This work uses a blend of reanalyses and a high-resolution GCM, with resolutions ranging from 0.25-0.5˚, to assess TC structures and processes relative to the deep-layer wind shear.

Individual TC snapshots are extracted from geopotential thickness and surface pressure fields using the TempestExtremes objective tracking algorithm, then composited by TC intensity and wind shear magnitude. In qualitative agreement with observations and high-resolution modeling, the strongest tangential winds are usually found left of shear, while inner-core rainfall, ascent, vortex tilt, and low-level inflow are favored either directly downshear or in the downshear left quadrant. Thermodynamic asymmetries are also apparent, with anomalous moisture right of shear, warmth in the upshear right quadrant (uptilt), and cloud properties suggestive of a transition from convective to stratiform precipitation in the upshear left quadrant. Quantitative diagnostic tools are then used to examine asymmetric processes in the inner core and outer rainband regions.

Tilt-following boundary layer asymmetries of tropical cyclones in moderately sheared environment

Chau Lam Yu
University at Albany

Previous observations and modeling studies showed that tropical cyclones (TCs) in a vertically sheared environment tend to develop an asymmetric kinematic structure in the boundary layer, including a deep radial inflow downshear and radial outflow upshear, and a maximum tangential wind at the left-of-shear quadrants. While the spatial correlationassociation between the observed boundary layer asymmetries and environmental shear has been robustly demonstrated in previous studies, the exact cause of these boundary layer asymmetries is not fully understood. In this study, we examine the dynamical processes leading to the asymmetric kinematic structure of the TC boundary layer in a sheared environment using idealized, convection-permitting model simulations.

Our results show that the emergence of the boundary layer asymmetries is closely related to the TC rainband processes. Specifically, stratiform diabatic processes at the rainband terminus region result in deep-layer inflow in the mid-troposphere, which becomes negatively buoyant and descends as it passes through thedue to diabatic cooling region. This descending inflow brings mid-tropospheric, low-θ_E air towards the boundary layer and forms an asymmetric surface cold pool at the downtilt-left quadrant. This descending inflow also advects high absolute angular momentum inward, causing a storm-scale tangential wind acceleration over within the cold pool region. As the boundary layer low-θ_E air advances inward, it becomes supergradient and decelerates radially, eventually becoming outflow near the downwind exit of the surface cold pool region.

As the tilted TC vortex and the accompanying rainband processes precess cyclonically over time, the above sequence of events and the resultant boundary asymmetries also precess cyclonically, maintaining a quasi-stationary configuration relative to the vortex tilt. These results suggest that the primary organizing factor of the boundary layer asymmetries is the tilted vortex structure, but and not necessarilystrictly the environmental shear direction.

An analytic model for tropical cyclone outer winds

Timothy Cronin
MIT

The variation of Tropical cyclone azimuthal wind speed (V) with distance from storm center (r) is a fundamental aspect of storm structure that has important implications for risk and damages. The theoretical model of Emanuel (2004), which applies well outside the rainy core of the storm, matches radiatively-driven subsidence and Ekman suction rates at the top of the boundary layer to obtain a nonlinear differential equation for dV/dr. This model is particularly appealing because of its strong physical foundation, but has no known analytic solution for V(r). Here, I obtain an analytic solution to V(r) for the Emanuel (2004) outer wind model. Following previous work, I then use this solution to explore properties of merged wind models that combine the outer model with an inner model that applies to the rainy core of a storm.

Improving hurricane track prediction in high-resolution models

Kun Gao
Princeton University, GFDL

High-resolution atmospheric models are powerful tools for hurricane track and intensity predictions. Although using high resolution contributes to better representation of hurricane structure and intensity, its value in the prediction of steering flow and storm tracks is uncertain. Here we present experiments suggesting that biases in the predicted North Atlantic hurricane tracks in a high-resolution (approximately 3 km grid-spacing) model originates from the model's explicit simulation of deep convection. Differing behavior of explicit convection leads to changes in the synoptic-scale pattern and thereby to the steering flow. Our results suggest that optimizing small-scale convection activity, for example through the model's horizontal advection scheme, can lead to significantly improved hurricane track prediction (~10% reduction of mean track error) at lead times beyond 72 hours. This work calls attention to the behavior of explicit convection in high-resolution models, and its often overlooked role in affecting larger-scale circulations and hurricane track prediction.

Inertial Instability and the Development of Outflow Channel in Modeled Tropical Cyclones

Minghao Zhou
University at Albany

Previous observational studies showed lowered inertial stability in the outflow layer of tropical cyclones (TCs). As a result, the upper-level circulation of a TC is more susceptible to perturbations in the surrounding environment and usually exhibits a greater degree of asymmetry. One commonly used version of the inertial parameter is expressed as the product of absolute vorticity and absolute angular momentum, scaled by half of the radius squared. The magnitude of the inertial parameter determines the resistance of a vortex to radial perturbations and when the sign is negative, it is inertially unstable.

A series of numerical simulations using the Weather Research and Forecasting (WRF) model are utilized to examine the structure of the TC outflow layer. The development of asymmetric outflow channels, which sometimes extend thousands of kilometers beyond the TC center, are of specific interest and are hypothesized to be related to the presence of inertial instability. In the case studies of Hurricane Ian (2022) and Typhoon Songda (2016), both of which underwent rapid intensification while interacting with upper-level troughs, two sources of inertial instability have been identified: one in area with positive absolute angular momentum but negative absolute vorticity, and one in area with positive absolute vorticity but negative absolute angular momentum. The former area is mainly associated with the diabatic generation of negative absolute vorticity through tilting (both in the eyewall and in rainbands), and the latter is driven by the convergence of environmental positive absolute vorticity at the periphery of the expanding TC outflow circulation and the continuous pressure gradient torque on anticyclonic winds. The most significant radial outflow channel spans across the two areas and orients itself in the southwest-northeast direction in this configuration of TC interaction with a trough coming in from the northwest.

Ongoing work is being conducted on quantifying the relation between the degree of instability and the intensity of radial mass flux, and whether these upper-level features are precursors to the overall TC intensification.

Impact of Cloud-Radiation Processes on Tropical Cyclone Development in Sheared Environments

Jannetta Richardson
University at Albany

Although the factors conducive to tropical cyclone (TC) development are well known, the key mechanisms governing whether an early-stage TC slowly or rapidly intensifies after genesis remain unclear. To better understand the processes responsible for the development of weak TCs, this research focuses on the role of radiative processes. Recent numerical modeling studies have shown that TC genesis is aided by radiative interactions with cloud hydrometeors, known as cloud radiative forcing (CRF). However, less is known about the relevance of CRF to early TC development after genesis, particularly in moderately sheared environments. Idealized Weather Research and Forecasting (WRF) simulations are conducted to investigate the physical mechanisms through which CRF modulates TC structure, including the size of the wind field and the structure of the stratiform region, and indirectly influences the timing of intensification.

Decomposing Forcing Mechanisms and Impacts of Simulated Diurnal Pulses

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University at Albany

Diurnal pulses, which can be cooling pulses (CPs) or warming pulses (WPs), depending on their infrared brightness temperature trend, are ubiquitous within tropical cyclones (TCs) worldwide. Recent research indicates that CPs are often coupled with convective rainbands in nature. Analysis of simulations of historic TCs corroborates this link between CPs and hazardous weather, while noting that CPs can also be restricted to the cirrus canopy without a connection to sensible weather at the surface. Precise generation mechanisms and impacts of CPs on TC structure and intensity, however, are less understood.

The current study will analyze global simulations of Hurricane Dorian (2019) with the Model for Prediction Across Scales (MPAS) to improve the understanding of CP generation and impact. Only CPs that occur at least five days following initialization will be considered for analysis to remove the effect of model spin-up. First, to test CP impact on TC intensity and structure, several variables will be calculated before and after CP onset (e.g., maximum 10-m wind speed, radius of maximum wind, cloud shield area). Second, since previous studies and preliminary results using the Weather Research and Forecast Model (WRF) identify pulses in simulations with no solar radiation (i.e., night only), the current study seeks to corroborate these results with MPAS night-only and day-only simulations. We hypothesize that without boundary conditions adding external forcing to WRF simulations multiple times a day, our night-only and day-only MPAS simulations will not show diurnal pulses occurring “on-the-clock.” They may, however, feature sporadic pulses “off-the-clock,” which could provide additional insight into how pulses manifest in the first place.

Global Characteristics of "On-the-Clock" and "Off-the-Clock" Tropical Cyclone Diurnal Pulses

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The radially-outward propagating, cloud-top cooling, diurnal pulse (DP) is a prominent feature in tropical cyclones (TCs) that has significant impacts on structure and intensity. Our recent study characterized DPs over ocean basins globally and examined their environmental conditions. DPs were found to occur on 52% of TC days globally, most frequently over the Northwest Pacific. The median duration and propagation distance of DPs were 12–15 h and 500–600 km, respectively. Although the mean propagation speed was 11–13 m s^{-1}, persistent DPs (lasting >15 h) propagated at speeds similar to internal inertial gravity waves (5–10 m s^{-1}). Most DPs initiated in the TC inner core overnight, in phase with deep convection; however, non-negligible numbers (~40%) of DPs initiated during the afternoon to evening hours and/or outside the inner core. This timing and initiation location differs from the diurnal pulse clock proposed by Dunion et al. (2014) and numerical modeling studies of the TC diurnal cycle. This presentation will explore the characteristics of "on-the-clock" and "off-the-clock" DPs including their basin variability, latitudinal distribution, and environmental characteristics.

Supplementary Material