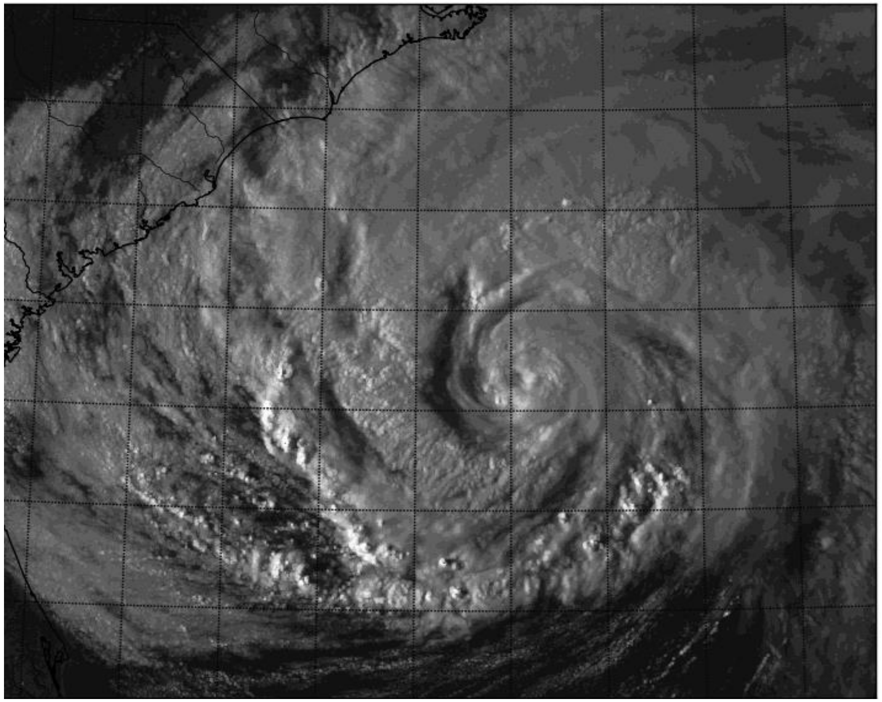
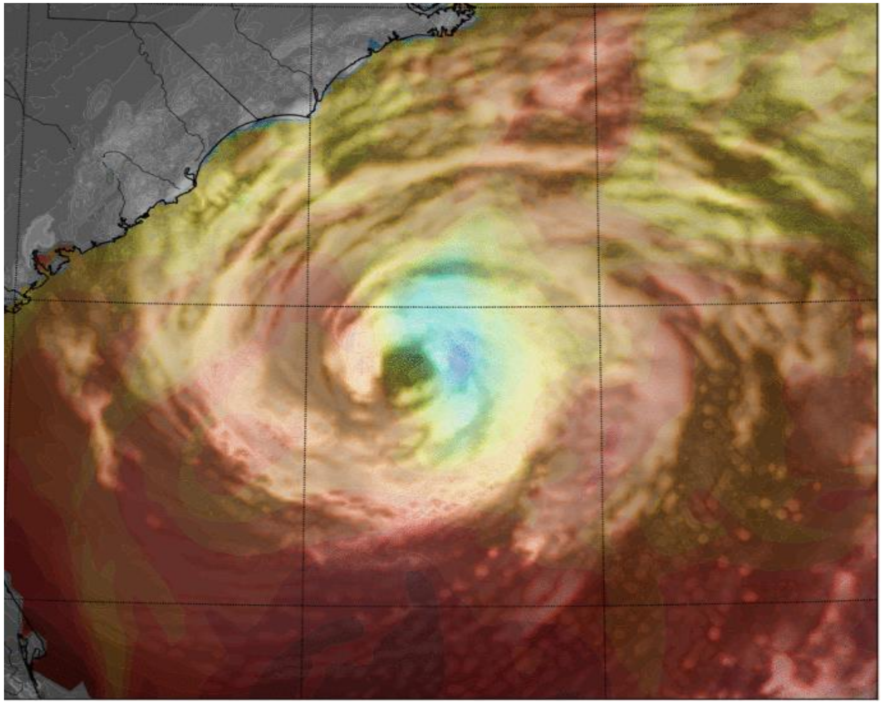
The role of atmosphere-ocean coupling in the structure and intensity evolution of Hurricane Ophelia (2005)

Andrew W. Smith[1]
[1]University of Miami Rosenstiel School of Marine and Atmospheric Sciences





Postdoctoral Fellow Interview, April 19, 2024 | University of Rhode Island, Narragansett, RI

THE UNIVERSITY OF RHODE ISLAND

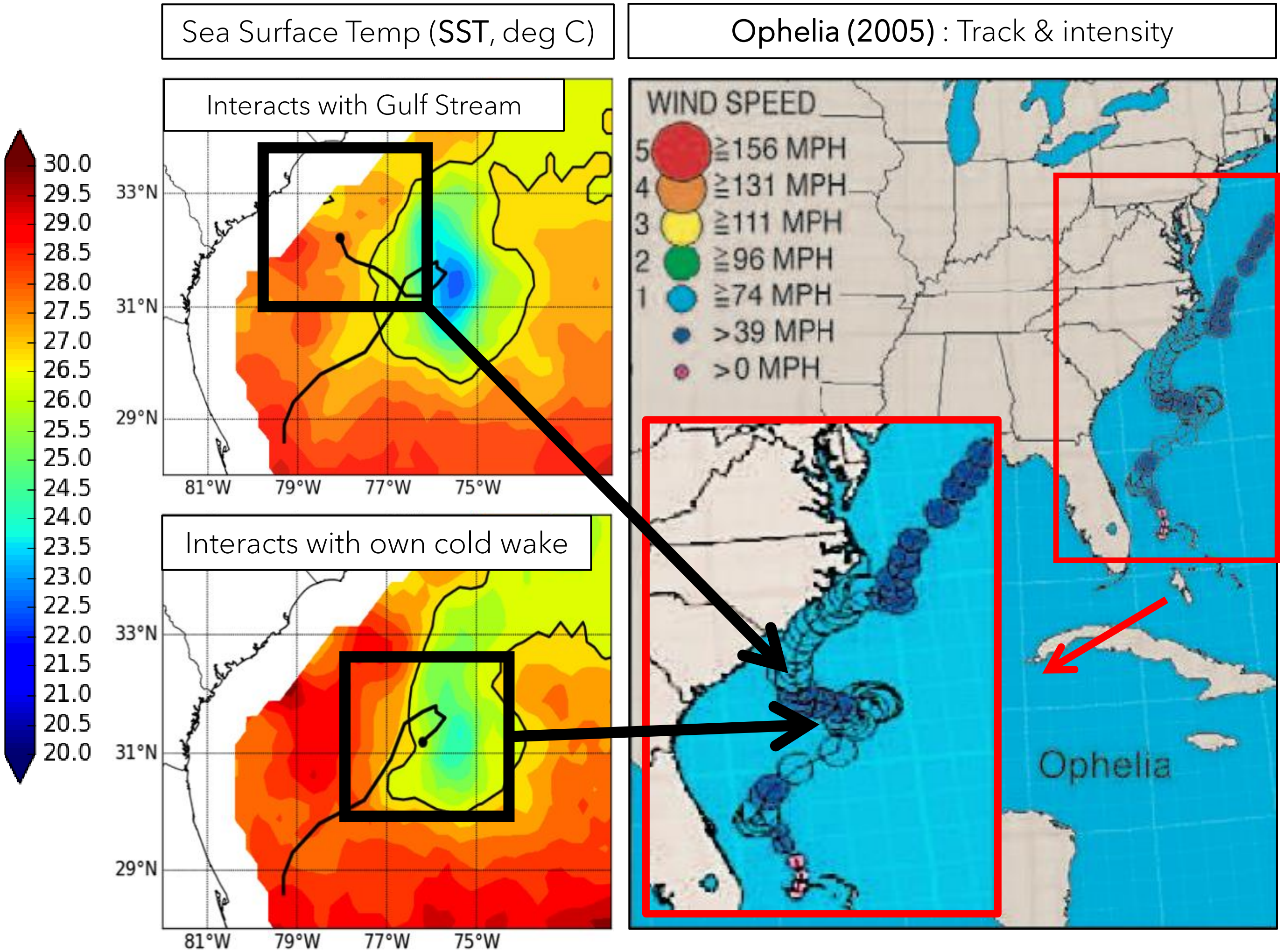
Hurricane Rainband and Intensity Change Experiment RAINEX 2005

GULF OF MEXICO RESEARCH INITIATIVE

NSF

- Hurricane Ophelia (2005) best known for its erratic track, atypically slow forward speed, was poorly forecasted
- Costly preparation by gov't and emergency response agencies in S.C., N.C. proved largely unnecessary
- Dynamic linkage between TC intensity and air-sea interaction shown in studies for decades (e.g., Anthes and Chang, 1978; Emanuel 1986; Chen et al. 2007)
- TC-induced upper ocean cooling impact on storm intensity also investigated (e.g., Leipper 1967; Price 1981; Shay et al. 1992; Price et al. 1994)
- More recent studies have shown air-sea coupling affects TC structure **and** intensity (e.g., Lee and Chen 2012, 2014; Chen et al. 2013)
- Prediction of TC structure and intensity change from complex interactions between TC environments (in both the atmosphere and ocean) and TC internal structure in a fully coupled system is still a major challenge

- Substantial structure changes observed in Ophelia during Hurricane Rainband and Intensity Change Experiment (RAINEX; Houze et al. 2006)



Scientific Objectives

1. Execute atmosphere-ocean coupled model experiments to simulate/re-create Hurricane Ophelia (2005)

   What are the key factors that affected Ophelia's structure and intensity?

2. Verify/validate coupled model performance using in-situ and remotely-sensed measurements taken during RAINEX field campaign

   Aircraft, satellite, buoy, and analysis products

3. With confidence in coupled model simulation of Ophelia, use model outputs to explain this unusual TC's structure and intensity evolution

Field Data: RAINEX and Other Observations

Aircraft

- 3D Doppler tail radar reflectivity & winds
  2-km horizontal, 0.5-km vertical to 18 km
- Stepped-frequency microwave radiometer (SFMR)
  Flight-level and surface winds along path (every 30 s)

Satellite

- TRMM Precipitation Radar (PR) radar reflectivity
  5x4-km horizontal swath, 0.25-km vertical to 20 km
- TRMM MI Advanced Scanning Radiometer (AMSR-E)
  Merged daily 0.25-degree SST
- NOAA HURSAT Microwave
  85-GHz brightness temperature (strong convection)

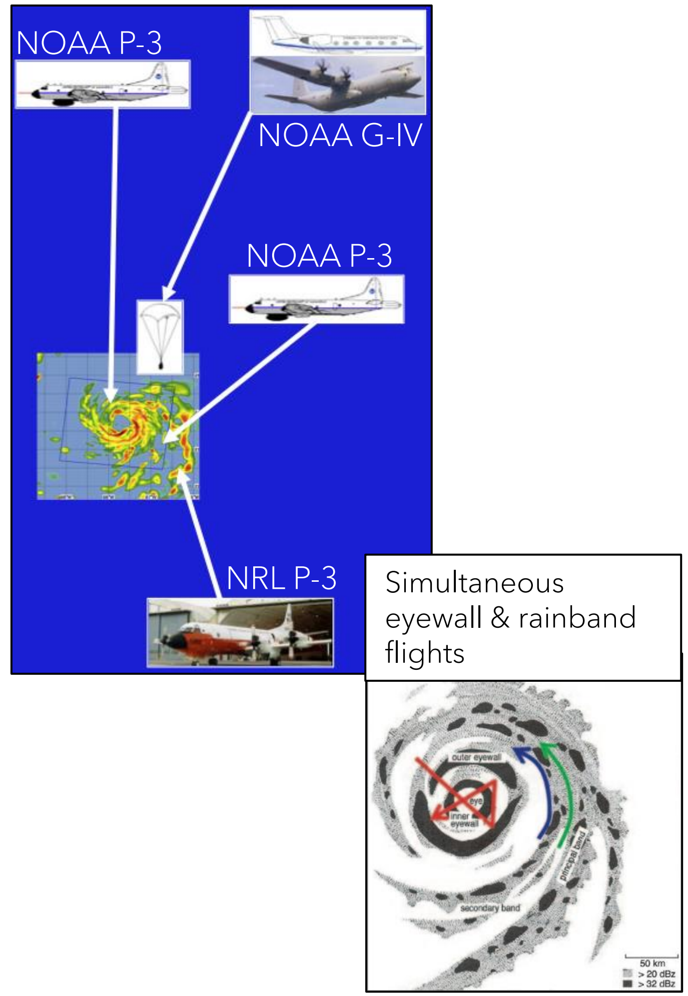
Buoy & Dropsonde

- NDBC buoy measurements (41002 & 41010)
  0.6m water temperature & surface pressure
- GPS dropsondes (232 total; 75 inner core, 175 ambient)
  p, T_{air}, RH, u, v, ϕ, θ_e (equiv. potential temp.)

Analysis Products

- SHIPS deep-layer shear
  200-850 hPa layer, using 200-800 km annulus from storm center (from real-time GFS)
- H*WIND surface wind analysis
  10-m wind components, every 6h from composite of ship, satellite, scatterometer observations

RAINEX (2005) observations schematic



Adapted from Willoughby (1988)

Model Data: UWIN-CM

- Ophelia simulated using Unified Wave INterface-Coupled Model (UWIN-CM), with two components:

- Weather Research & Forecasting (WRF) 3.7.1 – for the atmosphere

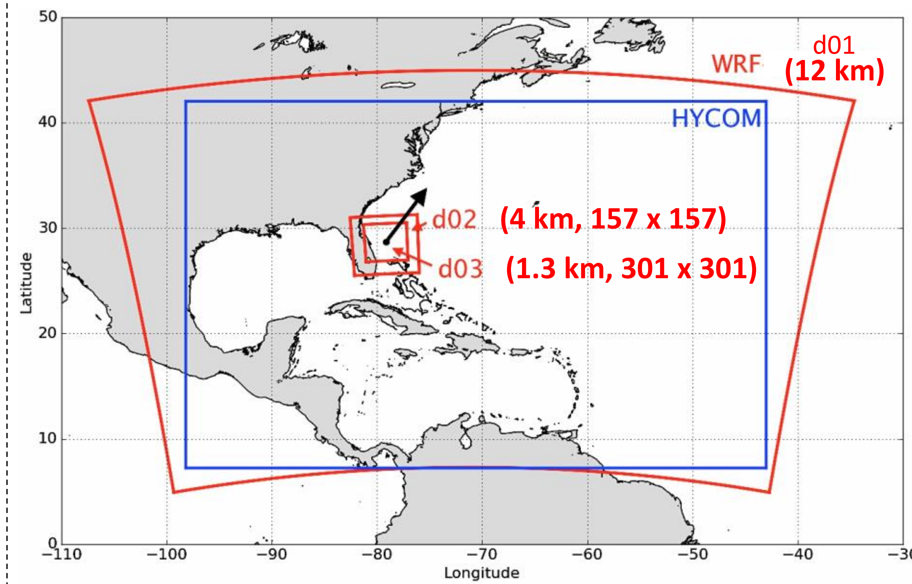
  Triply nested 12,4, **1.3** km domains
  Inner two follow vortex

  44 vertical levels
  6-hourly 0.5° NCEP final analysis (FNL) initial and boundary conditions

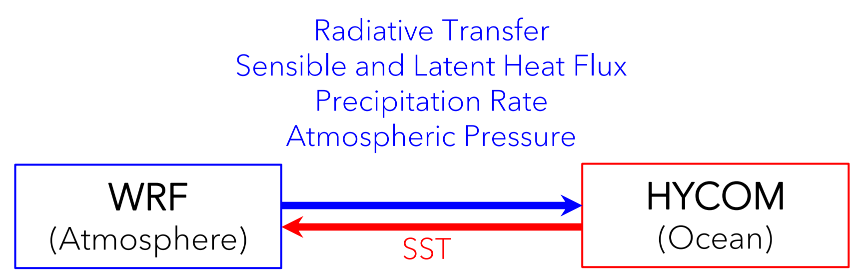
- HYbrid Coordinate Ocean Model (HYCOM) 2.2.98 – for the ocean

  4-km horizontal grid spacing
  32 vertical levels (hybrid)
  0.08° daily HYCOM global analysis initial and boundary conditions

UWIN-CM domains for Ophelia (2005)



UWIN-CM atmosphere-ocean coupling



via Earth System Modeling Framework : Hill et al. (2004)

Model Data: UWIN-CM

- UWIN-CM used to simulate hurricanes in several recent studies

  Ike, Sandy (Chen and Curcic, 2016)
  Frances (Chen et al., 2013)
  Isaac (Curcic, Chen, and Ozgokmen, 2016)

- Previous work has shown importance of high-resolution grid spacing to resolving TC inner core structures

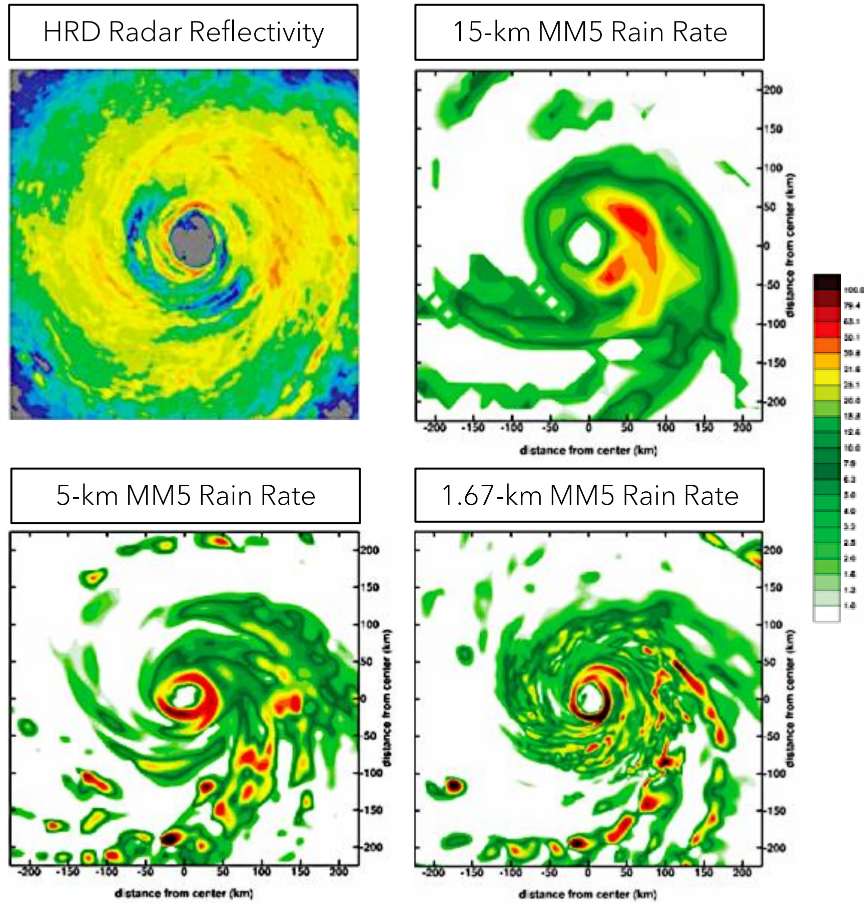
  Hurricane Bonnie (Rogers et al. 2003)
  Hurricane Georges (Cangialosi, 2005)
  Hurricane Frances (Chen et al., 2007)

- Convection explicit on Ophelia's inner two WRF-ARW grids

  Parent 12-km domain uses Kain-Fritsch cumulus scheme to parameterize

Resolution and Convective Parameterization

Hurricane Floyd, 1999 Sep 14 0000 UTC



Adapted from Chen et al. (2007)

Results: Track and Intensity

- Ophelia's model tracks similar
- Model over-intensifies both storms, but coupled (AO) storm intensity closer to observed
- Intensity similar early, but diverges when ocean becomes important

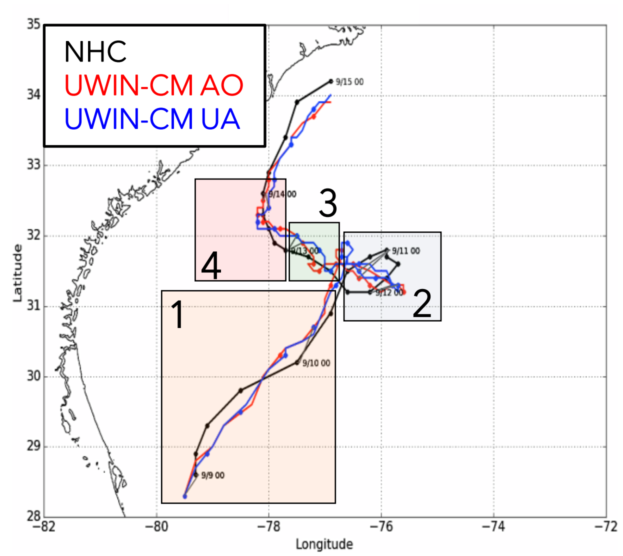
1 Organizing near hurricane
RAINEX RF04

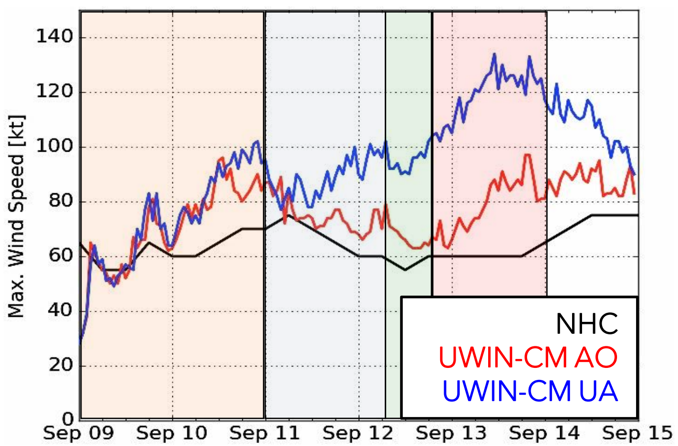
2 TC-induced cold pool interaction
RAINEX RF05

3 Expanded storm with discrete outer rainband

4 Recovery over Gulf Stream

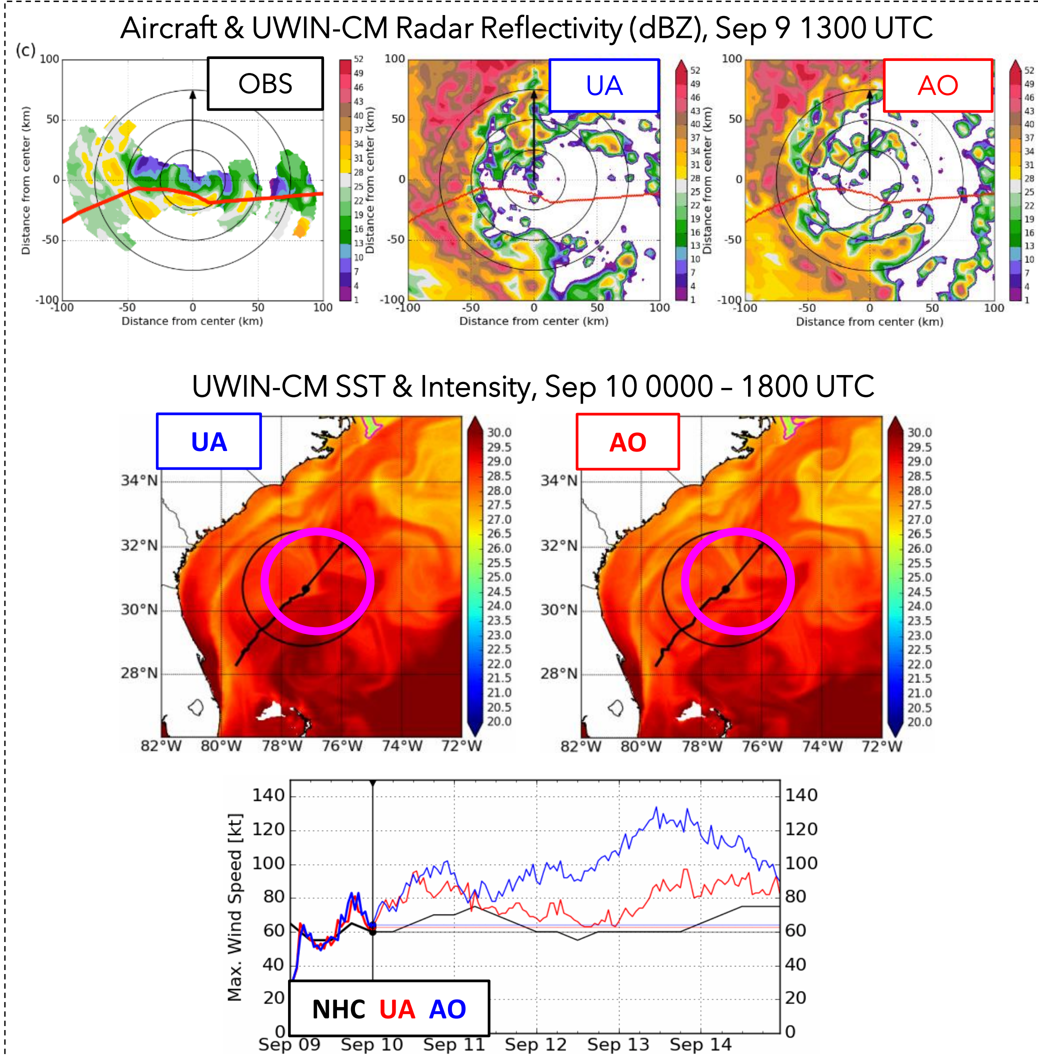
Track and Intensity (Maximum Winds, kt)





Results: Ophelia organizes into a hurricane

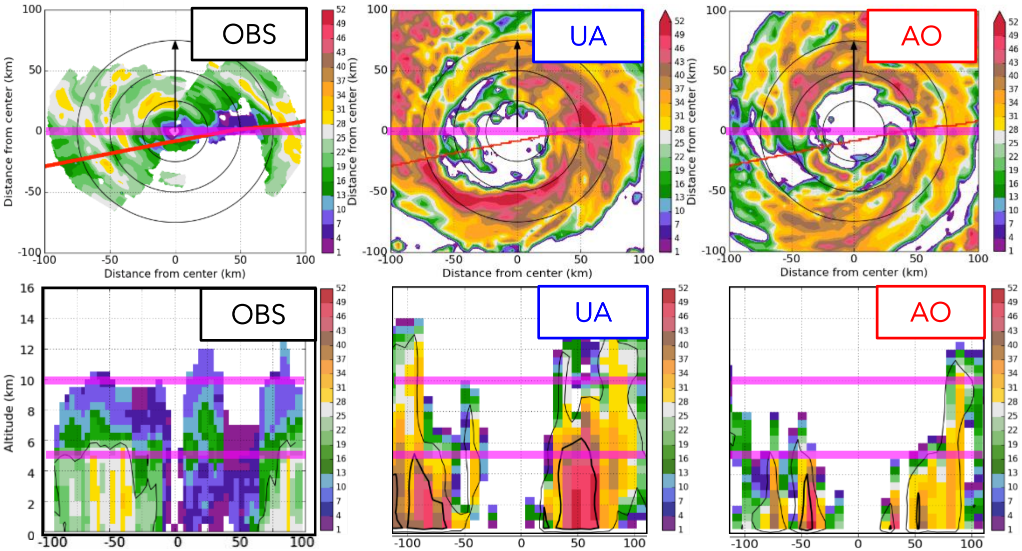
- Sep 9 0000 – Sep 10 1800 UTC
- Persistent radially inward rainband, organizes into eyewall later
- Ophelia has asymmetric, tilted vortex
- Ophelia experiences moderate 200-850 hPa wind shear (15-25 kt)
- SST cools, MLD shallows 1800 UTC onward as cold wake starts to form
- Coupled TC intensity begins to weaken due to ocean state



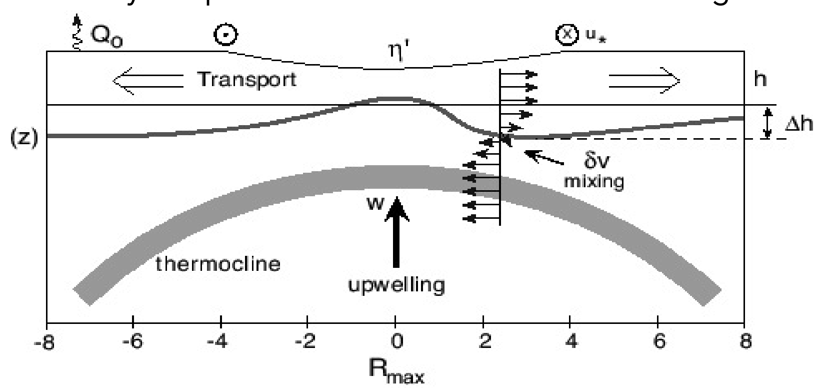
Results: Ophelia interacts with its induced cold wake

- Sep 10 1800 – Sep 12 0600 UTC
- Forward speed slows to < 5 m/s
- Ophelia traverses self-induced cold wake, SST cooled 0.5-2 deg C
- Ophelia's precipitation structure becomes weaker, vertically shallow, asymmetric
- Rain too intense in both models, but coupling captures collapse of inner core

Aircraft & UWIN-CM Radar Reflectivity (dBZ), Sep 11 2000 UTC



Physical processes in TC-induced ocean cooling



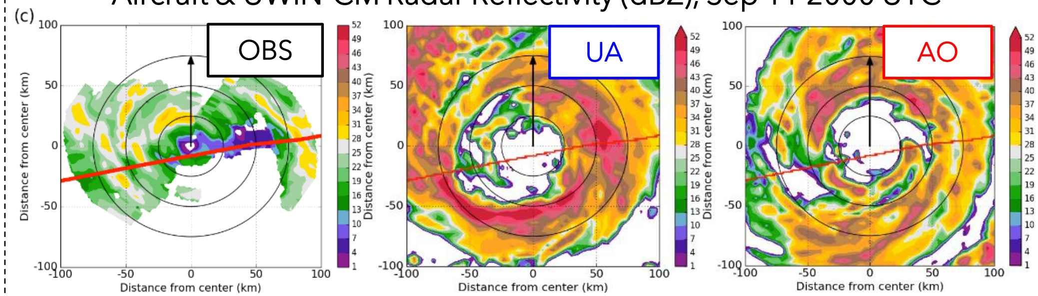
Results: Ophelia interacts with its induced cold wake

- Ophelia cools surface and upper 100 m, inner-core SSTa near -2°C, OHC deficit of -20 TJ

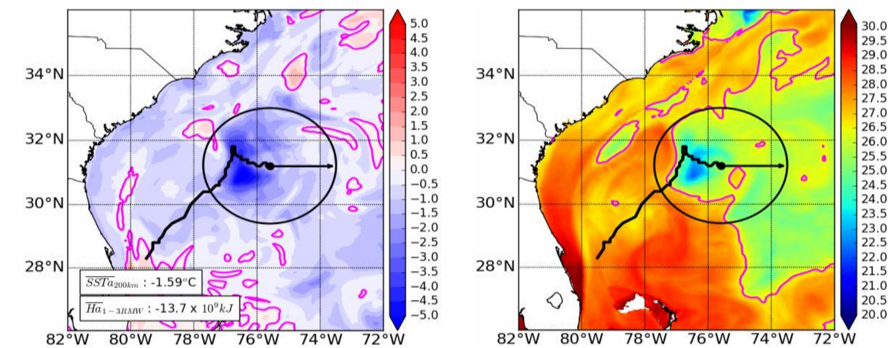
Ocean Heat Content Anomalies

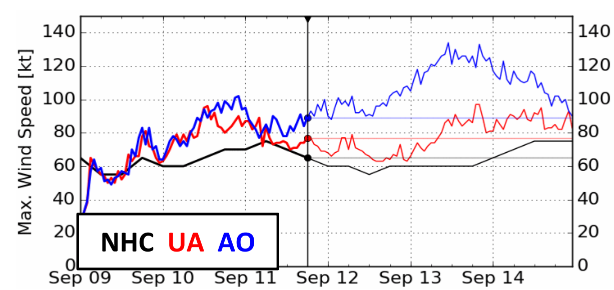
$$\underbrace{\overline{Ha}_{1-3\,RMW}}_{\text{OHCa}} = \int_{100m}^{0m} \rho_w c_p \underbrace{\overline{Ta}_{1-3\,RMW}}_{\text{Ta}} \underbrace{A_c}_{\text{Area of negative temperature anomalies}} dz$$

Aircraft & UWIN-CM Radar Reflectivity (dBZ), Sep 11 2000 UTC



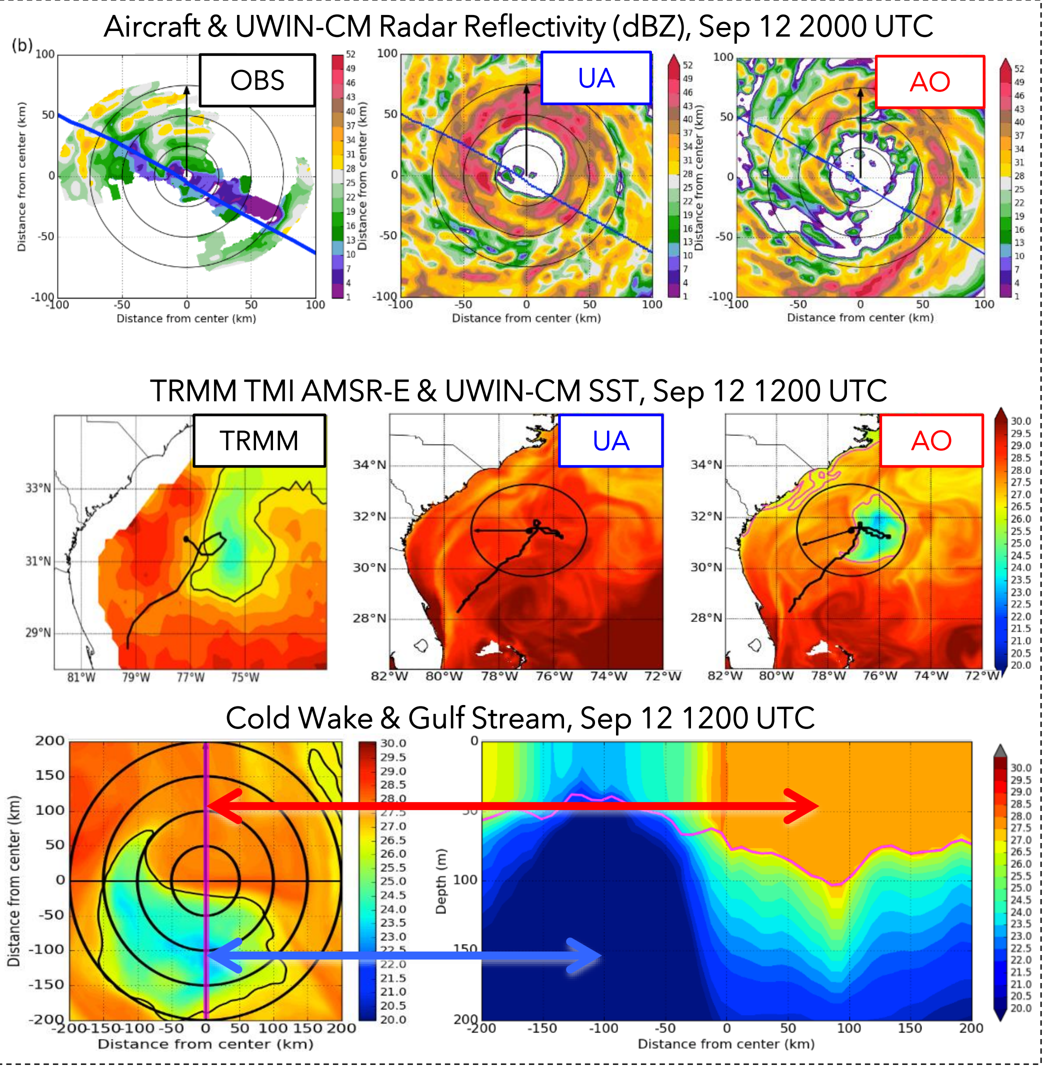
UWIN-CM SSTa, T100 & Intensity, Sep 11 1800 – Sep 12 0600 UTC





Results: Ophelia expansion and discrete outer rainband

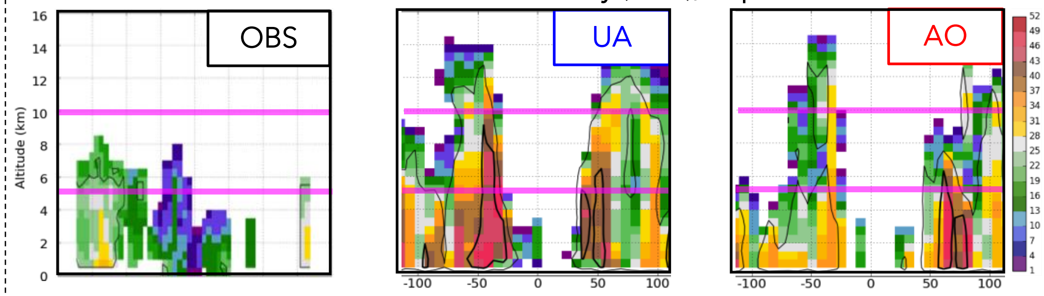
- Sep 12 0600 - Sep 13 0000 UTC
- Ophelia straddles warmer Gulf Stream ahead, strong cold wake behind
- Coupled upper ocean between 23.5-25.5°C over cold wake
- MLD 75-100m, warm and deep 27.5°C waters over Gulf Stream
- Convective, distant outer rainband and weaker inner core rain in real & coupled storm



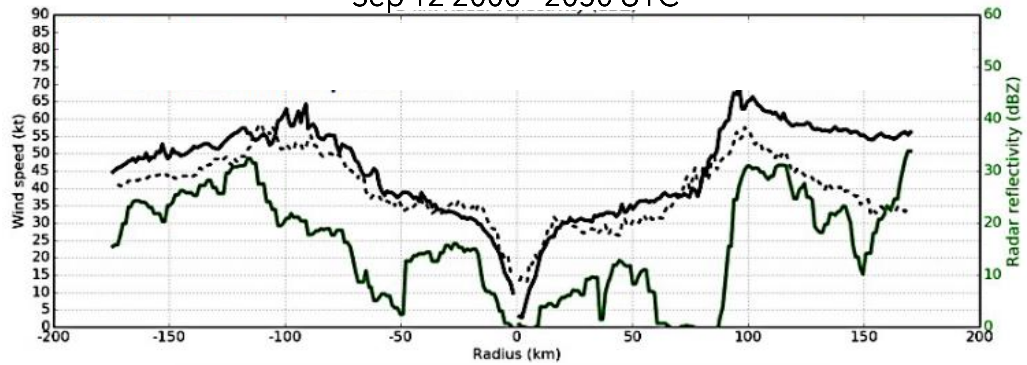
Results: Ophelia expansion and discrete outer rainband

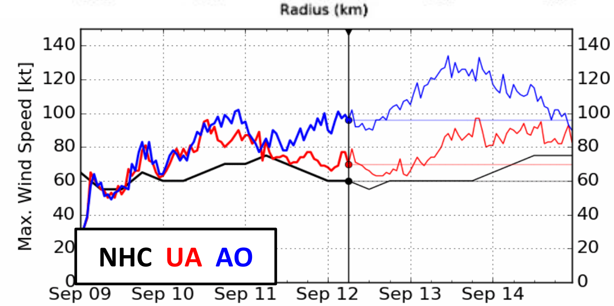
- Observed storm is shallower, with a weak inner core
- Models too strong and deep, but coupled TC has better location of strong precipitation, less strong vertical dBZ returns
- Ophelia's discrete outer rainband structure likely supported by near-surface convergence of non-local moisture

Aircraft & UWIN-CM Radar Reflectivity (dBZ), Sep 12 2000 UTC



Flight-Level and Surface Winds and Flight-Level Radar Reflectivity
Sep 12 2000 - 2050 UTC

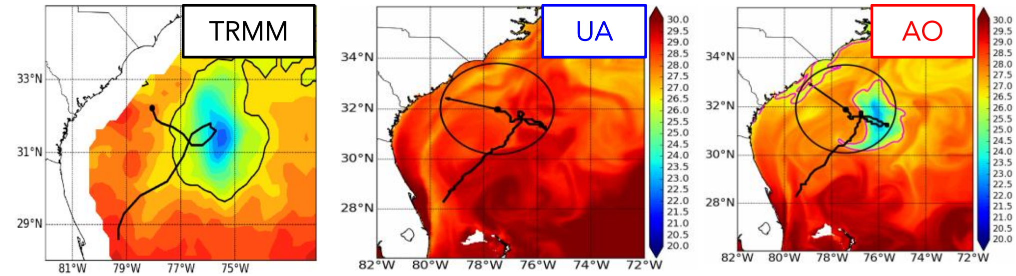




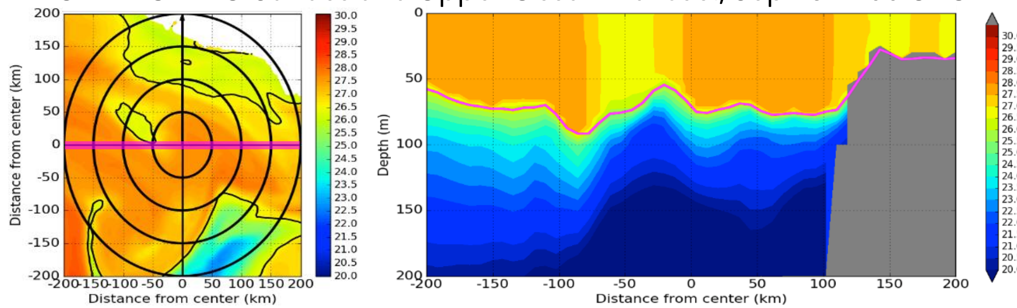
Results: Ophelia recovers over the Gulf Stream

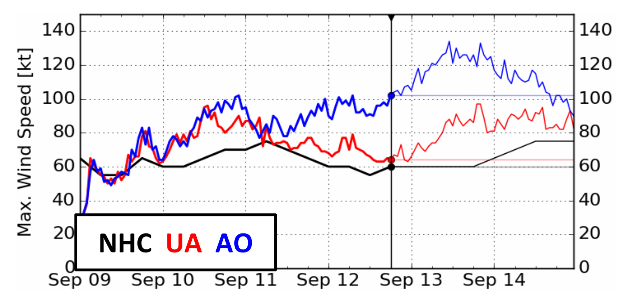
- Sep 13 0000 – Sep 14 0600 UTC
- Ophelia's inner core propagating over warm SST of Gulf Stream
- Coupled MLD 60-90m deep, 27-27.5°C waters over upper ocean

TRMM TMI AMSR-E & UWIN-CM SST, Sep 13 - 14 0000 UTC



UWIN-CM AO Surface and Upper Ocean Transect, Sep 13 1200 UTC

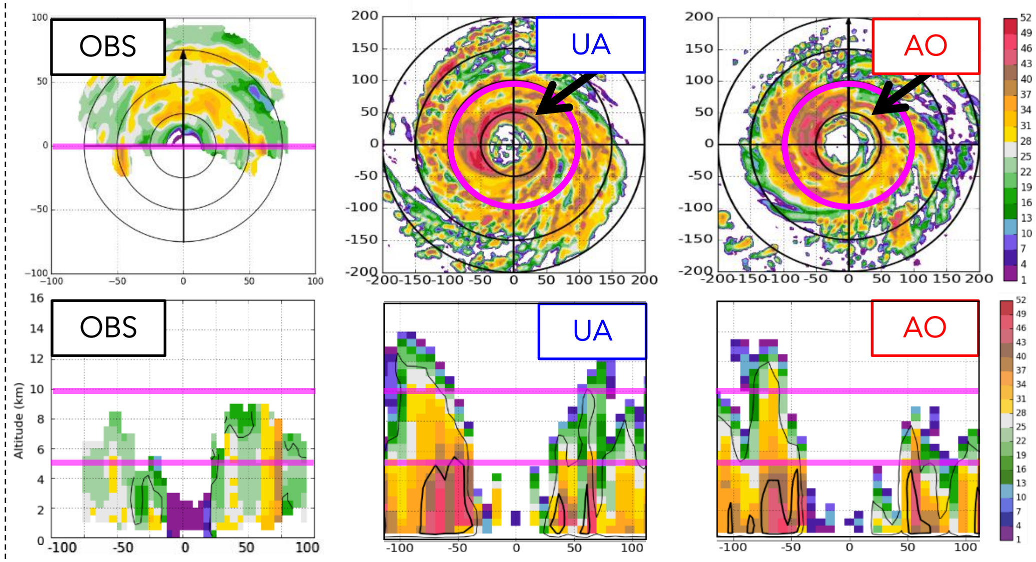




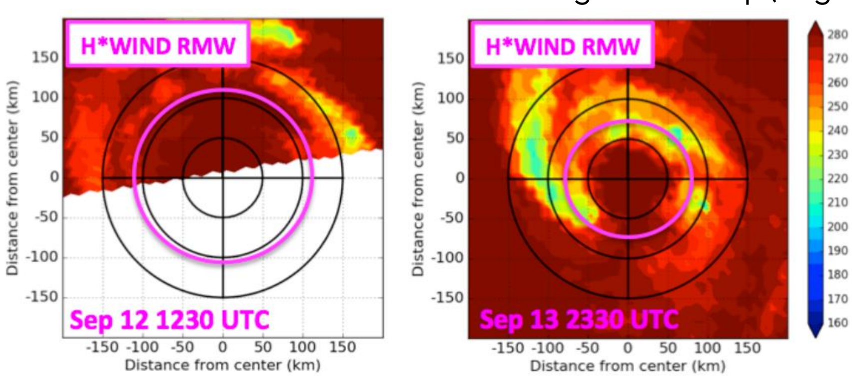
Results: Ophelia recovers over the Gulf Stream

- New eyewall forms, separated from inner rainband by small moat region
- Return of adjacent deep convection, stratiform structure

Airborne Doppler & UWIN-CM Radar Reflectivity, Sep 13 2300 UTC

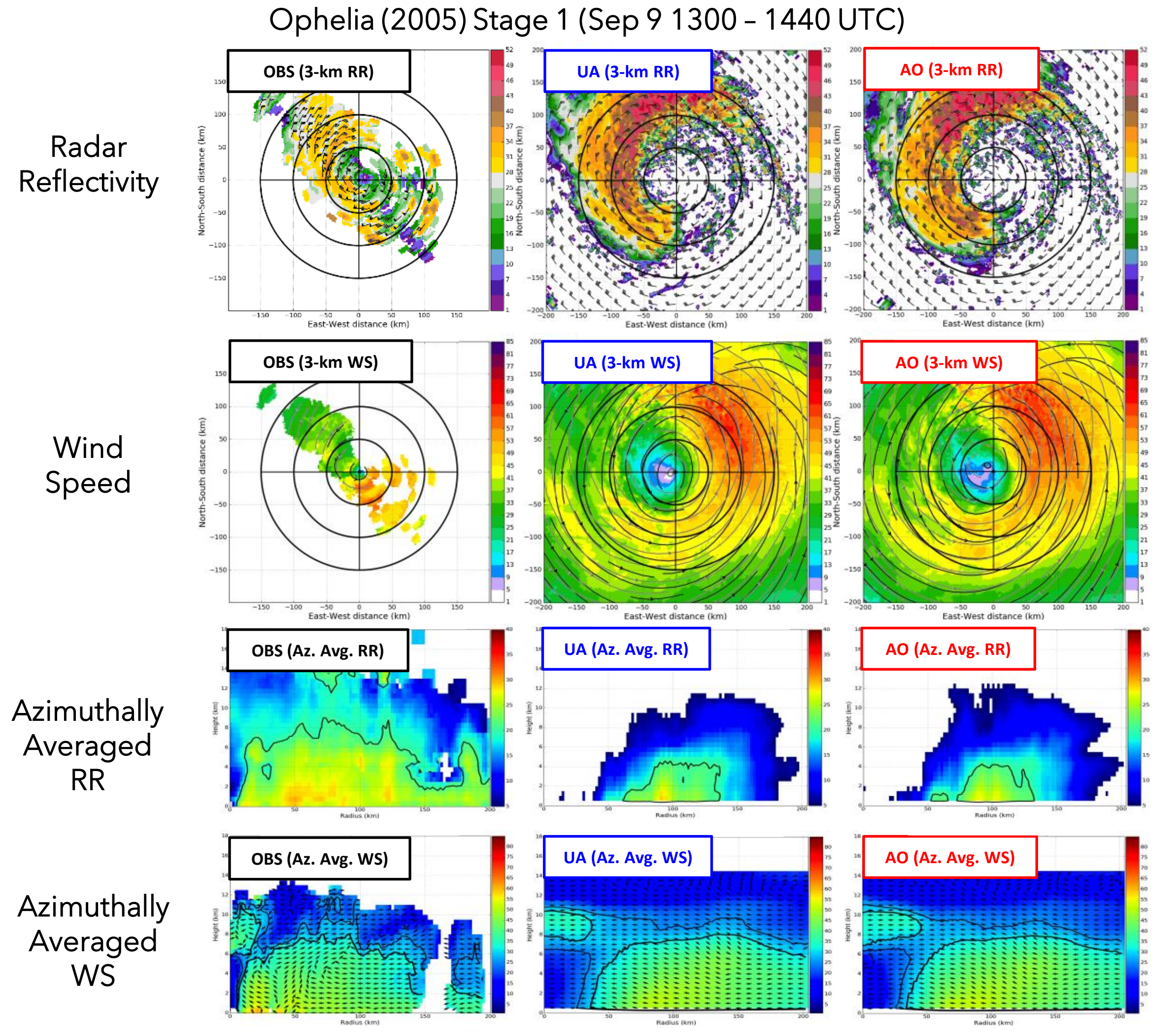


NOAA HURSAT 85 GHz PCT Microwave Brightness Temp (deg K)



Summary

- Ophelia's convection and wind field asymmetric due to moderate wind shear
- Ophelia able to attain hurricane strength with aid of warm SSTs, upper ocean, but intensity fluctuated
- UA, AO similar in organizing stage, too intense RR
- Azimuthal averages similar in UA, AO; more stadium-like eyewall in UA
- RR, WS weak in azimuthal averages: less vertical development, intensity due to weak returns in FR, RR quadrants



Summary

- Ophelia induces and traverses its cold wake travelling slowly during anti-cyclonic loop motion west
- Observed, AO TC show RR quadrant loss of convection, asymmetry with radial separation
- Azimuthally averaged RR, WS in AO match thin towers of rain, wind distributions similar
- Collapsing inner core, secondary horizontal rain, wind maxima in obs only captured by AO

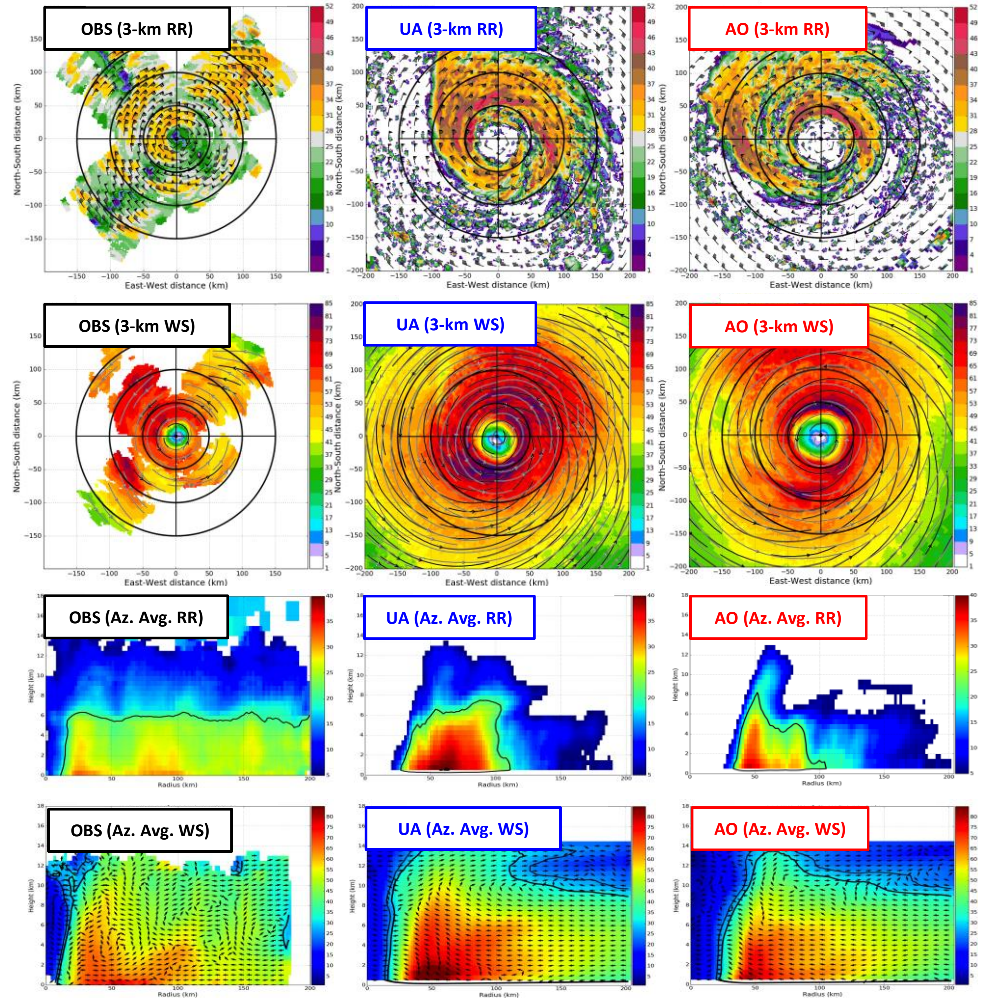
Ophelia (2005) Stage 2 (Sep 11 1616 – 1812 UTC)

Radar Reflectivity

Wind Speed

Azimuthally Averaged RR

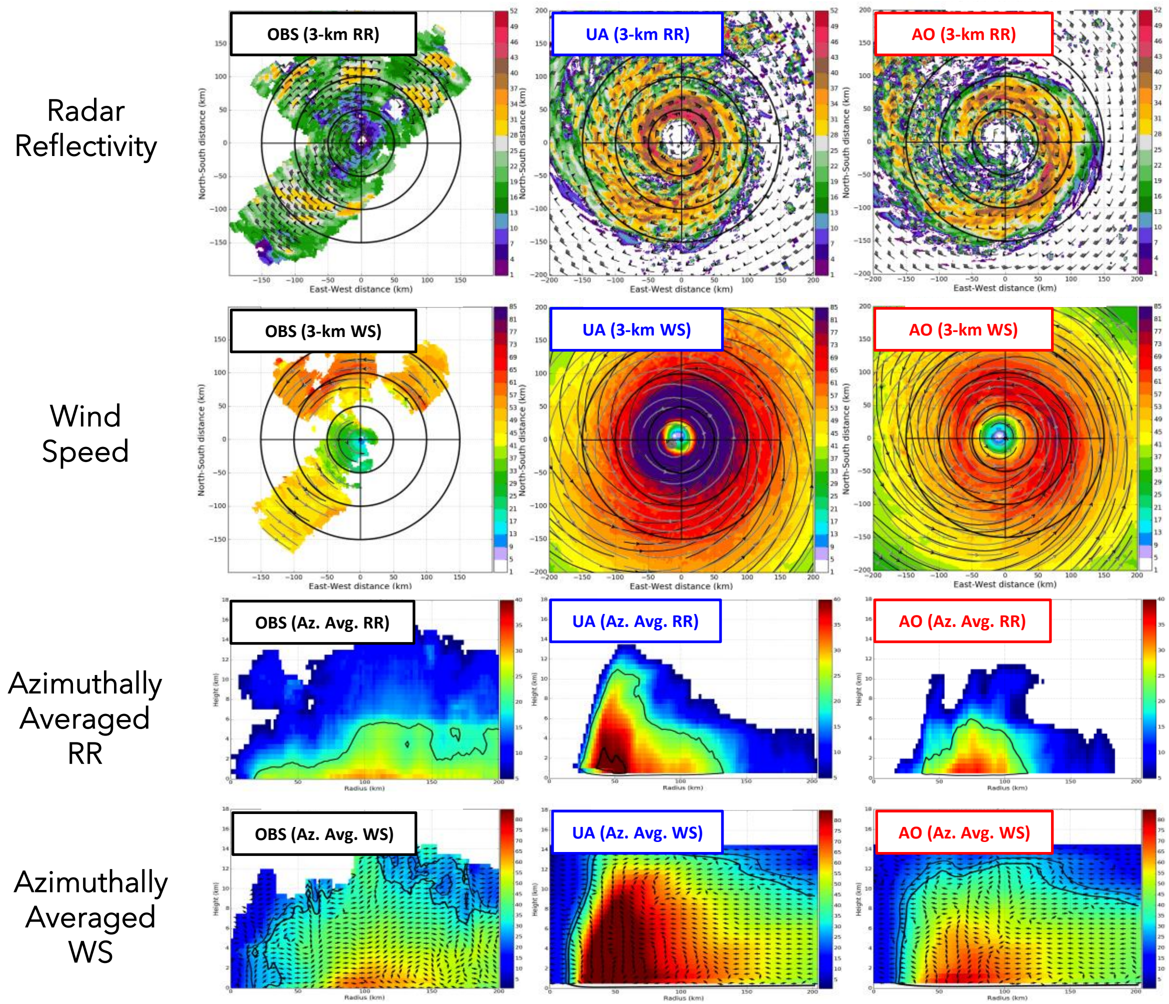
Azimuthally Averaged WS



Summary

- Ophelia shallowed and expanded (RMW from 48 – 108 km) between Sep 11,12
- Convection absent inside 75 km, loss seen in AO TC
- UA grossly overintense
- Deepest, strongest azimuthally averaged RR, WS match in obs and AO

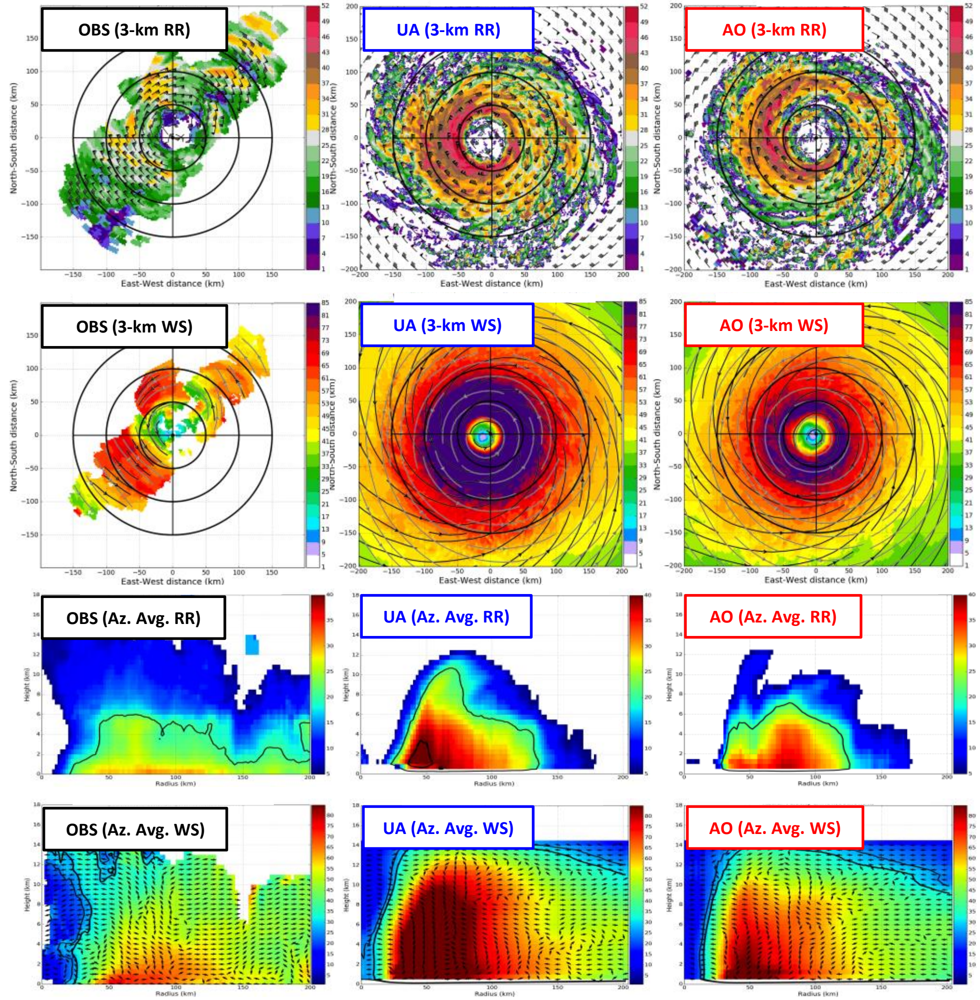
Ophelia (2005) Stage 3 (Sep 12 2000 – 2338 UTC)



Summary

- Ophelia recovers over the Gulf Stream, making advantage of warm SST, larger MLD, and higher forward speed
- Convection recovers in RR quadrant, RMW contracts
- Both UA, AO over intense, especially in wind fields
- Azimuthally averaged RMR approx. 80 km from center
- Azimuthally averaged WS distribution in AO still better than UA

Ophelia (2005) Stage 4 (Sep 13 2000 – Sep 14 0010 UTC)



Conclusions

1 The absence of air-sea coupling in UA simulation of Ophelia results in over-estimation of air-sea fluxes supplying energy to the TC, over-intense wind fields and convective structures – in spite of similar forward speed

2 The presence of an interactive ocean critical to representing cold wake, its evolution, the cooling/homogenizing of surface EPT in the collapsed inner core of Ophelia – and enthalpy advection in the far-field supporting Ophelia's distant discrete rainbands

3 Intensity change was rapid when cold wake reduced enthalpy flux, but delayed despite proximity to Gulf Stream until Sep 13 0000 UTC as Ophelia needed adjustment period to new fluxes (RMW/RMR contracted)

4 Ophelia's interactions with its cold wake and the Gulf Stream allowed it to survive while undergoing structural changes similar to the EWRC seen in intense TCs