# On the Role of the SAL in the Evolution of Hurricane Helene During NAMMA: Lessons Learned for GRIP

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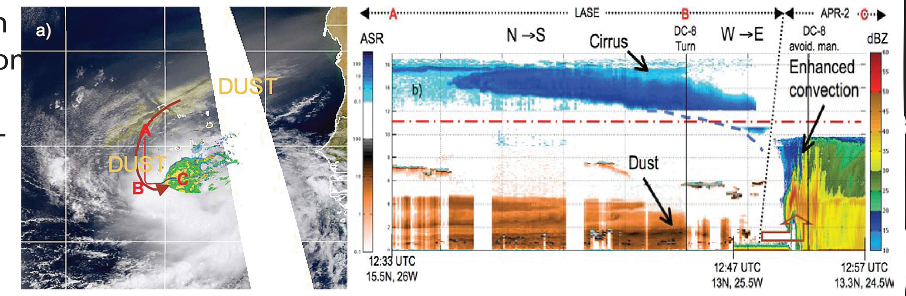
**Introduction.**
The role of the Saharan Air Layer (SAL) in modulating tropical cyclone genesis and intensity has received considerable attention recently. Early studies by Karyampudi and Carlson (1988) and Karyampudi and Pierce (2002) suggested that the SAL can have a positive influence on the growth of easterly waves and tropical cyclones through barotropic and baroclinic instabilities and by enhancing rising motion south of the SAL. More recent studies have focused on potential negative influences on storm development (Dunion and Velden 2004; Wu et al. 2006; Jones et al. 2007; Lau and Kim 2007a, 2007b; Wu 2007; Dunion and Marron 2008; Sun et al. 2008, 2009; Reale et al. 2009; Shu and Wu 2009) and have motivated field campaigns such as SALEX (Rogers et al. 2006) and NAMMA (Zipser et al. 2009).

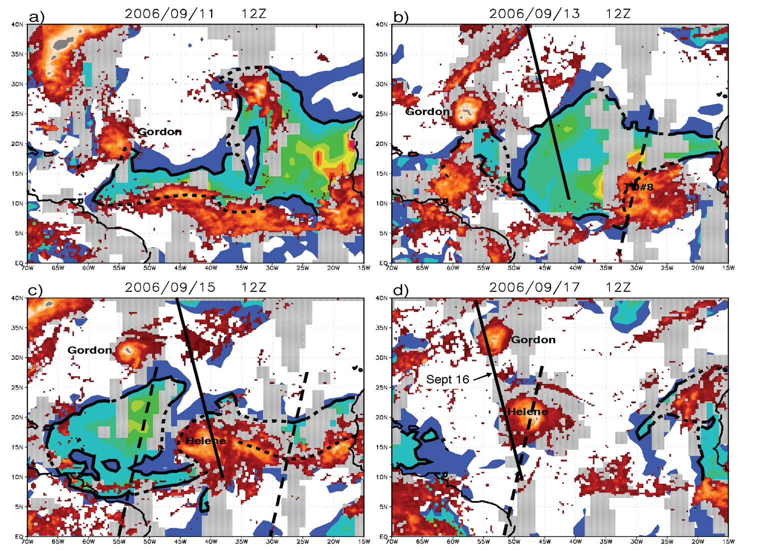


The NAMMA field campaign was focused on the transition of African continental convective systems to the maritime environment and the possible genesis of tropical cyclones. An important emphasis was the role of the SAL in the genesis and intensification processes (Zipser et al. 2009). Zipser et al. (2009) suggested a possible negative role of the SAL in the cases of Tropical Storm Debby and Hurricane Helene, both of which were investigated during NAMMA. Their figure (above) implies that dust was readily injested into the storm precipitation region.

In this study, we examine the potential role of the SAL in the case of Hurricane Helene using satellite data, multiple global meteorological analyses, NAMMA/SALEX aircraft observations, as well as a high-resolution simulation using the Weather Research and Forecast (WRF) model.

**MODIS AOD evolution**
The figure to the right shows the MODIS derived AOD (from Aqua and Terra) and TRMM multi-satellite (3B42) 24-h accumulated rainfall for the period Sept. 11-17. A broad area of Saharan dust is seen northward and northwestward of Helene during early stages, but by the 17th, little dust remains in the storm's vicinity.

The figure suggests that only a very small fraction of the dust was actually ingested into the storm circulation.

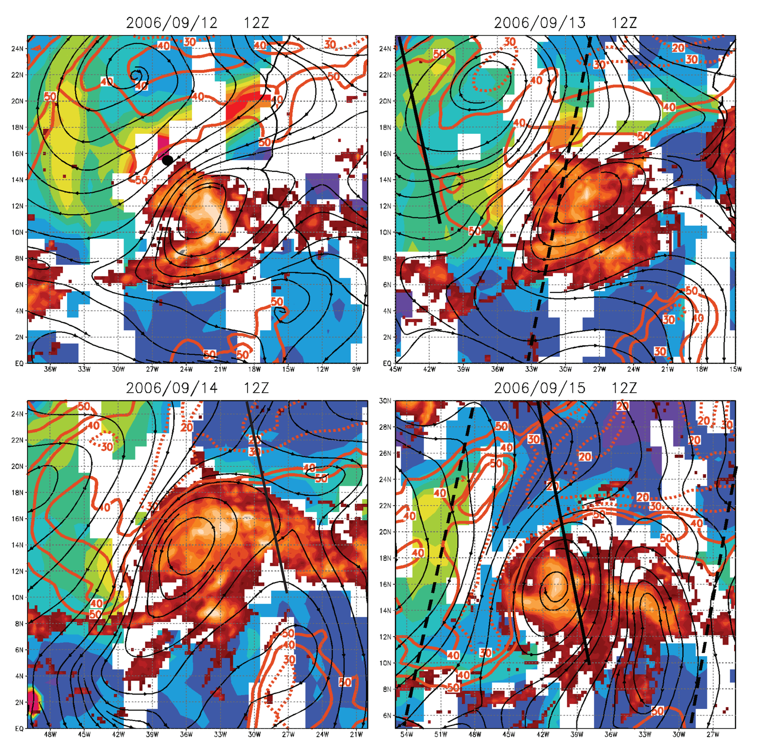


Solid line segments show daytime CALIPSO overpasses, coincident with the AOD data. Dashed line segments show nighttime passes, 12 h prior to the AOD image.

**Dust as seen in relation to the storm-relative flow**
The figure to the right shows a zoomed in view of the dust and rainfall for the period Sept. 12-15 along with the NCEP-derived 700 hPa storm-relative flow (streamlines). Also shown is the 700-hPa relative humdity field for values <50%.

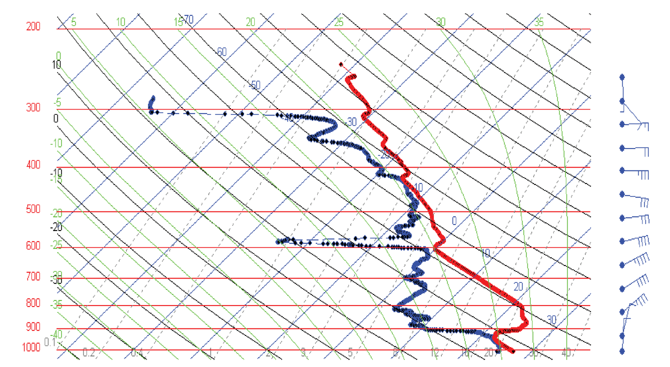
The figure shows the development of a low- or no-dust tongue of very dry air moving southward along the western edge of the storm. The RHs in this tongue are lower than in the original SAL air mass, so combined with the general lack of dust, suggests a non-SAL source of dry air. This dry air was eventually wrapped well around Helene's eastern and perhaps northern sides.

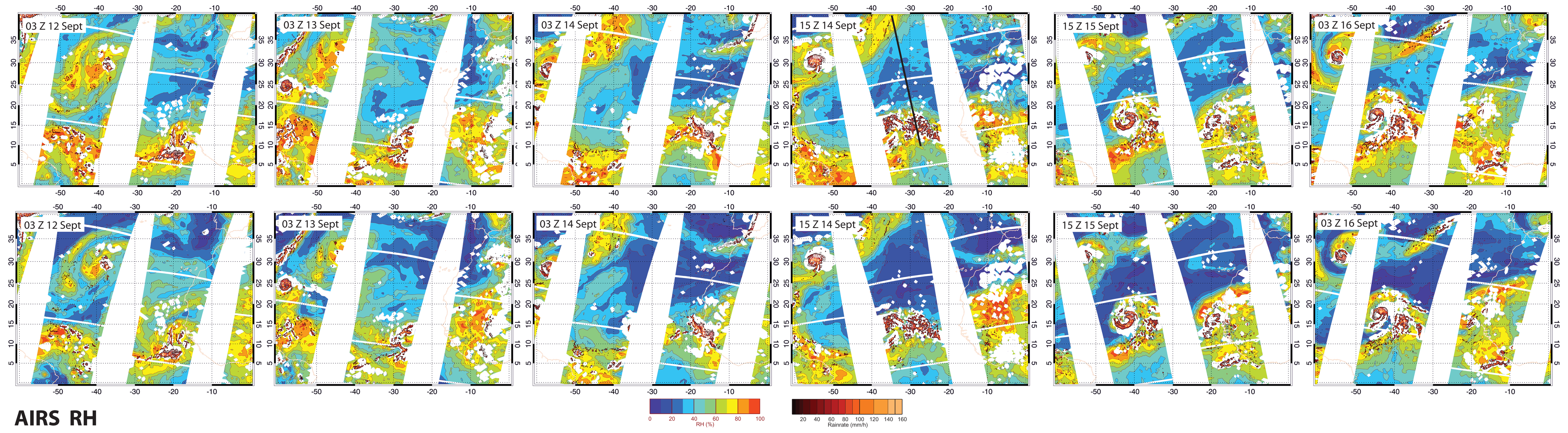
700 hPa Streamlines and RH



Solid line segments show daytime CALIPSO overpasses, coincident with the AOD data. Dashed line segments show nighttime passes, 12 h prior to the AOD image.

**Thermodynamic Structure of the SAL**
The figure to the right shows a sounding from the NASA DC-8 in the middle of the SAL layer on Sept. 12 (see black dot in upper left panel in previous figure). Note the isentropic layer between ~800-600 hPa in which RH increases with height, very dry near the base of the SAL, nearly saturated near the top.

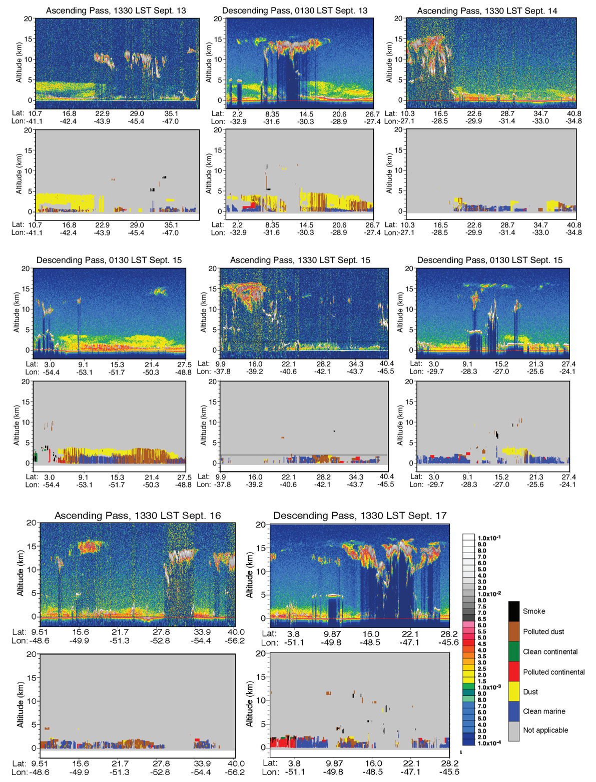


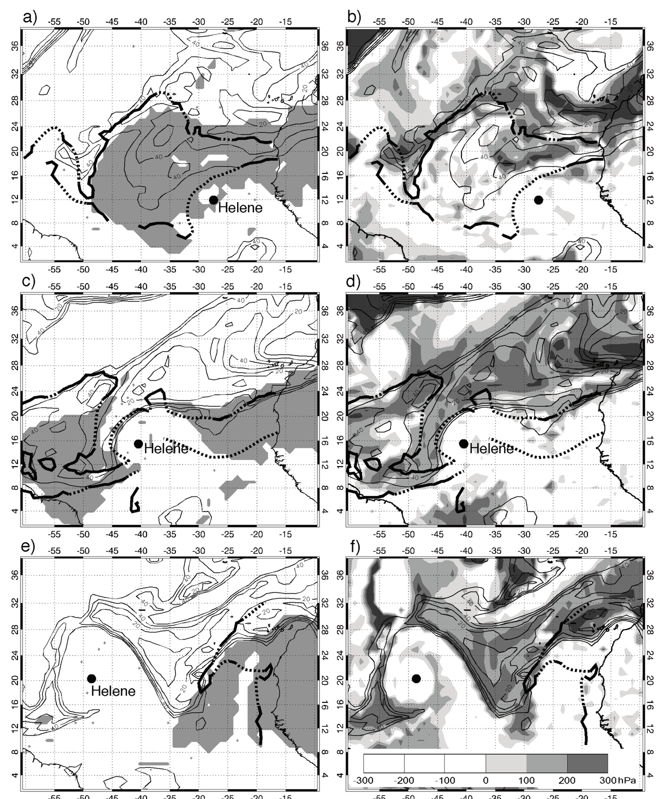


**AIRS RH**
This figure shows the AIRS layer-averaged relative humidity (850-700 hPa, top row; 700-600 hPa, bottom row) from September 12-16. Descending passes correspond to ~03 UTC, ascending passes to ~15 UTC. Also included is the coincident AMSR-E rainfall field within the data void regions of the AIRS product. Of particular note is the rapid drying of the air in the 700-600 hPa layer, which we propose is the result of subsidence rather than processes specifically related to the Sahara.

**CALIPSO Data**
The figure to the right shows overpasses from the CALIPSO satellite at various times.
• Passes on Sept. 13 show the deep dust layer adjacent to Helene.
• A pass on the 14th shows the shallower nature of the aerosol layer under the dry air
• Passes on the 15th show deep dust layer well west of Helene, but shallow aerosol layer (dust, pollution, oceanic aerosols) to the north and east.
• On Sept. 16th and 17th, aerosol layer is confined to <2 km and is a mix of different aerosol types.

• *The results suggest a significant shallowing of the SAL dust layer.*

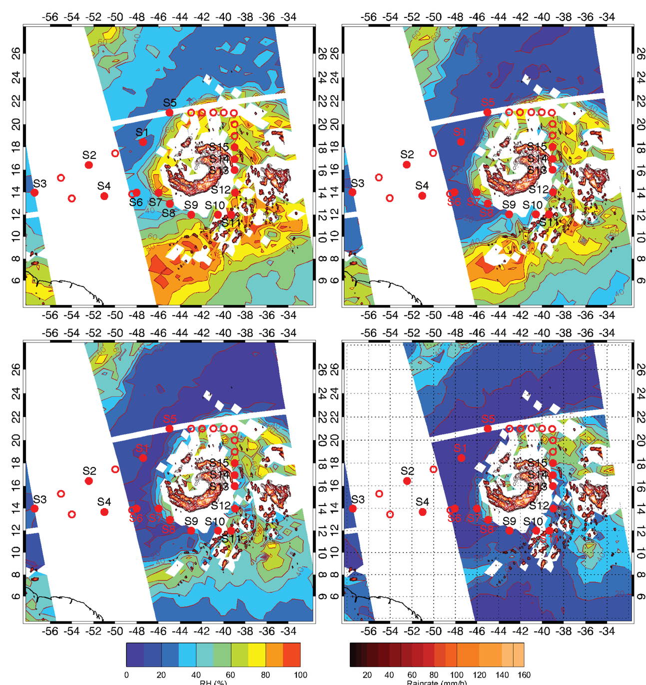


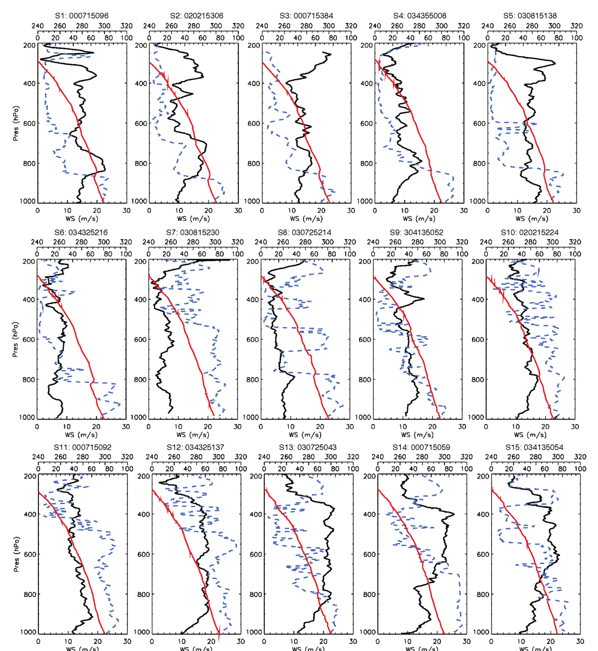


**Trajectory Calculations**
• 6-day backward air trajectories calculated from NCEP final analyses.
• Results for parcels released at 700 hPa for Sept. 13 (top), 15 (middle), and 17 (bottom).
• Left panels indicate likely SAL air (gray shading) and RH<50% (contours). Dark curves show the approximate MODIS dust boundary.
• Right panels show net descent along the trajectory (shading) and RH<50%.

• *Results suggest that subsidence is the key driver for dry air wrapping around Helene.*

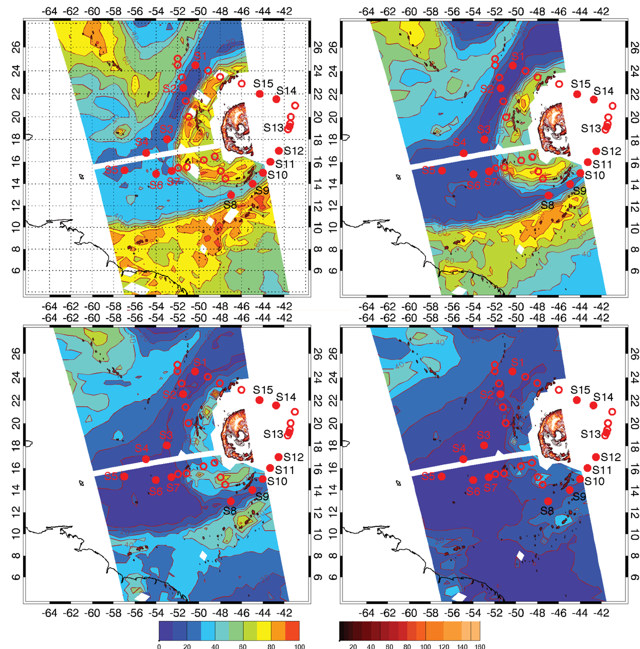
**AIRS close up and NOAA G-IV sounding locations for Sept. 15**
The figure to the right shows AIRS RH for different levels and AMSR-E rainfall. Soundings were taken within the SAL air mass to the west and within the dry tongue wrapping around the storm. Shaded circles indicate soundings shown in adjacent figure. Levels are as shown below:

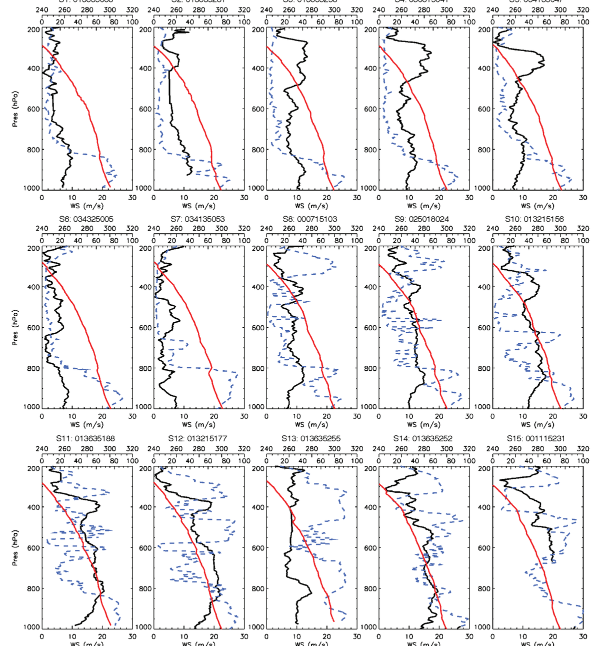





**Summary of G-IV soundings on Sept. 15**
• Soundings further west are clearly SAL (S1-S4).
• Soundings S5 and S6 shows deep dry layer, but no wind maximum. Colocated with dust-free tongue.
• Soundings S9, S13, and S14 align best with dry tongue and show driest air above SAL levels. Unclear whether dry air between 800-600 hPa is SAL.
• Soundings suggest little low-level dry SAL air wrapping around Helene.

**AIRS close up and NOAA G-IV sounding locations for Sept. 16**
Same as above, but for Sept. 16. Multiple soundings were obtained in the dry tongue wrapping around the storm. The AMSR-E data shows a small eyewall surrounding by a broader ring of precipitation.

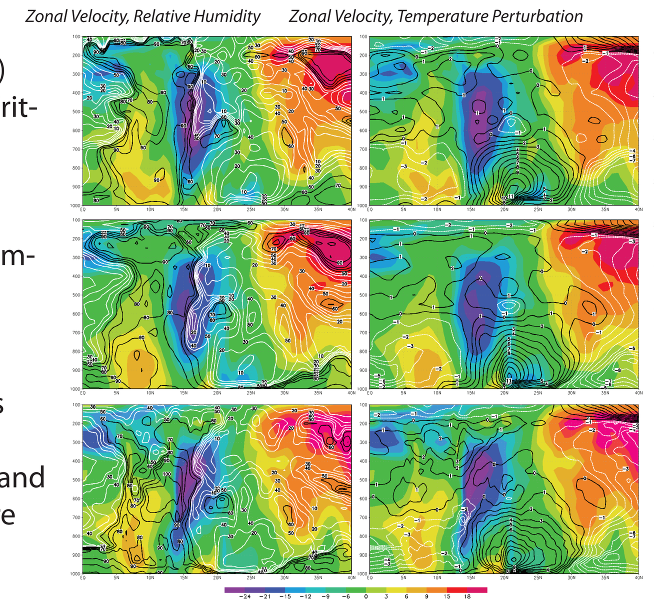


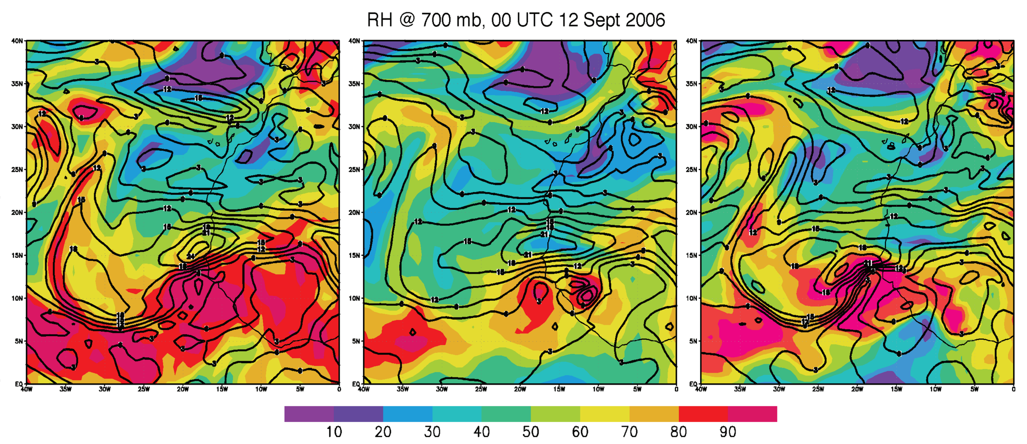


**Summary of G-IV soundings on Sept. 16**
• Soundings further west show deep dry layer, but no wind maximum. Colocated with dust-free tongue.
• Soundings S8-S12 align best with dry tongue and show driest air between ~800-350 hPa. Unclear whether dry air between 800-600 hPa is SAL.
• Soundings unclear about dry SAL air wrapping around Helene.
• Suggests dry air ~300-400 km away from storm center, potentially too far away to impact intensity (Braun et al. 2011; Riemer et al. 2011).

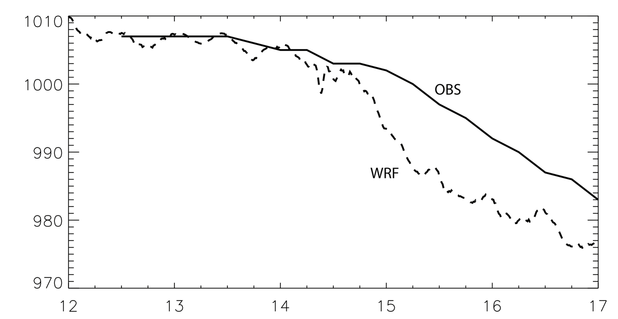
**WRF Simulation**
• Three domains (27, 9, 3 km)
• WSM6 microphysics, Kain Fritsch cumulus schemes
• YSU PBL, Garratt sfc fluxes
• Initialized with NCEP Final Analyses at 00 UTC 12 September
• 5 day simulation

For comparison, verticl cross sections at 25°W from NCEP (top), ERA-Interim (middle), and MERRA (bottom) analyses are shown to the right.

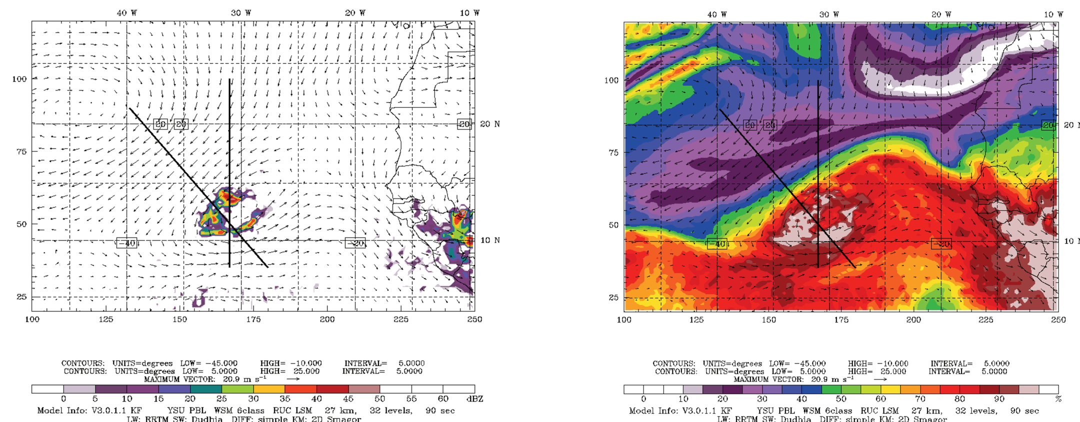



**SAL Representation in the Analyses**
Shown above is the 700 hPa RH (shaded) and wind speed (contours) from NCEP, ERA-Interim, and MERRA. All analyses represent the SAL, but with some variations in structure, particularly RH near the African Easterly Jet.

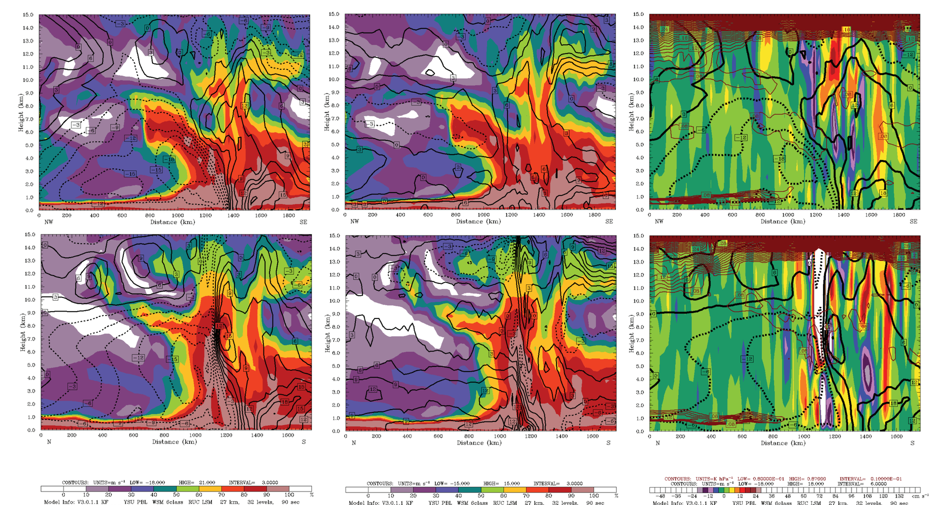



**Simulated Intensity Evolution**
The simulated intensity (above) compares very favorably with the observations, which are exlusively from satellite prior to the 17th. The intensity difference is within the error range expected from the Dvorak technique and can also be explained by an earlier onset to intensification (by ~12 h) in the model.

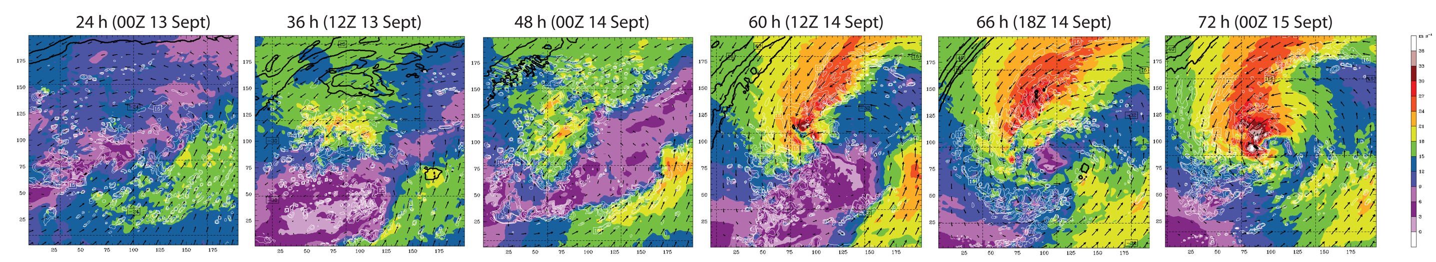


**Cross Section Locations at 00 UTC 14 September**
Shown above are the 800 hPa storm-relative winds and reflectivity (left) and RH (right). Cross section locations are indicated by the solid line segments.

**Vertical Cross Sections**
• Panels show vertical cross sections from NW-SE (top) and N-S (bottom).
• Shaded fields are RH (left and middle) and vertical velocity (cm/s, right).
• Contoured fields are:
  (Left) Storm-relative velocity normal to cross section
  (Middle) Storm-relative velocity in the cross section
  (Right) Static stability in red, storm-relative velocity normal to cross section in bold black.
• Results show that SAL suppresion north of the jet is well represented, but that convection and vortex development occur on south side of the jet.

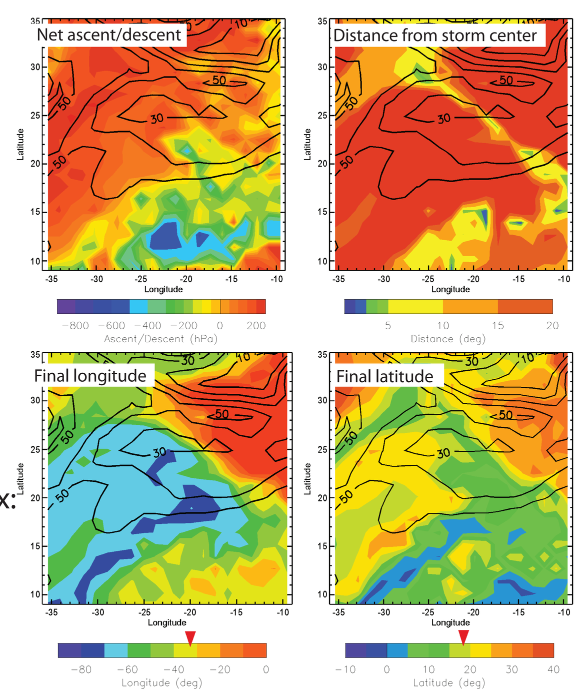


**Time Series of Surface Wind Fields**
Surface winds fields (at right) show the initially broad surface vortex and its evolution toward a concentrated one.
• Thin white contours show dBZ at 10 dBZ intervals starting at 15 dBZ
• Thick black contours show RH≤60% at 10% intervals



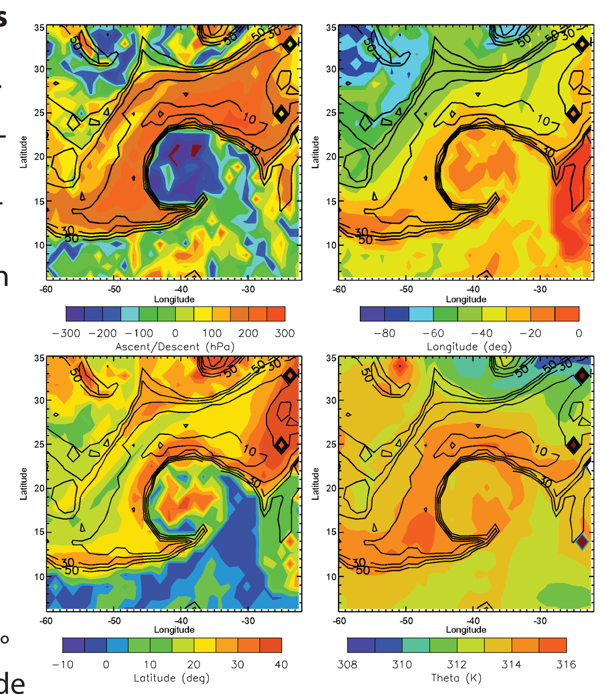

**Forward Trajectory Calculations**
• Initiated at 700 hPa at 12Z 12 Sept, run forward to 12Z 16 Sept
• Results plotted at starting location (trajectory release point)
• Black contours show 700 hPa RH at 12Z 12 Sept.
• Red triangles on lower color scales indicates storm longitude and latitude at 12Z 16 Sept.

• Results show that the SAL air largely moves largely moves by the storm with little entrainment into the vortex:
–Ascent concentrated in vortex region south of the dry SAL air
–SAL air >10° lat/lon from storm by Sept 16
–Western portion of SAL moves far west, eastern portion to the east of the storm




**Backward Trajectory Calculations**
• Forward trajectories and NCEP-trajectories suggest that the dry air wrapping around Helene is not SAL
• Additional trajectories initiated at 700 hPa at 12Z 16Sept, run backward to 00Z 12 Sept
• Results plotted at starting location (trajectory release point)
• Black contours show 700 hPa RH at 12Z 16 Sept.

• Results show that the dry air coincides with net subsidence as large as 200 hPa
–Air is coming from ~500 hPa, just above the SAL
–Much of the air comes from 20-30° latitude, and west of 20° W longitude



**Conclusions**
This study suggests that the direct negative effects of the SAL (vertical shear, dry and stable air) were not a primary influence on the evolution of Helene. At early stages, there is little evidence for intrusion of SAL air into the storm circulation. Most of the SAL air moved well westward of the storm by the time of its intensification. Trajectory calculations suggest that the dry air wrapping around Helene between Sept. 15-18 was predominantly non-Saharan and instead was associated with strong subsidence. Even that air remained at large radius so that its impact was probably not a primary driver of storm intensity.