BAMS Article

An Eye on the Storm

Integrating a Wealth of Data for Quickly Advancing the Physical Understanding and Forecasting of Tropical Cyclones

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ABSTRACT: Tropical cyclones (TCs) are among the most destructive natural phenomena with huge societal and economic impact. They form and evolve as the result of complex multiscale processes and nonlinear interactions. Even today the understanding and modeling of these processes is still lacking. A major goal of NASA is to bring the wealth of satellite and airborne observations to bear on addressing the unresolved scientific questions and improving our forecast models. Despite their significant amount, these observations are still underutilized in hurricane research and operations due to the complexity associated with finding and bringing together semicoincident and semi-contemporaneous multiparameter data that are needed to describe the multiscale TC processes. Such data are traditionally archived in different formats, with different spatiotemporal resolution, across multiple databases, and hosted by various agencies. To address this shortcoming, NASA supported the development of the Jet Propulsion Laboratory (JPL) Tropical Cyclone Information System (TCIS)—a data analytic framework that integrates model forecasts with multiparameter satellite and airborne observations, providing interactive visualization and online analysis tools. TCIS supports interrogation of a large number of atmospheric and ocean variables, allowing for quick investigation of the structure of the tropical storms and their environments. This paper provides an overview of the TCIS's components and features. It also summarizes recent pilot studies, providing examples of how the TCIS has inspired new research, helping to increase our understanding of TCs. The goal is to encourage more users to take full advantage of the novel capabilities. TCIS allows atmospheric scientists to focus on new ideas and concepts rather than painstakingly gathering data scattered over several agencies.

https://doi.org/10.1175/BAMS-D-19-0020.1
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In final form 26 April 2020

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Tropical cyclones (TCs) and disturbances are a key component of the climate system, and understanding their evolution and role in modifying the water and energy budgets is of great scientific interest. TCs are among the most destructive natural phenomena and have huge societal and economic impact. Each year they threaten the U.S. coast, cause damage worth billions, and take lives. The deadliest hurricane in U.S. history still is the 1900 Galveston storm, which killed 8,000–12,000 people and destroyed the city. More recently, Hurricane Harvey (2017) became the second-costliest storm in U.S. history at the time ($131.3 billion, values based on the 2020 Consumer Price Index adjusted cost) after 2005's Hurricane Katrina, which caused $170.0 billion in damage (according to the same index), killed some 1,200 people, and left hundreds of thousands homeless. In other parts of the world the effects are even more damaging. In one noteworthy case, it has been estimated that some 84,500 people died and another 53,800 disappeared when Tropical Cyclone Nargis struck Myanmar in 2008 (Swiss Reinsurance Company Ltd. 2009). Four billion-dollar hurricanes occurred during the very recent 2017 and 2018 Atlantic hurricane seasons (Harvey, Irma, Maria, and Michael). The damages caused by each of them are estimated to be between $50 and $131 billion (NOAA/NCEI 2019).

Readiness for TC landfall is vital and there is a well-recognized need to improve the forecast accuracy of the models. However, TCs form and evolve as the result of complex multiscale processes and nonlinear interactions and those interlinked processes enormously complicate their modeling. Even today there are still many unanswered questions about the physical processes that determine hurricane genesis, their rapid intensity changes (RIC), their structure, and their evolution in general. During the past 20 years there has been significant improvement in track forecast (Cangialosi 2019; Elsberry 2014; Goerss et al. 2004). However, the intensity forecasts have improved at a slower rate over the same period (DeMaria et al. 2005; Emanuel 2017, Kaplan et al. 2010; Krishnamurti et al. 2005). Current focus of research and development is toward improvement of forecasts of TC intensity and especially of TC RIC (Kaplan et al. 2010; DeMaria et al. 2014), posing questions about the sources of the intensity forecast errors. To improve TC forecasts, there is a need to better understand how well models reflect the physical processes (e.g., moisture convergence, turbulent mixing, microphysical processes that lead to hydrometeor production, associated latent heat release, and the development/intensity of the convective updrafts and vertical transport of mass and moisture) and their interactions. While today's satellite observations do not yet provide information on the processes, they provide information on the macroscale structure and evolution of the storms, which can be used as a constraint and guidance toward improving the models. Some specific questions include:

(i) How well is the complexity in precipitation structure simulated?
(ii) Are the vortex-scale processes and associated asymmetries captured correctly?
(iii) Is the representation of the surrounding environment accurate?
(iv) How accurate is the interaction between the storm vortex and the surrounding environment?

One avenue to improve tropical forecast modeling is through the better use of existing data in TC research and operations. The advanced use of satellite data should involve model validation through comparisons of observed and forecasted storms. It should also lead to model improvement by guiding the development of parameterization schemes such that the resulting storm structures compare better to those observed by the satellites. Besides improving models, model forecasts could also be improved through data assimilation. It has been widely recognized that the large-scale model forecasts have significantly improved over the last two decades due to the assimilation of satellite observations—mostly in the absence of precipitation. However, the model forecasts could be significantly improved further by the assimilation of satellite data inside the precipitating core. This remains still a challenging problem for two reasons: the direct satellite observations (e.g., microwave brightness temperatures) have indirect and very nonlinear sensitivity to the most important underlying model variables, and at the same time the satellite-based retrievals of the geophysical variables, directly related to the model fields, often carry significant uncertainty due to the variety of assumptions made in the retrieval algorithms.

The wealth of satellite and airborne observations collected over the past two decades can be brought to bear on addressing unanswered fundamental questions about the physics of a variety of processes. Major satellite data processing centers provide TC satellite imagery, including near-real-time capabilities (e.g., Hawkins et al. 2001). However, despite the significant amount of satellite data that is available today, such observations are still underutilized in a more quantitative way due to the complexity associated with finding and bringing together semicoincident and semicontemporaneous multiparameter data that are needed to describe the multiscale processes associated with complex phenomena such as tropical cyclones. Such data are traditionally archived in different formats, with different temporal and spatial resolutions, across multiple databases, and hosted by various agencies. To address this shortcoming, over the last 10 years NASA has developed information-system technology that promotes a fusion of observations and operational model output to help improve the scientific understanding of hurricanes, typhoons, and TCs in general.

One such example is the Jet Propulsion Laboratory (JPL) Tropical Cyclone Information System (TCIS; https://tropicalcyclone.jpl.nasa.gov). TCIS is a data analytic center framework that integrates model forecasts with multiparameter satellite and airborne observations from a variety of instruments and platforms. In practice, TCIS is an interactive system for visualization and includes online analysis tools that work with both observations and model output, allowing for quick investigation of tropical disturbances and TCs and their surrounding large-scale environments. Bringing multiparameter digital data in a semicoincident and semicontemporaneous framework and integrating them with online analysis tools should help the more quantitative model evaluation and improve the understanding through supporting joint analysis of different variables (e.g., wind and precipitation).

TCIS allows atmospheric scientists to spend more time on new ideas and concepts rather than painstakingly gathering observational and model data scattered over several agencies. Considering the growing interest in improving hurricane predictability, the societal implications of this meteorological phenomena, and the need of levering resources, JPL's TCIS provides an important service to the community.

The purpose of the article is to present NASA's TCIS and to inform potential users of the utility of TCIS for monitoring and analyzing the observed and forecasted evolution of TC track, intensity, and structure so anyone interested can use the resources provided in the portals. The paper also highlights some potential uses of the JPL TCIS through pilot projects and direct applications of the novel tool. These, however, are just a few examples intended to illustrate the potential. The system can be used by anyone to explore new avenues of research. The intent of the paper is to inform the community how TCIS can benefit our ability to understand and forecast such destructive phenomena.

A comprehensive data hub for tropical cyclone research

Recognizing the high societal value of accurate hurricane forecasts, the NOAA-led, multiagency Hurricane Forecast Improvement Project (HFIP) was established in 2007. The JPL TCIS was built to support this initiative, and today it is advanced enough to be reliably used by a variety of users, including the forecast and research communities.

The Tropical Cyclone Information System is a data analytic framework designed to help improve our understanding of what controls hurricane genesis and evolution, and tropical convection in general. Its development was driven by the goal to enable investigations of the multiscale interactions that sometimes lead to the development of storms and other times do not, and to facilitate model evaluation (e.g. Hristova-Veleva et al. 2012b) that goes beyond the comparison of "best track" metrics.

TCIS has two components: (i) a set of interactive portals that integrate model forecast with multiparameter satellite and airborne observations from a variety of instruments and platforms, providing interactive visualization and some online analysis tools that work with both observations and models, and (ii) a 12-yr global archive of multisatellite hurricane observations.

The objectives of the interactive systems are (i) to allow interrogation of a large number of atmospheric and ocean variables to help better understand the processes associated with tropical convection in general, and, in particular with tropical cyclone genesis, track, and intensity changes; (ii) to allow for easy evaluation of models by comparison with existing observations; and (iii) to serve as a rich information source during the planning and postcampaign analysis stages of field campaigns and to support in-depth posthurricane research. These interactive portals include the North Atlantic Hurricane Watch (NAHW; https://nahw.jpl.nasa.gov) site and the interactive data portals being developed to support field campaigns: NASA's Convective Processes Experiments (CPEX and CPEX-AW) site (https://cpex.jpl.nasa.gov) and the 2019 Cloud, Aerosol and Monsoon Processes Philippines Experiment ($CAMP^2Ex$) site (https://camp2ex.jpl.nasa.gov) for the study of tropical convection. All these portals, run also in near–real time, are designed with the same overarching goals in mind: (i) to increase the accessibility and utility of NASA and NOAA observational data and (ii) to enable the development of new information products. These portals provide the same capabilities and are developed using the same technology. Here we focus on presenting the NAHW portal, as this is the system that addresses the questions regarding hurricane genesis and evolution—a science problem with significant societal implications.

In addition to the three interactive portals, TCIS also includes a 12-yr-long (1999–2010) global data archive of satellite observations of tropical cyclones (Li et al. 2007; Turk et al. 2010). It is a one-stop place to obtain an extensive set of multiparameter data from multiple observing systems. The Tropical Cyclone Data Archive (TCDA; https://tcis.jpl.nasa.gov/data/

TC_Data_Archive/) offers both digital data and imagery that are subset to the domain and time of interest, thus greatly reducing the volume of unwanted data. This makes the TCDA a valuable source to quickly build statistics in support of research, forecast improvement, and algorithm development (e.g., Hristova-Veleva et al. 2014; Wu et al. 2012).

Table 1 presents a summary of the spatial and temporal coverage for all components of TCIS. The NAHW portal is the longest-running TCIS interactive portal. It contains data since 2012, though with somewhat variable coverage and product selection. The CPEX portal was run in support of the 2017 NASA CPEX field campaign and contains data covering the specific domain of interest, collected during the period 15 May–15 July 2017. The CPEX-AW portal, supporting NASA' s CPEX-AW 2021 field campaign, is active now, and will continue collecting data through 2022. The CAMP^{2}Ex portal has been running since 15 August 2017. However, it was under development in the first year and a half. It has been running with a full set of data since July 2019. The TCDA contains global satellite observations of TC, covering the period 1999–2010.

Science-wise, TCIS can be used as the empirical basis for a number of research directions aimed to advance our knowledge of hurricanes. The three critical pathways to hurricane forecast improvement that can be assisted by the system are (i) improved understanding of physical processes, (ii) validation and improvement of hurricane models through the use of satellite data, and (iii) development and implementation of new techniques for assimilation of satellite observations inside the hurricane precipitating core (e.g., Haddad et al. 2015). TCIS can be used in each one of the three directions thanks to the unique subsetting and coregistration of multiparameter observations and model output.

Data in TCIS

As mentioned, TCIS contains both observations and model forecasts. Figure 1 shows several of the key datasets (described below) and the complementary nature of the information they carry. It illustrates how these diverse data can be combined to capture the most important characteristics of the environment and the storm structure, depicting the confluence of factors, closely related with Hurricane Joaquin (2015), that led to the historic South Carolina floods of 1–5 October 2015. While Joaquin did not make a landfall in the United States but in the Bahamas (where it was devastating), it played a critical role in U.S. flooding by generating a plume of tropical moisture. The interaction of the hurricane circulation with the large-scale synoptic flow produced a moisture river that was persistently pushed toward the U.S. coast over a week-long period. This resulted in record rainfall over portions of South Carolina. Some areas experienced more than 20 inches (1 in. = 2.54 cm) of rainfall over the 5-day period. Many locations recorded rainfall rates of 2 in. h^{-1}. Flooding from this event resulted in 19 fatalities. South Carolina State Officials said damage losses were \$1.492 billion (NOAA/NWS 2016).

The observational data. The observational data of TCIS contain products from a number of NASA, NOAA, and international satellites pertaining to the cloud and precipitation structure of the storms, the environment in which the storms develop and evolve, and the air–sea interactions that provide the fuel for the storms. In addition, TCIS contains the best track data for the tropical cyclones that occurred within the time range and the spatial domain of each of the individual portals. Most importantly in terms of user experience, the best track data are organized in a database that can be searched by the year and the name of the tropical storm.

Table 1. Summary of the spatial and temporal coverage for all components of TCIS. The domain of the NAHW has expanded over the years. Given are the dimensions of the current domain.

Portals	Temporal coverage	Domain
NAHW	2012–present	10°S–60°N, 175°W–0°
CAMP2Ex	2018–present	15°S–35°N, 40°E–180°
CPEX	15 May–15 Jul 2017	10°–40°N, 45°–100°W
TCDA	1999–2010	Global

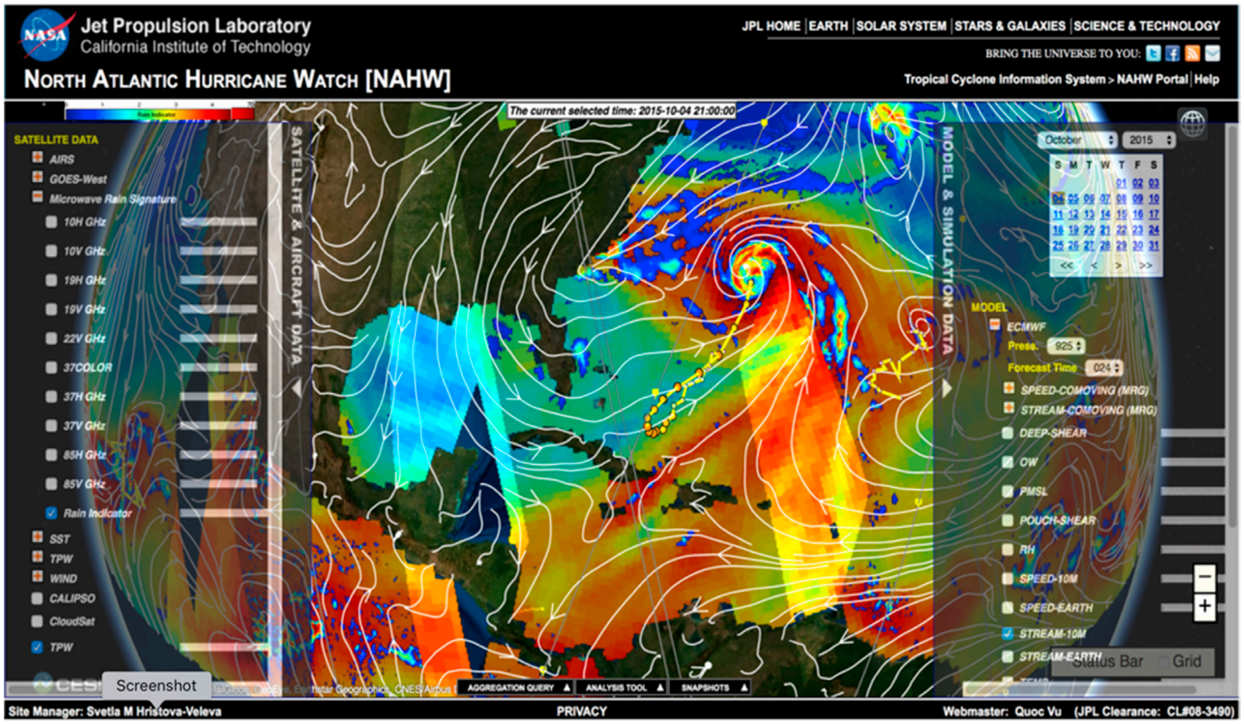

Fig. 1. The historic South Carolina floods of 1–5 Oct 2015 as depicted by observations and models in the NAHW. Illustrated is the variety of observational and model data available in the portal. The figure shows the different ways in which the data can be interrogated. Displayed are observations of TPW, overlaid with the RI, a special product developed to depict rain intensity and variability as a function of PMW observations. The model flow is overlaid on top to show the interaction of the hurricane circulation with the large-scale synoptic flow, producing a moisture river that was persistently pushed toward the coast, over a week-long period. Note that the RI is displayed with transparency, to illustrate the width of the swath and to help separate regions with available observations (and no rain), appearing darker, vs the brighter regions for which there was no observation of the rain.

Table 2 lists the specific satellite observations, including their sources, that have been routinely included in all interactive portals of TCIS. It should be pointed that the campaign portals (CPEX and CAMP^{2}Ex) might have alternative or additional satellite observations (e.g., CAMP^{2}Ex portal has geostationary observations from *Himawari* and includes specific-to-the-campaign Fire Hotspots, depicting the satellite-determined sources of smoke and aerosols).

Below is a quick summary of the data types. It is then followed by discussions on the value of each of the data types and illustrations of their potential use.

As mentioned above, the satellite observations included in the portal have the purpose to describe the storm and its environment, pertaining to the following:

(i) The precipitation structure of the storms that is captured well by passive microwave (PMW) brightness temperatures from a number of different instruments that are all part of the Global Precipitation Measuring (GPM) mission: Instruments like TMI, GMI, ASMR-E, AMSR2, and SSMIS provide high information content, piercing through the cloud tops, to depict details on the vertical structure, the evolution of intensity, and the organization of convection in the storms. TCIS also includes infrared (IR) data from AIRS and geostationary observations. While the geostationary data have even better temporal resolution, they often fail to discriminate between dead or decaying convection and a developing one. Incorporating the less frequent PMW observations from polar-orbiting satellites provides this complementary and important information, giving a comprehensive view of the storm development.

Table 2. Types and sources for the satellite data routinely included in TCIS. The color coding reflects atmospheric composition (red), thermodynamics (green), surface (blue), and convective activity (black).

Sensors	Data products	Data sources
MODIS	Aerosol optical thickness	LAADS DAAC
AIRS	Temperature and water vapor—vertical profiles	GES DISC
MHS, ATMS (NOAA, MetOp, NPP)	Total precipitable water	NOAA/NESDIS, CLASS
MUR-SST	Sea surface temperature	JPL PO.DAAC
QuikSCAT; RapidScat	Surface vector winds over the ocean	JPL PO.DAAC
ASCAT-A; ASCAT-B	Surface vector winds over the ocean	KNMI/JPL PO.DAAC
ScatSat	Surface vector winds over the ocean	JPL product from ISRO observations
SMAP	Surface wind speed over the ocean	JPL product
CYGNSS	Surface wind speed over the ocean	JPL product
GOES-E and GOES-W; *Himawari*-AHI	Geostationary IR (~11- and ~6.7-μm water vapor); visible	NOAA/CLASS; NRL; CIMSS-SSEC
TMI, GMI, AMSR-2, SSM/I, SSMIS	Brightness temperatures 10–89 GHz	NASA GSFC PPS GPM
TMI, GMI, AMSR-2, SSMIS	Rain Indicator: 2D maps of relative rain intensity	JPL Derived Product
GPM-IMERG	Integrated multi-instrument 1-h rain totals	NASA GSFC PPS GPM
Best track	Hurricane location, estimated maximum wind speed and minimum MSLP, updated every 6 h	NCAR/RAL*
TC DATA ARCHIVE ONLY		
OMI	Ozone–total column	GES DISC
MLS	Ozone–vertical profiles	GES DISC
MLS	Temperature, water vapor–vertical profiles	GES DISC
MLS	Ice content–vertical profiles	GES DISC
TRMM-PR	Precipitation; radar reflectivity–3D structure	NASA GSFC PPS GPM
CloudSat	Clouds and precipitation; radar backscatter; vertical profiles	*CloudSat* Data Processing Center/CSU

* The NCAR/RAL was chosen as the source of the operational best track data because of the accuracy, completeness, and ease of access to the data. According to NCAR's Real Time Guidance description (http://hurricanes.ral.ucar.edu/realtime/) "for the North Atlantic, Eastern Pacific, and Central Pacific basins, the [Tropical Cyclone Guidance Project] TCGP is just providing the b-decks obtained from the National Hurricane Center. For the other global basins, TCGP constructs the b-decks using information found in the tcvitals files that the U.S. Navy's Joint Typhoon Warning Center (JTWC) provides to the U.S. National Oceanographic and Atmospheric Administration's National Center for Environmental Prediction (NOAA/NCEP) for the purpose of initializing the model." The "b-deck" is "a data file that contains a complete history of the past estimates of the storm's center locations, intensity, and other parameters at the 6-hourly synoptic times: 0000, 0600, 1200, and 1800 UTC (note that the files can also contain information about the storm at off-synoptic periods, such as the time of landfall). During hurricane season, these files contain the best operational estimates of these parameters, and so are called the 'operational best tracks'."

(ii) Thermodynamics: Total precipitable water from AMSU-A, MHS, and ATMS and vertical profiles of vapor and temperatures from AIRS characterize the environment and the storm-induced perturbations.

(iii) Atmospheric composition: The aerosol optical thickness/depth indicates the variability in the aerosol content, which has implications for the microphysical composition of the storm that develops in this environment.

(iv) Air–sea interactions: The global high-resolution SST estimates from merged satellite (NOAA/POES AVHRR, TMI, GMI, AMSR-E, AMSR2) and in situ measurements characterize the storm's energy source and potential. They complement surface wind vector observations from QuikSCAT, RapidSCAT, ASCAT-A/-B, ScatSat, and scatterometers to depict the SST–wind interactions, including surface convergence/divergence and vorticity of the systems. SMAP and Cyclone Global Navigation Satellite System (CYGNSS) surface wind speeds are also included to characterize the surface fluxes.

Following is a discussion on the information content of the different data types with some illustrations about their possible use within the TCIS.

The cloud and precipitation structure of the storms, including the convective processes, is best captured by two complementary observing systems: geostationary observations in visible and IR wavelengths, and passive microwave observations from low-Earth-orbiting (LEO) satellites. The main advantage of the geostationary observations is their high temporal and spatial resolutions. Indeed, imagery from geostationary satellites are widely used in day-to-day operational forecasting to visualize the evolution of a hurricane. However, such data depict mainly the structure of the cloud tops, with little information on the storm structure below, thus often failing to discriminate between decaying clouds and the ones that are developing under the cloud canopy. To be able to sense below the cloud cover, one can use passive microwave observations that provide complementary information. Such observations are available from a number of satellites at LEO orbits (NASA's GMI, JAXA's AMSR-2, NOAA's SSMIS series, *Suomi NPP* ATMS). While not as frequent as the geostationary data, the constellation of similar instruments, each with wide swaths, observes every point in the tropics on average every 80 min and allows the detection of convection that is growing underneath the cloud cover. These observations carry significant potential, when used together, to provide detailed information to capture the evolution of intensity and organization of convection in the storms, even providing some limited information on the vertical structure of clouds and precipitation inside hurricanes.

Examples are the passive microwave data, which are available under the "Microwave Rain Signature" from the "Satellite Data" menu on the left (Fig. 1). Presented are the 6-h composite images that include observations from a number of radiometers. Such compositing allows for quick overview of the cloud and precipitation structure over the entire ocean basin, revealing the interactions between storms that occur simultaneously and in close proximity. Available for display are the brightness temperatures at a number of different frequencies and polarizations, each providing a different view, as each is sensitive to different characteristics of the precipitation [e.g., amount of precipitation, its phase (liquid vs frozen)]. For example, the difference between the horizontal and vertical polarization of a given channel signifies the presence and the intensity of the precipitation. This is because the precipitation particles in the atmosphere reduce the polarization difference in the highly polarized radiation emitted from the ocean surface. Hence, the polarization difference is representative of the precipitation itself. Furthermore, the different frequencies interact differently with the precipitation particles. Microwave signals at the top of the atmosphere can be classified into two categories: (i) an emission signal that is dominant at lower frequencies and shows a warming signature in the presence of rain, especially in the absence of frozen particles, and (ii) a scattering signal that is dominant at higher frequencies and exhibits a cooling signature in the case of heavy precipitation with significant amount of frozen particles. Because the emission signal tends to dominate in light rain conditions while the scattering signal tends to dominate in heavy rain cases, both have to be considered to cover the entire rainfall spectrum.

Overlaying the different frequencies with variable transparency easily creates a fused product that allows one to see whether and where the intense surface rain is associated with intense frozen precipitation aloft.

Probably the best way to quickly grasp the organization and intensity of the precipitation is to display the Rain Indicator (RI; Hristova-Veleva et al. 2013), found at the bottom of this list. It combines, nonlinearly, brightness temperatures from a number of channels to form a single measure that presents a cohesive depiction of the rain and the graupel above and has characteristics similar to that of a 2D radar image (Hristova-Veleva et al. 2018b). As Fig. 1 illustrates, the Rain Index shows a capability to depict small-scale features and to capture both regions of light precipitation as well as regions of heavy rain, thus providing information on the storm structure and a first-order estimate of the intensity of the precipitation. These features of the Rain Index make it a desirable tool to use in studying the 2D distribution and variability of precipitation as it provides a 2D structure, much like a 2D map of radar reflectivity (Hristova-Veleva et al. 2013, 2016).

It is important to note that the RI can be computed not only from observations but also from models. The inputs to the RI, in the case of the models, are the synthetic brightness temperatures that can be produced from the model fields, as described in more detail in the "Model forecasts" section. This allows for a more direct comparison between models and observations that is based on the satellite-like depiction of the modeled storms.

PMW observations have proven to be fundamental to enhance our physical understanding (and thus the forecasting) of storm evolution (Kieper and Jiang 2012; Tao and Jiang 2015; Wimmers et al. 2019; Cossuth et al. 2012; Hristova-Veleva et al. 2011, 2012a). Bringing together, within the same system, the less frequent PMW observations from polar-orbiting (or LEO) satellites with the geostationary data provide complementary and more quantitative, physically based information on the clouds, yielding a comprehensive view of hurricane development, as high temporal and spatial resolution is combined with better hydrometeor discrimination capabilities.

Understanding the environment in which the storms grow is a critical component of hurricane research. To describe this environment, we incorporate data that capture the thermodynamics and the aerosol loading of the atmosphere. The more important subsets here are the total precipitable water (TPW) data from a number of microwave sounders (e.g., AMSU-A, MHS, ATMS) and the vertical profiles of water vapor and temperature from AIRS, which are used to characterize the thermodynamic environment and the storm-induced perturbations (the storm-induced modification of the shear and the removal of instability that result from the fluxes of momentum and sensible and latent heating that accompany the convective processes). The distribution of temperature and water vapor are known to play a key role in hurricane development, and their precise determination is crucial for predicting hurricane genesis and intensity changes, trajectory, and landfall location (e.g., Chen and Zhang 2013; Montgomery et al. 2009; Wang 2012; Wu et al. 2012).

Figure 2 provides an illustration on how the aerosol and the thermodynamic state of the environment can be revealed in TCIS. In this example, the aerosol optical thickness from MODIS is overlaid with the estimates from AIRS of the convective available potential energy (CAPE) shown as dots that are colored by the CAPE value. Clicking on each dot gives the user the CAPE value with the time and location of the observation. In addition, the estimated vertical structure of the temperature and humidity are available as a skew-*T* plot.

Another valuable category of data that has not been systematically exploited comprises satellite data on aerosol loading of the environment. Observations from MODIS on *Aqua* and *Terra* are also integrated into the system and can be readily used to elucidate the role of aerosols in the radiative and microphysical processes yielding hurricane genesis and intensification (Braun et al. 2013; Nowottnick et al. 2018; Rosenfeld et al. 2012).

Air–sea interactions are recognized as critical to improve modeling (e.g., Chen et al. 2007; Moon et al. 2007; Bender et al. 1993; Bender and Ginis 2000), and in order to advance investigation into this realm, the system includes the global high-resolution SST estimates from merged satellite (NOAA/POES AVHRR, TMI, GMI, AMSR) and in situ measurements (Chin et al. 2017). These can be used to characterize the storm's energy source and potential, and can complement surface wind observations from QuikSCAT, ASCAT, OceanSat

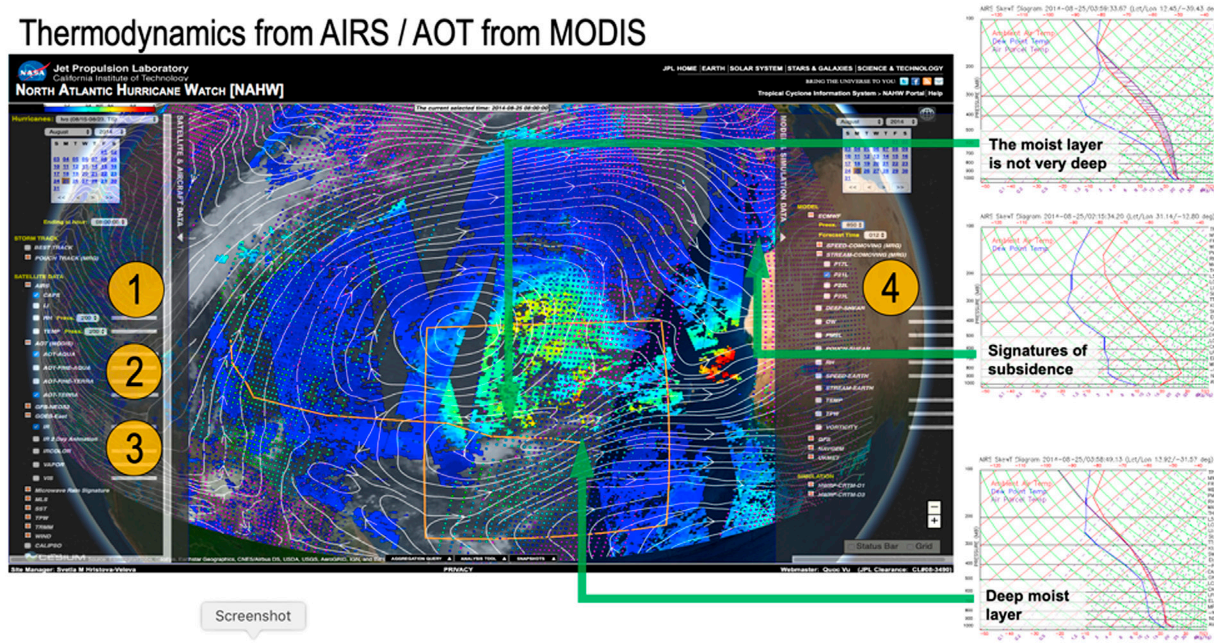

Fig. 2. Illustration of how the portal can be used to investigate the thermodynamic structure of the environment together with the aerosol loading. The image shows a 6-h composite of the aerosol optical thickness (AOT) from MODIS observations (in blue to red colors), together with the geostationary IR data (in grayscale). Overlaid are two additional fields: the streamlines showing storm-relative flow field at 850hPa from the 12-h forecast of ECMWF to allow investigation of the type of air that is entering the storm and the CAPE from AIRS retrievals, shown as place markers (dots) that are color coded by the CAPE value. Clicking on the place markers allows the user to view the retrieved thermodynamic structure, shown as a skew-*T* plot, at the particular location and allows comparison of the vertical profiles of humidity and temperature at various locations around the storm. Note that the numbers point to the observational and model data that are shown.

Scatterometer (OSCAT), and RapidScat scatterometers that directly depict the SST–wind interactions (Black et al. 2007; Emanuel 1986, 1999; Knaff et al. 2013; Zhu and Zhang 2006).

A very important component of TCIS is the inclusion of the best track data, available in all three portals. In addition, model tracker forecast tracks are available in the Atlantic and east Pacific (Fig. 3). Having the best track data allows researchers to understand the observed storm structure and environmental conditions in the context of storm evolution (its intensity and life cycle stage).

Model forecasts. Model forecasts are also an integral part of TCIS. Table 3 lists the forecasts models and the individual fields that are included in TCIS.

Model data provide a dynamically consistent picture of the relationship between the different characteristics of the storms and the interplay between the environment and the storm (e.g., Fig. 4). They contribute critical information on variables that we cannot observe routinely (e.g., the 3D structure of the flow). In the end, models are the ultimate tool for testing and validation of physical hypothesis regarding hurricane genesis and evolution: discrepancies between model simulations and observations indicate areas that need improvement, and the actual concrete differences may help to guide where, when, and why the model fails to simulate a process. Model data in the TCIS come from a variety of sources but with different selection available through the years. The model-richest period was during the Hurricane and Severe Storm Sentinel (HS3) campaign (2012–14; each year from 1 August to 1 November). Collaboration with the Montgomery Research Group (MRG) resulted in having the meteorological forecasts from a number of large-scale models [ECMWF, GFS, UKMET, and Navy

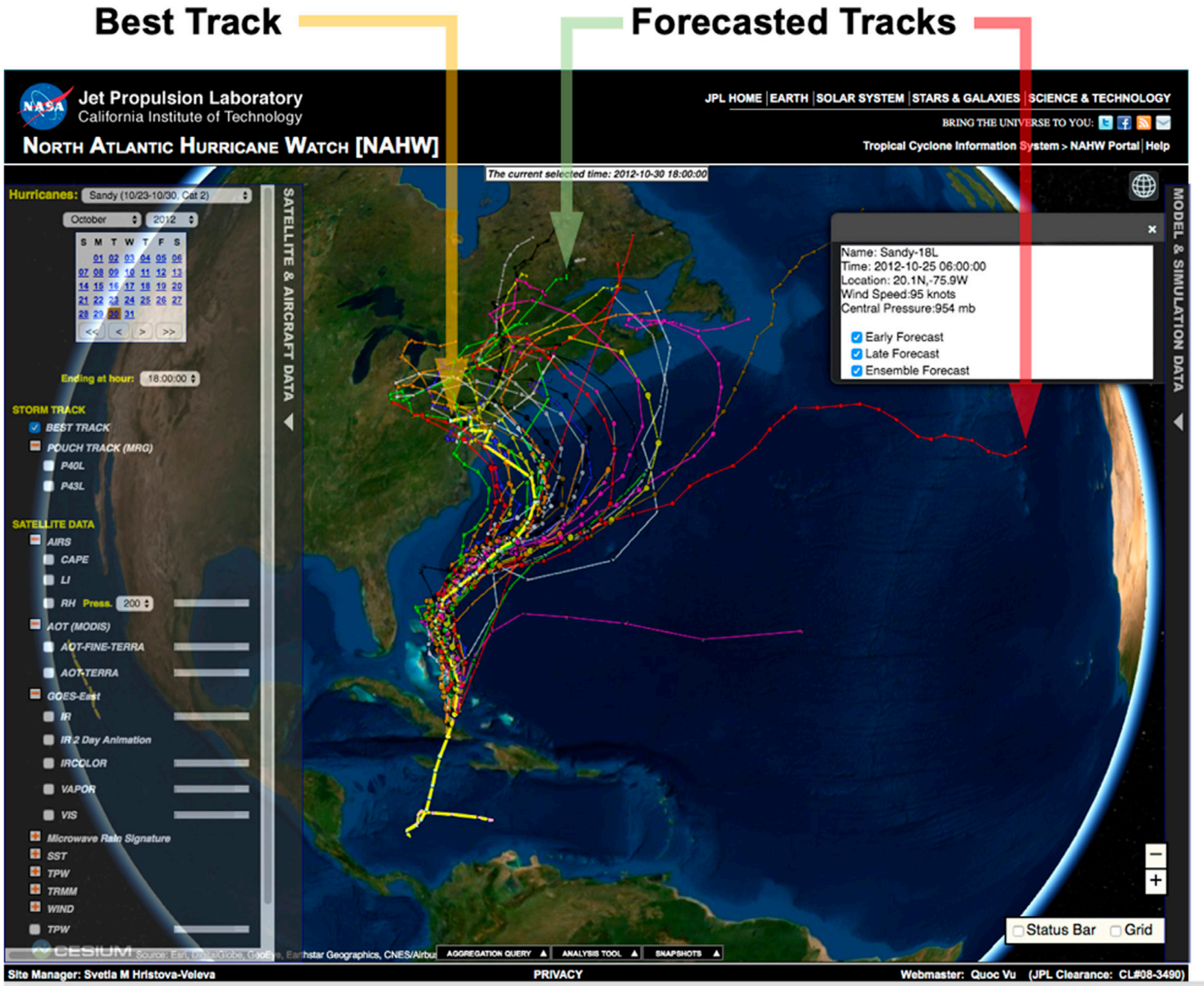

Fig. 3. Best Track data are included in the TCIS portals. The goal is to quickly provide information on the past evolution of the storm. In addition, forecast tracks from a number of models are made available to facilitate the understanding of the forecast uncertainty. The figure shows the best track data for Hurricane Sandy as of 29 Oct 2012. Each position is marked by a symbol (circle) whose size and color reflect the intensity of the storm at each 6-h interval. Clicking on any given position opens a small window that displays the name of the hurricane, the time and location of the hurricane, and its intensity in terms of maximum wind speed and minimum surface central pressure. In addition, the window allows the user to display the forecasted tracks from a number of models (each model forecast in a different color), all these forecasts starting at the selected location and time. These model forecasts are arranged in three groups [following Automated Tropical Cyclone Forecast (ATCF) designation]. Clicking on the individual symbols for a given forecast track shows information on the model, the time and location, the forecast hour, and the storm intensity. A very important feature of the TCIS interactive portals is the ability to search for a particular storm, from a database that is displayed under the menu "Hurricanes" at the very top of the "Satellite and Aircraft Data" menu on the left. Selecting a hurricane would then bring the user to the very last day of the storm's life cycle, showing the entire track. This allows the users to quickly navigate in time to point of their interest.

Operational Global Atmospheric Prediction System (NOGAPS)]. The MRG also provided the NAHW with daily analyses that depicted the "Pouch" center and track and computed the storm-relative flow. Such analyses provide critical information in determining the potential for hurricane genesis for each identified tropical disturbance according to the "Pouch theory" (Dunkerton et al. 2009; Montgomery et al. 2010). The Pouch tracks and storm-relative flow were available for all forecast models and forecast times. The Pouch tracks were made available in the same format as the best tracks to facilitate comparison between observed circulations and their model predictions (Fig. 4).

Table 3. Types and sources of model fields available in TCIS. For each model, the specific portals that provide the data are listed. Period of availability is given in parentheses.

Models	Data products	Data sources
GFS - NAHW - CPEX - CAMP2Ex	- Temperature, relative humidity, horizontal wind at standard pressure levels - 2D fields: ∘ 10-m winds, 2-m temperature, SST, MSLP ∘ Integrated precipitable water; shear (deep and low level)	NOMADS/ NCEP/NOAA MRG
ECMWF - NAHW (2012–16)	- Temperature, relative humidity, horizontal wind at standard pressure levels - 2D fields: ∘ Integrated precipitable water ∘ Shear (deep and low level)	MRG
UKMET - NAHW (2012–14)	- Temperature, relative humidity, horizontal wind at standard pressure levels - 2D fields: ∘ Integrated precipitable water ∘ Shear (deep and low level)	MRG
ECMWF - CAMP2Ex (2019–present)	- Temperature, relative humidity, horizontal wind, vertical velocity at standard pressure levels - 2D fields: ∘ 10-m winds, 2-m temperature, 2-m dewpoint, SST, MSLP ∘ Integrated precipitable water ∘ Total precipitation	CAMP^{2}Ex Team
GEOS5 - CAMP2Ex (July 2019–present) - NAHW (October 2019–present)	- Temperature, relative humidity, horizontal wind, vertical velocity at standard pressure levels - 2D fields: ∘ 10-m winds, 2-m temperature, 2-m humidity ∘ Integrated precipitable water; integrated ice water path; integrated liquid water ∘ Aerosol optical depth/thickness (AOD) total ∘ AOD coarse mode ∘ AOD fine mode	NCCS/GSFC MDISC
HWRF (regional model) - NAHW (2013–15)	- Synthetic microwave brightness temperatures - Rain Index	EMC/NCEP/ NOAA

In addition, collaboration with the Environmental Modeling Center (EMC) resulted in the integration of the hurricane operational forecast produced by the high-resolution regional Hurricane Weather Research and Forecast (HWRF) model into TCIS. A moving-domain strategy was followed to better capture hurricane dynamics and mitigate the effects of lateral conditions. The most important benefit of the collaboration was the inclusion of the synthetic brightness temperatures produced using the Community Radiative Transfer Model (CRTM) under development at the Joint Center for Satellite Data Assimilation (JCSDA). CRTM is an instrument simulator that took as input the hydrometeors, temperature, humidity, and surface conditions as forecasted by the HWRF model. Having side-by-side observed and the simulated passive microwave brightness temperatures allowed for direct comparison between models and observations. It also facilitated the comparison of the observed and simulated storm structure as revealed by the RI and analyzed by the hurricane-specific online analyses tools described below.

In recent years the model data available in the NAHW have focused on the GFS large-scale model forecasts. However, recently, as part of CAMP^{2}Ex portal development, the team gained new ability in incorporating other models (ECMWF, GEOS-5) and creating ensemble means. Some other new features have also been developed (e.g., overlaying coasts, synchronizing

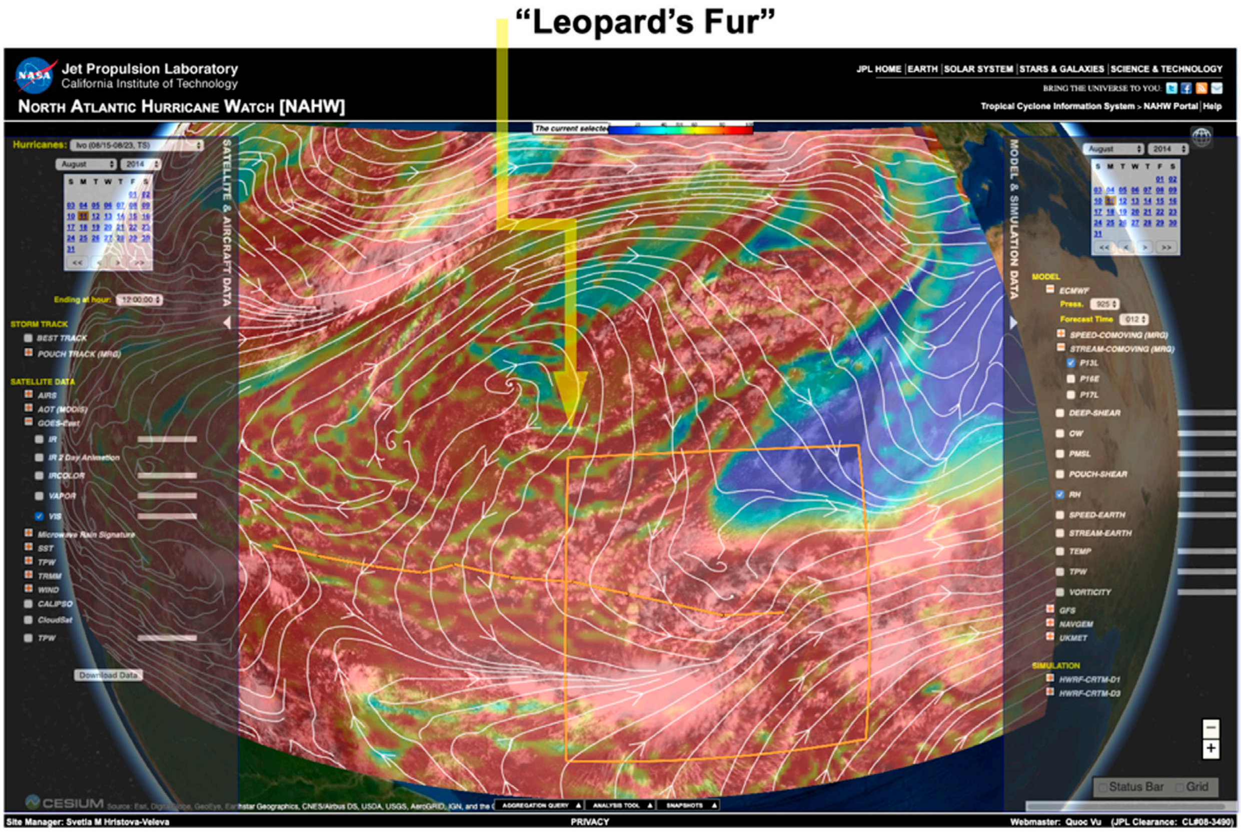

Fig. 4. Model relative humidity at 925 hPa from the 12-h forecast from ECMWF is colored. It is overlaid with the storm-relative flow (courtesy of MRG) from the same model forecast. In the background is the visible imagery from geostationary satellite observations. The model-forecasted relative humidity is displayed with transparency, allowing the user to see the correlation between the model relative humidity and the observed low-level clouds.

model and observation dates, option to download KML/KMZ tar files with the data being viewed at a particular time) These will soon be incorporated in the NAHW portal as well. TCIS allows quick access to both individual and merged data and offers seamless tools to combine apparently dissimilar sources.

From data to research: Interactive visualization and online analysis tools

In terms of user experience, TCIS integrates a variety of satellite observations from a number of instruments with the forecasts of several models in a virtual globe. To help users navigate the system, we recently developed a tutorial video for the NAHW portal (https://nahw.jpl.nasa.gov/NAHW_Tutorial_Video.mp4). A similar tutorial with a focus on the CAMP^{2}Ex portal (https://camp2ex.jpl.nasa.gov/CAMP2Ex_Tutorial_Video.mp4) is also available. Below is an illustration of the several features that can help the users.

Menus. Figure 1 provides an illustration of the wealth of data available in the NAHW portal. User choice is driven by two independent menus—one for the observations (left panel) and one for the model data (right panel). Each menu is driven by an independent calendar, allowing the user to display observations together with the user-defined model forecast cycle or forecast hour.

Discovering a storm. Figure 3 demonstrates a very important feature of the TCIS interactive portals, namely, the ability to search for a particular storm from a database that is displayed under the menu "Hurricanes" at the very top of the "Satellite and Aircraft Data" menu on the left (Sandy in Fig. 3). Selecting a hurricane would then bring the user to the very last day of the storm's life cycle, showing the entire track. This allows the users to quickly navigate in time to point of their interest.

Overlays. TCIS also contains an interactive system for visualization of highly complex systems (storms that evolve as the result of nonlinear multiscale interactions) that allows for user-driven overlay of different parameters, with transparencies. This architecture supports interrogation of observations to reveal relationships between different environmental and storm characteristics (e.g., precipitation and surface wind, forecasted flow, and observed relative humidity) and for comparison of forecasted and observed parameters. Figure 4 presents an example of how the portal can be used to interrogate models and observations to understand how different features are related. In this case, an interesting structure often observed in the model forecasts was investigated. Dr. Tim Dunkerton (2014, personal communication) called it "leopard's fur" pattern in ECMWF boundary layer relative humidity (RH) because of the stripe-like appearance of the alternating narrow regions of high and low relative humidity. The model/observations overlay corroborates his suggestion that "shallow overturning circulations are responsible for vorticity and relative humidity anomalies alike in these regions." The low-level clouds in the visible imagery are well correlated with the model's relative humidity and vorticity fields (not shown). The ability to overlay products/variables, with different transparency, proved very helpful in this case.

Analysis tools. Most importantly in terms of investigating the physics, TCIS has a set of online analysis tools that work both with observations and models and that allow quick investigation of storm structure and evolution (Figs. 5–8). Geospatial data searches and analysis tools work together through intuitive user interfaces. The framework we adopted has the following critical components: (i) subset and reformat data into consistent format, (ii) develop a geospatial database architecture to support the analysis tools, (iii) develop the user interface and its integration with the database and the tools—we call this the "subsetting tool," and (iv) develop the analysis tools.

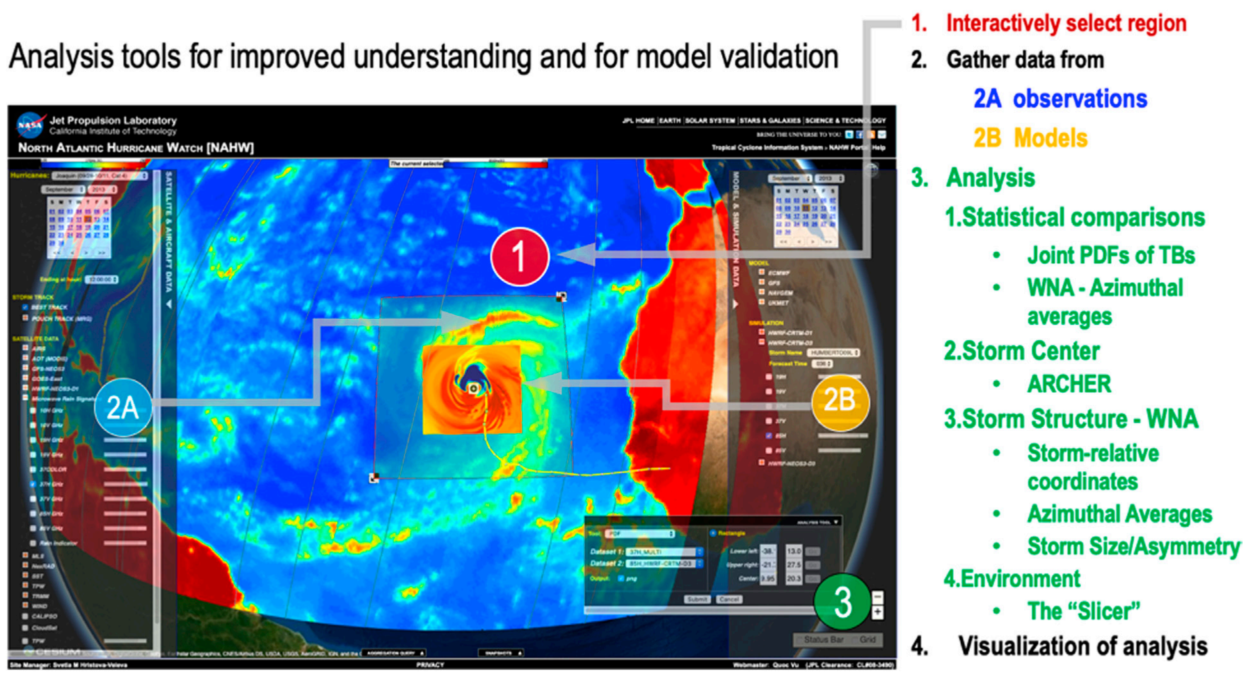

Fig. 5. List of the main hurricane-specific analysis tools of the system: WNA, ARCHER, the Slicer, and the computation of the joint statistics of brightness temperatures from any two channels (the joint PDFs).

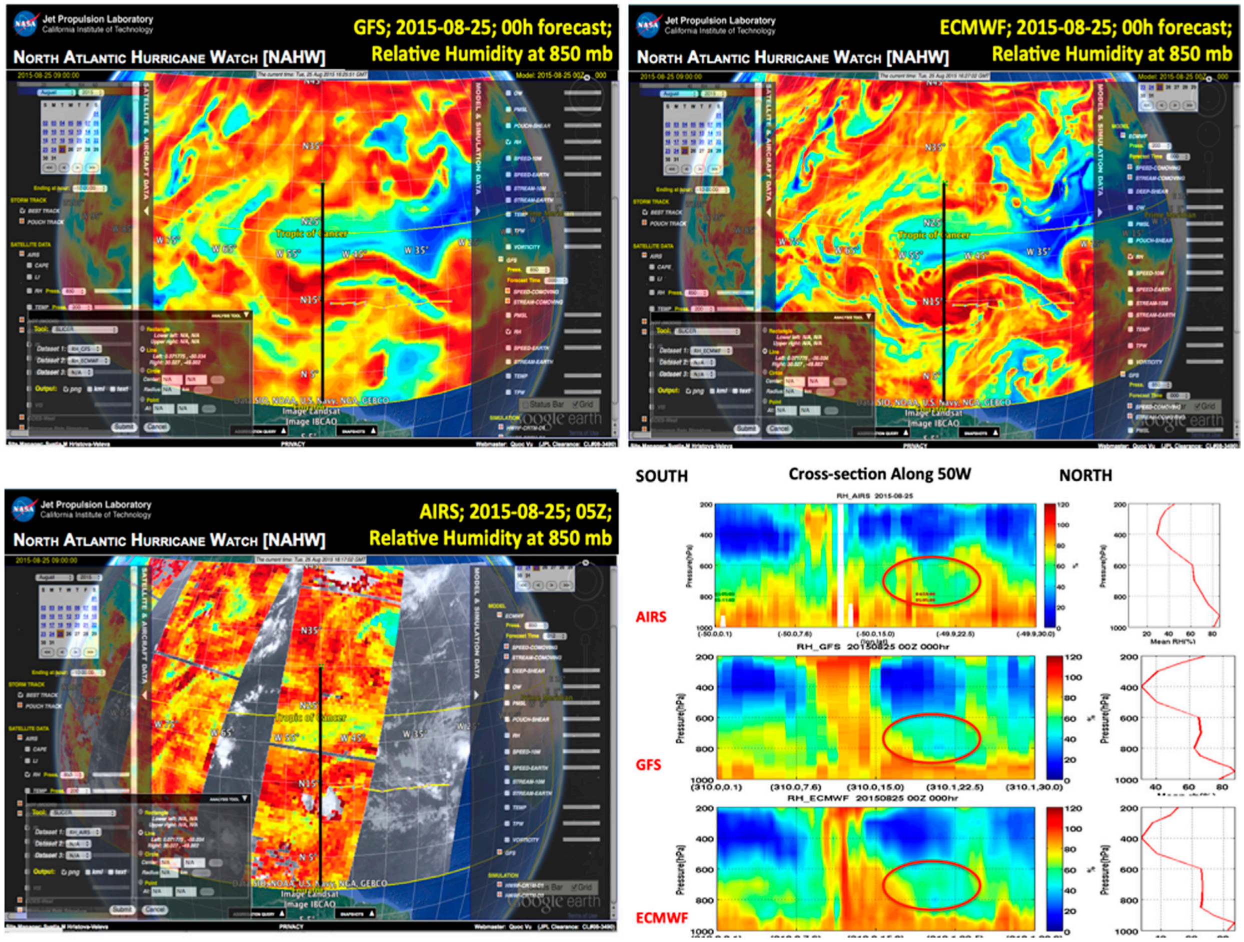

Fig. 6. Illustration of how the horizontal fields at different pressure levels and the vertical Slicer tool can be used to evaluate the environment around the storm and to compare how accurately it is depicted in the model forecasts. (top left) The 850-hPa relative humidity in the GFS analysis. (top right) As in the top-left panel, but in the ECMWF analysis. We see generally similar fields in both models but with a better resolution and more detail in the ECMWF analysis. (bottom left) Retrievals from AIRS observations, however, show a field with more moisture just north of the storm. (bottom right) To evaluate the vertical structure in the observations and the two models, we run the Slicer tool along the black line in all three fields. Indeed, the comparison between the observations and the two models shows a dry tendency for the models.

Figure 5 summarizes the concept and lists the main analysis tools of the system—the Wave Number Analysis (WNA), Automated Rotational Center Hurricane Eye Retrieval (ARCHER; Wimmers and Velden 2016), the computation of the joint statistics of brightness temperatures from any two channels (the PDF tool), and the "Slicer." Table 4 provides more information on each of the tools, describing their purpose and inputs.

Tropical Cyclone Data Archive. As mentioned earlier, in addition to the three interactive portals for user-driven visualization and online analyses, TCIS includes a static stand-alone searchable MySQL-based TCDA (https://tcis.jpl.nasa.gov/data/TC_Data_Archive/) that contains a 12-yr global record (1999–2010) of satellite observations of tropical cyclones from a number of instruments and missions pertaining to (i) the thermodynamic and microphysical structure of the storms, (ii) the air–sea interaction processes, and (iii) the larger-scale environment. The digital data (and imagery) are subset to the domain and time of interest, thus greatly reducing the volume of unwanted data. The data are organized by ocean basin, year, and storm. As such, the TCDA provides an easy way to determine when coincident observations from multiple instruments are available—a very valuable and unique feature that saves researchers

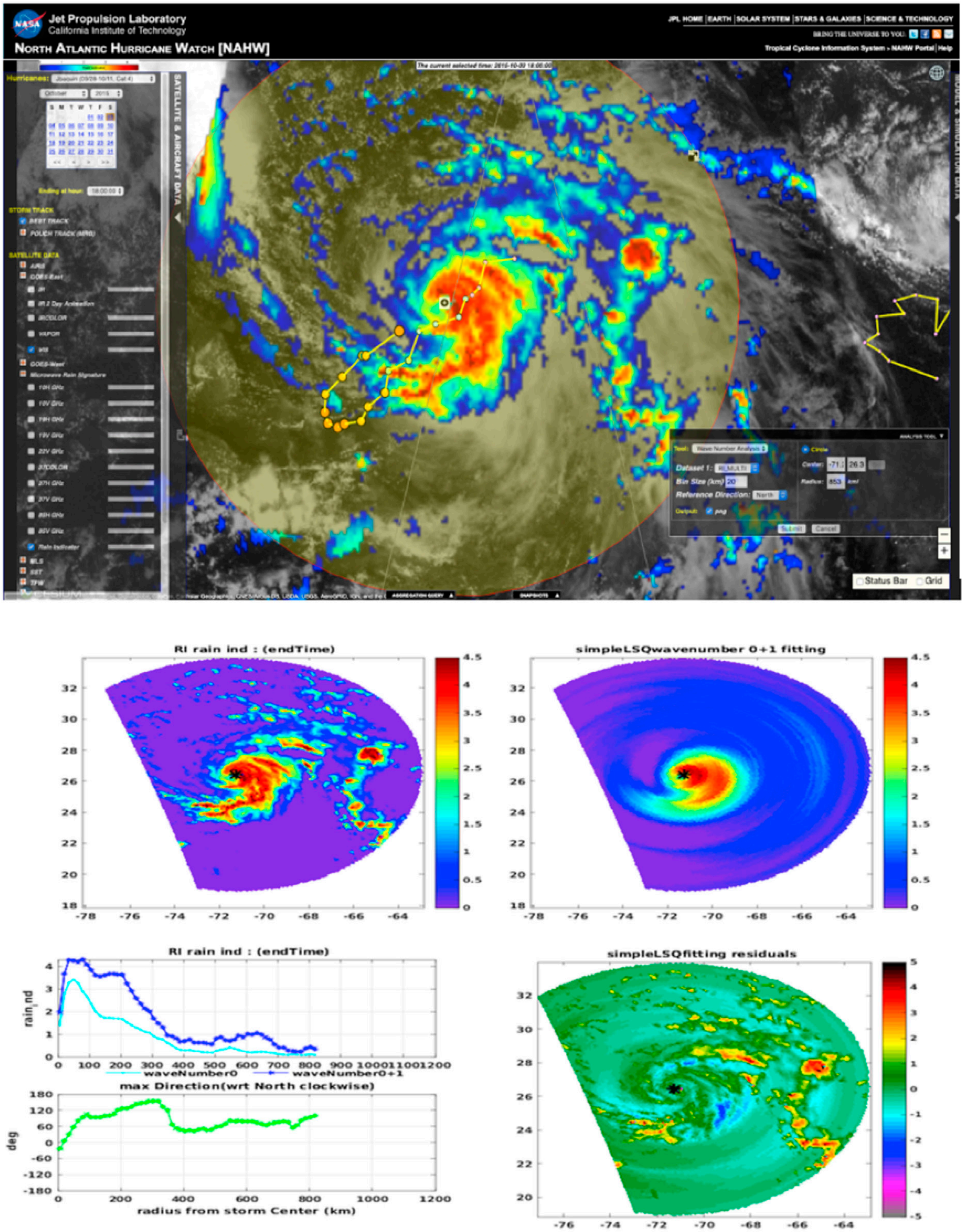

Fig. 7. (top) The NAHW portal and how the WNA tool can be initiated and (bottom) the results from the WNA of the storm's precipitation structure (as depicted by the RI on 10 Oct 2015). The four bottom panels show (in clockwise direction from top left): the full field, the representation as depicted by wavenumbers 0 and 1, the residual, and the radial distribution of wavenumber 0 (cyan) and the amplitude of wavenumbers 0 and 1 (blue) in the top line plots and the radial distribution of the direction in the peak of wavenumber 1 (green) in the bottom line plot. The distance between the two curves in the top line plot signifies the degree of storm asymmetry: the larger the distance, the more energy there is in wavenumber 1, and the more asymmetric the storm is. The green curve shows the azimuthal location (in degrees from north) of where the peak in wavenumber 1 is, as a function of distance from storm center. By simply subtracting the direction of storm motion, or the direction of the environmental shear, this green curve will represent where the peak of the field is, in storm-relative

coordinates with dynamical significance. Several recent studies (e.g., Chen and Gopalakrishnan 2015; Rogers et al. 2016) have pointed to the significance of the azimuthal location of the deep convection with respect to the shear vector and the presence or absence of counterclockwise propagation of this convective peak. Analyses of the data reflected by the green curve will prove very informative in these types of studies.

a significant amount of time dedicated to discovering the data alone. Particularly useful in this regard is a user interface we developed in the past (Figs. 9, 10). This interface (https://tropicalcyclone.jpl.nasa.gov/tcda/index.php) is now undergoing upgrades and while being functional, it is expected to be further improved by December 2020. In addition, work is underway to extend the 12-yr record. The purpose of the TCDA is to facilitate the quick build of statistics, including development of statistical relationships between different parameters, in support of research, forecast improvement, and algorithm development (e.g., Hristova-Veleva et al. 2014; Wu et al. 2012; F. J. Tapiador et al. 2019, unpublished manuscript).

Examples of applications

Tropical cyclones are the product of complex multiscale nonlinear interactions. The role of the environment in influencing an RIC has long been recognized (e.g., Kaplan and DeMaria 2003; Kaplan et al. 2010). However, as noted above, recent research has shown that convective-scale processes in the hurricane core might also play a crucial role in determining the rapid change in TC intensity (e.g., Gray 1998; Chen and Zhang 2013; Rogers et al. 2013; Guimond et al. 2010). A third set of controls is the interaction between the storm-scale and the large-scale processes.

The overarching goal of TCIS is to support investigations of these complex multiscale interactions. To achieve that goal, TCIS brings together multiparameter data to help better understand the large-scale and storm-scale processes associated with tropical convection in general, and, in particular with hurricane genesis, track and intensity changes. The more specific goals are fourfold: (i) to allow near-real-time (NRT) interrogation of a large number of atmospheric and ocean variables; (ii) to allow for easy evaluation of models by comparison with existing observations; (iii) to serve as a very rich information source during the analysis stages of the field campaigns—both the CPEX and the CAMP^{2}Ex portals have already been used to characterize the large-scale environment of the airborne observations taken during the 2017 CPEX and the 2019 CAMP^{2}Ex campaigns (Fig. 11); (iv) to support in-depth posthurricane research. Indeed, posthurricane analyses of a number of storms (e.g., Hristova-Veleva et al. 2016) has led to the development of possible satellite-based predictors for hurricane RIC—a topic of intense research, with potential for supporting decision-making during disaster management (e.g., Bhalachandran et al. 2018, 2019; Hristova-Veleva et al. 2018a; F. J. Tapiador et al. 2019, unpublished manuscript).

RIC: Focus on the hurricane core. A recent composite study (Rogers et al. 2013) and a case study (Reasor et al. 2009) of airborne Doppler observations have indicated that a very important aspect of the hurricane RIC process might involve the location of the convective activity with respect to the radius of maximum wind (RMW). Motivated by this, the TCIS system has been used to perform analyses of satellite hurricane observations, looking for predictors of RIC. The system allows examination of the joint behavior of the structure of the 2D precipitation and the near-surface wind for TCs that undergo rapid intensification and rapid decay using satellite observations of Atlantic hurricanes. Using the online WNA (e.g., Vukicevic et al. 2014) tool available in the TCIS system, a number of case studies were carried out (e.g., Figs. 7, 8) and potential predictive capabilities for hurricane RIC were found (Hristova-Veleva et al. 2016). These studies uncovered the importance of monitoring the amount of precipitation inside versus that outside the radius of maximum wind—precipitation

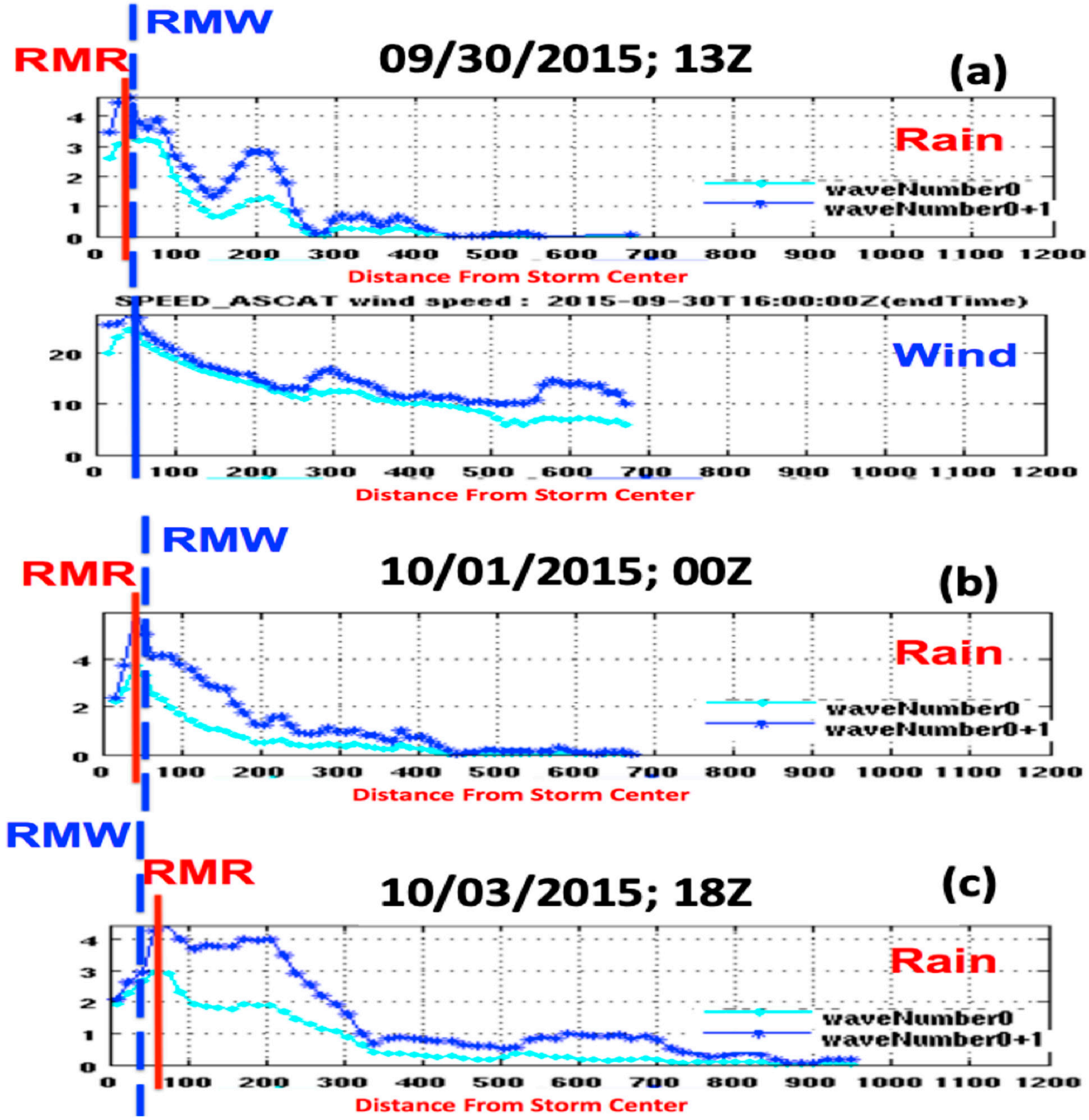

Fig. 8. Radial distribution of the wind and rain fields as determined using the WNA tool on satellite observations of Hurricane Joaquin showing results from analyses at three different times. (a) Relationship in the radial distribution of the rain and wind fields. Several important observations can be made: (i) the storm is more asymmetric in rain than in wind and (ii) RMW is just a bit larger than the radius of maximum rain (RMR). There is significant precipitation inside RMW. According to previous research, this suggests that the conditions are conducive to RI (e.g., Rogers et al. 2013). It is very interesting to note that this analysis was performed just before the onset of the RI—it was done using observations during 1300–1600 UTC 30 Sep while RI seems to have begun after 1800 UTC. It is also important to note that this RI was not predicted by the models with forecast cycles starting at 1800 UTC 30 Sep 2015. (b),(c) WNA of the rain field only, still relating it to the RMW determined from the WNA of the wind field. Note the very intense precipitation, inside the RMW, observed at 0000 UTC 1 Oct 2015 in (b), suggesting again the strong potential for further intensification. Indeed, this analysis was performed during the early stages of RI. All this comes in contrast to the results from the analysis at 1800 UTC 3 Oct 2015 in (c). The storm is becoming very asymmetric away from the center. The RMR is now outside the RMW, suggesting that the conditions at this time are not conducive to intensification. Indeed, this analysis is at the end of the peak storm intensity.

Table 4. Online analysis tools: Purpose and inputs. Note that for the inputs, the data need to be displayed for the tool to be initiated.

Analysis tools	Purpose	Inputs
WNA (Wave Number Analysis)	Provides an objective and concise depiction of the 2D distribution of a given field. Fourier decomposition of the 2D field is performed along the azimuthal direction for an arbitrary distance from the storm center. The decomposition is truncated at the first harmonic respectively, keeping the amplitudes of axisymmetric (wavenumber 0) and first harmonic (wavenumber 1). WNA can be used to evaluate several important characteristics of the storm and to quantify: (i) the degree of storm symmetry as a function of distance from the storm center. (ii) the radial distribution of a given filed field (wind, rain), as the wavenumber decomposition is performed in several user-defined (default is 20 km) annuli, at distances that are progressively farther away from the storm center. The relative location of the peaks of the different fields (here the distribution of rain in relation to the RMW, with dynamical consequences for the rapid intensification). (iii) the azimuthal location of the peak in wavenumber 1 relative to important dynamical factors such as the shear vector or the direction of storm motion.	- Rain Indicator from observations or models - Surface winds from observations
ARCHER (Wimmers and Velden 2016)	Finds the center of rotation using spirally oriented brightness temperature gradients in the TC banding patterns in combination with gradients along the ring-shaped edge of a possible eye. Calibrated and validated using 85–92-GHz passive microwave imagery because of this frequency's relative ubiquity in TC applications.	- Brightness temperature at 85H GHz (horizontal polarization) from observations and models - Brightness temperature at 85V GHz (vertical polarization) from observations
Slicer	Provides vertical cross section at user-specified location, orientation, and horizontal extent. Helps interrogations of the environment around the storms. Helps evaluate models through comparison to observations.	- 3D temperature (displayed at any pressure level) from observations and models - 3D relative humidity (displayed at any pressure level) from observations and models
PDF (probability density function)	Computes joint probability distribution of brightness temperatures of user-specified frequencies. Helps reveal relationships between liquid and frozen precipitation. Helps evaluate model forecasts of hydrometeors by comparison of modeled and observed joint PDFs.	- Any combination of brightness temperatures at two user-specified frequencies from observations and models (HWRF)

and wind being two variables that are well represented within TCIS. In the process, we developed a new method for identifying the storm center, which is a critical component in the wavenumber-based analysis of the storm structure.

TCDA statistical analyses of RIC. The case studies above found that significant precipitation inside the RMW was associated with RI while the development of intense rainbands outside the RMW was often associated with rapid weakening of the storms. These results are in agreement with expectations, based on theoretical work and airborne data. However, all observational studies so far have been based on a limited set of cases. Motivated by the desire to establish the statistical significance of the results, another study was carried out using the TCDA to test the robustness of the potential predictors (F. J. Tapiador et al. 2019, unpublished manuscript). The study used the observations of precipitation and ocean surface wind available from the 12-yr record of satellite observations over the Atlantic. Only semicoincident satellite wind and

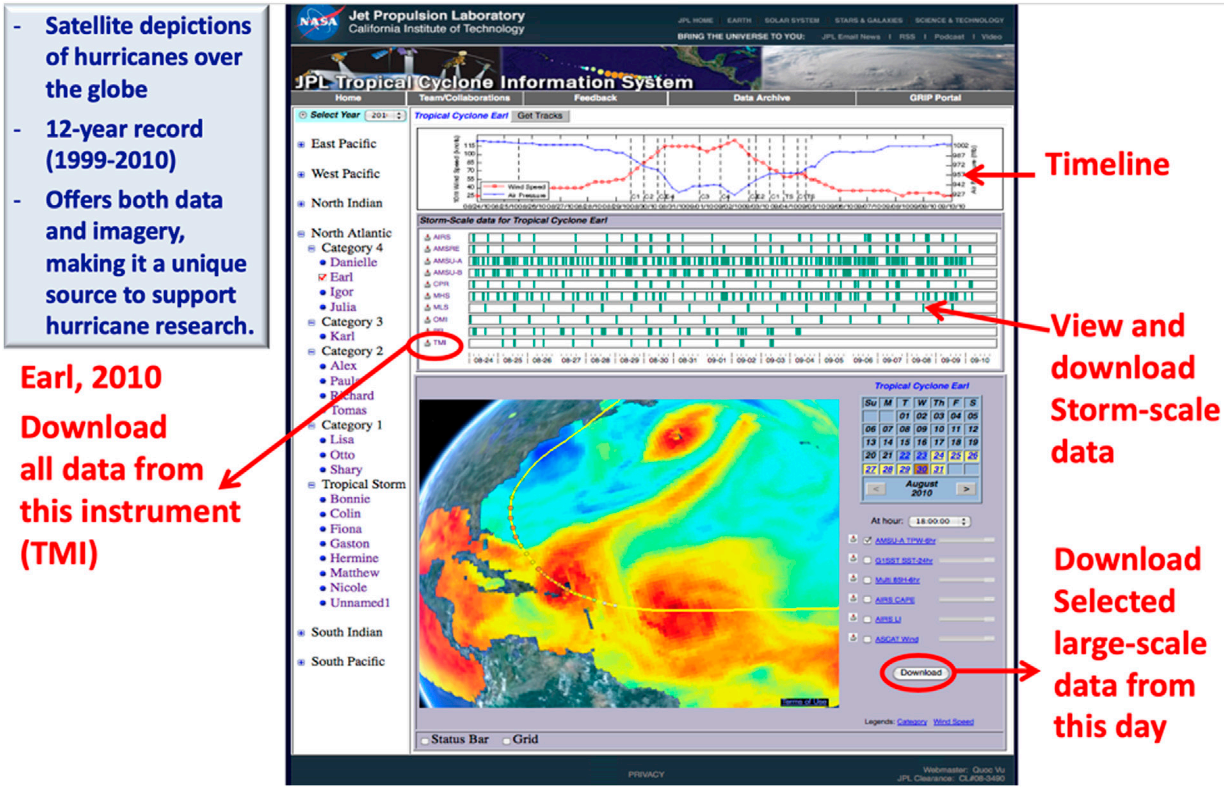

Fig. 9. The user interface to the TCDA we developed in the past. The top-left menu allows the selection of the year, followed by selection of the ocean basin. After that, the menu on the left is populated with the names of the observed tropical cyclones, organized by storm category. Once a storm is selected by the user, the right-hand side is populated with the specific information on that storm. It provides a quick overview of the storm evolution (the timeline on the top that shows the evolution of the surface wind maximum and the minimum of the surface pressure). The best track data are shown at the bottom, overlaid with the TPW. Both are shown on the last day of the TC life cycle. The calendar on the right allows the user to go back in time to a point of interest and also to select what large-scale environmental data should be displayed. A particularly useful feature is the box with green bars in the middle. Each bar indicates the time when a particular satellite flew over the storm. This table provides a very quick and easy way to determine when coincident observations of the storm are available. Clicking on the bars opens another window (see Fig. 10) where these data are visualized and can be downloaded. In addition, there are two other ways to download the data—by clicking on the instrument name to the left of the green bars, one can download a tar file with all observations of this storm by this instrument. By clicking on the "Download" button on the right side, one can download all large-scale data that depict the basin-scale observations of the environment. This interface (https://tropicalcyclone.jpl.nasa.gov/tcda/index.php) is now undergoing upgrades, and while being functional, it is expected to be further improved by December 2020.

rain data (within 3 h of one another) were retained. Using the WNA approach, these data were used to characterize the joint distribution of the wind and rain at the initial time and to relate this distribution to the subsequent changes in intensity. Again, the importance of monitoring the distribution of precipitation with respect to RMW was established.

Machine learning: The role of the vortex vs that of the environment. Stimulated by previous research, a machine learning (ML) approach was developed and applied to a large number of model simulations to study the multiscale interactions between the environment and storm-scale processes (Bhalachandran et al. 2018, 2019). Using linear discriminant analysis (LDA), they compared the relative importance of vortex and environmental processes, symmetric versus asymmetric precipitation, the presence/absence of deep convective bursts defined by upward vertical velocity limit, within the radius of maximum wind (RMW), and associated processes toward causing RIC. This new LDA methodology proves the existence of a

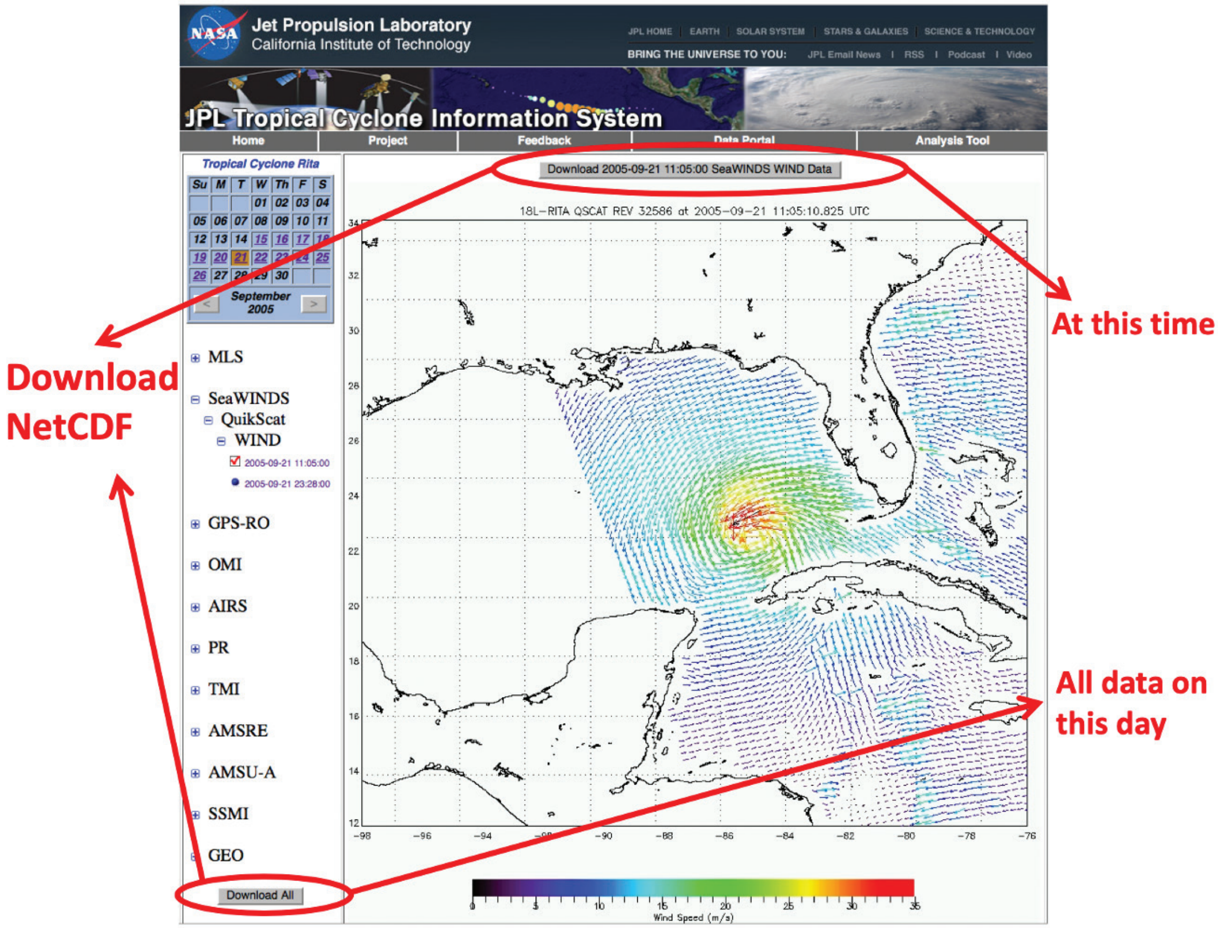

Fig. 10. The user interface invoked by clicking on the storm-scale data in the table of green bars available from the top-level TCDA user interface (Fig. 9). This interface provides several options: (i) visualization of the particular image; (ii) a download button for the data that correspond to this image; (iii) a button to download all other satellite overpasses on this data, from all instruments available in the TCDA; and (iv) a calendar that allows the user to go to another day of the storm's life cycle (note the days in life cycle of the storm are color coded in the calendar, appearing in purple, to facilitate the quick discovery of days with available data).

discriminant that can effectively separate Rapidly Intensifying (RI) from Rapidly Weakening (RW) storms, using a combination of vortex and environmental variables with equal importance (55:45). LDA computed with just the precipitation variables confirms the importance of monitoring the amount of precipitation inside and outside the RMW. The processes were first uncovered using the interactive system for satellite data visualization and online analyses into the NAHW—a platform to visualize and analyze the dynamical (wind related) and thermodynamical (precipitation related) components ultimately impacting the fate of the vortex.

Model evaluation to provide "guidance on guidance." A great improvement that will enable the more realistic forecasting of tropical cyclones would be the use of high-resolution ensembles whose prototypes still present significant shortcomings due to the uncertainty in the initial conditions and in the physical representation of the processes. TCIS has also been used to develop metrics to allow subselection of the most the realistic members of an ensemble forecast, based on objective measures of the similarity between the observed and the forecasted structure of the storm and its environment. This approach would allow forecasters to provide "guidance on guidance" to reduce the forecast uncertainty (cf. Hristova-Veleva et al. 2018a).

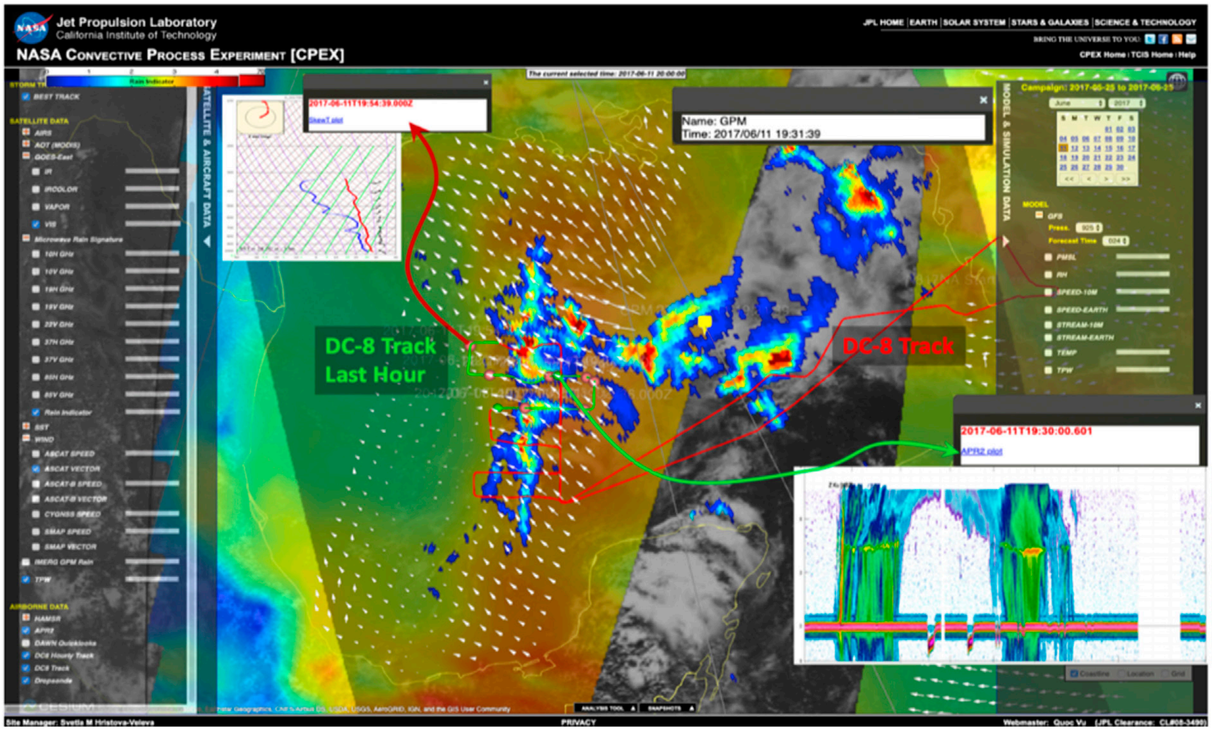

Fig. 11. A snapshot of the CPEX Data Portal we developed in support of the 2017 CPEX NASA field campaign. The figure depicts the variety of satellite and airborne observations, combined with model forecasts, that were collected on 11 Jun 2017. The satellite (and model) data are available in separate layers that can be interactively overlaid, with variable transparency, to create a user-defined depiction of the storm and its environment, together with the aircraft data and tracks. The airborne observations are presented in several ways: (i) the flight tracks, for different planes, are plotted either for the entire flight (here in red for the DC-8) and/or for the last hour (here in green) and (ii) the variety of airborne observations are plotted as pop-up figures, evoked by clicking on the place markers that appear when a particular set of airborne data is selected from the menu on the left [examples here are quick looks of the radar observations from Airborne Second Generation Precipitation Radar (APR-2) and the skew-*T* plots from the dropsondes]. This complex presentation of all available observations allows the users to very quickly (i) find out what observations were available when and (ii) understand the large-scale context in which the airborne observations were collected. In this example, note that the observed storm [as revealed by the RI (sharp colors, from dark blue to dark red), computed from GPM observations] had developed in a region of sharp gradient in the moisture (seen in the satellite-derived TPW, depicted in the faded colors—from light blue and green to orange) and in an area of strong surface convergence (as revealed by the near-surface winds derived from satellite-based scatterometer observations).

Conclusions

The JPL Tropical Cyclone Information System is a valuable resource for hurricane research that is open to the community. TCIS is being developed to help scientists improve their understanding and forecasting of tropical convection. The goals are (i) to allow interrogation of a large number of atmospheric and ocean variables to help better understand the multiscale nonlinear interactions that lead to storm development and intensification, (ii) to allow for easy evaluation of forecast models by comparison with existing observations, and (iii) to serve as a rich information source during the planning and analysis stages of field campaigns and to support in-depth posthurricane research.

This paper highlights some potential uses of the JPL TCIS through pilot projects and direct applications of the novel tool. These, however, are just a few examples intended to illustrate the potential. The system can be used by anyone to explore new avenues of research. TCIS allows atmospheric scientists to spend more time on new ideas and concepts rather than painstakingly gathering observational and model data that typically reside in separate databases and even across different agencies. Considering the growing interest in improving hurricane predictability, the societal implications of this meteorological phenomena, and the need of levering resources, JPL's TCIS provides a needed service. Indeed, the new resource has already achieved three important goals: (i) increase the accessibility and utility of NASA and NOAA observational data, (ii) enable the development of new information products, and (iii) demonstrate the applicability to this technology to respond to the challenges posed by hurricanes on life and property.

We plan on using the TCIS framework in support of other upcoming field campaigns [e.g., the 2020 NASA field campaign Convective Processes Experiment–Aerosols and Winds (CPEX-AW) and a couple of the upcoming Earth-Venture Suborbital-3 (EVS-3) campaigns—Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) and Aerosol Cloud Meteorology Interactions over the Western Atlantic Experiment (ACTIVATE)]. Our future work will be directed toward moving the TCIS into the cloud to make it more scalable, with more flexible resources. This will have two benefits: (i) it will allow us to run TCIS globally, and (ii) it will make the novel software readily accessible for other programs (e.g., other field campaigns or small missions) to easily configure and run a similar information system in support of their own needs.

Acknowledgments. The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). This system was developed with the support of several NASA programs—the Earth Science Technology Office/Advanced Information Systems Technology (ESTO/AIST) Program; the Hurricane Science Research Program (HSRP); *CloudSat*; QuikSCAT/RapidScat; the Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP^{2}Ex); the Convective Processes Experiment (CPEX); the Weather and Atmospheric Dynamics Program; and the Making Earth Science Data Records for Use in Research Environments (MEaSUREs) program. TCIS was built in close collaboration with NOAA/AOML/HRD, NOAA/EMC, and the Naval Postgraduate School to support hurricane research. F. J. Tapiador and Andrés Navarro acknowledge projects PID2019-108470RB-C21, CGL2013-48367-P, and CGL2016-80609-R to carry out the pilot project on rapid intensification. We would like to acknowledge three anonymous reviewers, whose comments and suggestions on an earlier version greatly benefited the article. Special thanks go to Ms. Robin Vane for the development of the TCIS tutorial videos.

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