Importance of the Coupling of Tropical Cyclone
Outflow Vents with the Environment: Observational
and Model Sensitivity Studies

Co-PI: Christopher Velden
University of Wisconsin – SSEC/CIMSS
1225 W. Dayton St., Rm 229
Madison, WI 53706
Phone: (608) 262-9168 Fax: (608) 262-5974
Email: chrisv@ssec.wisc.edu

Co-PI: Brett Hoover
UW-SSEC/CIMSS
1225 West Dayton Street
Madison, WI 53706
bthoover@wisc.edu

Collaborator: Sharanya J. Majumdar (separate funding)
RSMAS/MPO, University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
Phone: (305) 421 4779 Fax: (305) 421 4696
Email: smajumdar@rsmas.miami.edu

Collaborator: James D. Doyle (separate funding)
Naval Research Laboratory
7 Grace Hopper Avenue
Monterey, CA 93943-5502
Phone: (831) 656-4716 Fax: (831) 656-4769
Email: james.doyle@nrlmry.navy.mil

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LONG-TERM GOALS

Forecasts of TC intensity change are often lacking in skill due in part to the paucity of conventional
observations over the oceans that are assimilated into the operational models. The inability to
accurately map the three-dimensional atmosphere and the underlying upper ocean has also constrained
our understanding of how intensity fluctuations are governed by internal and environmental processes.
Remotely-sensed observations from multiple satellite sources have become more routinely available as
part of the atmospheric/oceanic observing system. As an important input to global numerical data
assimilation and forecast systems, these data are providing crucial large-scale environmental
information for better predicting such parameters as TC outflow fields. However, in regard to TC
intensity change, it is clear that a dedicated research effort is needed to optimize the satellite data processing strategies, assimilation, and applications within a higher resolution modeling framework.

Our study addresses the fundamental aim of the Office of Naval Research (ONR) Tropical Cyclone Intensity (TCI) initiative: to enhance the understanding of the upper-level outflow associated with tropical cyclones (TCs) and its connections with the larger-scale environment, in order to improve the prediction of TC intensification and structure changes that occur in response to these influences. The outflow characteristics, evolution, and configurations are being investigated in a comprehensive manner using innovative new observing systems and satellite observations, as well as state-of-the-science data assimilation and prediction models. Our study, in association with our Collaborators, is focused on observational analysis and numerical model forecast impacts to address the TCI scientific issues.

OBJECTIVES

The overarching goal of this research is to document the influence of upper-tropospheric outflow configurations on TC structure and intensity change. The basis for our investigation centers on the premise that ambient upper-tropospheric environmental conditions can influence TC outflow configurations and sustainability, and thereby modulate intensity/structure changes. A limited body of previous research has addressed this topic, primarily through the utilization of numerical global model analyses. However, recent and ongoing TC field programs offer new observational capabilities and datasets to examine these upper-level processes in unprecedented detail. Coupled with advanced, state-of-the-art data assimilation and regional models, we believe the tools exist to take a fresh look at the goals of TCI, and examine specific aspects outlined below. These include sensitivity and diagnostic studies which are being performed in collaboration with NRL-Monterey and U-Miami investigators.

APPROACH

Our project is taking advantage of unique datasets being made available through dedicated recent and ongoing field experiments. The NASA Hurricane and Severe Storm Sentinel (HS3) project included a 3-year field program (2012-2014) in the Atlantic basin to study hurricanes using high-altitude NASA Global Hawk (GH) drones. The NOAA follow-on is SHOUT, which conducted similar GH investigations during the 2015 TC season, and may return in 2016. Co-PI Velden and his team was/is involved in both of these efforts, and datasets are being collected and analyzed. The TCI initiative overlaps these projects, and will leverage the datasets that are collected.

In addition to routinely-available operational satellite imagery and data, other special satellite-derived datasets and products critical to the mission planning, in-flight track adjustments, and post-analyses are being made available by the CIMSS team to contribute to the field campaign analyses. Specifically, these include estimates of cloud-top heights and temperatures, over-shooting tops products, rapid-scan atmospheric motion vectors (AMVs) and derived products such as vertical wind shear analyses. All of these special products are being derived in real time by UW-CIMSS, and made available for both the mission support and the project archive for post-analysis. The AMV datasets (and derived fields) are being made available at hourly intervals during the field campaign periods. Diagnostic analyses from the field campaign cases will be used to address some of the TCI hypotheses. Where applicable and available, our studies will also rely on the NAVGEM global model system and high-resolution analyses from the Navy’s Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS-TC) regional model, in collaboration with our NRL-MRY colleagues.
An approach to diagnosing areas where the TC environment may be impacting intensity change is to employ adjoint tools. Specifically, we are investigating the interaction of TC outflows with larger-scale features. The relationship between TC outflow and surrounding environmental features can be diagnosed from sensitivity gradients, through the use of response functions designed specifically for the purpose of investigating these relationships. This can be done both from the perspective of investigating how the environment influences the TC outflow (through a prescribed response function defining the TC outflow, and observing which features of the environment the outflow is most sensitive), as well as how the environment is impacted by the outflow (through prescribed response functions defining a forecast feature of interest, such as the intensity of a downstream wave feature, and observing how sensitive that feature is to the TC outflow region). Also, the morphology and evolution of the TC outflow and its dependence on the environment is being investigated. Sensitivity gradients for response functions defining the intensity of the TC can be used to find outflow/environment interactions that are important for the analysis and forecasting of TC intensity.

These issues can be addressed through direct, dynamical interpretation of sensitivity gradients for select case studies; an examination of sensitivity structures near the outflow level can provide valuable information about the relationship of a simulated TC and its outflow environment that would otherwise be difficult or practically impossible to obtain.

Several response functions are being tested for their usefulness as a TC-intensity function, providing comprehensive information towards addressing the fundamental question “What dynamical processes/environmental features are most important to the future intensity of the TC?”

**WORK COMPLETED AND RESULTS**

This report represents the second year from which the project is funded. The research is being led by UW/CIMSS Co-PIs Velden and Hoover. The following tasks have been addressed in the past year (Lead investigator in parentheses):

**Year 2**

- Participation in the planning/execution of the 2015 TCI/SHOUT field campaign, and processing/collection of satellite-derived datasets for post analyses. (Velden)
- Developed adjoint sensitivity methodologies for perturbing the TC and its environment. (Hoover)

**TCI Field Campaign Support**

Data have been collected during Global Hawk and WB-57 flights of selected TCs in 2015. The PI and his team were responsible for contributing to mission planning, analysis and forecasting. All types of satellite data (including special GOES rapid scan observations) were collected and archived for post-season analysis. We plan to collaborate with TCI colleagues to analyze this data through comparative studies and diagnoses of the outflow layer behavior. An example of the satellite-derived atmospheric motion vectors (AMVs) produced by the CIMSS team during Hurricane Joaquin are shown in the figure below. Good depiction of the outflow structure by the AMVs will be complemented by the vertical structure obtained from concurrent WB-57 dropsonde winds. More cases will be compared and analyzed in the next reporting year.
Figure: Plots of upper-level AMVs produced by CIMSS for TC Joaquin (2015) during the time of TCI WB-57 missions at 1800UTC on Oct 1st (top), 2nd (middle) and 3rd (lower). All winds are plotted in knots. The plots indicate snapshots of the storm outflow and interaction with a trough to the northwest during the 3-day period. However, the AMV data are available on an hourly basis and the flow evolution is much better presented via the time-continuous observations.

Adjoint-Derived Observation Impact

Observation impact is computed using the adjoint of the NAVGEM NWP model and NAVDAS-AR data assimilation system, for simulations of Hurricane Ingrid (2013), which formed in the Gulf of Mexico. This was chosen as an ideal retrospective case in-part because its formation takes place in the same geographic region where the TCI reconnaissance program has ample opportunity to engage. Techniques and methodologies produced from the retrospective case are expected to be implemented in case studies of TCI reconnaissance missions as they become available.

Observation impact is computed for the 6-hr forecast. Focus is maintained on the short forecast because the observation-impact relies on assumptions of (1) linearity, and (2) small influence of moist physics, which are byproducts of the adjoint system. The 6-hr forecast is chosen because the 6-hr forecast defines the background-state of the next analysis cycle, wherein new observations are assimilated. Observation assimilation is constrained in large-part by the background state, through quality control checks against the model background and during minimization when blending of observation and background information is performed relative to the respective errors of both sources. With this in mind, we wish to know how assimilated observations improve the forecast that serves as the background for the next analysis. This methodology is similar to that employed by Jung et al. (2013) when they investigate observation impact for tropical forecasts in the WRF model.
Observation impact is computed for two response functions. The first is an energy-based error norm in a 9x9 degree box centered on the forecast position of the TC. The formulation is identical to the global energy-based error norm, except that a local projection operator is applied to restrict focus to the TC. The second function focuses on the intensity of the TC, taken as the stretching-term of the baroclinic vorticity equation: \( R = - (f + \zeta) \delta \), where \( f \) is the planetary vorticity, \( \zeta \) is the absolute vorticity, and \( \delta \) is the divergence. Since the vorticity equation is a prognostic for the intensity of the TC vortex, it is expected that this function has bearing on the future intensity of the TC as well, extending the value of this evaluation further into the forecast. The stretching function is evaluated over the same 9x9 degree box as the error norm.

The observation-impact is strongly controlled by choice of norm. Impact summed by observation type for an example forecast initialized at 0000 UTC 15 September 2013 shows that aircraft observations from MDCRS, radiosondes, and ship surface observations all have a large (negative) impact on vortex stretching, while the contribution of these observation-types to the error in the forecast is comparatively much smaller (Fig. below). Very few observation-types increase stretching for this forecast; the largest contributors are SSMI brightness temperatures, AQUA brightness temperatures, and GPS radio occultation temperature moisture profiles. Synthetic (bogus vortex) observations have a large impact on reducing error, but contribute little to stretching.

Similarly, when observation impact is viewed geographically, patterns can emerge in one norm that are not apparent in another (Fig. below). Observation impact on stretching appears to have a latitudinal dependence, with observations within a latitude band north of Ingrid contributing mostly negatively to stretching while observations both poleward and equatorward contribute mostly positively. No such relationship is apparent in the error norm.

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**Figure:** Observation impact summed by observation type for a 6-hr forecast of Hurricane Ingrid (2013) initialized at 0000 UTC 15 September 2013. Observation impact is computed for (a) the stretching norm, and (b) the error norm, over a 9x9 degree box centered on the forecast position of the TC.
**Figure:** Observation-impact summed in latitude-longitude boxes for a 6-hr forecast of Hurricane Ingrid (2013) initialized at 0000 UTC 15 September 2013. Observation impact is computed for (a) the stretching norm, and (b) the error norm, over a 9x9 degree box centered on the forecast position of the TC. Warm (cool) colors indicate a positive (negative) contribution to the norm for observation impact summed within a box.

**Sensitivity of environmental shear, lead times, and observation targeting guidance**

We plan to produce close to real-time guidance for observation targeting using the NAVGEM adjoint. The NAVGEM adjoint is run with dry physics, which makes its applicability to TC intensity difficult to justify beyond short time scales. However, the NAVGEM adjoint, by virtue of being a global model, is uniquely qualified to provide information on the large-scale environment that can influence the intensity of a TC. With this in mind, we are investigating the application of the adjoint for producing sensitivity to mid-tropospheric and upper-tropospheric shear over major portions of the Atlantic TC basin. A response function can be defined for wind shear between an upper-level $k_2$ and lower-level $k_1$ as:

$$R = \frac{\tilde{v}_{k_2}^{k_1}}{\tilde{v}_{k_2}^{k_1}} = \left( \frac{(u_{k_2} - u_{k_1})^2 + (v_{k_2} - v_{k_1})^2}{\tilde{v}_{k_2}^{k_1}} \right)^{0.5}$$

This function is differentiable with respect to the model state at each level, producing a response function defined for $u$ and $v$ on each of the evaluated levels:

$$\frac{\partial R}{\partial u_{k_1}} = -\frac{(u_{k_2} - u_{k_1})}{\tilde{v}_{k_2}^{k_1}}$$

$$\frac{\partial R}{\partial u_{k_2}} = \frac{(u_{k_2} - u_{k_1})}{\tilde{v}_{k_2}^{k_1}}$$

$$\frac{\partial R}{\partial v_{k_1}} = -\frac{(v_{k_2} - v_{k_1})}{\tilde{v}_{k_2}^{k_1}}$$

$$\frac{\partial R}{\partial v_{k_2}} = \frac{(v_{k_2} - v_{k_1})}{\tilde{v}_{k_2}^{k_1}}$$
We plan to produce sensitivity of $R$ with respect to the model state for 24-hr simulations with lead times of 24 and 48 hours. These can be used in conjunction with sensitivity plots being produced with the COAMPS-TC for TC intensity specifically, to provide guidance for highly-sensitive targets for both the TC and the large-scale environment of the TC (or regions the TC is expected to move into) that can affect TC intensity.

REFERENCES


IMPACT/APPLICATIONS/TRANSITIONS

The longer-term impact of this study will be an improved understanding of how TC outflow interacts with its environment to affect intensity change, leading to improved use of high-resolution satellite and dropsonde observations in Navy (and other) models that should translate into superior numerical forecasts of TC structure and intensity.

We anticipate that the TC outflow sensitivity techniques developed in this study will apply broadly to TC cases globally. In addition, it would be desirable to take the methodology developed here for the NAVGEM model and apply it to the COAMPS-TC, which has both an adjoint and an observation-impact system. Discussions are on-going with collaborators at NRL-MRY to define the parameters of such a study.

RELATED PROJECTS

This project is related to the Univ. of Miami by ONR Grant N00014-14-1-0115: “Environmental Sensitivity of Tropical Cyclone Outflow”, and to two projects at NRL Monterey: (i) “Prediction of Tropical Cyclone Track and Intensity Using COAMPS-TC” and (ii) “Improvement of High-Resolution Tropical Cyclone Structure and Intensity Forecasts using COAMPS-TC”.

PUBLICATIONS


HONORS/AWARDS/PRIZES

Co-PI Velden and his tropical research team received an AMS Special Award, presented at the AMS Annual Meeting in January, 2015.