Investigating the Convective Morphology and Diurnal Cycle in Pre-genesis Disturbances using Object-Based Analysis of Geostationary Satellite Observations

Short Title:

Using GLM to Examine Developing Tropical Cyclones

A proposal created in response to the 2022 NASA ROSES solicitation NNH22ZDA001N: A.33 Earth Science Research from Operational Geostationary Satellite Systems

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1. Project Summary

The Geostationary Lightning Mapper (GLM) provides a wealth of information regarding the organization of convection in developing tropical cyclones that has yet to be fully taken advantage of by the research and operational community. The use of lightning as a predictor for tropical cyclone genesis was first explored by Leary and Ritchie (2009), who found that developing cloud clusters in the East Pacific were associated with significantly more lightning than non-developers. Leppert et al. (2013) found that lightning flash rates were not a distinguishing factor between developing and non-developing easterly waves in the Atlantic; however, the study used snapshots of lightning from the Lightning Imaging Sensor (LIS) which did not allow for a complete examination of the spatial and temporal evolution of the lightning. An examination of the spatial and temporal evolution of lightning in pre-genesis disturbances such as African Easterly Waves (AEWs) has yet to be explored.

The objective of this proposal is to use GLM and the Advanced Baseline Imager (ABI) from GOES-16/17/18 to examine the evolution and organization of convective processes that leads to tropical cyclogenesis. The three goals of the project include: 1) to explore the use of GLM and ABI to predict the location and timing of the formation of the low-level vortex center, 2) to evaluate convective elements and their morphology for identification of key features in the attributes of lightning clusters that can be used to discriminate between developing and non-developing tropical disturbances, and 3) to characterize the temporal, spatial, and feature attributes of lightning flashes and its variability over the diurnal cycle in pre-genesis disturbances.

Deep convection is required to organize within a vorticity-rich and thermodynamically favorable environment for a tropical cyclone to form; however, work has shown that stratiform precipitation can also promote tropical cyclogenesis through continued maintenance of mid-level vorticity and by the pre-conditioning of the low-level thermodynamics to favor deep convection (Bell and Montgomery 2019; Tang et al. 2020). GLM can be used to differentiate between deep convective and stratiform features by examining the area and intensity of lightning flashes. Small and intense convective updrafts can be indicated by frequent small and low energy lightning flashes and broad weaker updrafts typically found in stratiform regions are indicated by a small number of large and energetic flashes (Bruning and MacGorman 2013; Duran et al. 2021). This project will employ an object-based approach to examine the morphology of lightning clusters within ABI defined cloud clusters to elucidate differences in lightning flash characteristics at small scales. An evaluation of GLM clusters, ABI data, and Global Forecast System (GFS) analysis fields will be conducted over a large dataset of developing and non-developing tropical cyclones in the Atlantic and East Pacific basins.

The proposed work directly addresses NASA’s goal to improve our capability to predict weather and extreme weather events by leveraging high frequency output from ABI and GLM. This work fits into NASA’s area of investigation focused on characterizing and understanding fast changing processes in pre-genesis disturbances, including over the diurnal cycle, to evaluate how these processes organize and grow upscale during the development of a tropical cyclone. While the primary objective of this work is an improved understanding of the convective processes during tropical cyclogenesis, the framework and results of this project will be documented for future application to forecasts of developing tropical cyclones.

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Table of Contents

2. SCIENTIFIC/TECHNICAL/MANAGEMENT

2.1 Introduction

2.1.1 Background and Motivation

Tropical cyclones are extreme weather events that have caused the most damage ($1,194.4 billion, CPI-adjusted) and have the highest average event cost of all U.S. Billion-dollar disaster events from 1980 to 2022 (NCEI 2022). As Earth continues to warm, tropical cyclones (TCs) are expected to be more intense on average and be able to intensify more quickly (Kossin 2020, Bhatia et al. 2019). The National Oceanic and Atmospheric Administration (NOAA) has already recognized that improving the accuracy and extending tropical cyclone genesis forecasts will be critical in the future to mitigate potential impacts on the U.S. Through the Hurricane Forecast Improvement Project (HFIP, Gall et al. 2013), NOAA aims to improve guidance on pre-formation disturbances, including genesis timing, track, and intensity forecasts to maximize the lead time of tropical cyclone impacts (Gopalakrishnan et al. 2020).

Forecasting tropical cyclogenesis remains a challenge because of its multiscale nature that requires ingredients from convective to synoptical scale (Rappaport et al. 2009, Nam and Bell 2021). Within pre-genesis tropical disturbances there can be an amalgam of cloud types at different scales. Figure 1 shows an idealized distribution of clouds within a pregenesis disturbance based on Houze (2010). Tropical invests contain isolated deep convective cells that can be classified as vortical hot towers (VHTs) or convective bursts, mesoscale convective systems (MCSs), and broad stratiform regions. Within the idealized cloud distributions highlighted in Houze (2010), rotating deep convective cells also called VHTs are the building block of tropical cyclones. As VHTs cycle, the vorticity that has been stretched and advected upwards, form an MCS and a mesoscale convective vortex (MCV) will remain once the VHTs completely die off. The lifecycle of deep convective cells could be tracked using the Geostationary Lightning Mapper (GLM) by examining the spatial characteristics and lightning attributes, such as the area and energy of lightning flashes. Small and intense convective updrafts can be indicated by frequent small and low energy lightning flashes and broad weaker updrafts typically found in stratiform regions are indicated by a small number of large and energetic flashes (Bruning and MacGorman 2013; Duran et al. 2021). Therefore, we posit that lightning could be used to track the morphology of deep convection as it organizes and transitions into MCSs and MCVs.

Although there is a dearth of work examining lightning as a discriminator of tropical cyclogenesis, the importance of lightning as a predictor for tropical cyclone intensity change has been studied extensively using ground-based lightning detection networks with sometimes ambiguous results (Molinari et al. 1999). The presence of lightning within the eyewall of TCs has been hypothesized to suggest the presence of deep convection and suggest a period of intensification (Squires and Businger 2008; Abarca et al. 2011; Zhang et al. 2015), although several studies have found more lightning prior to the TC weakening (Jiang and Ramirez 2013; Stevenson et al. 2016; Xu et al. 2017, Stevenson et al. 2018). DeMaria et al. (2012) found that lightning outbreaks in the rainbands of TCs are more indicative of intensification because it suggests a large-scale favorable environment. Zawislak (2020) found that the relative area of deep convection defined by the extent of IR brightness temperatures <240 K was a good predictor of tropical cyclogenesis, likely because

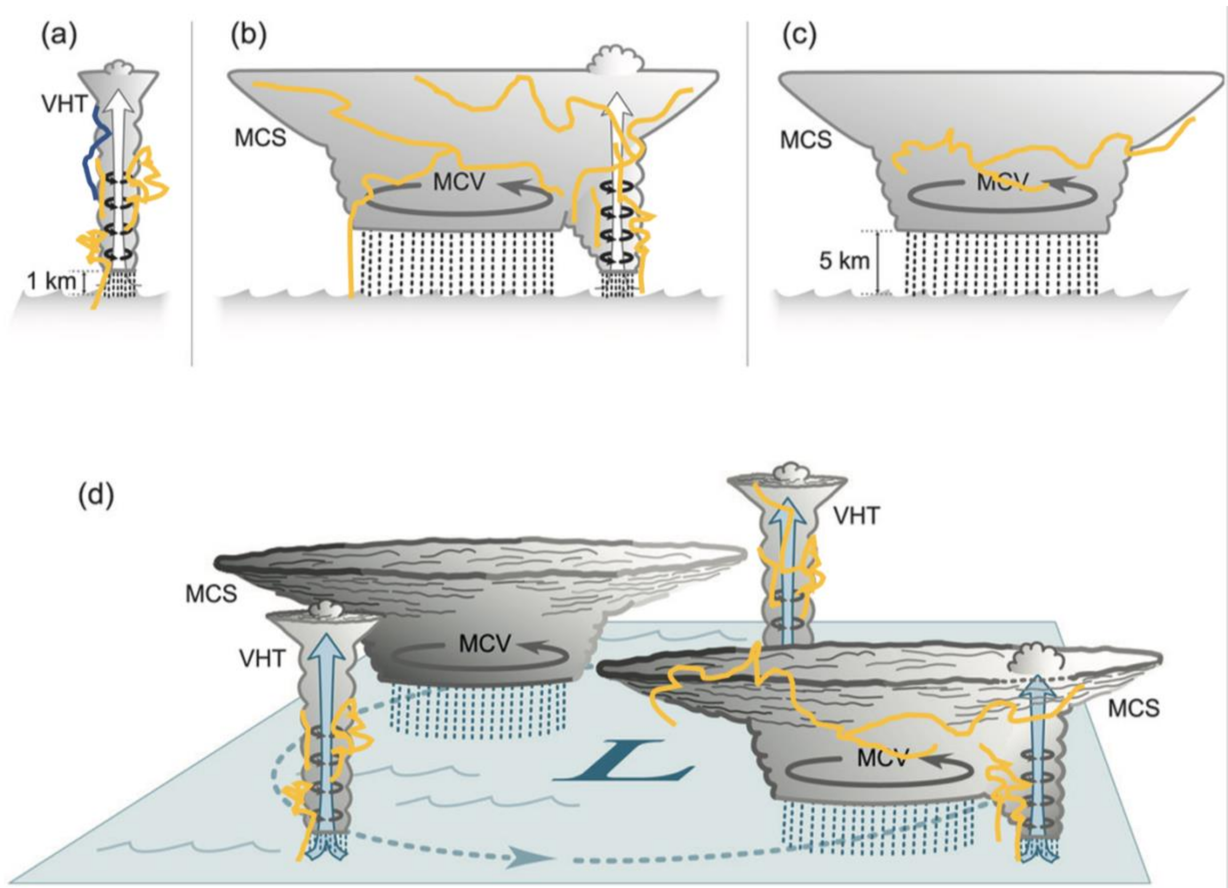

Figure 1: *The MCS life cycle and lightning characteristics within a developing TC. (a) The MCS begins as a set of one or more isolated deep vertical convective bursts that produces lightning within a small area. (b) The convective-scale cells are transient components of a larger and longer-lived MCS that at its mature stage of development has both convective and stratiform components. (c) In the late stages of the MCS life cycle, new cell development ceases while the MCV vorticity remains in the precipitating stratiform cloud region. (d) An idealized distribution of VHTs and MCSs in various stages of development with idealizations of lightning overlaid. The MCS life cycle with lightning is adapted from Houze (1982) and Houze et al. (2009).*

it was associated with favorable environmental conditions such as lower-vertical wind shear. This suggests that although lightning is fundamentally related to ice microphysics and deep convection, its variability within tropical disturbances is also a function of the favorability of the large-scale environment for deep convection.

Vertical wind shear can have a large impact on pregenesis disturbances by tilting easterly waves causing the low-level (if present) and mid-level circulations to be mis-aligned (Molinari et al. 2006, Rios-Berrios and Torn 2017). The realignment of the low- and mid-level circulation centers can occur through several pathways including an advective vortex procession (Jones 1995), merger processes (Van Sang et al. 2008), or a reformation of the low-level center (Chen et al. 2018). All of these processes show that the tilt, being a measure of the displacement between the low and mid-level vortex, needs to be reduced to a sufficient magnitude for tropical cyclogenesis to occur

(Nam and Bell, 2021; Rios-Berrios et al. 2018). Stevenson et al. (2014) found that lightning outbreaks upshear in the direction of the tilt vector preceded the rapid intensification of Hurricane Earl (2010) and suggested that the spatial orientation of lightning along the tilt vector could be a useful metric for identifying the realignment of the vortex or predicting a future center relocation. The relocation of the low-level center commonly occurs within weak and unorganized tropical cyclones but are difficult to forecast and often lead to large operational forecast errors by the National Hurricane Center (NHC)(Latto and Berg 2022). It is hypothesized that lightning, when associated with deep convection having low flash area and energy concentrated within the mid-level circulation but offset from the low-level center, could be an indicator for a center relocation. Areas of enhanced lightning associated with an MCS in close proximity to or upshear of the low-level center could indicate a realignment of the vortex and subsequent genesis. By relating lightning associated with deep convection to the wave structure, we can better forecast structural changes that may or may not lead to genesis.

Although the environment can explain a large amount of variability in tropical cyclogenesis, it is still unclear why some easterly waves develop into tropical cyclones while others do not in similar thermodynamic environments (Hopsch et al. 2010). The intensity of deep convection within the easterly waves has been suggested to be a determining factor in identifying developing tropical waves, although studies have offered conflicting results using lightning observations. Using lightning from Vaisala's Long-Range Lightning Detection Network as an estimate for convective intensity, Leary and Ritchie (2009) found that developing cloud clusters in the East Pacific were associated with significantly more lightning than non-developers. In contrast, Leppert et al. (2013) found that lightning as a convective intensity estimate was not statistically different in Atlantic tropical disturbances that developed versus those that did not. The lack of significant findings using lightning by Leppert et al. (2013) could be due to the use of the Lightning Imaging Sensor (LIS) which only provides snapshots of lightning and cannot evaluate spatial or temporal trends in lightning. The use of high temporal and spatial lightning observations to understand the evolution and organization of convection during tropical cyclogenesis has yet to be explored.

In this proposal we seek to leverage the high temporal and spatial observations from the GLM the Advanced Baseline Imager (ABI) from GOES-16/17/18 to examine the evolution and organization of convective processes that leads to tropical cyclogenesis. It is hypothesized that the spatial orientation of lightning and its attributes, in concert with additional observational datasets, need to be leveraged in order to appropriately interpret the forecast implications of lightning within the broad distribution of clouds. Lightning can occur within developing VHTs and decaying MCSs concurrently within pre-genesis disturbances; therefore, an object-based approach could provide more useful metrics to relate lightning to the potential for tropical cyclogenesis. The temporal attributes of lightning are equally important on both convective and diurnal time scales, but the episodic nature of lightning has not been quantified and used because of spatial and temporal averaging (e.g. DeMaria et al. 2012, Leppert et al. 2013). By tracking areas of lightning and examining its spatial extent, temporal variability, and feature attributes such as the area and energy of the flashes, we can provide better context of the environment and cycling of convection within pre-genesis disturbances to better predict the formation of tropical cyclones.

2.1.2 Objectives

There are three key objectives of the proposed research which are as follows:

1. *Examine lightning attributes and trends prior to the formation of the low-level center.* The spatial orientation of the lightning with respect to the positions of the low- and mid-level circulation centers could determine the likelihood for a center relocation or realignment. Higher GLM flash rates with lower flash areas and higher flash intensity indicating deeper convection persistent in clusters upshear could indicate a realignment of the circulation centers and subsequent tropical cyclogenesis.

2. *Evaluate lightning characteristics and morphology as a discriminator for genesis.*
As mesoscale convective systems mature, precipitation features will shift from deep convective to stratiform. GLM flash rates with a large spatial extent, larger lightning flash areas, and lower flash intensity could be used to indicate stratiform precipitation. It is hypothesized that enhanced lightning with stratiform characteristics near the mid-level center will be more common in the days leading up to tropical cyclogenesis while lightning signatures associated with sustained deep convection will be more prominent in the hours leading to genesis.

3. *Quantify the importance of lightning variability from the diurnal cycle on genesis timing.*
While GLM has a diurnal cycle in detection efficiency, we will identify the mean and the deviations in the diurnal cycle. Anomalous GLM flash rates relative to the diurnal cycle of lightning could be an indicator of external forcing of convective invigoration that suggests a less favorable environment for the organization of pre-genesis tropical disturbances.

Each of the objectives above will support future development and use of lightning products for forecasting and nowcasting tropical cyclogenesis. The outcome of this project will be guidance on how to use GLM observations as a nowcast tool to identify potential areas for the formation of the low-level center or realignment of the circulation centers within developing tropical cyclones. Tropical cyclone invest relative imagery will be created in real-time for processing and evaluation. This project will also provide guidance on how GLM observations can discriminate between developing and non-developing tropical disturbances on short time scales. Outcomes of this work will include new spatial and temporal lightning variables that can be tested in the future for implementation into probabilistic tropical cyclogenesis forecast techniques.

Figure 2 shows a flowchart of the input data, methods, and output for the three objectives listed above. Section 2.2 will explore in depth how the objectives of this proposal will be accomplished.

2.1.3 Significance of Proposed Research

Improving our capability to predict developing tropical cyclones requires greater understanding of the fast-changing convective processes and their organization. This proposal addresses the NASA call to use observations from the new generation of operational geostationary satellites to improve our understanding of fast changing processes within tropical cyclones. Tropical cyclones are

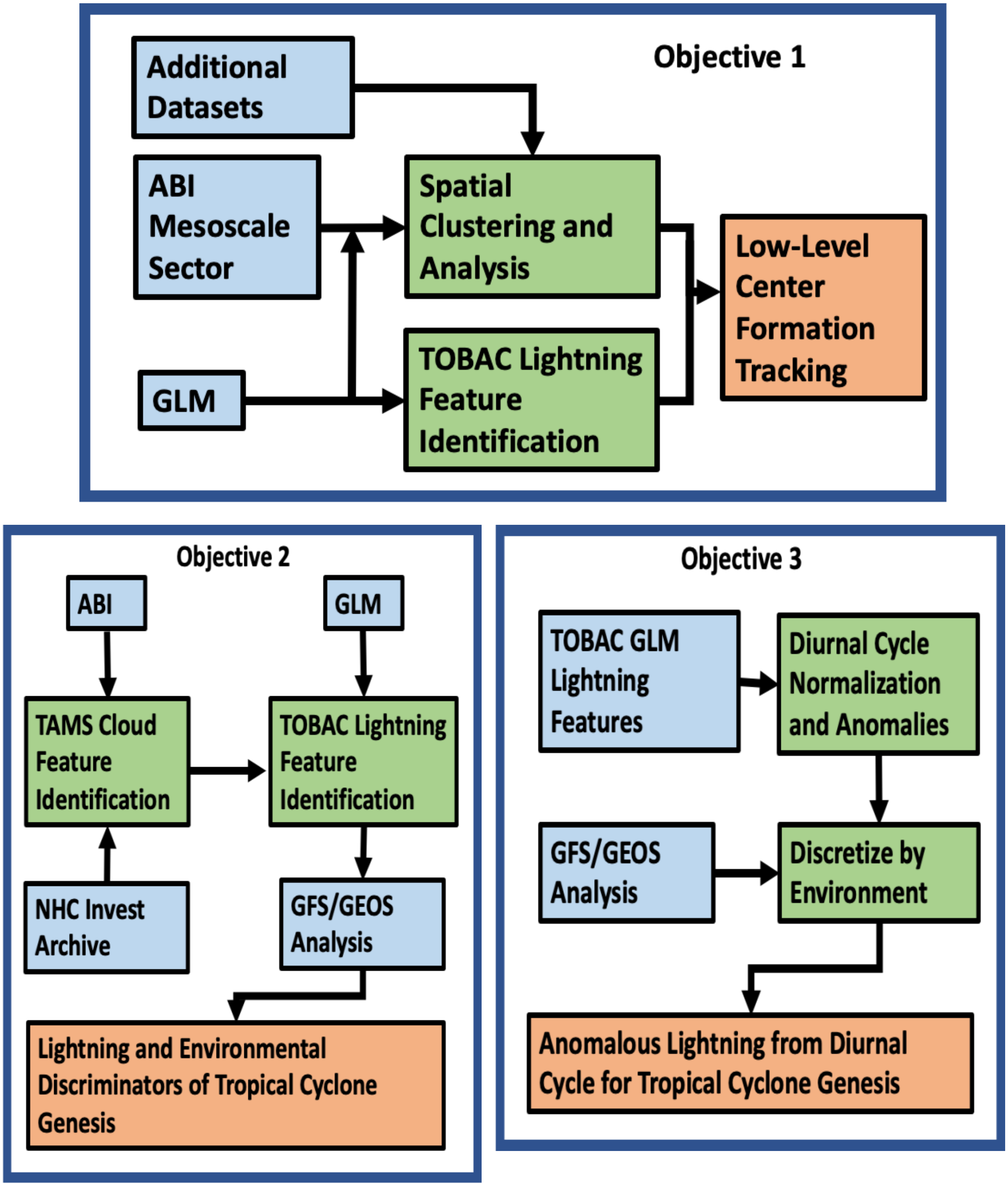

Figure 2: *A flowchart outlining work plan for the three objectives proposed. Each blue box contains one objective with shaded blue boxes showing the datasets. The green boxes show techniques and methods used, and the main results of the proposed work are shown in orange.*

extreme weather events with high impacts as tropical cyclone losses dominate the distribution of damage from U.S. Billion-dollar disaster events from 1980 to 2022 (NCEI 2022).

The objectives of the proposed work fit well within the goals outlined in the NASA and NOAA Strategic Plans and the 2017 Decadal Survey. Specifically, it addresses:

- NASA's Earth Science research objective to *improve the capability to predict weather and extreme weather events*
- NOAA's 2022-2026 strategic plan to advance forecasts for tropical cyclones and coastal storms to better prepare for coastal inundation and flooding
- The 2017 Decadal Survey goal to extend and improve weather forecasts with a focus on using time-continuous observations of severe storms.

2.2 Technical Approach and Methodology

2.2.1. Satellite Based Observations

In order to achieve the goal of improving our understanding of fast evolving convective processes during tropical cyclone genesis, this project will use the high spatial and temporal resolution observations from GOES 16/17/18. Geostationary satellite imagery is critical for tracking developing tropical cyclones by measuring the reflectance and brightness temperatures of clouds. Infrared (IR, 10.3 micron) and water vapor (6.2-6.9 micron) channels of ABI will provide the basis for objectively analyzing the extent of cold clouds, moisture, and upper-level flow patterns of tropical cloud clusters.

The first project will specifically leverage ABI observations from the mesoscale sectors which have been under-utilized in the research community. Because the mesoscale sectors are constantly moved based on operational forecaster needs, the mesoscale sectors cannot be easily utilized for long-term evaluations; however, it is the perfect tool for detailed high-resolution case studies. In 2021, the mesoscale sectors of GOES16 were constantly monitoring the tropical invest that developed into Hurricane Ida. This project will leverage the mesoscale sector for a detailed evaluation of the cloud and lightning evolution during the genesis of Hurricane Ida, in addition to future cases as available. The evaluation of lightning within specific cases will be enhanced by observations from the global observing system. Passive microwave imagery from polar orbiting satellites can be used to provide snapshots of deep convection because the 85-GHz channel is sensitive to scattering by ice particles (Wilheit 1986). Active microwave sensors, such as the Advanced Scatterometer (ASCAT), will also be leveraged to assess the low-level kinematic field.

As evident by the objectives of this proposal, observations from GLM will be heavily utilized. GLM has provided an unprecedented look at deep convection, particularly in the tropics where ground-based lightning observations have limited detection efficiency (Goodman et al. 2013). However, GLM observations are known to have several artifacts that could complicate our understanding of the physical processes ongoing within developing tropical cyclones (Rudlosky et al. 2019). The PI has developed quality control methods to remove GLM false flashes caused by the Bahama bar, sun glint, blooming events, and spurious lightning that takes advantage of the variance in GLM group area and group energy. Additional reprocessing of GLM observations from older flash identification algorithms is being undertaken with the development of the Lightning

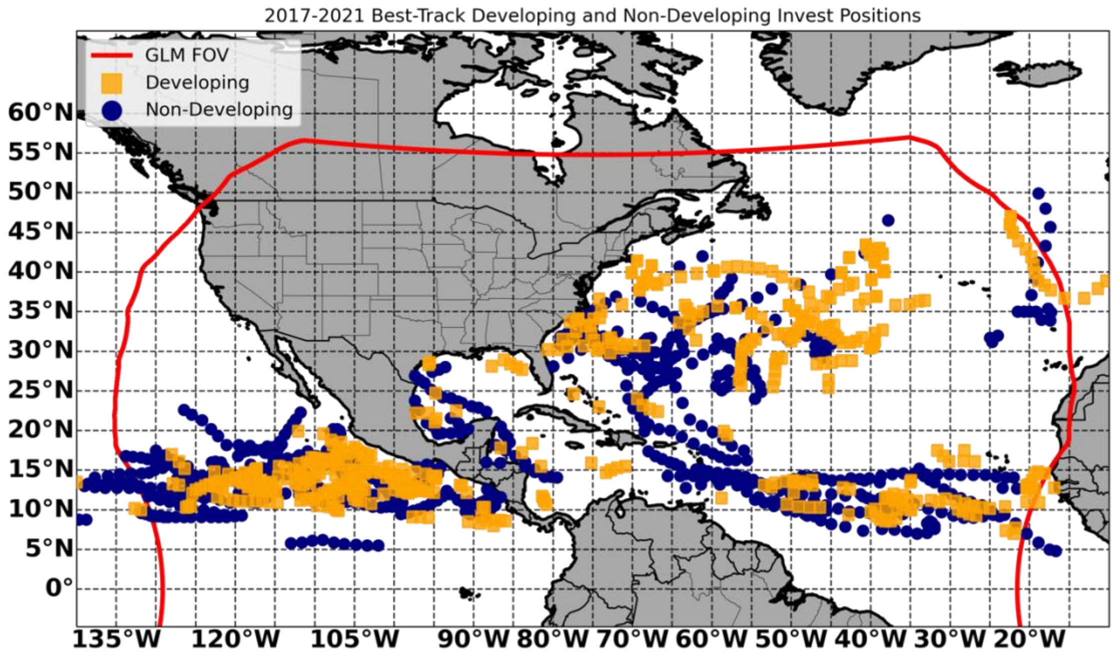

Figure 3: *The developing and non-developing 6-houly positions for NHC defined invests in the Atlantic and East Pacific basins from 2017-2021. The red outline shows the GLM field of view.*

Enterprise Science Algorithm (LESA). The goal of LESA is to improve the data quality metrics and to assist the science community in determining GLM data quality. Once available in 2024, the long-term database created by LESA will be utilized to provide a consistent GLM dataset spanning 2017 to present day.

2.2.2 Additional Datasets

Although satellite-based observations have been shown to have predictive capability for tropical cyclogenesis (Leppert et al. 2013, Wang 2018), kinematic and thermodynamic observations are also needed to fully resolve the parameter space. Analysis fields of relevant quantities for tropical cyclogenesis will be used from the Global Forecast System (GFS). The GFS will provide 6-hourly analysis fields of the best estimate of the thermodynamic and kinematic environment throughout the depth of the troposphere. Derived quantities such as the vorticity at multiple altitudes will enable the study to examine how the convective structure evolves to grow the areal coverage and magnitude of the low- and mid-level vorticity. In addition, the vorticity centers will be used to calculate the tilt vector of the circulation centers. The low-level relative humidity will also be included for analysis which has been shown to be an indicator of genesis (Brammer and Thorncroft 2015).

Lightning has been shown to have a dependence on aerosols by influencing the cloud microphysics (Yuan et al. 2011). Greater concentrations of aerosols can lead to smaller drop sizes which suppresses warm rain microphysical processes causing higher amounts of super cooled liquid droplets that promotes lightning charge induction (Fuchs et al. 2015). To account for the different background aerosol environments, this proposal will utilize aerosol optical depth (AOD) analysis fields from the NASA Goddard Earth Observing System (GEOS) and the Navy Aerosol Analysis and Prediction System (NAAPS) reanalysis. Both GEOS and NAAPS provide AOD estimates using input from satellite instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (Reale et al. 2014; Lynch et al. 2016). The datasets of AOD are broken up into relevant components from sea salt, sulfates, dust, and smoke aerosols.

As discussed in the previous section, this project will identify how lightning characteristics evolve and vary between developing and non-developing tropical cyclones. To distinguish between developing and non-developing tropical cyclones, we will use the operational invest dataset from the NHC. The NHC dataset includes position and maximum surface wind estimates for organized areas of deep convection that could develop into a tropical cyclone. The dataset of invests are subjectively defined by NHC forecasters, meaning that operational procedures may impact which systems get classified as invests. However, the benefit of using the operational invest archive is that the results are easier to transition to operational forecast tools, such as the tropical cyclone genesis index (TCGI) which uses the same dataset. Figure 3 shows the 6-hourly invest positions for developing and non-developing tropical cyclones within the NHC invest dataset from 2017-2021. There is a modest sample size of cases in the Atlantic and East Pacific basin from 2017-2021 within the GLM field of view (FOV) to perform the analysis. The dataset will be expanded each year with the observations from the most recent season to further improve the sample size.

2.2.3 Methodology to Meet Objectives

2.2.3.1 *Examine lightning attributes and trends prior to the formation of the low-level center*

The center of a tropical cyclone is critical for forecasters to identify in order to accurately predict its future track and because the strongest winds in a tropical cyclone are found there. The center of a developing tropical cyclone is not always easily identifiable as it can be obscured by upper-level cirrus clouds. In addition, multiple areas of low-level vorticity can be present and rotate around a broad mid-level vortex. Lightning can be used to identify areas of deep convection which are efficient at generating low-level vorticity. However, the application of lightning to tracking and identifying areas where the low-level center could form has yet to be completed.

The first component of this study will be a proof-of-concept evaluation of the lightning evolution observed by GLM and the ABI mesoscale sectors in the tropical disturbance that developed into Hurricane Ida (2021). Figure 4 shows a snapshot of the GLM observed lightning group areas and total group energy overlaid on ABI infrared imagery approximately 24 hours prior to the genesis of Hurricane Ida (2021). At 17Z on August 25, the lightning located further to the northeast of the center were high energy and covered a large area suggesting that the mesoscale convective system located there had a large stratiform component. The smaller clusters of thunderstorms to the south of the MCS had lower total group energy and lower areas indicating deep convection. Both areas of lightning are offset to the low-level center but suggests a continued development of both mid-level and low-level vorticity within the wave envelope and a potential for center relocation in the area where deeper convection is found. The low-level center of pregenesis Ida relocated to the Northeast in the following 6 hours which is evident in Fig. 4 and suggests that lightning could be a key variable in forecasting center-relocations.

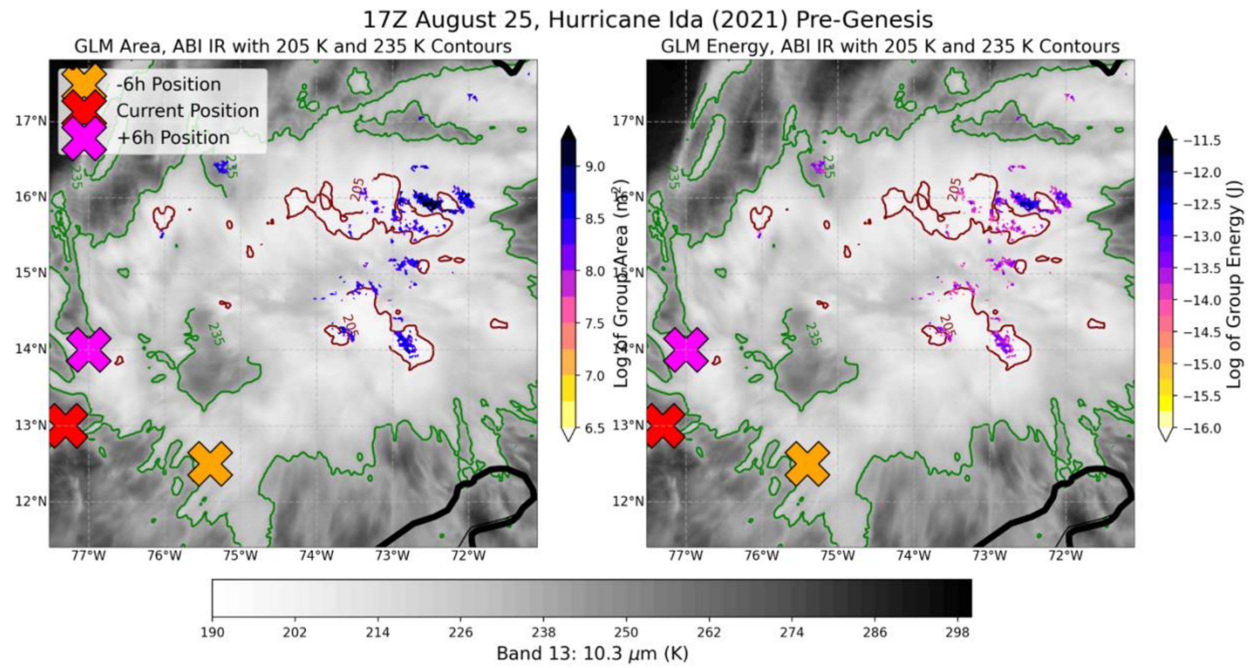

Figure 4: *GLM lightning group area (left) and group energy (right) are overlaid on ABI 10.3 μm imagery. Imagery is of the pre-genesis disturbance that formed Hurricane Ida (2021) at 17Z August 25. The green and maroon contours indicate where IR brightness temperatures are colder than 235 K and 205 K, respectively. The red 'X' shows the 18Z position of the invests low-level center. The orange 'X' is the previous 6-hour position, and the magenta 'X' is the position of the low-level center in the following 6 hours at 00Z August 26. The thick black line is the coastline boundary.*

Additional datasets, such as the analysis fields from GFS and GEOS/NAAPS, passive and active microwave imagery, and other available in-situ observations will be leveraged for the analysis of pregenesis Ida. Unfortunately, there were no P3 flights into Ida prior to genesis; however additional cases with ABI mesoscale coverage and available in-situ flight-level data from NOAA P3's will be sought.

Instead of compositing lightning and binning lightning by radii which has been done by previous studies, in this project we will take an object-based approach to examine how the characteristics of lightning change over convective to daily time scales. The Tracking and Object-Based Analysis of Clouds (TOBAC; Heikenfeld et al. 2019) framework will be leveraged. TOBAC is a flexible software that can be used with multiple gridded input datasets to analyze how specified variables characteristics evolve. The software includes feature detection with tunable thresholds at multiple levels, segmentation of identifiable features using watershedding techniques, and trajectory linking.

TOBAC will be employed in two ways within this study. TOBAC will be applied to ABI infrared imagery which will allow for the tracking of cloud clusters to identify how the cloud distribution changes. By first categorizing the cloud clusters, we can then aggregate the lightning data from GLM to examine how the lightning characteristics change as a function of the cloud tracking. This approach is similar to that employed by Schultz et al. (2009), which established the lightning jump algorithm for quantifying rapid growth of thunderstorms and their severe potential tracked by the Next Generation Weather Radars (NEXRADs). Because lightning is often episodic, only by tracking the cloud features from ABI can we quantify how the temporal fluctuations change within the cloud cluster lifetime. Stevenson et al. (2014) showed in a case study of Hurricane Earl that a 9-h duration outbreak of lightning was found associated withbtr a convective burst preceding rapid intensification of the vortex. Temporal variables such as the total duration of lightning, time between lightning flashes, and periodicity of lightning can be examined in this framework to contextualize how long-lived convective bursts may relate to changes in the pregenesis disturbance structure and intensity.

The second way TOBAC will be implemented is directly on the gridded lightning flash density. While lightning is episodic, the highest density lightning areas are likely associated with the strongest updrafts. By tracking the lightning clusters, we can identify and separate long-lived lightning outbreaks from transient small-scale lightning events. We hypothesize that long lived lightning outbreaks can be directly related to convective bursts and VHTs. It is likely that TOBAC will be sensitive to the temporal binning of lightning for use in the tracking algorithm, so the sensitivity of TOBAC to temporal bin length will be analyzed in the case study evaluation of Hurricane Ida before extending it to the larger sample of invests. However, TOBAC's tracking algorithm can account for missing timesteps and which will allow us to link lightning outbreaks with small temporal breaks in between.

The characteristics of the TOBAC identified lightning clusters and the evolution of lightning within cloud clusters will be examined in reference to the position of the 800-750 hPa vorticity maximum. As shown in Fig. 4., the low-level center can have large jumps in time while the 800-750 hPa vorticity maximum will be more consistent. A tilt vector, or vectors in case of multiple surface vorticity maxima, will be calculated which quantifies the displacement from the surface to mid-level vorticity maxima from the GFS analysis fields. We will evaluate how the spatial and temporal lightning distribution varies near to and along the tilt vector to determine how lightning can be used to forecast center reformations or center realignments.

2.2.3.2 Evaluate lightning characteristics and morphology as a discriminator for genesis

Very few studies have examined how lightning relates to tropical cyclogenesis and with mixed results owing to the study of different basins and lightning observing instruments (Leary and Ritchie 2009, Leppert et al. 2013). Here we will use the object-based techniques on the high resolution GLM data using TOBAC to examine whether lightning can be used as a discriminator for genesis. Wang (2018) found that the intensity, area, and asymmetry of IR brightness temperatures associated with deep convection could be used to differentiate disturbances that undergo genesis and suggests that the spatial attributes of lightning could also be significant. The methods here will closely follow the best practices found in examining Ida from Objective 1 discussed in 2.2.3.1.

First, tropical invests will be tracked using the operationally defined invests by the NHC in the Atlantic and East Pacific basins. The archive of pregenesis disturbances from the NHC includes both developing and non-developing disturbances from both tropical and subtropical origins. By using the NHC invest dataset, we can better align our results with operations because it is the same dataset that current operational genesis aids utilize; however, the dataset includes operational constraints and times prior to invest declaration could also be important. The locations of cloud clusters prior to invest declaration that originate from AEWs will be NHC will be incorporated using a wave tracking algorithm developed by Brammer and Thorncroft (2015). The algorithm features a logistic regression model that uses a combination of trough-centric variables to objectively define AEWs. The use of a consistent AEW dataset derived using this method will be utilized should inconsistencies with the NHC invest dataset arise.

Since both the NHC invest dataset and AEW dataset only define the center of the pregenesis, the Tracking Algorithm for Mesoscale Convective Systems (TAMS; Nunez et al. 2020a) technique will be used to identify MCS within the wave pouch and divide the cloud features associated with the disturbance and the larger-scale field. TAMS uses brightness temperature thresholds with forward and backwards trajectory calculations to identify MCS features. TAMS has already been applied to analyze a subset of AEWs in Nunez et al. (2020b) and will allow for the separation between MCS features and small-scale convective features. The lightning attributes can subsequently be examined within the context of the MCS evolution. The lightning features identified using TOBAC will be linked to parent MCS feature identified by TAMS using a time and distance weighting function along the tracks of each. Areas of lightning that do not overlap with an MCS will be classified as isolated convective burst.

It is important to contextualize the lightning within the different cloud types because of the relevant time scales that will be impacted. Lightning within transient small scale convective bursts may be more important for suggesting low-level spin up on short time scales, while MCS lightning might suggest maintenance and intensification of the mid-level vortex that will influence genesis on longer time scales. This breakdown using TAMS will allow us to further examine the relationship between lightning area and energy and the associated distribution of convective and stratiform clouds. In addition, the amount of lightning could be less significant for identifying future trends towards genesis if it is contained within multiple MCS rotating around the mid-level vortex compared to one dominant MCS feature.

An invest-relative lightning dataset will result from this project for developing and non-developing invests. The ABI and lightning data will have identification masks that classify each grid cell with coherent lightning outbreaks identified through TOBAC and the parent MCSs identified through TAMS. The dataset will be leveraged to evaluate the lightning characteristics and its morphology as a discriminator for genesis by breaking the sample into relevant groups.

2.2.3.3 Quantify the importance of lightning variability from the diurnal cycle on genesis timing.

The diurnal cycle of deep convection has been shown to be a consistent feature of tropical cyclones as evidenced by diurnal pulses found in the infrared brightness temperatures (Dunion et al. 2014, Ditchek et al. 2019, Trabing and Bell 2021). The diurnal cycle of deep convection has been found regardless of tropical cyclone intensity and is also pronounced in organized tropical convection (Gray and Jacobson 1977, Nesbitt and Zipser 2003). Stevenson et al. (2016) has already shown that lightning exhibits a diurnal cycle in TCs of both basins. It was found that lightning detected by the World Wide Lightning Location Network (WWLLN; Lay et al. 2004, Rodger et al. 2006) in eastern Pacific TCs peaks around 0800 LST and that lightning in the Atlantic peaks later around 0900–1100 LST.

Within easterly waves there is a favorable region for convective organization has been suggested based on "pouch" theory, where a Lagrangian closed circulation provides a protected area from some negative environmental conditions such as dry air entrainment (Dunkerton et al. 2009; Bell and Montgomery 2019). It is hypothesized that the diurnal cycle of deep convection and lightning will occur predominantly in favorable thermodynamic environments and that the occurrence of lightning at anomalous times relative to the diurnal cycle will be indicative of external forcing on developing tropical wave. This hypothesis will be tested using GLM observations within developing and non-developing tropical disturbances. First, a composite diurnal cycle of lightning will be calculated for all tropical invests in each basin. Tropical convection typically has an overnight to early morning maximum in lightning which has been observed by WWLLN. Because the GLM detects lightning optically, it has a higher detection efficiency around 90% at night compared to 70% during the day. The diurnal cycle of lightning observed by GLM is therefore expected to be slightly earlier than WWLLN caused by detection efficiency variations of the sensor.

After deriving a mean diurnal cycle of lightning, a smoothing function will be applied to reduce high amplitude noise. Then anomalies from the diurnal cycle of lightning will be calculated based on the local time of day. Data will subsequently be aggregated on daily time scales into four groups based on the amount of lightning and similarity to the diurnal cycle. The groups include where there was no lightning, where the diurnal cycle of lightning is similar to the climatological mean, where the diurnal cycle is dissimilar to the climatological mean but in phase, and where the diurnal cycle is dissimilar to the climatological mean but out of phase. By compositing each group, we can easily compare how the diurnal cycle of lightning relates to future tropical cyclogenesis. Because there is a potential for some long track invests to have repeated diurnal cycles of lightning prior to genesis or dissipation, this analysis will be repeated but normalized by the time until genesis.

Next, we will identify the physical mechanisms that contribute to the variations in the diurnal cycle of lightning. It is hypothesized that variations in the environmental thermodynamics, vertical wind shear, and aerosol fields will contribute to anomalous amounts of lightning within developing tropical cyclones. Jenkins et al. (2008) documented enhanced lightning production in the TC outer rainbands with a Saharan air layer (SAL) in the vicinity and attributed this to small aerosols acting as ice nuclei. Stevenson et al. (2016) and DeMaria et al. (2012) have found additional variations in the lightning amounts associated with SST and vertical wind shear. Composites of the environmental variables derived from GFS and GEOS/NAAPS around the mid-level vortex center will be conducted to evaluate how the environment may influence the amount of lightning over the diurnal cycle.

2.2.4 Risk Reduction

Since GLM16 does not extend east of 20W within the tropics, there will be several times where lightning trends will not be fully evaluated. Observations near the limb of GLM are also more prone to artifacts which could limit the sample size of genesis events that form just west of Africa.

Should additional samples be needed, observations from the WWLLN will be leveraged to supplement GLM observations. While WWLLN does not provide energy/area characteristics of lightning flashes, Fierro et al. (2018) noted that WWLLN observations in Hurricane Maria were similar to what was shown by GLM.

The GLM dataset currently extends backwards to 2017, although the quality of data in 2017 is degraded compared to the latest output with newer QC algorithms. The PI has already developed a QC algorithm that objectively removes artifacts in the GLM domain associated with sun glint, bar features, and blooming events by examining the variance of the lightning energy and area. Similar QC algorithms could be employed here to improve confidence in the results. The examination of lightning during the diurnal cycle will be complicated by the day-night detection efficiency differences of GLM. Observations from WWLLN will be used to improve confidence in the results.

The TOBAC framework has already been shown to be applicable to ABI imagery; however, additional clustering methods such as density-based spatial clustering of applications with noise (DBSCAN; Liu et al. 2011) algorithms for lightning observation and the TAMS for the tropical disturbance areas could also be leveraged with some modifications. Each of these approaches will be compared within Ida prior to genesis.

2.3 Work Plan

2.3.1 Milestones

Year 1

- Assemble ABI, GLM, GFS and GEOS/NAAPS analysis fields, and tropical cyclogenesis database
- Calculate derived variables including vortex tilt from gridded datasets
- Identify additional case studies of tropical cyclogenesis observed with the ABI mesoscale sectors
- Test and optimize the TOBAC feature identification and tracking algorithm
- Test and compare TOBAC and TAMS feature identification with density-based clustering technique
- Examine the spatial and temporal evolution of lightning during the genesis of Hurricane Ida and/or additional cases focused on the ABI mesoscale sector

Year 2

- Create dataset of lightning features using TOBAC and TAMS within NHC invest dataset
- Compare lightning feature characteristics in developing and non-developing tropical disturbances
- Prepare manuscript on the lightning evolution during the genesis of Hurricane Ida and/or other cases using ABI mesoscale sector
- Compare lightning characteristics in developing tropical disturbances accounting for the thermodynamic and kinematic environmental variables
- Make visuals of derived lightning variables overlaid with ABI imagery for real-time display

Year 3

- Update ABI and GLM database with observations from 2024 hurricane season
- Prepare manuscript on the temporal, spatial, and feature attributes of GLM lightning clusters during tropical cyclogenesis
- Quantify the mean diurnal cycle of GLM observations in tropical disturbances
- Compare tropical disturbances that have similar and dissimilar lightning evolutions compared to the mean diurnal cycle
- Prepare manuscript on the use of the diurnal cycle of lightning in identifying developing and non-developing tropical disturbances

2.3.2 Management Structure

The team assembled for this project have expertise on tropical cyclones, tropical cyclone genesis, the tropical cyclone diurnal cycle, and the interplay of tropical cyclones with lightning observations. The team members have ongoing research to better understand the multi-scale processes that lead to tropical cyclone genesis, to implement new techniques to improve tropical cyclone genesis forecasts, and to relate lightning with tropical cyclone structure to improve intensity change forecasts. The responsibilities of the team members include but are not limited to the following.

Principal Investigator Benjamin Trabing will provide expertise in tropical cyclone structure, TC lightning observations, and the TC diurnal cycle. Benjamin will lead the establishment of a coherent lightning dataset within tropical disturbances. Benjamin will co-mentor a graduate research assistant in conducting the analysis of GLM lightning features in tropical disturbances.

Co-Investigator Alan Brammer will provide expertise in tropical cyclone genesis and statistical techniques. Alan is the focal point for the development of a new ensemble genesis index based on global ensembles and will provide feedback for the incorporation of lightning into genesis prediction models. Alan will update the NHC invest dataset used in this project each year and implement the tropical wave detection algorithm.

Co-Investigator Michael Bell is an expert in tropical cyclone observations and theory. Michael will provide support for understanding the physical mechanisms that lightning signals in tropical cyclogenesis. Michael will co-mentor a graduate research assistant in conducting the analysis of GLM lightning features in tropical disturbances.

Collaborator Patrick Duran is an expert in tropical cyclone observations. Patrick has ongoing work evaluating GLM characteristics and its relationship to tropical cyclone intensity change. Patrick will provide insight into relevant GLM quality control techniques and provide support for GLM observational analysis.

Collaborator Justin Whitaker is an expert on TC genesis. Justin will provide guidance on tropical wave tracking and assist in the establishment of an Atlantic invest dataset. Justin will also assist in the interpretation of the lightning evolution in tropical disturbances.

Collaborator Stephanie Stevenson is an expert on TC lightning, structure, and intensity change. Stephanie will provide guidance on the use of GLM observations at the NHC and provide feedback and support on the future inclusion of lightning variables into AWIPS.

2.4 Data Sharing Plan

We will adhere to the NOAA Data Publication and Sharing Directive, making our data discoverable and accessible to the general public in a timely fashion. CIRA facilities provide the computer and network infrastructure required to comply with these requirements. Our Data Management Plan is provided in Section 4.

3. REFERENCES

Abarca, S. F., K. L. Corbosiero, and D. Vollaro, 2011: The World Wide Lightning Location Network and convective activity in tropical cyclones. *Mon. Wea. Rev.*, **139**, 175–191.

Bell, M.M., and M.T. Montgomery, 2019: Mesoscale processes during the genesis of Hurricane Karl (2010), *J. Atmos. Sci.*, **76**, 2235-2255.

Bhatia, K.T., Vecchi, G.A., Knutson, T.R. and Coauthors, 2019: Author Correction: Recent increases in tropical cyclone intensification rates. *Nat Commun.* **10**, 979.

Brammer, A., and C. D. Thorncroft, 2015: Variability and Evolution of African Easterly Wave Structures and Their Relationship with Tropical Cyclogenesis over the Eastern Atlantic, *Mon. Wea. Rev*., ***143***(12), 4975-4995.

Bruning, E. C., and D. R. MacGorman, 2013: Theory and observations of controls on lightning flash size spectra. *J. Atmos. Sci.*, **70**(12), 4012–4029.

Chen, X., Y. Wang, J. Fang, and M. Xue, 2018: A numerical study on rapid intensification of Typhoon Vicente (2012) in the South China Sea. Part II: Roles of inner-core processes. *J. Atmos. Sci.*, **75**, 235–255.

DeMaria, M., R. T. DeMaria, J. A. Knaff, and D. Molenar, 2012: Tropical cyclone lightning and rapid intensity change. *Mon. Wea. Rev.*, **140**, 1828–1842.

Ditchek, S. D., K. L. Corbosiero, R. G. Fovell, and J. Molinari, 2019: Electrically active tropical cyclone diurnal pulses in the Atlantic basin. *Mon. Wea. Rev.*, **147**, 3595–3607.

Dunion, J. P., C. D. Thorncroft, and C. S. Velden, 2014: The tropical cyclone diurnal cycle of mature hurricanes. *Mon. Wea. Rev.*, **142**, 3900–3919.

Dunkerton, T. J., Montgomery, M. T., and Wang, Z. 2009: Tropical cyclogenesis in a tropical wave critical layer: easterly waves, *Atmos. Chem. Phys.*, **9**, 5587–5646.

Duran, P., Schultz, C. J., and Coauthors, 2021: The evolution of lightning flash density, flash size, and flash energy during Hurricane Dorian's (2019) intensification and weakening. *Geophys. Res. Lett.*, **48**, e2020GL092067.

Fierro, A. O., S. N. Stevenson, and R. M. Rabin, 2018: Evolution of GLM-observed total lightning in Hurricane Maria (2017) during the period of maximum intensity. *Mon. Wea. Rev.*, **146**, 1641–1666.

Fuchs, B. R., Rutledge, and Coauthors, 2015: Environmental controls on storm intensity and charge structure in multiple regions of the continental United States. *J. Geophys. Res. Atmos.*, **120**, 6575– 6596.

Gall, R., J. Franklin, F. Marks, E. N. Rappaport, and F. Toepfer, 2013: The hurricane forecast improvement project. *Bull. Amer. Meteor. Soc*., **94**, 329–343.

Goodman, S. J., and Coauthors, 2013: The GOES-R Geostationary Lightning Mapper (GLM). *Atmos. Res.*, **125-126**, 34–49.

Gopalakrishnan, S. and Coauthors, 2020: 2020 HFIP R&D Activities Summary: Recent Results and Operational Implementation, HFIP Technical Report: HFIP2021-1, 49 pg.

Gray, W. M., and R. W. Jacobson Jr., 1977: Diurnal variation of deep cumulus convection. *Mon. Wea. Rev.*, **105**, 1171–1188.

Heikenfeld, M., Marinescu, P. J., Christensen, M., Watson-Parris, D., Senf, F., van den Heever, S. C., and Stier, P. 2019: tobac 1.2: towards a flexible framework for tracking and analysis of clouds in diverse datasets, *Geosci. Model Dev.*, **12**, 4551–4570.

Hopsch, S. B., Thorncroft, C. D., and Tyle, K. R., 2010: Analysis of African Easterly Wave Structures and Their Role in Influencing Tropical Cyclogenesis, *Mon. Wea, Rev., **138***(4), 1399-1419.

Houze, R. A., Jr., 1982: Cloud clusters and large-scale vertical motions in the tropics. *J. Meteor. Soc. Japan,* **60**, 396-410.

Houze, R. A., Jr., W.-C. Lee, and M. M. Bell, 2009: Convective contribution to the genesis of Hurricane Ophelia (2005). *Mon. Wea. Rev.*, **137**, 2778–2800.

Houze, R. A., Jr., 2010: Clouds in Tropical Cyclones, *Mon. Wea. Rev*., **138**(2), 293-344.

Jenkins, G. S., A. S. Pratt, and A. Heymsfield, 2008: Possible linkages between Saharan dust and tropical cyclone rain band invigoration in the eastern Atlantic during NAMMA-06. *Geophys. Res. Lett.*, **35**, L08815.

Jiang, H., and E. M. Ramirez, 2013: Necessary conditions for tropical cyclone rapid intensification as derived from 11 years of TRMM data. *J. Climate*, **26**, 6459–6470.

Jones, S. C., 1995: The evolution of vortices in vertical shear. I: Initially barotropic vortices. *Quart. J. Roy. Meteor. Soc*., **121**, 821–851.

Kucienska, B., G. B. Raga, and R. Romero-Centeno, 2012: High lightning activity in maritime clouds near Mexico. *Atmos. Chem. Phys.*, **12**, 8055–8072.

Latto, A. S. and R. Berg, National Hurricane Center Tropical Cyclone Report: Hurricane Nicholas, NOAA/National Hurricane Center, 2022.

Lay, E. H., R. H. Holzworth, C. J. Rodger, J. N. Thomas, O. Pinto Jr., and R. L. Dowden, 2004: WWLL global lightning detection system: Regional validation study in Brazil. *Geophys. Res. Lett.*, **31**, L03102.

Leary, L. A., and Ritchie, E. A., 2009: Lightning Flash Rates as an Indicator of Tropical Cyclone Genesis in the Eastern North Pacific, *Mon. Wea. Rev*., ***137***(10), 3456-3470.

Leppert, K. D., Cecil, D., and W. Petersen, 2013: Relation between tropical easterly waves, convection, and tropical cyclogenesis: A Lagrangian perspective. *Mon. Wea. Rev.*, **141**(8), 2649–2668.

Liu, L.X., Song, J.T., Guan, B., Wu, Z.X., He, K.J., 2011: Tra-DBScan: An Algorithm of Clustering Trajectories. *AMM* 121–126, 4875–4879.

Lynch, P. and Coauthors, 2016: An 11-year global gridded aerosol optical thickness reanalysis (v1.0) for atmospheric and climate sciences. *Geosci. Model Dev.*, **9**, 1489–1522.

Molinari, J., P. Moore, and V. Idone, 1999: Convective structure of hurricanes as revealed by lightning locations. *Mon. Wea. Rev.*, **127**, 520–534.

Molinari, J., P. Dodge, D. Vollaro, K. L. Corbosiero, and F. Marks, 2006: Mesoscale aspects of the downshear reformation of a tropical cyclone. *J. Atmos. Sci.*, **63**, 341–354.

Nam, C. C., and M. M. Bell, 2021: Multi-scale shear impacts during the genesis of Hagupit (2008). *Mon. Wea. Rev*., **149**, 551-569.

Nesbitt, S. W., and E. J. Zipser, 2003: The Diurnal Cycle of Rainfall and Convective Intensity according to Three Years of TRMM Measurements, *J. Climate*, **16**, 1456-1475.

NOAA National Centers for Environmental Information (NCEI), 2020: U.S. Billion-Dollar Weather and Climate Disasters, DOI: 10.25921/stkw-7w73

Núñez Ocasio, K., Evans, J. L., and G S. Young, 2020a: Tracking mesoscale convective systems that are potential candidates for tropical cyclogenesis. Mon. *Wea. Rev.*, **148**(2):655 – 669.

Núñez Ocasio, K., Evans, J. L., and G S. Young, 2020b. A wave-relative framework analysis of aew–mcs interactions leading to tropical cyclogenesis. *Mon. Wea. Rev*., **148**(11):4657 – 4671.

Rappaport, E. N., and Coauthors, 2009: Advances and challenges at the National Hurricane Center. *Wea. Forecasting*, **24**, 395–419.

Reale, O., K. M. Lau, A. da Silva, and T. Matsui, 2014: Impact of assimilated and interactive aerosol on tropical cyclogenesis. *Geophys. Res. Lett.*, **41**, 3282–3288.

Rios-Berrios, R., and R. D. Torn, 2017: Climatological analysis of tropical cyclone intensity changes under moderate vertical wind shear. *Mon. Wea. Rev.*, **145**, 1717–1738.

Rios-Berrios, R., Davis, C. A., and R. D. Torn, 2018: A hypothesis for the intensification of tropical cyclones under moderate vertical wind shear. J. Atmos. Sci., 75, 4149-4173.

Rodger, C. J., S. Werner, J. B. Brundell, E. H. Lay, N. R. Thomson, R. H. Holzworth, and R. L. Dowden, 2006: Detection efficiency of the VLF World-Wide Lightning Locations Network (WWLLN): Initial case study. *Ann. Geophys.*, **24**, 3197–3214.

Rudlosky, S. D., S. J. Goodman, K. S. Virts, and E. C. Bruning, 2019: Initial Geostationary Lightning Mapper observations. *Geophys. Res. Lett.*, **46**, 1097–1104.

Schultz, C. J., W. A. Petersen, and L. D. Carey, 2009: Preliminary Development and Evaluation of Lightning Jump Algorithms for the Real-Time Detection of Severe Weather, J. *of Applied Meteor. and Clim.* **48**, 12: 2543-2563.

Squires, K., and S. Businger, 2008: The morphology of eyewall lightning outbreaks in two category 5 hurricanes. *Mon. Wea. Rev.*, **136**, 1706–1726.

Stevenson, S. N., K. L. Corbosiero, and J. Molinari, 2014: The convective evolution and rapid intensification of Hurricane Earl (2010). *Mon. Wea. Rev.*, **142**, 4364–4380.

Stevenson, S. N., K. L. Corbosiero, and S. F. Abarca, 2016: Lightning in eastern North Pacific tropical cyclones: A comparison to the North Atlantic. *Mon. Wea. Rev.*, **144**, 225–239.

Stevenson, S. N., K. L. Corbosiero, M. DeMaria, and J. L. Vigh, 2018: A 10-year survey of tropical cyclone inner-core lightning bursts and their relationship to intensity change. *Wea. Forecasting*, **33**, 23–36.

Tang, B. H., and Co-authors, 2020: Recent advances in research on tropical cyclogenesis. *Tropical Cyclone Research and Review,* **9,** 87-105.

Trabing, B. C., and M. M. Bell, 2021: Observations of Diurnal Variability under the Cirrus Canopy of Typhoon Kong-rey (2018). *Mon. Wea. Rev.* **149**, 2945–2964.

Van Sang, N., R. K. Smith, and M. T. Montgomery, 2008: Tropical- cyclone intensification and predictability in three dimensions. *Quart. J. Roy. Meteor. Soc.*, **134**, 563–582.

Wang, Z., 2018: What is the key feature of convection leading up to tropical cyclone formation? *J. Atmos. Sci.* **75**, 1609e1629.

Wilheit, T. T., 1986: Some comments on passive microwave measurement of rain. *Bull. Amer. Meteor. Soc.*, **67**, 1226–1232.

Xu, W., S. A. Rutledge, and W. Zhang, 2017: Relationships between total lightning, deep convection, and tropical cyclone intensity change. *J. Geophys. Res. Atmos.*, **122**, 7047–7063.

Yuan, T., L. A. Remer, K. E. Pickering, and H. Yu, 2011: Observational evidence of aerosol enhancement of lightning activity and convective invigoration. *Geophys. Res. Lett.*, **38**, L04701.

Zawislak, J., 2020: Global Survey of Precipitation Properties Observed during Tropical Cyclogenesis and Their Differences Compared to Nondeveloping Disturbances, *Mon. Wea. Rev*., **148**(4), 1585-1606.

Zhang, W., Y. Zhang, D. Zheng, F. Wang, and L. Xu, 2015: Relationship between lightning activity and tropical cyclone intensity over the northwest Pacific. *J. Geophys. Res. Atmos*., **120**, 4072–4089.

4. DATA MANAGEMENT PLAN

The proposed research will generate the following output:

1. GLM and ABI dataset centered on tropical cyclone invests

    An archive of Geostationary Lightning Mapper (GLM) flash data and select bands from the Advanced Baseline Imager (ABI) centered on pre-genesis tropical disturbances will be created. The gridded dataset will have feature attributes of lightning contained within masks as well as appropriate metadata. Files will be created for each tropical invest in a compressed netCDF format. File sizes will range based on the duration of the tropical invest from <100 MB to 12 GB.

2. GLM imagery overlays on ABI for tropical cyclone invests

    An archive of GLM flash data imagery centered on tropical cyclones invests will be created. Relevant lightning variables will be overlaid on imagery from the ABI to give context to the lightning location in the developing tropical cyclone. The imagery will be hosted in GIF format and is expected to use approximately 10 MB/day per storm. Real-time generation of invest-centered GLM imagery will be made available starting in 2024.

The real-time and archived imagery created in this project will be displayed on the Regional and Mesoscale Meteorology Branch (RAMMB) TC Real-Time website (http://rammb-data.cira.colostate.edu/tc_realtime/) beginning at the end of Year 2 with an appropriate description of the imagery and information on the location of the original data sources. The TC-Realtime website is publicly available. The extended dataset of lightning variables within pre-genesis disturbance will also be made available to the public on the RAMMB website with appropriate metadata following the 2024 hurricane season. Results that utilize the data from this project will be published in the open literature.

Point of Contact for this Data Management Plan
This data management plan is authored by Benjamin Trabing, Research Scientist I and Principal Investigator.
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5. BIOGRAPHICAL SKETCHES

Dr. Benjamin C. Trabing (Principal Investigator)

Relevant Skills and Experience

Dr. Trabing provides expertise in tropical cyclone (TC) structure, TC lightning observations, and the diurnal cycle. His relevant area of interests includes TC predictability, statistical modeling, and TC intensity change. Dr. Trabing has ongoing work evaluating how large-scale environmental factors affect the amount of lightning in TCs.

Education

Ph.D.	Atmospheric Science	Colorado State University	2020
M.S.	Atmospheric Science	Colorado State University	2018
B.S.	Meteorology	University of Oklahoma	2016

Professional Development

2022 –	Research Scientist I	CIRA, Fort Collins, CO
2020 – 2022	Research Associate II	CIRA, Miami, FL
2016 – 2020	Graduate Research Assistant	CSU, Fort Collins, CO
2015 – 2016	NOAA Hollings Intern	CIRA, Fort Collins, CO
2014 – 2016	Undergraduate Research Assistant	OU, Norman, OK

Select Publications

Trabing, B. C., K. Musgrave, M. DeMaria, and E. Blake, 2022: A Simple Bias and Uncertainty Scheme for Tropical Cyclone Intensity Change Forecasts. *Wea. Forecasting.* in press, https://doi.org/10.1175/WAF-D-22-0074.1

Trabing, B. C. and M. M. Bell, 2021: Observations of Diurnal Variability under the Cirrus Canopy of Typhoon Kong-rey (2018). *Mon. Wea. Rev.* 149, 2945–2964, https://doi.org/10.1175/MWR-D-20-0327.1

Trabing, B. C. and M. M. Bell, 2021: The Sensitivity of Eyewall Replacement Cycles to Shortwave Radiation. *J. Geophys. Res: Atmospheres*, 126, e2020JD034016. https://doi.org/10.1029/2020JD034016

Sobal, A. H., Sprintall, J., Maloney, E. D., Martin, Z. K., Wang, S., deSzoeke, S., **Trabing, B. C.** and S. A. Rutledge, 2021: Large-scale state and evolution of the atmosphere and ocean during PISTON 2018. *J. Climate.*, 34, 5017–5035, https://doi.org/10.1175/JCLI-D- 20-0517.1

Trabing, B. C. and M. M. Bell, 2020: Understanding Error Distributions of Hurricane Intensity Forecasts During Rapid Intensity Changes. *Wea. Forecasting* 35, 2219–2234. https://doi.org/10.1175/WAF-D-19-0253.1

Trabing, B. C., M. M. Bell, and B. R. Brown, 2019: Impacts of Radiation and Upper-Tropospheric Temperatures on Tropical Cyclone Structure and Intensity. *J. Atmos. Sci.*, 76, 135–153. https://doi.org/10.1175/JAS-D-18-0165.1

Trabing, B. C., J. A. Knaff, and K. Musgrave, 2016: Analysis of Hurricanes Using Long-Range Lightning Detection Networks. *Commons@SHAREOK*(Published online at https://hdl.handle.net/11244.46/70)

<u>Dr. Alan Brammer (Co-Investigator)</u>

<u>Relevant Skills and Experience</u>

Dr. Brammer is a researcher in the Tropical Cyclone group at CIRA - CSU, working on ensemble based probabilistic guidance for Tropical cyclone forecasts, software development and maintenance of new and existing tropical cyclone guidance tools as well as facilitating the transition of new research software to operations.

<u>Education</u>

Ph.D.	Atmospheric Science	University of Albany, NY	2015
B.S.	Earth System Science	University of Leeds, UK	2010

<u>Professional Development</u>

2019 –	Research Scientist III	CIRA, Fort Collins, CO
2018 – 2019	Atmospheric Data Scientist	Climacell, Boston, MA
2016 – 2018	Postdoctoral Fellow	University of Albany, NY

<u>Field Campaign</u>

2022	Mission Scientist for CPEX-CV	NASA

<u>Select Publications</u>

Schenkel, B.A., D. Chavas, N. Lin, T. Knutson, G. Vecchi, and **A. Brammer**, 2022: North Atlantic Tropical Cyclone Outer Size and Structure Remain Unchanged by the late 21st Century, *J. Climate*, in press., https://doi.org/10.1175/JCLI-D-22-0066.1.

Núñez Ocasio, K.M, **A. Brammer**, J.L. Evans, G. S. Young, and Z. L. Moon, 2021: Favorable Monsoon Environment over Eastern Africa for Subsequent Tropical Cyclogenesis of African Easterly Waves. J. *Atmos. Sci.* **78**, 2911-2925, https://doi.org/10.1175/JAS-D-20-0339.1

Brammer, A., C.D. Thorncroft and J.P. Dunion, 2018: Observations and Predictability of a NonDeveloping Tropical Disturbance over the Eastern Atlantic, *Mon. Wea. Rev.* **146**, 3079-3096, https://doi.org/10.1175/MWR-D-18-0065.1

Schenkel, B.A., Lin, N., Chavas, D., Vecchi A., Oppenheimer, M., and **A. Brammer**, 2018: Lifetime Evolution of Outer Tropical Cyclone Size. *J. Climate,* **31**, 7985-8004, https://doi.org/10.1175/JCLI-D-17-0630.1

Brammer, A. and C.D. Thorncroft, 2017: Spatial and temporal variability of the three-dimensional flow around African Easterly Waves. *Mon. Wea. Rev.* **145,** 2879-2895, https://doi.org/10.1175/MWR-D-16-0454.1

Brammer, A., and C. D. Thorncroft, 2015: Variability and Evolution of African Easterly Wave Structures and Their Relationship with Tropical Cyclogenesis over the Eastern Atlantic, *Mon. Wea. Rev*., ***143***(12), 4975-4995, https://doi.org/10.1175/MWR-D-15-0106.1

<u>Dr. Michael Bell (Co-Investigator)</u>

<u>Professional Experience</u>

Colorado State University – Fort Collins, Colorado

Professor	2021 – Present
Associate Professor	2016 – 2020

University of Hawai'i at Mānoa – Honolulu, Hawai'i

Assistant Professor	2012 – 2016

Naval Postgraduate School – Monterey, California

Research Assistant Professor	2010 – 2012
Research Associate	2007 – 2010

National Center for Atmospheric Research – Boulder, Colorado

Associate Scientist	2001 – 2011

<u>Education</u>

2010 Ph. D. in Meteorology, Naval Postgraduate School.
2006 M.S. in Atmospheric Science, Colorado State University.
2001 B.S. in Applied Mathematics, Minor in Meteorology, Metropolitan State College of Denver.
1996 B.A. in Religion, University of Florida.

<u>Honors and Awards</u>

- 2017, Presidential Early Career Award for Scientists and Engineers (PECASE), President Obama and White House Office of Science and Technology Policy, Fort Collins, CO
- 2015, Young Investigator Program Award, Office of Naval Research, Honolulu, Hawaii
- 2014, NSF CAREER Award, National Science Foundation, Honolulu, Hawaii

<u>Select Publications</u> **(**Research group members are highlighted by *)

Martinez*, J., C. A. Davis, and **M. M. Bell**, 2022: Eyewall Asymmetries and Their Contributions to the Intensification of an Idealized Tropical Cyclone Translating in Uniform Flow. *J. Atmos. Sci., in press*.

Tao, D., P. J. van Leeuwen, **M. M. Bell**, and Y. Ying, 2022: Dynamics and predictability of tropical cyclone rapid intensification in ensemble simulations of Hurricane Patricia (2015). *J. Geophys. Res. Atmos.*, **127**.

DesRosiers*, A., **M. M. Bell**, and T.-Y. Cha*, 2022: Vertical vortex development of Hurricane Michael (2018) during Rapid Intensification. *Mon. Wea. Rev.*, **150**, *99-114*.

Boehm*, A. M., and **M. M. Bell**, 2021: Retrieved Thermodynamic Structure of Hurricane Rita (2005) from Airborne Multi-Doppler Radar Data. *J. Atmos. Sci.,***78**, *1583-1605*.

Martinez*, J. M., C.-H. Nam*, and **M. M. Bell**, 2020: On the contributions of incipient vortex circulation and environmental moisture to tropical cyclone expansion. *J. Geophys. Res. Atmos., 125*.

Cha*, T.-Y., **M. M. Bell**, W.-C. Lee, and A. DesRosier*, 2020: Polygonal eyewall asymmetries during the rapid intensification of Hurricane Michael (2018). *Geophys. Res. Letters, 47*.

Bell, M. M., and M. T. Montgomery, 2019: Mesoscale Processes During the Genesis of Hurricane Karl (2010). *J. Atmos. Sci.*, ***76***, *2235–2255*.

Feng,* Y.-C., and **Bell, M. M**, 2018: "Microphysical characteristics of an asymmetric eyewall in major Hurricane Harvey (2017)". *Geophys. Res. Lett.*

6. TABLE OF PERSONNEL AND WORK EFFORT

TABLE OF WORK EFFORT

Name	Role	Commitment (months per year)											
		Year 1			*Year 2*			*Year 3*			*Sum*		
		This Project		*Other Funded Projects*	*This Project*		*Other Funded Projects*	*This Project*		*Other Funded Projects*	*This Project*		*Other Funded Projects*
Name	**Role**	*NASA Sup-port*	*Total*		*NASA Support*	*Total*		*NASA Support*	*Total*		*NASA Support*	*Total*	
Benjamin Trabing	PI	3	3	1	3	3	0	3	3	0	9	9	1
Alan Brammer	Co-I	.75	.75	.3	.75	.75	0	.75	.75	0	2.25	2.25	.3
Michael Bell	Co-I	1	1	1.75	1	1	1.25	1	1	.25	3	3	3.25
TBD GRA		6.75	6.75	0	6.75	6.75	0	6.75	6.75	0	20.25	20.25	0
Patrick Duran*	Collaborator	N/A			N/A			N/A			N/A	N/A	
Justin Whitaker*	Collaborator	N/A			N/A			N/A			N/A	N/A	
Stephanie Stevenson*	Collaborator	N/A			N/A			N/A			N/A	N/A	
Sum of work effort:		**11.50**	**11.50**	**3.05**	**11.50**	**11.50**	**1.25**	**11.50**	**11.50**	**.25**	**34.50**	**34.50**	**4.55**

Comments: (*) Collaborator is critical to the proposal, but does not have any funded work effort through this proposal. Their contributions are expected to be de minimis.

7. CURRENT AND PENDING SUPPORT

Dr. Benjamin Trabing (Principal Investigator)

Current

Title: CIRA Support for Tropical Cyclone Model and Product Development (HFIP)
Role: Research Scientist
Source of Support: NOAA
Total Award Period Covered: 7/1/2022 - 6/30/2023
Person-Months Per Year Committed to the Project: 5.88

Title: CIRA Support to NOAA ROSES--Forecast Apps
Role: Research Scientist
Source of Support: NOAA
Total Award Period Covered: 9/1/2022 - 8/31/2023
Person-Months Per Year Committed to the Project: 4.0

Title: Extending the Tropical Cyclone Genesis Index to Global Ensemble Forecasts
Role: Research Scientist
Source of Support: NOAA
Total Award Period Covered: 9/1/2020 - 8/31/2023 (1st year NCE)
Person-Months Per Year Committed to the Project:1.0

Title: Unification and Improvements to Guidance for National Weather Service Tropical Cyclone Wind and Storm Surge Hazard Products
Role: Research Scientist
Source of Support: NOAA
Total Award Period Covered: 8/1/2021 - 7/31/2023
Person-Months Per Year Committed to the Project: 1.0

Dr. Alan Brammer (Co-Investigator)

Current

Title: CIRA Support for Tropical Cyclone Model and Product Development (HFIP)
Role: Research Scientist
Source of Support: NOAA
Total Award Period Covered: 7/1/2022 - 6/30/2023
Person-Months Per Year Committed to the Project: 5.88

Title: Accelerate Improvements in National Hurricane Center Forecast Techniques - Statistical Techniques and Advanced Model Diagnostic Tools
Role: Research Scientist
Source of Support: NOAA
Total Award Period Covered: 9/1/2022 - 8/31/2023
Person-Months Per Year Committed to the Project: 0.50

Title: Extending the Tropical Cyclone Genesis Index to Global Ensemble Forecasts
Role: PI
Source of Support: NOAA
Total Award Period Covered: 9/1/2020 - 8/31/2023 (1st year NCE)
Person-Months Per Year Committed to the Project: 2.0

Title: Unification and Improvements to Guidance for National Weather Service Tropical Cyclone Wind and Storm Surge Hazard Products
Role: Research Scientist
Source of Support: NOAA
Total Award Period Covered: 8/1/2021 - 7/31/2023
Person-Months Per Year Committed to the Project: 1.0

Title: CIRA Support to NOAA ROSES--ProxyVis
Role: Research Scientist
Source of Support: NOAA
Total Award Period Covered: 9/1/2022 - 8/31/2023
Person-Months Per Year Committed to the Project: 1.00

Title: Research and Applications Development for Situational Awareness in Theater (RAD-SAT)
Role: Research Scientist
Source of Support: DOD NRL
Total Award Period Covered:1/1/2021 - 12/31/2023
Person-Months Per Year Committed to the Project: 0.50

Title: Using Aircraft and Satellite Observations to Characterize African Easterly Wave Variability and Environmental Factors Associated with Downstream Tropical Cyclogenesis
Role: PI
Source of Support: NASA
Total Award Period Covered: 4/13/2020 - 4/12/2023
Person-Months Per Year Committed to the Project: 1.00

Dr. Michael Bell (Co-Investigator)

Current
Title: CIF: A Sea-Going and Land Deployable Polarimetric (SEA-POL) Radar for the Science Community
Role: PI
Source of Support: National Science Foundation
Total Award Period Covered: 08/2021-07/2026
Person-Months Per Year Committed to the Project: 0.75 PM/YR

Title: Collaborative Research: ELEMENTS: The LROSE Science Gateway LIDAR/RADAR Analysis in the Cloud
Role: Co-PI
Source of Support: National Science Foundation
Total Award Period Covered: 08/2021-07/2024
Person-Months Per Year Committed to the Project: 0.25 PM/YR

Title: Heating, Cooling, and Rapid Intensity Change in Tropical Cyclones
Role: PI
Source of Support: Office of Naval Research
Total Award Period Covered: 12/2019-12/2022
Person-Months Per Year Committed to the Project: 1 PM/YR

Title: Collaborative Research: Dynamics, Thermodynamics, and Microphysics of Extreme Rainfall observed during PRECIP
Role: PI
Source of Support: National Science Foundation
Total Award Period Covered: 06/2019-05/2023
Person-Months Per Year Committed to the Project: 1.0 PM/YR

Title: Forecaster Support Products for Analysis of Tropical Cyclone Intensity and Structure from Aircraft Reconnaissance Observations
Role: PI
Source of Support: National Oceanic and Atmospheric Administration
Total Award Period Covered: 08/2022-07/2025
Person-Months Per Year Committed to the Project: 1.0 PM/YR

Title: Micro and Macrophysics of Tropical Cyclone Intensification
Role: PI
Source of Support: Office of Naval Research
Total Award Period Covered: 09/2022-08/2023
Person-Months Per Year Committed to the Project: 4.5 PM/YR (Sabbatical)

Pending
Title: Airborne Phased Array Radar (APAR) Mid-scale Research Infrastructure
Role: Co-I

Source of Support: NCAR (NSF prime)
Total Award Period Covered: 08/2020-07/2025
Person-Months Per Year Committed to the Project: 0.25 PM/YR

Title: AGS-FIRP Track 3: Snow Sensitivity to Clouds in a Mountain Environment (S2noCLIME) Field Campaign
Role: Co-PI
Source of Support: U. Michigan (NSF Prime)
Total Award Period Covered: 05/2023-04/2026
Person-Months Per Year Committed to the Project: 0.25 PM/YR

8. STATEMENTS OF COMMITMENT AND LETTERS OF SUPPORT

Memo For Acknowledgement of Federal Collaboration

DATE: October 11, 2022
MEMORANDUM FOR: NASA ROSES Competition Manager
FROM: Dr. Stephanie Stevenson, Science and Operations Officer (acting), NOAA/NWS/NCEP/NHC
SUBJECT: Federal Collaboration on 2022 NASA ROSES solicitation NNH22ZDA001N: A.33 Earth Science Research from Operational Geostationary Satellite Systems

NOAA/NWS/NCEP/National Hurricane Center acknowledges federal collaboration with the Principal Investigator(s) listed below on the development of the proposal listed below. The applicants have sufficiently coordinated the development of this proposal, including any relevant infrastructure costs and/or plans for proposed testbed activities.

Principal Investigator(s): Benjamin Trabing (CIRA/CSU)
Co-Principal Investigators: Alan Brammer (CIRA/CSU) and Michael Bell (CSU)
Proposal Title: Investigating the Convective Morphology and Diurnal Cycle in Pre-genesis Disturbances Using Object-Based Analysis of Geostationary Satellite Observations

Our role in this collaborative project will include (check all that apply):
_X_ Providing (unfunded) research and development support
___ Providing equipment, office space, or computer access to non-federal PIs
_X_ Providing operational guidance to support the eventual transition of this project
___ Coordinating NOAA Testbed activities for this project
___ Other: ____

Any additional information, comments, or concerns about federal collaboration on this proposal are listed below:

The objective of this proposal is to use the Geostationary Lightning Mapper (GLM) and the Advanced Baseline Imager (ABI) from GOES-16/17/18 to examine the evolution and organization of convective processes that leads to tropical cyclogenesis, which remains a significant forecast challenge. The National Hurricane Center (NHC) supports the proposal listed above. The mission of the NHC is "to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts and analyses of hazardous tropical weather [...]" (Hurricanes.gov). The proposed work is in support of this mission and approved by NHC.

Stephanie Stevenson
____
Signature

Stephanie Stevenson, Ph.D.
Science and Operations Officer (acting)
Technology and Science Branch, National Hurricane Center

9. BUDGET JUSTIFICATION: NARRATIVE AND DETAILS

Proposal Title:
Investigating the Convective Morphology and Diurnal Cycle in Pre-genesis Disturbances using Object-Based Analysis of Geostationary Satellite Observations Period of Performance:
7/1/2023 – 6/30/2026
PI:
Benjamin Trabing, CSU/CIRA

	7/1/2023 - 6/30/2024			7/1/2024 - 6/30/2025			7/1/2025 - 6/30/2026			Total
DOMESTIC TRAVEL:			**5,268**			**5,603.00**			**4,917.00**	**15,788.00**
INTERNATIONAL TRAVEL:			-			-			-	-
MATERIALS AND SUPPLIES			**1,000**			**1,000**			**1,000**	**3,000**
OTHER DIRECT COSTS										
In-State Tuition:	-	-	**16,594**	-	-	**17,922**	-	-	**19,356**	**53,872**
Publications:			-			**3,100**			**3,100**	**6,200**
Equipment Use Fees:			-			-			-	-
Consultants:			-			-			-	-
Other:	235.00	3.7500	**881.00**	235.00	3.7500	**881.00**	235.00	3.7500	**881.00**	**2,643.00**
	48.00	7.7500	**372.00**	49.00	7.7500	**380.00**	50.00	7.7500	**388.00**	**1,140.00**
TOTAL OTHER DIRECT:			**17,847.00**			**22,283.00**			**23,725.00**	**63,855.00**
SUBCONTRACTS: <$25,000			-			-			-	-
>$25,000			-			-			-	-
EQUIPMENT:			-			-			-	-
TOTAL DIRECT COSTS:			**24,115.00**			**28,886.00**			**29,642.00**	**82,643.00**

I. DOMESTIC TRAVEL

The PI of this project requests funding for the following trips:

1. One trip annually to attend NASA Geostationary REsearch and Application Team (GREAT) meeting for collaboration with the scientific community and to share research results
   a. Year 1: Hampton, VA ($2,254)
   b. Year 2: Mountain View, CA ($2,783)
   c. Year 3: Huntsville, AL ($2,462)
2. One trip annually to attend AMS Annual to disseminate research results and collaborate with the tropical cyclone scientific community. Though AMS Annual is nominally budgeted, a similar conference may be substituted if deemed more appropriate as the project progresses (for example, travel can be assigned to a NASA project meeting if required).
   a. Year 1: Baltimore, MD ($3,014)
   b. Year 2: New Orleans, LA ($2,820)
   c. Year 3: Houston, TX ($2,455)

Per diem rates for all trips are applied to the destination location as listed in the CSU per diem/city publication. Standard mileage distances and rates are used for transportation to and from the airport (DIA) from Fort Collins. Airfares are obtained from state approved travel agencies. Standard mileage costs to Denver International Airport (DIA) and back is 150 miles at $0.53/mile. Average parking cost at DIA is $14/day. Roundtrip toll way is $19/trip.

II. OTHER

1. The CIRA infrastructure charge provides for high-end computing capacity such as high speed network and associated equipment including 10G firewall, router, multiple subnets, DNS, DHCP, switches, and central computer rooms. The rate is determined by CIRA, applied to all Fort Collins, CO users and correlates to the actual effort above at a rate of $235 per person month.
2. ATS Network Use: In order to perform the proposed research, it is necessary to use the Atmospheric Science Ethernet to connect to the Internet (this is a specialized network used by employees). The Department charges a fee for such connections. The Computer Service charge rate is developed using Section 200.468 (Specialized Service Facilities) of the OMB Uniform Guidance and Colorado State University's internal policy for computing, charging and auditing such Service Facilities. The estimated rate for CUS's FY24 is $48 per person month and is subject to an annual 3% inflation factor.
3. Tuition: Funding is requested to pay 2 semesters of tuition for the graduate student per year. The anticipated tuition rate is $7,017. Each additional year includes an 8% inflation factor
4. Publication: This proposal requests funds to publish the results of this research in years 2 and 3. Standard AMS page charges are $120 per page (15 pages) plus a $1,300 open choice fee.

III. MATERIALS AND SUPPLIES

Funds are requested ($1,000 per year) for miscellaneous computer repair, necessary computer upgrades and data storage over the course of the project. The estimate of these costs is based on past program expenditures.