ABSTRACT

Project Title: Understanding the Mechanisms Leading to Early Warning of Meteorological and Hydrological Drought in the U.S. Caribbean
Competition Name: Characterizing and Anticipating U.S. Droughts' Complex Interactions
Introduction and Rationale: In groundwater-limited settings, such as the U.S. Caribbean, societal, ecological, and agricultural water needs are largely supplied by regular rainfall. Consequently, these islands, Puerto Rico and the U.S. Virgin Islands, are vulnerable to even short, rapid-onset, dry spells, known as "flash drought," and drought early warning is immensely valuable for civil authorities on the islands. In the wake of the 2015 drought, precipitation deficits were linked to the early arrival of an elevated hot, dry, dust-laden feature, termed the Saharan air layer (SAL). The SAL increased static stability, largely suppressing convective precipitation during a typically rainy time of year. The SAL is a precursor of Caribbean drought.
Summary: This project will first examine and diagnose drought through a suite of hydrometeorological variables, drought indices, and drought definitions, such as the Palmer Drought Severity Index, Standardized Precipitation Evaporation Index, etc. Episodes of low drought metrics will be compared to in-situ hydrologic measurements, such as USDA Soil Climate Analysis Network data, in the U.S. Caribbean to infer their ability to capture flash drought onset. Next, concurrent meteorological fields from renanalysis products will be examined during the flash drought periods to identify the local meteorological conditions driving flash drought and how these differ from conventional drought. Third, drought frequency will be characterized as a function of SAL activity over the U.S. Caribbean. Self-organizing maps, a machine learning technique, will mine historical 2D fields of the Galvez-Davison Index, a recently developed tool well-suited for detecting SAL outbreaks, to determine common historical SAL behavior during the hydrologically critical early rainfall season in the U.S. Caribbean. Teleconnection indices and seasonal numerical weather forecasts will be analyzed for their ability to provide early warning of SAL, and therefore drought, in the U.S. Caribbean.
Broader Impacts: This project provides critical monitoring and drought early warning improvements in U.S. Caribbean islands with limited water resources for human populations, unique drought-vulnerable ecosystems, and a recent history of economic hardship and natural hazards, including a major drought in 2015. The project includes a co-PI located in the region, and one of the objectives of this project is to actively engage with local stakeholders who have recently asked for improved drought information. This project will serve a large population that is an ethnic and linguistic minority in the U.S., and the project will actively recruit and mentor students who are under-represented in climate science.
Relevance: This project is relevant by engaging Priority Area C by examining the predictability of U.S. droughts, as well as their multi-scale evolution. Seasonal model forecasts are mined for the presence of a precursor mechanism that can inform contextualized forecasts of drought likelihood and severity. The project establishes a new methodology for prediction by identifying the flash drought indices which correspond most strongly to parameters that can be derived from existing seasonal forecast models. On a broader, programmatic level, this project advances the MAPP primary objective #3 to improve methodologies for global to regional scale analysis, predictions, and projections.

RESULTS FROM PRIOR RESEARCH

Understanding Ecosystem Change in Northeastern Puerto Rico, National Science Foundation, González (Co-PI) and Mote (Senior Personnel). During the fifth and sixth rounds of funding (LUQ V, 2012–2018; LUQ VI, 2018–2024) for the Luquillo PR Long-term Ecological Research (LTER) site, we compiled mean annual precipitation locations for 100+ rain gages in the Luquillo Mountains and surrounding area, spanning more than 100 years (Murphy et al. 2017), and we examined how droughts and hurricanes affect tropical forest ecosystems. During LUQ V, we captured the impact of the 2015 drought, a year with only 50% of long-term average rainfall. We studied the influence of large-scale climate drivers on precipitation variability at LUQ (Van Beusekom et al. 2017, Murphy et al. 2017, Mote et al. 2017). Ramseyer and Mote (2016, 2018) showed that high wind shear environments are associated with the driest regimes in eastern Puerto Rico, indicating these variables are the most useful for downscaling studies of local climate, which is ongoing in LUQ VI. We showed that April – July is responsible for ~60% of the inter-annual variability in rainfall in Puerto Rico (Miller et al. 2019b) and is most susceptible to factors causing drought. We showed that the 2015 drought was likely caused by earlier than usual intrusions of hot, dry, dust-laden air arriving from Africa (Mote et al. 2017). Moreover, African dust inputs, which reduced irradiance levels, combined with drought to affect tree seedling performance. Strong effects of the 2015 drought on species-specific patterns of seedling mortality were recorded (Uriarte et al. 2018); the drought increased soil O_2 availability, lowered soil P availability, and increased soil C emissions (O'Connell et al. 2018). We also explored changes in cloud base height, a critical attribute of LUQ potentially linked to canopy heights and growth rates (González et al. 2013). Changes in cloud base height were associated with large-scale changes, unrelated to local effects (Van Beusekom et al. 2017, Miller et al. 2018). All data are publicly available in the LUQ LTER Data Catalog, and results are shared through numerous education and outreach activities and through the peer-reviewed literature.

Persistent Hydrological Consequences of Hurricane Interactions with the Georgia Coastline, NOAA Sea Grant, Miller (PI) and Mote (Co-PI). During a one-year project funded in the wake of Hurricane Irma, we conducted a series of observational and modeling analyses of post-hurricane hydrometeorology within afflicted landfall zones. Remotely sensed vegetation indices from post-Hurricane Maria in Puerto Rico established a "worst-case scenario" for the defoliation and deforestation that could be expected following a strong hurricane landfall. Thus, this storm and location served as the archetype for the hurricane-landscape-hydrology nexus. During the defoliated period following Maria, cloud cover and precipitation was anomalously correlated to the thermodynamic profile of the atmosphere, suggesting the absence of dense surface vegetation removed a confounding physical factor and allowed primarily atmospheric processes to dominate post-hurricane hydrometeorology (Miller et al. 2019a). Additionally, modeled surface and subsurface runoff was anomalously high once standardized for incident precipitation, implying the absence of forest canopy interception allowed more efficient precipitation transmission to the terrestrial stream network (Miller et al. 2019a). Lastly, a numerical weather model initialized over coastal Georgia with Maria-scale defoliation resolved a net reduction in post-landfall precipitation for the one-month period selected for the simulation (Miller et al. 2019b). No new datasets were produced, but the results are made available to the public through outreach activities and to other scientists through the peer-reviewed literature.

PROJECT NARRATIVE

0. List of Abbreviations

CFSR	Climate Forecast System Reanalysis
DEWS	Drought Early Warning System
EDDI	Evaporative Drought Demand Index
ENSO	El Niño - Southern Oscillation
ERS	Early Rainfall Season
ESR	Evaporative Stress Ratio
GDI	Galvez-Davison Index
GHCN	Global Historical Climate Network
GLDAS	Global Land Data Assimilation System
IITF	International Institute for Tropical Forestry
ITCZ	Intertropical Convergence Zone
LRS	Late Rainfall Season
LTER	Long-Term Ecological Research
LUQ	Luquillo, PR
MJO	Madden-Julian Oscillation
MSD	Mid-Summer Drought
NAD	North African Dipole
NADP	National Atmospheric Deposition Program
NAO	North Atlantic Oscillation
NCEI	National Centers for Environmental Information
NDMC	National Drought Mitigation Center
NIDIS	National Integrated Drought Information System
PDSI	Palmer Drought Severity Index
PR	Puerto Rico
RCI	Rapid Change Index
SAL	Saharan Air Layer
SCAN	Soil Climate Analysis Network
scPDSI	Self-Calibrating Palmer Drought Severity Index
SOM	Self Organizing Map
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SST	Sea Surface Temperature
TWI	Trade Wind Inversion
USDM	U.S. Drought Monitor
USVI	U.S. Virgin Islands

1. Introduction and Objectives

1.1. Identification of the Problem

In groundwater-limited settings, such as Puerto Rico (PR) and the U.S. Virgin Islands (USVI), societal, ecological, and agricultural water needs are largely supplied by regular rainfall. Because these islands are located in the tropical Atlantic, where evaporation normally exceeds precipitation, and the geology of the islands provides few potable groundwater or surface water resources, their population depends on regular rainfall for water supplies. Consequently, these islands are particularly vulnerable to drought, including short, rapid-onset dry-spells. A rapid onset to drought, known as flash drought, presents unique challenges for drought forecasting (e.g., Svoboda et al. 2002; Otkin et al. 2018). During the 2015 Caribbean drought, the effects of the rapid onset and slow recovery were evident in the tropical rainforests that serve as the headwaters of rivers that provide drinking water for much of San Juan and eastern PR (e.g., O'Connell et al. 2018). Anticipating the length and frequency of the dry spells prior to their onset is immensely valuable for civil authorities on the islands. In the wake of the 2015 Caribbean drought, precipitation deficits were linked to the early arrival of an elevated hot, dry, dust-laden feature, termed the Saharan air layer (SAL) (Mote et al. 2017). The SAL increased static stability over the U.S. Caribbean largely suppressing convective precipitation during a typically rainy time of year, a process potentially mediated by other low-frequency modes of variation in atmospheric circulation and sea surface temperatures (SSTs). **This project will create a multi-product assessment of drought, including flash drought, and then evaluate climate mechanisms, with a focus on the role of the SAL, that are critical in improving drought early warning in the U.S. Caribbean.**

1.2. Background

1.2.1. Drought in the U.S. Caribbean. The U.S. Caribbean (PR and USVI), including the San Juan metropolitan area, suffered a major drought in 2015 that caused severe water shortages and water rationing for hundreds of thousands of residents. Only three of the 77 municipalities in PR were not included in the drought at the peak of the event in August 2015, and the island experienced its first "extreme drought" recorded by the Drought Monitor (NDMC 2019). The percentage of the island classified as "moderate to severe drought" reached nearly 45% of the island, while more than 20% had moved into the more intense rating of "extreme drought" by early August (Fig. 1). Agricultural sector losses exceeded $12 million by early August and cost the Puerto Rico Aqueduct and Sewer Authority as much as $15 million

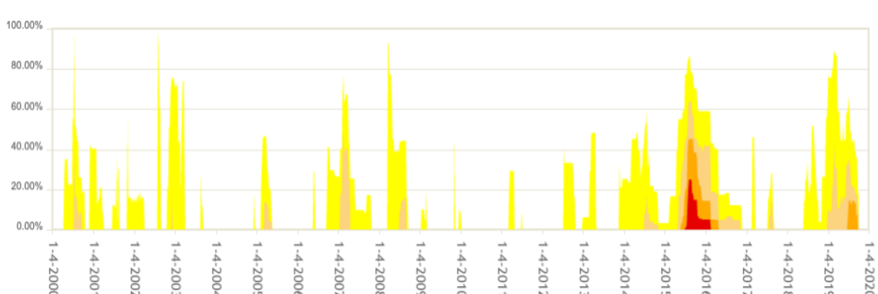

Fig. 1. *Percent areas of PR in D0 (yellow), D1 (tan), D2 (orange), and D3 (red), and D4 (brown) from the U.S. Drought Monitor.*

a month (USDA 2015), exacerbating ongoing economic hardship on the island for more than a decade.

Streamflow reached record lows at or below 3% of their historic average flows for major rivers in PR, (USDA 2015, Fig. 2), and key reservoirs registered at or below levels from previous droughts (USGS 2019). On the Rio de La Plata, discharge fell below the 10th percentile for almost the entire April-July period (Fig. 2). Rainfall in parts of PR was more than one-half meter below normal over the first half of 2015 (NOAA 2015). Portions of the U.S. Caribbean have limited perennial streams and rivers, and those rivers require precipitation and sustained wet periods to maintain flow.

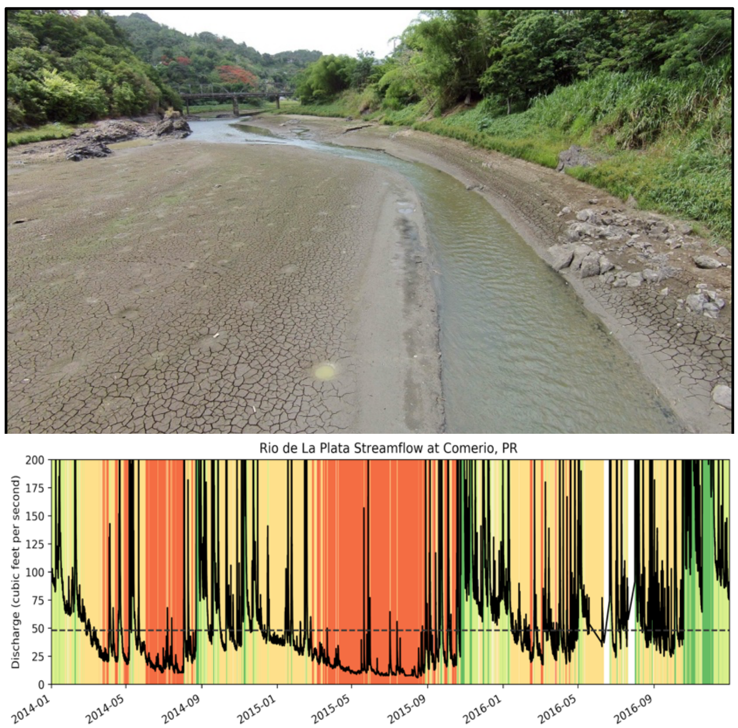

Fig. 2. *(top) Rio de La Plata near Naranjito, PR, on 1 July 2015 (AP). (bottom) Streamflow data from the Rio de La Plata at Comerio, PR, for 2014–2016 showing the instantaneous discharge (solid) and 2000–2016 median discharge (dashed). The orange shading indicates observations that were in the climatological 10th percentile or lower (data source: USGS).*

The 2015 drought was most severe over the most densely populated and biologically diverse region of eastern PR, which contains both San Juan metropolitan area of 2.35 million people, representing more than two-thirds of the island residents, as well as the El Yunque National Forest, the only tropical rainforest in the U.S. National Forest system. In this setting of high biodiversity, droughts have widespread and lasting impacts on unique and critical ecosystems (Beard et al. 2005; Covich et al. 2003; Heartsill-Scalley et al. 2007), being related with tree mortality and its direct stress on tropical ecosystems fluxes (Anderegg et al. 2016).

However, the 2015 drought was not an isolated event. Other major droughts affected the U.S. Caribbean in 1966–68, 1971–74, 1976–77, and 1993–95 (Larsen 2000), with drought being recorded somewhere in PR every 10 years (Scatena 1995). From 1981 to 2018, there were 50% more dry periods than wet periods in PR, with extremely dry conditions being registered in both 1986 and 1994 (Hernández Ayala and Heslar 2019). Anecdotally, flash drought events occur even more frequently, but have not been documented.

Even on these Caribbean islands with high average annual rainfall and extensive tropical rainforests, drought remains a common feature of the climate system.

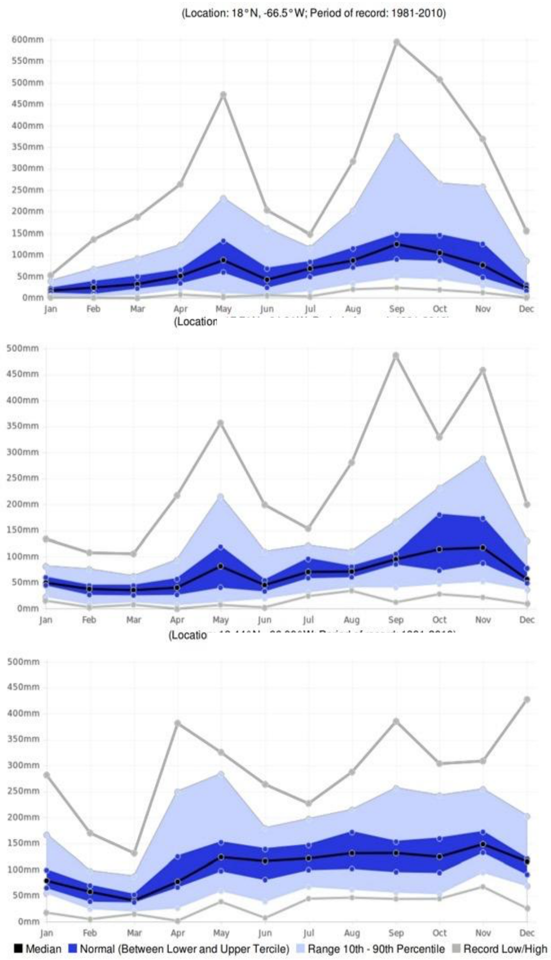

Fig. 3. *Median and record monthly rainfall (1981–2010) for St. Croix, USVI (top), Ponce, PR (middle), and San Juan, PR (bottom) from the Caribbean Institute for Meteorology and Hydrology archive.*

1.2.2. Seasonal precipitation climate in the U.S. Caribbean. Regardless of the various climate mechanisms influencing rainfall in the U.S. Caribbean, there are common seasonal precipitation patterns that present themselves in the region. Fig. 3 shows the boreal winter (Dec-Mar) as the period when the absolute minimum amount of precipitation occurs, referred to as the dry season, and a relative minimum occurs annually during the summer (mid-June-July) and is known as midsummer drought (MSD) (Giannini et al. 2001a; Jury et al. 2007). The short dry period in mid-June-July separates the rainy seasons in the Caribbean into an early rainfall season (ERS, April – July) and a late rainfall season (LRS, August–November) (Angeles et al. 2010; Taylor et al. 2002).

The seasonality of Caribbean precipitation is driven by its latitudinal position, and the resulting atmospheric dynamics of the region. The insular Caribbean is located between the latitudes of 10-25°N, centered between the North Atlantic subtropical high and the Intertropical Convergence Zone (ITCZ). The presence of this subtropical high maintains an easterly trade wind regime over the U.S. Caribbean, while the movement of the ITCZ also govern the precipitation distribution (Granger 1985) (Fig. 4). A recent study suggested that the western flank of the North Atlantic subtropical high, the Eastern Pacific ITCZ, and the Atlantic ITCZ are the three primary drivers promoting moisture convergence during the two rainy seasons: the early rainfall season (April-July; ERS) and the late rainfall season (August-November; LRS) (Martinez et al. 2019). This bi-modal structure of Caribbean precipitation is still not well understood (Gamble and Curtis 2008). The two maxima are separated by what has been termed the mid-summer drought (MSD) (Magaña et al. 1999), the source of which is an active area of inquiry. Conceptually, as the North Atlantic high pressure strengthens and expands during the summer, enhancing subsidence in the Caribbean (Giannini et al. 2000), the Caribbean Low-Level Jet simultaneously intensifies (Herrera et al. 2015). The Caribbean Low-Level Jet is associated with a decrease in SST and a westward shift of low-level moisture convergence (away from the insular Caribbean), which combined with the subsidence from the North Atlantic high pressure result in the MSD (Herrera et al. 2015). Additionally, other physical factors such as strong vertical wind shear and surface divergence decrease precipitation likelihood in the U.S. Caribbean (Giannini et al. 2000; Gamble and Curtis 2008; Angeles et al. 2010; Gamble 2014).

1.2.3. Climate mechanisms influencing rainfall in the U.S. Caribbean. Low-frequency modes of atmospheric circulation and SSTs, which can be represented as teleconnections, play an important role in U.S. Caribbean rainfall. Among these teleconnections are the El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), which is described as a large-scale seesaw in atmospheric mass between North Atlantic regions of the subtropical high and the subpolar low (Charlery et al. 2006; Lamb and Peppler 1987). Ropelewski and Halpert (1987) affirmed that during El Niño years, the Caribbean tends to be slightly drier than normal. More specifically, ENSO warm phases are associated with drought in Central America and parts of the Caribbean during July to October (e.g., Ropelewski and Halpert, 1987). The NAO index is negative correlated with precipitation anomalies, a relationship strongest for the southeast Caribbean/Lesser Antilles (e.g., Giannini et al. 2000; Giannini et al., 2001a; Giannini et al. 2001b; Jury et al. 2007). Additionally, several studies have noted the SST influence on Caribbean rainfall (Wu and Kirtman 2011; Jury and Gouirand 2011; Gouirand et al. 2012). Glenn et al. (2015) found higher SSTs in the Atlantic Warm Pool are associated with increased rainfall during the LRS, while Taylor et al. (2011) demonstrated the role of a SST-driven geopotential gradient between the eastern tropical Pacific and tropical North Atlantic on Caribbean rainfall. Interannual SST variability in the tropical North Atlantic, within the main development region for tropical waves, is correlated with Caribbean rainfall, but the influence declines in the LRS (Taylor et al. 2002). Gamble (2014) noted that ENSO events are associated with decreased late summer and fall precipitation due to lower hurricane frequency (e.g., Ropelewski and Halpert, 1987; Patricola et al., 2016). However, Torres-Valcárcel (2018) determined that ENSO alone does not significantly affect PR precipitation and was not the cause of local drought for the past 114 years.

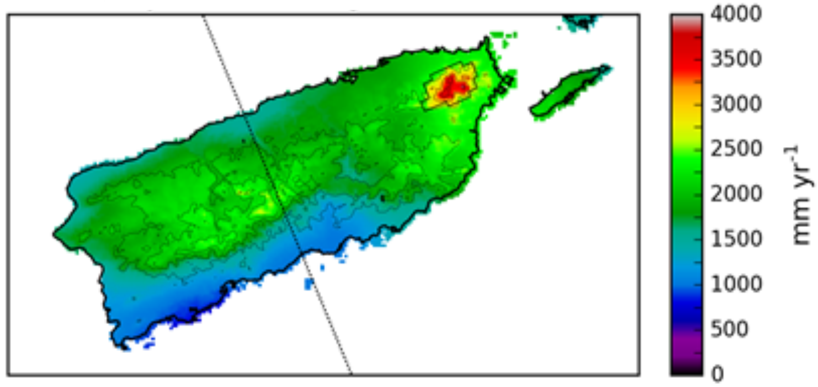

Fig. 4. *Puerto Rico 30-year annual average rainfall (1985–2014) from Mote et al. (2017). Average annual precipitation ranges from less than 1000 mm on the southern coastal plain to greater than 3500 mm in the mountains. The dashed line corresponds to 66.5°W.*

In addition to the large-scale teleconnection pattern associated with drought in the U.S. Caribbean, the region's high annual precipitation is directly contingent on the regular occurrence of deep moist convection. Though mesoscale convective systems contribute the majority of precipitation across the world's tropics, uniquely within the U.S. Caribbean, isolated convective cells contribute a much larger proportion of the annual precipitation total (Nesbitt et al. 2006) (Fig. 5). Thus, annual precipitation totals in the region are dependent on both the regular occurrence of large convective clusters, as well as the cumulative activity of smaller, isolated cells. Both of these convective modes are strongly regulated by the near-storm convective environment, which can either favor or discourage the transition from shallow, non- or lightly precipitating convection to deep moist convection as well as the upscale growth of deep moist convection to larger clusters once this transition occurs.

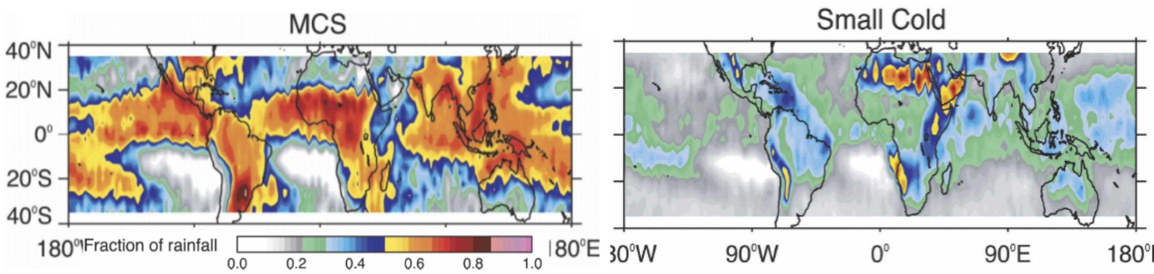

Fig. 5. Fraction of total annual rainfall contributed by (left) MCS versus (right) isolated events (Nesbitt et al. 2006).

One such mechanism that profoundly modifies the near-storm convective environment in the U.S. Caribbean is the SAL. During the historic 2015 Caribbean drought, the SAL dramatically and persistently deteriorated thunderstorm environments over PR, serving as the primary drought-causing mechanism (Mote et al. 2017). The SAL physically discourages the transition from shallow to deep convection by serving as a strong stabilizing layer (Dunion and Velden 2004). Occupying the altitude between 600 and 800 hPa, the SAL transports westward much of the 800 Tg yr^{-1} of mineral dust emitted over North Africa annually (Huneeus et al. 2011) via large outbreaks from mid-June to late July often visible in satellite images (Prospero and Mayol-Bracero 2013) (e.g., Fig. 6). Soundings during SAL events are 50–60% drier than a typical moist tropical sounding between 700 and 500 hPa and have ~20% less total precipitable water (Dunion 2011). Because the SAL is composed of hot, dry air from Saharan Africa, it is often warmer than the surfaced-based parcels that have adiabatically cooled during their ascent toward the SAL. Thus, nascent updrafts encounter a strongly stable layer, which limits cloud vertical extent and warm rainfall processes. Additionally, the dry SAL air, when entrained into the updrafts, further stabilizes the

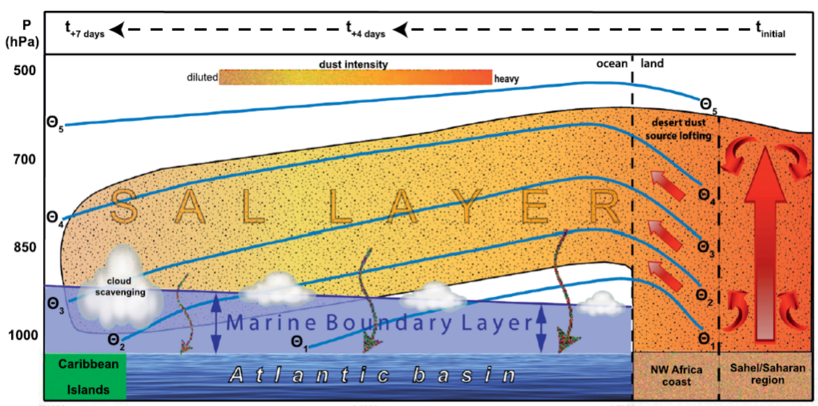

Fig. 7. Vertical profile of SAL air mass transported westward from its Saharan source region. The color shading represents the transition from coarse, large dust particles (red) to finer more diffuse particles (yellow), while the vertical brown arrows depict settling. Potential temperature contours are in blue, and the marine boundary layer is shown sloping from east to west from Kuciauskas et al. (2018).

parcel by evaporatively cooling any cloud water (Powell 1990).

Further, SAL dust aerosols can inhibit convective cloud development and rainfall via microphysical processes (e.g., Dagan et al. 2015a,b; Dagan and Chemke 2016) while enhancing the trade wind inversion (TWI) thereby limiting rainfall through thermodynamic and radiative effects (Rosenfeld et al. 2001) (Fig. 7). Dark aerosols absorb incoming solar radiation and further warm the SAL, while the abundance of particulate matter in this layer modifies the microphysical behavior of shallow convection penetrating the SAL by providing more nucleation opportunities for cloud droplet formation. In some settings, the abundance of nuclei can be detrimental to cloud and precipitation processes by preventing cloud droplets from growing to precipitation-efficient radii (Rosenfeld and Gutman 1994) and enhancing hydrometeor evaporation rates. Angeles et al. (2010) demonstrated the role of the Saharan aerosols and associated changes in vertical wind shear on the mid-summer dry period. Particle concentrations have also been linked to summer rainfall reductions during at multiple Caribbean locations (Fig. 8) (Hosannah et al. 2019).

Recent research has determined that SAL-driven summer dust intrusions toward the U.S. Caribbean are occurring increasingly earlier in the year (Zuidema et al. 2019). This is particularly problematic for the U.S. Caribbean as Miller et al. (2019c) documented that ERS precipitation accounts for a majority of the variance in annual precipitation. Thus, earlier dust intrusions into the U.S. Caribbean, as was the case in 2015, could lead to more frequent occurrences of drought in the region.

1.3. Scientific Objectives

This project will advance our understanding of how climate affects drought processes in the U.S. Caribbean, including an integrated examination of relevant processes that are unique to this region. The scientific objectives from this project draw upon recent work by the USGS National Climate Adaptation Science Centers and the USDA Caribbean Climate Hub that addressed drought-related research needs in the U.S. Caribbean. The two centers conducted a series of workshops with regional stakeholders and in 2018 identified four key research needs for understanding drought in this region[1]. (González participated in a workshop hosted at IITF). Two of the four research needs are

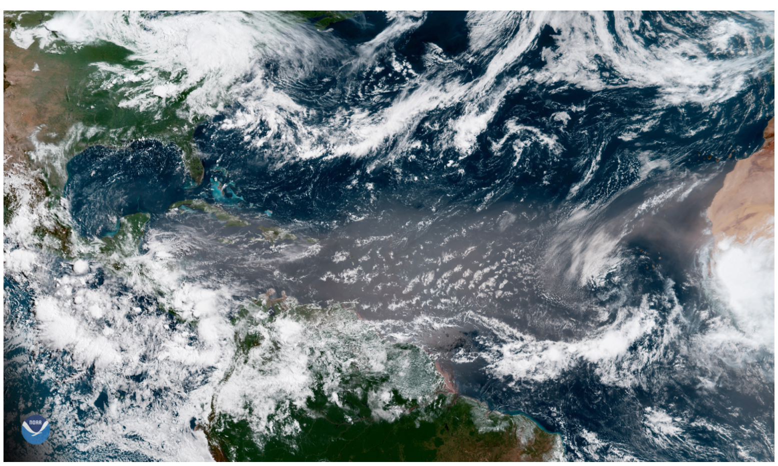

Fig. 6. *GOES 16 GeoColor enhanced imagery of Saharan dust transported across the tropical North Atlantic to the U.S. Caribbean on 27 Jun 2018 (NOAA Environmental Visualization Laboratory).*

[1]https://www.usgs.gov/land-resources/climate-adaptation-science-centers/drought-impacts-freshwater-ecosystems-us-caribbean

directly addressed by this proposed project: (1) improved long-term monitoring in the U.S. Caribbean, including monitoring before and after drought events, and (2) more accurate projections of drought conditions for the region to support planning and the development of management strategies. Specifically, this effort will address the following key scientific objectives:

- *Characterize meteorological drought, including flash drought, and long-term hydrologic drought; create a series of analogs of antecedent and concurrent atmospheric drivers associated with drought in the U.S. Caribbean.*
- *Characterize historical SAL pathways and the relationship to U.S. Caribbean drought and relate SAL intensity to atmospheric and oceanic teleconnections.*
- *Identify the association of prototypical SAL events with drought occurrence in the U.S. Caribbean and the limits of their predictability using teleconnection indices and numerical weather models.*
- *Engage with regional stakeholders in the U.S. Caribbean to understand local relevant drought metrics and disseminate findings.*

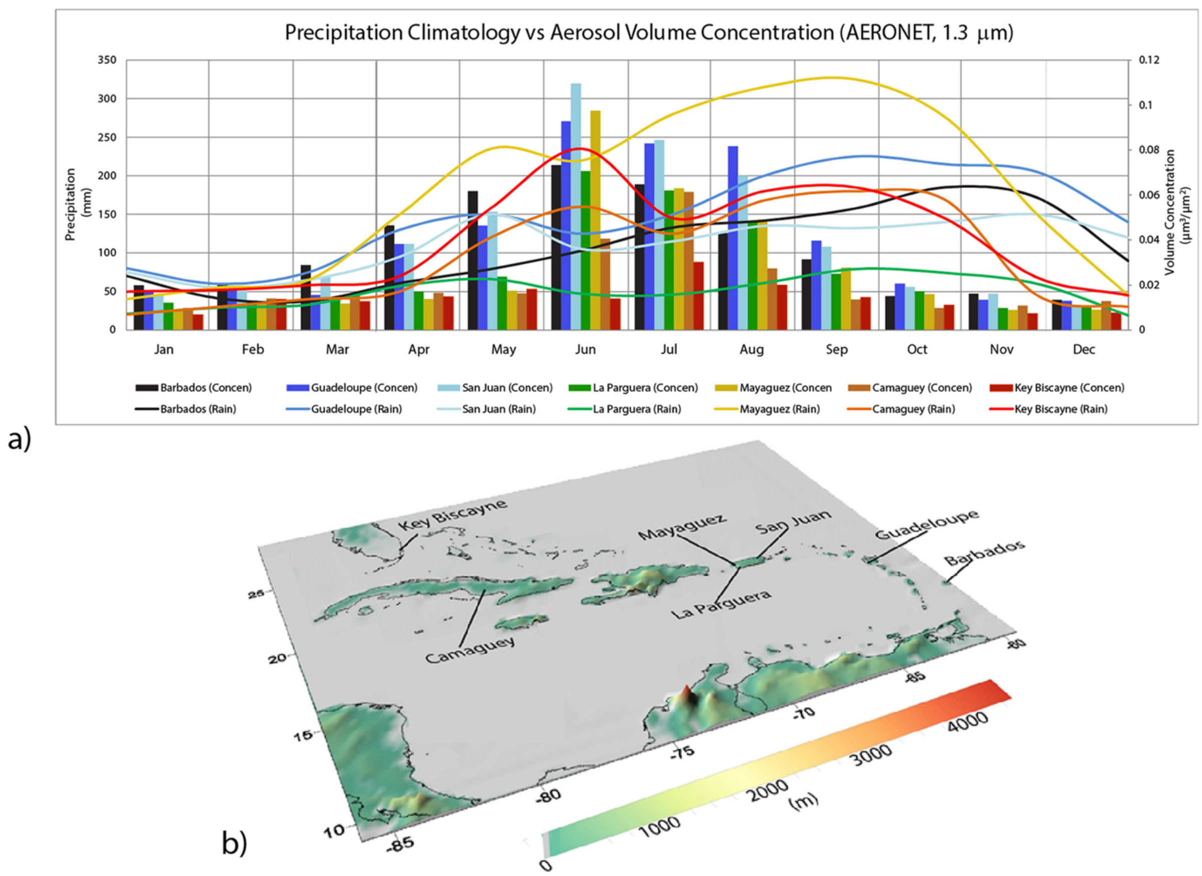

Fig. 8. *(a) Average monthly precipitation (lines) and aerosol volume concentration (bars, denoted by "concen") at multiple sites in the Caribbean, and (b) regional location and topographic map from Hosannah et al. (2019).*

2. Methodology

2.1. Objective 1: Characterizing drought in the U.S. Caribbean and its impacts on hydrology and soil moisture

This study will examine and diagnose drought and flash drought in the U.S. Caribbean through a suite of hydrometeorological variables and drought indices, while analyzing the impacts of drought on other physical systems. In addition to defining long-term drought, a working definition for U.S. Caribbean flash drought will be developed. The antecedent synoptic atmospheric drivers of flash drought will be investigated to improve early warning for these high impact events.

Because the U.S. Caribbean is an underserved region in terms of reliable, long-term, spatially contiguous climate monitoring, numerous data sources are required to define and identify drought. In addition to leveraging data from Global Historical Climate Network (GHCN) sites, meteorological data is available from several sites in the Luquillo Mountains through the LUQ LTER and the National Atmospheric Deposition Program (NADP). Meanwhile, upper-air circulation fields from gridded atmospheric reanalysis will be examined for the Caribbean. Though several reanalysis datasets are available for the study area, Objective 1 will employ the high-resolution Climate Forecast System (CFS) Reanalysis (CFSR) produced by the National Centers for Environmental Prediction (Saha et al. 2010) to maintain consistency with the CFS-related work in Objectives 2 and 3.

Soil moisture observations will be integrated from the 10 USDA Soil Climate Analysis Network (SCAN) as well as the additional in-situ measurements collected by the LUQ LTER program from the Luquillo Mountains in northeast PR. To complement the SCAN and LUQ LTER soil moisture records, multiple high temporal and spatial resolution gridded soil moisture data will be used, including but not limited to, NASA Global Land Data Assimilation System (GLDAS, v2.1), the European Centre for Medium-Range Weather Forecasts 5th generation reanalysis land (ERA5-Land), NASA SMAP L4 Global Surface and Root Zone Soil Moisture Analysis, and ESA Soil Moisture CCI product. The gridded soil moisture products will be enhanced with existing spatial downscaling approaches for soil moisture (Peng et al. 2017) and validated against station data (Ford and Quiring 2019).

2.1.1 Objective 1a: Evaluation of common drought indices to resolve U.S. Caribbean meteorological drought. Existing drought indices and definitions will be evaluated to determine which perform best for the U.S. Caribbean. Most of these indices were developed and tuned for mid-latitude drought, thus, it may be necessary to develop a new drought metric that is more appropriate for the U.S. Caribbean. The U.S. Drought Monitor (USDM) for PR only begins in 2000; one goal of this project is to produce drought products that extent from 1980 to present.

The Palmer Drought Severity Index (PDSI) (Alley 1984; Palmer 1965), Standard Precipitation Index (SPI) (McKee et al. 1993; Naresh Kumar et al. 2009), and Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2009) all serve as well established meteorological drought indices and are well validated for mid-latitude sites. The "self-calibrating" PDSI (scPDSI) is a self-calibration version of PDSI, which does not use empirically derived climatic characteristics and duration factors, but values based upon the historical data of a location (Wells et al. 2004). Therefore, the scPDSI should be a better fit for regions outside of the mid-latitudes, including the U.S. Caribbean (Herrera and Ault 2017).

This study will evaluate the ability of these indices to identify drought events in the U.S. Caribbean, with a focus on their ability to capture the onset of drought. Recognizing drought before it intensifies is highly desirable for stakeholders in the region as it can reduce impacts. PDSI, scPDSI, SPI, and SPEI indices will be calculated for a representative group of GHCN, LUQ LTER, and NADP sites that will be selected to ensure spatial coverage across the U.S. Caribbean. Sites will also be selected based on length of record and temporal consistency. To evaluate the indices' ability to predict drought onset for each meteorological drought, the indices will be ranked based on the lead time they provided. The cumulative ranks will be used to determine which index best characterized drought onset. Summary statistics will also be provided showing average lead time for each index. Additionally, these drought indices will be compared to the USDM to determine if the PDSI, SPI, scPDSI, and/or SPEI can provide additional lead time to drought onset (Svoboda et al. 2002).

2.1.2 Objective 1b: Developing a working definition and climatology for flash droughts in the U.S. Caribbean. While all drought will be of interest, this objective will be particularly focused on identifying optimal criteria for defining flash droughts in the U.S. Caribbean, including determining which metrics are best to predict these high-impact events. Flash droughts cause large agricultural impacts and can stress short-term water resources, particularly in areas with vulnerable municipal water supplies like those found in the U.S. Caribbean. This is currently a highly active research topic for CONUS drought, and thus, recent research has developed new drought metrics that properly diagnose the onset and intensity of flash droughts. Those new metrics include the Evaporative Drought Demand Index (EDDI) (Hobbins et al. 2016), the Evaporative Stress Ratio (ESR) (Otkin et al. 2017), and the Rapid Change Index (RCI) (Otkin et al. 2013). Flash drought events will be defined with a variety of approaches based on soil desiccation rates (e.g., Ford and Labosier 2017) and EDDI change rates and compared to USDM drought stage.

This methodology will not only aid in producing a climatology of flash drought events, but also help identify those flash droughts that had the fastest onset. That subset of flash droughts will be further analyzed in Objective 1c to identify the atmospheric drivers of those highest impact events. Related to this objective, the spatial contiguity of flash drought will be analyzed to determine if flash drought is always observed simultaneous across the spatial domain, or if certain areas are more prone to flash drought. This will help inform Objective 1c, in that it may indicate different modes of flash drought and thus, multiple atmospheric environments capable of producing flash drought somewhere in the U.S. Caribbean. The soil moisture data used to identify flash drought will be selected to ensure spatial coverage across the domain and temporal consistency. This will likely involve using a combination of the observed and gridded reanalysis data above. Preference will be given to in-situ observations and supplemented by the reanalysis.

2.1.3 Objective 1c: Evaluation of antecedent and concurrent synoptic-scale atmospheric drivers of flash drought. Building upon the findings and deliverables in Objective 1b, the atmospheric drivers of drought, and particularly flash drought, will be investigated. This effort will examine a series of relevant meteorological fields including radiation, temperature, potential evapotranspiration, precipitation deficit, vapor pressure deficit, and relative humidity as well as synoptic fields including geopotential height, lower tropospheric moisture, lapse rate/TWI strength, among other fields.

The CFSR data will be composited for the highest magnitude flash droughts to provide a better understanding of the atmospheric forcing mechanisms driving these high impact events at the synoptic scale. The similarity and differences in antecedent meteorological conditions for flash drought versus conventional drought that does not meet the flash drought criteria will be of particular interest. In addition to identifying the unique atmospheric drivers of flash drought, an examination of the modes of variability of those drivers will be conducted. For example, this study will address questions related to the spatial patterns of flash drought such as, "*Do the atmospheric drivers of flash drought in western Puerto Rico also cause flash drought in the USVI?*"

2.1.4 Objective 1d: Characterizing long-term drought impacts on hydrologic conditions. The impact of flash drought on hydrology will be analyzed, with an emphasis on the streams and rivers of northeast and central PR. These are of interest to stakeholders in the region due to these tributaries being primary sources of the municipal water supply for the San Juan metropolitan area. To analyze hydrologic drought, streamflow gauges from USGS, which operates over 100 streamflow gauges in PR and USVI, the LUQ LTER, and the Luquillo Critical Zone Observatory will be leveraged. Mote and González are senior members of the LUQ LTER, and González is co-PI of the LTER and Luquillo Critical Zone Observatory. The streamflow data will be quality controlled to remove any gauge data after 2017 that experienced changes in their channel geometry and, by extension, rating curves following Hurricanes Maria and Irma (2017).

The meteorological droughts identified in Objective 1a will be used to determine the impacts on hydrologic conditions. The meteorological droughts will be stratified by intensity and duration into minor, moderate, and severe drought and the resultant hydrologic drought for each category will be explored to determine if the hydrologic drought manifests differently depending on the intensity of the meteorological drought. An analysis on lag times between meteorological drought and hydrologic drought will be conducted. This will aid in determining the impacts of meteorological drought strength to the hydrologic response.

Objective 1 outcomes and deliverables: *Evaluation of existing drought indices to diagnose drought and flash drought onset; a working definition for U.S. Caribbean flash drought and a climatology of flash drought events; a set of historical analogs of antecedent and coincident meteorological and hydrological conditions associated with drought and flash drought in U.S. Caribbean; identifying hydrologic drought response to meteorological drought severity*.

2.2. Objective 2: Understanding seasonal drought mechanisms in U.S. Caribbean

Recent analyses of PR hydroclimate have been aided by the Galvez-Davison Index (GDI), a convective potential index particularly well-suited to identify the thermodynamic signature of the SAL. The GDI, which was developed specifically for the tropics (e.g., Mote et al. 2017; Miller et al. 2019c; Ramseyer et al. 2019), is the sum of three component terms, the column buoyancy index, the inversion index, and the mid-level warming index. The column buoyancy index corresponds to the vertical concentration of heat and humidity, whereas the inversion index and the mid-level warming index represent the effects of the TWI and 500-hPa temperature, respectively. Recent drought research has specifically leveraged the inversion index GDI component to track SAL activity, as it acts to strengthen the TWI and reduce precipitation. The GDI's development has catalyzed the advancement of Caribbean drought analyses by allowing a specific hydrometeorological feature to be identified and monitored through time (Fig. 9).

Consequently, Objective 2 will examine the historical role of the SAL in U.S. Caribbean drought, and in doing so, identify a physical drought-causing mechanism associated with the region. Objective 2 will be divided into three sub-objectives: (2a) Characterize historical SAL pathways and the relationship to U.S. Caribbean drought, and (2b) Relate thermodynamic SAL intensity to coincident and antecedent teleconnection patterns. Objective 3 will use these findings to examine the representation of SAL development and pathway structure in state-of-the-art numerical forecast models.

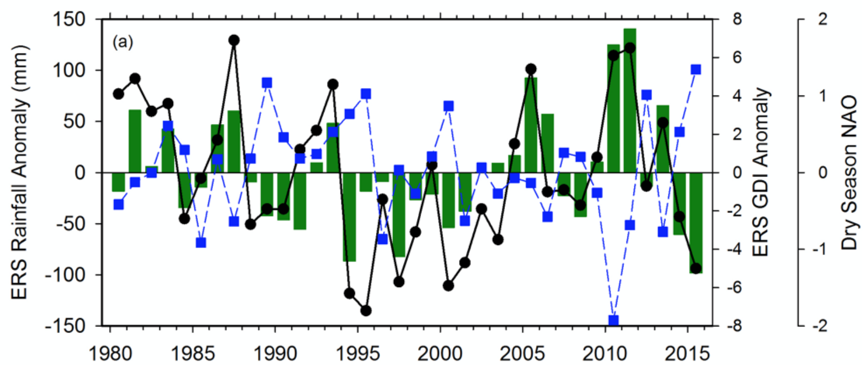

Fig. 9. *Rainfall anomaly (green bars) and Galvez-Davison Index (GDI) anomaly (solid black) during the Early Rainfall Season (Apr-Jul), and the North Atlantic Oscillation (NAO) Index (blue dashed) during the preceding Dry Season (Dec-Mar) for eastern PR from Mote et al. (2017).*

Before proceeding to the specifics of Objective 2, *we acknowledge that tropical cyclones are an important contributor to rainfall in the U.S. Caribbean* (e.g., Gamble and Curtis 2008). We also acknowledge that Saharan dust is related to frequency of tropical cyclone (e.g., Evan et al. 2006; Evan et al. 2011; Wang et al. 2012; Bretl et al. 2015), although the impact on African Easterly Waves is less conclusive (Grogan et al. 2016). However, Miller et al. (2019c) showed that the ERS accounts for a majority of the interannual variability in precipitation in PR and that this relationship in strongest in drought years. For instance, the ERS precipitation anomaly accounted for 41% of the variability in the annual precipitation anomaly over Puerto Rico during the driest tercile of years between 1980 and 2016. In contrast, the LRS, which largely aligns with tropical cyclone season in the U.S. Caribbean, accounted for only 13% of the annual variability. Further, Zuidema et al. (2019) has shown a trend toward SAL intrusions occurring earlier in the year. Furthermore, the record available from the USDM for PR indicates that droughts typically originate during the ERS (Fig. 1). Therefore, our focus in Objectives 2 and 3 is during the ERS, when tropical cyclones are a limited contributor to rainfall.

2.2.1. Objective 2a: Characterize historical SAL pathways and the relationship to U.S. Caribbean drought. Historical GDI will be derived for the 41-year (1979–2019 period) from the CFSR (1979-2011) and CFSv2 operational analysis (2012-2019), a global, 0.5º-resolution coupled atmosphere–ocean–land surface–sea ice system (Saha et al. 2014). The GDI calculation will be performed according to the method described in Galvez and Davison (2016), a workflow which the investigators have successfully implemented on several occasions (e.g., Mote et al. 2017; Miller et al. 2019c; Ramseyer et al. 2019). The GDI will be used to train a self-organizing map (SOM), a machine learning approach, which will model the common modes of variability among SAL pathways that impact the U.S. Caribbean climate.

In this SOM methodology, whole ERSs during the 41-year period, each containing 122 daily CFSR/CFSv2 GDI fields for the tropical Atlantic, will be used to train the SOM. By training the SAL on the time varying GDI, the analysis will not only identify different spatial SAL pathways, but the different SAL evolutions that occupy these paths. Though previous studies have examined trans-Atlantic SAL pathways (e.g., Meng et al. 2017), to our knowledge these efforts only examined dust aerosol loadings and did not characterize the SAL via its thermodynamic signature in coupled land-ocean-atmosphere reanalyses, nor have they examined the temporal development of this feature. The SOM analysis will produce a rectangular (i.e., 2x3, 3x4, etc.) set of SAL paths extracted from the 41-year historical period. For each ERS that is mapped to each SOM node (i.e., one of the SOM-defined pathways), the flash drought frequency, as determined in Objective 1b, will be computed. Thus, each archetypical SAL evolution will be linked to an observed flash drought frequency.

SOMs have several advantages compared to other synoptic classification techniques, such as empirical orthogonal functions and principal component analysis. SOMs offer a larger number of patterns that are easier to understand and interpret because the nodes exist on a continuum instead of discrete patterns, like those produced by the aforementioned techniques (Sheridan and Lee 2011). SOMs enable an understanding of transitional zones between atmospheric nodes, which can be helpful when examining subtle climate variability that may occur in the tropics and subtropics. The other distinctive advantage of SOMs is the capability to utilize multiple visualization techniques, which allows for a more coherent and clear depiction of the SOM array. This is particularly helpful as it pertains to the SOMs produced in this study as it will allow for 2- and 3-dimensional visualizations of the SAL. This will enable a 3-dimensional understanding of how certain "types" of SAL pathways modify the TWI, moisture, and thermodynamic environment to activate drought in the U.S. Caribbean.

2.2.2. Objective 2b: Relate thermodynamic SAL intensity to antecedent and concurrent teleconnections. For each SOM node identified in Objective 2a, contemporaneous and antecedent teleconnection indices will be examined, tying dominant teleconnection patterns to specific SAL trajectories and temporal evolutions. The relationship between teleconnection patterns and SAL evolutions will be characterized using the relative risk, a method successfully employed by Miller and Mote to characterize the risk of severe weather events as a function of environmental convective parameters (Miller and Mote 2018). Essentially, relative risk compares the frequency of an event (in this case the SOM node) when a background condition is met (threshold of antecedent/coincident teleconnection index) to the frequency of the same event when the background condition is not met. In this method, the relative likelihood of specific SAL evolution (identified by its SOM node in Objective 2a), will be calculated as a function of a teleconnection index, allowing statements such as, "*When the mean antecedent winter NAO is less than -2.0, the likelihood of ERS SAL intrusions to the U.S. Caribbean increases by 4-fold.*" The relative risk can then be re-calculated for each SAL evolution using varying thresholds of the four teleconnection indices, NAO, ENSO, Madden-Julian Oscillation (MJO), and North African dipole (NAD), and the time periods over which they are computed. By examining all the possible relative risks from different SAL evolutions, teleconnections, index thresholds, and the time periods during which the indices are averaged, Objective 2b will identify the most reliable teleconnection relationships for drought early warning in the U.S. Caribbean. This approach establishes a physical, mechanistic connection between teleconnection patterns and U.S. Caribbean drought, an improvement upon previous research that agnostically relates Caribbean precipitation to teleconnection indices (e.g., Angeles et al. 2010).

Specifically, Objective 2b will characterize the NAD, the NAO, ENSO, and the MJO. Cuevas et al. (2017) showed that the NAD was influential in modulated pulses of Saharan dust export while the antecedent NAO has been shown to generate cooler Atlantic SSTs during the ensuing ERS, leading to reduced precipitation. MJO is known to influence Caribbean rainfall (e.g., Martin and Shumacher 2011), but a recent modeling experiment by Benedetti and Vitart (2018) tied SAL dust transport to distinct phases of the MJO. Lastly, while ENSO has largely been discredited as a drought-causing mode of variability for PR (Malmgren et al. 1998; Jury et al. 2007; Mote et al. 2017; Torres-Valcárcel 2018), research has nonetheless linked ENSO to dust emissions (or vice versa) (Pausata et al. 2017). Historical NAO and ENSO indices will be accessed from publicly available NOAA websites[2]. Meanwhile NAD values will be computed from the same CFSR/CFSv2 fields used to derive the GDI following the method outlined by Rodriguez et al. (2015) whereby the NAD is computed as a difference of 700 hPa geopotential height anomalies over Africa's Atlantic coast. The MJO phases will be provided by the Australian Bureau of Meteorology via a publicly accessible archive[3].

Objective 2 outcomes and deliverables: *Characterization of the common trans-Atlantic SAL evolutions during the critical ERS; the observed frequency of U.S. Caribbean flash droughts for each archetypal SAL; the antecedent/concurrent teleconnection states for each archetypal SAL.*

2.3. Objective 3: Representation of drought mechanisms in state-of-the-art numerical weather prediction models

Objective 3 will leverage the results of 2a and 2b to determine the predictability of U.S. Caribbean drought. The two sub-components of Objective 2 will have established the role of SAL intensity and seasonal evolution to the critical ERS hydrometeorological period. However, Objectives 2a and 2b also establish two potential paths of SAL predictability.

Because the SAL is a definable physical mechanism with a known thermodynamic signature and geographic origin, it can easily be identified and extracted from seasonal numerical models, as in Objective 2a. However, the results of Objective 2b also provide a workflow predictability whereby historical drought-causing SAL trajectories and evolutions are related to concurrent and antecedent teleconnection patterns. Objective 3 will replicate Objective 2a, however, instead of extracting GDI values from historical reanalyses/CFSv2 analysis fields, GDI values will be supplied by archived seasonal CFSv2 forecasts for the U.S. Caribbean ERS, the operational version of the CFSR. Because the CFSv2 is a fully coupled atmosphere–ocean–land model, it should plausibly detect the trans-Atlantic advection of hot, dry Saharan air with long lead times. Fig. 10 shows a qualitative comparison between 2015, a drought year in the U.S. Caribbean, and 2016, a slightly wetter-than-average year, in which the CFSv2 does anticipate SAL outbreaks with as much as a 3-mo lead time.

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[2] https://www.cpc.ncep.noaa.gov/ products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table ; https://origin.cpc. ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

[3] http://www.bom.gov.au/ climate/mjo/graphics/rmm.74toRealtime.txt

The CFSv2 is initialized four-times daily with each run producing a 9-mo forecast period at 6-hr output intervals. However, only 6-7 months of each forecast are archived for public consumption by the National Centers for Environmental Information. For each year the CFS was operational for the entire ERS (2012–present), all CFSv2 forecasts initialized between January and March preceding the ERS will be retrieved and 122 daily mean GDI fields will be calculated for the tropical north Atlantic (Fig. 10). Each ERS forecast for each year (4x daily forecasts for 90 days between January-March = 360 forecasts/yr), will be classified to the closest pathway/evolution pattern in the historical record according to the SOM developed in Objective 2a. By classifying the CFS forecast to a SAL SOM node, hydrometeorological information from its historical analogues (the ERSs from the 41-yr dataset also grouped to the same node in Objective 2a) can be used to broadly characterize typical drought (or non-drought outcomes).

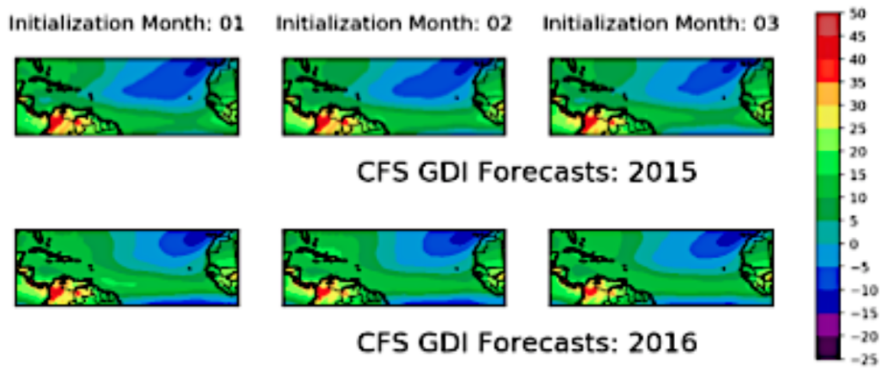

Fig. 10. *Preliminary results showing mean ERS GDI forecast for 0000-UTC CFS runs during January (01), February (02), and March (03) prior to 2015 and 2016 ERSs (April-July). In 2015 (drought year), the CFS detects a more prominent extension of low GDI values toward the U.S. Caribbean than in 2016 (near normal).*

Prior to feeding the forecasts into the SOM, a training dataset will be used to bias-correct the CFSv2 forecasts to ensure they map to representative historical nodes, rather than all clustering to a single, rare historical node due to a systematic bias in the forecast. Our group has conducted preliminary research examining the representation of SAL in CFSv2 forecast output. While CFSv2 GDI forecasts can depict SAL-like features with ~3-mo lead time (Fig. 10), the magnitudes of the GDI within the SAL-like features tend to be overestimated (i.e., GDI too high), and thus underestimate the magnitude of the negative forcing on precipitation (Miller and Ramseyer, in preparation). The forecast SAL node will be tracked as the CFSv2 forecast approaches the start of the forecast period (i.e., lead time decreases), and compared to observed SOM node for the ERS being forecast. The percentage of CFS forecasts that correctly predict the observed SAL node will be tracked for each year, and ERS with poor CFSv2 performances will be further analyzed, in regard to their GDI subcomponents, spatial forecast error, and temporal error.

An analysis of the CFSv2 ERS forecasts at varying lead times will be used to assess the reliability of SAL depiction in the numerical forecasts. In cases of poor SAL forecasts (i.e., many forecasts mapped to wrong node), the source of the error, i.e. the limit of predictability, will be investigated. For instance, was the SAL's spatial pathway poorly resolved? Did it develop too late or too early? Was the GDI disproportionately influenced by a single, poorly resolved sub-component? These analyses will help determine the current limits of drought predictability for the U.S. Caribbean and help target areas of future model improvement. Objective 3 will also help

U.S. Caribbean decision-makers understand whether numerical models are best suited for drought predictability or whether concurrent/antecedent teleconnection indices can provide more generalized, but perhaps more reliable early warning tools.

Objective 3 outcomes and deliverables: *Error statistics for CFSv2 SAL forecasts with diagnoses of the limiting physical processes to more reliable early warning.*

2.4. Objective 4: Engaging stakeholders in the U.S. Caribbean

In order to fully understand the specific stakeholder-relevant thresholds of drought as well as the most relevant timescales, this project will engage with regional stakeholders. The incorporation of locally relevant drought information is vital in a region like the tropics, where critical drought thresholds and impacts are dissimilar from the continental U.S. As stated in the MAPP solicitation, the regional Drought Early Warning Systems (DEWS) "*encourage innovation by integrating new, locally relevant drought information*." However, because the U.S. Caribbean is not currently assigned to a DEWS region, stakeholder engagement to determine locally relevant drought information is especially critical for this project.

We also propose to create a U.S. Caribbean drought monitoring clearinghouse on either the IITF or partner website, possibly the USDA Caribbean Climate Hub. We will link the stream gauges, LTER datasets, NCEP GDI forecasts, CPC teleconnection index pages, USDM, etc, in one place to facilitate easier drought monitoring by local stakeholders, which will be made available in Spanish and English. We will first engage with NIDIS (drought.gov) and the National Drought Mitigation Center (NDMC) to provide complementary information and avoid duplication of effort.

Potential stakeholders engaged as part of Objective 4 include the PR Department of Natural and Environmental Resources, the U.S. Fish and Wildlife Service, the U.S. Geological Survey, the Southeast Climate Adaptation Science Center, the Caribbean Climate Hub, and the University of the Virgin Islands Water Resources Research Institute. In Year 1 of this project, we will engage in person or by teleconference with the individual stakeholders to assess their interest in the science outcomes of this project. In the latter half of Year 2 or early in Year 3, we will host a workshop at IITF and invite representatives of the organizations listed above, as well as any others identified in Year 1. The workshop will provide a platform for the participatory engagement of the stakeholders in the science efforts outlined in Objectives 1-3. Workshop sessions will be devoted to presenting the drought metrics, the use of historical analogs created as part of Objective 1, and the use of the GDI for characterizing drought as described in Objectives 2 and 3, with a focus on "how we know" the information. The workshop will provide opportunities to guide stakeholders to publicly available outlets for real-time drought monitoring and GDI forecasts, including the U.S. Caribbean drought monitoring clearinghouse described above.

Objective 4 outcomes and deliverables: *A drought workshop hosted by the International Institute for Tropical Forestry in San Juan, PR; drought monitoring clearinghouse website tailored to local stakeholders.*

3. Work Plan

The previous section provided details addressing each of the project objectives. Here, a timeline of project milestones and deliverables is presented, and the roles and responsibilities of team members are discussed. Fig. 11 summarizes our planned approach toward addressing project objectives and ensuring that data sets and products are generated and delivered to NCEI. Each series of arrows defines the general type of activity being undertaken. Note that in many cases the milestones/deliverables will continue beyond the initial year in which they are introduced. They are not repeated under listings for subsequent years, rather they are depicted on the accompanying timeline as shaded arrows.

	Year 1: 9/1/20-8/31/21	Year 2: 9/1/21-8/31/22	Year 3: 9/1/22-8/31/23
Task 1a.b: *Characterizing drought in the U.S. Caribbean*	Integration of available datasets to create blended soil moisture product	Production of drought metrics, incl. scPDS and soil moisture	Delivery of drought metric datasets to archive(s)
Task 1c,d: *Characterizing antecedent and concurrent conditions*	Create/extract relevant meteorological fields from renalysis products	Creation of historic analog fields for instances of meteorological (flash) and hydrologic drought	Delivery of drought analog datasets to archive(s)
Task 2a: *Characterize historical SAL pathways and the relationship to drought*	Create historical GDI from CFSR/CFSv2	Create self-organizing maps from GDI fields; identify preferred SAL pathways	
Task 2b: *Relate SAL intensity to coincident and antecedent teleconnections*		Characterize dust transport by teleconnection phase	Relate SAL pathways from SOM analysis to teleconnection phase
Task 3: *Examine the SAL development, pathway structure in NWP models*		GDI from archived seasonal forecasts by the CFSv2; SOM training	Analysis of CFSv2 ERS forecasts to assess the reliability of SAL depiction
Task 4: *Engaging stakeholders in the U.S. Caribbean*	Seeking input on drought metrics from stakeholders	Creation of U.S. Caribbean drought clearinghouse	Workshop at IITF to disseminate findings

Fig. 11. *Timeline outlining key objectives by year with solid cells indicating primary activities in a year and open cells indicating secondary activities.*

While investigator mini teams for each objective have been defined, all four investigators will play roles in each of them. Experience shows that we work together exceedingly well. Miller worked as a postdoc and Ramseyer as a graduate student on projects related to Caribbean climate in Mote's laboratory at the University of Georgia. Both Miller and Ramseyer now work independently on related projects at Louisiana State University and Virginia Tech, respectively. González and Mote have been senior personnel on LUQ LTER V and VI and regularly meet in PR. All of the PIs have published papers together in various combinations. We confer regularly via email and phone and often at national conferences as well as meetings in PR.

Ramseyer, Mote, and González will take the lead on characterizing drought in the U.S. Caribbean and producing historical analogs of meteorological and hydrologic drought (Objective 1). Miller, Ramseyer, and Mote will lead efforts to understanding seasonal drought mechanisms in U.S. Caribbean with particular attention to the role of major atmospheric and oceanic teleconnections (Objective 2). Miller will lead the analysis of the representation of drought mechanisms in a state-of-the-art numerical weather prediction model (Objective 3). Mote and

González will lead efforts to engage and disseminate research findings to regional stakeholders (Objective 4). Miller will take the lead with use of CFSR/CFSv2, and Ramseyer has extensive experience working with SOM machine learning tools. González has expertise regarding the use of long-term records of precipitation and soil moisture in the region. Data production efforts will flow through Mote's laboratory, which has experience producing climate data records, created metadata, and making data available to archives. Flávia Moraes, a doctoral research assistant at the University of Georgia, will assist with Objectives 1 and 2.

4. Relevance to the Competition

On a broader, programmatic level, this project advances the MAPP primary objective #3 to improve methodologies for global to regional scale analysis, predictions, and projections. This project is relevant by engaging Priority Area C to "*examine the predictability (of) U.S. droughts considering the interdisciplinarity of intervening processes and their multi-scale evolution*" through the use of "*state-of-art modeling systems in combination with observational data*" and "*develop(s) key metrics and apply observational data to demonstrate that proposed analyses are statistically robust, physically... defensible, objectively quantifiable.*" Seasonal model forecasts and historical analogs are mined for the presence of a precursor mechanism (i.e., low-GDI SAL layer) that can inform contextualized forecasts of drought (including flash drought) likelihood and severity. By examining numerous (~360) CFS seasonal forecasts for each year between 2012–2019, this project will leverage a large sample size by which to infer "*the signal to noise ratios and thresholds that can inform early warning.*" Specifically, the archived seasonal forecasts will be examined to determine the limiting factors of their predictability (i.e., SAL pathway geometry, GDI intensity, temporal evolution, etc.) which can be used to develop "*new/improved modeling and/or methodologies for prediction/projection.*" In addition to the numerically forecast precursors, this project examines the comparative reliability of concurrent and antecedent teleconnection indices to serve as early warning signs of active SAL periods. Thus, the results will inform drought monitors about the most effective currently available tools as well as direct earth system modelers towards the most needed areas of improvement for SAL early warning. An improved understanding of SAL will have additional benefits of improved forecasting of human health impacts of Saharan dust (e.g., Kuciauskas et al. 2018).

This project (1) operates at a regional scale, with an effort that could lay the groundwork for a future DEWS site, (2) examines both the 2015 case study as well as drought over a longer period in a broader statistical sense, and (3) makes use of use of machine learning methodologies through the use of SOMs. This project will also entrain locally relevant drought information by partnering with the USDA International Institute for Tropical Forestry to leverage unique soil moisture datasets collected in mountainous regions of PR.

This project will support NIDIS as outlined in the NIDIS Reauthorization Act of 2018 as it will "*utilize existing forecasting and assessment programs*" in Objective 1 through the use of USDM and related tools and in Objective 4 through coordination with the USDA Caribbean Climate Hub, located at IITF. Efforts in Objectives 2 and 3 will lead to "*improvements in seasonal and subseasonal precipitation and temperature and low flow water prediction*" and contribute to "*research and monitoring activities related to drought, including research activities relating to the prediction of drought*." Finally, the project, by definition, will "*facilitate the development of academic cooperative partnerships*" through this collaborative effort that includes three universities and a federal agency.