Hurricane Forecast: Basics and Challenges

Ping Zhu
Department of Earth and Environment
International Hurricane Research Center
Florida International University

1. Where does a hurricane come from?

2. How can a hurricane maintain its strength?

3. What determines the movement of a hurricane?

4. Why sometimes we cannot accurately predict the track of a hurricane?

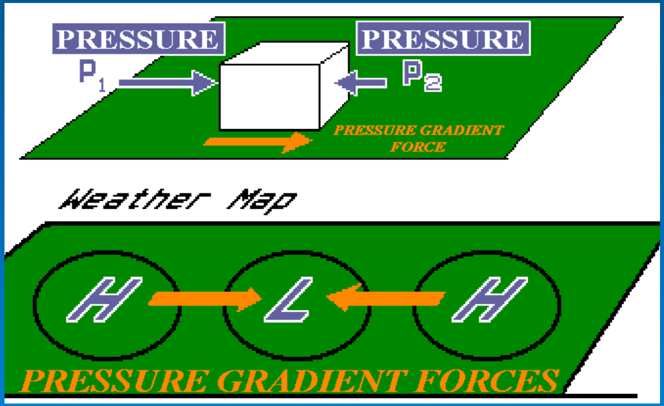
5. Why it is difficult to provide accurate hurricane intensity forecast?

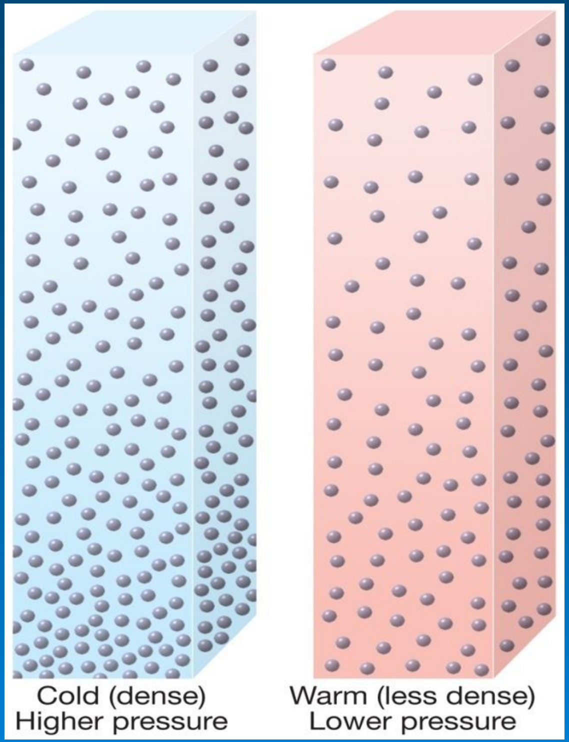
6. How can we improve hurricane forecast?

1. Where does a hurricane come from?

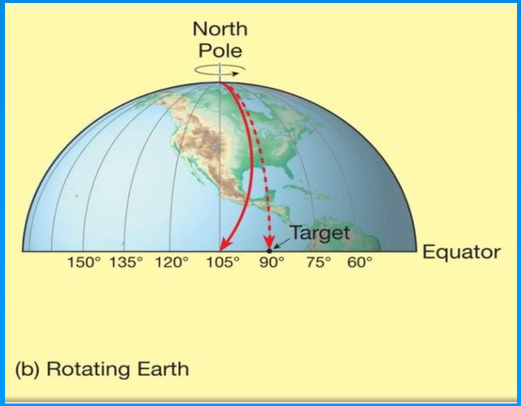
What fundamentally drives air motion?

Pressure gradient force

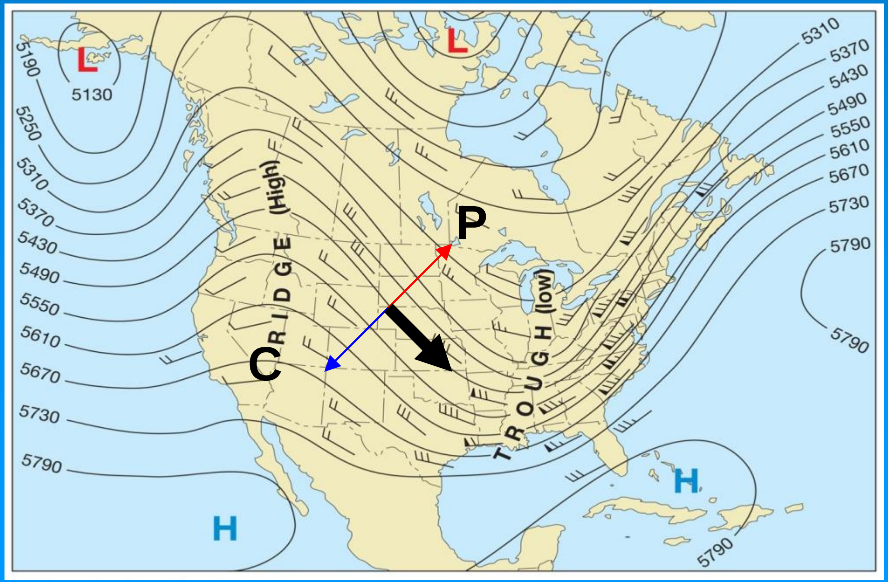


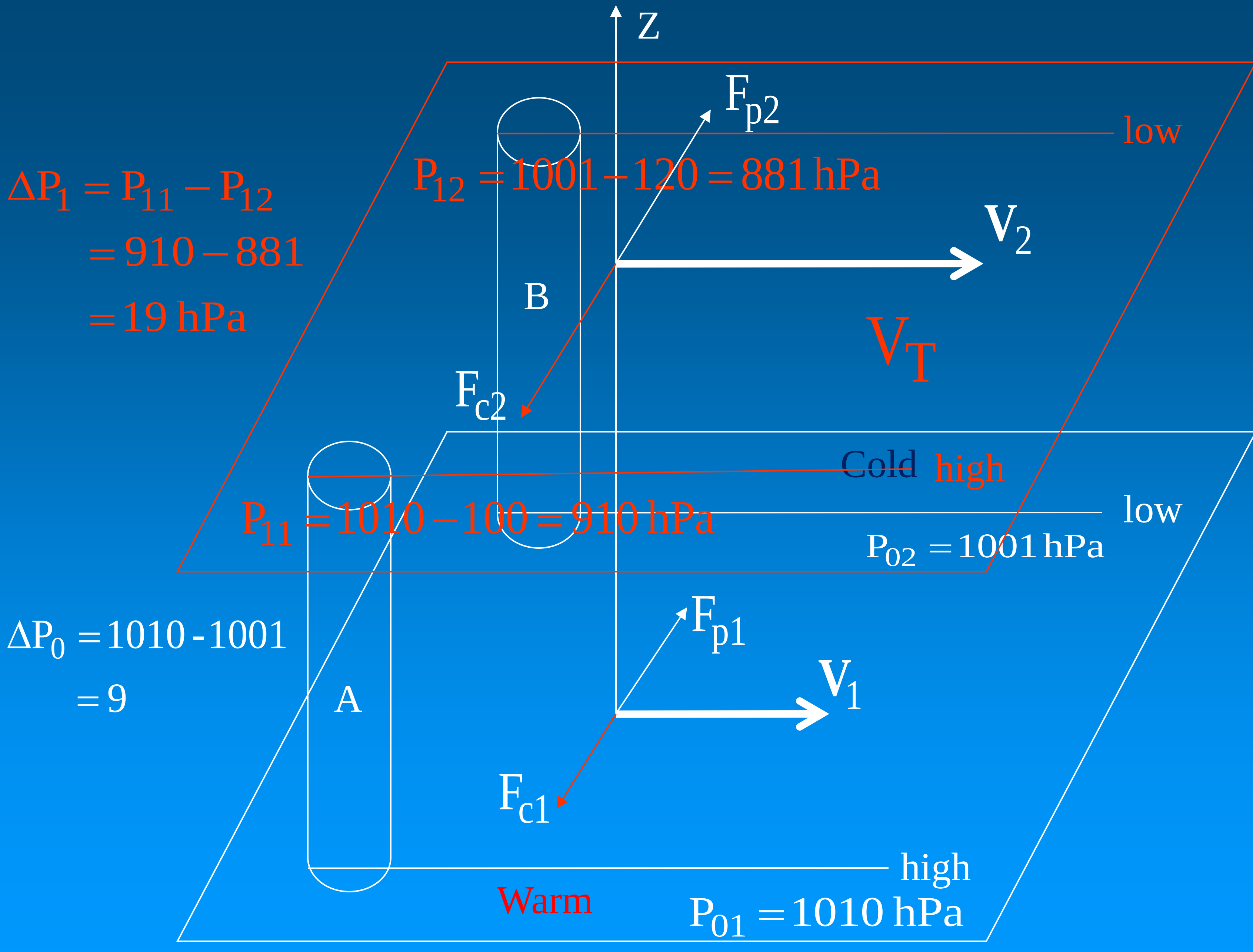


Coriolis force

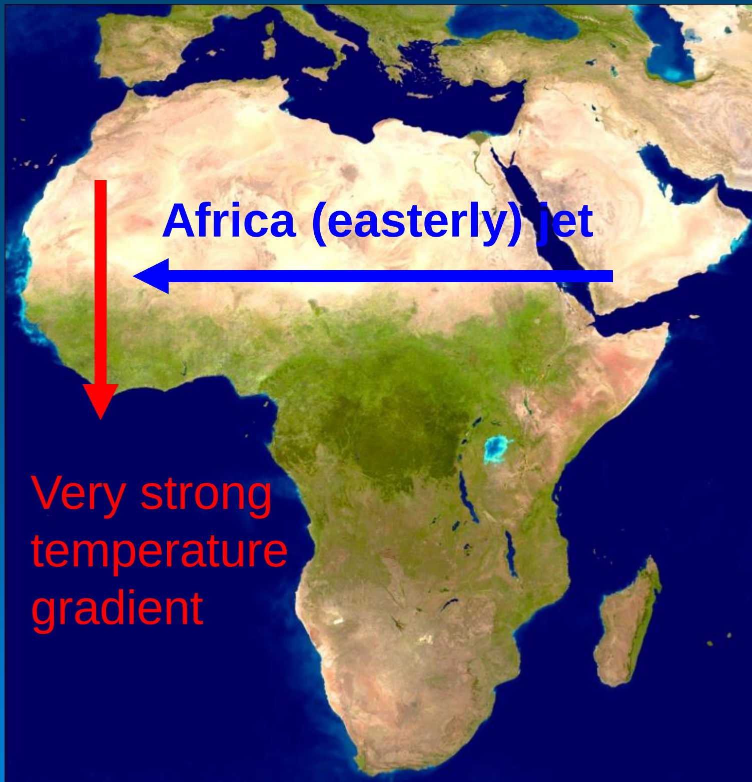


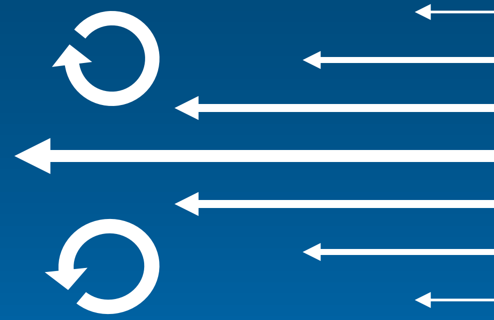
Newton Law





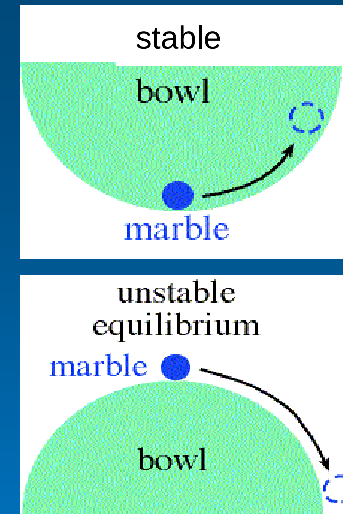
z
F_{p2}
low
$P_{12} = 1001 - 120 = 881\,hPa$
$\Delta P_1 = P_{11} - P_{12}$
$= 910 - 881$
$= 19\,hPa$
V_2
B
V_T
F_{c2}
Cold
high
$P_{11} = 1010 - 100 = 910\,hPa$
low
$P_{02} = 1001\,hPa$
$\Delta P_0 = 1010 - 1001$
$= 9$
F_{p1}
V_1
A
F_{c1}
high
Warm
$P_{01} = 1010\,hPa$



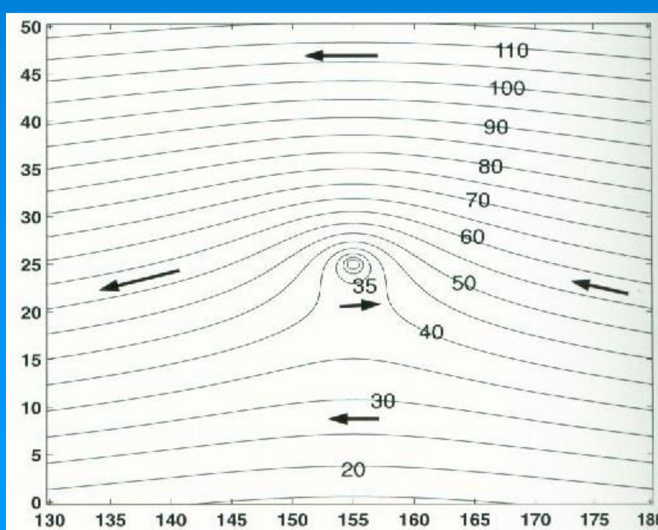


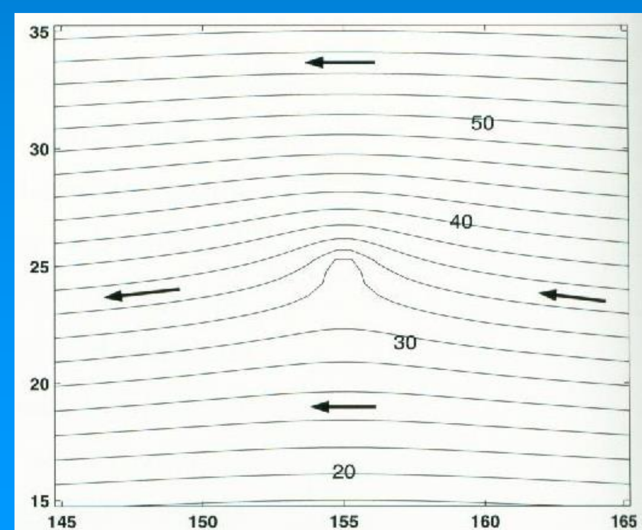
Dynamic Instability

Barotropic Instability



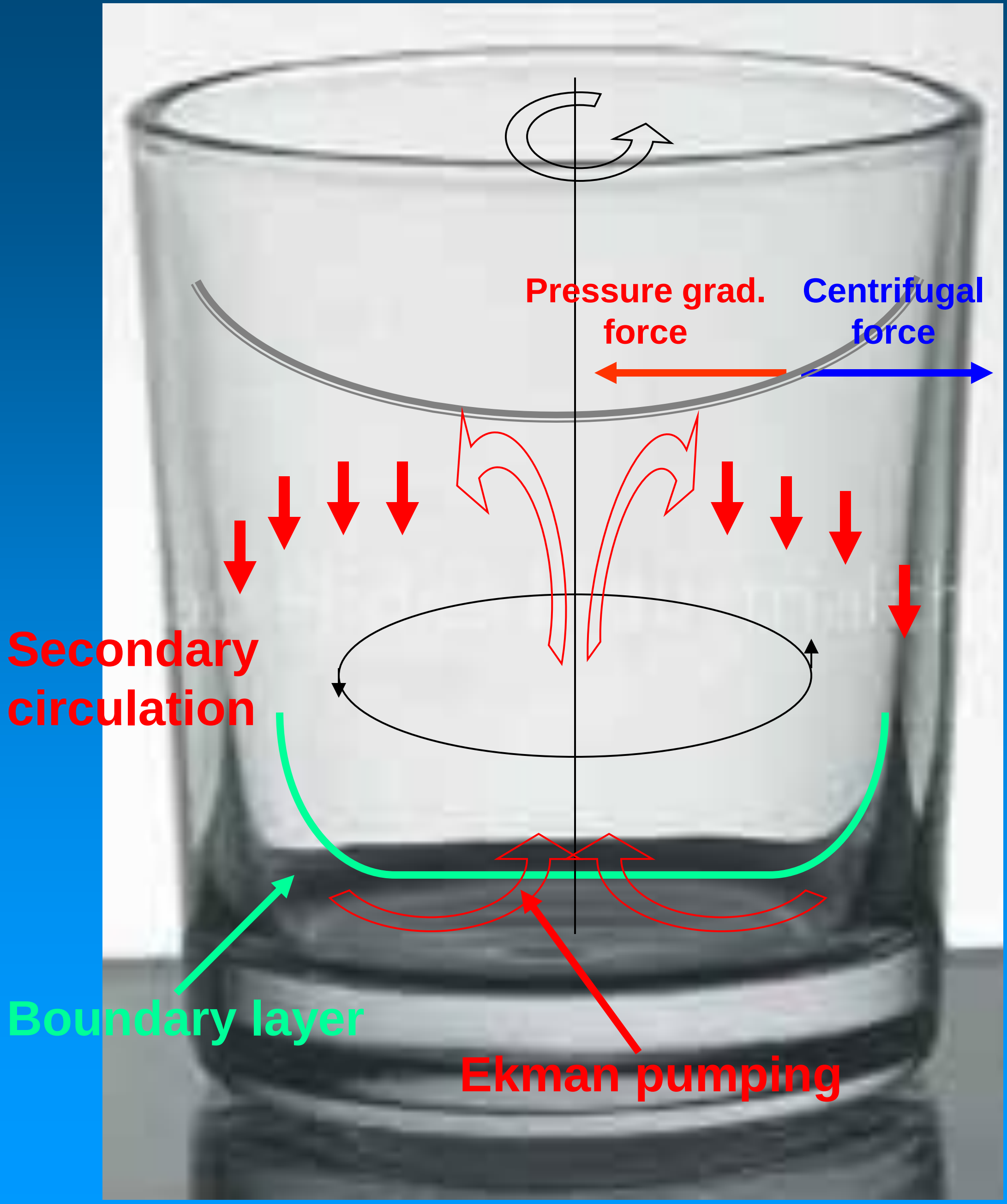
Static instability

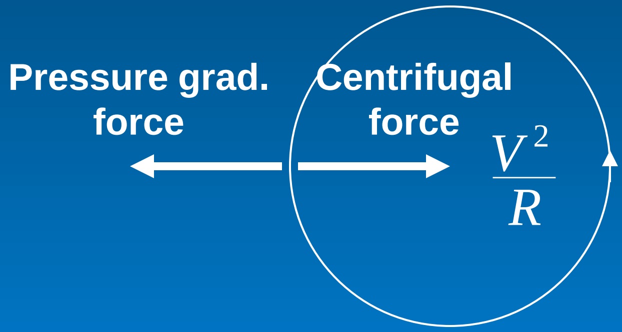


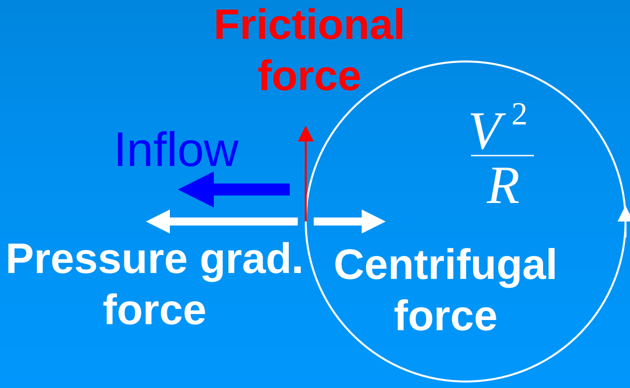


Easterly (tropical) wave

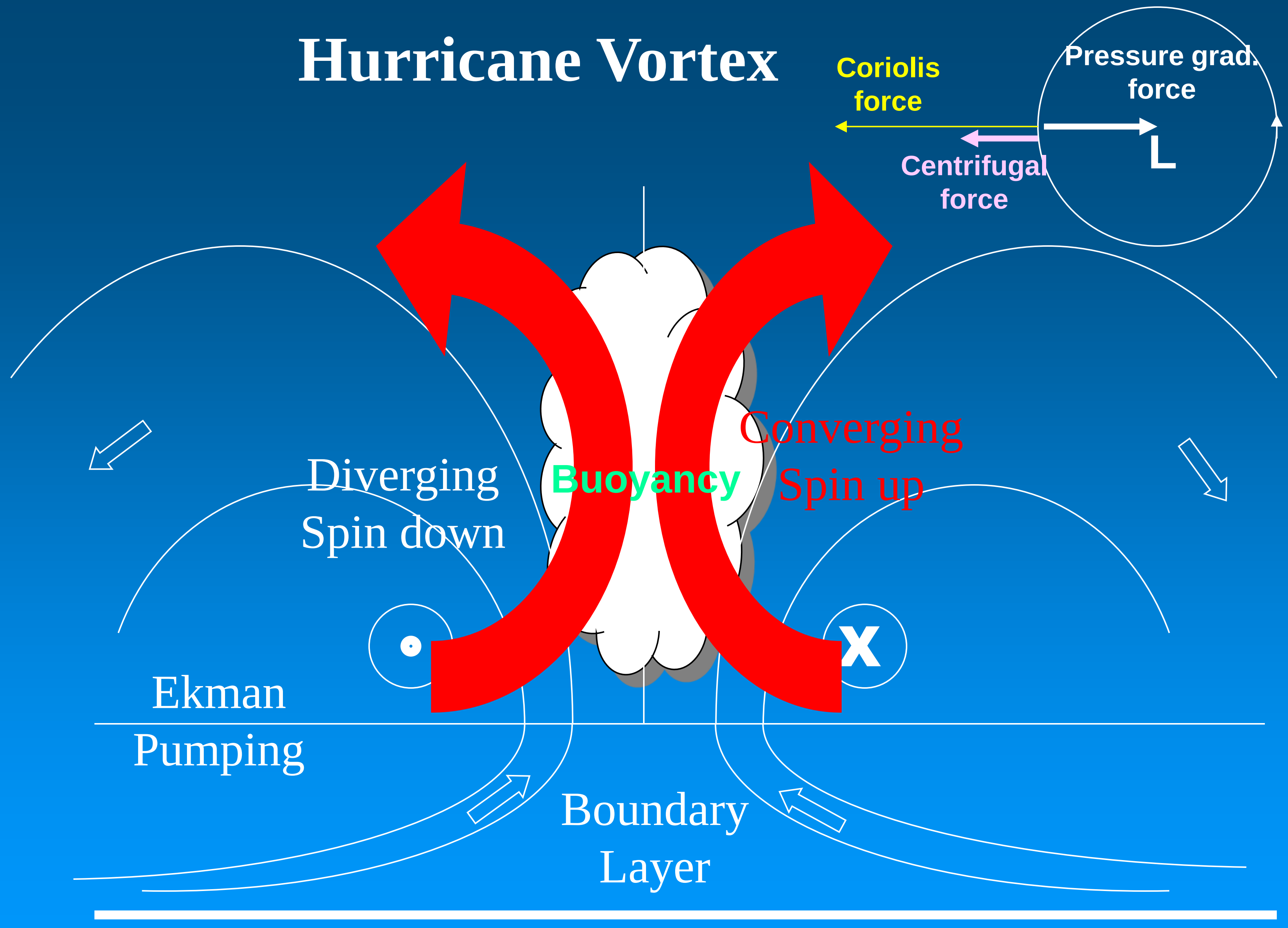
2. How can a hurricane maintain its strength?







Hurricane Vortex



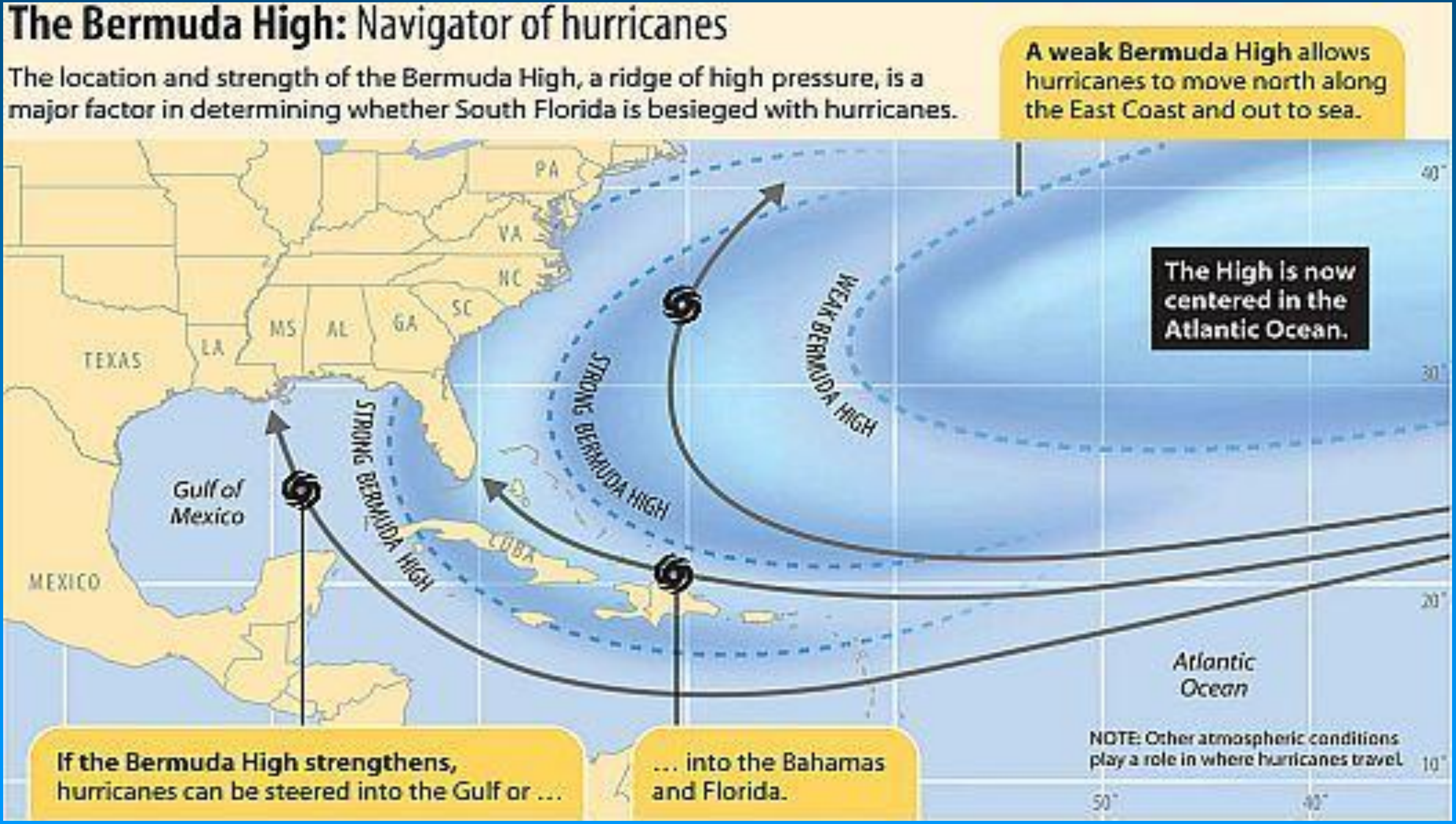
It is the convective clouds that generate spin up process to overcome the spin down process induced by the Ekman pumping

Where do energy and moisture come from to foster a large amount of convection in a hurricane?

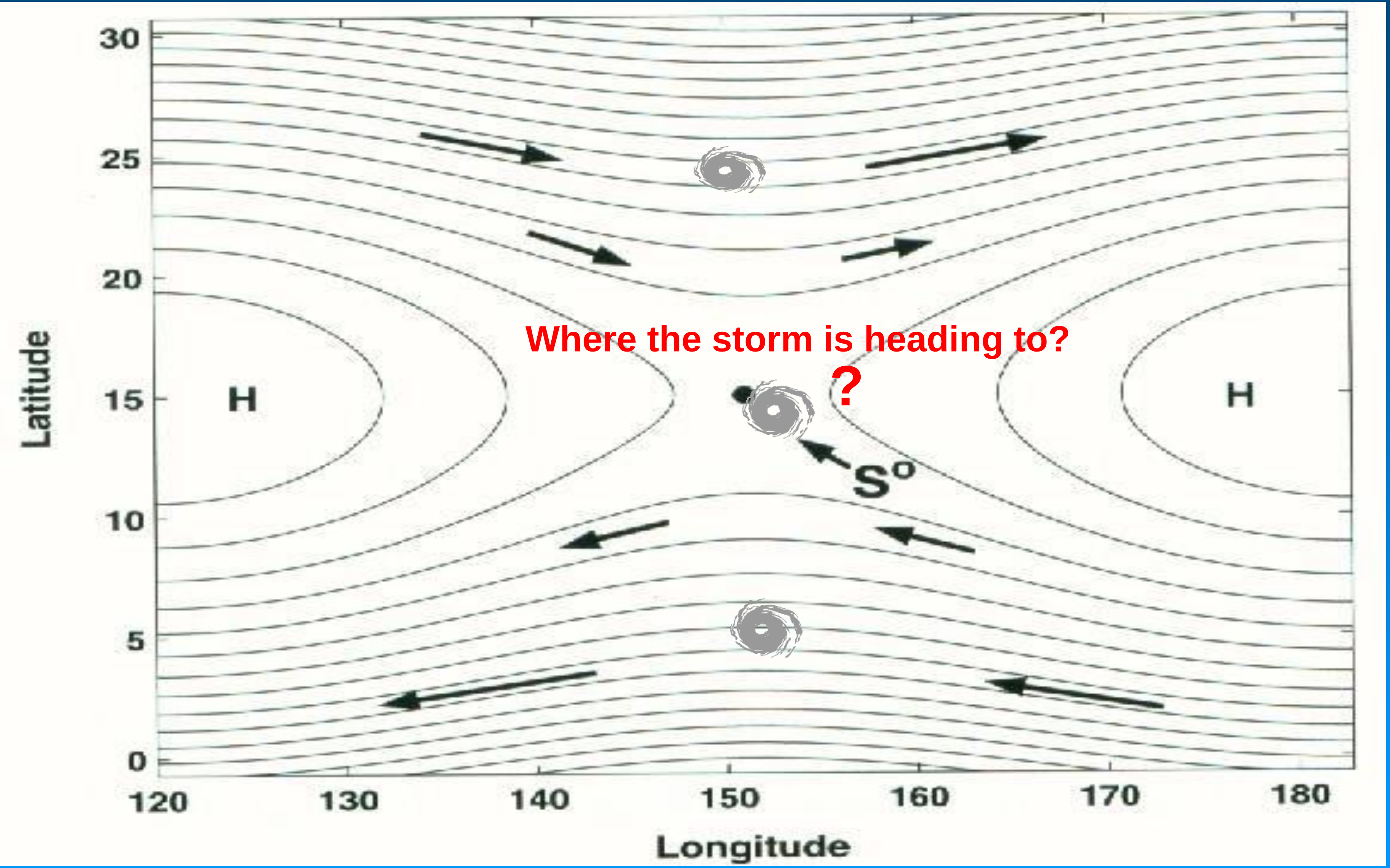
What process is responsible for bringing the energy and moisture taken from the ocean surface to the atmosphere?

Boundary layer turbulent transport process

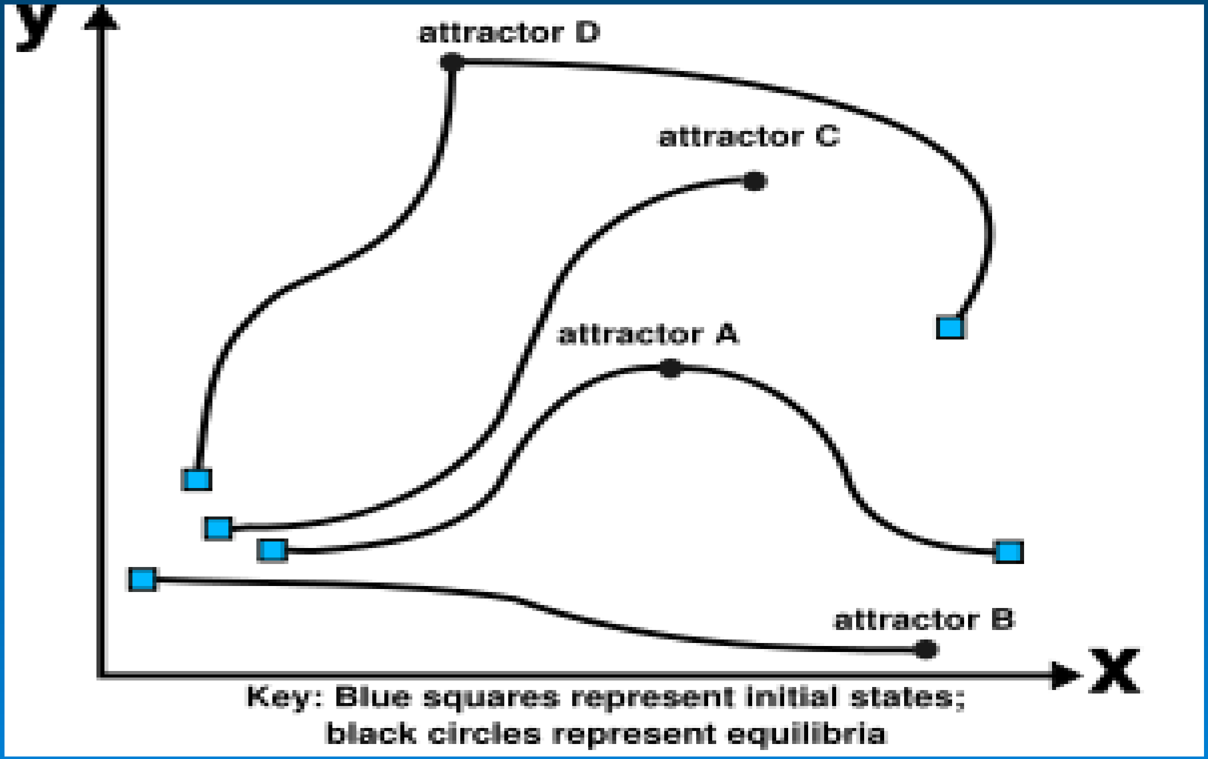
3. What determines the movement of a hurricane?

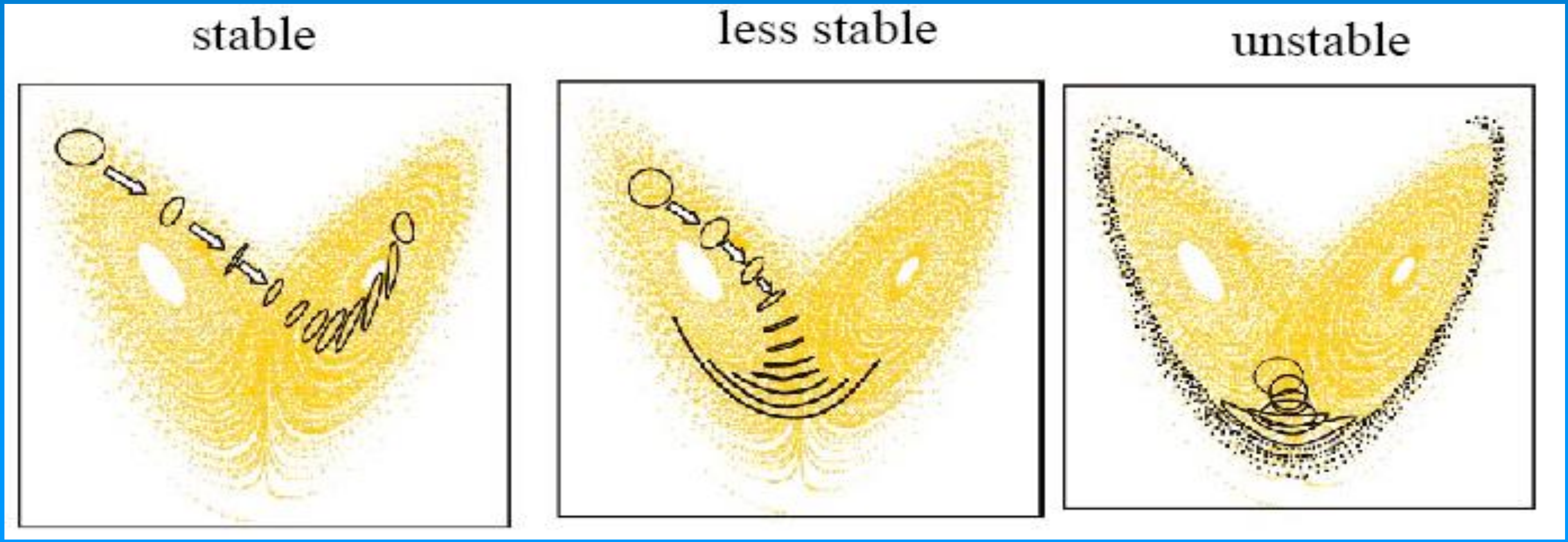


4. Why we cannot accurately predict the track of a hurricane sometimes?



Sensitive dependence on initial conditions, butterfly effect


y
attractor D
attractor C
attractor A
attractor B
x
Key: Blue squares represent initial states;
black circles represent equilibria


stable
less stable
unstable

Issues with numerical forecasts

Newton's law of motion governs hurricane movement.

$$\frac{dV}{dt} = F$$

$$\frac{V_{t+dt} - V_t}{\Delta t} = F_t$$

Initial value problem

- British scientist L. F. Richardson
  Weather Prediction by Numerical Process, 1922

- American meteorologist J. G. Charney
  Quasi-geostrophic model, 1950

What is the problem?

Pressure gradient force, $P \approx g$ Gravity force, g

$$\frac{dw}{dt} = P - g$$

Acoustic waves need to be removed from numerical model

- In the 50s, people are optimistic about numerical weather forecast due to:
  - Global observational network of the atmosphere has been established, which can provide more accurate initial fields.
  - Great success of numerical calculation in other fields, such as calculating the trajectories of planetary orbits and long-range missals.
- The accuracy of numerical forecast improved dramatically during the 60s, 70s, and 80s.
- But unfortunately, improvement slowed nearly to a standstill beginning around 90s.

Why?

5. Why it is difficult to provide accurate hurricane intensity forecast?

Chaotic nature of the atmosphere

Insufficient observations

Inherent deficiency of numerical models

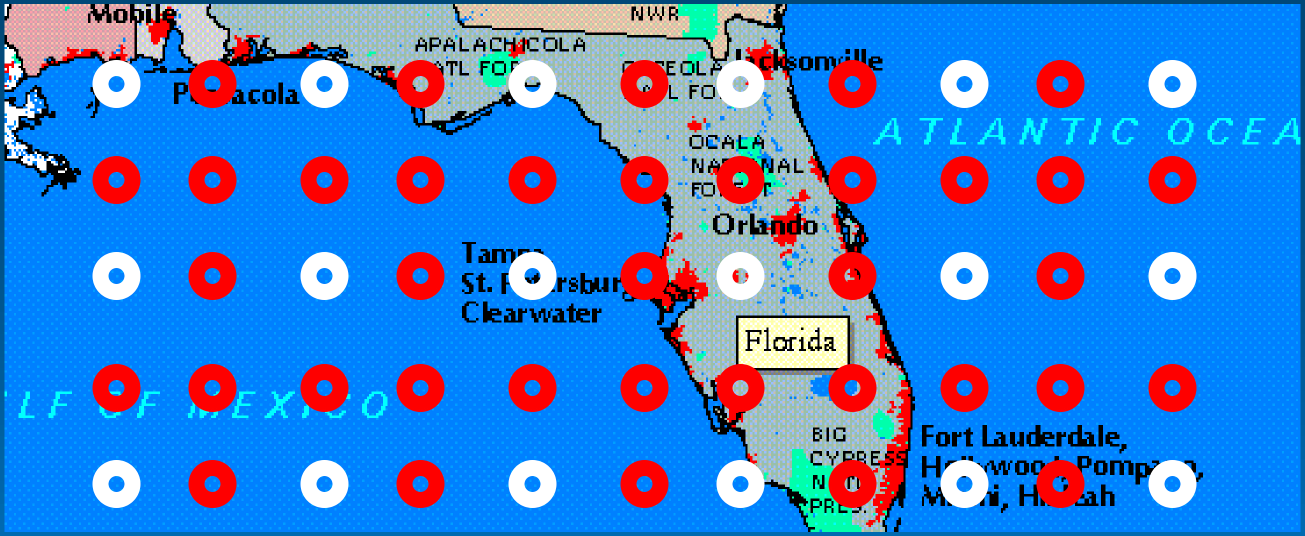
How to generate initial conditions for numerical simulations?

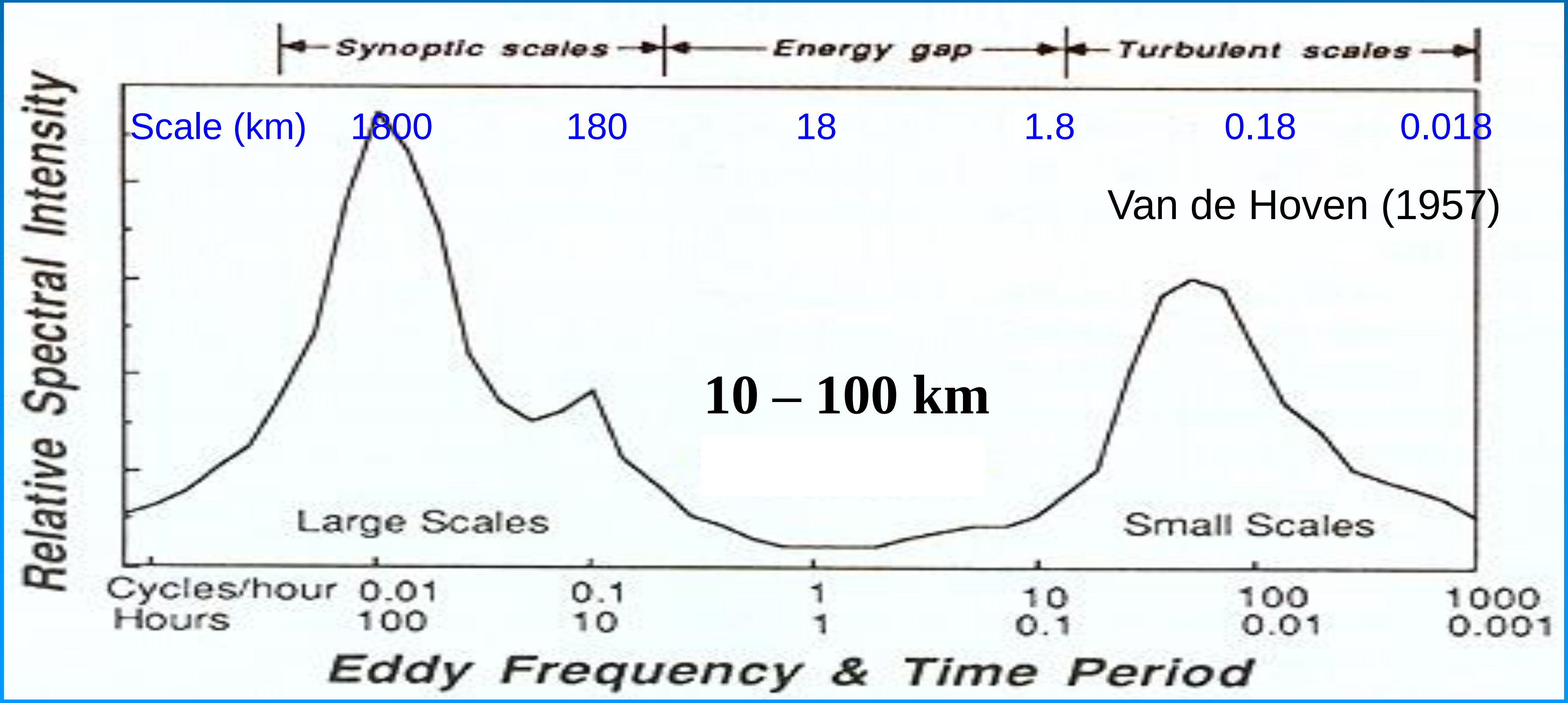
First guess of the current state of the atmosphere (previous 12-hour forecast of current conditions)

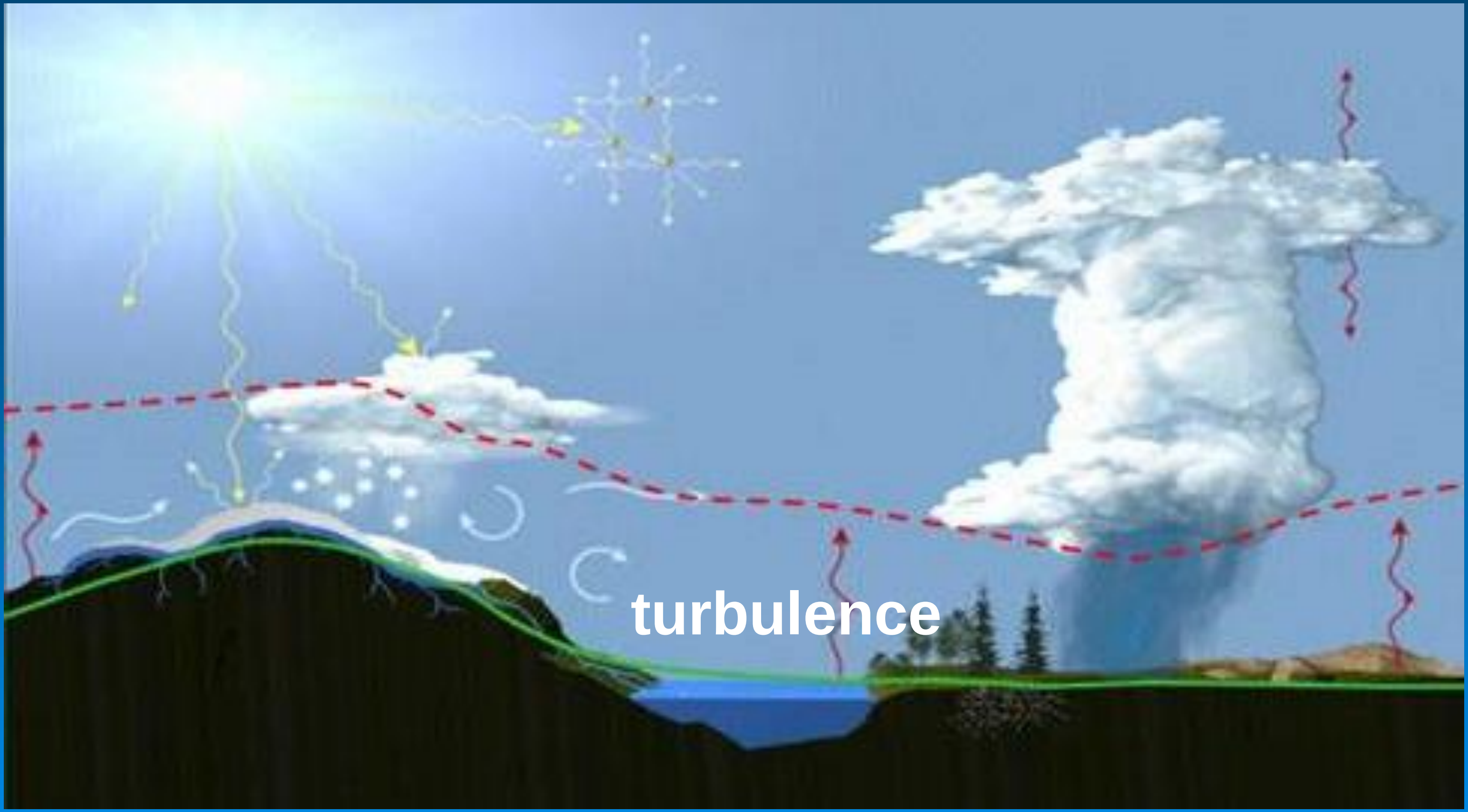
↓

Data assimilation (blending in OBS) → **Initial Condition**

Sub-grid scale (SGS) processes



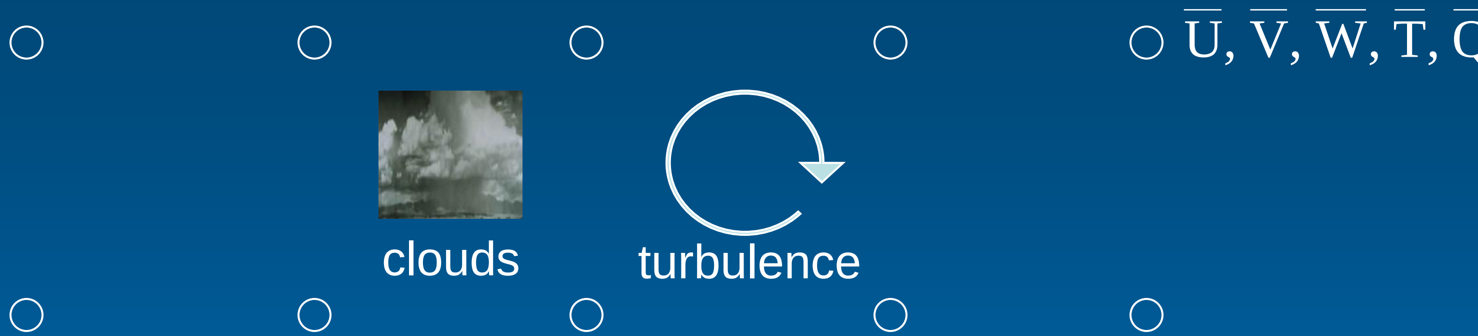




a. Boundary layer heat, moisture, and momentum transport by turbulence

b. Cloud convection and cloud microphysics

c. Radiation



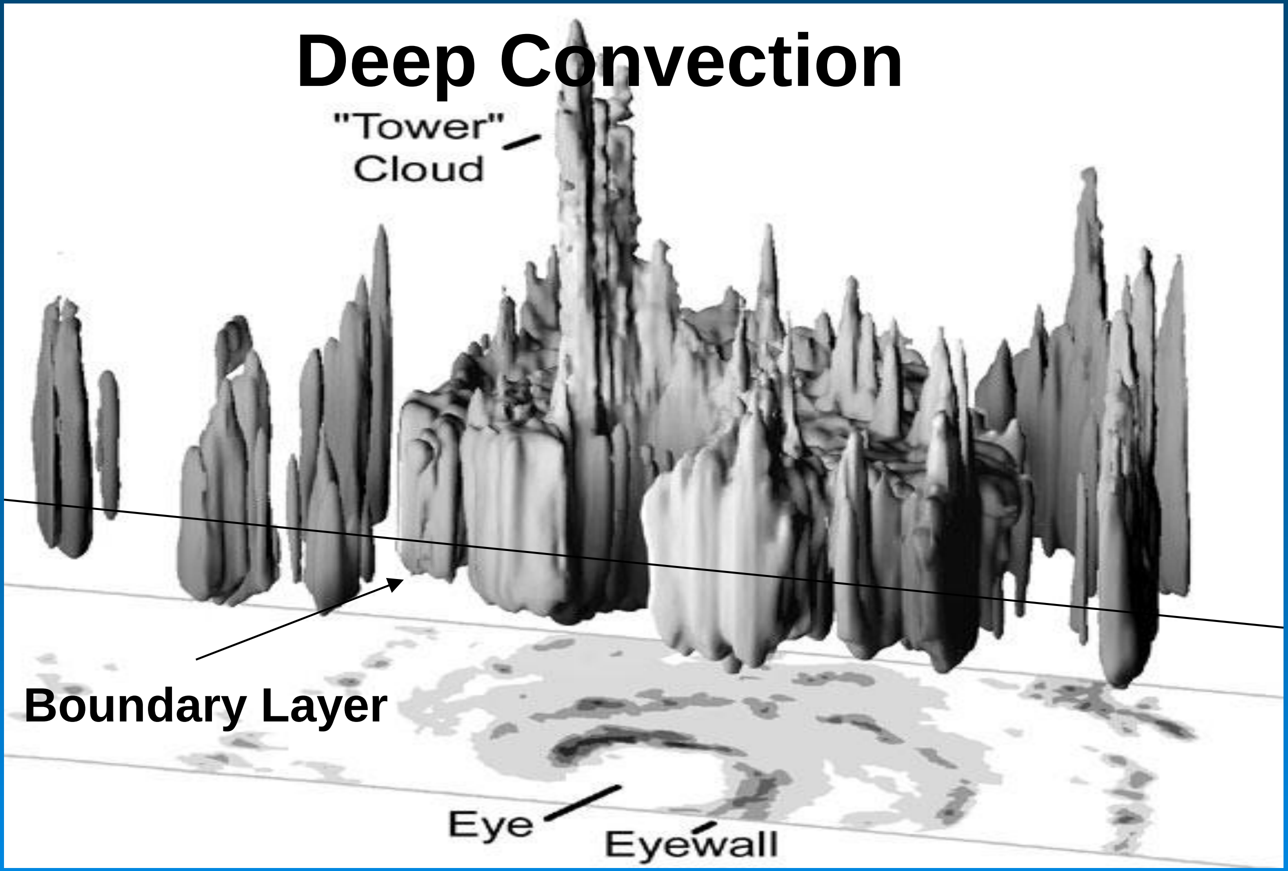
$$\textit{transport of heat, moisture, momentum}$$
$$= f(\overline{U}, \overline{V}, \overline{W}, \overline{T}, \overline{Q})$$

Parameterization

Hurricane Boundary Layer (HBL)

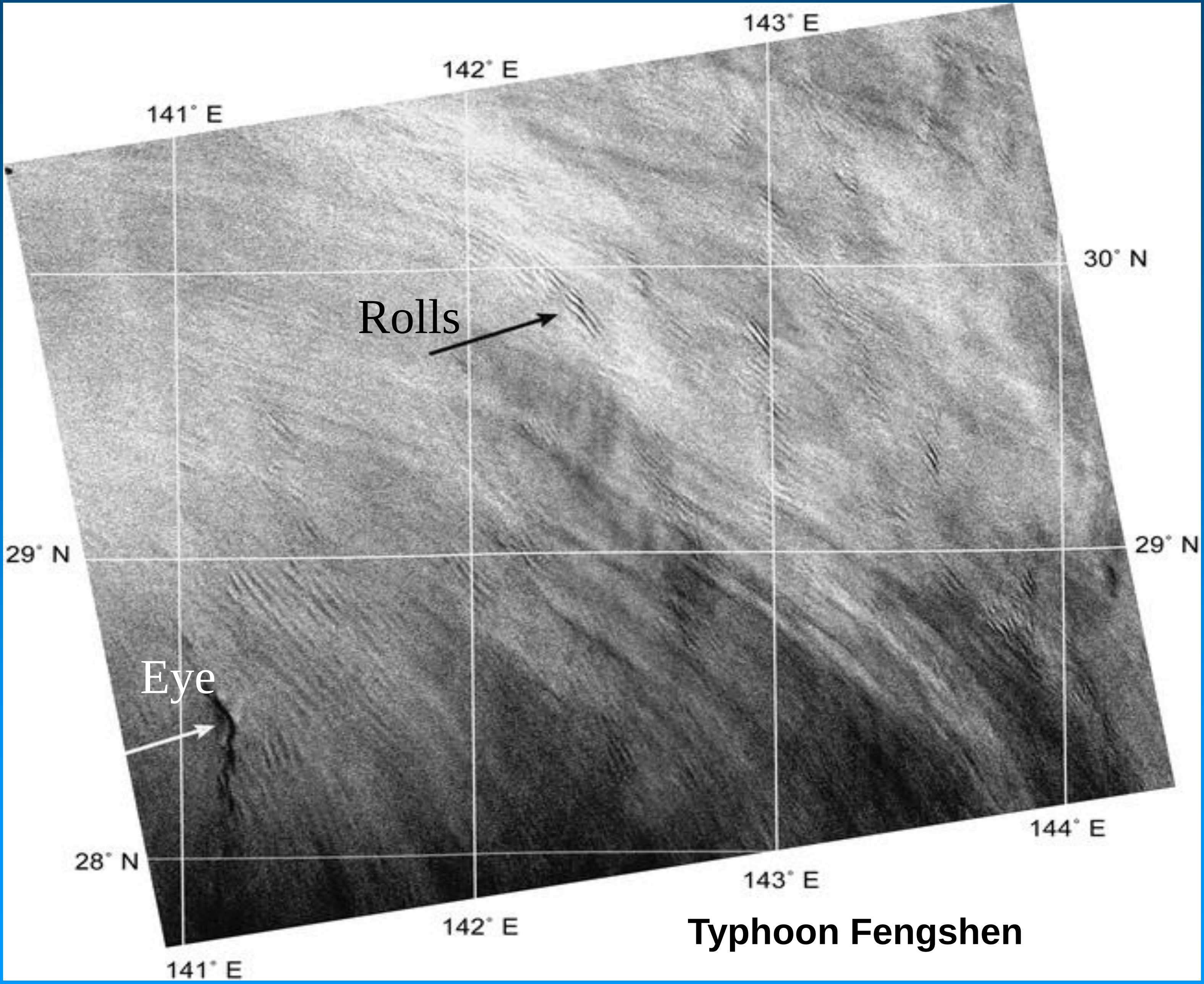
Currently almost no exception, the boundary layer parameterizations developed in non-hurricane conditions are also used without any modification in the simulation and prediction of hurricanes to account for the turbulent transport in the hurricane boundary layer.

But hurricane boundary layer has its own unique characteristics.

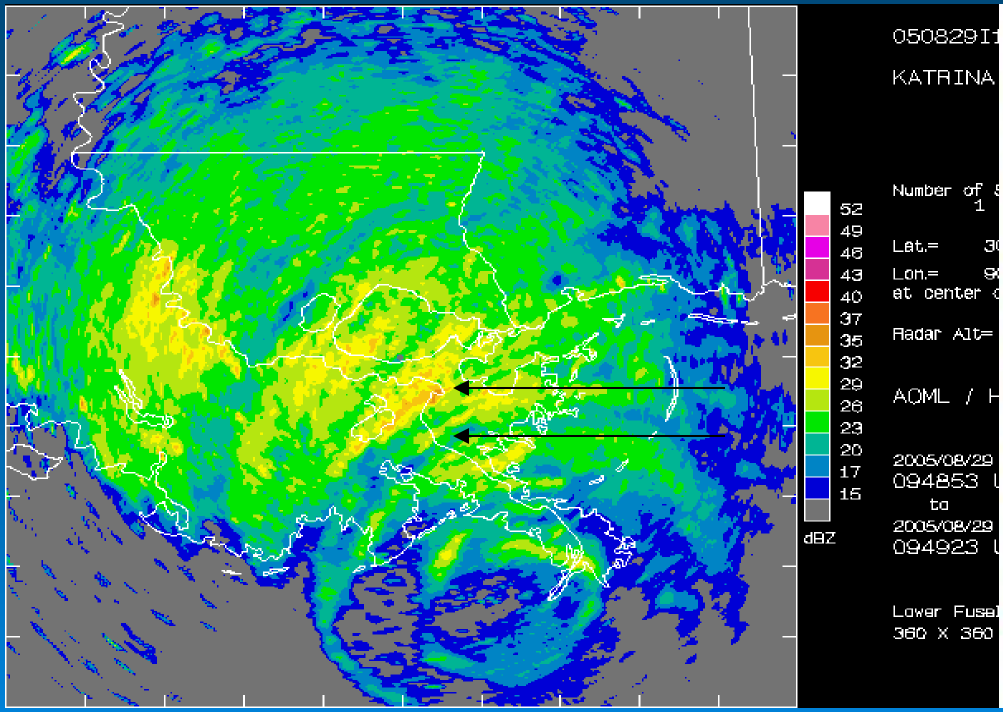


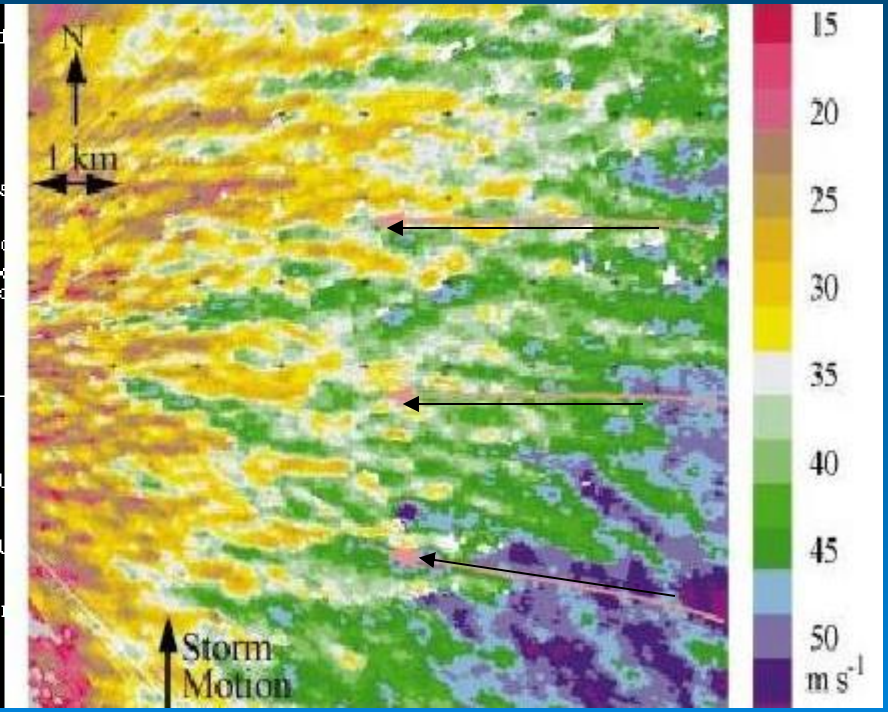
1. To what extent can convection modify the hurricane boundary layer structure and turbulent processes?
2. How does the interaction between convection and boundary layer turbulent processes affect the vertical transport?
3. Whether the existing turbulent mixing scheme and convection scheme can realistically represent this interaction?

Hurricane boundary layer roll vortices

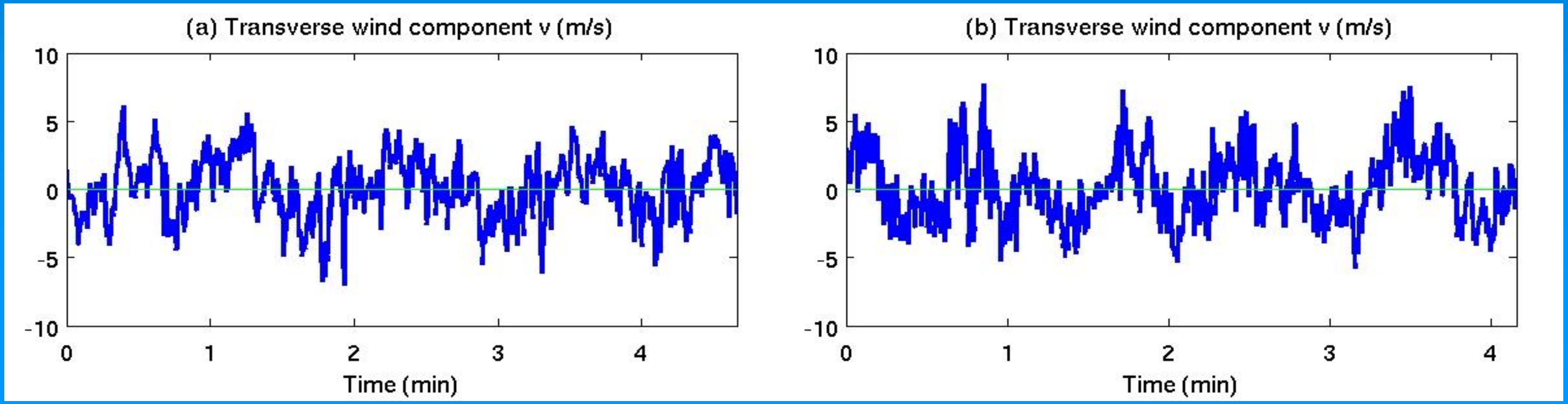


Doppler Radar Observations

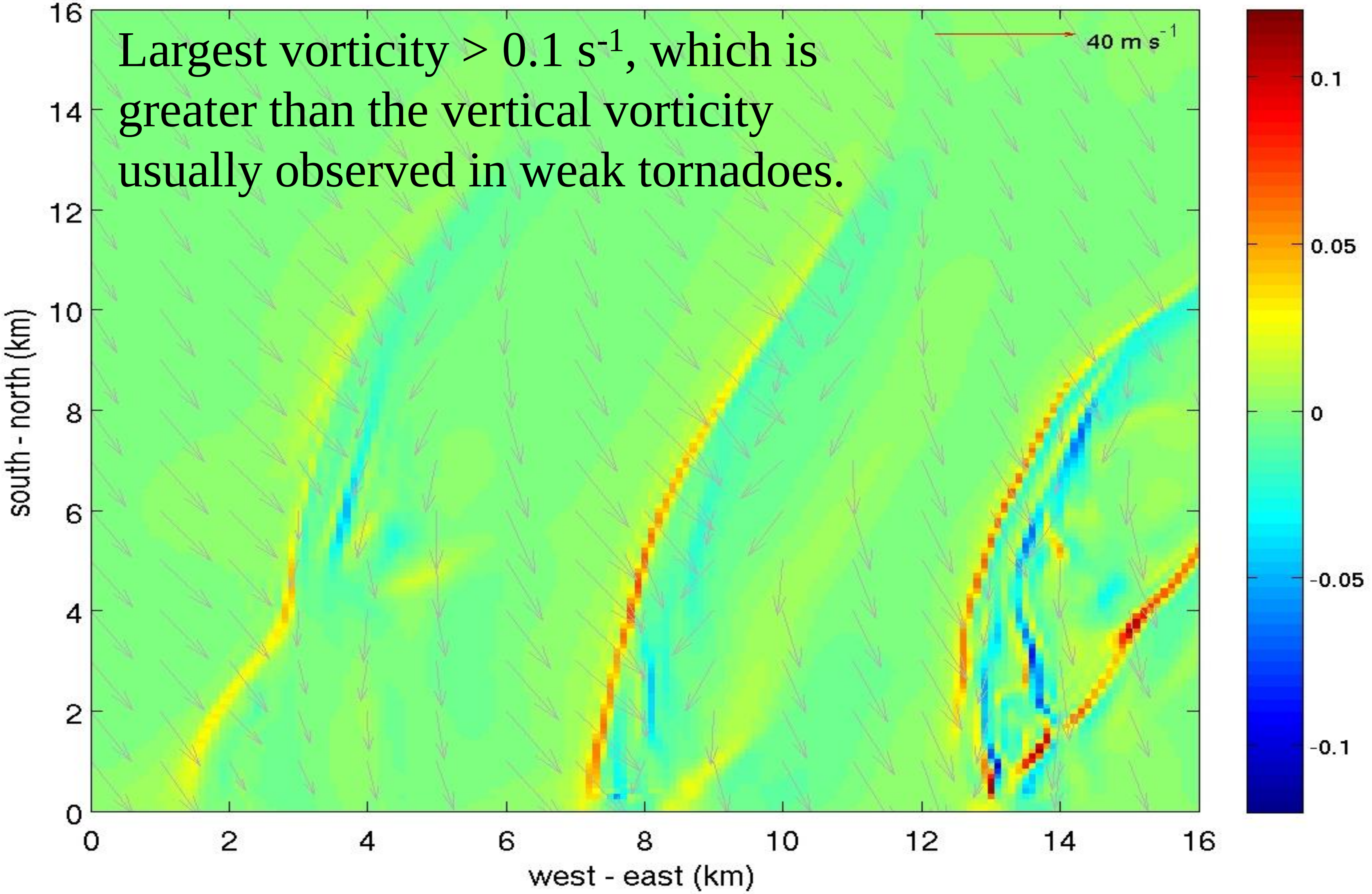




IHRC Tower Observations



Vorticity front from the simulation of Hurricane Katrina

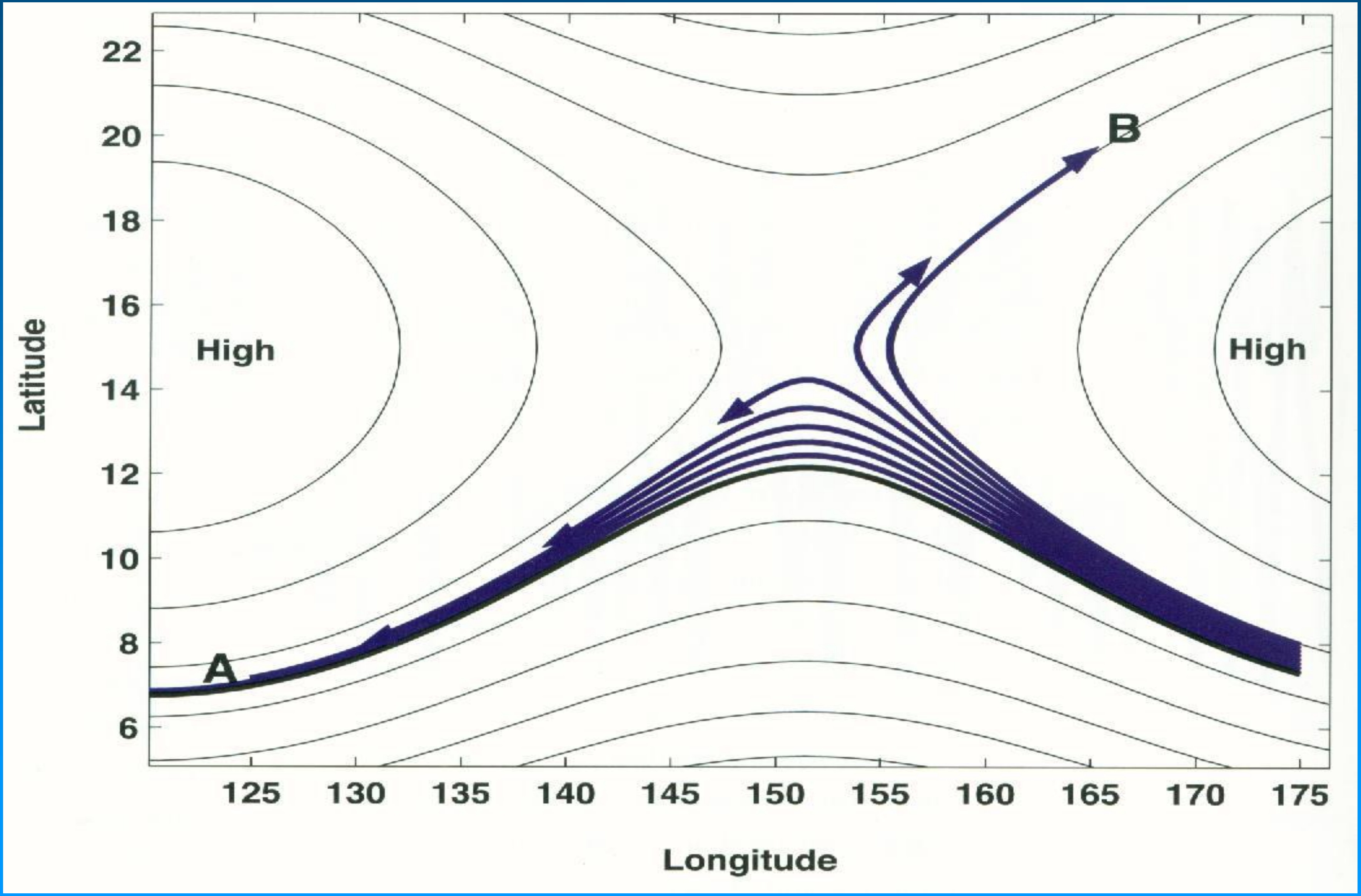


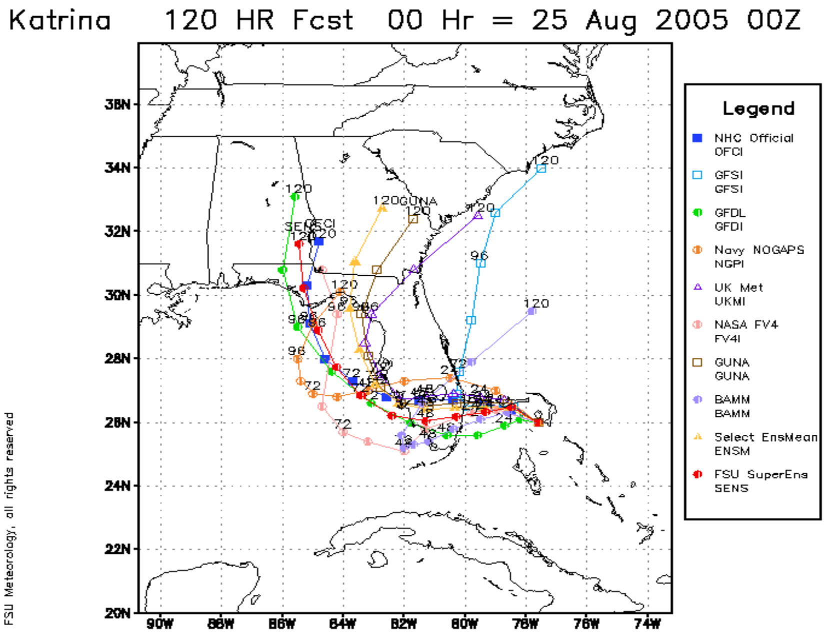
Eyewall Mesovortices

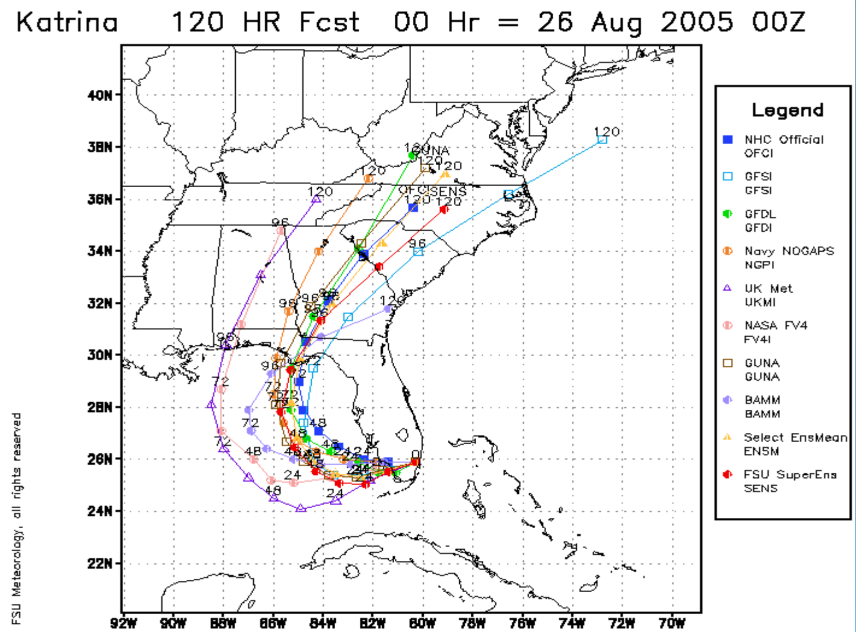
Observations show that the hurricane intensification seems to be always accompanied by the occurrence of eyewall meso-vortices.

6. How to improve hurricane forecasting?

Ensemble forecasting




Katrina 120 HR Fcst 00 Hr = 25 Aug 2005 00Z
Legend
NHC Official OFCI
GFSI GFSI
GFDL GFDI
Navy NOGAPS NGPI
UK Met UKMI
NASA FV4 FV4I
GUNA GUNA
BAMM BAMM
Select EnsMean ENSM
FSU SuperEns SENS
FSU Meteorology, all rights reserved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Legend
NHC Official OFCI
GFSI GFSI
GFDL GFDI
Navy NOGAPS NGPI
UK Met UKMI
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GUNA GUNA
BAMM BAMM
Select EnsMean ENSM
FSU SuperEns SENS
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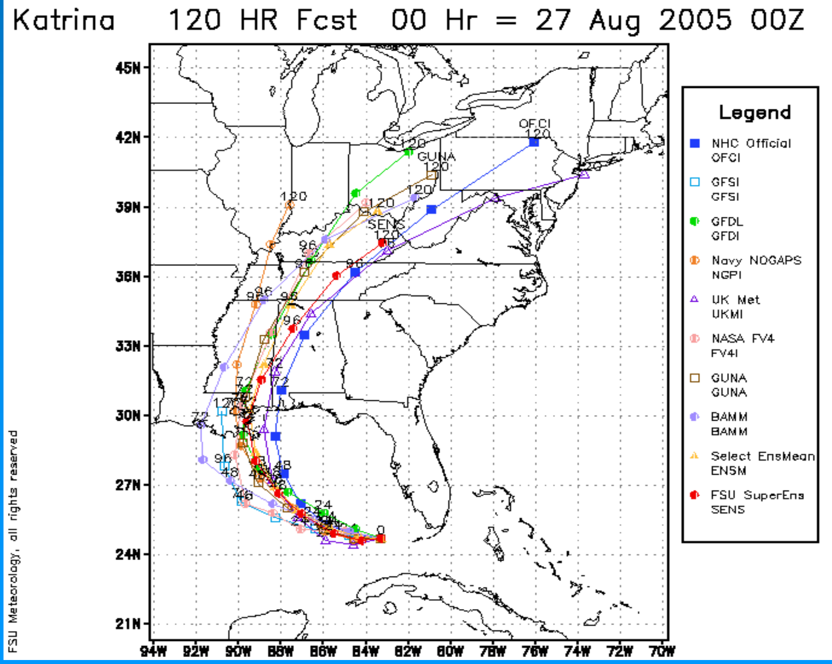
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Legend
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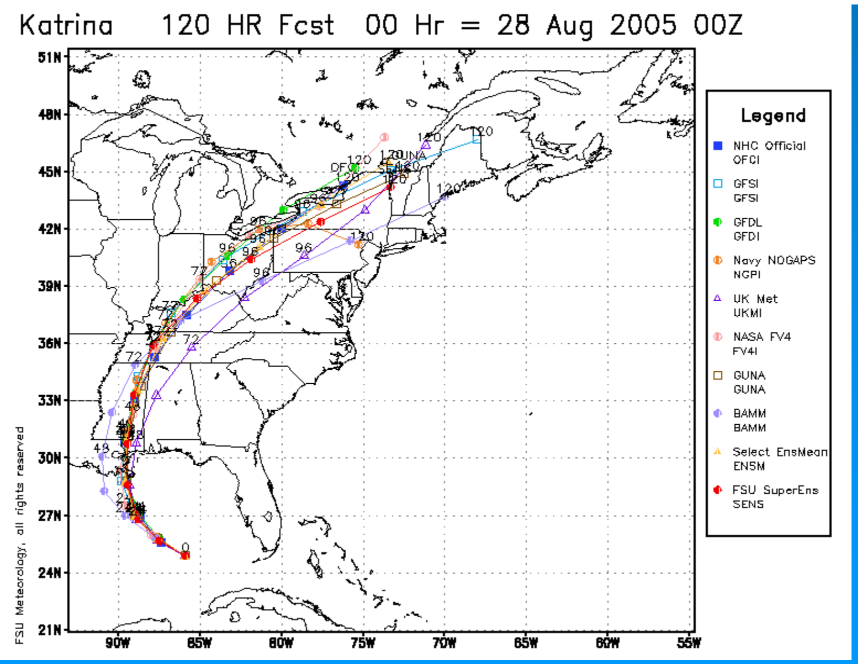
GFDL GFDI
Navy NOGAPS NGPI
UK Met UKMI
NASA FV4 FV4I
GUNA GUNA
BAMM BAMM
Select EnsMean ENSM
FSU SuperEns SENS
FSU Meteorology, all rights reserved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Legend
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GFSI GFSI
GFDL GFDI
Navy NOGAPS NGPI
UK Met UKMI
NASA FV4 FV4I
GUNA GUNA
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Select EnsMean ENSM
FSU SuperEns SENS
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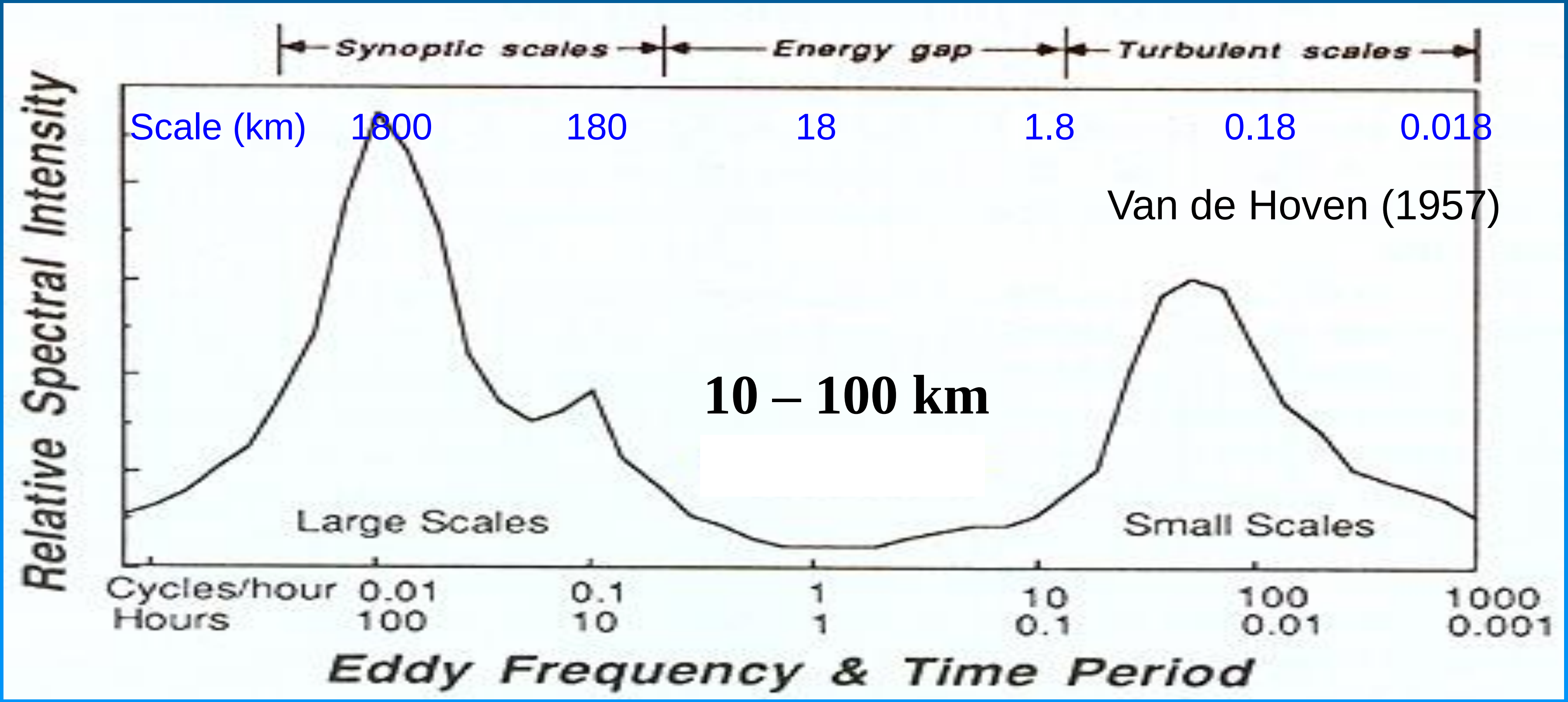
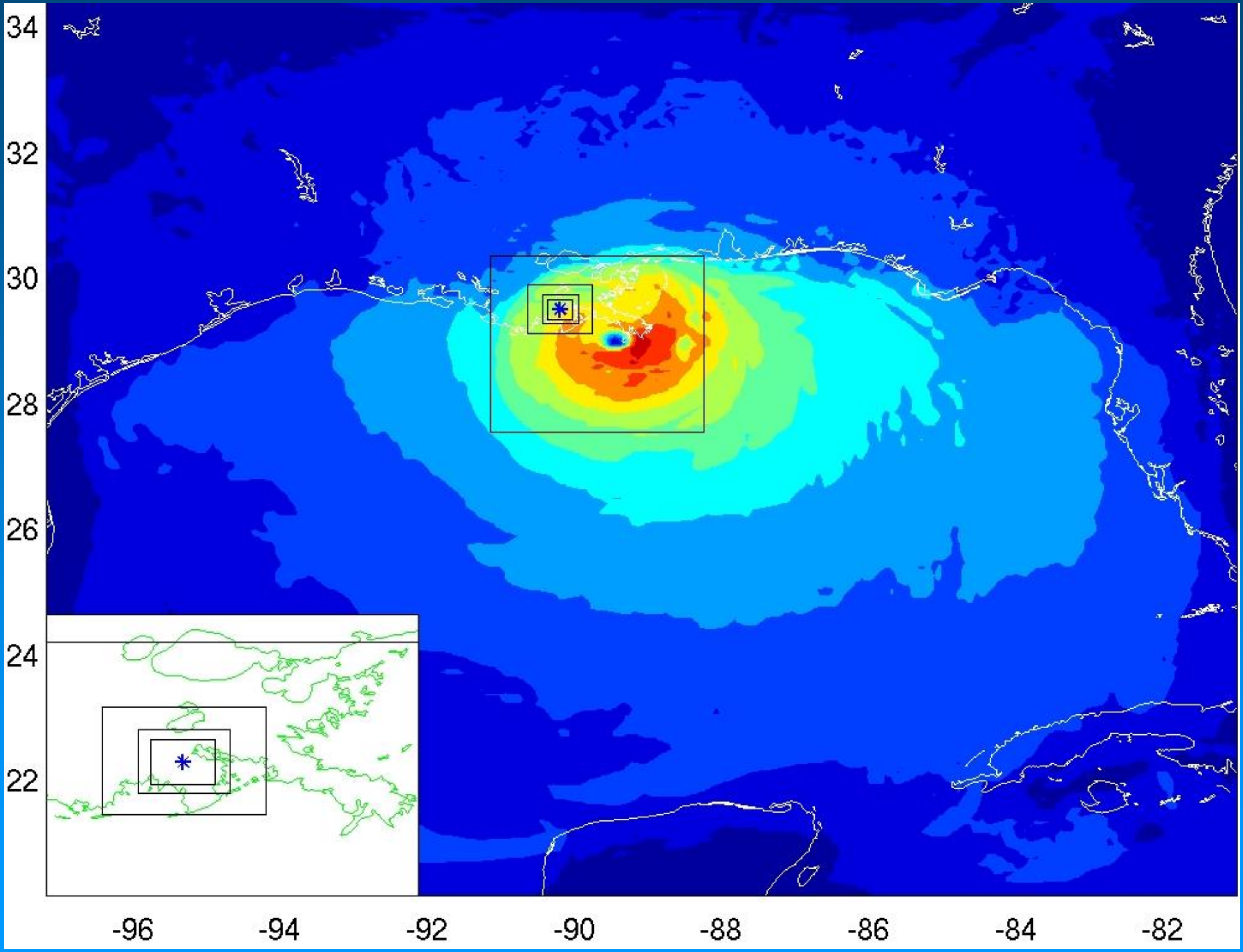
Study sub-grid processes and improve parameterizations

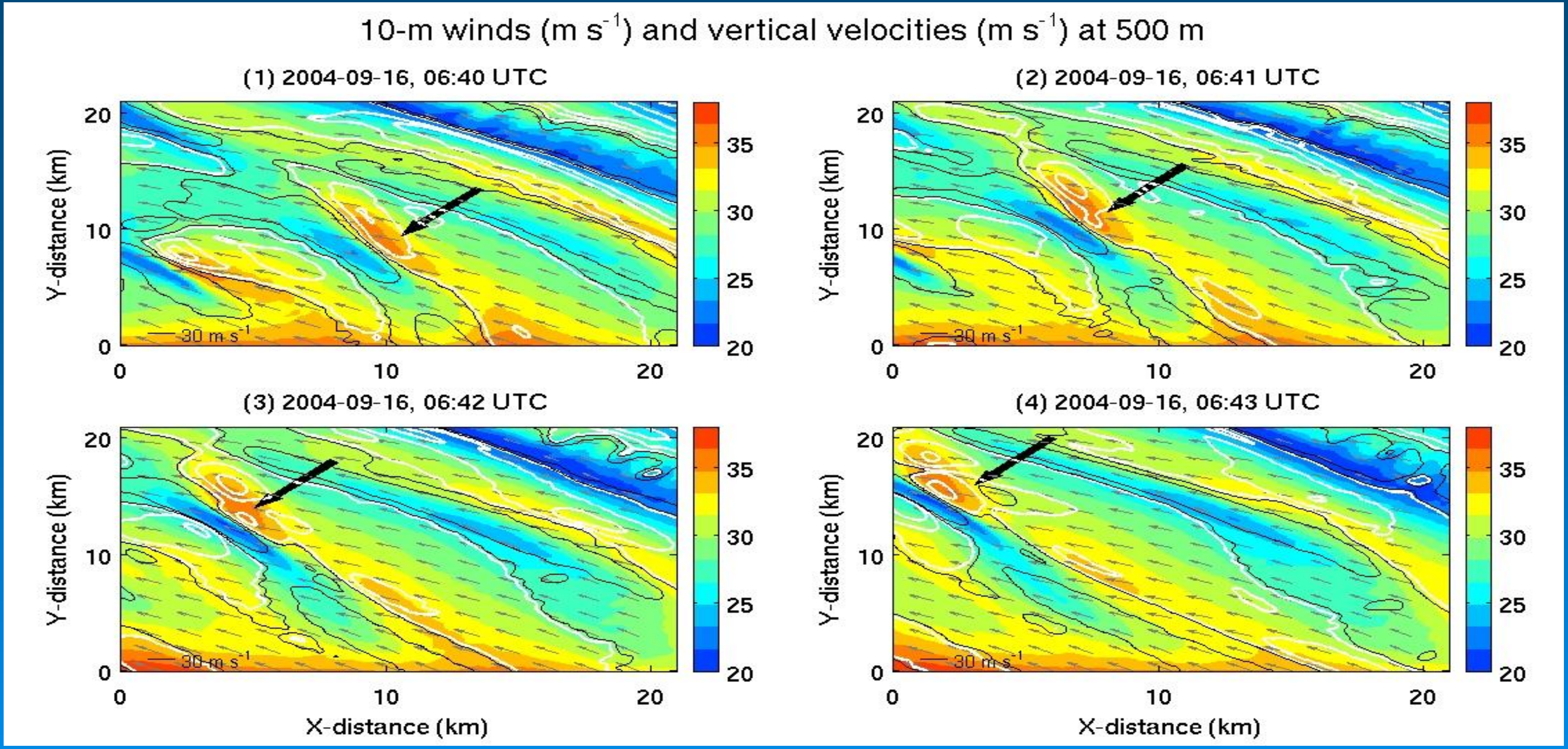
Large eddy simulation (LES)

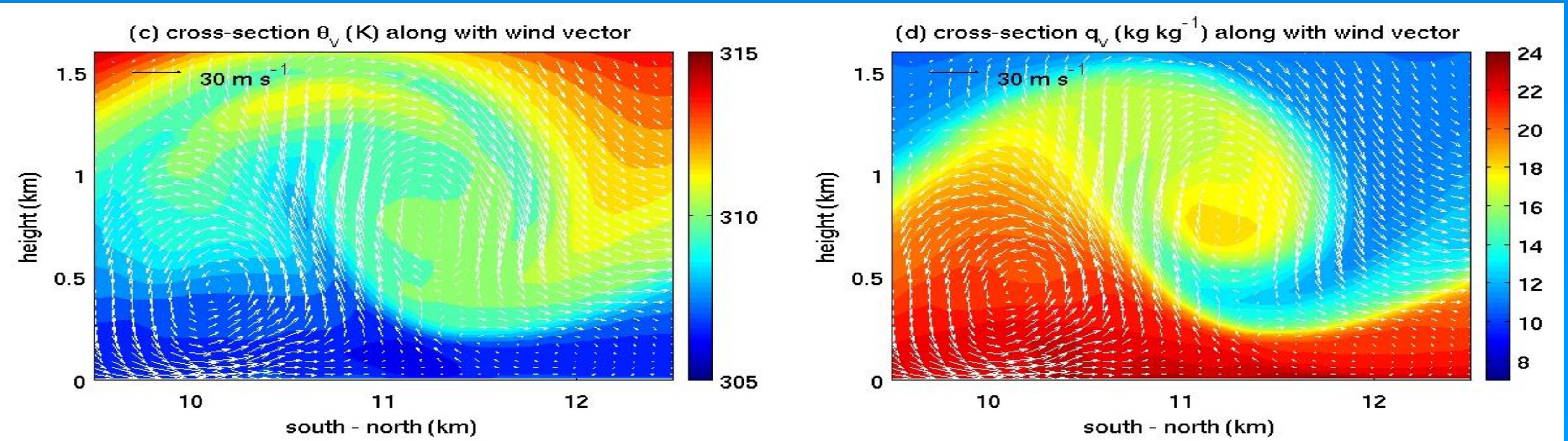


Multiple-scale large-eddy simulation

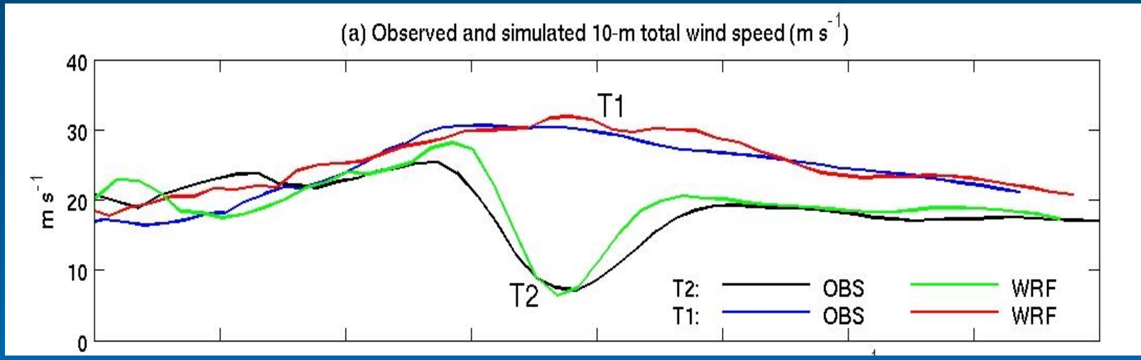


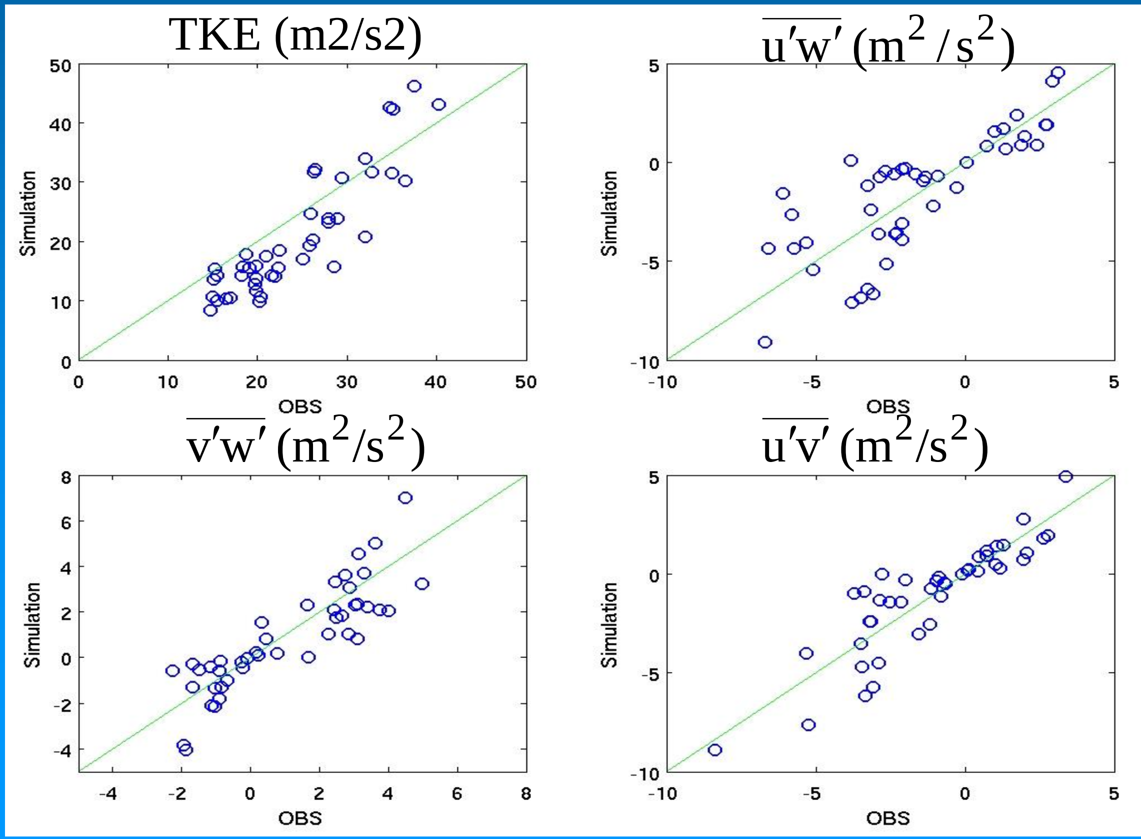
Simulated hurricane boundary layer roll vortices





IHRC Tower Observations





Summary

Causes for numerical forecast errors:

- Insufficient observations;
- Chaotic nature of the atmosphere;
- Inherent deficiency of numerical models with limited resolution that fails to resolve sub-grid physical processes.

Our answers to reduce forecast errors:

- Data assimilation;
- Ensemble forecast;
- Parameterization.