JCSDA 2012 Summer Colloquium on Data Assimilation,
Santa Fe, NM, July 24 – August 3, 2012

ENSEMBLE DATA ASSIMILATION FOR HURRICANES

Milija Zupanski and Man Zhang

(contributed by Karina Apodaca, John Knaff, Mark DeMaria, Ming-Jeong Kim)

Cooperative Institute for Research in the Atmosphere
Colorado State University
Fort Collins, Colorado, U. S. A.

Acknowledgements:

- **JCSDA**
- **NOAA NESDIS/GOES-R**
- **NSF Collaboration in Mathematical Geosciences**
- **JCSDA S4 computer, NCAR computing (bluefire)**

OVERVIEW

- ☐ Tropical cyclones (TC)
- ☐ Inner core observations
- ☐ Challenges of TC data assimilation and forecasting

HOW TROPICAL CYCLONES FORM ?

❑ Four major phases

1- tropical disturbance

2- tropical depression

3- tropical storm

4- tropical cyclone (hurricane, typhoon)

❑ Required initial conditions

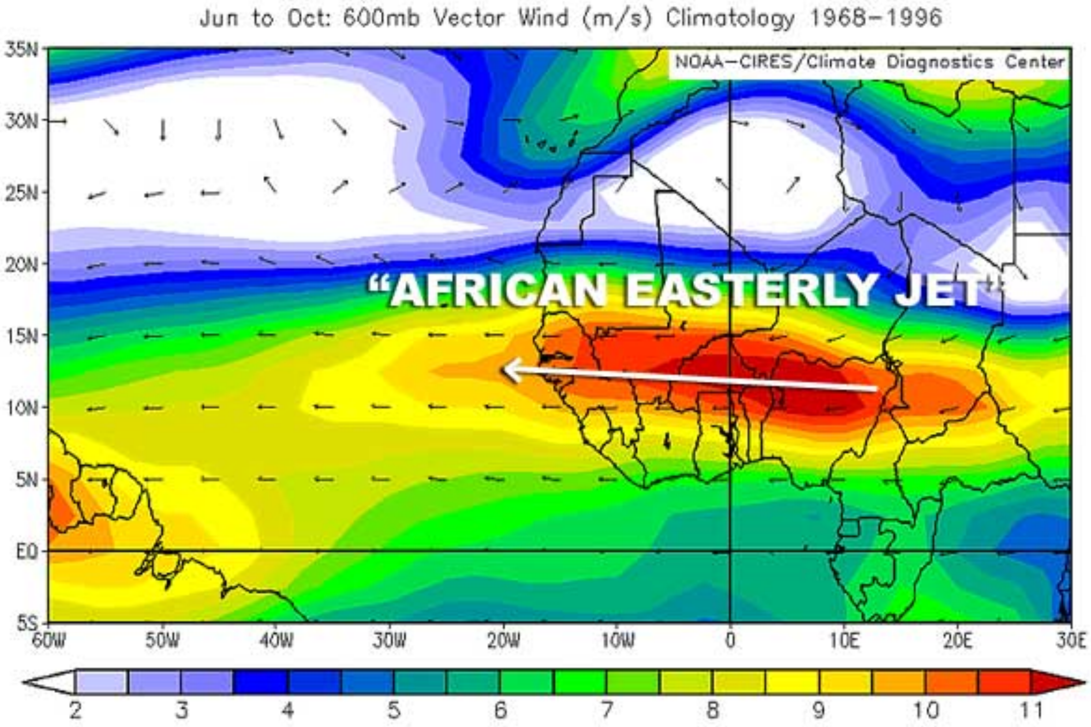
- warm ocean water over 80 F (26.5 C)
- water vapor
- initial cluster of thunderstorms
- weak winds
- Coriolis force (8-20 degrees)

1- TROPICAL DISTURBANCE

- initial perturbation in the form of a group of small thunderstorms over the tropics
- convergence of surface winds, air lifting at the center
- for Atlantic Ocean, these are the easterly waves off the west coast of Africa, created from undulation of East African Jet

East African Jet (EAJ)

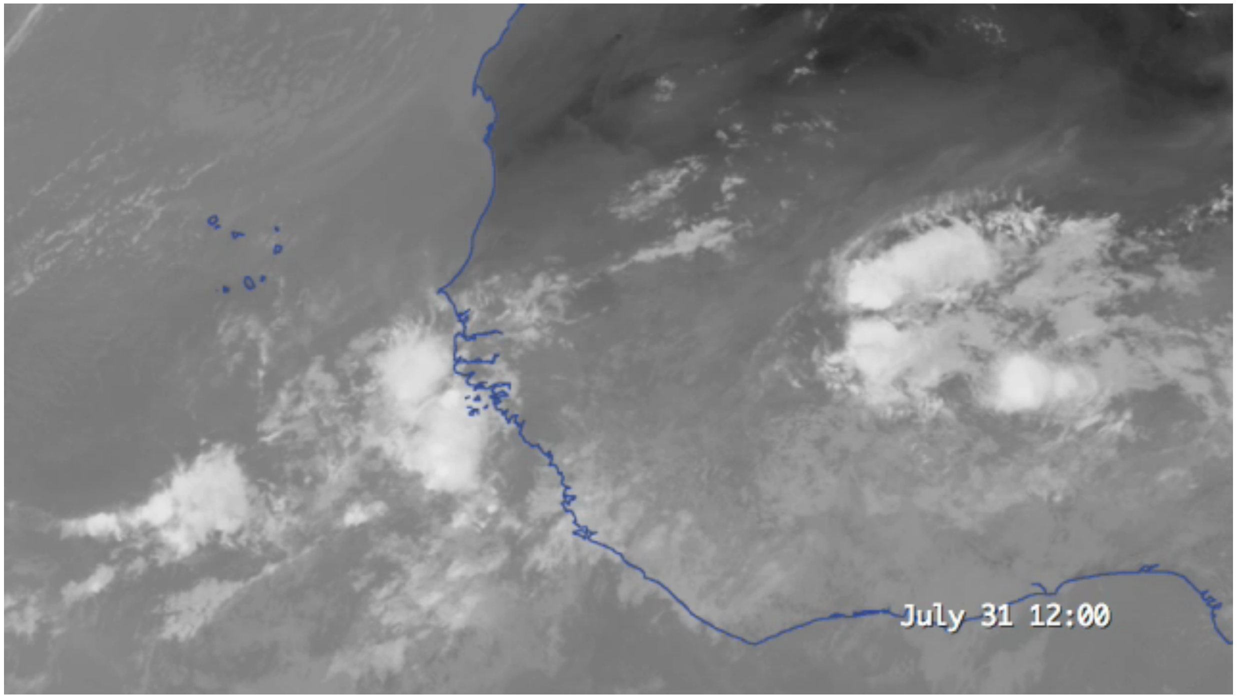
- Warm and dry Sahara to the north
- Cooler and moist ocean over the Gulf of Guinea to the south
- High temperature gradient creates a mid-level jet (10,000 ft)



TROPICAL DISTURBANCES IN ATLANTIC OCEAN

- Not all tropical disturbances grow
- Active area of research

EUMETSAT, Meteosat-8, July-August 2005



2- TROPICAL DEPRESSION

- sustained wind speed > 23 mph [37 km/h])

- falling surface pressure at the center as a consequence of the latent heat release due to condensation of water vapor

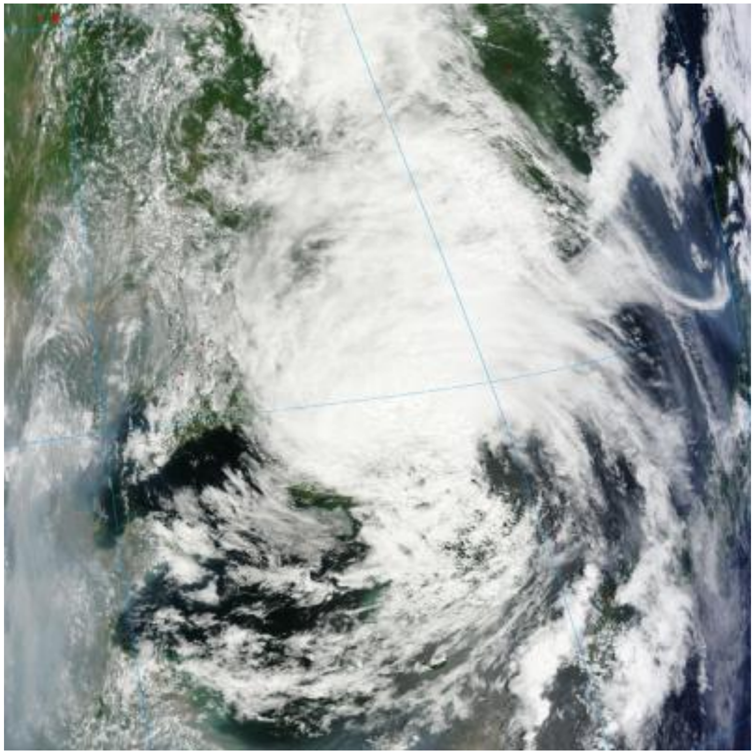
- additional heat reduces the air density and air rises, enhancing condensation and circulation

- with latent heat release the center becomes warmer, resulting in further reduction of central pressure

- reduced low pressure enhances the low-altitude moist air inflow

- more latent heat is released

TD Kanhun, July 19, 2012, 0225 UTC Over South Korea, MODIS, NASA Terra satellite



- Organized group of thunderstorms
- Visible rotation

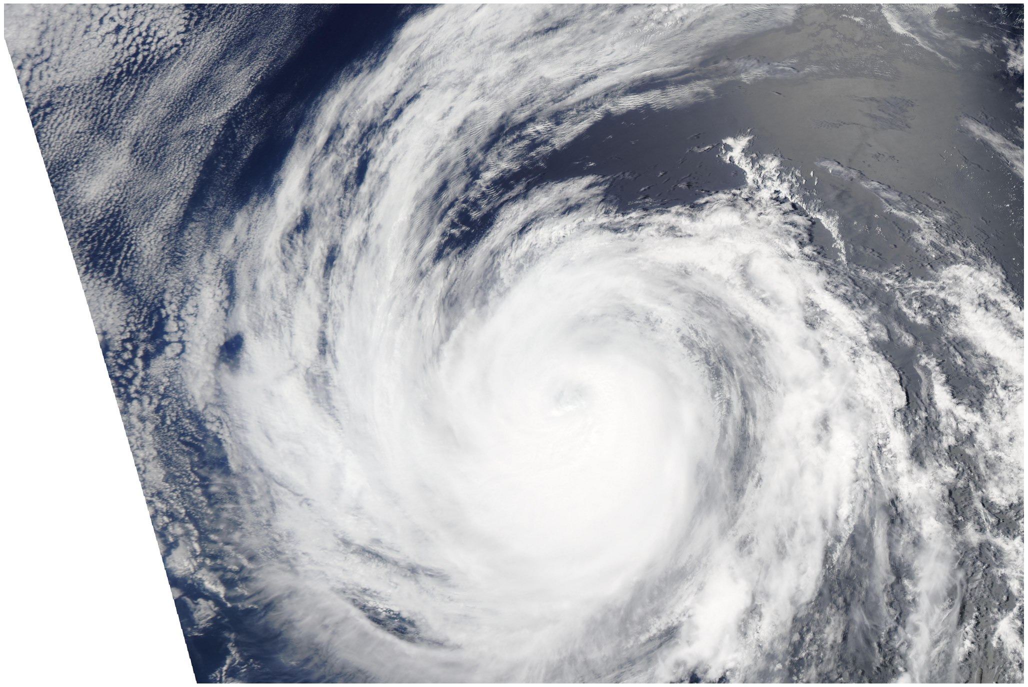
3- TROPICAL STORM

- sustained wind speed > 39 mph [63 km/h]

- storm begins to take on its characteristic appearance as a rotating spiral with bands of clouds circulating around the point of lowest surface pressure at its center.

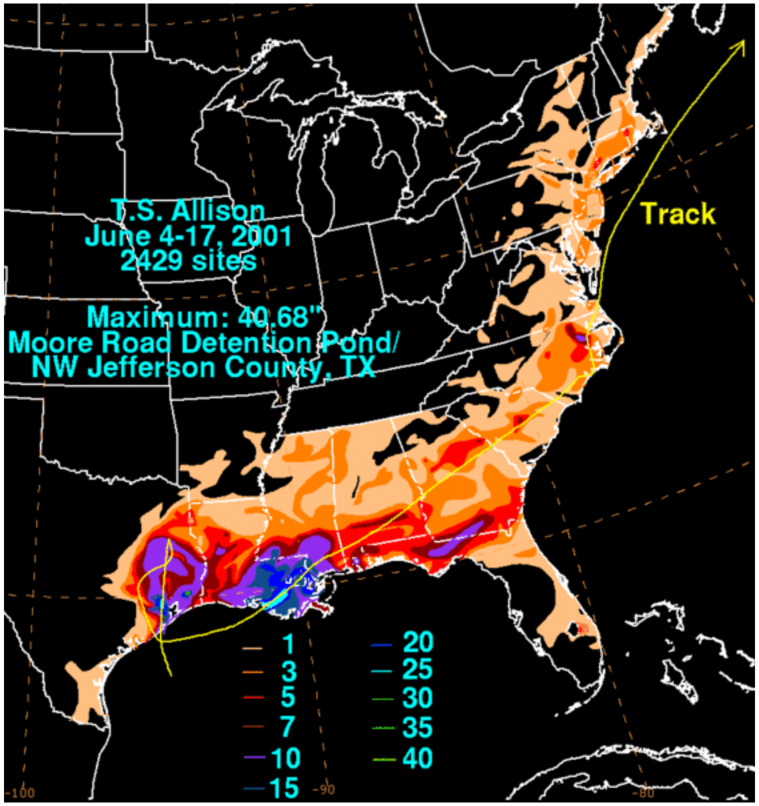
TS Fabio, July 2012

GOES-13 visible



- Organized spiral bands

TROPICAL STORMS ARE DANGEROUS: TS ALISON (2001)



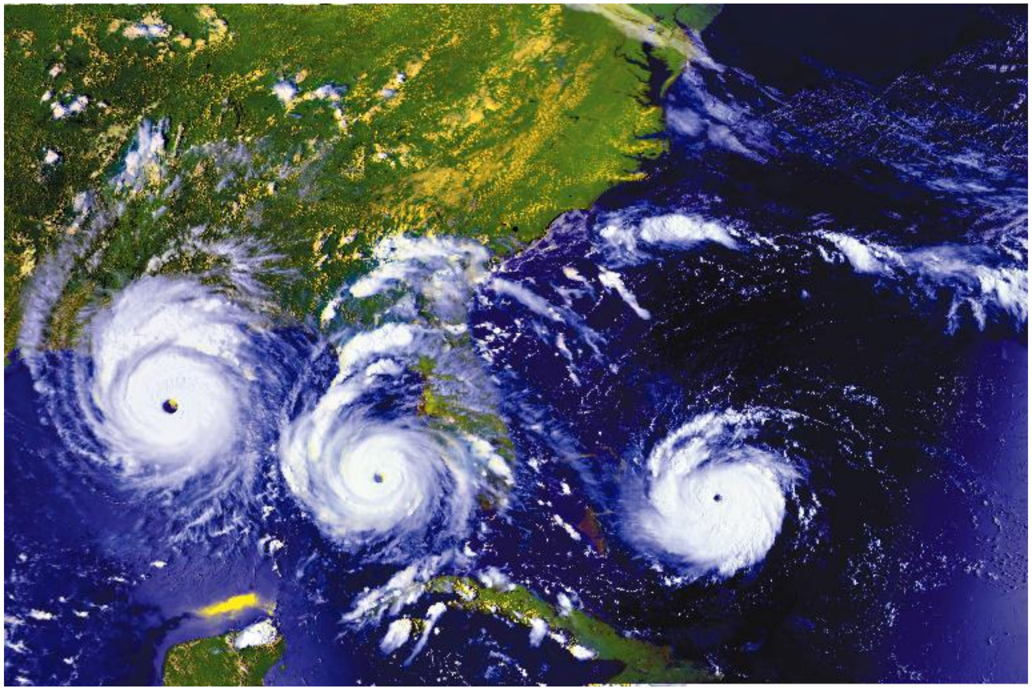
Tropical storms can create considerable rainfall and flooding

Houston, TX, before and after TS Alison (2001)

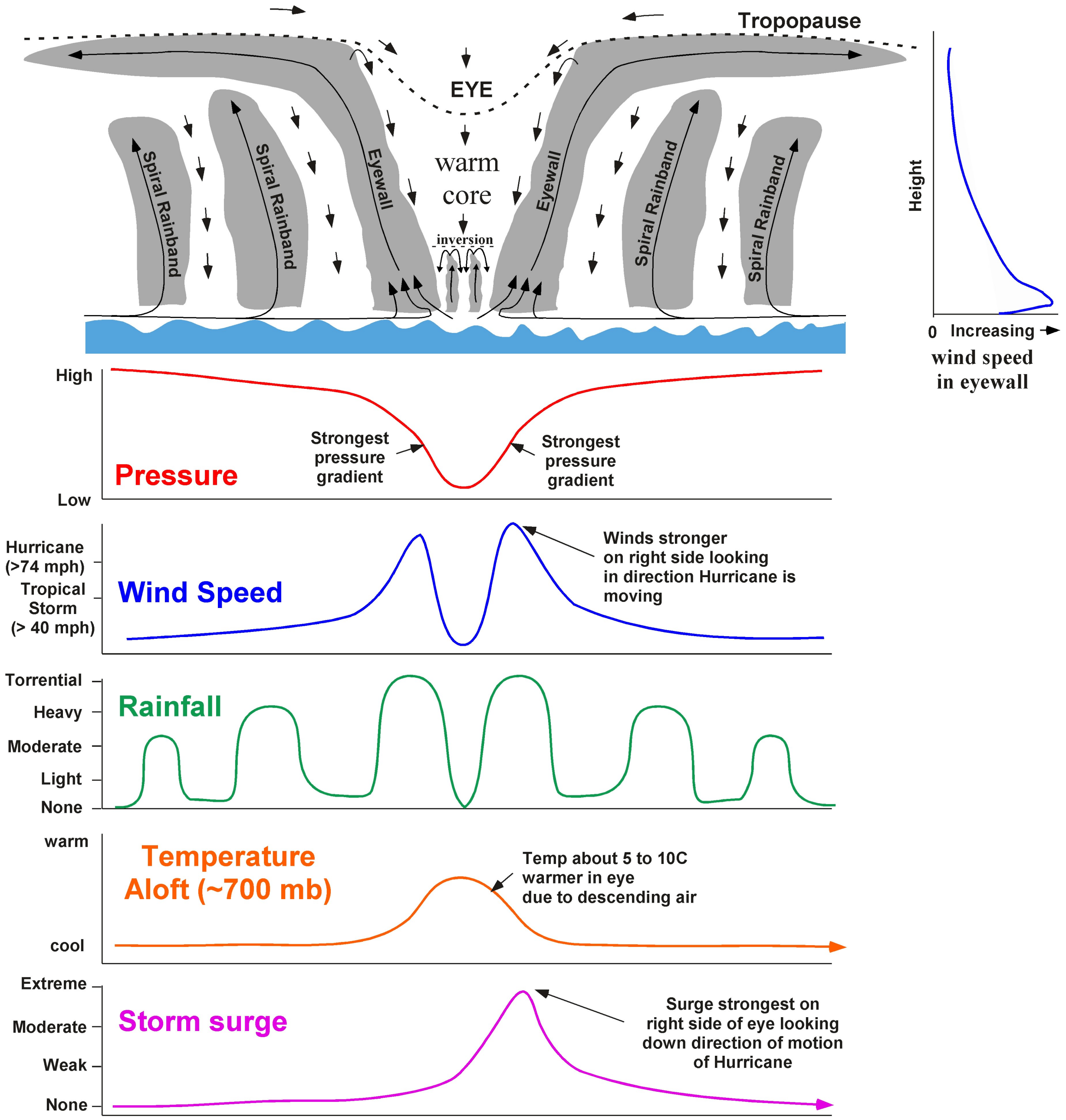
4- TROPICAL CYCLONES (HURRICANES, TYPHOONS)

- Sustained wind speed > 39 mph [63 km/h]
- No fronts
- Warm-core system (warmer than the environment)
- The storm develops an ***eye*** at the center of the circulating spirals where there is very little wind, few clouds, and extremely low atmospheric pressure.
- Surrounding the eye is an area called the ***eyewall*** that circulates around the eye and contains the highest clouds. The eyewall contains the strongest winds, heaviest precipitation, and most intense thunderstorms of any part of the hurricane.

Hurricane Andrew (1992) - sequence



TROPICAL CYCLONE STRUCTURE



Strongest pressure gradient

Strongest pressure gradient

Winds stronger on right side looking in direction Hurricane is moving

Temp about 5 to 10C warmer in eye due to descending air

Surge strongest on right side of eye looking down direction of motion of Hurricane

TROPICAL CYCLONE SIZE

- A typical mature hurricane is about 300 miles (480 km) across

- One of the *largest* tropical cyclone ever recorded was Typhoon Tip (1979) that struck Japan. Tip's diameter was 1,350 miles, with maximum sustained wind speed of 190 mph (305 km/h)

- One of the *smallest* tropical cyclone was Tracy (1974) that struck Darwin, Australia. Tracy's diameter was only 30 miles, with maximum sustained wind speed of 110 mph.

HURRICANES AS NATURAL HAZARDS:

HIGH WINDS, RAINFALL, FLOODS, TORNADOES, RIP CURRENTS

Hurricane Andrew was one of the most destructive hurricanes in U.S. history, tearing into South Florida in August, 1992, with sustained winds of 165 mph, and wind gusts as high as 177 mph. The hurricane destroyed over 25,000 homes and damaged over 100,000 others - primarily through wind-caused damage. Winds were strong enough to shoot this piece of plywood through a tree trunk in Homestead, FL. Image credit: NOAA.

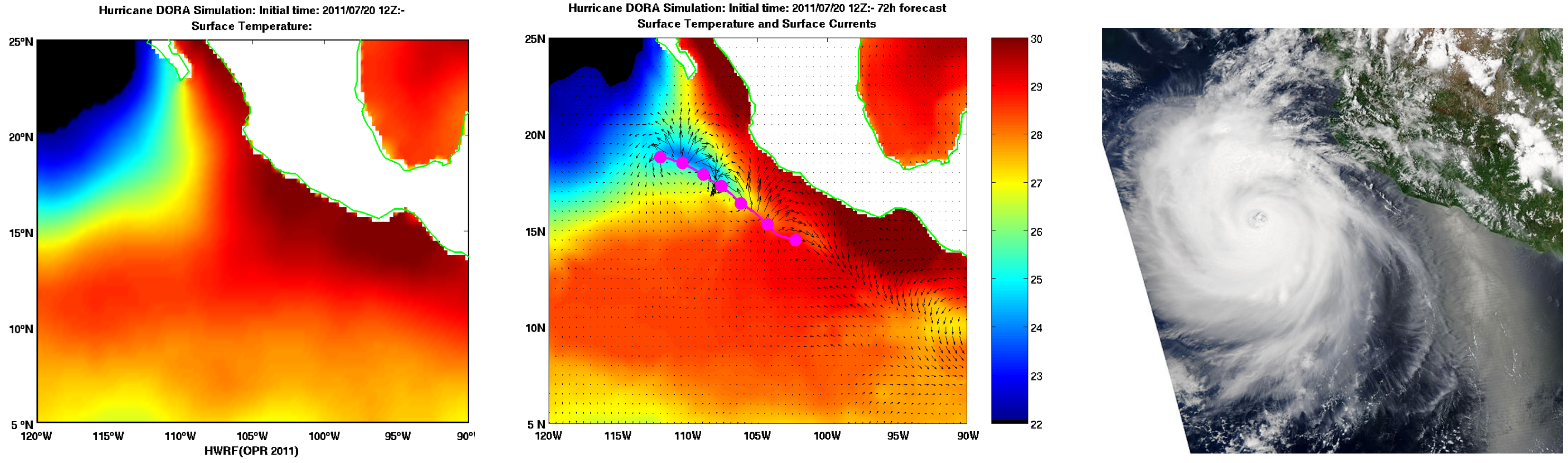
CHALLENGES OF TC DATA ASSIMILATION (AND FORECASTING)

- Coupled models:
  - atmosphere and ocean
  - environment conditions surrounding TC
- Physical processes:
  - complex cloud microphysics to adequately describe cloud/rain processes
  - interaction between atmosphere and ocean (SST)
- High spatial resolution:
  - small-scale, at least 1-3 km resolution

COUPLED ATMOSPHERE-OCEAN MODELS

- NOAA Hurricane WRF (HWRF), NCAR Advanced hurricane WRF (AWH)
- Ocean is needed to account for circulation and currents, heat source, SST
- Atmospheric component required for cloud/rain processes, environment surrounding TC

Impact of ocean-atmosphere coupling on 72-hour forecast: hurricane Dora (2011)



Current operational

EMC Pre-release testing

GOES-13

Coupling represents SST better and eventually helps improve hurricane intensity prediction

(From Bernardet et al. 2012, WRF user workshop)

PHYSICAL PROCESSES

Microphysics

- Hurricane intensity is sensitive to the ice

- Melting and evaporation help strengthen downdrafts and reduce intensity

- Ice processes have a role in the horizontal distribution of rain bands

- The weight of liquid water within the eyewall updrafts of the storm may act to limit the eyewall updraft magnitudes

- Subtle changes in microphysical processes result in a very wide range of storm intensities. This highlights the importance of microphysics and the dynamics of the inner eye region in hurricane intensity.

HIGH SPATIAL RESOLUTION

- NOAA HWRF:
  - 27:9:3 km
  - need to resolve rain bands, cloud/rain processes
  - optimal resolution could be 1 km or even less
  - computational overhead limitations
  - vortex initialization at 3 km
  - related requirement for shorter time steps

TC INNER CORE OBSERVATIONS

Airborne inner-core observations

- flight level: wind, T, q, surface wind
- dropwind sondes: wind, T, q, pressure
- tail Doppler radar: radial winds

Ground based Doppler radars:

- radial wind, reflectivity
- restricted coverage

Satellite radiances:

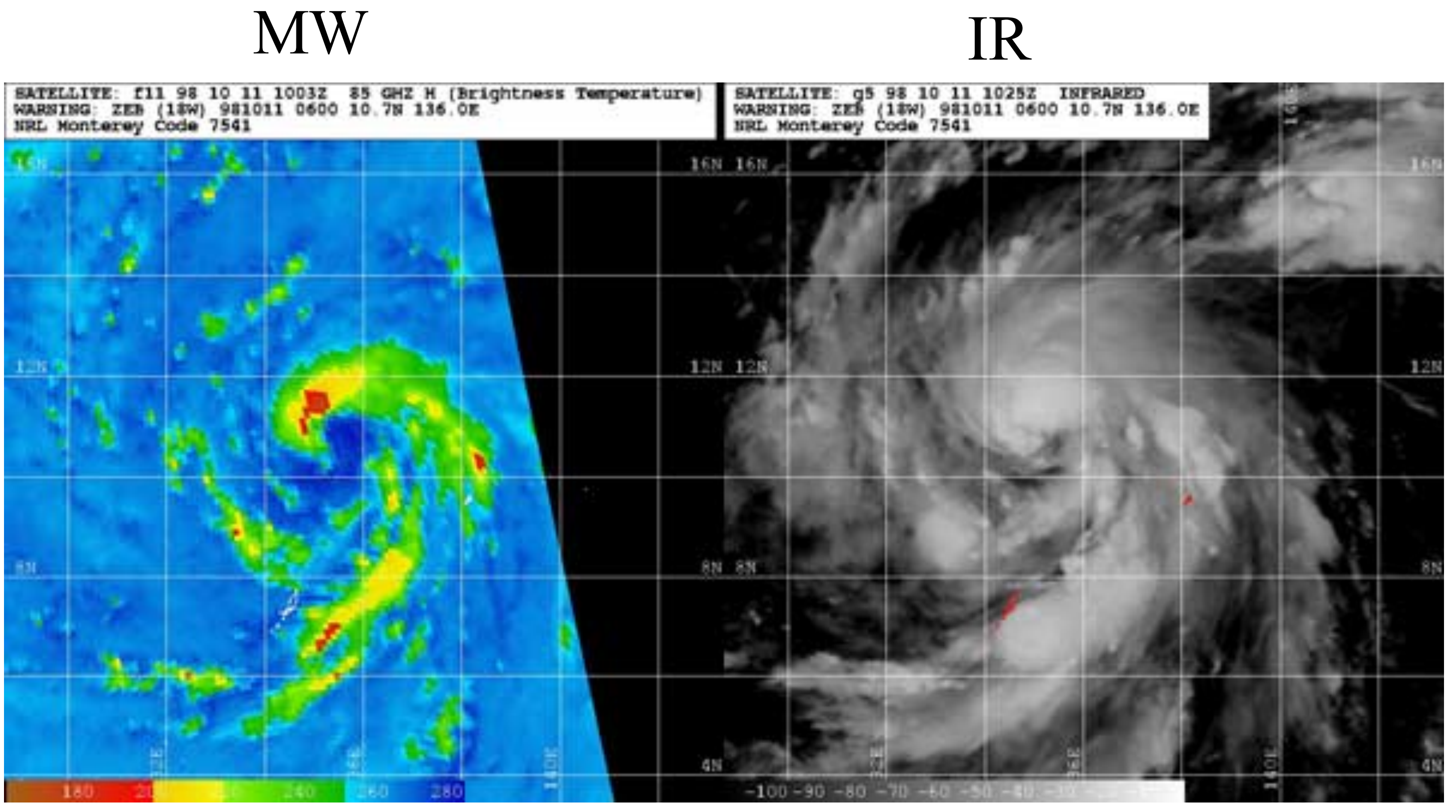
- related to microphysics and model dynamics
- microwave, infrared, water vapor
- can cover any part of the globe

New observation types:

- Lightning (e.g., WWLLN, GOES-R GLM)

Insufficient availability and use of inner-core observations

SATELLITE OBSERVATIONS OF CLOUDS


MW

IR

Two images of typhoon Zeb (1998) intensifying in the western Pacific. In the microwave image on the left, dark blue marks a developing eye at the center of circulation. This dark blue coloration suggests abundant low-level cloud water in the eye but no deep convection above. The greens and yellows in the spiral bands represent scattering signatures from precipitation-size ice particles above the freezing level. The infrared image on the right shows the cirrus clouds and cumulonimbus that covers most of the storm. It shows a portion of the eye. However, the northern part of the eye is covered by cirrus clouds. Navy Research Lab Monterey, Marine Meteorology Division.

Lightning observations

- World-Wide Lightning Location Network (WWLLN) - surface
- GOES-R Global Lightning Mapper (GLM) - satellite

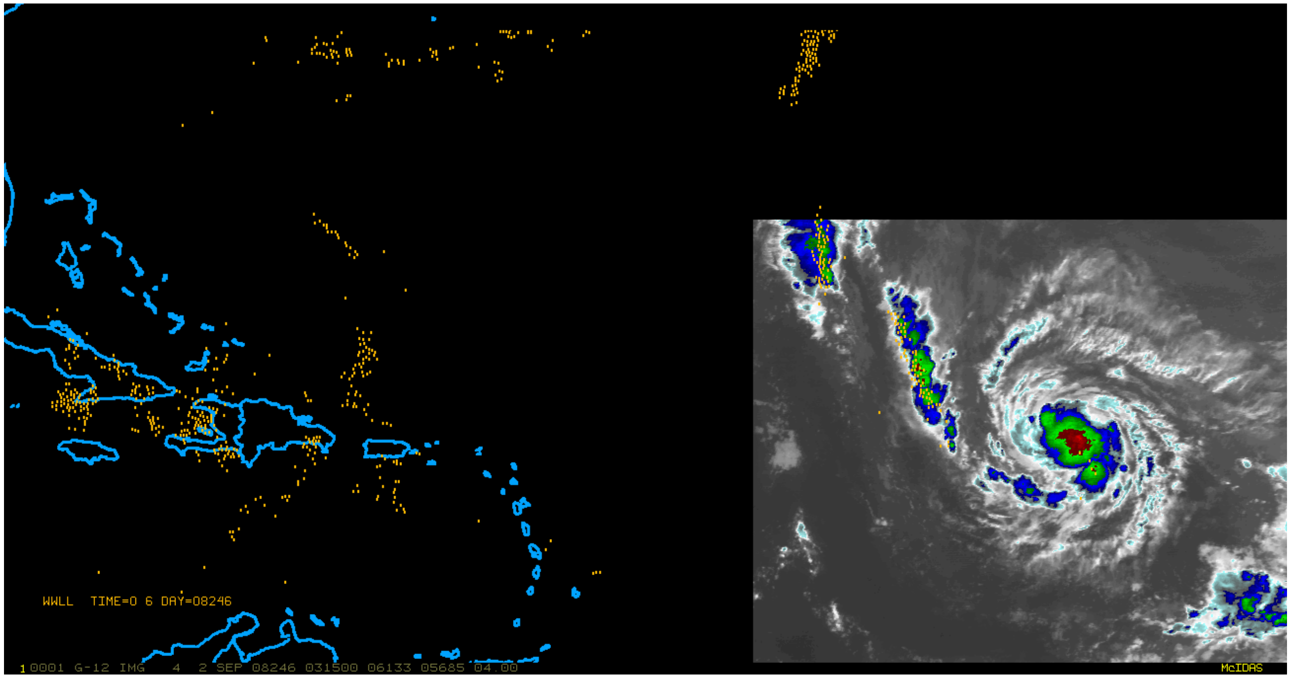
Lightning observation operator:

1- explicit relationship between model/cloud variables and electric charge
  - Physically correct, but computationally expensive, need more research

2- implicit link through empirical regressions
  - Vertical updrafts (max vertical velocity)
  - Cloud properties (cloud ice)

6-hour lightning obs

Hurricane Ike (2008)



CURRENT STATUS OF ALL-SKY RADIANCE DATA ASSIMILATION: IMPLICATIONS FOR TC DATA ASSIMILATION

➢ Most operational centers assimilate only clear-sky radiances

- The wealth of cloud-related measurements is discarded

- However, most high impact weather events are characterized by the presence of clouds and precipitation

- The consequence is a sub-optimal use of satellite observations

➢ Limited research and operational efforts

- All-sky microwave data assimilation operational at ECMWF since 2009 (Bauer et al. 2010; Geer et al. 2010 - SSM/I, TMI. AMSR-E)

- Pre-operational testing at NCEP, also pursued at other operational weather centers

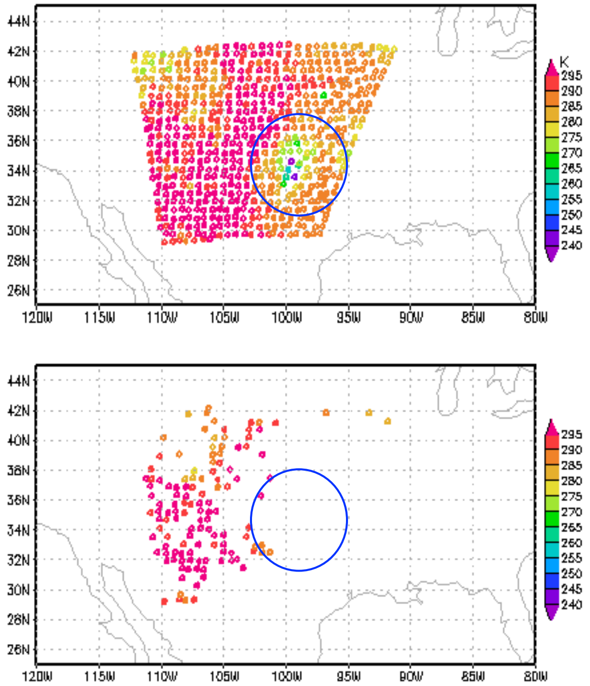
➢ Potential benefit of all-sky radiance assimilation is generally acknowledged, but it is difficult to extract the maximum information from these observations

- modeling of clouds (e.g., microphysics)

- data assimilation methodology

- computing resources, high resolution

Impact of cloud clearing (radiance assimilation)



Re-development of the TS Erin (2007): Distribution of AMSU-B radiance data in the NCEP operational data stream: (a) all observations, (b) accepted observations after cloud clearing. Data are collected during the period 15-18Z, August 18, 2007. Note that almost all observations in the area of the storm got rejected by cloud clearing. (from Zupanski et al. 2011, *J. Hydrometeorology*)

Need assimilation of all-sky radiances to improve the observation information value

CHALLENGES OF ALL-SKY RADIANCE DATA ASSIMILATION FOR TROPICAL CYCLONES

- Data assimilation: Methodological and computational issues
- Microphysical control variables
  - allow cloud observations to impact hydrometeors
- Forecast error covariance
  - needs to be state-dependent, and also to represent dynamical and microphysical correlations
- Nonlinearity and non-differentiability of Radiative Transfer (RT) operator
- Correlated observation errors
- Non-Gaussian errors
- Quantifying all-sky radiance information:
  - How to provide a maximum utility of these data, and how to measure success?
- Other relevant issues: verification, code maintenance, radiance bias correction, …
- **Everything is connected, need to take into account all components**

OVERVIEW OF TROPICAL CYCLONES

- No fronts
- Warm-core
- Enormous latent heat release due to condensation of moist air at higher altitudes
- Total energy through cloud/rain formation

TC latent heat energy

An average hurricane produces 1.5 cm/day (0.6 inches/day) of rain inside a circle of radius 665 km (Gray 1981). Converting this to a volume of rain gives 2.1 x 10^{16} cm3/day. Using the latent heat of condensation, this amount of rain produced gives

5.2 x 10^{19} Joules/day

This is equivalent to four times the US yearly consumption/production of electric energy.

TC wind power energy

For a mature hurricane, the amount of kinetic energy generated is equal to that being dissipated due to friction. The dissipation rate per unit area is air density times the drag coefficient times the wind speed cubed (Emanuel 1999). Assuming an average wind speed for the inner core of the hurricane at 40 m/s (90 mph) and winds on a scale of radius 60 km, one gets a wind dissipation rate (wind generation rate) of

1.3 x 10^{17} Joules/day

This is equivalent to one year US electricity consumption/production.

The latent heat to wind energy ratio 400:1 calculated above define the energy required for maintaining the hurricane.

Yearly US electric energy consumption/production (as of 2009): ~1.4x10^{19} J

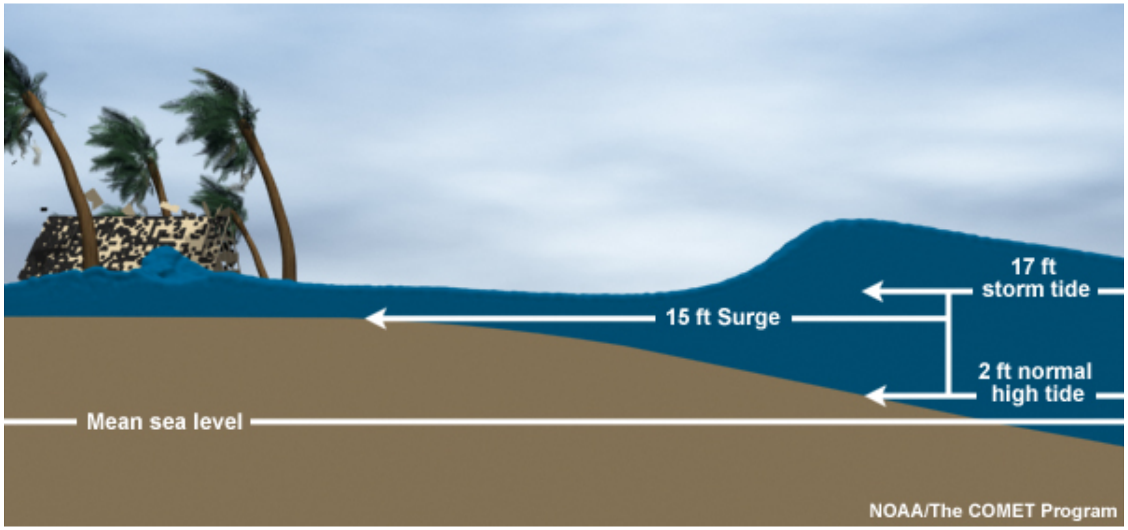
Average hurricane energy from producing rain: ~5.0x10^{19} J

Emanuel, K. A., (1999): "The power of a hurricane: An example of reckless driving on the information superhighway" Weather, 54, 107-108

Gray, W.M. (1981): "Recent advances in tropical cyclone research from rawindsonde composite analysis" World Programme on Research in Tropical Meteorology, World Meteorological Organization, Geneva, 407 pp.

HURRICANES AS NATURAL HAZARDS: STORM SURGES/TIDES

- Low-pressure driven surge (5%)
- Wind driven surge (95%)
- Water is lifted at the center, creating a tsunami-like effect



Damage from Hurricane Camille (1969) along the Mississippi Gulf Coast. Image credit: NOAA.

The storm surge of Hurricane Ivan (2004) pushed sand off of the shore of Pensacola Beach and into this Florida house. Image credit: FEMA/Mark Wolfe.

TROPICAL CYCLONE INNER CORE

Light-shading: cloud and precipitation

Dark regions: convective eyewall and spiral rainbands

EIL: : Eye inversion layer (slash-hatched areas)

OEA: occluded eye air with low q_e (cross-hatched regions)

MTD: moist downdrafts between the convective bands

SR: Spiral rainband updrafts

RO: Return outflow

SU: Sloping updraft of eyewall

MI: Main inflow

MO: Main outflow

RI: Return inflow

DF: Divergent flow

VC: Forced vertical circulation

LX: Lateral mixing

GO: Gravity wave oscillations

MD: Mean decent in eye

Dashed line: Freezing level