Modeling the effects of dust-radiative forcing on the movement of Hurricane Helene (2006)

Shu-Hua Chen

University of California, Davis

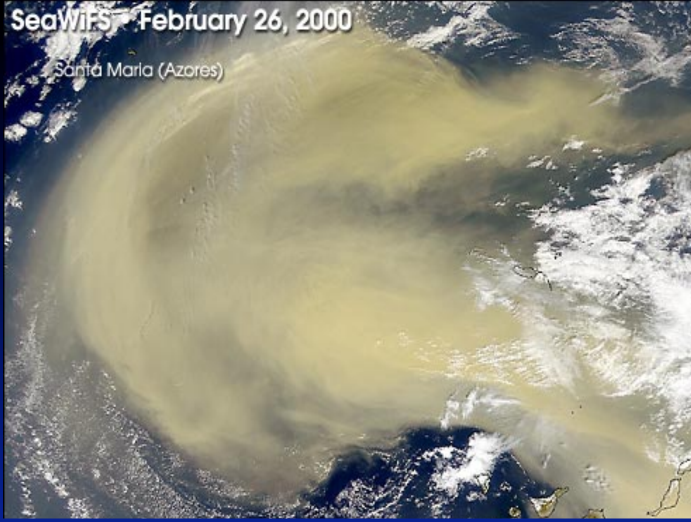
Other Contributors

UCD: Yi-Chin Liu, Terrence Nathan, Nicholas Sowa, Hsiang-He Lee

NCAR: Chris Davis

State University of New York, Albany: Ryan Torn

Taiwan: Jen-Ping Chen, Chao-Tzuen Cheng, Yi-Chiu Lin, I-Chun Tsai

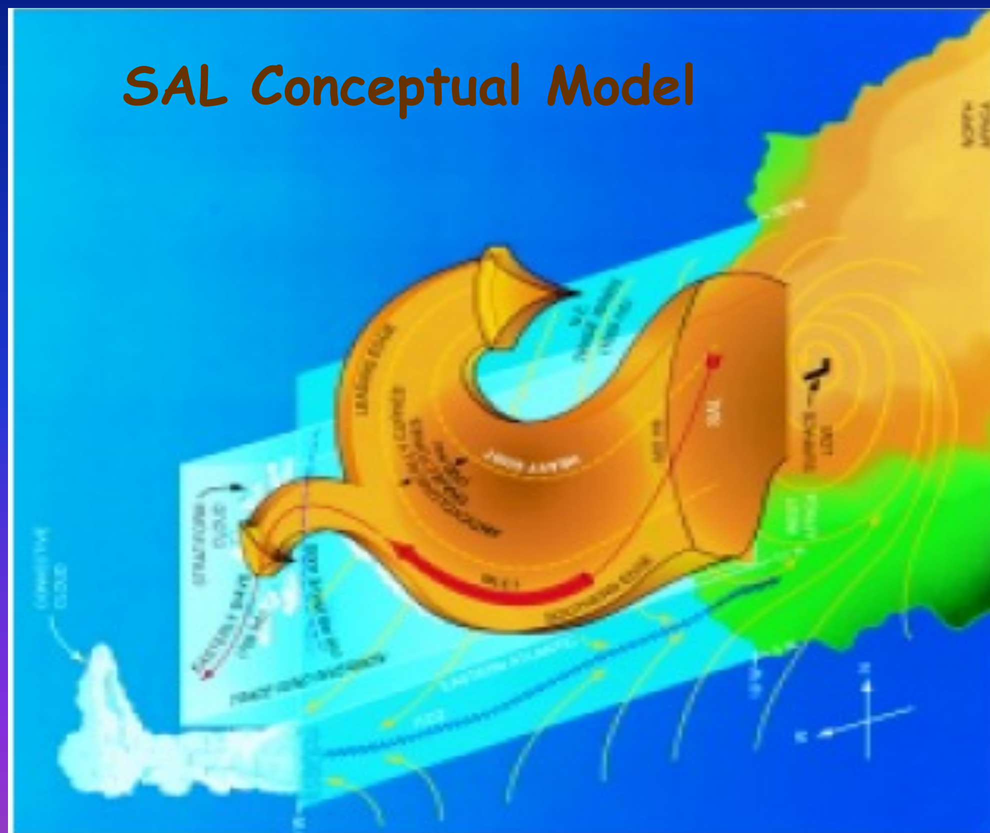


OUTLINE

- Introduction
- WRF dust model
- Impact of dust on TC track forecast
  - Numerical Experiments
  - Results
- Summary

Saharan Air Layer (SAL)

- An extended warm, dry, and potentially dusty air layer from the Saharan Desert to the Atlantic Ocean (~ 850 to 500 mb over ocean)
- Potential influence on African easterly waves and TC activities



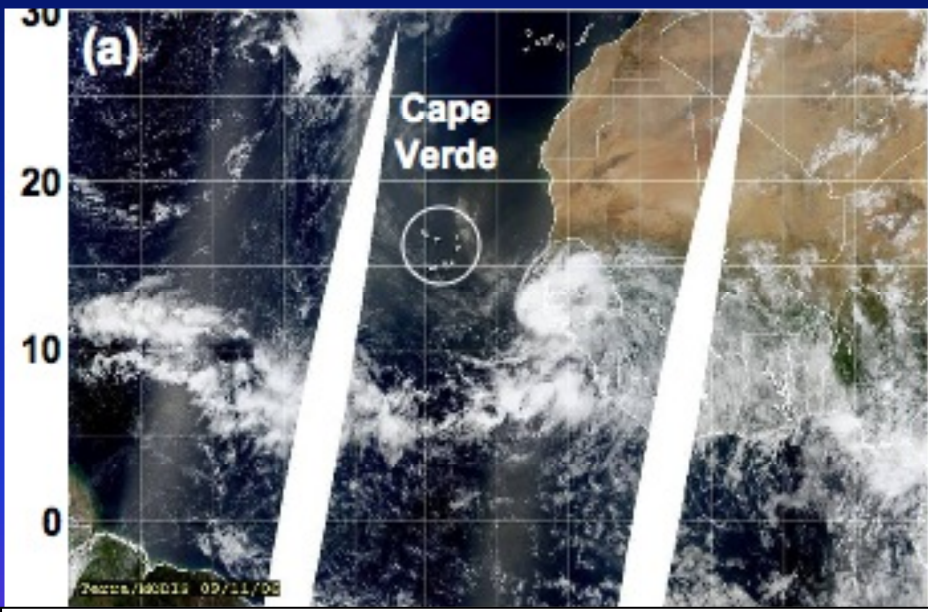
Karyampudi et al. 1999 BAMS

Thermal wind balance

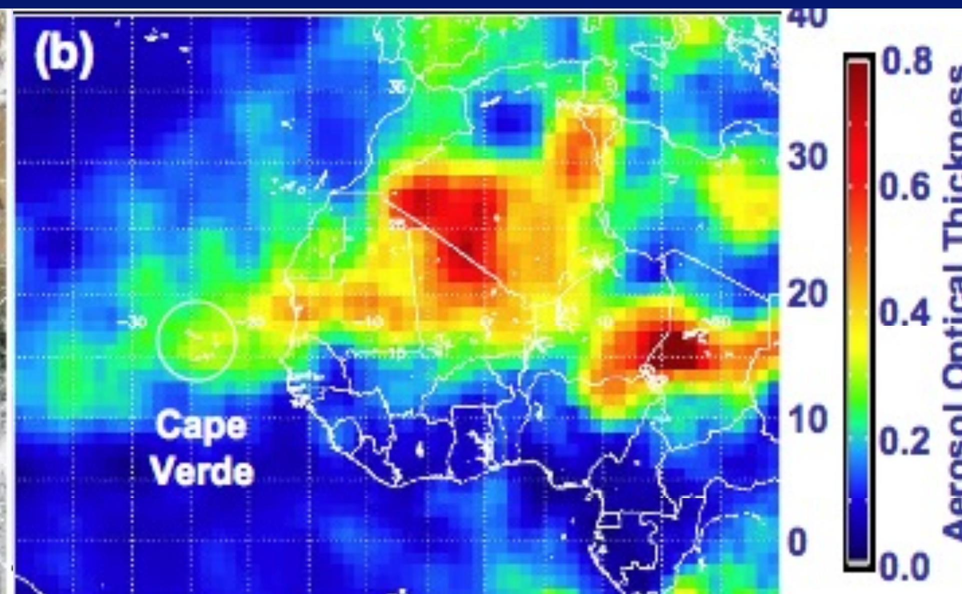
$$\vec{V}_T = \frac{R}{f}\,\hat{k} \times \nabla \overline{T} \ln \frac{p_L}{p_U}$$

$$\vec{V}_T = \vec{V}_{Ug} - \vec{V}_{Lg}$$

Dust & TC

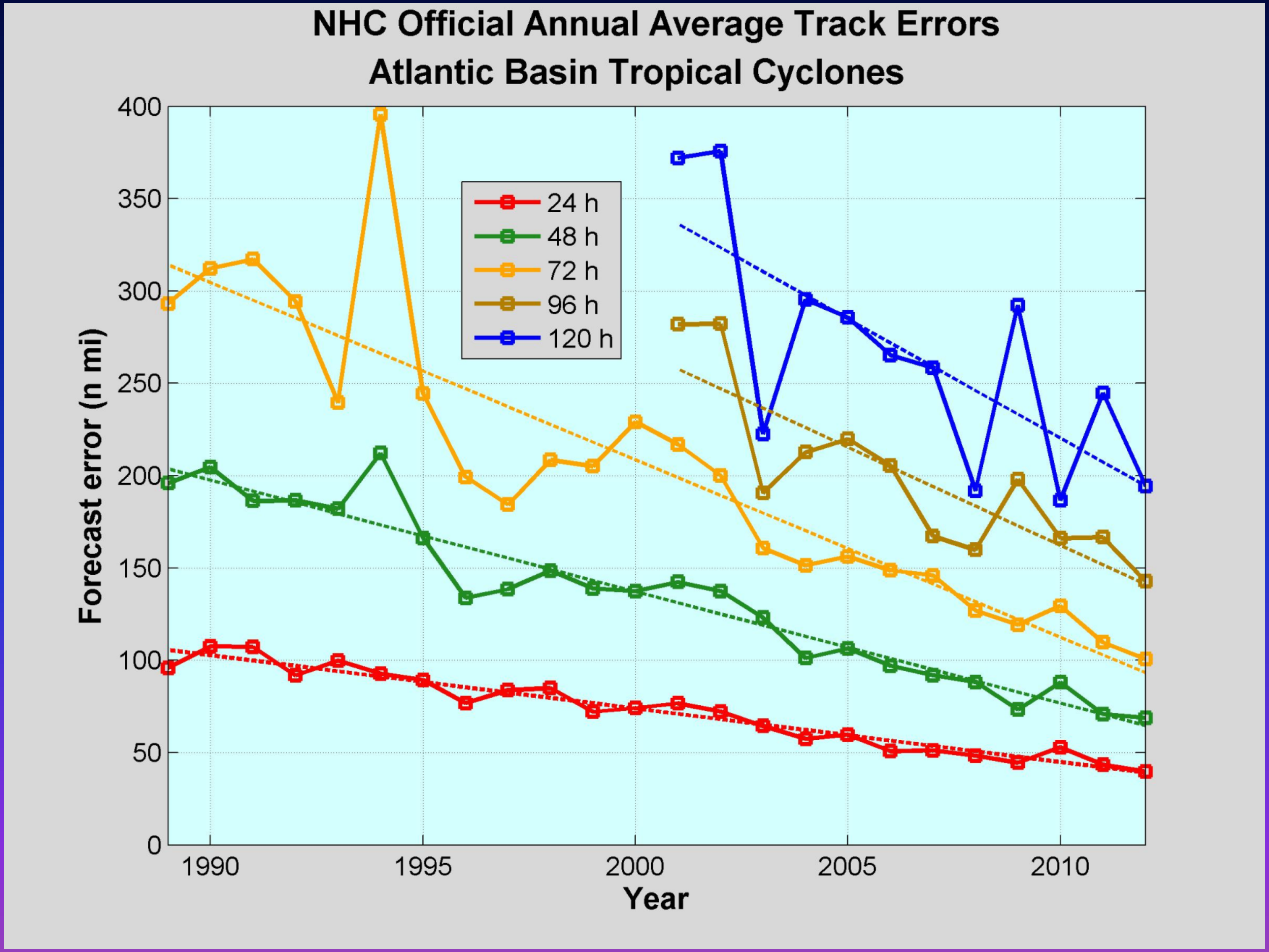


MODIS/Terra on Sep 11, 2006 Saharan dust outbreak passing over Cape Verde (Courtesy S.-C. Tsai, NASA).



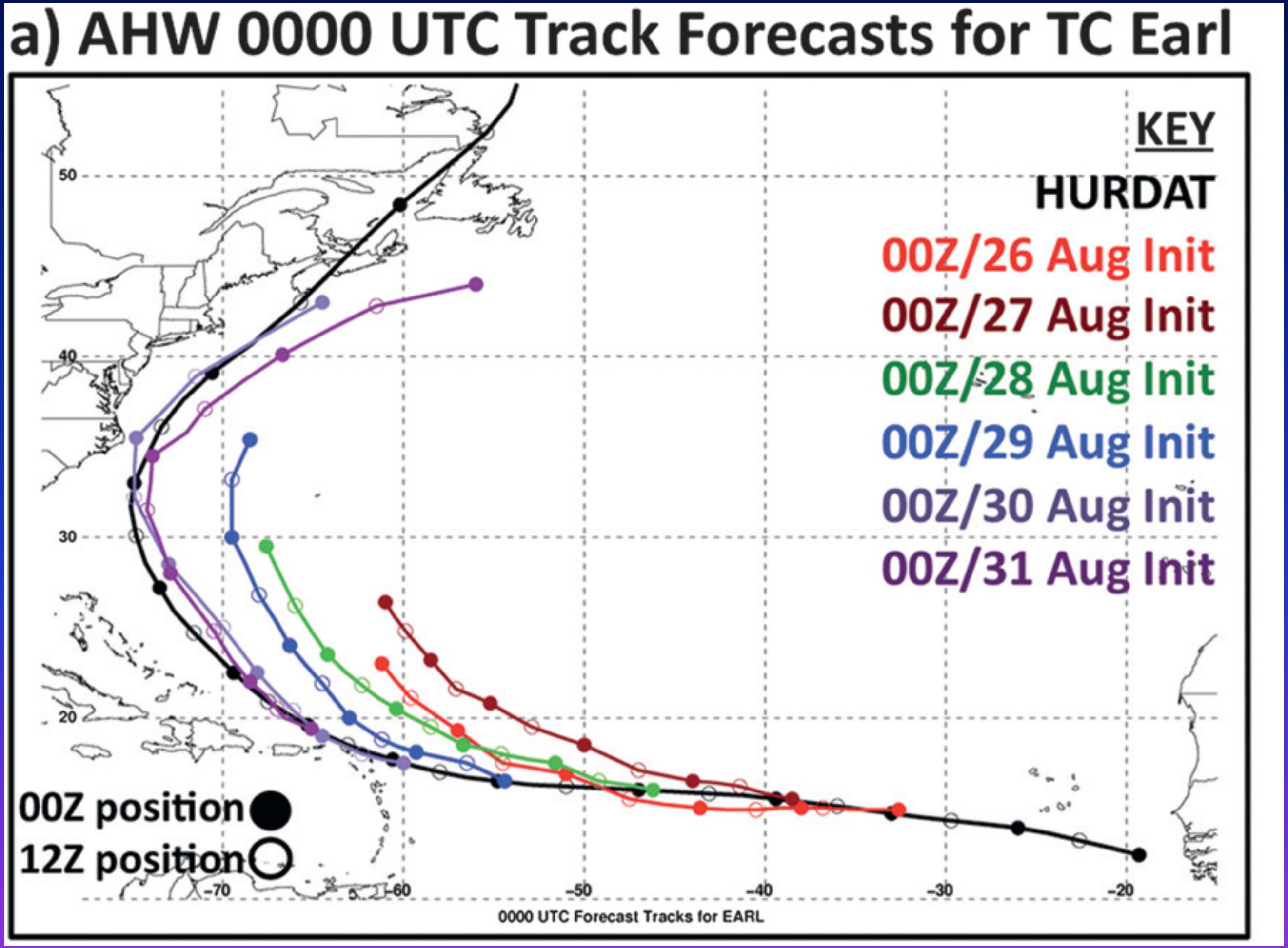
Sep 05-14 averaged, 2006 aerosol optical thickness (MODIS/Deep-Blue algorithm).

TC Track Forecast Error (NHC)



NOAA/AMOL

TC Earl (2010) Track Forecasts



Galarneau and Davis (2013)

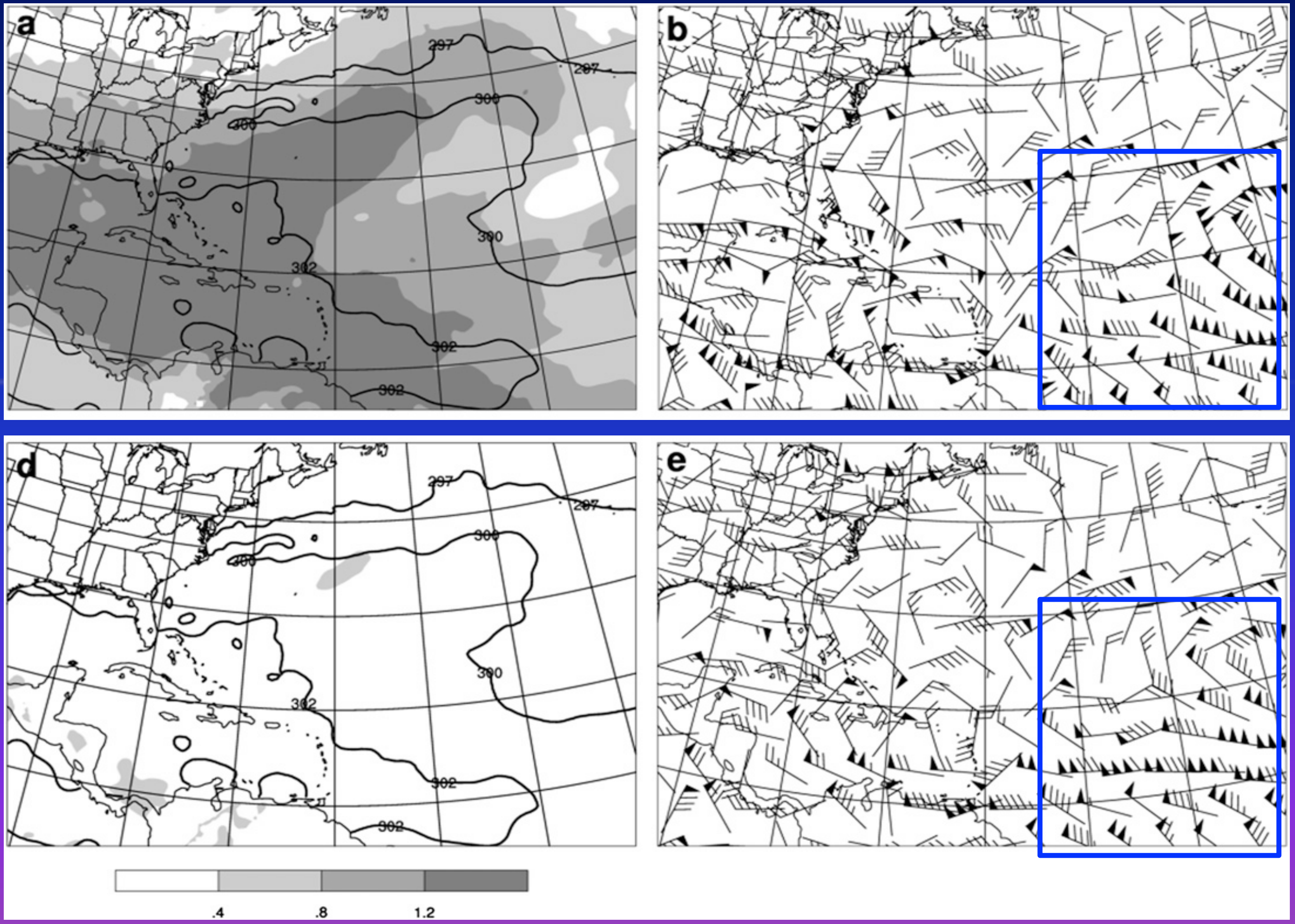
TC Track and Shallow Convective Scheme

Compared to KF, Tiedtke reduced track error by 25%.

6-h ensemble-mean 700-mb T 700-mb wind (1 month)

KF - GFS

Tiedtke - GFS

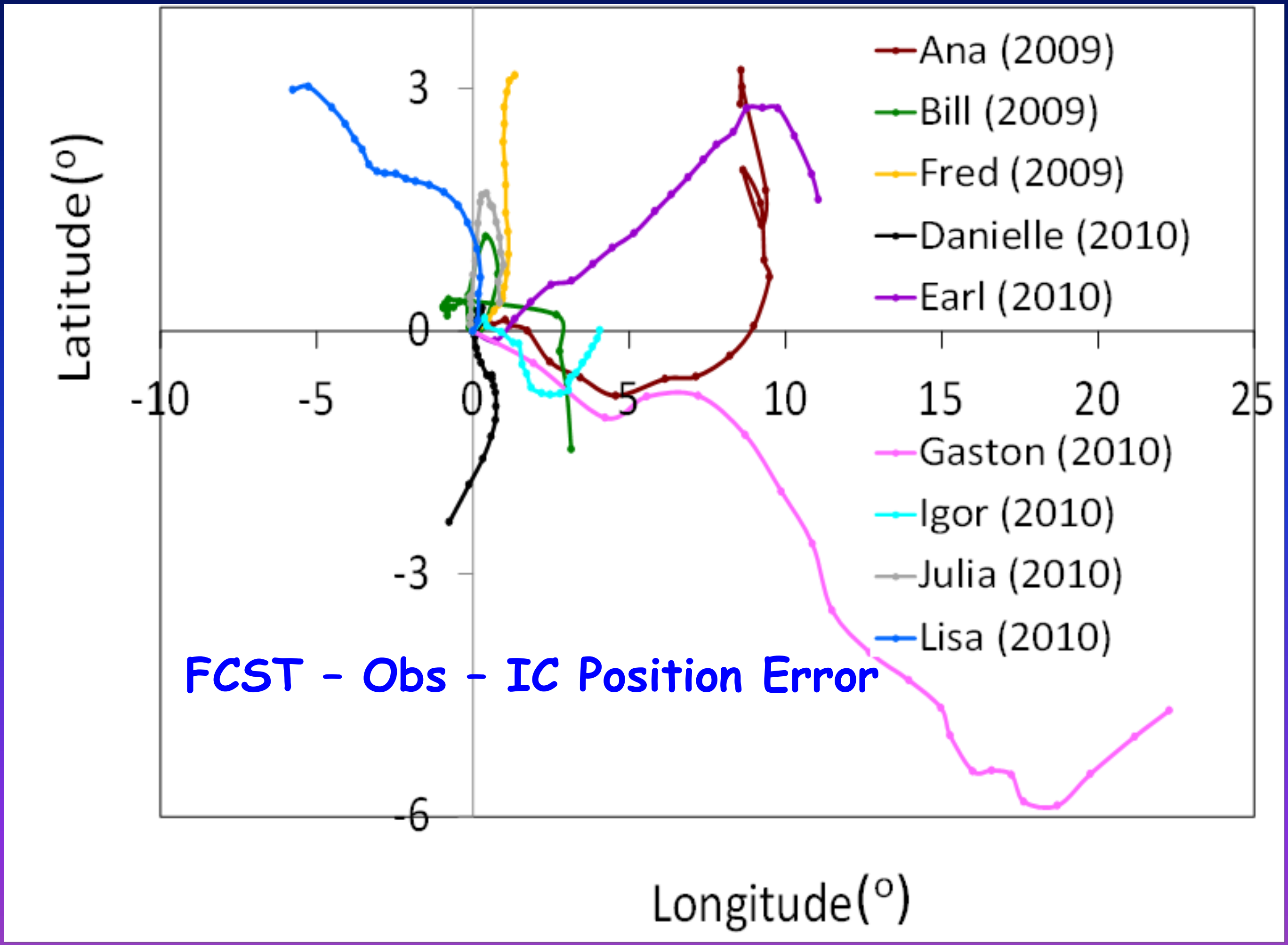


Torn and Davis, 2012

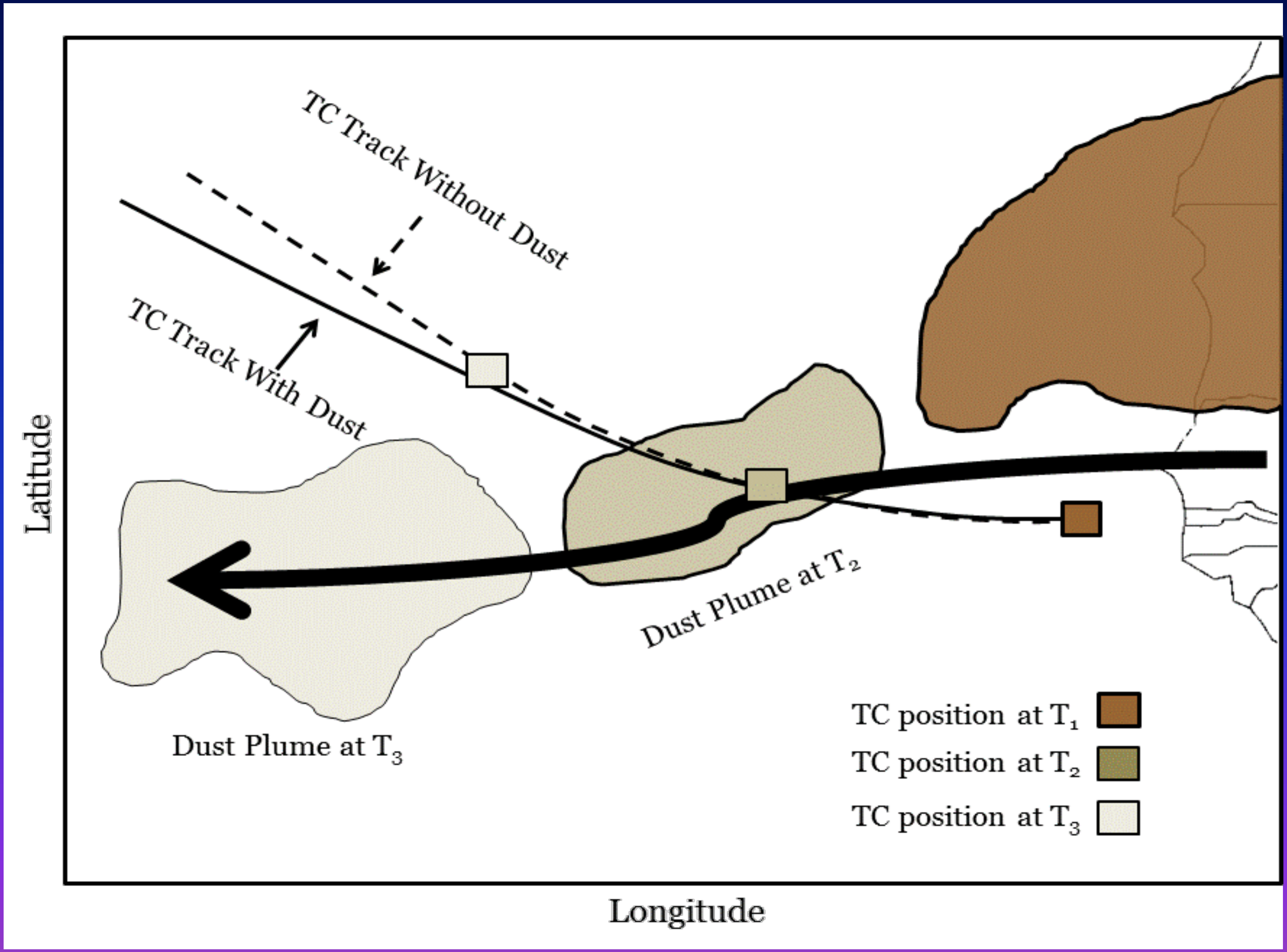
a flag = 1 m/s bias

5-day TC Track Forecast Error (degree)

Data from Torn and Davis (2012)



Hypothesis



Chen et al. 2015

Modification of Energy by Dust

Influence on the energy budget

Direct effect: dust absorbs and scatters radiation

=> directly modifies energy budget

Indirect effect: dust acts as cloud condensation nuclei and ice nuclei

=> changes cloud properties

=> indirectly modifies energy budget

Development of WRF Dust Model (V3.2.1)

WRF + Dust continuity equation (12 bins)

+ Dust-cloud-radiation effects

$$\frac{\partial C}{\partial t} = -\nabla \cdot \vec{V}C + C_{pbl} + C_{cov} + C_{mic} + S_c + E_c$$

$C = \mu c$ (coupled dust variable, c)

$\mu = p_{hs} - p_{ht}$

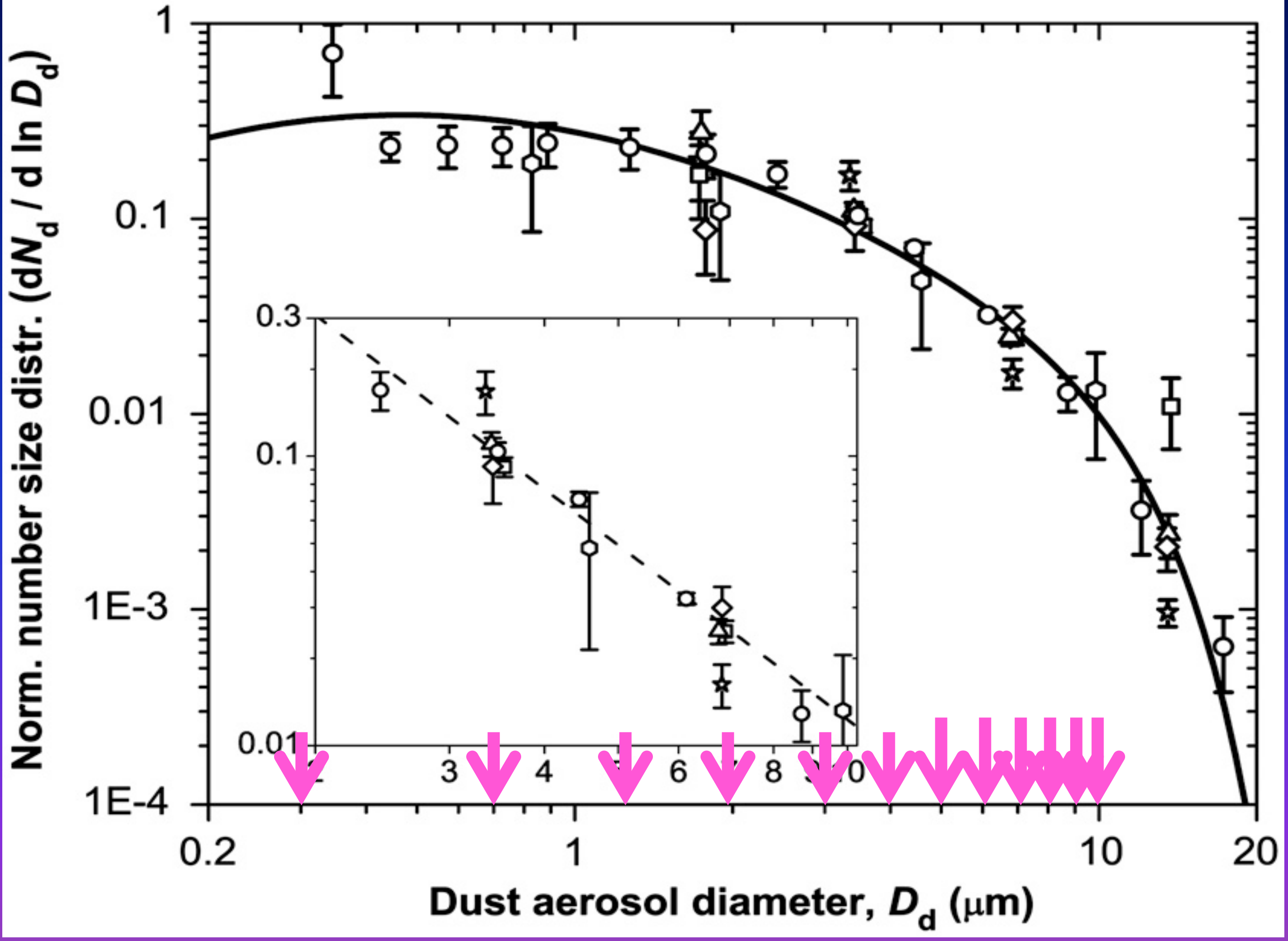
c : Dust mixing ratio

S_c : Sedimentation (time splitting)

E_c : Source / Sink - emission (strong wind, dry soil, veg. type), wet scavenging, dry deposition

Dust Particle Distribution

12 dust bins



(Kok et al. 2011)

Dust Emission

- Vegetation Type – Barren
- Moist volumetric fraction < 0.2
- Wind > 6.0 ms^{-1}
- Soil size – 12 bins

Surface dust flux

$$E_c(\mu g\, s^{-1} m^{-2}) = \max\left\lfloor c_1 (u_{10} - u_c) u_{10}^2,\ 0. \right\rfloor$$

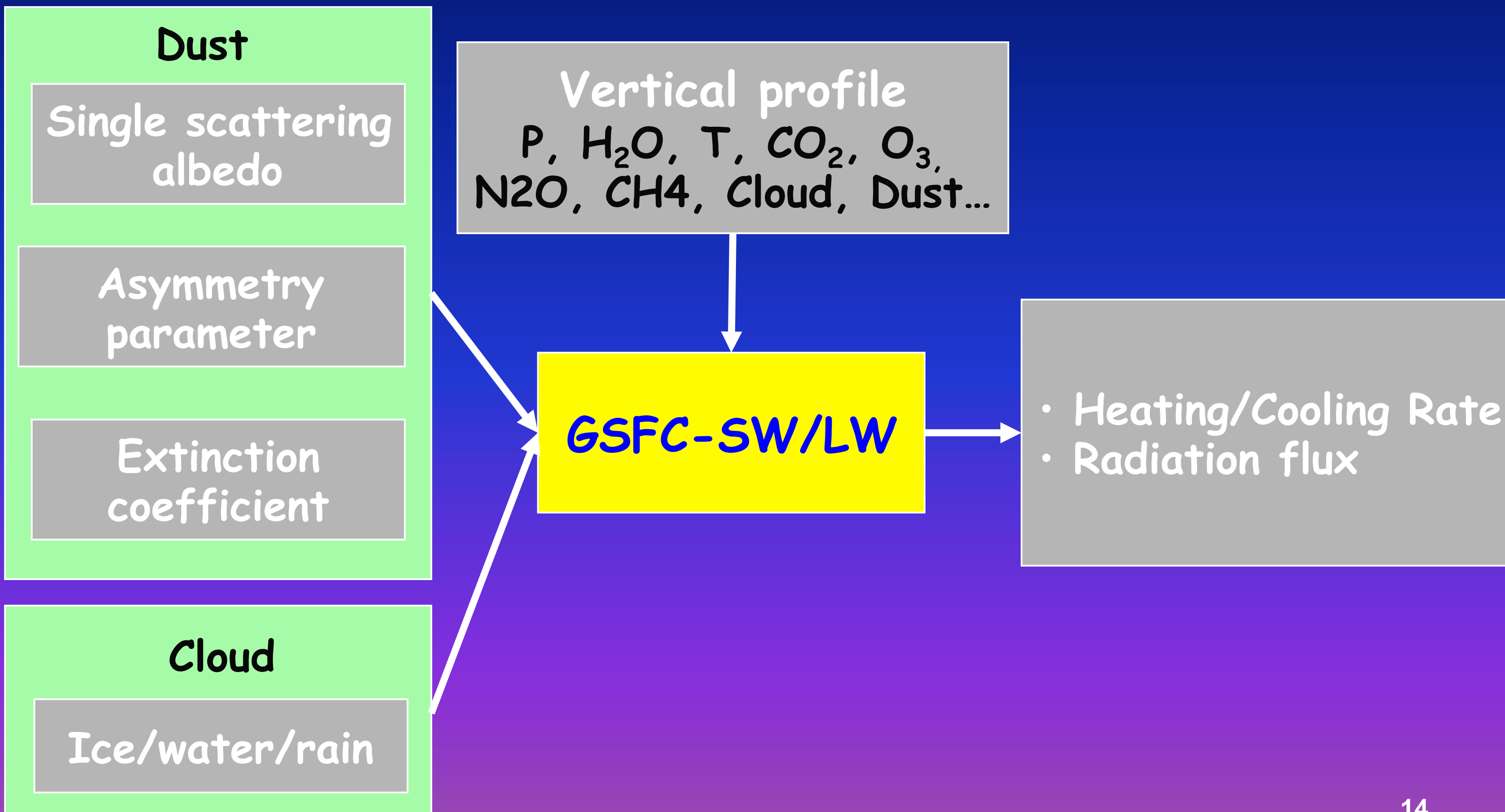
$$c_1 = 0.4\, \mu g\, s^2\, m^{-5}, \quad u_c = 6.0\, m\, s^{-1}$$

Tegen and Fung (1994)

OPAC & GSFC SW/LW Rad Schemes

OPAC - Optical Properties of Aerosols and Clouds

(Hess, et al., 1998, BAMS)



2-Moment Microphysics Scheme

- **Cheng et al. (2010) – modifications based on**

  Warm cloud microphysics – J. P. Chen and Liu (2004)

  Mixed-phase cloud microphysics - Reisner et al. (1998)

- **Two moments - cloud, ice, rain**

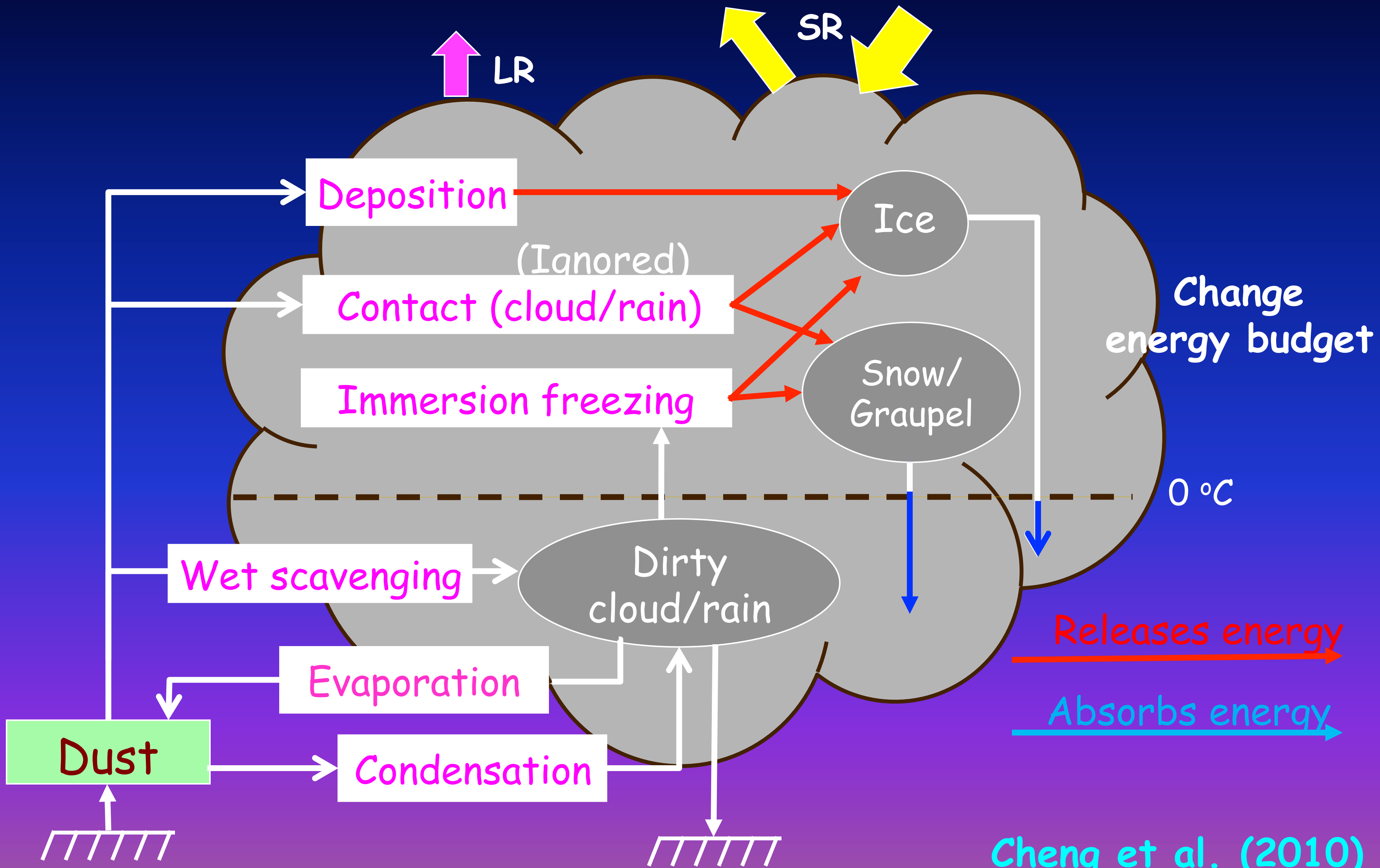
  One moment - snow, graupel

- **Deposition and immersion freezing rates**

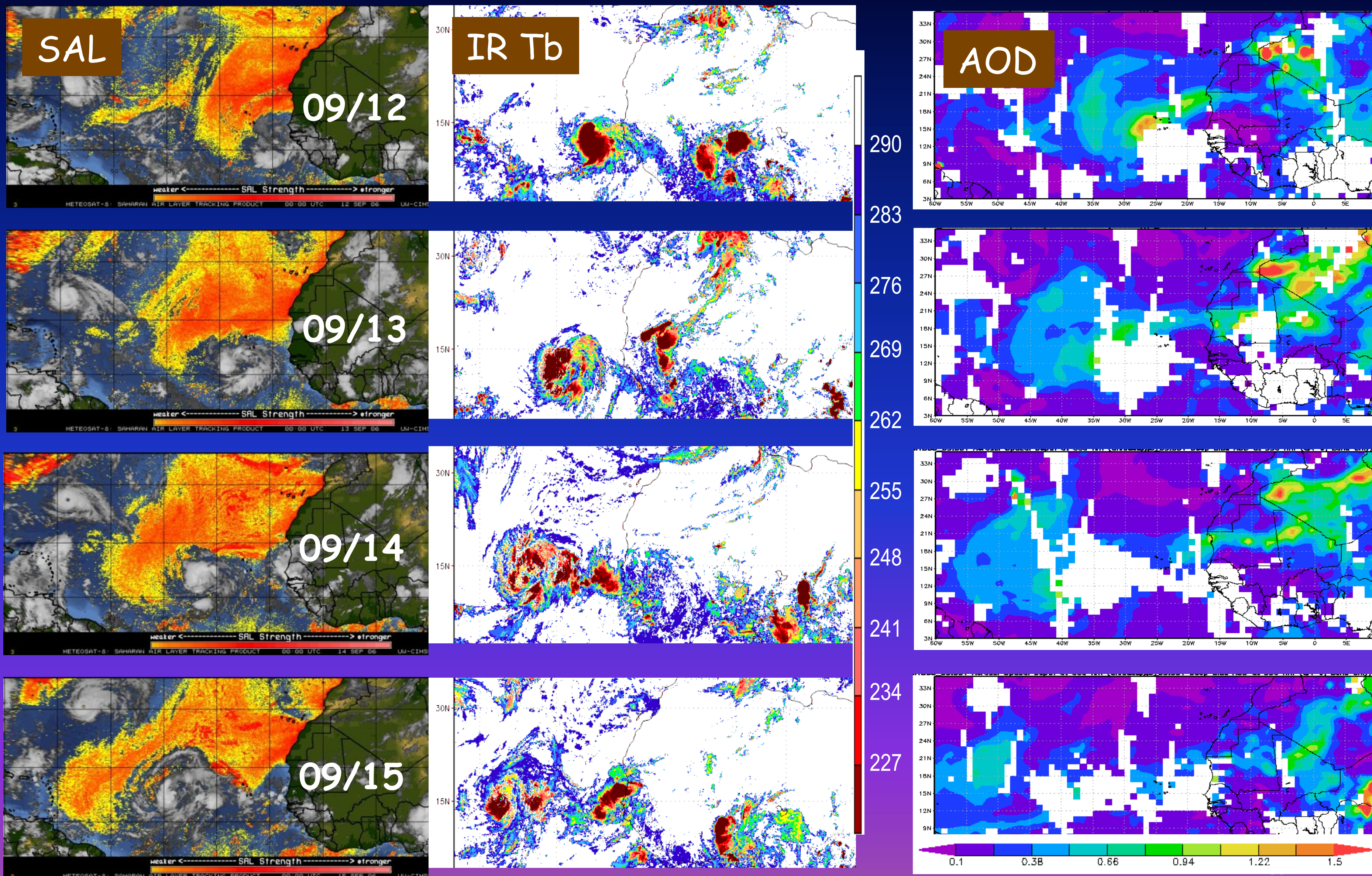
  - T, saturation ratio w.r.t. ice, dust surface area

    (J. P. Chen et al. 2008, Hoose et al. 2010)

Dust-Microphysics Processes



Case Study: Hurricane Helene (2006)

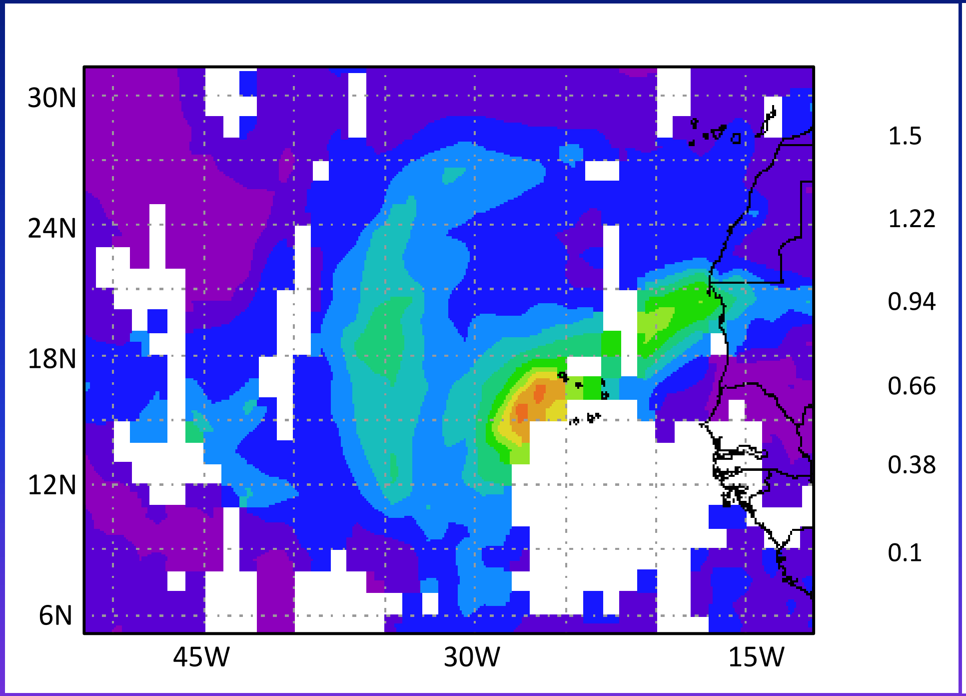


(METEOSAT, CIMSS/UW) (IR brightness T) MODIS/MISR

EXP	*Microphysics*	*Dust-rad.*
PL-DA	**Purdue Lin**	ON
PL-DD	**Purdue Lin**	OFF
W6-DA	**WSM 6-class graupel**	ON
W6-DD	**WSM 6-class graupel**	OFF
TM-DA	**Two momentum**	ON
TM-DD	**Two momentum**	OFF

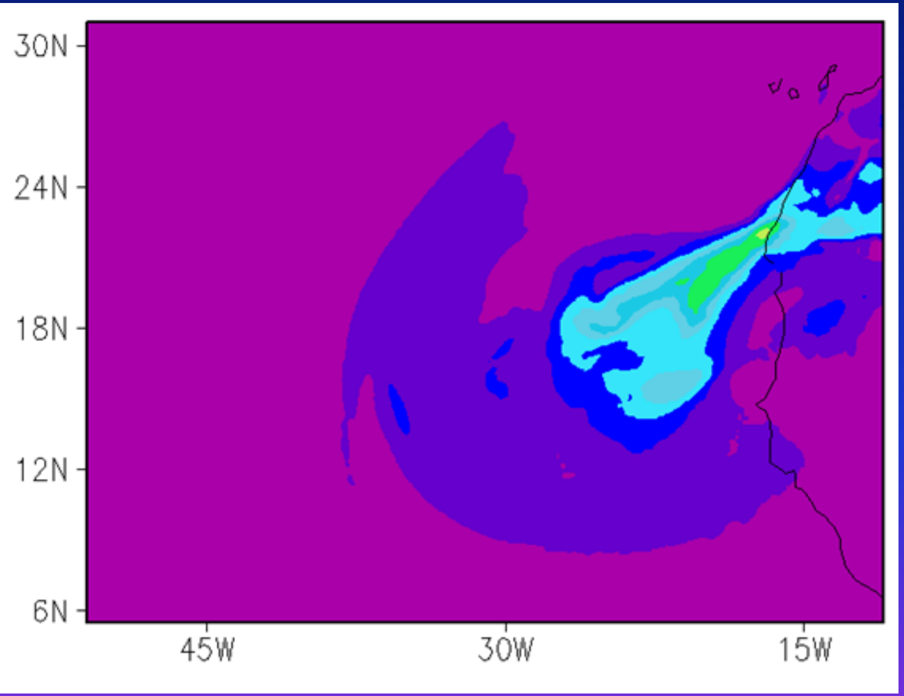
Aerosol Optical Depth @ 36h (12Z 12 Sep)

MODIS AOD

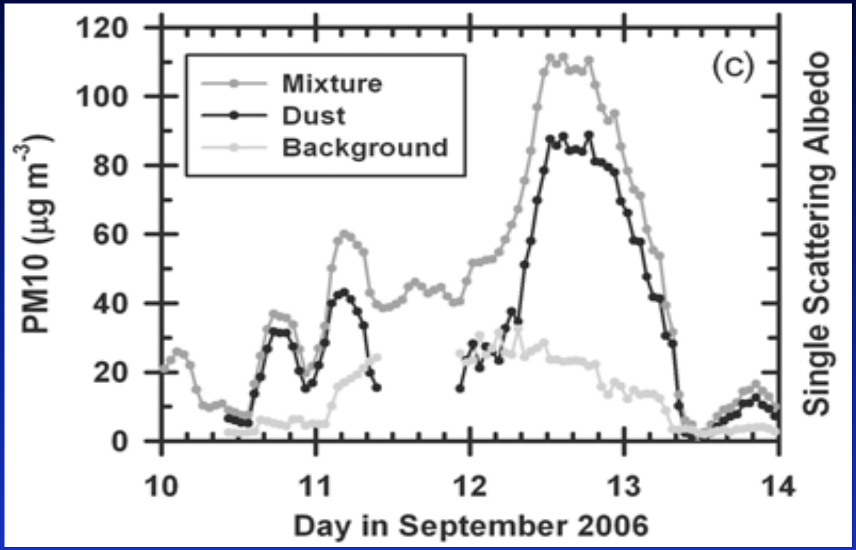


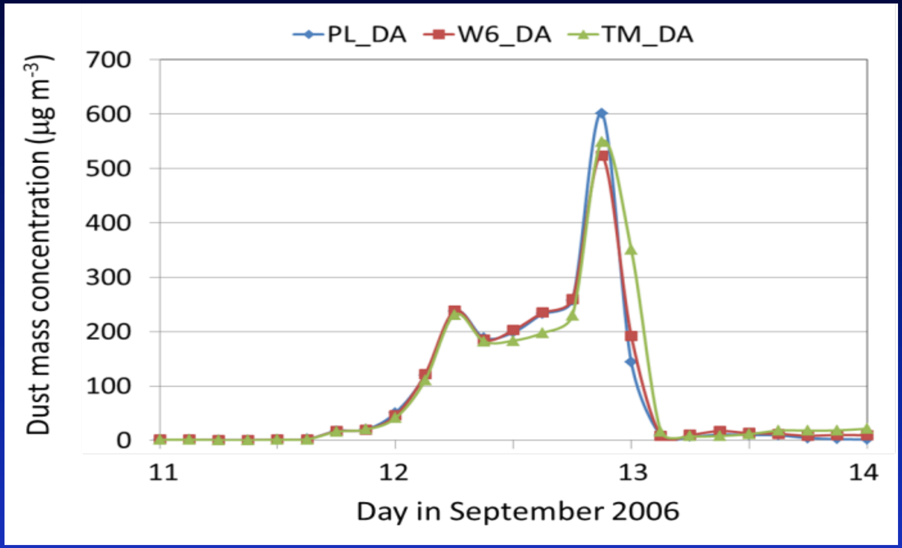
NASA JPL

Simulated AOD (ON)

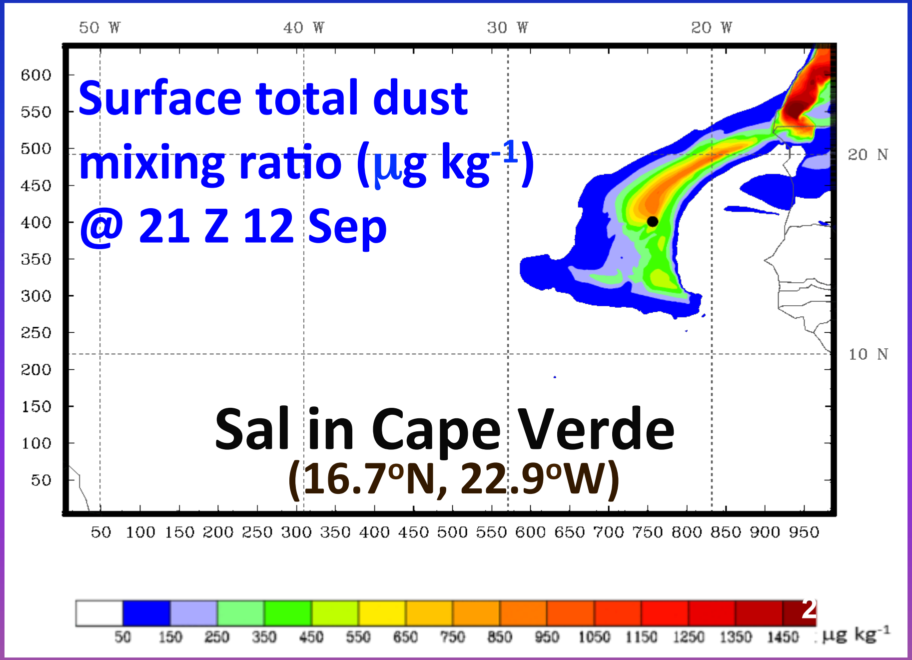


Surface Dust Mass Concentration



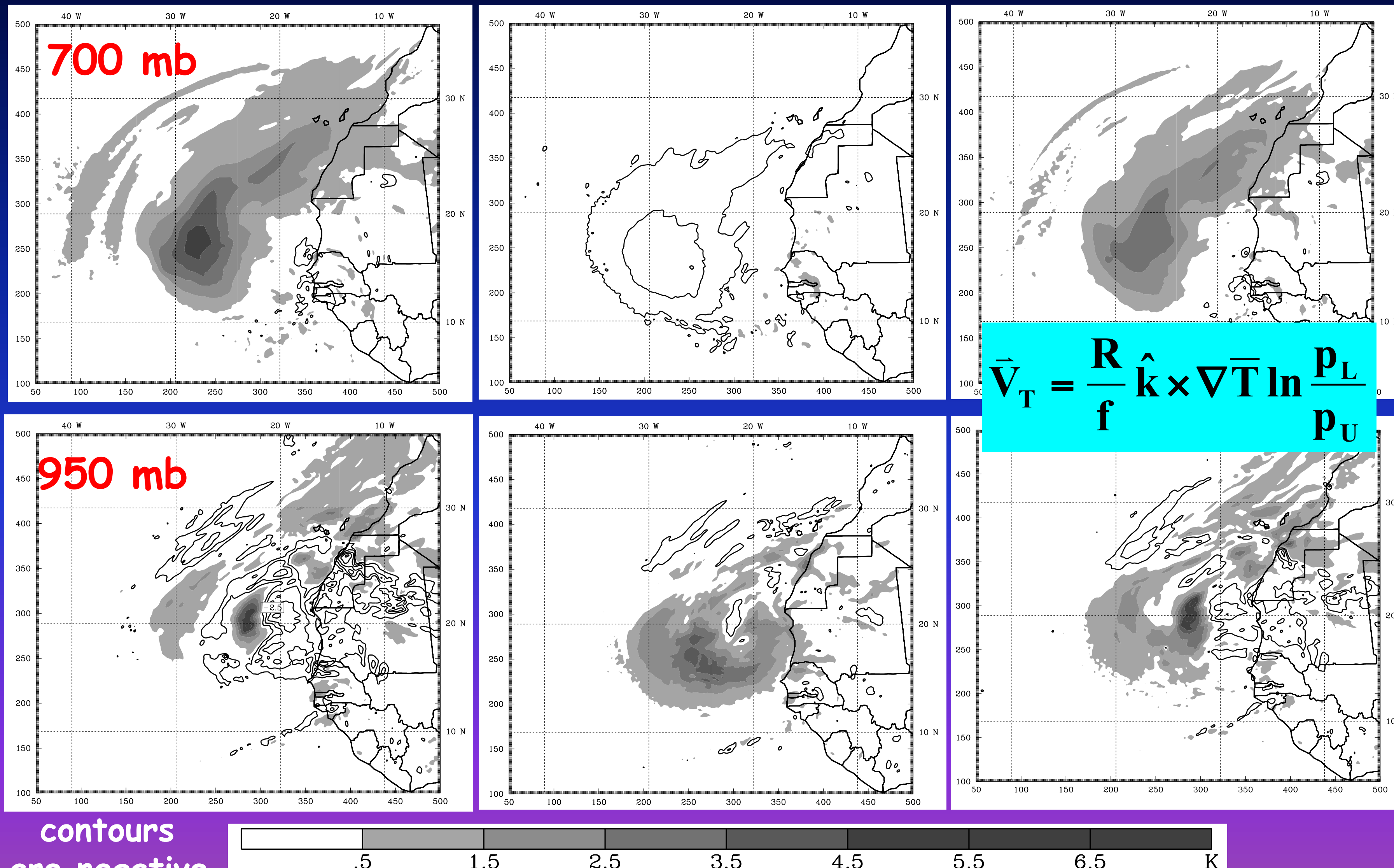


Jeong et al. 2008



Dust-rad, T Difference (60h) (ON – OFF)

Shortwave | Longwave | Total



$$\vec{V}_T = \frac{R}{f}\,\hat{k} \times \nabla \overline{T} \ln \frac{p_L}{p_U}$$

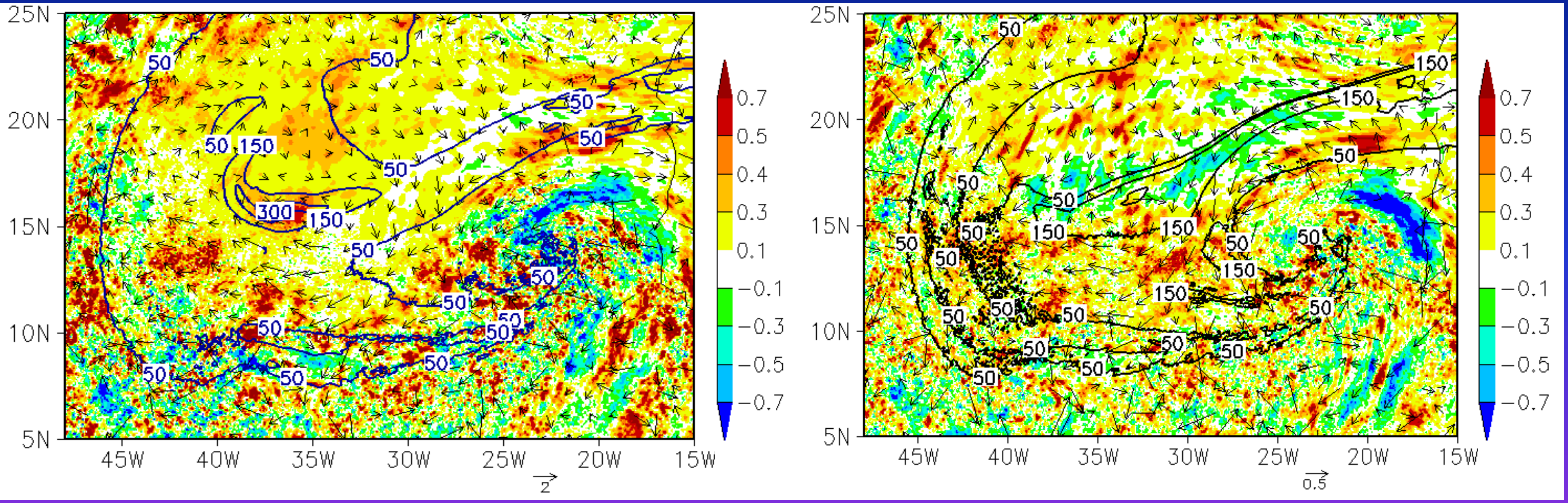
contours are negative

Dust storm outbreak 18-22 July 2005 (Chen et al. 2010)

Difference (ON – OFF) @ 60h

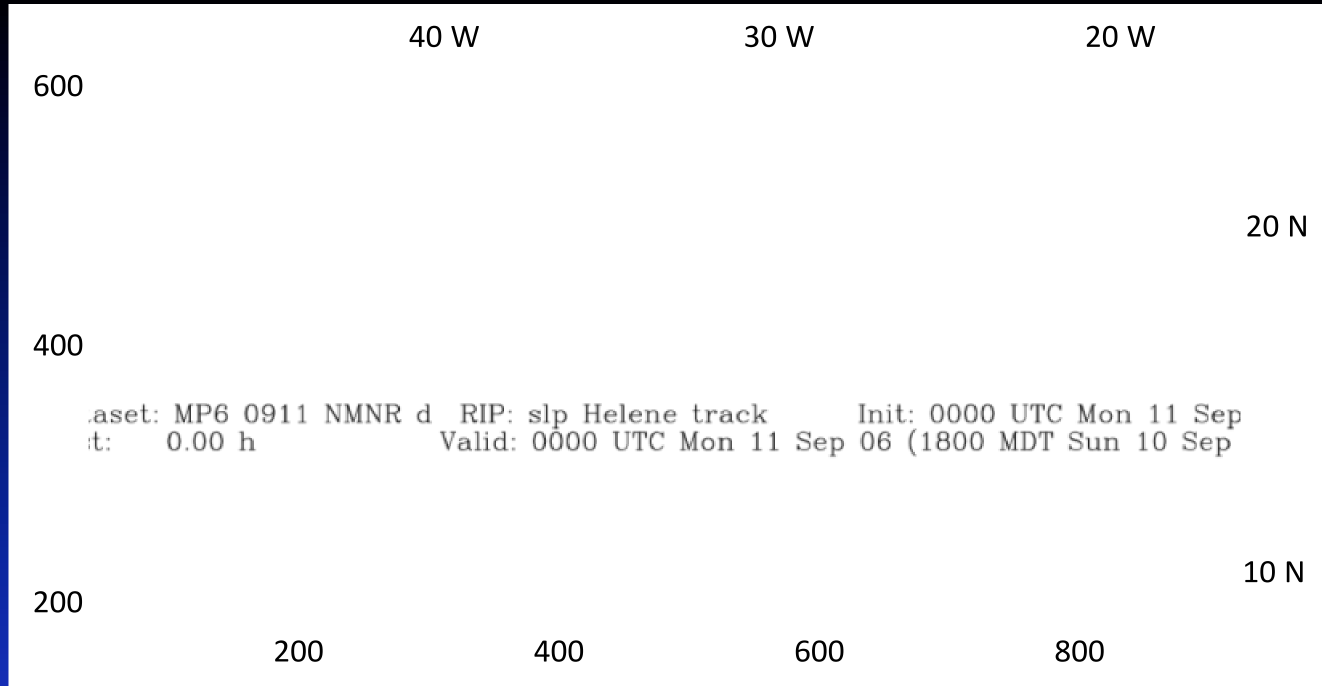
750 mb potential T (shading)
600 mb – 900 mb wind shear
Black contours – total dust
Skip difference > 3 m/s

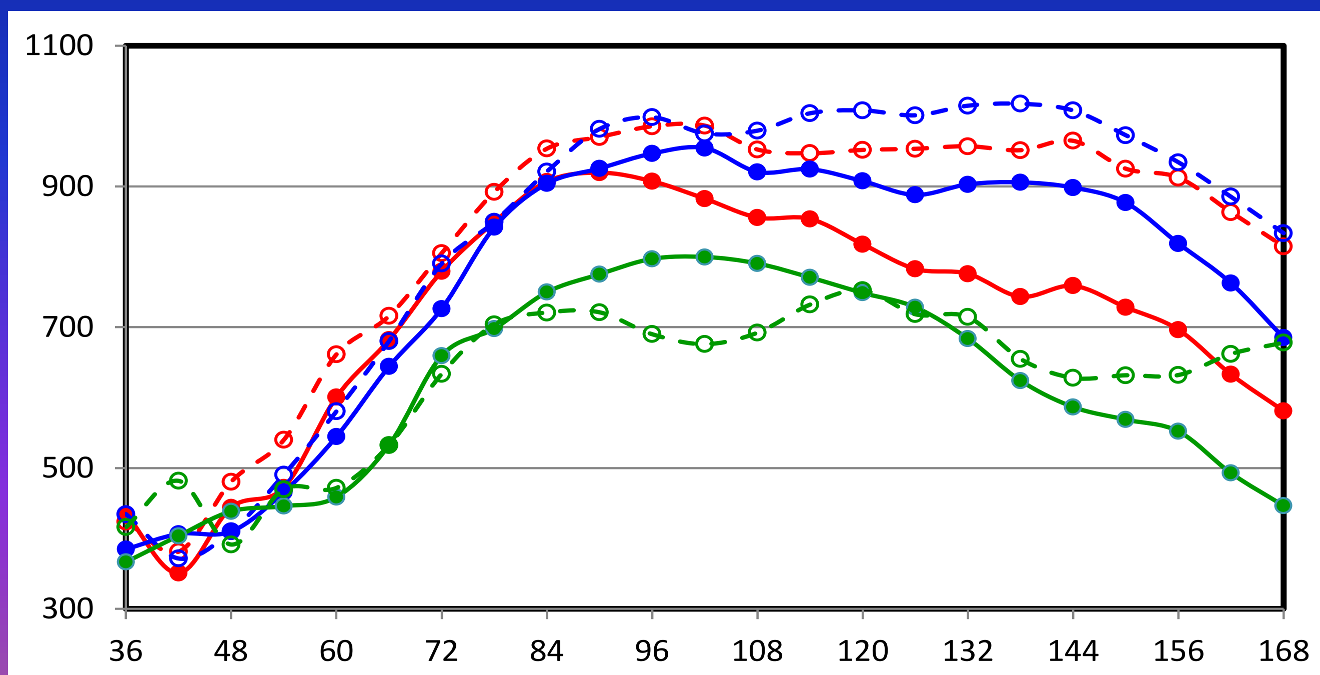
850 mb potential T (shading)
850-200 mb mean wind vectors
Black contours – 850 mb total dust
Skip difference > 0.5 m/s



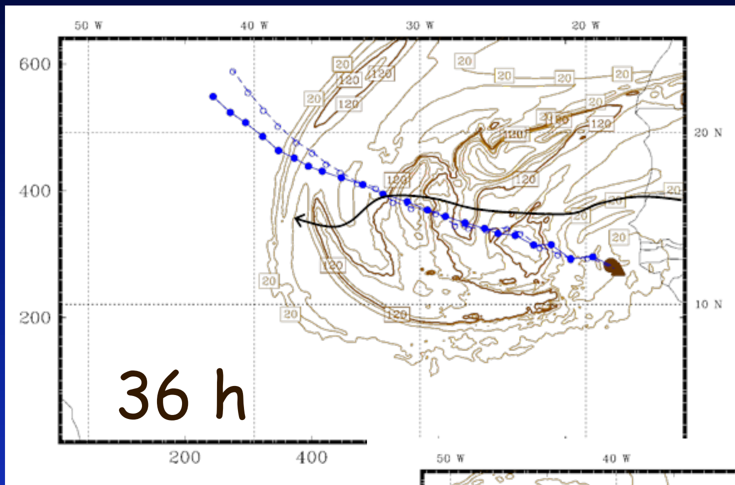
$$T = \frac{2\pi}{f} = \frac{2\pi}{2\Omega \sin(15^{o})} \approx 46h$$

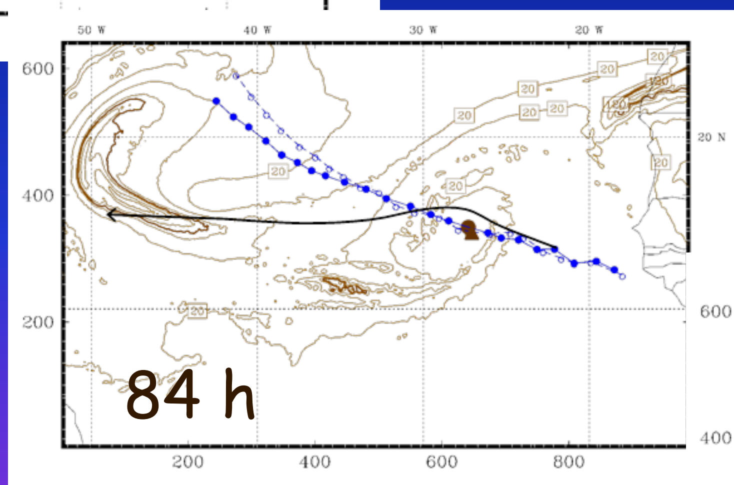
Track forecast

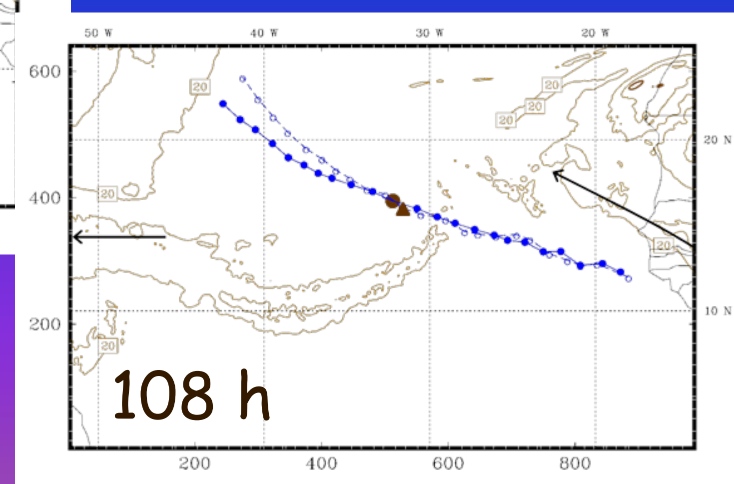




750-mb Total Dust from W6-DA

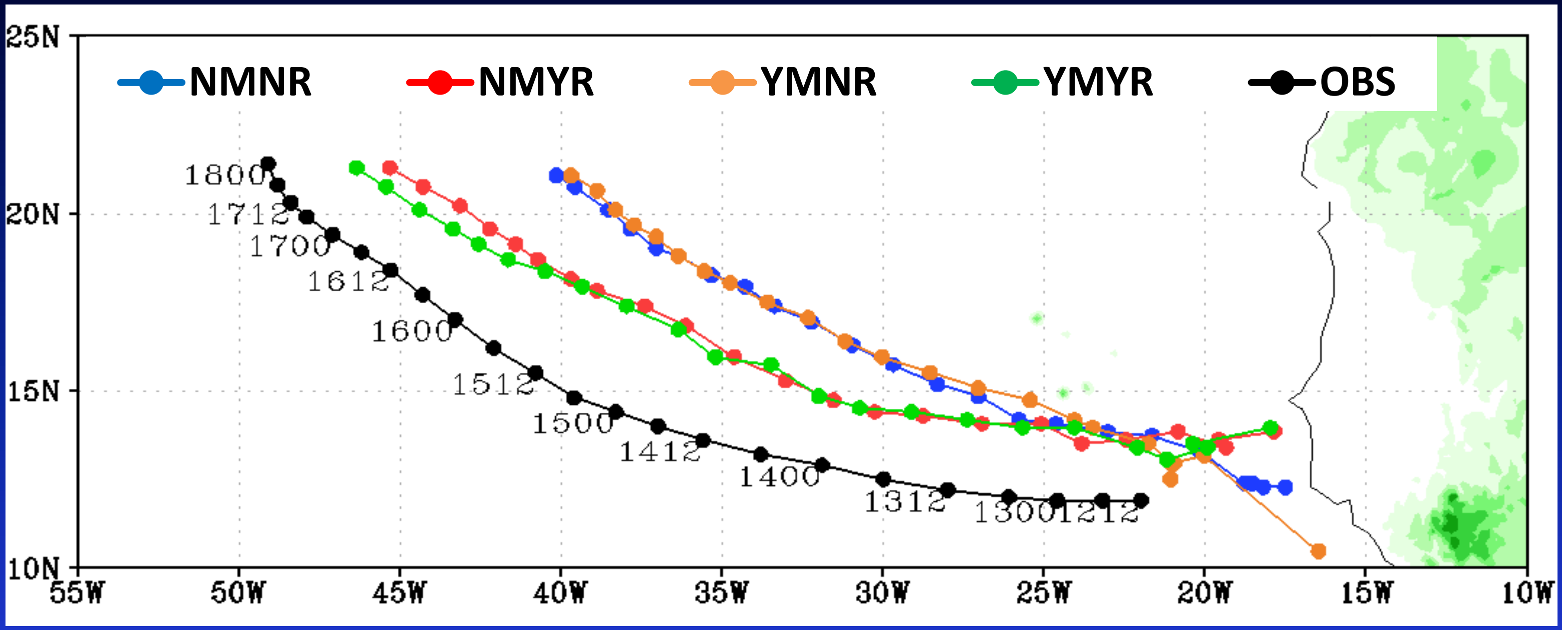


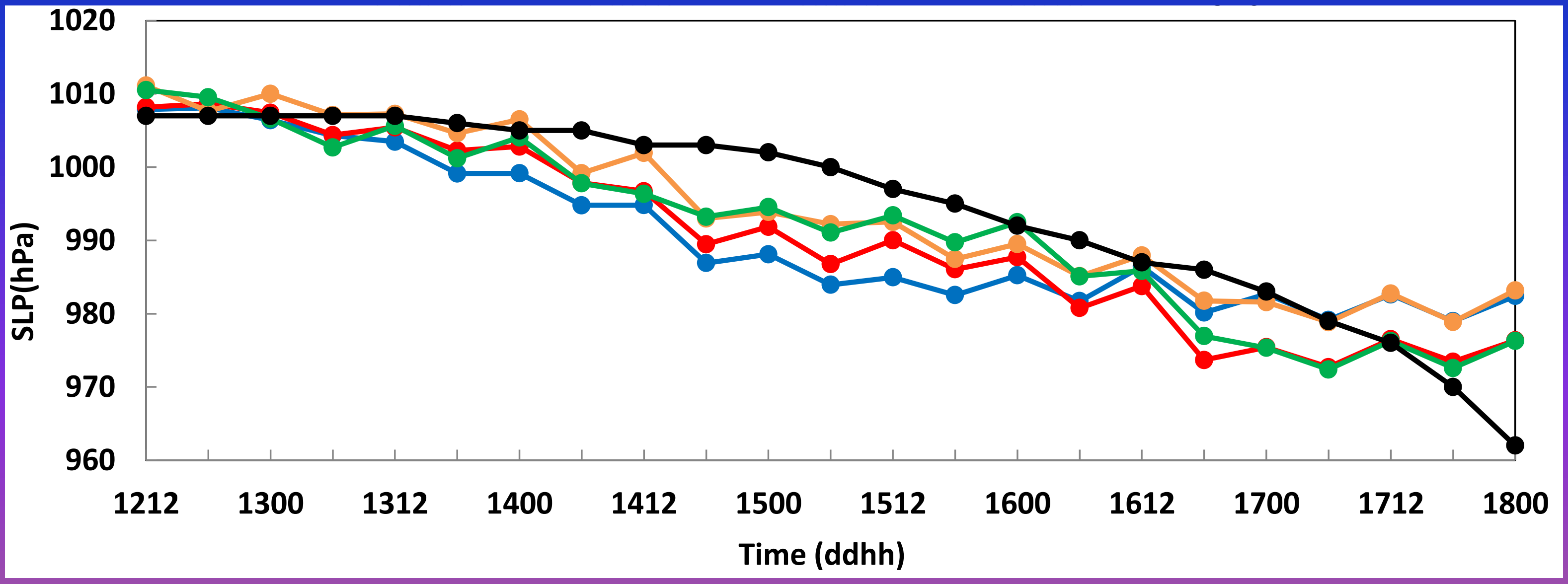




Blue solid line: W6-DA (●)
Blue dashed line: W6-DD (▲)
Black arrows: Jets

Tracks & Intensity (Sep 2006)





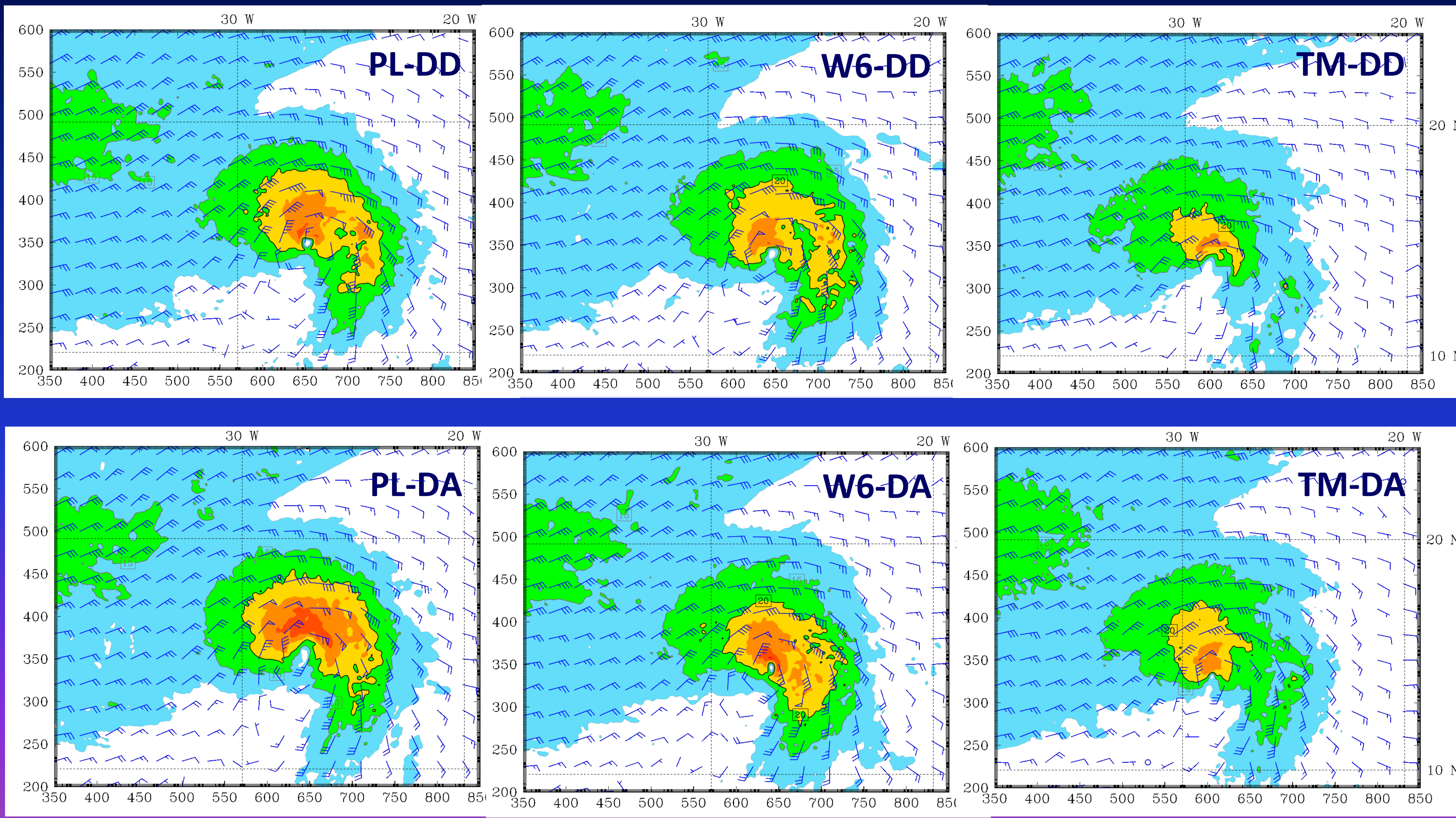
SUMMARY

- Despite recent improvements in TC track forecasts, track forecasts over the East Atlantic are characterized by northeastward and southeastward biases.
- Simulated dust plume modifies the thermal field, causing a clockwise turning of the vertical shear and the deep-layer mean flow surrounding the plume, which modulates Helene's moving speed and direction.
- The error in the model's 7-day track forecasts is reduced by an average of 27% (~205km) after including the dust-radiative forcing.

Thank you!

850-mb Wind Speed & Vectors @ 84h

Black contours – 20 m/s Gray contours – 15 m/s



Cloud Top T & SLP @ 144h (Obs = 984 mb)