Simulating Hurricane Joaquin (2015) with WRF-ARW: Challenges and progress

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Objectives

- Perform a successful simulation of Hurricane Joaquin (2015) using the WRF-ARW model;
- Study the environment-vortex interactions that caused the storm to follow a looping track; and
- Examine the physical mechanisms responsible for two episodes of rapid intensification, including the relationship between the upper outflow and boundary-layer inflow through trajectory analysis.

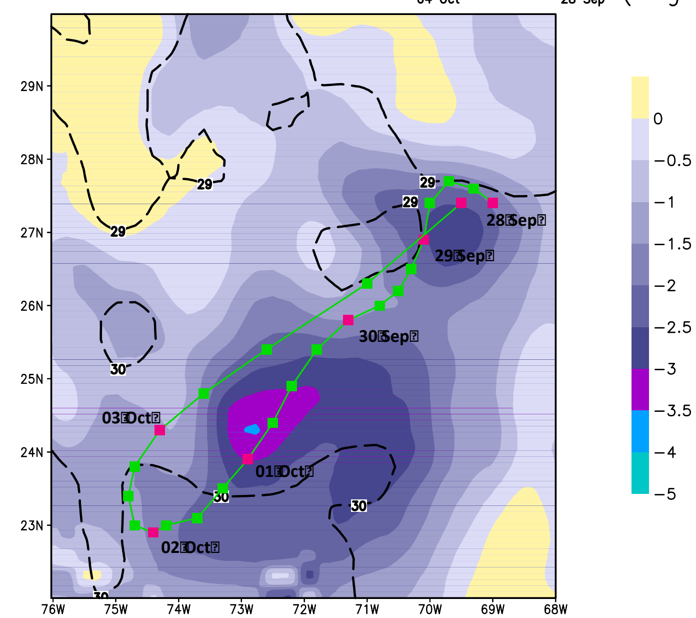
Overview

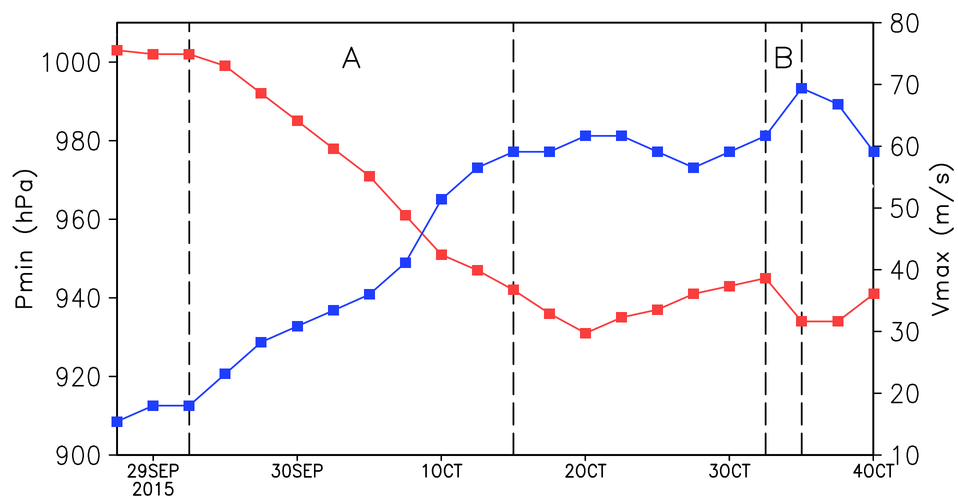
- "Looping" track:
- Two distinct rapid intensification (RI) episodes:

  A) 29 Sep 0600 UTC – 01 Oct 1200 UTC (41 m s^{-1} 2.25 day^{-1})

  B) Re-intensification; 03 Oct 0600 UTC - 03 Oct 1200 UTC (7.7 m s^{-1} 6 h^{-1})
- Both track and intensity dependent on UL ridge and trough configuration
- Operational models (except for ECMWF) performed poorly in storm track prediction

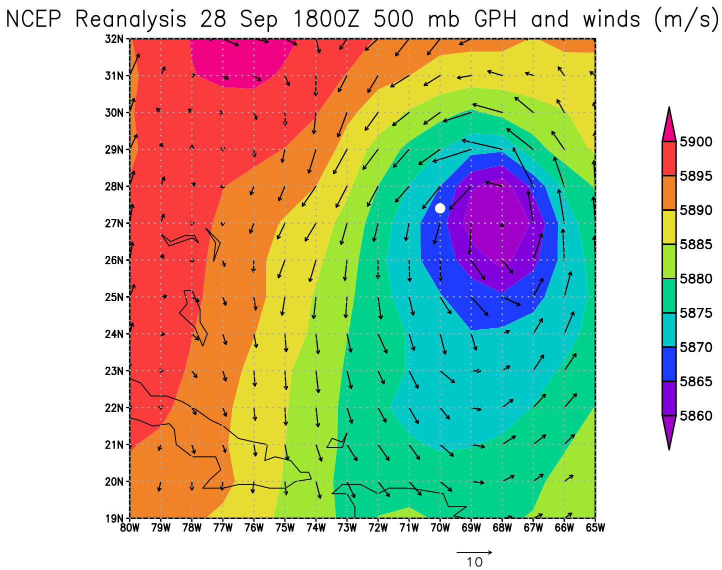
Joaquin track with AVHRR–derived $SST_{04\ Oct}$ – $SST_{28\ Sep}$ (deg C)

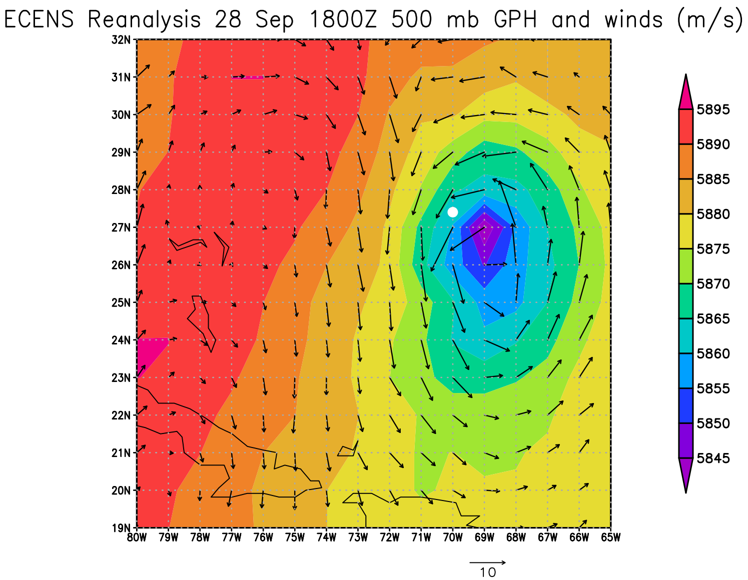




Major Challenges For Track Prediction

1) sensitivity of track to initial vortex structure
2) **Hypothesis:** a stronger, deeper vortex should be more influenced by mid-to-upper level steering flows.





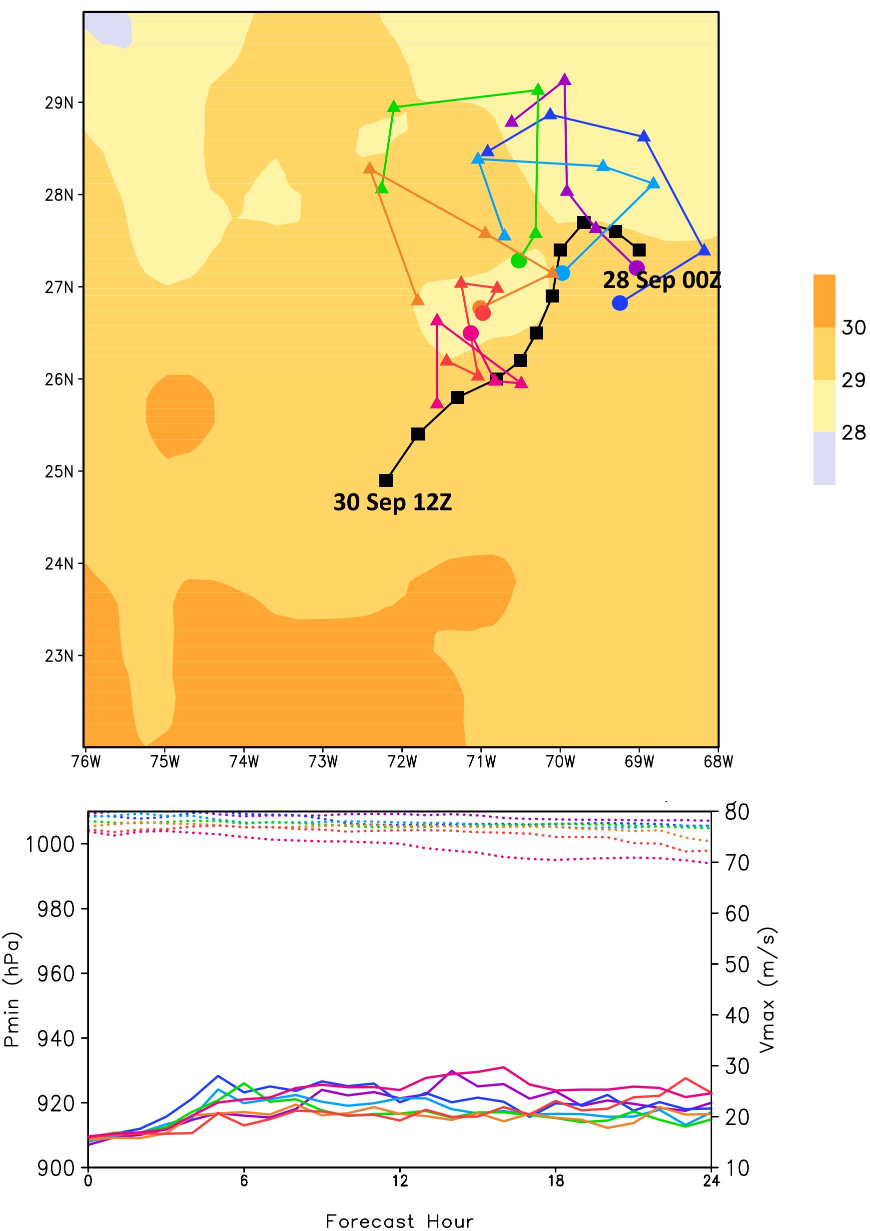
2) accurately modeling upper-level ridge-trough configuration

- Strategies:

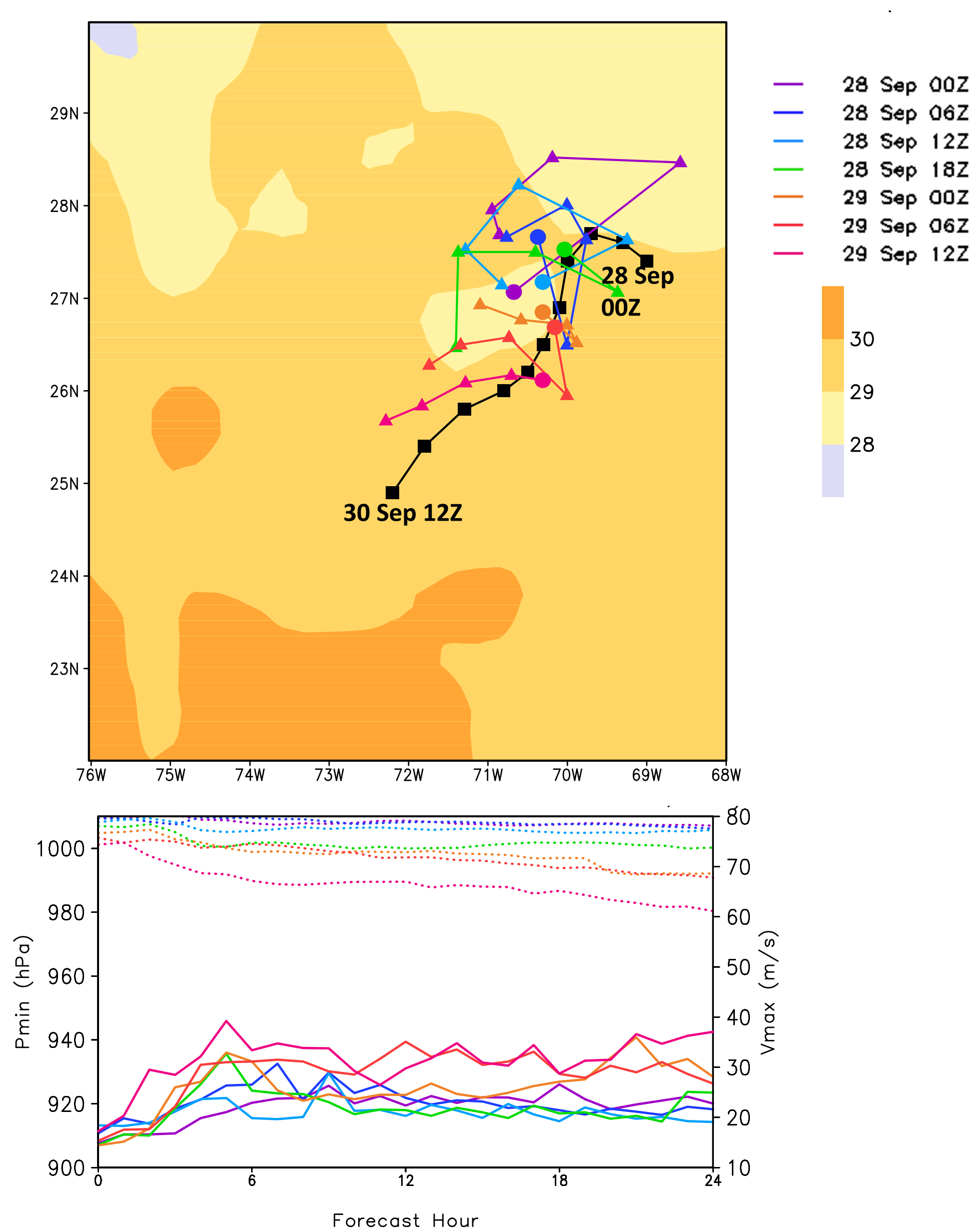
- Initialize WRF using European Center Ensemble (ECENS) Reanalysis data
- Generate bogus vortex (Kwon and Cheong *MWR* 2009) relocated SE of best-track position
- Use WRF Data Assimilation System (WRFDA, Huang et al. *MWR* 2009) to generate an improved analysis at initialization time

24-h WRF forecasts initialized every 6 h, from 28 Sep 00 UTC – 29 Sep 12 UTC

NCEP Reanalysis

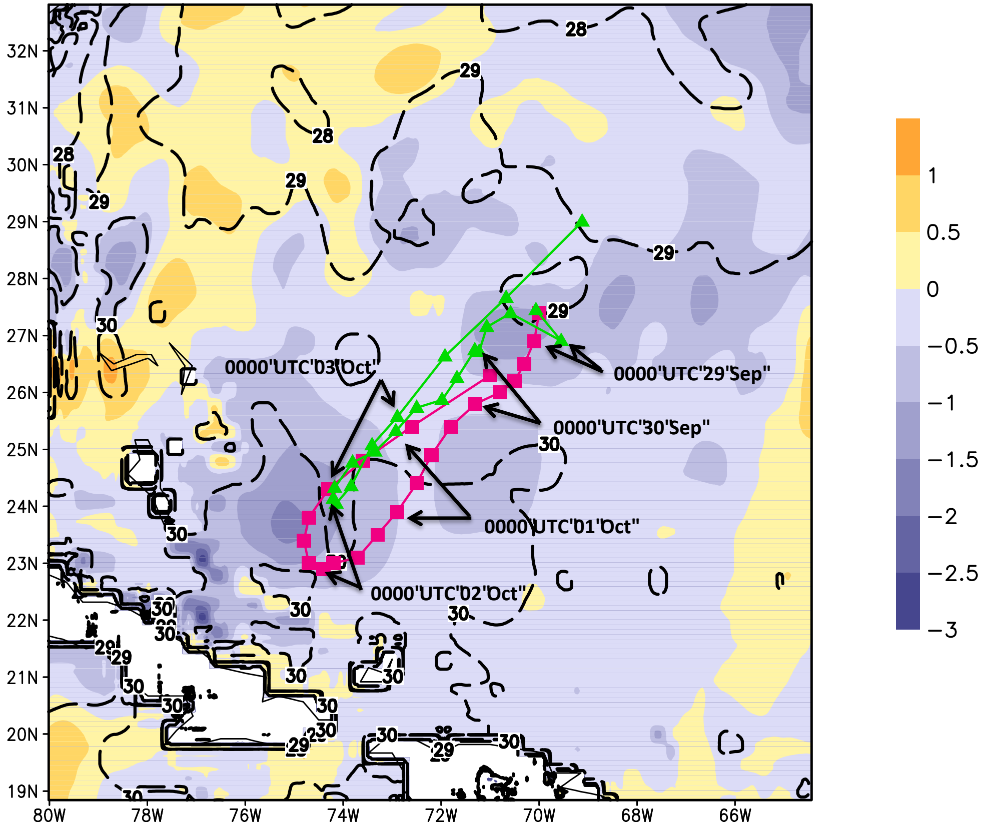


ECENS Reanalysis

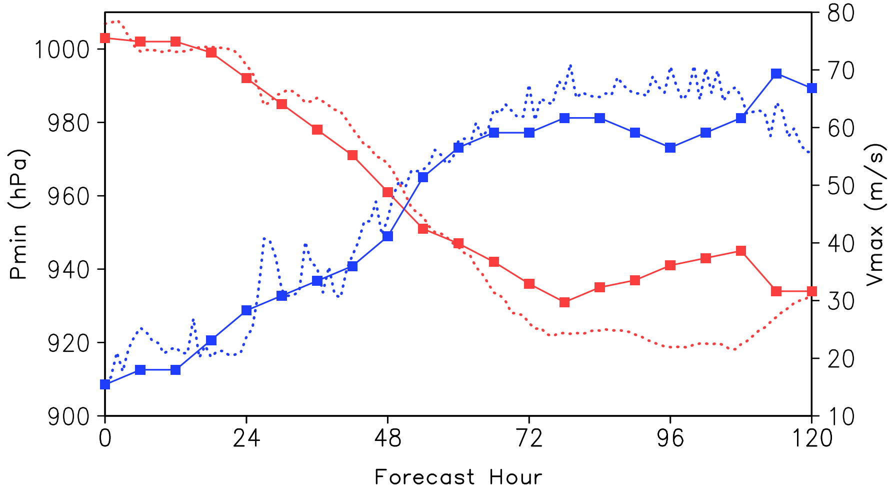


WRF-ARW 1-km Control Simulation Results

WRF-predicted (green squares) and best-track 6-hourly storm positions superimposed over the SST change from initial time to 1200 UTC 02 Oct

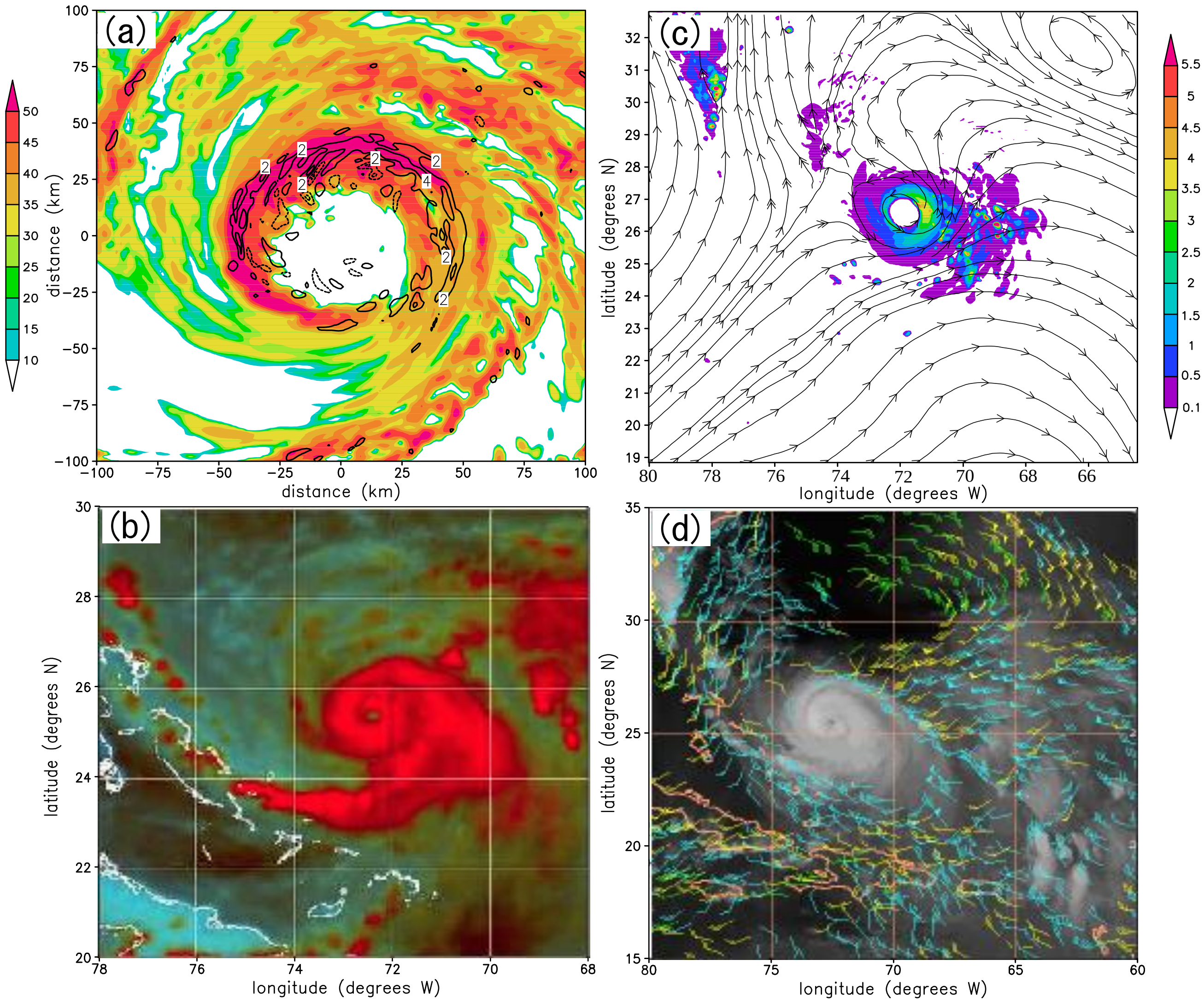


WRF-predicted (dotted) and best-track (solid) intensity



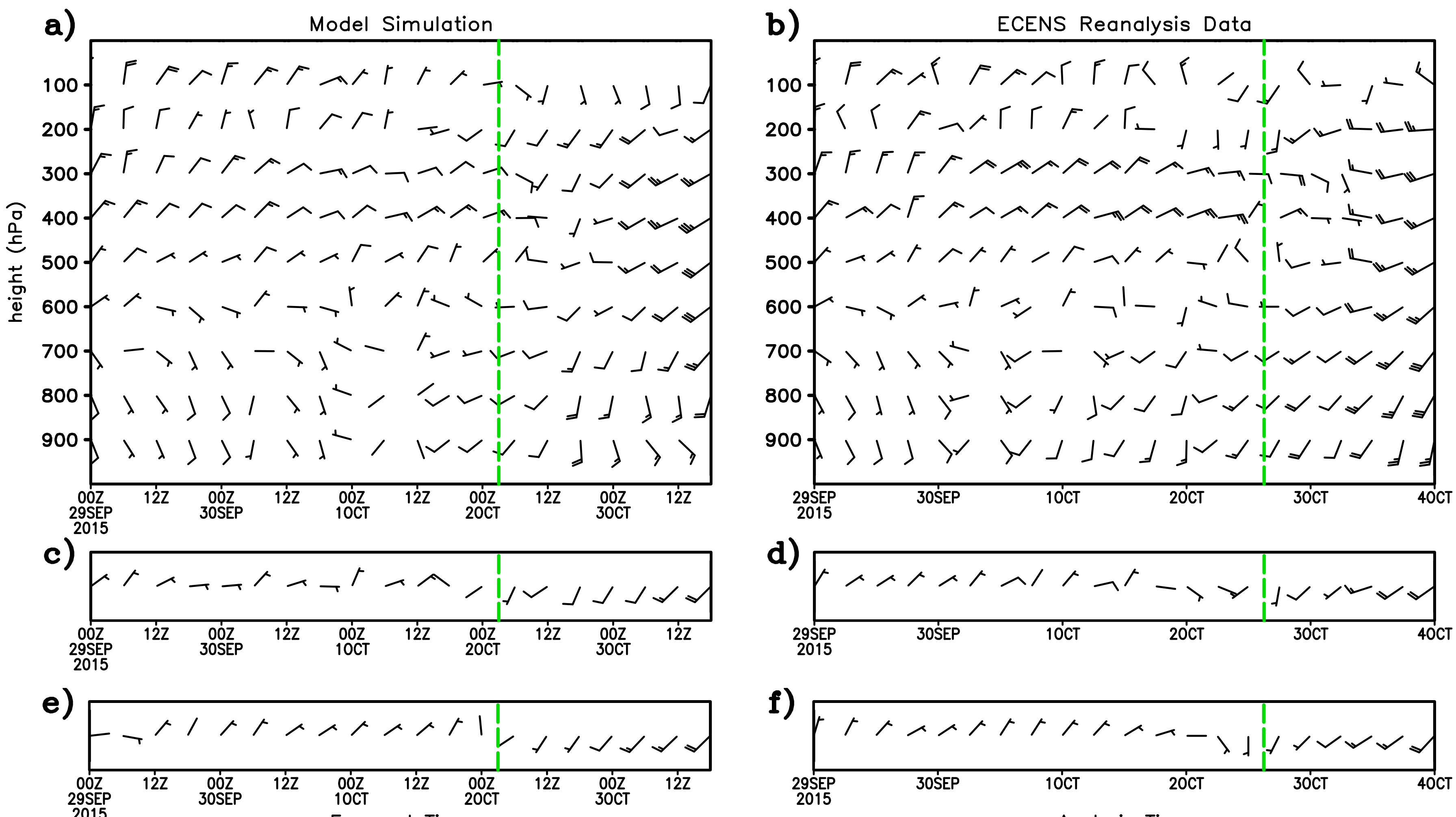
Control Structures at Peak Intensity Time

- Model-simulated fields (a,c) at 0600 UTC 03 Oct
- SSMI/S 91-GHz color composite (b) with satellite AMVs (d) at 1200 UTC 03 Oct



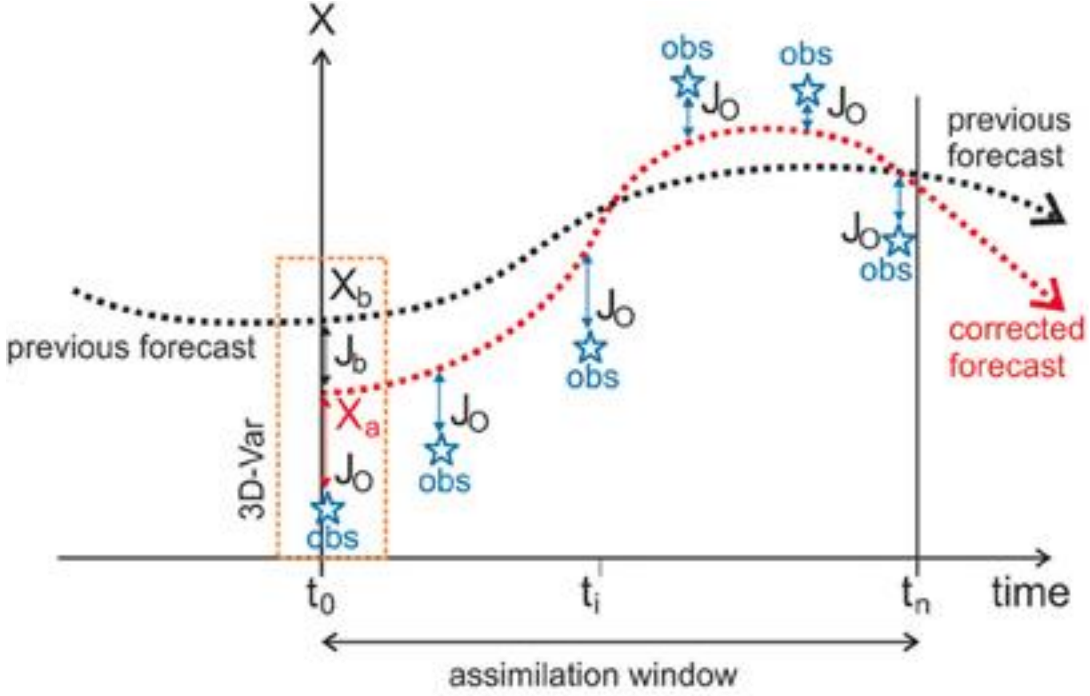
Steering Flow Analysis

- Winds averaged horizontally over a 6 deg × 6 deg box surrounding storm center
- (a,b) : winds as a function of height
- (c,d) : deep-layer 200 – 900 hPa mass-weighted averages
- (e,f) : storm motion vectors



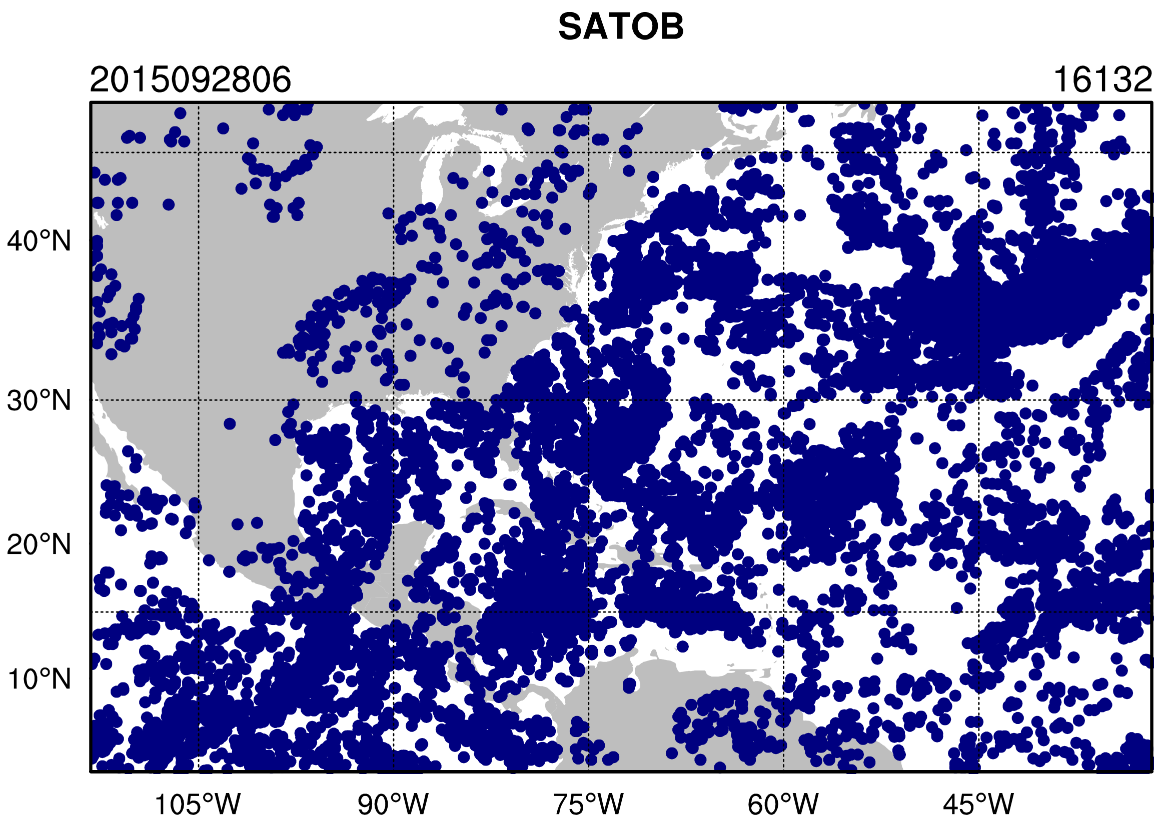
Using 4DVAR Data Assimilation to Improve Model Initialization

- Like 3DVAR data assimilation, minimizes a cost function to find the analysis solution where both model errors and observational errors are smallest
- Unlike 3DVAR, data can be assimilated over a much larger time window → more observations, model errors are "flow dependent"
- Uses a linear tangent/adjoint WRF model to advance the analysis through the time window to compare against observations → also provides a dynamical constraint in cost function minimization



WRFDA strategy for Joaquin (2015)

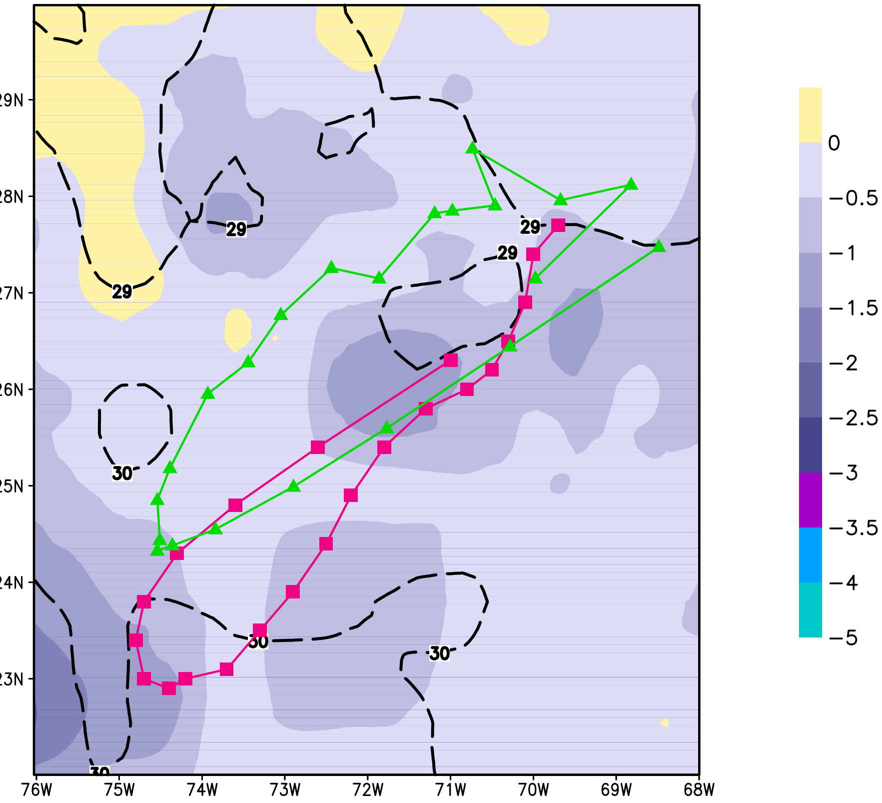
- Generate background error matrix using a 1-month period of WRF forecasts, using the difference between the 24-h and 12-h forecasts verifying at the same time as a proxy for model error (NMC Method, Parrish and Derber *MWR* 1992)
- Experiment with both "cold start" and cycling WRFDA-initialized runs
- Assimilate as many observations as possible, including satellite AMV winds, station soundings, aircraft reports (AIREPS), recon plane dropsondes, satellite radiances
- For now, only perform DA on the outermost 27-km domain



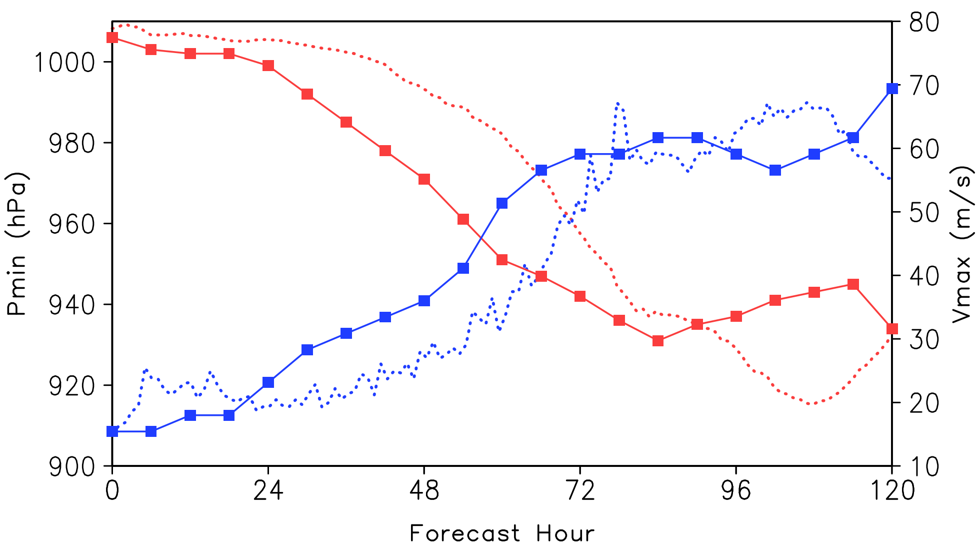
5-day WRF simulation Initialized from WRFDA Analysis

- Using daily-averaged AVHRR SSTs as boundary conditions
- Assimilate AMVs and conventional observations over 6-hr window
- Re-intensification is now simulated

WRF-predicted (green squares) and best-track 6-hourly storm positions superimposed over the SST change from initial time to 1200 UTC 02 Oct



WRF-predicted (dotted) and best-track (solid) intensity

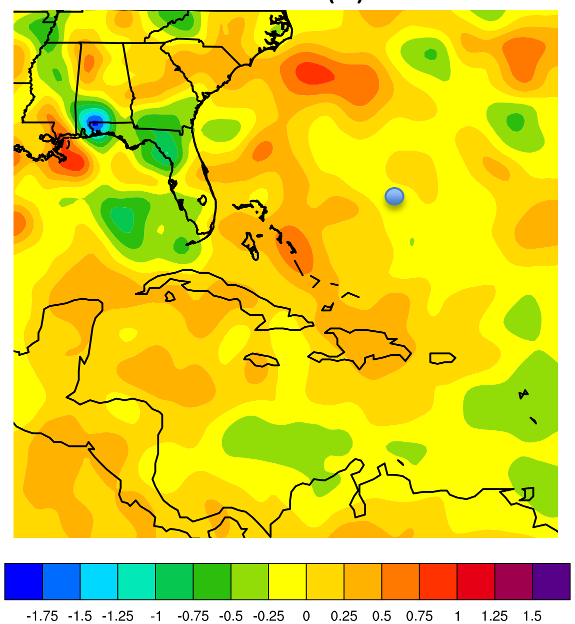


Was the analysis at 28 Sep 1200 UTC Improved by Data Assimilation?

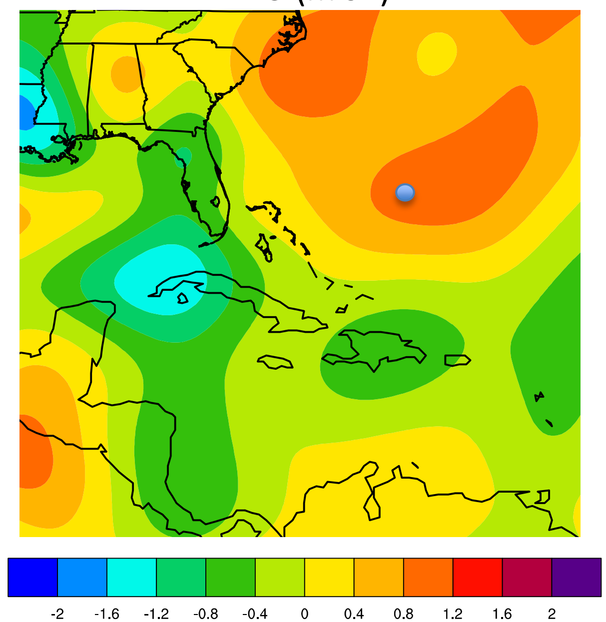
- WRFDA analysis – NCEP reanalysis difference fields for ~500 hPa level
- Stronger Bahamas ridge
- Mid-upper level large scale flows

  become more northerly over Joaquin

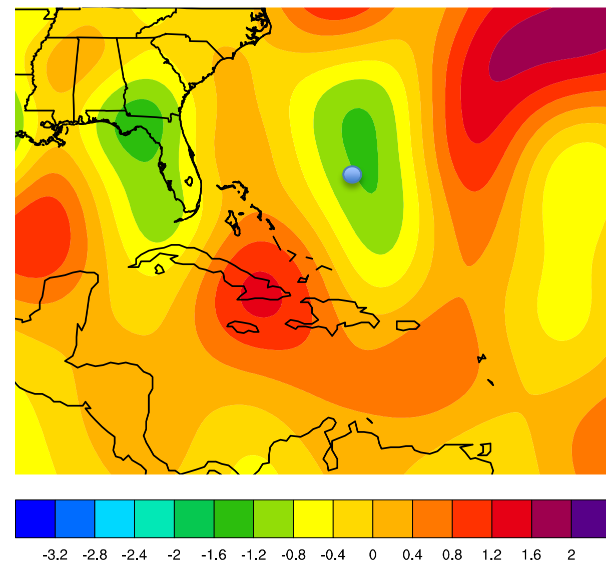
Theta (K)



U (m s^{-1})

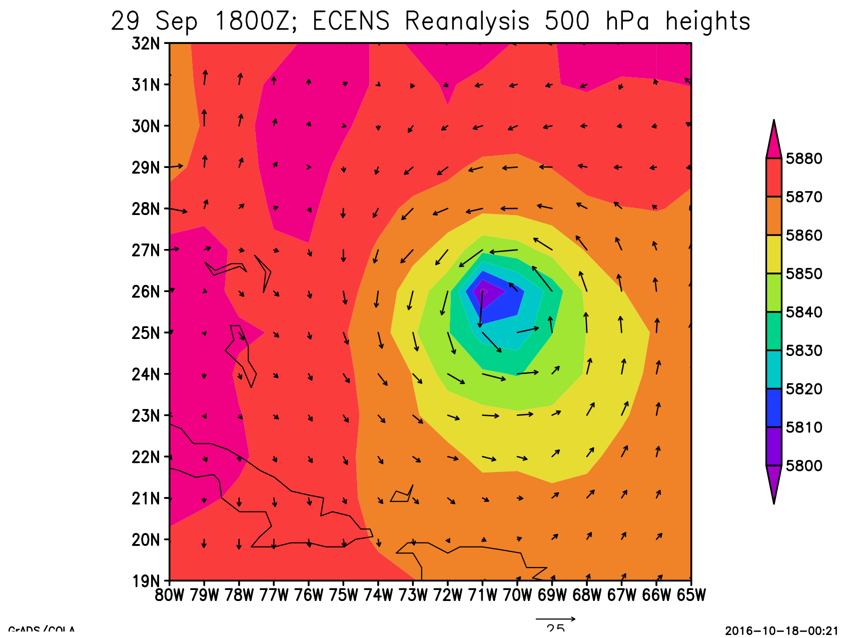


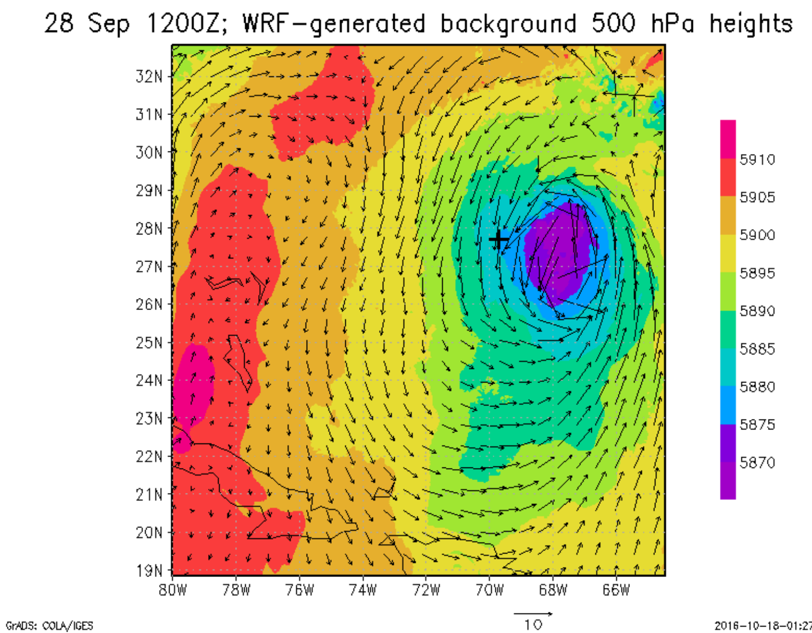
V (m s^{-1})

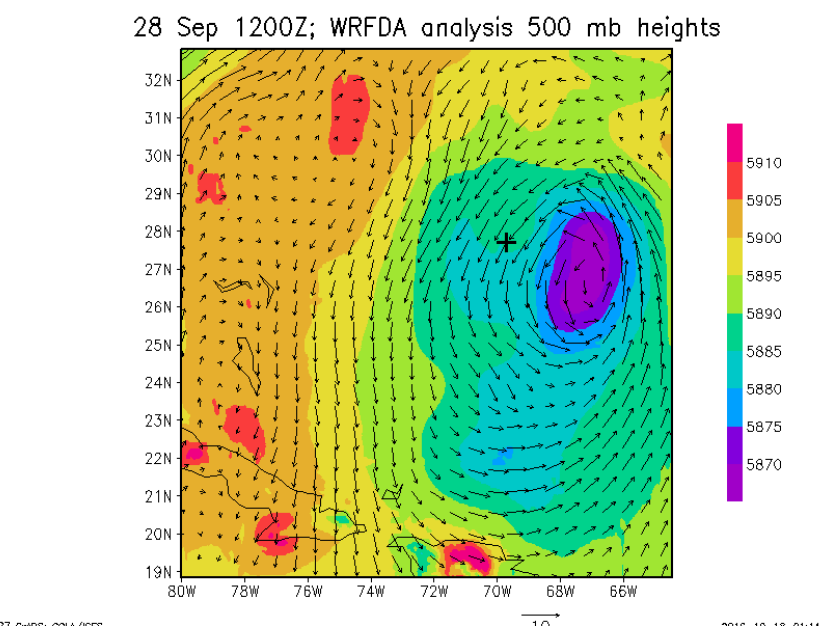


Now Zooming in on Mid-upper Level Vortex

- WRF-generated vortex at 28 Sep 1200Z is weaker than the NCEP reanalysis vortex
- WRFDA has small impact on 500-hPa vortex structure

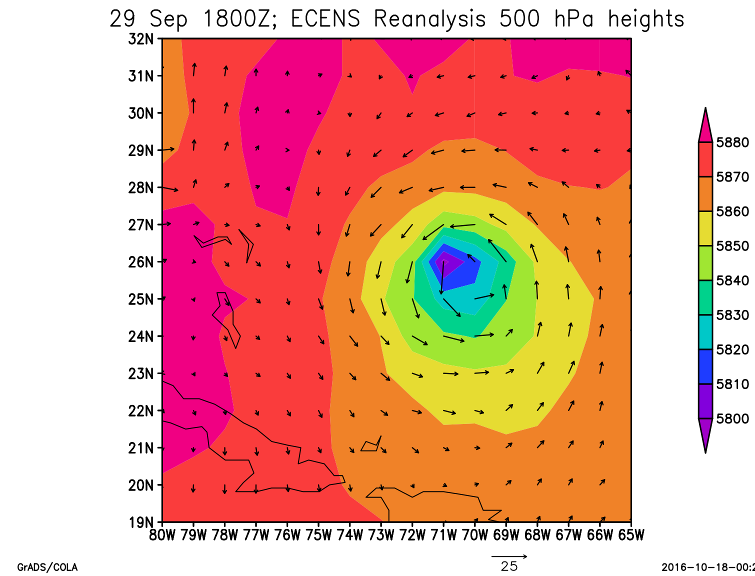


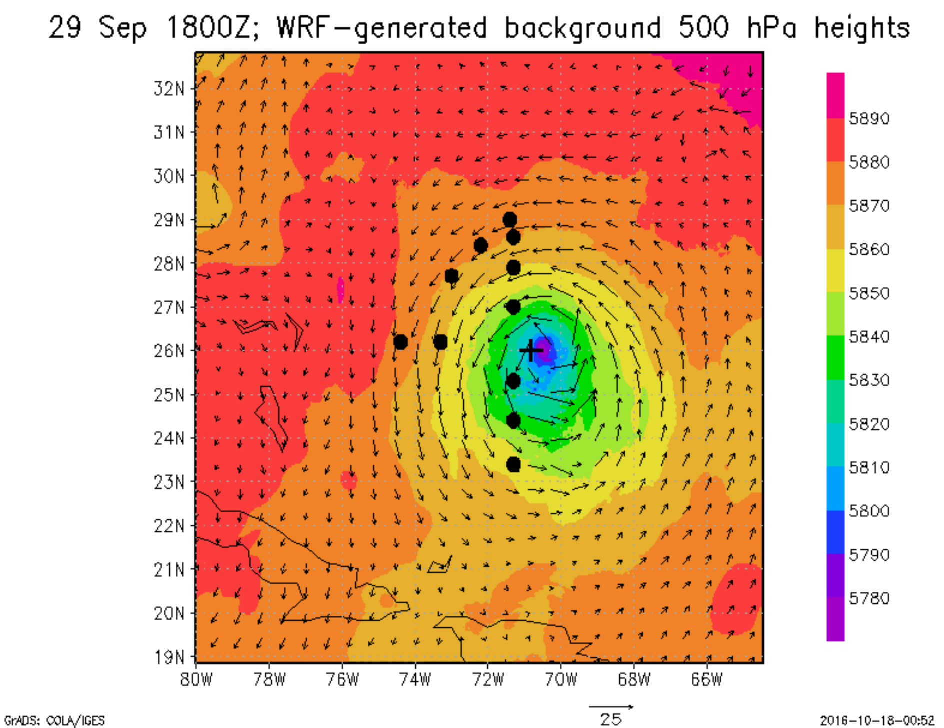


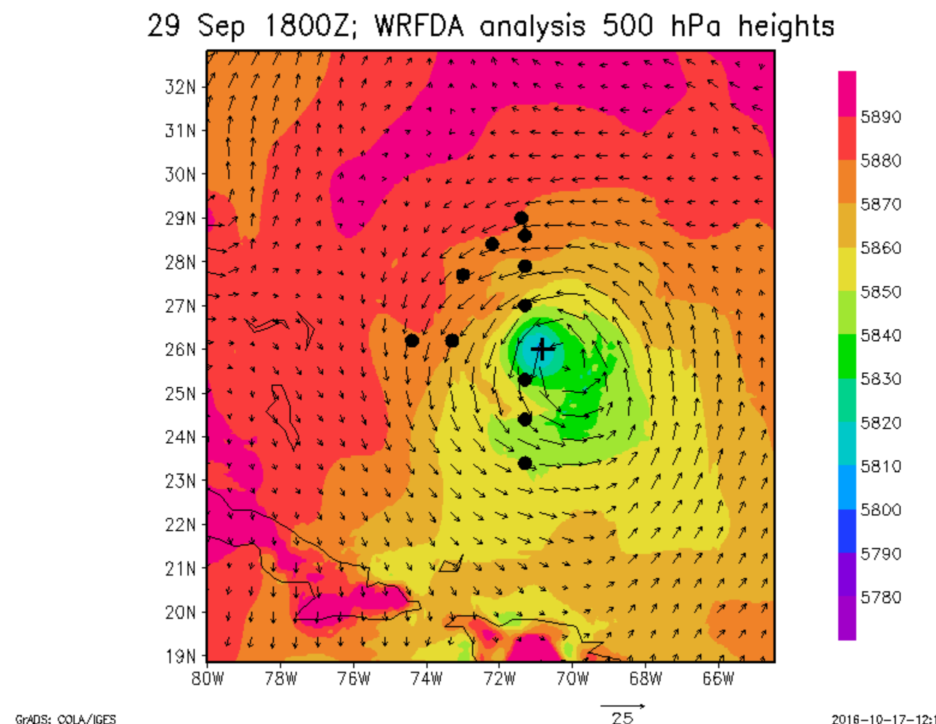


How Does WRFDA Impact Vortex at Later Initialization Time?

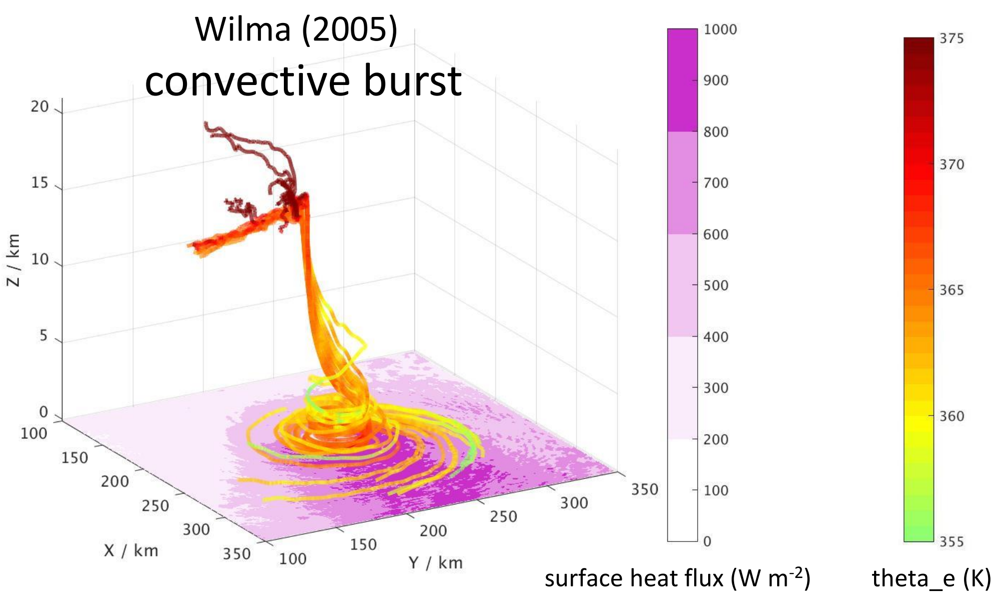
- Continue cycling process through 29 Sep 1800 UTC
- Here we assimilate a wide variety of observations:
  - AMVs, AIREPs, upper-air soundings
  - satellite radiances: AMSU-A, MHS, AIRS
  - 11 NOAA G-IV dropsondes (released at 2000 & 2100 UTC 29 Sep)
- WRFDA strengthens 500 hPa ridging NW of storm, but weakens vortex!

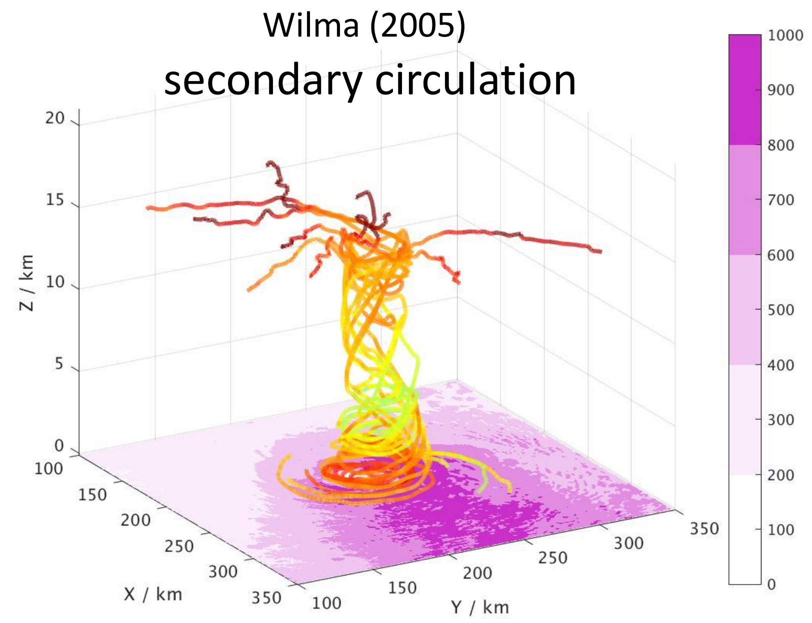






Calculating Trajectories from WRF Model Output





- Trajectory analysis to address TCI objectives:
  - Investigate relationship between high surface fluxes and outflow layer development through inner-core deep convection
  - Study thermodynamics of convective bursts
  - Compare the Wilma (2005) and Joaquin (2015) cases
- Calculating trajectory algorithms:
  - Kinematic trajectories computed from gridded 5-min resolution model-output winds
  - 2^{nd} order Runge-Kutta forward and backward time integrations with a 10-s time step
  - Advection correction (Shapiro et al. *JAS* 2015) used in time interpolations

Summary

- CTL simulation (no DA) Successes:
  - Reproduces loop-shaped track
  - Captures timing and intensity of first RI period reasonably well
  - Inner-core convection and outflow layer structures compare well against satellite observations at time when the storm is most intense
- CTL simulation (no DA) room for improvement:
  - Does not show the observed slow counterclockwise turn to NE
  - Track errors increase substantially after 0000 UTC 03 Oct
  - No re-intensification period
- Preliminary results with assimilating AMVs:
  - Synoptic-scale analysis increments favorable for southward early track
  - Weakening of upper-level vortex structure a problem that still needs to be resolved
- Trajectory Analysis of Outflow Layer – surface flux connection:
  - New methodology using advection correction currently being tested
  - Early results show that convective bursts originate from regions of PBL where surface heat fluxes are higher
  - Early results show that profiles of thermodynamic and microphysical variables through CBs traced to PBL are consistent with those shown in other modeling studies (Fierro et al. 2009, 2012)

Plans For Future Work

- Continue trying to improve upon ECENS analysis with WRFDA:
    - Perform single-observation tests to study impact of domain-tailored static background error, and fine-tune as necessary
    - Assimilate radiance data
    - Consider removing inner-core AMVs or accounting for possible height/speed biases
    - Try multiple "outer loops" in 4DVAR minimization → standard practice now for operational NWP centers using 4DVAR

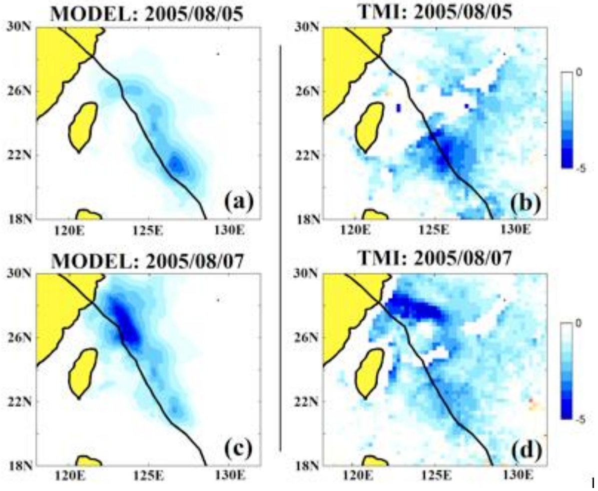
- Dealing with the SST cooling impact on Joaquin's intensity forecast

- SST cooling parameterization being developed for WRF-ARW:

Liu, X., J. Wei, D.-L. Zhang, W. Miller, 2016 *MWR* accepted with major rev.

- SST tendency computed at every model time step
- scheme generates ocean currents using the WRF-predicted 10-m horizontal winds
- vertical mixing and advection drive SST cooling, with mixed-layer depth accounted for
- SST recovery following TC passage also computed

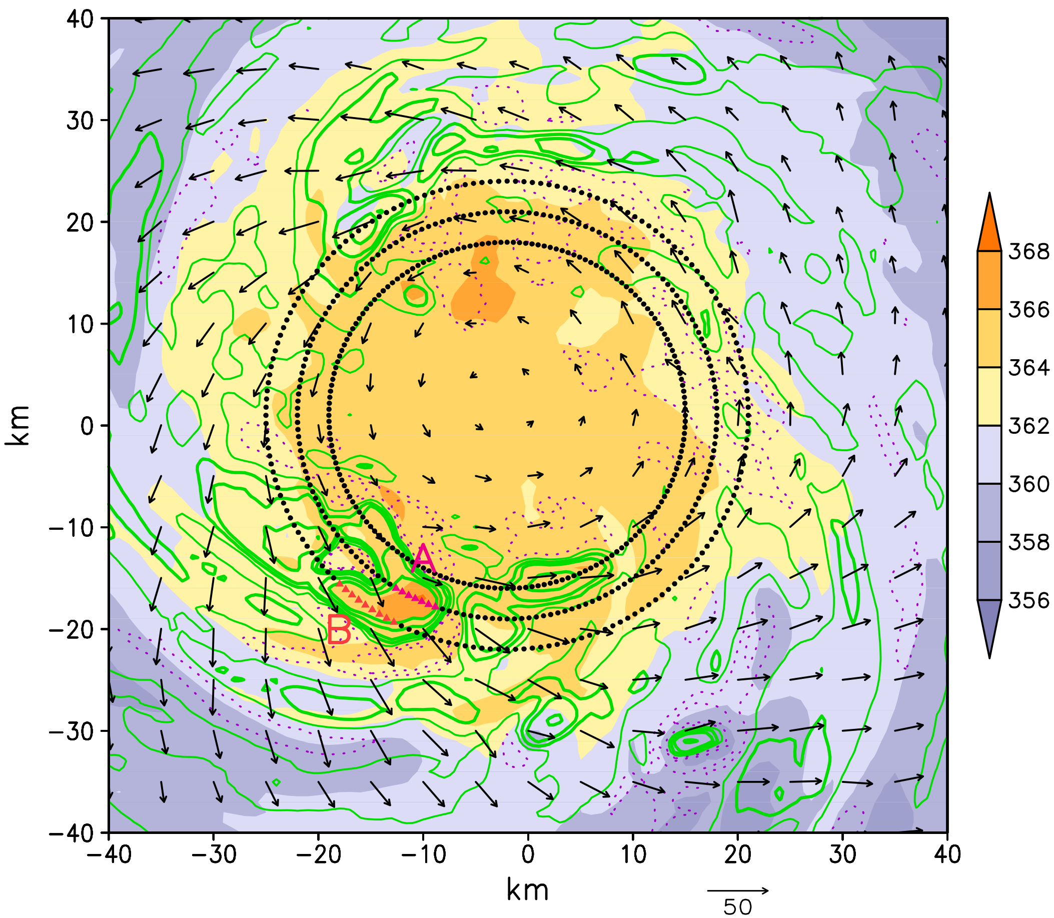
Typhoon Matsa (2005) WRF simulation



- Perform statistical analysis on trajectory data on CBs versus background secondary circulation: thermodynamic characteristics, outflow layer composition

Advection Correction:
accounting for advection of flow disturbances when performing time interpolations of gridded data

z= 14 km vertical velocity (contours) with theta_e (shaded) and storm-relative flow vectors



One-dimensional translating wave schematic comparing linear time interpolation (LI) with advection correction (AC)