Planned TCI Research:

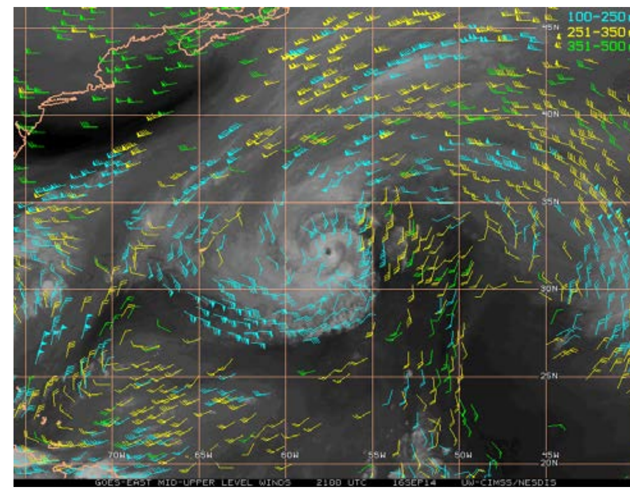
UW-CIMSS TC Group

3 Primary Focus Areas

1) High-res. Satellite-Derived Atmospheric Motion Vectors (AMVs)

Lead: Velden (CIMSS)

Collaborators: Hendricks/Elsberry (NPS), Doyle (NRL-MRY), Hoover (CIMSS), Pu (Utah), Wang (OU), McNoldy/Majumdar (RSMAS), Bell (Hawaii), Dunion (HRD), Black (SHOUT)



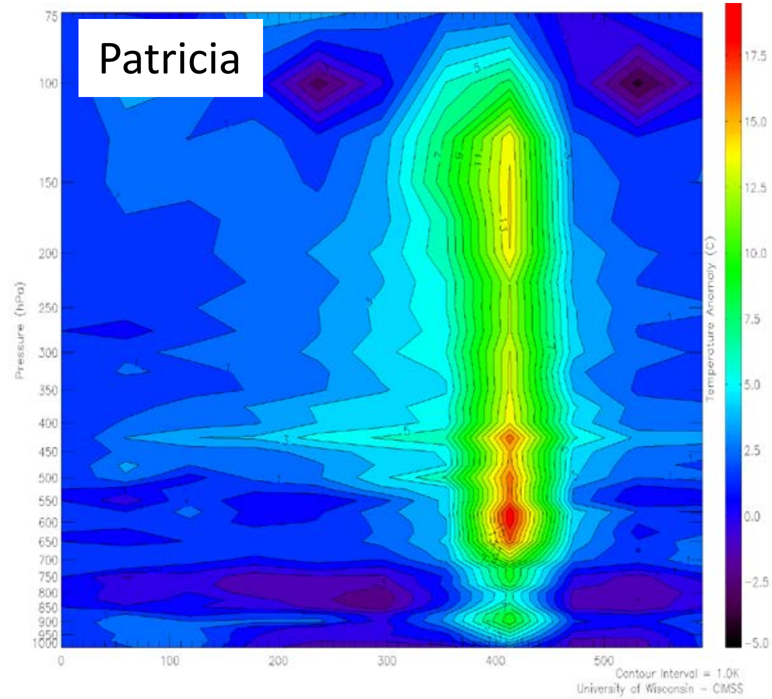
- **AMV Characterization**
  - -- Compare to TCI dropsonde winds
  - -- Analysis increments in TC environment (e.g., SAMURAI)
  - -- Diurnal pulses—can AMVs capture them?
- **Model Assimilation Impact Studies (NAVGEM, COAMPS, WRF/HWRF)**
  - -- COAMPS-TC Dynamic Initialization using 15-min AMV datasets + Samurai increments

Planned TCI Research:

UW-CIMSS TC Group

2) TC Warm Core Structures as Observed by TCI Dropsonde Observations and Satellites

Leads: Herndon/Velden



- **Process temp anomaly xsects for TCI flights with high-res dropsonde curtains**

-- Joaquin Oct 2, 4 and 5

-- Marty (examine weak cases as well)

-- Patricia on Oct 21-23

-- HS3 cases

- **Science questions:**

1) How do the satellite MW sounder signatures compare?

2) Does tilt impact the sounder-based intensity estimates?

3) Can we use the dropsonde obs to help correct satellite undersampling biases, especially in stronger cases with dual maxima?

Planned TCI Research:
UW-CIMSS TC Group

3) Sensitivity and Ob-impact on TC model intensity forecasts

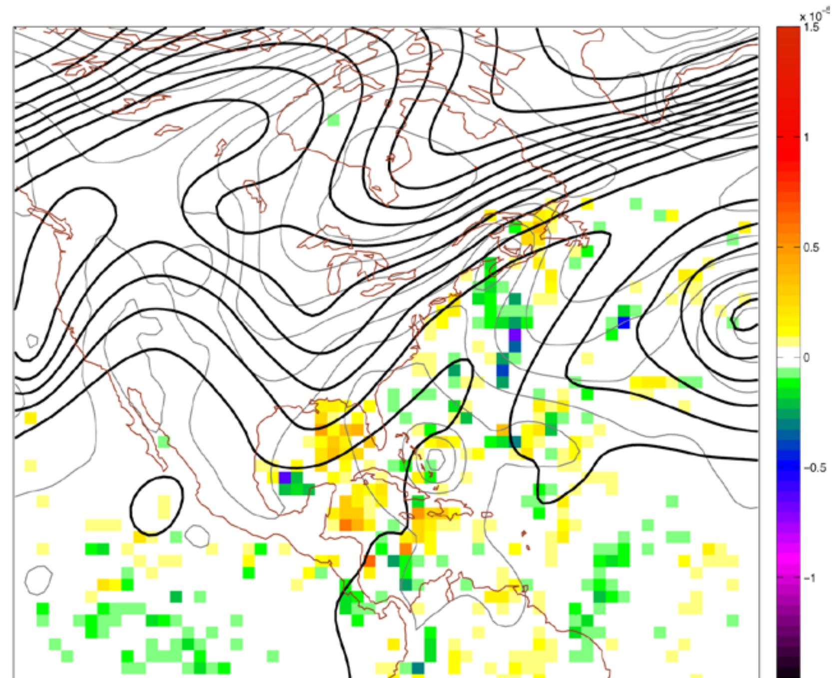
Leads: Hoover/Velden

- **NAVGEM sensitivity studies on TCI storms**

-- Assimilate and identify the influence of TCI observations using observation-impact techniques

-- Investigate sensitivity and ob-impact on TC intensity at 24-hr and 48-hr forecast ranges

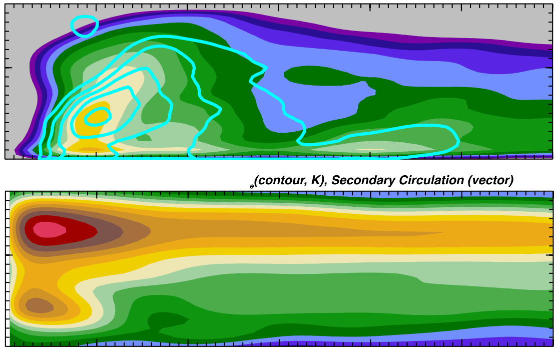
-- Extend investigation to other functions relevant to TC structure (e.g. vortex stretching, size)



Ob-impacts of upper-level AMVs during Hurricane Joaquin

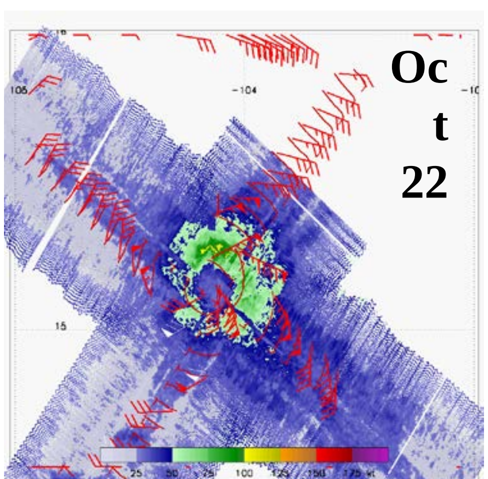
SAMURAI analyses for TCI

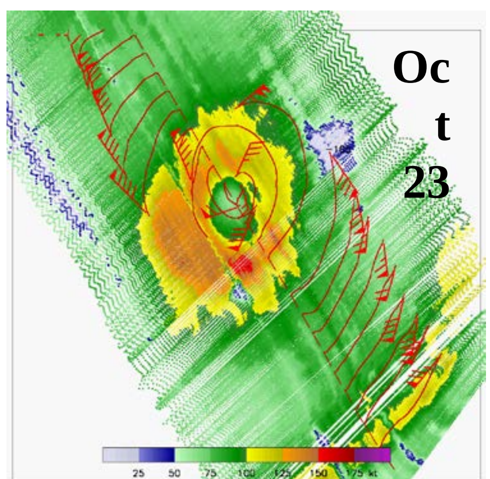
- **Investigators:** Michael Bell (U. Hawaii)
- **Objectives:**
  - Investigate the structure of Patricia during rapid intensification and weakening (first priority for publication is axisymmetric structure)
  - Compare the observed boundary layer structure of Joaquin with high-resolution model structure
- **Technical Approach:**
  - TCI Cases of priority: Patricia & Joaquin
  - Observations: TCI sondes, P3 Doppler radar, AMVs
  - Models: GFS or ECMWF(?) (for SAMURAI background); WRF & COAMPS-TC (for Joaquin validation)
  - Analysis Tools: SAMURAI analyses ***(open for collaboration)***
- **Key Preliminary Results:**
  - Axisymmetric SAMURAI analyses of Patricia show strong connection between kinematic and thermodynamic structure

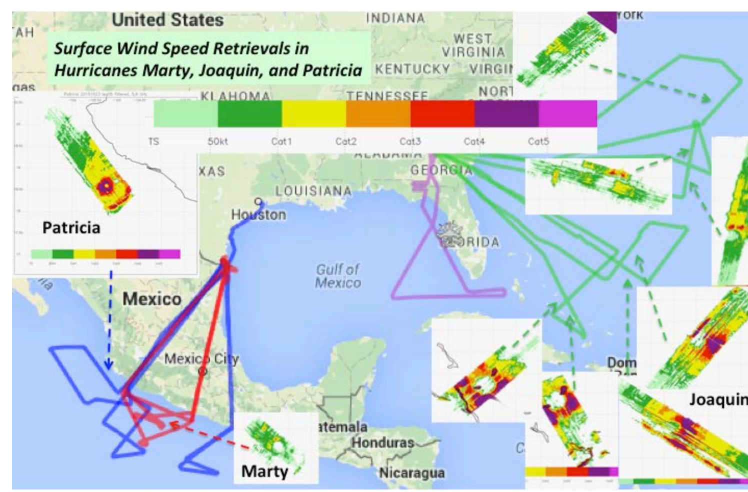


HIRAD

- **Investigator:** Dan Cecil , NASA MSFC, Daniel.J.Cecil@nasa.gov
- **Objectives:**
  - Map surface wind speed over ~50 km wide swath
  - Minimum detectable ~35 kt (uncertain)
- **Technical Approach:**
  - Priority cases: all Patricia and Joaquin flights, but especially Patricia 10/23, 10/22
  - Compare with sondes for cal-val
- **Key Preliminary Results:**
- Patricia data fairly clean; some flights need more clean-up







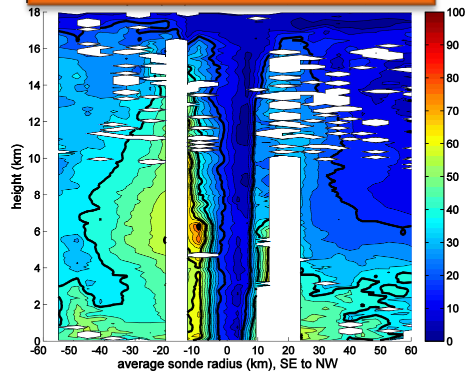
NRL TCI Research

- **Investigators:** Jim Doyle, Josh Cossuth, Will Komaromi, Jon Moskaitis, Alex Reinecke, Dave Ryglicki (NRC), Dan Stern (UCAR)
- **Collaborators:** Bell (Hawaii), Black (NOAA), Cecil (NASA), Dunion/Rogers (HRD), Emanuel (MIT) Hendricks-Elsberry (NPS), Majumdar (RSMAS), Pu (Utah), Sanabia (USNA), Tripoli (UW), Velden (CIMSS), Wang (OU)
- **Outflow Studies: (W. Komaromi, Moskaitis, Ryglicki, Doyle)**
  - TCI Obs (HDSS, HIRAD), COAMPS-TC, ensembles, satellite data (AMVs, MW)
  - Outflow characteristics, role in intensity changes
  - Joaquin (also Patricia Marty)
- **COAMPS-TC Assimilation Studies: (J. Doyle, Komaromi, Moskaitis, Reinecke)**
  - TCI Obs (HDSS, HIRAD), satellite data (AMVs), P3 Radar, HIRAD
  - COAMPS-TC 4D-Var, EnKF
  - Marty, Joaquin, Patricia (Can Patricia's intensification be captured?)
- **TCI Predictability Studies: (J. Doyle, Komaromi, Reinecke)**
  - TCI Obs (HDSS, HIRAD), AMVs, COAMPS-TC ensemble, nested high-resolution adjoint
  - Understand and quantify the sensitivity and predictability of TC outflow
  - Examine predictability of TC intensity and track

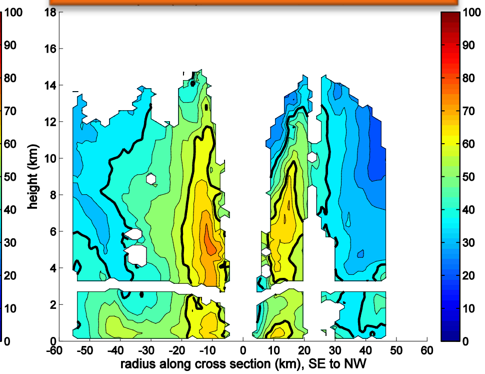
NRL TCI Research

- **Vertical Structure of Eyewall and Eye (Lead D. Stern, Doyle, Cossuth)**
- **Key questions:**
  - Why does Patricia exhibit a mid-level wind speed maximum?
  - How does the warm core structure of the eye evolve in time in the TCI observations?
  - How does the eyewall and eye structure compare to previous obs and simulations?
- **Technical Approach:**
  - TCI dropsondes, P3 radar, Satellite (IR, MW)
  - Cases: Patricia, Joaquin, Marty
- **Preliminary results:**
  - Mid-level wind maximum has been observed in a few other intense/small TCs; similarity to previous idealized simulations suggests that this is associated with unbalanced flows.
  - Dual warm core maxima at 4-5 km and 15-16 km in Patricia, with greatest warming at mid-levels.

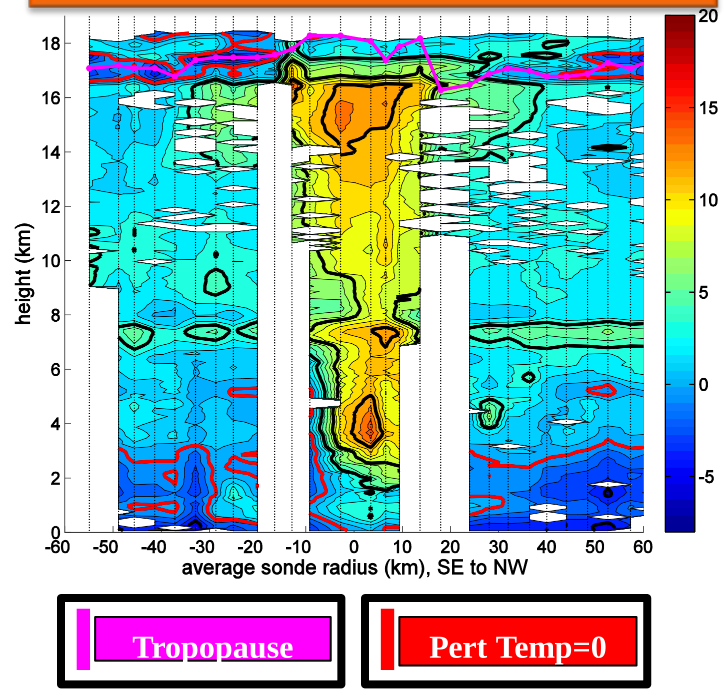
Sonde Windspeed



Radar Windspeed



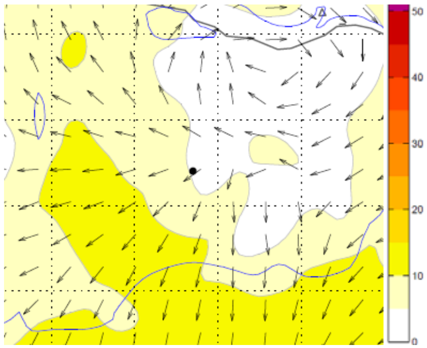
Perturbation Temperature



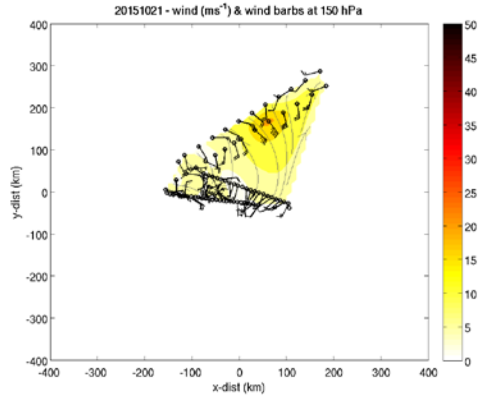
NRL TCI Research

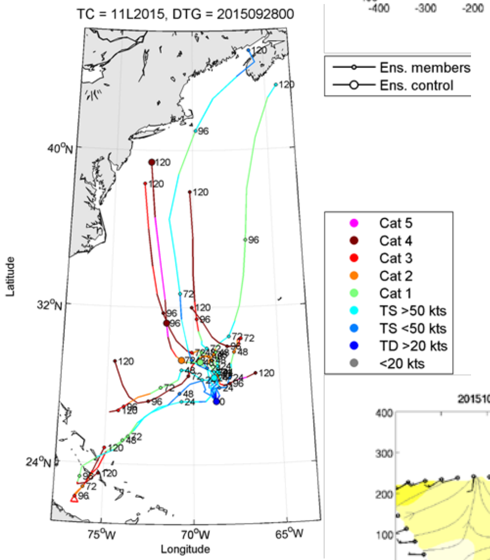
- **COAMPS-TC Evaluation (Lead J. Moskaitis, Komaromi, Doyle, Ryglicki)**
- **Key questions:**
  - Why did COAMPS-TC miss RI/RD (Patricia)?
  - Why were only 2 ensemble members able to correctly capture SW movement of Joaquin?
- **Technical Approach:**
  - Operational COAMPS-TC & ensembles
  - TCI dropsonde data: Joaquin, Marty, Patricia
  - Error/uncertainty sources: initialization and forecast evolution
- **Preliminary results:**
  - COAMPS analyses, particularly at upper levels were poor during the pre-RI stage

150mb - CTCX

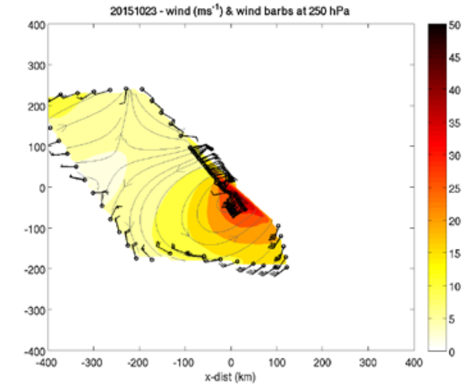


150mb – TCI dropsondes

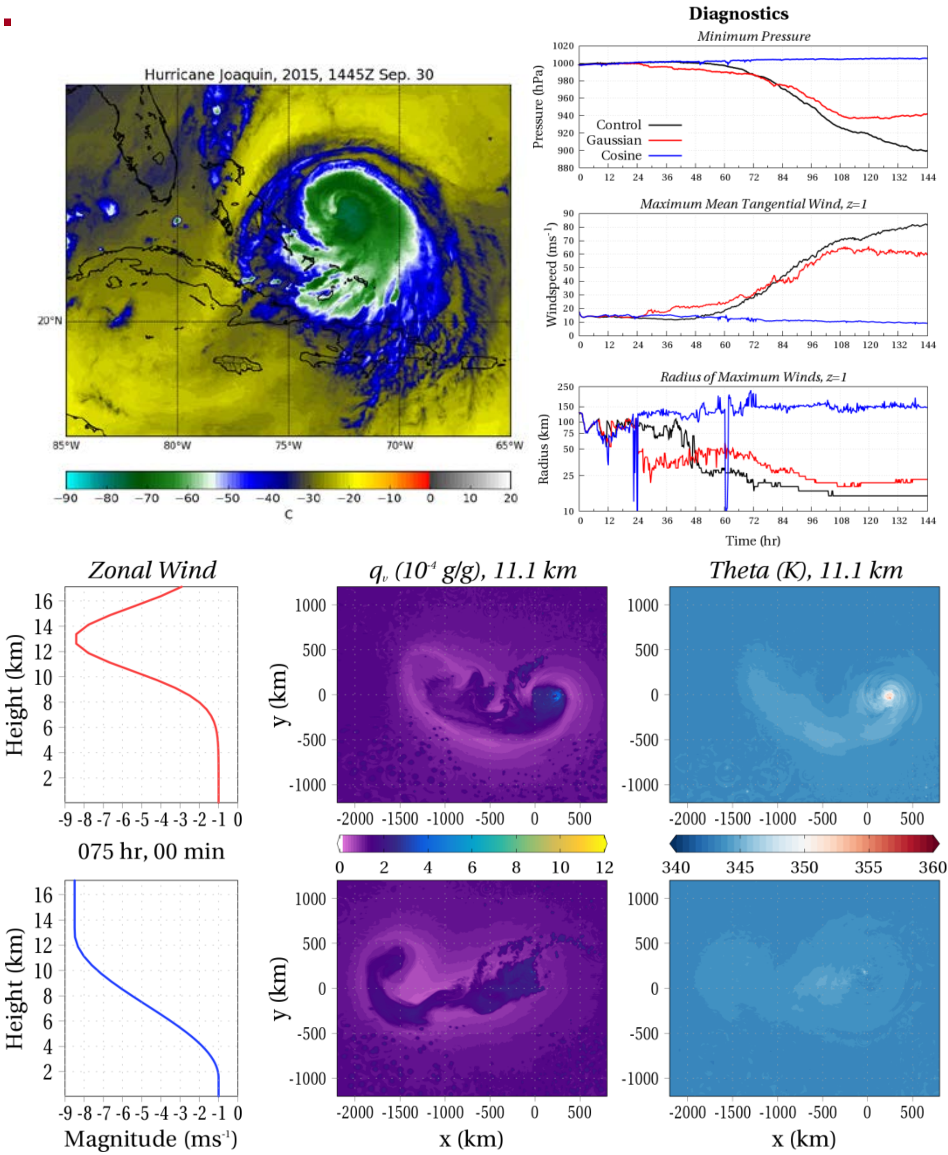




- **Patricia Intensity (W. Komaromi, Moskaitis, Doyle)**
- **Objectives:**
  - Understand "super" RI and RD of Patricia (2015)
- **Technical Approach:**
  - TCI dropsonde, P-3, Mexican radiosondes, satellites
- **Preliminary results:**
  - SW'rly shear and dry air began to negatively affect Patricia ~6 h prior to landfall, resulting in weakening

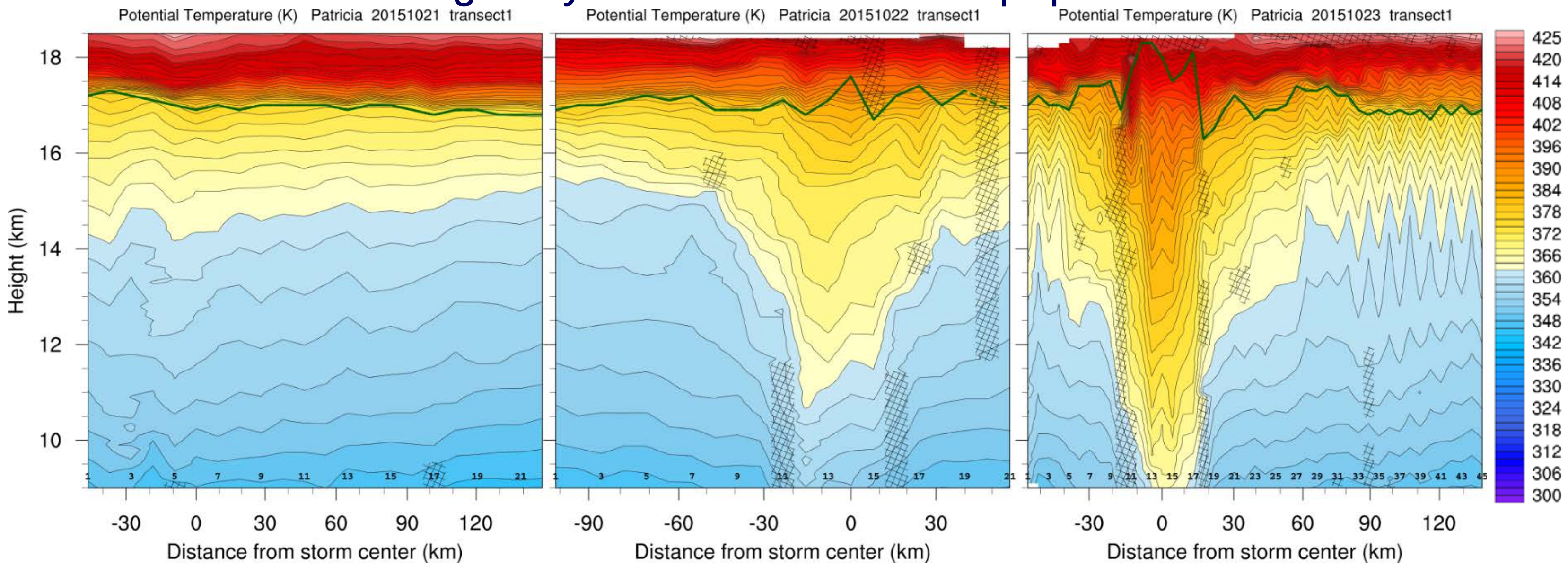


- **Idealized "Joaquin" simulation (Lead: D. Ryglicki, Doyle, Cossuth)**
- **Objectives:**
  - Examine the outflow-environment boundary
  - Analyze the dependence on environmental wind profiles
- **Technical Approach:**
  - Obs: satellite, TCI dropsondes, reanalyses
  - Modelling: CM1, COAMPS-TC
- **Preliminary results:**
  - With strongest winds confined to upper levels of storm, idealized TC rapidly intensifies
    - Dry boundary evident, matches WVap satellite imagery.

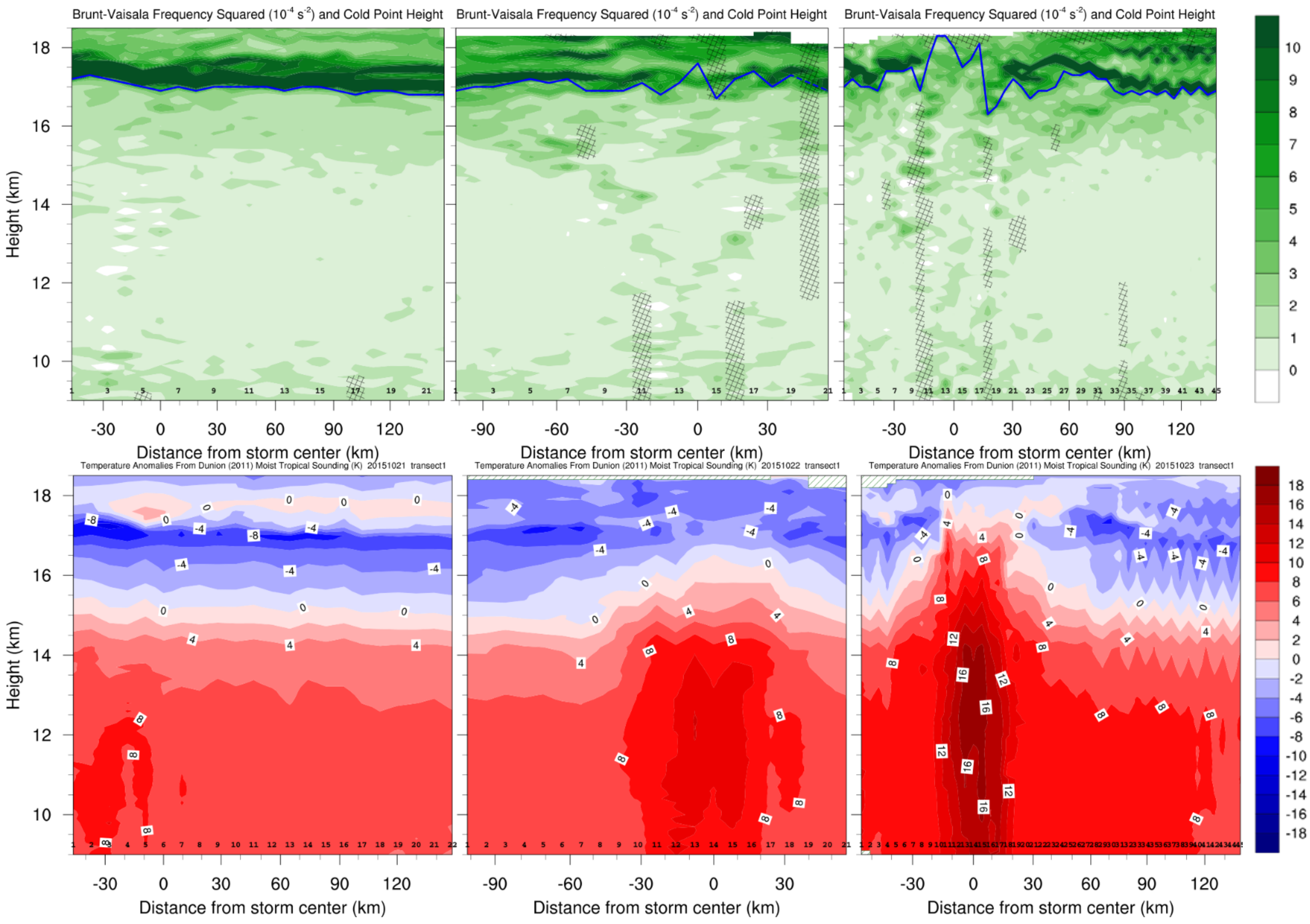


Inner-Core Tropopause Variability

- **Investigators:** John Molinari and Patrick Duran – SUNY Albany
- **Objectives:**
  - Determine the radial-vertical structure of the tropopause in the inner core of Hurricanes Joaquin and Patricia and how it evolves with time.
  - Investigate the causes of the observed structure
- **Key Preliminary Results:**
  - The tropopause rises during the RI period of both storms, dramatically in Patricia.
  - This rise appears to relate to subsidence from the lower stratosphere over the eye
  - Evidence for ducted gravity waves below the tropopause.



Inner-Core Tropopause Variability

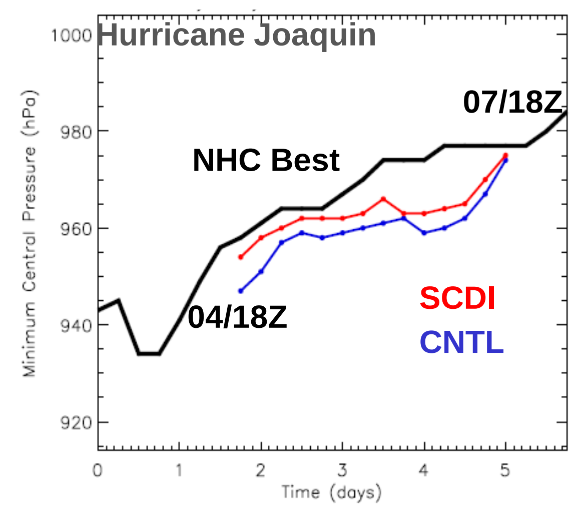


- **Investigators:** **Russ Elsberry (UCCS/NPS), Bob Creasey (NPS), Eric Hendricks (NPS), Dave Ryglicki (NRL), Chris Velden (CIMSS), Michael Bell (UH)**

- **Objectives:** Analyze intensity and structure changes in Hurricane Joaquin
  - Understand processes by which Hurricane Joaquin underwent changes in track direction and speed, plus a rapid intensity decrease interrupted by an extended period of constant V_{max}
  - Relate the vortex structure (vertical and horizontal) changes to the environmental and internal physical processes
- **Technical Approach:**
  - Observations: HDSS sondes, CIMSS AMVs, HIRAD surface winds, satellite IR and Microwave
  - Cases of priority: Joaquin from missions on 2, 3, 4 and 5 October 2015
  - Models/Assimilation Systems: SAMURAI/COAMPS-TC dynamic initialization
  - Analysis Tools: Creasey-Elsberry Zero Wind Center (ZWC) tool
- **Key Preliminary Results:**
  - Creasey and Elsberry (2016, draft manuscript) have used sequences of HDSS sondes to calculate the ZWCs at 1 km intervals in the vertical that indicate vortex tilt from 1.5 km to 9.5 km during the 4 October 2015 mission in Hurricane Joaquin
  - First proof-of-concept of SAMURAI/COAMPS-TC dynamic initialization for 4 October mission (see Eric Hendricks report) will blend special TCI-15 observations with environmental fields for detailed analysis

- **Investigators:** Eric Hendricks (NPS, PI), Robert Creasey (NPS), Mary Jordan (NPS), LT Adam Jorgensen and LT Kevin Breach (USN MS students)
- **Collaborators:** Russ Elsberry (UCCS), Chris Velden (CIMSS), Michael Bell (U-Hawaii), Dan Cecil (NASA), Jim Doyle (NRL), and NRL COAMPS-TC group
- **Objectives:**
  - Develop and test new TC initialization scheme utilizing 10-minute AMVs and TCI data (Hendricks, Bell, Elsberry, Velden, Cecil)
  - Understand intensity/structure change in vertical wind shear (Creasey and Elsberry)
  - Utilize environmental data to estimate TC formation time in ensemble forecasts (Jordan, Elsberry, Hendricks)
  - Role of outflow in vortex structure/intensity change (Hendricks, Jorgensen, Breach)
- **Technical Approach:**
  - Observations: HDSS/HIRAD data, AMVs, NOAA/AF recon
  - Primary cases: Joaquin and Patricia
  - Models/tools: COAMPS-TC / SAMURAI / ZWCs
- **Key Preliminary Results:**
  - New TC initialization scheme developed (SCDI) and tested
  - New zero-wind-center (ZWC) tool, first high vertical resolution depiction of TC tilt (see Elsberry slide)

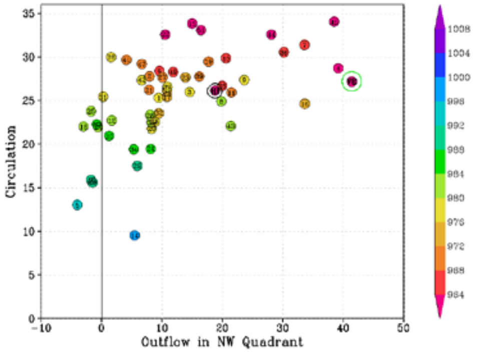
IMPACT OF SAMURAI/ COAMPS-TC/DI (SCDI) Scheme



Environmental sensitivity of TC outflow

- **Investigators:** Sharan Majumdar (PI), Brian McNoldy and Yi Dai (U. Miami)
  - Collaborators: Chris Velden's group (CIMSS), Jim Doyle's group (NRL)
- **Objectives:**
  - Sensitivity of TC intensity change and outflow to environmental interactions
  - Evaluation of satellite Atmospheric Motion Vectors (AMVs) using dropwindsondes
- **Technical Approach:**
  - Sensitivity studies:
    - Correlation and causation exhibited across ensemble members
    - Idealized modeling: effect of jet on secondary eyewall formation
  - AMV evaluation: TCI dropwindsonde observations
    - Erika (2015), Joaquin (2015), Patricia (2015)
- **Key Preliminary Results:**
  - Intensification of Joaquin associated with outflow structure
  - Jet-outflow interaction triggers secondary eyewall formation
  - AMV evaluation to begin in Summer 2016

ECMWF ensemble: NW outflow vs intensity



Dropsonde Derived Vertical Velocity Fields

Investigators: T. Connor Nelson (ASRC); **Advisor:** Lee Harrison (ASRC)

Objectives: Evaluate methods to calculate vertical velocity from XDD Dropsondes

Examine the strength of isentropic flow in the inner core and secondary circulation

Evaluate Richardson Numbers in the vicinity of inner core convection (?)

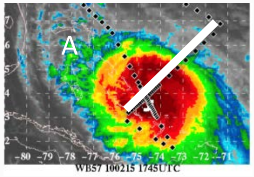
Technical Approach: Use 7 transects from Joaquin (131 Sondes) and 5 transects from Patricia

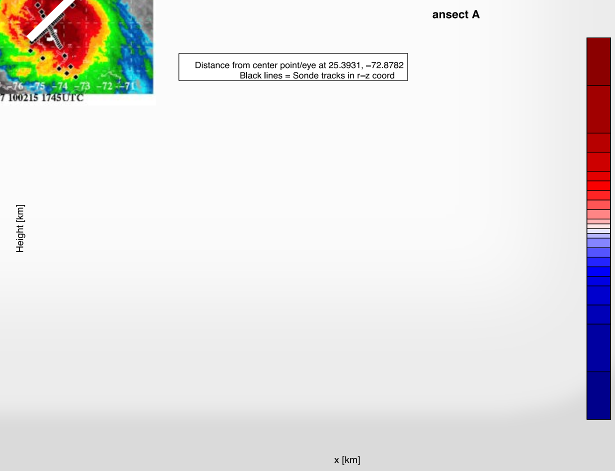
Calculate vertical velocity using fall speed, density adjustment, and assuming surface vertical velocity is zero

Preliminary Results:

Only calculated vertical velocity for 7 transects of Joaquin

Interesting convective signatures in the inner core in relation to the warm core





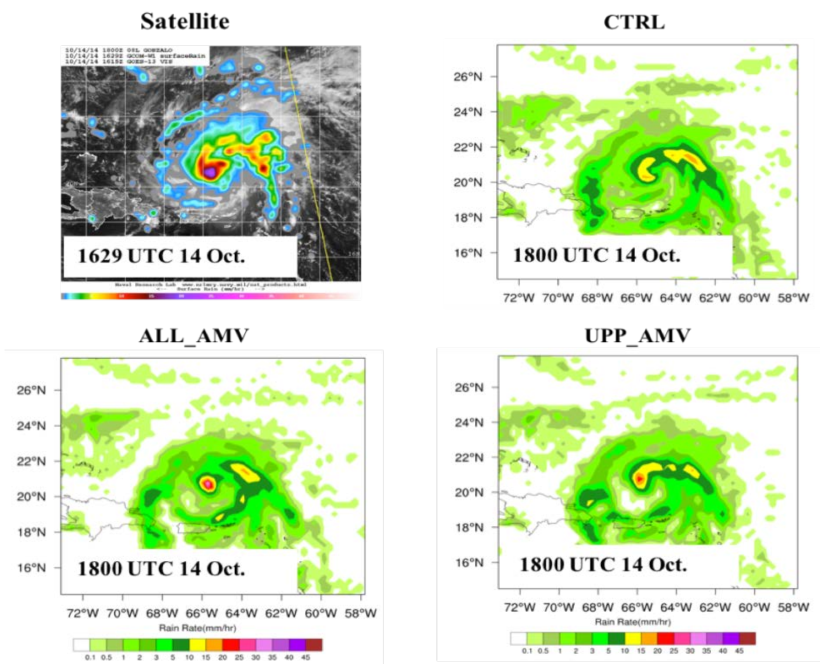
Understanding influence of upper-level atmospheric processes on TC intensity changes through assimilating TCI observations

- **Principal Investigators:** Zhaoxia Pu, U. of Utah; Carolyn Reynolds and Allen Zhao, NRL
- **Objectives**
  - Understanding influence of the upper level atmospheric processes on tropical cyclone (TC) intensity changes through data assimilation and high-resolution numerical simulations
  - Evaluating NAVGEM global analysis and forecasts for TC track and intensity
- **Technical Approach:**
  - Hurricane Edouard and Gonzalo (2014); Hurricanes Joaquin and Patricia (2015)
  - **Observations:** Enhanced AMVs (C. Velden, U of WI); HIRAD (D. Cecil, NASA), HS3 dropsondes; WB-57 HDSS dropsondes; AIRS satellite data
  - **Models / Assimilation Systems:** HWRF/WRF and GSI data assimilation system, moving to COAMPS
  - **Analysis Tools:** Process studies using numerical simulations
- **Key Preliminary Results: (if you have them)**
  - Assimilation of data during TCI experiments results in positive impacts on numerical simulations of TCs. Results indicate the enhanced upper-level warming plays a key role in TC rapid intensification
  - NAVGEM analysis/forecast can reasonably represent TC track, intensity trend, environmental conditions and the vortex structure at its resolution.

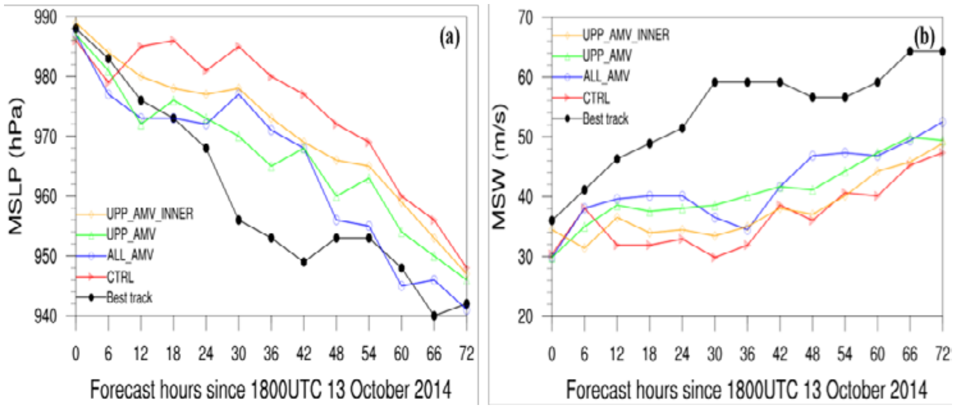
Impact of assimilating enhanced Atmospheric Motion Vectors (AMVs) in numerical prediction of rapid intensification of Hurricane Gonzalo (2014)

Zhaoxia Pu, Shixuan Zhang (*University of Utah*), **Chris Velden** (*CIMMS, Univ. of Wisconsin*)

Hourly precipitation at 1800 UTC 14 Oct. 2014 (24 h FCST)



Intensity forecast (3 days from 1800 UTC 13 Oct. 2014)



CTRL: HWRF forecast, assimilation of all routine observations (operational setting)
ALL_AMV: assimilation of all routine observations and enhanced AMVs with GSI-based ensemble-3DVAR hybrid
UPP_AMV: Assimilation of all routine observations and upper level (350-100 hPa) of enhanced AMVs
UPP_AMV_INNER: Assimilation of all routine observations and upper level inner-core data from enhanced AMVs

- **The enhanced AMVs provide denser coverage in and around TCs**
- **Assimilation of enhanced AMVs results in significant improvements in prediction of rapid intensification of Gonzalo.**
- **Assimilation of upper level (350-100hPa) AMVs results in comparable positive impacts on the intensity and structure forecasts. Specifically, the upper level inner core data from enhanced AMVs contribute more than 50% of improvements in the intensity forecasts, implying the important role of upper-level atmospheric processes in rapid intensification of Gonzalo.**

Ocean to Outflow

- **Investigators:** Beth Sanabia (USNA, co-PI), Brad Barrett (USNA, co-PI)
- **Objectives:**
  - Identify the relationship between the ocean, eyewall convection, and outflow within TCs to further understand the mechanisms within the TC secondary circulation and the impact of these processes on TC intensification.
  - Investigate lead / lag in the branches of the secondary circulation
- **Technical Approach:**
  - TCI Cases: Iselle & Julio (2014); Joaquin (2015)
  - Observations: AXBTs, AMVs, dropsondes
  - Models / Assimilation Systems: COAMPS-TC, NCODA, NAVGEM
- **Key Preliminary Results:** Iselle & Julio outflow study is complete; ocean study is in progress.
  - Maximum outflow in the NAVGEM model was consistently near 200hPa
  - Relationship between outflow & intensity:
    - *TC intensity increased* during periods of greater outflow and when the outflow was located closer to the TC center
    - *TC intensity was greatest* when dual outflow channels were present
  - Outflow channels were greatly impacted by adjacent large-scale features
  - Cooling SSTs were prevalent within 200km of the TC center during slower (<5 m/s) translation speeds as well as when there was strong outflow aloft.

Ocean to Outflow

- **Key Preliminary Results:** Iselle & Julio (2014) outflow study

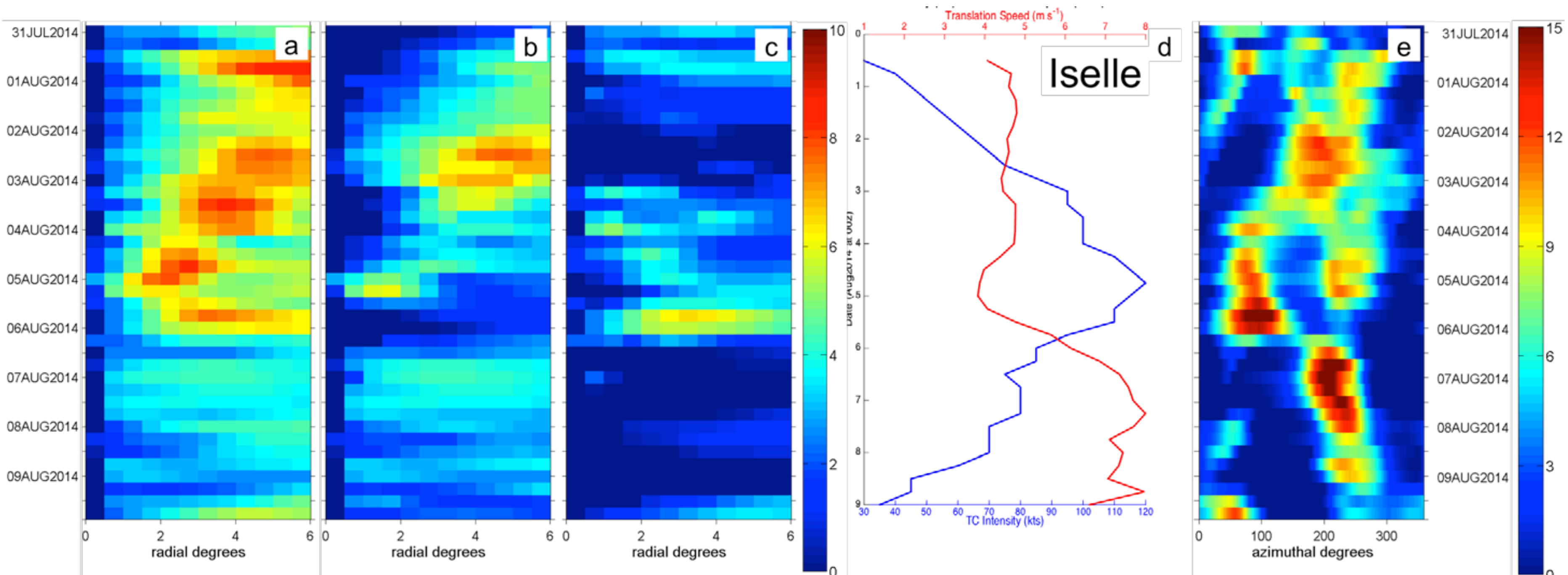
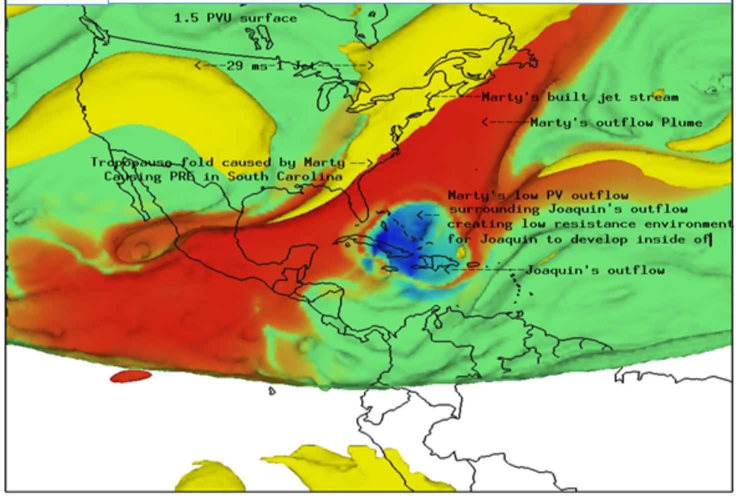


Fig. 1. Radial variation in the mean (a) total, (b) equatorward, and (c) poleward outflow (m/s) derived from 200-hPa NAVGEM analyses for Hurricane Iselle (shaded, scales at right. (d) Best track intensity (kts, blue) and translation speed (m/s) for Iselle. (e) As in (a), except azimuthal variation. Plots are aligned by date.

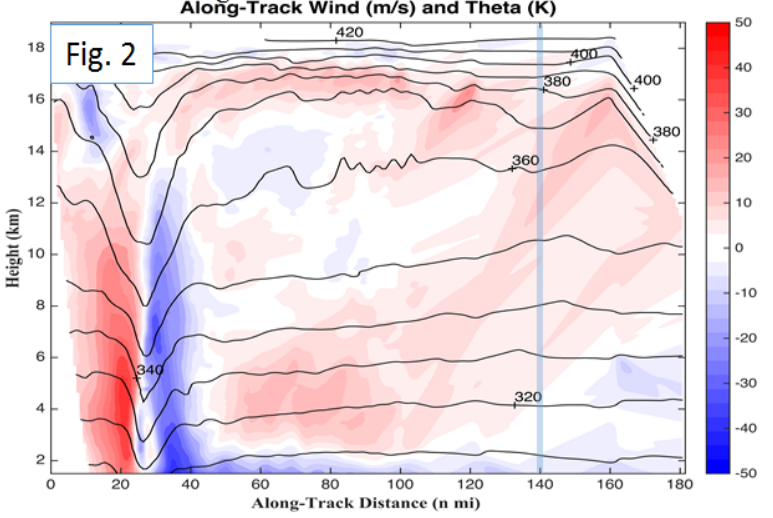
Greg Tripoli (UW-Madison, PI), Jason Dunion (NOAA-HRD, co-I) and William Lewis (UW-Madison)

- **Objectives:**
  - Clarify the role of Hurricane Marty (in particular the evolution of Marty's outflow anticyclone) in the subsequent intensification of Hurricane Joaquin
  - Explore the connection between diurnal pulsing and the structure of (transient) deep-layer outflow features
  - Quantify the importance of high-frequency cycling in the assimilation of HDSS observations
  - Use HDSS observations to verify the up- folding process predicted in model simulations (low PV outflow steepening and folding over tropopause wall)
  - Relate TC inner structure to outflow using model simulations verified with HDSS soundings in Patricia and Joaquin
- **Technical Approach:**
  - Use GEFS and Wisconsin Ensemble Data Assimilation System (WENDAS), including HDSS and AMV assimilation, to create an ensemble of model analyses to establish:
    - the importance of tropopause folding in the Marty / Joaquin complex (figure 1)
    - the role of outflow-environmental interactions on storm intensity and intensity change for Joaquin and Patricia
  - Correlate model analyses with HDSS observations to create a fuller phenomenology of diurnal pulses, including observed deep-layer storm structure; if possible, establish causal relationships (figure 2 – Blue vertical line indicates leading edge of diurnal pulse)

Fig. 1 Marty-Juan Complex at 21Z 30 SEP 2015



X-Section through Patricia from HDSS 1945Z 23 Oct 2015



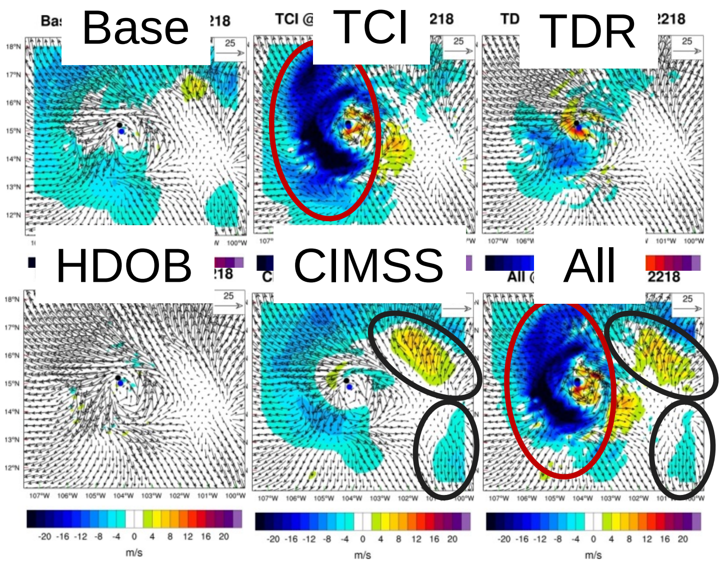
Understanding the impact of outflow on hurricane intensification through ensemble-based data assimilation and ensemble simulation

- **Investigators:** Xuguang Wang (OU, PI), Lance Leslie (OU), Xu Lu (OU)
- **Collaborators**: M. Bell (Hawaii), C. Velden (CIMSS), D. Cecil (NASA), J. Doyle (NRL)
- **Objectives:**
  - What is the impact of assimilating observations sampling outflow layer on TC analysis and prediction? What is the most efficient way to extract information from data which sample various aspects of the TCs through DA?
  - Through diagnosing the 4D, ensemble of analyses and forecasts produced by DA, what is the impact of outflow on TC intensity change and predictability of TC intensification?
    - How is the TC outflow coupled with the inner core convection and therefore affects intensity change?
    - What is the relationship between upper level outflow and low level wind structure?
- **Technical Approach:**
  - Cases: Patricia, Joaquin, Marty
  - Observations: TCI WB57 dropsondes, TCI WB57 HIRAD, CIMSS AMV, IFEX P3 &GIV Tail Doppler Radar data, flight level obs., SFMR, NWS operational data, etc.
  - Models/DA system: hybrid EnKF-Var DA system for HWRF (may extend to COAMPS-TC ensemble DA system)
  - Analysis tools: ensemble based diagnostics

Understanding the impact of outflow on hurricane intensification through ensemble-based data assimilation and ensemble simulation

- **Key Preliminary Results:**
  - In the upper level, assimilating TCI dropsondes can effectively correct the upper level winds, producing the upper level outflow consistent with the independent CIMSS AMV. Additionally, the TCI dropsondes can be complementary with CIMSS AMV data.
  - In the mid-low levels, the assimilation of TCI dropsondes alone can produce very good inner core structures as verified against the independent tail dopper radar observations. The mid-low level analysis produced by assimilating TCI dropsonde is very similar to the analysis produce by assimilating the TDR data alone.
  - Over all, assimilating ALL (TCI dropsonde + TDR + flight level+ CIMSS AMV + NWS operational data) produced the best analysis.
  - We plan to assimilate TCI HIRAD and SFMR also to confine surface wind.

150hPa radial wind increment



3km horizontal wind analysis