

Final Report

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

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ONR MM322 DRI: "Understanding and Predicting the Impact of Outflow on Tropical
Cyclone Intensification and Structure

For the Period: 1 January 2014 – 30 March 2017

28 April, 2017

Executive Summary

The overarching goal of this research grant was to observe and document the influence of upper-tropospheric outflow configurations on TC structure and intensity change. The basis of the 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 had addressed this topic, primarily through the utilization of numerical global model analyses. However, recent field programs offered 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, the tools exist to take a fresh look at the goals of this DRI. A series of sensitivity and diagnostic studies were performed in collaboration with NRL-Monterey, Naval Postgraduate School, and U-Miami investigators.

Brief Background and Scope of the Project

Our project takes advantage of unique datasets 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 and 2016 TC seasons. Co-PI Velden and his team was involved in both of these efforts, and datasets

were collected and analyzed. The TCI initiative overlapped 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 were 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 were derived in real time by UW-CIMSS, and made available for both the TCI mission support and the project archive for post-analysis. The AMV datasets (and derived fields) were made available at hourly intervals during the field campaign periods. Diagnostic analyses from the field campaign cases are being used to address some of the TCI hypotheses.

Where applicable and available, our studies also relied on the NAVGEM global model system, and the 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. 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 was 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 were 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?”

Research Objectives and Summary of Accomplishments

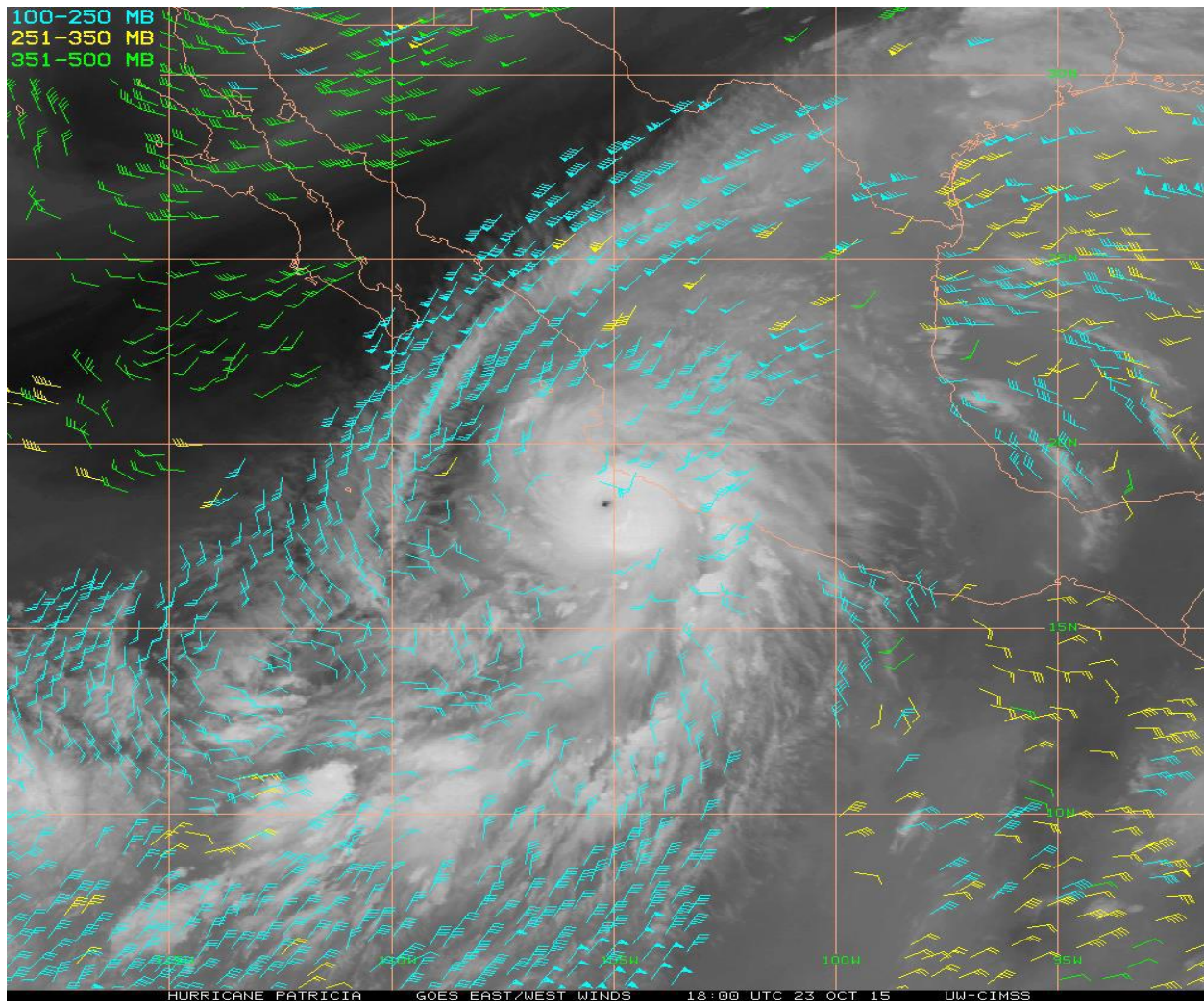
This final report summarizes the 3-year project accomplishments. The following tasks have been addressed/accomplished (Lead investigator in parentheses):

- Participation in the planning/execution of the TCI/SHOUT field campaigns, and processing/collection of satellite-derived datasets for post analyses. (Velden)
- Preliminary analysis and data assimilation studies using the collected TCI datasets. (Velden)

- Developed and tested adjoint sensitivity methodologies for perturbing the TC and its environment. (Hoover)
- Validation of the satellite-derived AMV datasets vs. collocated HDSS profiles to assess accuracies and diagnose potential situational biases in the AMVs. (Velden, in collaboration with UM).
- Collaborations with NRL, NPS, and UHawaii on post-TCI-experiment investigations of novel data assimilation approaches that exploit the high spatio-temporal attributes of the AMVs in conjunction with HDSS observations. (Velden)
- Explored observation-impact on the sensitivity to the TC intensity and intensification-rate, with special attention to both routine and TCI reconnaissance observations that can be used to help define the TC outflow. (Hoover)

TCI Field Campaign Support

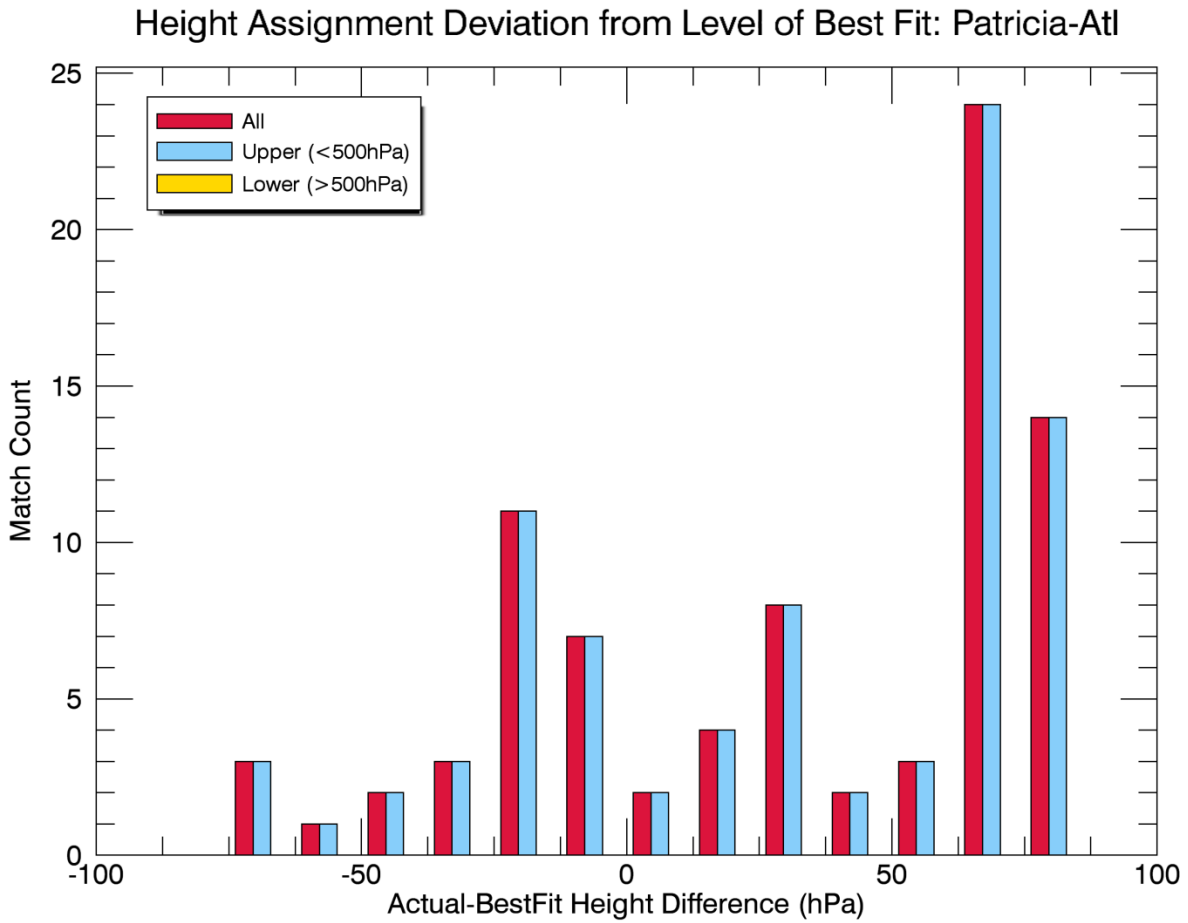
Data have been collected during Global Hawk and WB-57 flights of selected TCs in 2014-2016. The PI and his team were responsible for contributing to mission planning, analysis and forecasting. All types of satellite data (including special GOES rapid scan observations) were collected and archived for post-season analysis. We are collaborating with TCI colleagues to analyze this data through comparative studies and NWP impact studies. An example of the satellite-derived atmospheric motion vectors (AMVs) produced by the CIMSS team during Hurricane Patricia's record intensity is shown in the attending figure below. Good depiction of the dual-channel outflow structure by the AMVs will be complemented by the vertical structure obtained from concurrent WB-57 dropsonde winds.



Diagnostic analysis studies using the TCI datasets

A preliminary assessment of the AMV datasets collected during the TCI field campaign has been completed. In collaboration with colleagues at the University of Miami, the AMV datasets have been collocated with HDSS sonde profiles in space and time for direct comparisons. An example is shown below for Hurricane Patricia. In this case we have discovered that the spike in higher values (>50 hPa) of AMV height assignment errors is due to a processing threshold. From this analysis, we have learned that for TC applications we need to increase the highest-allowable height assignment

for AMVs to accommodate the higher tropopause (and associated cloud canopy) often found in stronger storms.



A collective research team with NRL-MRY, NPS, UH and CIMSS collaborators has been organized for an intensive study of the intensity and structure changes of Hurricane Joaquin and Patricia observed during the respective TCI. Neither storm was well forecast by NWP, and was a potential threat to any Fleet ships that might be in the path.

For Joaquin, the environmental variables are being analyzed that accounted for the translation speed /direction changes, and the vertical wind shear (VWS) changes that may have contributed to the intensity and structure changes. Three VWS estimates were related to the Joaquin vortex tilt revealed by the HDSS sondes. Second, infrared and microwave satellite imagery have been collected to test the hypothesis that the moderate VWS on 4 October lead to an asymmetric convective structure with repeated convective bursts associated with a persistent mesoscale vortex that appears to be corroborated by the HDSS measurements. AMVs created by CIMSS have been combined with the HDSS sondes to describe how the tilted vortex blends in with the outflow layer (and its changes).

Data assimilation studies using the TCI datasets

Another research thrust is in collaboration with Eric Hendricks (NRL), Michael Bell (UH), and Russ Elsberry (NPS). A special set of 15-minute AMVs processed by CIMSS for the six-hour period 12 UTC – 18 UTC 4 October leading up to the TCI-15 mission during Hurricane Joaquin was utilized for a proof-of-concept demonstration for more effective data assimilation to improve TC forecasts. A SAMURAI/COAMPS dynamic initialization (SCDI) technique is being tested that will have the capability to assimilate those TCI-15 AMVs at full temporal and spatial resolution. The TCI data sets will provide excellent wind and pressure fields for validating the vortex structure and intensity. First results of this SCDI were presented at the April 2016 Hurricane and Tropical Meteorology Conference (Hendricks et al., Paper 15D.6).

Adjoint-Derived Sensitivity Gradients and Observation Impact Experiments

1. Background

Observation-impact computed from adjoint-derived sensitivity gradient information is typically used to describe the impact of assimilated observations on the 24-hr forecast error, through the use of a generalized energy-based error norm (Langland and Baker 2004). While this information is valuable for routine monitoring of the observing/analysis/forecast system, it does not explicitly provide information on the impact of observations on the development of specific high-impact weather events, such as the intensity forecast for tropical cyclones. However, the same basic framework for observation-impact can be applied to these specific aspects of the forecast through the application of specifically defined response functions.

In this project, we sought information on the impact of assimilated observations on the forecast intensity of tropical cyclones that were part of the TCI/SHOUT/HS3 field campaigns, where both routine and novel, targeted observations were deployed. Methodology is described in Section 2, and specific questions relevant to the TCI initiative were addressed through the sensitivity gradient observation-impact information made available in the NAVDAS-AR/NAVGEN system, described in Section 3.

2. Methodology

For each examined case (Joaquin 2016 and Matthew 2017), the NAVDAS-AR was cycled 6-hourly to produce analyses throughout the life-cycle of the cyclone, with NAVGEN forecasts performed out to 54 hours on each cycle. For each forecast, the sensitivity with respect to initial conditions was computed along the background-

trajectory by using the portion of the trajectory from $t=6$ hrs to $t=t_f+6$ hrs, representing the forecast trajectory initialized from the background state of each new analysis. Sensitivity was computed for the 12 hr, 24 hr, 36 hr, and 48 hr background-trajectory forecasts for a response function R defined as the summed surface pressure in a box centered on the forecast position of the TC:

$$R = \sum_{i,j \in D} p_s|_{i,j} \quad (1),$$

where surface pressure is indexed zonally by i and meridionally by j for every point existing in the box D . This function is lower when the storm intensifies and higher when the storm weakens, so negative (positive) sensitivity or observation-impact implies an intensification (weakening) of the TC.

A byproduct of the methodology produces sensitivity or observation-impact of the *rate of intensification* through a centered-difference approximation. The sensitivity of the rate of intensification between $t=t_f$ is merely the difference between the sensitivity of intensity at $t = t_f - \Delta t$ and $t = t_f + \Delta t$; for example, once the sensitivity of intensity (based on the response function in Eqn. 1) is produced for the 24 hr and 36 hr forecast, the sensitivity of the rate of intensification for the 30 hr forecast can be approximated as the difference between the 36 hr and 24 hr sensitivities already computed. Since the rate of intensification can conceivably be driven by different dynamics than the intensity at a given time, calculating the sensitivity and observation-impact of the rate of intensification provides useful, not entirely overlapping information about the dynamics that drive the evolution of the cyclone.

The sensitivity and observation-impact are highly flow-dependent. These fields can be observed from forecast-to-forecast to determine how the sensitivity and observation-impact are related to the flow, but in order to obtain some generalized information about the impact of observations on the intensity forecast the fields must be composited over many forecasts. Both techniques are applied in this study, and normalization by the geographic size of the response function box D is performed in order to obtain a fair comparison between forecasts.

3. Science Questions Addressed in this Research

3a What is the role of defining the TC outflow for forecasting TC intensity at lead times between 12-48 hrs?

This project particularly focuses on the role of the anticyclonic TC outflow in defining the intensity of the TC. TC intensity can be framed in a “top-down” philosophy whereby the intensity is strongly modulated by available outflow channels capable of evacuating mass from the column above the rotating center, or in a “bottom-up” philosophy whereby the intensity of the TC is modulated primarily by upward forcing from latent heat release within the rotating center, and the outflow is relegated to being a byproduct of the heating. Both positions have merit, but it is difficult to determine for a given TC how much one or the other applies to the TC’s development.

Compositing sensitivity of forecast TC intensity at 12 hrs, 24 hrs, 36 hrs, and 48 hrs reveals a transition from the bottom-up philosophy to the top-down philosophy as the lead-time increases (Fig. 1). Sensitivity to initial-time vorticity perturbations in a 12 hr forecast is largely relegated to the rotating center in the low-to-mid troposphere (Fig.

1a), with no sensitivity to vorticity in the anticyclonic outflow layer. However, as the lead-time is increased from 12 hrs through 48 hrs, the sensitivity to initial-time vorticity perturbations relaxes within the rotating center in the low-to-mid troposphere, and a cap of oppositely-signed sensitivity develops in the outflow layer (Fig. 1c,d). Recalling that negative (positive) sensitivity corresponds to intensifying (weakening) the cyclone, it can be seen that the cyclone can intensify in the 12 hr forecast mainly through increasing vorticity in the rotating center in the low-to-mid troposphere (bottom-up), but to intensify in the 48 hr forecast vorticity can be reduced in the outflow layer (top-down).

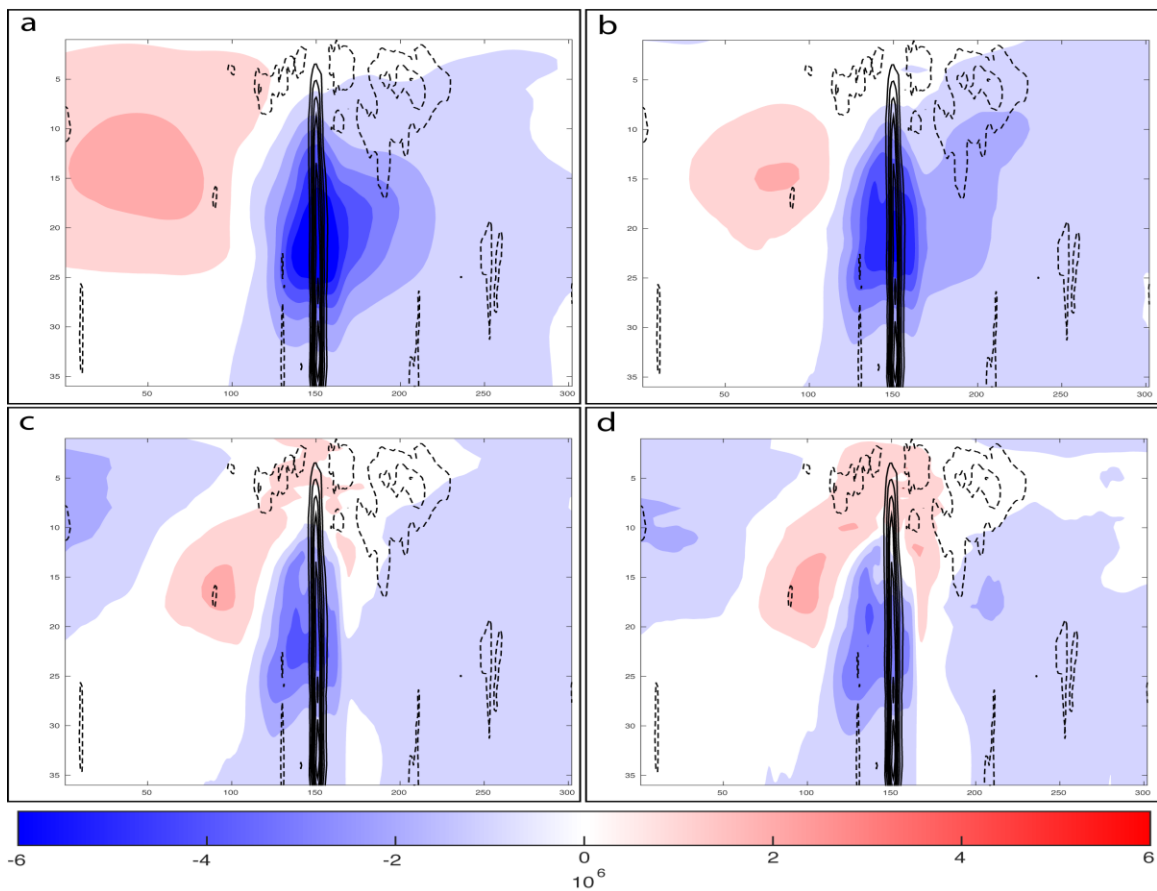


Figure 1. West-east cross-section of composite sensitivity of forecast TC intensity to initial vorticity perturbations (shading, cool colors negative) and basic-state initial vorticity (contours, dashed negative) for Hurricane Joaquin (2015) for forecasts with lead-times of (a) 12 hrs, (b) 24 hrs, (c) 36 hrs, and (d) 48 hrs. Composite includes all forecasts from 6-hourly analysis-times from 0600 UTC 30 September – 1800 UTC 04 October, with the forecast from 0600 UTC 02 October omitted due to unstable sensitivity for the 48 hr lead-time.

This analysis implies that greater accuracy in defining the vorticity of the anticyclonic outflow layer of a TC can translate into greater accuracy in TC intensity forecasts for lead-times greater than 24 hrs.

3b What is the relative impact of atmospheric motion vectors (AMVs) defining upper-tropospheric and low-to-middle tropospheric features on TC intensity forecasts at lead times between 12-48 hrs?

The adjoint-derived observation-impact provides specific information about the ability of each individual assimilated observation's ability to impact the TC intensity forecast. Once this information has been produced, it can be dissected in any number of ways to investigate the relative impacts of different components of the observing system on TC intensity forecasting.

Demonstrating that there exists *sensitivity* of the TC forecast to outflow layer perturbations of the vorticity does not necessarily guarantee that outflow layer observations that shape the wind field, like AMVs, will demonstrate significant impact. Since the observation-impact is the inner product of both the sensitivity to the observation and the observation's innovation, observations will project both positively and negatively onto the sensitivity structures and create large cancellations in their overall impact. Furthermore, some locations in the atmosphere are more prone to large innovations than others, and these regions can be highly flow-dependent. Composites over a large number of forecasts can provide a glimpse into some generalities regarding

the observation-impact of observations in the outflow layer, but they are still prone to significant amounts of noise.

When observation-impact is collected and composited onto a 2-D phase-space representing the distance from the TC center and the pressure-level of the observation, it can be shown that the total (absolute value) observation-impact of AMVs generally increases with increasing lead-time (Fig. 2). Furthermore, while there is a tendency for both low-to-mid tropospheric AMVs and upper tropospheric (outflow layer) AMVs to exert larger impacts on longer forecast lead-times, the outflow layer AMVs tend to increase in impact more dramatically, especially for impact composites for Hurricane Matthew (2016) (Fig. 2c,d). ***While the dominant source of impact from AMVs still appears to be low-to-mid tropospheric AMVs, the outflow layer AMVs play an increasingly large role as lead-time increases.***

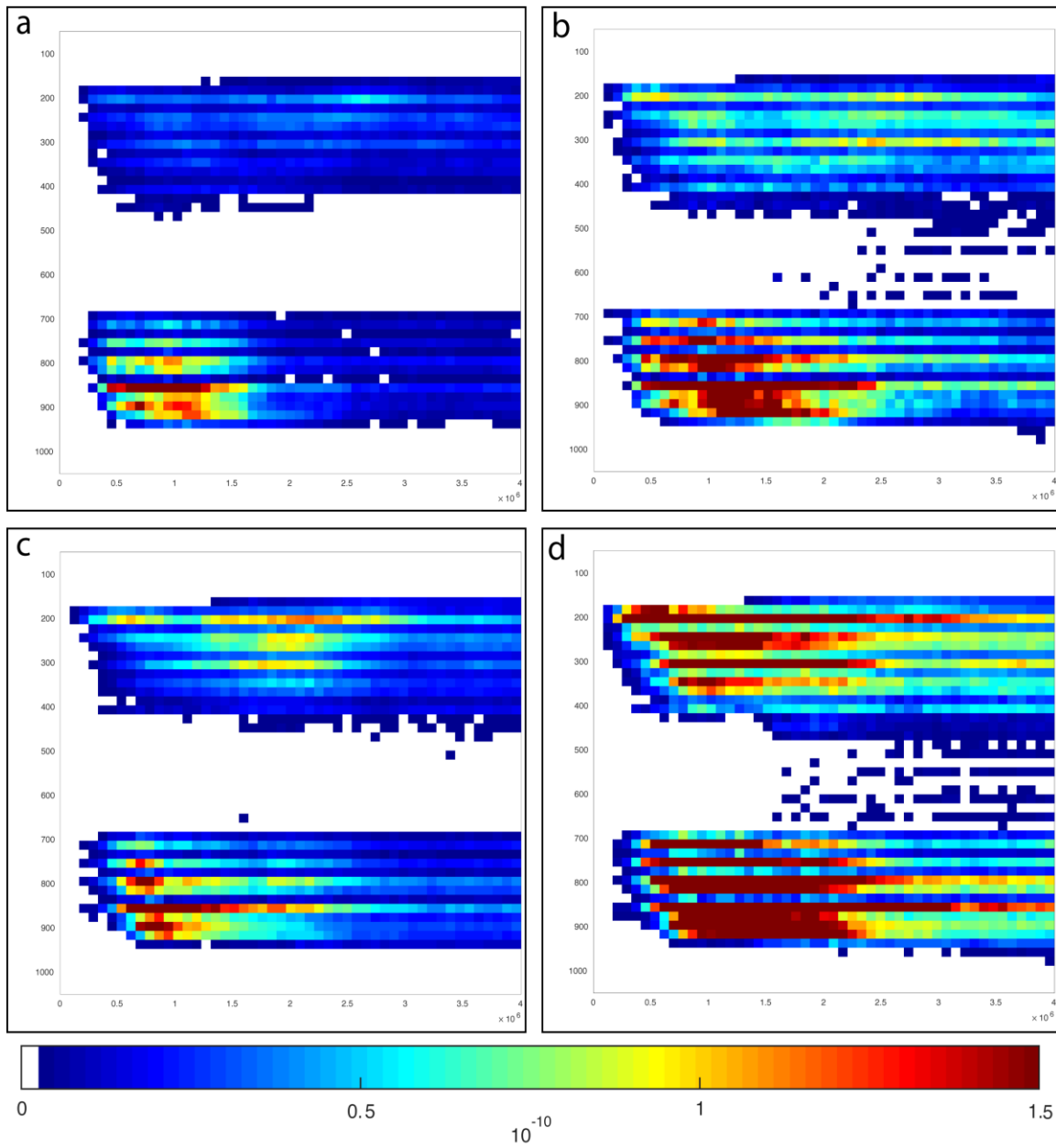


Figure 2. Composite total (absolute value) observation-impact of AMVs on forecast intensity of (a) Hurricane Joaquin (2015) for 12 hr lead-times, (b) Hurricane Joaquin (2015) for 48 hr lead-times, (c) Hurricane Matthew (2016) for 12 hr lead-times, and (d) Hurricane Matthew (2016) for 48 hr lead-times. Computed across all Hurricane Joaquin (2015) forecasts from 0600 UTC 30 September – 1800 UTC 04 October, and across all Hurricane Matthew (2016) forecasts from 1200 UTC 29 September – 1800 UTC 18 October.

3c What is the relative impact of targeted observations from field campaign missions?

Ultimately this technique can be applied to investigate the impact of field observations, provided that those observations can be adequately assimilated into the model and be distinctly identified in observation-space as field observations. A simple example of this technique is provided in Figure 3. The impact of rawinsonde temperature observations on the 24 hr forecast intensity of Hurricane Matthew (2016) is computed and collected across 0.5-degree latitude-longitude boxes for forecasts between 0000 UTC 01 October and 1200 UTC 18 October, which included periods where observations were collected by dropsondes (which are included in the rawinsonde dataset). Dropsonde data is easy to identify in this case, since traditional rawinsondes are launched from surface stations and Hurricane Matthew (2016) spends this period largely over the Caribbean and then moves north into the Gulf Stream.

Rawinsonde/dropsonde temperature observations between 150 hPa and 450 hPa in Matthew's near environment are scarce on 0000 UTC 01 October and 1200 UTC 02 October, with the few nearby observations producing a mixture of positive and negative impacts on the 24 hr forecast intensity (Fig. 3a,b). Rawinsondes on the US mainland are too far away to impose any significant impact at this time. On 0000 UTC 04 October and 1200 UTC 05 October there are densely packed observations along lines that intersect or orbit Matthew (Fig. 3c,d) – these are most likely dropsonde observations.

The dropsonde observations impose significant impacts on the 24 hr intensity of Matthew that are predominantly negative, which translates to an increase in TC intensity (see Eqn. 1). As Matthew moves close to the southeast coast on 0000 UTC 07 October and 1200 UTC 08 October, the mainland rawinsonde observation network

begins to exert a significant impact on Matthew's intensity forecast, even from stations that are far remote from the hurricane (Fig. 3e,f) – these observations are likely communicating information between Matthew and the midlatitude waveguide that Matthew interacts with as it moves poleward.

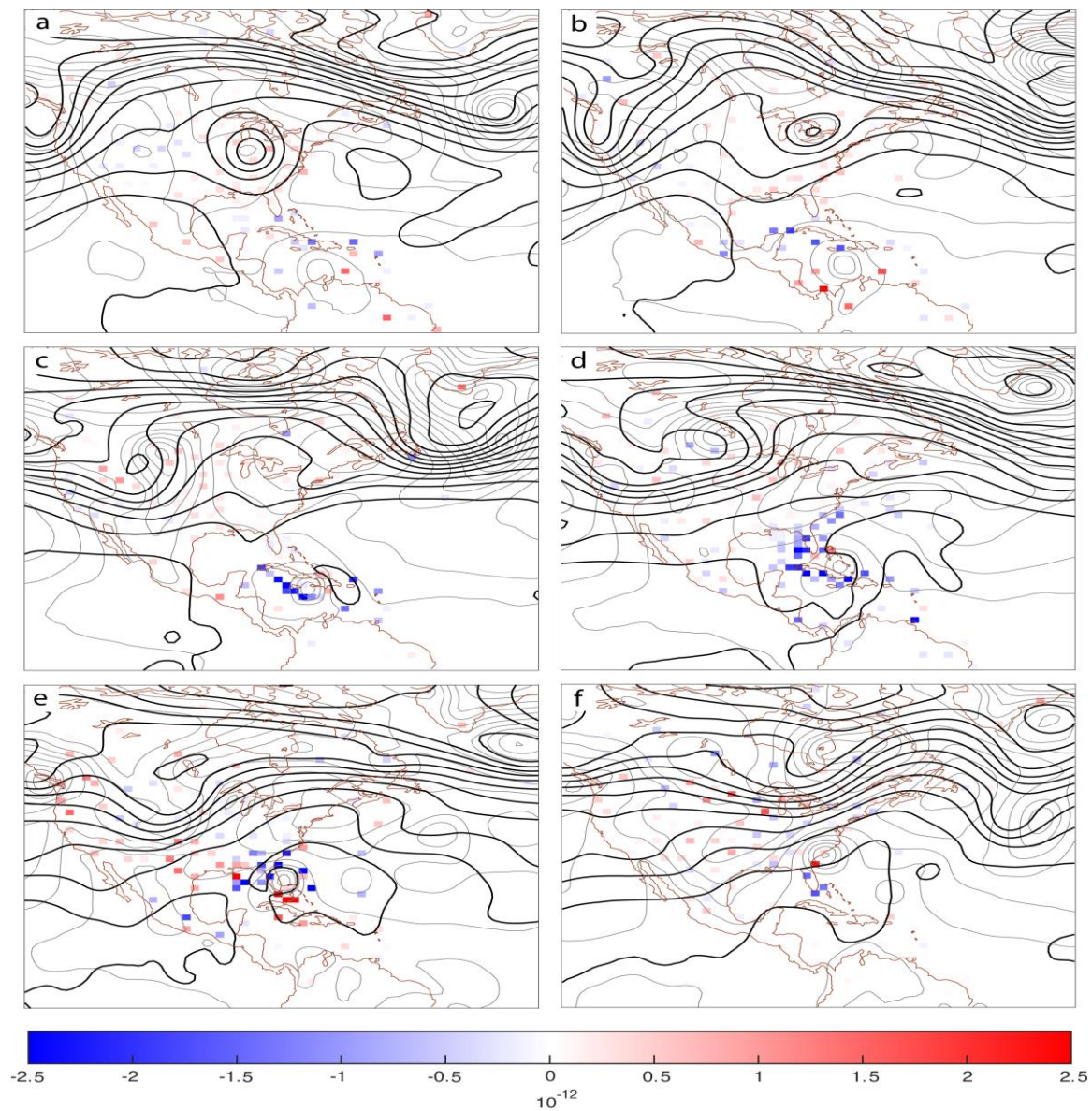


Figure 3. Impact of rawinsonde and dropsonde temperature observations between 150 hPa and 450 hPa on the 24 hour forecast intensity of Hurricane Matthew (2016) for forecasts initialized on (a) 0000 UTC 01 October, (b) 1200 UTC 02 October, (c) 0000 UTC 04 October, (d) 1200 UTC 05 October, (e) 0000 UTC 07 October, and (f) 1200 UTC 08 October. Impact is shaded in 0.5-degree boxes (cool colors negative), and the sea level pressure and 300 hPa geopotential heights are shaded in gray and black, respectively.

References

Langland, R. H., and N. L. Baker, 2004: Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system. *Tellus*, **56A**, 189-201.

Results and Dataset Dissemination

All of the TCI field campaign datasets produced by CIMSS were made available to the TCI research community upon quality control and completion. This was accomplished through a local archive site at CIMSS with a web-based portal, as well as providing all datasets to the TCI data management group at UCAR. Results of post-experiment data analysis and impact studies will be disseminated via TCI workshops scientific journal publications.

Impacts/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.

Publications and Presentations

- Doyle, J., C. Velden and many other authors, 2017: A View of Tropical Cyclones from Above: The Tropical Cyclone Intensity (TCI) Experiment. Accepted in the Bull. Amer. Meteor. Soc.
- Elsberry, R., C. Velden, M. Bell, E. Hendricks, M. Peng, E. DeLap, and A. Zhao, 2017: Use of the TCI-15 Datasets to Demonstrate New-Generation Satellite Atmospheric Motions Vectors for Improved Tropical Cyclone Predictions. Submitted to Mon. Wea. Rev.
- Hoover, B., 2014: Adjoint-Based Analysis of Observation Impact on Tropical Cyclone Intensity Forecasts. American Meteorological Society 31st Conference on Hurricanes and Tropical Meteorology.
- Hoover, B., 2016: Adjoint-derived initial-condition sensitivity and observation-impact on intensification of Hurricane Joaquin (2015) using the NAVGEM (TCI Workshop, 2016)
- Hoover, B., 2017: A forthcoming publication is being developed for an AMS special collection of papers from the TCI project.
- Sears, J. and C. S. Velden, 2014: Investigating the Role of the Upper-Levels in Tropical Cyclone Genesis. Tropical Cyclone Research and Review, 3(2), 91-110.
- Velden, C.S. and J. Sears, 2014: Computing Deep-Tropospheric Vertical Wind Shear Analyses for Tropical Cyclone Applications: Does the Methodology Matter? *Wea. Forecasting*, **29**, 1169–1180.
- Zhang, S, Z. Pu and C. Velden, 2017: Impact of Enhanced Atmospheric Motion Vectors on HWRF Hurricane Analyses and Forecasts with Different Data Assimilation Configurations. Submitted to Mon. Wea. Rev.

HONORS/AWARDS/PRIZES

While only indirectly related to the TCI DRI, the CIMSS Tropical team received a group Special Award from the AMS in 2015 for “providing the weather community with valuable TC-related satellite information and derived products”.

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