Metrics For General Circulation Model Biases In Extratropical Cyclone Clouds And Precipitation: Evaluating Their Skill And Identifying Processes To Be Improved

Final Report

1. General Information

Project Title:
Metrics For General Circulation Model Biases In Extratropical Cyclone Clouds And Precipitation: Evaluating Their Skill And Identifying Processes To Be Improved

PI/co-PI names and institutions:
James F. Booth, City University of New York, City College
Catherine Naud, Columbia University
Zhengzhao Johnny Luo, City University of New York, City College
Leo Donner, NOAA Geophysical Fluid Dynamics Laboratory

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

- **a)** Create a set of process-oriented metrics to evaluate model ability to produce realistic extratropical cyclones. The metrics will range from the planetary scale to the frontal scale.
- **b)** Use model gridded outputs to: (i) locate and track extratropical cyclones, (ii) locate the warm and cold fronts, (iii) measure cyclone-local characteristics through the use of compositing techniques and (iv) use conditional subsetting to identify the sensitivity of cyclone cloud and precipitation to changes in dynamics and thermodynamics.
- **c)** Combine a comprehensive set of satellite observations and reanalysis output using both state-of-the-art and innovative approaches to assess models beyond the simple map-to-map comparison.
- **d)** Design specific metrics to inform on the reliability of components of the model that directly participate in the formation of clouds and precipitation, namely their convection, cloud and boundary layer schemes.
- **e)** Use the process-based metrics to analyze output from the GCMs participating in CMIP experiments.
- **f)** Generate improved metrics related to convection within extratropical cyclones and determine what influence convection has on storm rain rates and surface wind speed.

3. Results and accomplishments

3.1 Pithy Summary of Key Outcomes

The project accomplished results in three main areas related to modeling extratropical cyclone clouds and precipitation: (1) developing new: (a) observational benchmarks, and (b) methodologies; (2) explaining key physical processes using observations; and, (3) exhaustively analyzing NOAA GCMs.

For item (1a), new benchmarks, the most important will be the extratropical cyclone precipitation composite mean and observational uncertainty. For item (1b) new methodologies – we moved close to fully automating our cyclone-centered and front-centered compositing analysis.

For item (2) we have explained the temporal link between precipitation processes and storm circulation processes for extratropical cyclones. Also, a relationship between cloud cover and inversion strength, long-known for the subtropics, holds in post-cold frontal regions. Cyclone track path and propagation speed, especially for those most dangerous to the US east coast have a quantifiable probabilistic relationship to atmospheric blocking. The primary reason that extratropical cyclone precipitation usually peaks before the peak in cyclone circulation strength is that the storms are moving northward.

For item (3), we have analyzed the extratropical cyclone precipitation and clouds and their sensitivity to the convection scheme and cloud tuning in the GFDL CMIP model. GFDL's CMIP6 models can capture the top of atmosphere cloud structure of extratropical cyclones, however, in some regions of the storms this is correct answer is due to a compensation between too much high cloud and not enough low cloud. Furthermore, we have determined the link between these relative biases in cloud and the behavior of the convection schemes and the cloud tuning parameters. We also found that GCMs can capture the synoptic structure and rainfall intensity of extratropical cyclones. GCMs can capture the spatial changes in the surface storm track associated with vertical momentum mixing.

3.2 Detailed Summary

3.2.1 Overview

This project resulted in 10 publications, over 25 talks or poster presentations (at national meetings, government laboratories, and university atmospheric science departments). What follows is a summary of each of the publications in chronological order.

But first, I provide a brief background on the analysis methods. The main tool developed and utilized in this work has been cyclone-relative and front-relative analysis, i.e., analysis in which the clouds and precipitation are considered in a spatial orientation relative to the cyclone center or its fronts. For this type of work, we first use numerical algorithms to tracks the cyclones in space and time. Then we repeat this for the fronts. Having done this, we use this Lagrangian information to grab precipitation and clouds (as well as other atmospheric variables) in cyclone-centered perspectives. Then we can average over multiple events. These averages are not meant to represent the exact same phenomena seen in individual cyclone events. However, the advantage of this method is that it allows us to compare observations with free-running climate models.

3.2.2 Summaries of Publications

Paper 1
Naud, C. M., J. F. Booth, A. D. Del Genio, 2016: The relationship between boundary layer stability and cloud cover in the post-cold frontal region. J. Climate, 29, 8129–8149

This work establishes observational benchmarks for comparison with models, and includes the description of our frontal detection metric. Using NASA-Aqua MODIS and AIRS data, the relationship between low-level cloud cover (cloud top below the 700 hPa level) and boundary layer stability is explored in post-cold frontal conditions. A linear relationship is found between cloud cover and two separate measures of inversion strength, the lower tropospheric stability (LTS) and the estimated inversions strength (EIS), when looking at two specific regions in the north Atlantic and Pacific in quiescent and weakly subsiding conditions. A fairly good correlation between cloud cover and EIS is found in both hemispheres and across all seasons, suggesting that the relation between cloud cover and inversion strength proposed for quiescent conditions can be generalized to more dynamically active subsiding post-cold frontal conditions.

Paper 2
Booth J. F., Y.-K. Kwon, S. Ko, J. Small, R. Madsek, 2017: Spatial Patterns and Intensity of the Surface Storm Tracks in CMIP5 Models. *Journal of Climate*, 30, 4965–4981.

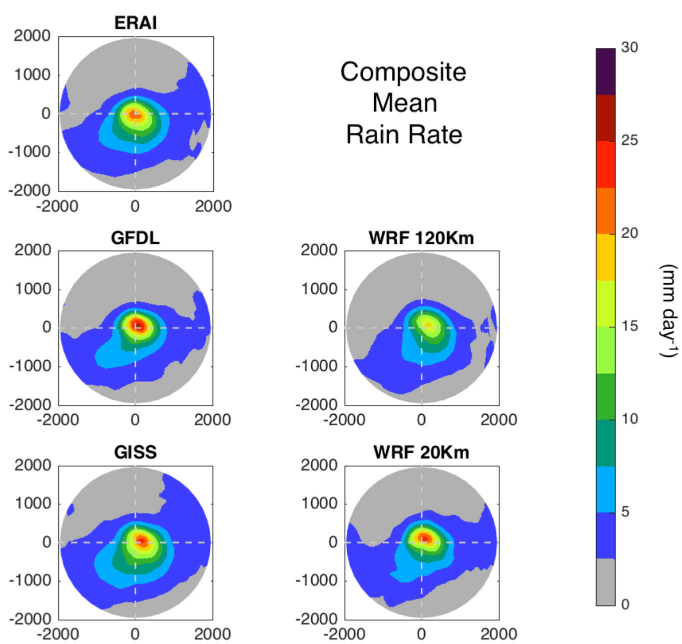
Forcing from Western boundary currents (WCBs) causes surface storm tracks to have a distinct pattern as compared to the storm tracks above the boundary layer. The study addresses the question as to whether or not GCMs can capture this forcing from the surface. Using GCMs from the CMIP5 archive, a series of analyses show that the models capture the change in spatial pattern in the surface storm tracks relative to those above the boundary layer. The study examines possible mechanisms for the forcing and finds that in most models the spatial shift is linked to vertical momentum mixing and storm development. The study tests if biases in the models' representations of the ocean surface temperatures in the WBC regions create biases in the spatial pattern in the storm track. Such a relationship is only found to be statistically significant in the North Atlantic, where the large ocean surface temperature biases in the model are closest to the storm track. The study examines that strength of the surface storm tracks and finds that: (1) the strength of the surface storm track is not explained by the strength of the storm track above the boundary layer, and (2) some of the models are excessively too strong.

Paper 3
Booth, J. F., E. Dunn-Sigouin, S. Pfahl, 2017: The relationship between extratropical cyclone steering and blocking along the North American East Coast. *Geophysical Research Letters*, 44.

This work is motivated by the fact that the path of a cyclone has a strong influence on what kind of impact the cyclone has, in terms of weather hazards. The paper determines the statistical and geographical relationship between extratropical cyclone tracks and atmospheric blocking. A novel metric for assessing extratropical cyclone propagation speed and direction is developed. The study also provides new insight into the similarities and differences in the impact of blocking and the North Atlantic Oscillation on extratropical cyclones that impact the northeast US coast.

Paper 4
Booth J. F., C. M. Naud, J. Willison, 2018: Evaluation of Extratropical Cyclone Precipitation in the North Atlantic Basin: An analysis of ERA-Interim, WRF, and two CMIP5 models. *J. Climate*, 31:6, 2345-2360.

This work is motivated by the fact that extratropical cyclones provide the majority of precipitation to the midlatitudes and previous studies have shown CMIP3 GCMs are biased in their representation of extratropical cyclone precipitation. The research tracks cyclones and uses cyclone-centered compositing. We compare CMIP5 model output from the NOAA GFDL and NASA GISS GCMs with reanalysis and output from WRF run as a regional climate model (RCM) at two separate horizontal resolutions: 120-km (corresponding to GCM resolution) and 20-km (corresponding to RCM resolution). The study finds that GCMs and weather models are able to capture the spatial distribution and rain rate distribution of extratropical cyclone precipitation reasonably well (Fig. 1). The results also show that when WRF is run at a resolution comparable to that of the GCMs, it does not generate cyclone precipitation rates that are strong enough. The reanalysis creates nearly 20% of its extratropical cyclone rainfall via its convection scheme. This is nearly equal to that of the GISS model, but more than that generated by the WRF model. Also, all of the models partition convective and stratiform precipitation differently, even though they all generate similar composite mean rates. The study also analyzed the sensitivity of extratropical cyclone precipitation to changes in environmental water vapor and cyclone strength. The analysis shows that the modeled response to changes in strength and water vapor matches the behavior of reanalysis, and that this is true regardless of the amplitude of the contribution from the convection schemes. This work is relevant to goals (b), (d), and (f) from the list in Section 2.



<u>Figure 1</u>: Cyclone-centered composite mean for precipitation. Cyclones used in each composite occur 1.25-days and 1-day prior to the life cycle maximum in cyclone-averaged surface windspeed. To generate this plot: cyclones are first identified based on their central pressure minimum, then cyclone tracks are generated by linking cyclones in time. The precipitation around the storm is extracted from the gridded data and projected onto a stereographic projection. The life cycle of each track is determined by grabbing cyclone-centered surface wind speed and area averaging the data within 2000 km of the center, and then identifying the time of the wind speed maximum. Axes show distance to cyclone center in km.

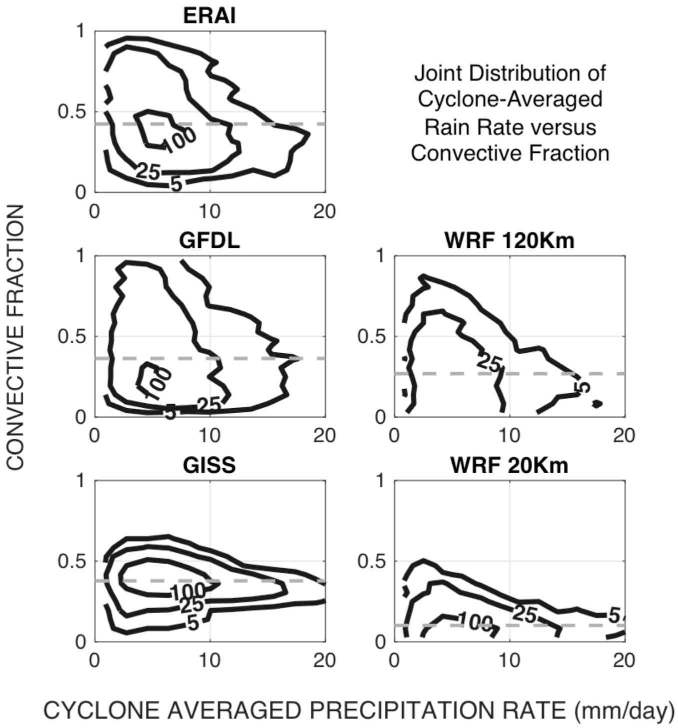


Figure 2: *Joint distribution of cyclone-averaged precipitation and convective fraction using all cyclones in all tracks. Units on contours are cyclone counts per 1.1 mm day^{-1} by 0.055 convective fraction bins. The gray dashed line cuts each set in two halves: one half with larger convective fraction and one half with smaller convective fraction. The location of the smallest contour relative to the x-axis indicates each models most common cyclone precipitation rate; and relative to the y-axis it indicates the most common relative contribution from the convection scheme. ERAI is the reanalysis data; GFDL and GISS are the CMIP5 models from the respective centers. WRF 120km and 20km are regional climate model integrations for two different horizontal resolutions.*
[Adapted from Booth et al. 2018]

Paper 5

Naud, C. M., J. F. Booth, Lebsock, M. and M Grecu, 2018: Observational Constraint for Precipitation in Extratropical Cyclones: sensitivity to data sources. Journal of Applied Meteorology and Climatology, 57, 991–1009.

This paper provides an observational constraint for extratropical cyclone precipitation, and to determine the skill of reanalysis products at capturing this phenomenon. The study compared multiple state-of-the-art precipitation datasets. We found that the most recent active satellite platform from NASA, GPM, underestimates extratropical cyclone precipitation compared to CloudSat. The analysis examined multiple metrics for precipitation, such as, the rain-rate when raining, and established benchmarks and observational uncertainties in extratropical cyclone composites of precipitation. These were made available on a publicly-accessible website, and will be useful for future analyses of GCMs.

Paper 6

Small, J., R. Msadek, Y.-O. Kwon, J. F. Booth, and C. Zarzycki, 2018: Atmosphere surface storm track response to resolved ocean mesoscale in two sets of global climate model experiments. Climate Dynamics.

The work addresses the questions: how does changing the horizontal resolution of the ocean impact midlatitude cyclones and storm tracks. The study utilized coupled GCMs from both NCAR and GFDL: models with high-resolution oceans and models with low-resolution oceans. The high-resolution ocean models captured the ocean western boundary currents with greater fidelity, and this meant the models had stronger near-surface baroclinicity. However, these changes did not lead to a stronger atmospheric storm track. Our analysis determined that multiple factors, including the spatial extent of the warm water east of the western boundary currents but still close to the coastline, also impact the strength of the storm tracks. The analysis also compared multiple metrics for analyzing the response of the storm tracks including: the track density for strong extratropical cyclones, the precipitation, and the Eulerian storm tracks.

Paper 7

Booth, J. F., Naud, C. M., & J. Jeyaratnam, 2018: Extratropical cyclone precipitation life cycles: A satellite-based analysis. Geophysical Research Letters, 45, 8647-8654.

This work examines the relationship between the precipitation life cycle and the cyclone wind circulation life cycle. Cyclone-centered compositing involves first generating Lagrangian tracks of the cyclones and then analyzing the atmosphere in the vicinity of the cyclone center. For this study, we applied the analysis technique to cyclones in reanalysis and observed precipitation from the merged satellite dataset: IMERG. This analysis is motivated by a result that exists in the literature showing that the peak in precipitation in extratropical cyclones often occurs before the peak in the cyclone's wind intensity. We confirmed this result in our analysis (Fig. 3). Our analysis determined that the reason for this is not likely to be related to a thermodynamic/dynamic coupling, but instead is mainly due to the fact that as the storms intensify they more poleward, away from the regions with larger amounts of moisture (Figure 1b). We believe that this is a very important result for understanding extratropical cyclone dynamics, and it provides a new metric for analyzing the dynamics and precipitation in GCMs. From the proposal, the paper aligns with goals 2c, and 2d.

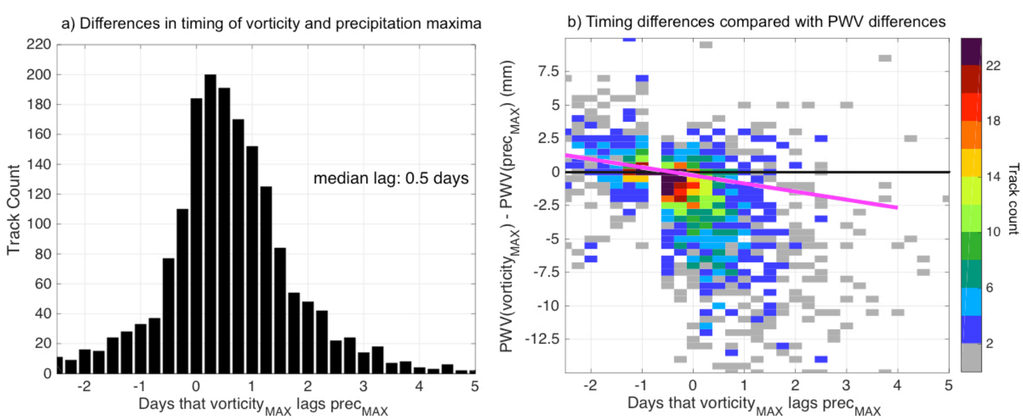


Figure 3: Cyclone-centered comparison of vorticity and precipitation maxima. Panel a shows the distribution of the difference in days between the track lifecycle peak in cyclone-averaged vorticity and the peak in cyclone-averaged precipitation; i.e., each point that goes into this distribution is derived from a extratropical cyclone track, which were detected via a Lagrangian tracker and the track must exist for at least 48 hours. The histogram shows that in most extratropical cyclones, the timing of the life cycle maximum in precipitation leads the maximum in vorticity by a median of 0.5 days. Panel b has the same data plotted on the x-axis, but now the y-axis shows the differences in precipitable water vapor (PWV) for the time of maximum vorticity as compared to the timing of maximum precipitation. The negative linear relationship (pink line) shows that the cyclones have access to more water vapor at the time of their precipitation maximum as compared to the time of their vorticity maximum. Color shading shows the count of cyclone tracks per x,y value.

Paper 8

Naud C. M., J. F. Booth, Leo J. Donner and Charles J. Seman, Ming Zhao, Huan Guo, and Yi Ming: Extratropical Cyclone Clouds in the GFDL climate model: diagnosing biases and the associated causes.

Journal of Climate*. https://doi.org/10.1175/JCLI-D-19-0421.1*

The clouds in southern hemisphere extratropical cyclones generated by the GFDL climate model are analyzed against MODIS, CloudSat and CALIPSO cloud and precipitation observations. Two model versions are used: one is a developmental version of AM4, a model GFDL will utilize for CMIP6, the other is the same model with a different parameterization of moist convection. Both model versions predict a realistic top-of-atmosphere cloud cover in the southern oceans, within 5% of the observations. However, an examination of cloud cover transects in extratropical cyclones reveals a tendency in the models to overestimate high-level clouds (by differing amounts) and underestimate cloud cover at low-levels (again by differing amounts), especially in the post-cold frontal (PCF) region, when compared to observations (Fig. 4). Focusing on only the models, their differences in high and mid-level clouds are consistent with their differences in convective activity and relative humidity (RH), but the same is not true for the PCF region. In this region, RH is higher in the model with less cloud fraction. These seemingly contradictory cloud and RH differences can be explained by differences in the cloud parameterization tuning parameters that ensure radiative balance. In the PCF region, the model cloud differences are smaller than either of the model biases with respect to observations, suggesting other physics changes are needed to address the bias. The process-oriented analysis used to assess these model differences will soon be automated and shared.

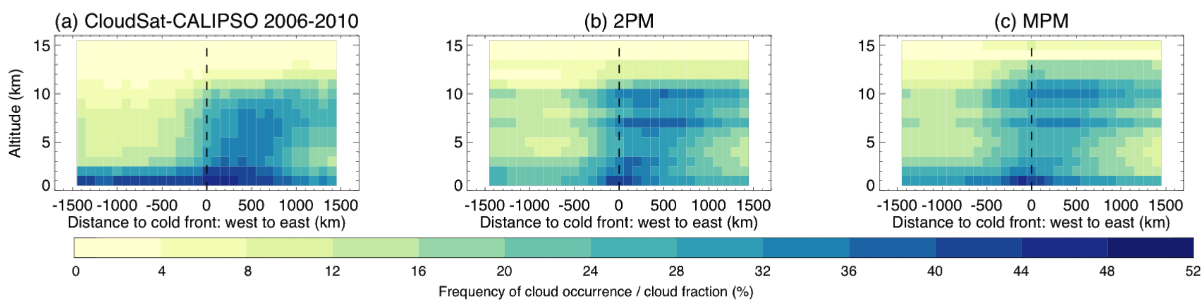


Figure 4: Cold front centered composites of vertical cloud distribution from (a) CloudSat-CALIPSO averaged over 2006-2016, (b) as modeled with devAM4 2PM and (c) as modeled with devAM4-MPM. The vertical dashed line indicates the location of the surface cold front: the post-cold frontal or cold side of the front is to the left of this line, while the pre-cold frontal or warm side of the front is to the right. These are southern hemisphere cold fronts during November-March.

Paper 9

Naud, C. M., J. F. Booth, J. Jeyaratnam, M. Zhou, A Gettelman, 2019: Evaluation of modeled precipitation in oceanic extratropical cyclones using IMERG. *Accepted, J. Climate*

We find that the models rain too little in the cyclone warm sector and this is caused by biases in intensity: the rain rates are too small in the model compared to IMERG. We also find that the models (both the free running GCMs and the reanalyses) rain to much in the cold sector of the cyclones and this is caused by biases in frequency: the models rain too often. Finally, we find that these biases change if we conditionally sort the cyclones based on environmental moisture; i.e., comparing the biases for cyclones with a lot of moisture versus the cyclones with small amounts of moisture. This result could potentially mean that the modeled response of extratropical cyclone precipitation to climate change is also biased..

Paper 10
Jeyaratnam, J., Z. Lou, J. F. Booth, C. M. Naud, and Cameron Homeyer: How much convection occurs in extratropical cyclones? A ground-based radar analysis. *In revision, Geophysical Research Letters.*

Using a pre-existing, surface-radar based algorithm to identify deep convection, we analyzed the relationship between deep convection and extratropical cyclone precipitation. We find that the percentage of precipitating regions with deep convection within extratropical cyclones over the United States in below 10%. This amount is near constant throughout the life cycle of the cyclones, however, the location of the deep convection moves. During the early stages of the cyclone life cycle, deep convection mainly occurs within the warm sector. Late in the cyclone life cycle the deep convection predominantly occurs near the cold front. The precipitation rates in the regions in which deep convection is detected are stronger than otherwise, consistent with observational records of tropical storms.

3.2.3 Advances in automating the metric

We have been working to make our cyclone-centered analysis completely automated. Although this venture was not part of the original proposal, the monthly meetings of the Model Diagnostics Task Force (MDTF) have motivated us to try to make this happen. Thus, far we have the cyclone tracking code completely automated: all that is needed is model or reanalysis sea level pressure data, and the model topography in netcdf format. Then with one call, Lagrangian tracks are calculated. We have transferred the frontal tracking to python as well. These advances have been very useful to the work flow. A final stand alone version will not be completed within the work of this award. But there is a possibility that we will complete the metric and add it to the MDTF API through a separate award. If we were to complete this, we would then have a metric that any modeling center could utilize to diagnose cloud and precipitation biases in their modeled extratropical cyclones.

3.2.4 Conference Posters and Talks

James Booth

- *American Geophysical Union Fall Meeting, San Francisco, CA, 14 December 2015 "The Surface Storm Tracks in Three CMIP5 Global Climate Models"*
- *American Meteorological Society Air-Sea Interactions Meeting, Aug 2016. Madison, WI, "The Surface Storm Tracks in CMIP5 Global Climate Models"*
- *American Geophysical Union Fall Meeting, Dec. 2016, San Francisco, "Storm Track and Extratropical Cyclone Metrics: Applications for the CMIP5 Archive"*
- *Clouds and Precipitation in GCM Extratropical Cyclones: An Analysis Based On Cyclone-Centered Metrics, NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, May 2018. [Talk]*
- *Evaluation of Extratropical Cyclone Precipitation and Clouds in CMIP5 and CMIP6-prototype models. NASA Goddard Space Flight Center, GMAO Seminar Series. Greenbelt, MD, Sept. 2017. [Talk]*
- *Evaluation of Extratropical Cyclone Precipitation and Clouds in CMIP5 and CMIP6-prototype models. J. F. Booth, Marine, Earth, and Atmospheric Sciences Department Seminar, North Carolina State University, Raleigh, NC, July 2017 [Talk]*
- *Clouds And Precipitation In General Circulation Model Extratropical Cyclones: An Analysis Based On Cyclone-Centered Metrics. J. F. Booth, C. M. Naud, and other, Working Group on Numerical Errors Meeting, World Meteorological Organization, Montreal, Quebec, June 2017. [Talk]*

- Extratropical Cyclone Precipitation Life Cycles and Cloud Vertical Structure in Observations and Climate Models, J. F. Booth, C. Naud, J. Jayaratnam, American Geophysical Union Fall Meeting, Washington D.C., Dec 2018. [Talk]
- Extratropical Cyclone Precipitation Life Cycles and Cloud Vertical Structure in Observations and Climate Models, J. F. Booth, C. Naud, J. Jayaratnam, European Geophysical Union Annual Meeting, Vienna, Austria, Apr 2019. [Talk]

Catherine Naud

- *American Geophysical Union Fall Meeting, San Francisco, CA, 14 December 2015. "A-train based observational metrics for model evaluation in extratropical cyclones".*
- *Clouds Seminar, NASA-GISS (NY) in November 3 2015 "GCMs evaluation for their representation of clouds in extratropical cyclones using A-train observations".*
- *NASA CloudSat-CALIPSO science team meeting in Newport News, VA, 1, March 2016 "CloudSat-CALIPSO based observational constraint for the representation of post-cold frontal clouds in general circulation models.*
- *American Geophysical Union Fall Meeting, Dec. 2016, San Francisco, "An A-train climatology of extratropical cyclone clouds"*
- *Department Seminar at Stony Brook, February 2017, "Clouds and Precipitation in extratropical cyclones: a global climatology for GCM evaluation"*
- *A climatology of clouds and precipitation in satellite observations based on satellite observations. Clouds, their properties, and their climate feedbacks: a symposium to celebrate William B. Rossow's science contributions and retirement", New York, NY, June 2017 [Talk]*

Leo Donner

- *American Physical Society, Baltimore, MD, 15 March 2016 (invited): "Aerosols, clouds, and precipitation as scale interactions in the climate system and controls on climate change"*
- *European Geosciences Union, Vienna, Austria, 18 April 2016 (invited): "Cloud dynamical controls on climate forcing by aerosol-cloud interactions: New insights from observations, high-resolution models, and parameterizations"*
- *World Climate Research Programme, 2 November 2016, Princeton University, Princeton, NJ, ``Physical process realism and model 9hierarchies."*
- *CESM Atmosphere Model Working Group Meeting, 27 February 2017, NCAR, Boulder, CO, "Strategies for cumulus parameterization for CAM"*
- *GEWEX Upper Tropospheric Clouds and Convection Process Evaluation Study Meeting, 28 March 2017, City University of New York, New York, NY, "Convective updraft speeds: A correlate to climate sensitivity?"*
- *Rossow Symposium, Columbia, NYC, June 2017*
- *GEWEX Aerosols-Clouds-Convection, Oxford, UK, June 2017*
- *Cumulus Parameterization Workshop, Delft, Netherlands, July 2017*
- *Cloud Feedbacks Model Intercomparison Program (CFMIP), Tokyo, September 2017*
- European Geophysical Union Annual Meeting, Apr 2019.
- Convection Parameterization: Progress and Challenges, 19 July 2019, UK Met Office, Exeter, UK, ``Diagnosing convection in extra-tropical cyclones in GFDL AM4."

4. Highlights of Accomplishments

YEAR 1

- Analyzed the Eulerian storm tracks in the western boundary current regions from three CMIP5 models: NCAR CESM1-LE, NOAA GFDL-CM3, and NASA GISS-ModelE2.
- Determined the biases in the free-tropospheric and surface Eulerian storm tracks in the NCAR, GFDL and NASA GISS models.

- Determined that the estimated inversion strength acts as a reliable predictor of cloud behavior in post-cold frontal cloud regions.

YEAR 2

- Co-I Naud published a paper in J. Climate showing the relationship between lower tropospheric stability and cloud cover in the post cold-frontal region of extratropical cyclones. The research also found variability in large-scale subsidence of the storms had minimal impact on low-level cloud behavior.
- PI Booth published a paper in J. Climate on CMIP5 models' storm tracks, with a focus over the ocean western boundary current regions. The work shows that models properly capture the shift in location of the surface storm track relative to the free tropospheric storm track, though the placement and magnitude do not match with reanalysis. The work also introduces metrics to show that the shift in location is most likely caused by lower tropospheric vertical stability, which impacts the baroclinicity and the vertical mixing of horizontal momentum. Analysis of storm track strength found good correlations between strength of the storm track at different vertical layers in the free troposphere, and weak or no correlation between the strength above the free troposphere and at the surface.

- We generated a dataset of satellite and reanalysis based cyclone-centered composites of clouds, vertical motion, surface winds, and precipitation. This dataset will soon be posted online.
- The team worked with Charles Seaman at GFDL to generate two new time slice model integrations using the GFDL model. These complement the integrations that were created for the NOAA Model Diagnostic Task Force (MDTF).

YEAR 3

- PI Booth was the lead author on a journal article published in Geophysical Research Letters titled: The relationship between extratropical cyclone steering and blocking along the North American East Coast. The analysis featured a new metric for characterizing extratropical cyclone propagation, in terms of both speed and direction. Future work is planned to apply the metric to CMIP models.
- PI Booth was the lead author on a journal article published in Journal of Climate titled: Evaluation of Extratropical Cyclone Precipitation in the North Atlantic Basin: An analysis of ERA-Interim, WRF, and two CMIP5 models. The analysis focused on cyclone-centered composites of extratropical cyclone precipitation and the role of parameterized convection. The work finds that GCMs generate spatial patterns and intensity distributions of precipitation that are very similar to reanalysis, despite the fact that the models have for different contributions to total precipitation from their convection schemes. The work also shows that the models properly represent the sensitivity of cyclone precipitation to changes in cyclone strength and precipitable water vapor.
- co-I Naud was the lead author on a journal article published in Journal of Applied Meteorology and climatology titled: Observational Constraint for Precipitation in Extratropical Cyclones:

sensitivity to data sources. The analysis compared satellite-derived precipitation estimates from multiple different platforms in a cyclone-centered compositing analysis.
- PI Booth was a co-author on a paper published in Climate Dynamics titled: Atmosphere surface storm track response to resolved ocean mesoscale in two sets of global climate model experiments. Climate Dynamics. The analysis determined the processes in coupled climate models that cause the oceans' western boundary currents to impact the atmospheric storm tracks.
- We carried out analysis of cyclone-centered precipitation and cold-front relative clouds in the GFDL CMIP6-prototype models. The analysis focused on the impact of parameterized convection on the clouds and precipitation.
- We analyzed extratropical cyclone precipitation and the contribution from convection using ground-based radar to create a ground-truth for comparison with models.

YEAR 4 (due to NCE)
- PI Booth led a paper that examines the reason why precipitation usually peaks in an extratropical cyclone before the maximum in cyclone wind intensity. The work used reanalysis and observations to show that the timing difference is most likely related to the poleward movement of the cyclones while they intensify. This work provides necessary insight into the coupling between thermodynamics and dynamic processes within the cyclones. This paper is published in Geophysical Research Letters.
- PI Booth and Co-I Naud contributed to the Model Diagnostic Task Force BAMS paper.
- Co-I Naud led a paper that examines the cloud amount in extratropical cyclones in GFDL's GCMs. The work finds that the models capture the total cloud cover, but do so through compensating biases above the cold sector: too much cloud at 5 – 10km and too little cloud at 1km. The analysis also looks at the sensitivity of the clouds to changes in the convection scheme.
- PI Booth gave a highlighted talk at the AGU Fall meeting in Washington D.C., in which he discussed all of the methodology and results funded by this award.

5. Transitions to Applications

At this point, there have been no transitions to applications.

6. Estimate of current technical readiness level of work

The cyclone-based and front-based compositing tools developed herein are currently at Technical Readiness Level 5. There are efforts in place to transition to RL7.

7. Publications for this Award

Naud, C. M., J. F. Booth, A. D. Del Genio, 2016: The relationship between boundary layer stability and cloud cover in the post-cold frontal region. J. Climate, 29, 8129–8149, doi: 10.1175/JCLI-D-15-0700.1.

Booth J. F., Y.-K. Kwon, S. Ko, J. Small, R. Madsek, 2017: Spatial Patterns and Intensity of the Surface Storm Tracks in CMIP5 Models. *Journal of Climate*, 30, 4965–4981.

Booth, J. F., E. Dunn-Sigouin, S. Pfahl, 2017: The relationship between extratropical cyclone steering and blocking along the North American East Coast. *Geophysical Research Letters*, 44. https://doi.org/10.1002/2017GL075941.

Booth J. F., C. M. Naud, J. Willison, 2018: Evaluation of Extratropical Cyclone Precipitation in the North Atlantic Basin: An analysis of ERA-Interim, WRF, and two CMIP5 models. *J. Climate*, 31:6, 2345-2360.

Naud, C. M., J. F. Booth, Lebsock, M. and M Grecu, 2018: Observational Constraint for Precipitation in Extratropical Cyclones: sensitivity to data sources. Journal of Applied Meteorology and Climatology, 57, 991–1009, https://doi.org/10.1175/JAMC-D-17-0289.1

Small, J., R. Msadek, Y.-O. Kwon, J. F. Booth, and C. Zarzycki, 2018: Atmosphere surface storm track response to resolved ocean mesoscale in two sets of global climate model experiments. Climate Dynamics, https://doi.org/10.1007/s00382-018-4237-9

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8. High Performance Computing Use

Not Applicable

9. PI Contact Information

James F. Booth
Dept. of Earth and Atmospheric Science, City University of New York, City College
Room 926, Marshak Building, CCNY, 160 Convent Ave. New York, NY, 10031
Phone: 212-650-6471
Email: jbooth@ccny.cuny.edu