Tropical Cyclone (TC) Structures in Operational Models

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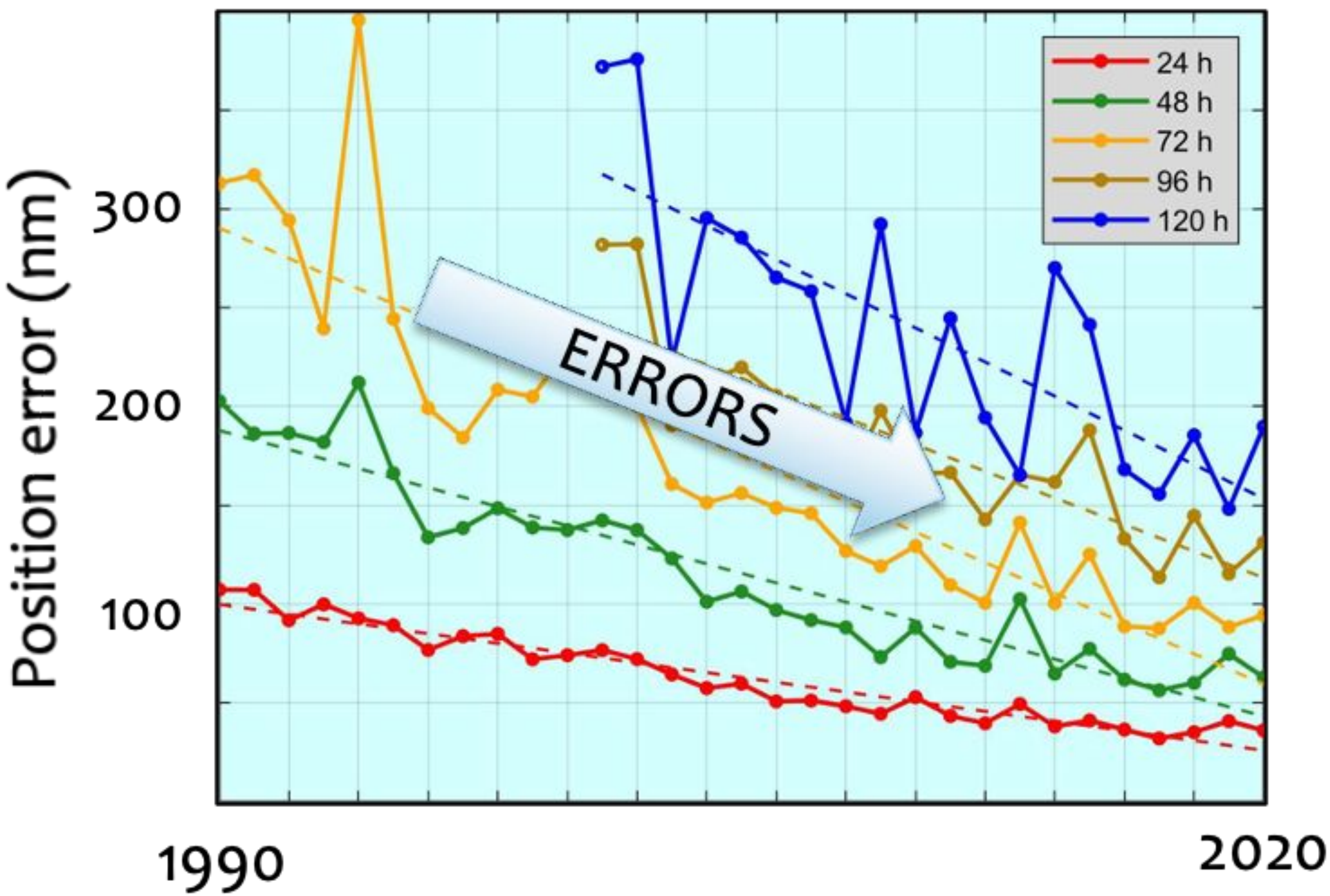
About Me

- Professor at the University of Miami (UM, 21 years)
  - https://majumdar.earth.miami.edu/
  - Recent Associate Dean of UM's Rosenstiel School
  - Interim Co-Director, UM Climate Resilience Academy (https://resilience.miami.edu)
  - Teaching: Tropical Weather & Forecasting (undergraduate), Hurricanes (graduate), Predictability (graduate)
  - Research: TC predictability, TC formation ("genesis"), TC intensity change, model diagnostics, targeted observations, data assimilation, graphical risk communication ...
  - Various WMO working groups, inter-agency research coordination activities, NOAA Joint Hurricane Testbed etc.

Outline

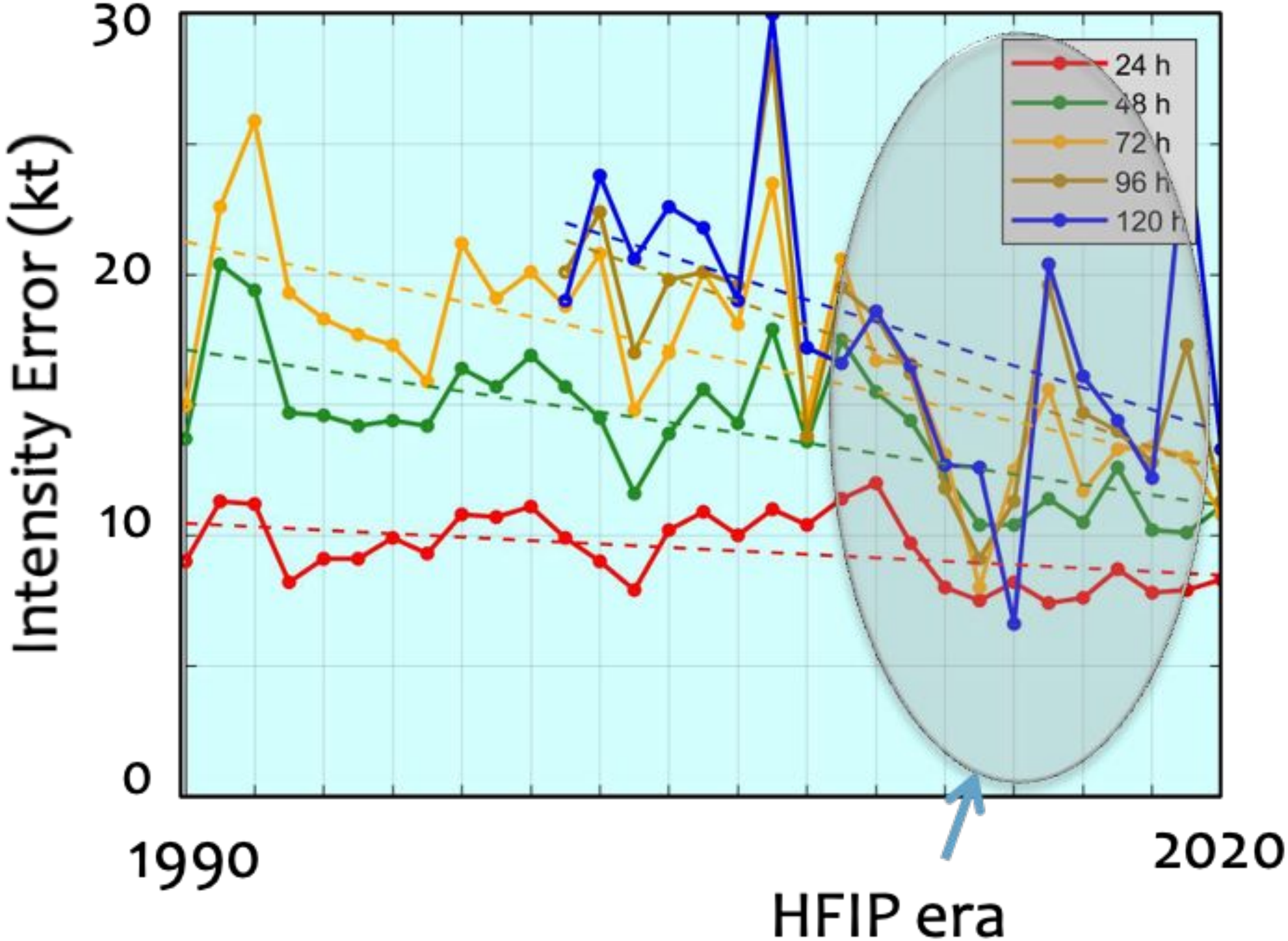
I. How do operational models work?
II. What do TCs look like in numerical models?
III. Graphical communication of weather risk
IV. Final remarks

Official TC Track Forecast Errors: 1990-2020



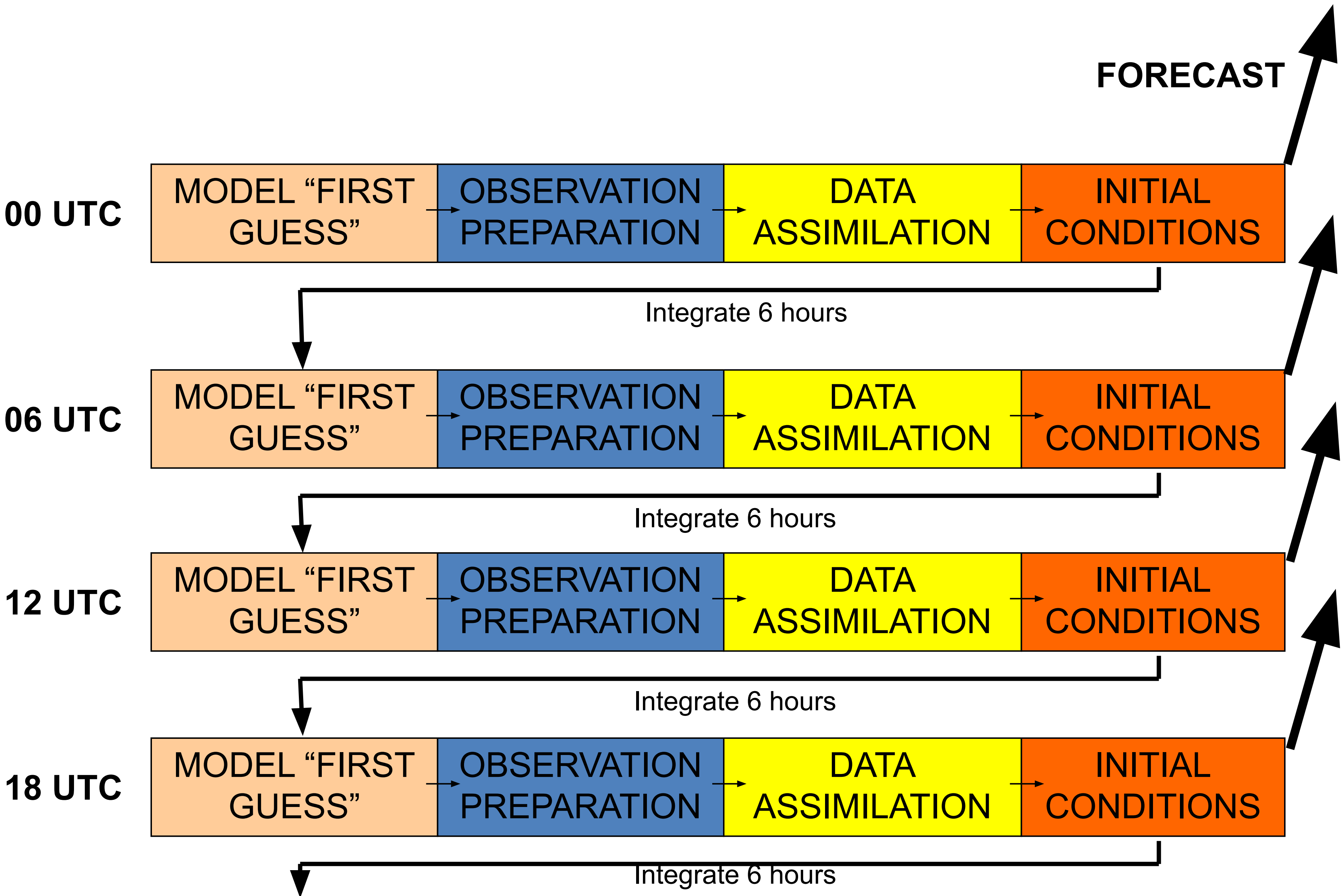
From NHC via Jason Sippel

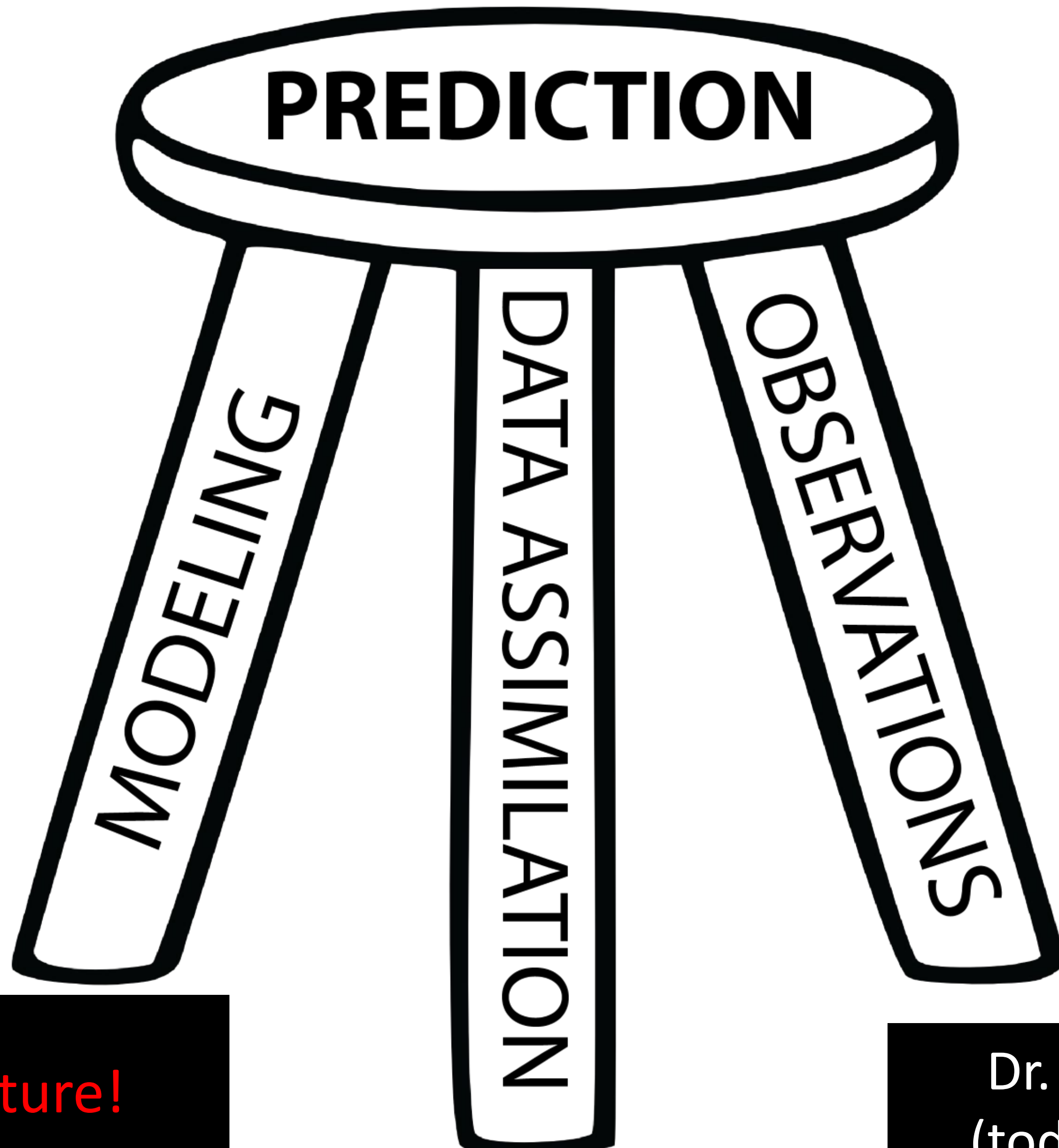
Official TC Intensity Forecast Errors: 1990-2020



From NHC via Jason Sippel

Numerical Weather Prediction Cycle



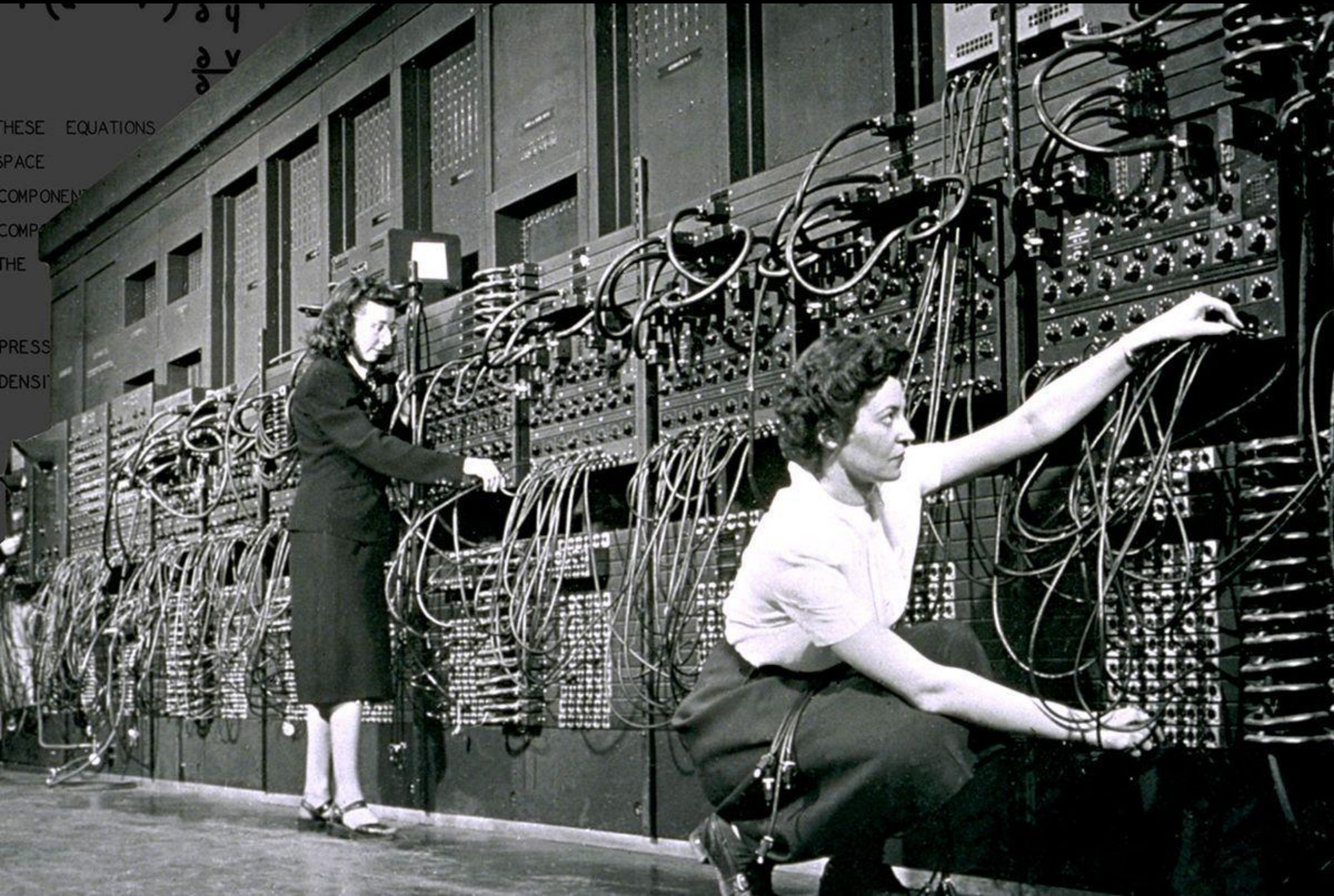


This Lecture!

Dr. Jason Sippel
(tomorrow morning)

Dr. Rob Rogers
(today, aircraft),
many others
(satellite)

Numerical Weather Prediction: 70 Years Ago



Numerical Weather Prediction: 2023

ECMWF’s new supercomputers in Italy

Numerical Weather Models

- **Solve primitive equations following conservation laws:**
  - **Momentum (3-d)**
  - **Mass**
  - **Thermal Energy**
    - **Including laws governing phase changes between vapor, liquid, and ice**
- Initial Conditions (data assimilation)
- Boundary Conditions (ocean, land etc.)
- External Forcing (radiation)

Primitive Equations

Conservation of momentum, energy, mass and moisture:

$$\frac{\partial \vec{V}}{\partial t} = -(\vec{V}\cdot\nabla)\vec{V} - \frac{1}{\rho}\nabla p - \vec{g} - 2\vec{\Omega}\times\vec{V} + \nabla\cdot\left(k_\omega \nabla\vec{V}\right) - \vec{F}_d$$

$$\rho c_p \frac{\partial T}{\partial t} = -\rho c_p\left(\vec{V}\cdot\nabla\right)T - \nabla\cdot\vec{R} + \nabla\cdot(k_\tau \nabla T) + C + S$$

$$\frac{\partial \rho}{\partial t} = -(\vec{V}\cdot\nabla)\rho - \rho\left(\nabla\cdot\vec{V}\right)$$

$$\frac{\partial q}{\partial t} = -(\vec{V}\cdot\nabla)q + \nabla\cdot\left(k_q \nabla q\right) + S_q + E$$

Equation of state:

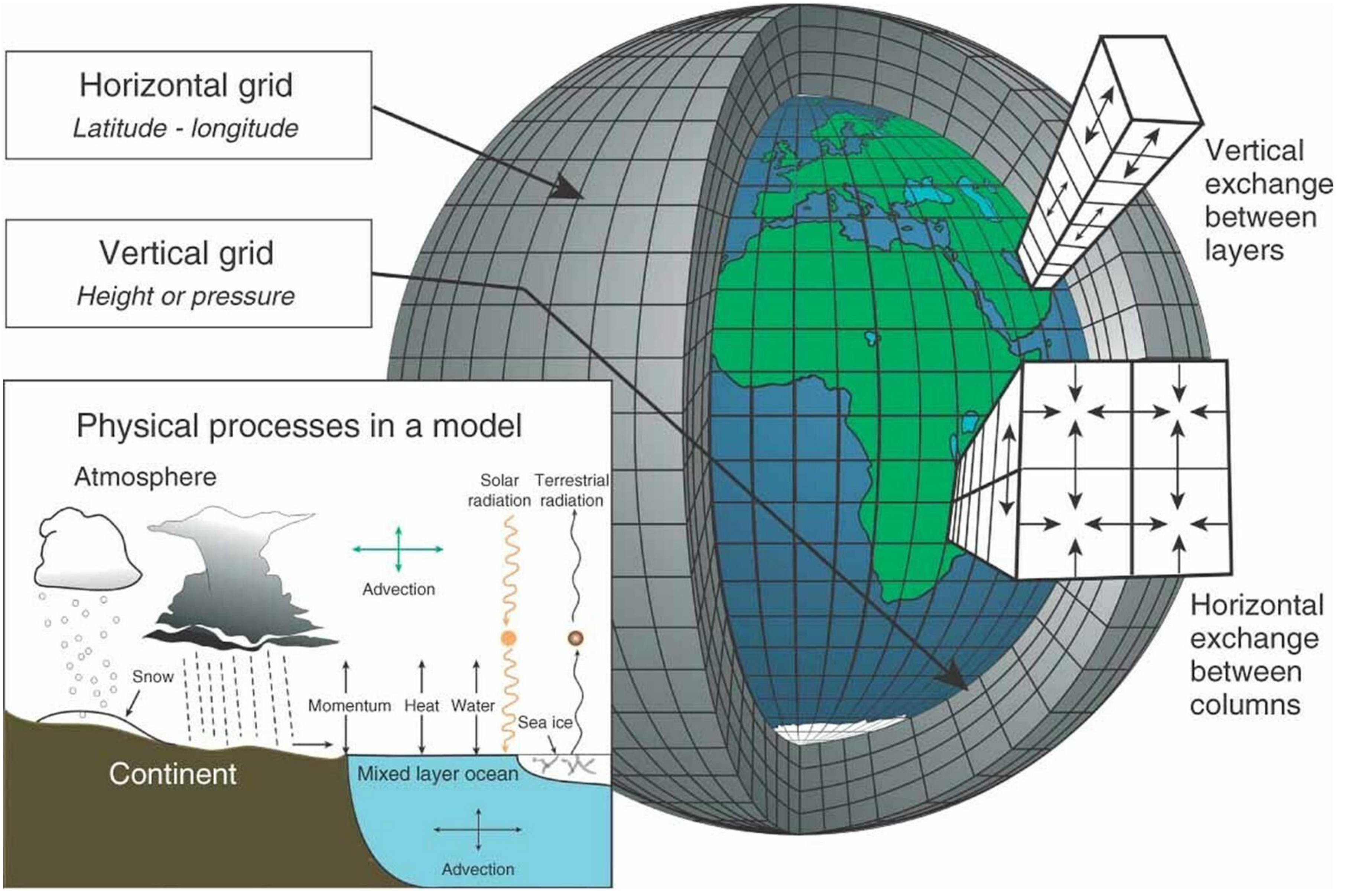
$$p = \rho R_d T$$

$V = velocity$
$T = temperature$
$p = pressure$
$\rho = density$
$q = specific\ humidity$
$g = gravity$
$\Omega = rotation\ of\ Earth$
$F_d = drag\ force\ of\ Earth$
$R = radiation\ vector$
$C = conductive\ heating$
$c_p = heat\ capacity, constant\ p$
$E = evaporation$
$S = latent\ heating$
$S_q = phase\ change\ source$
$k = diffusion\ coefficients$
$R_d = dry\ air\ gas\ constant$

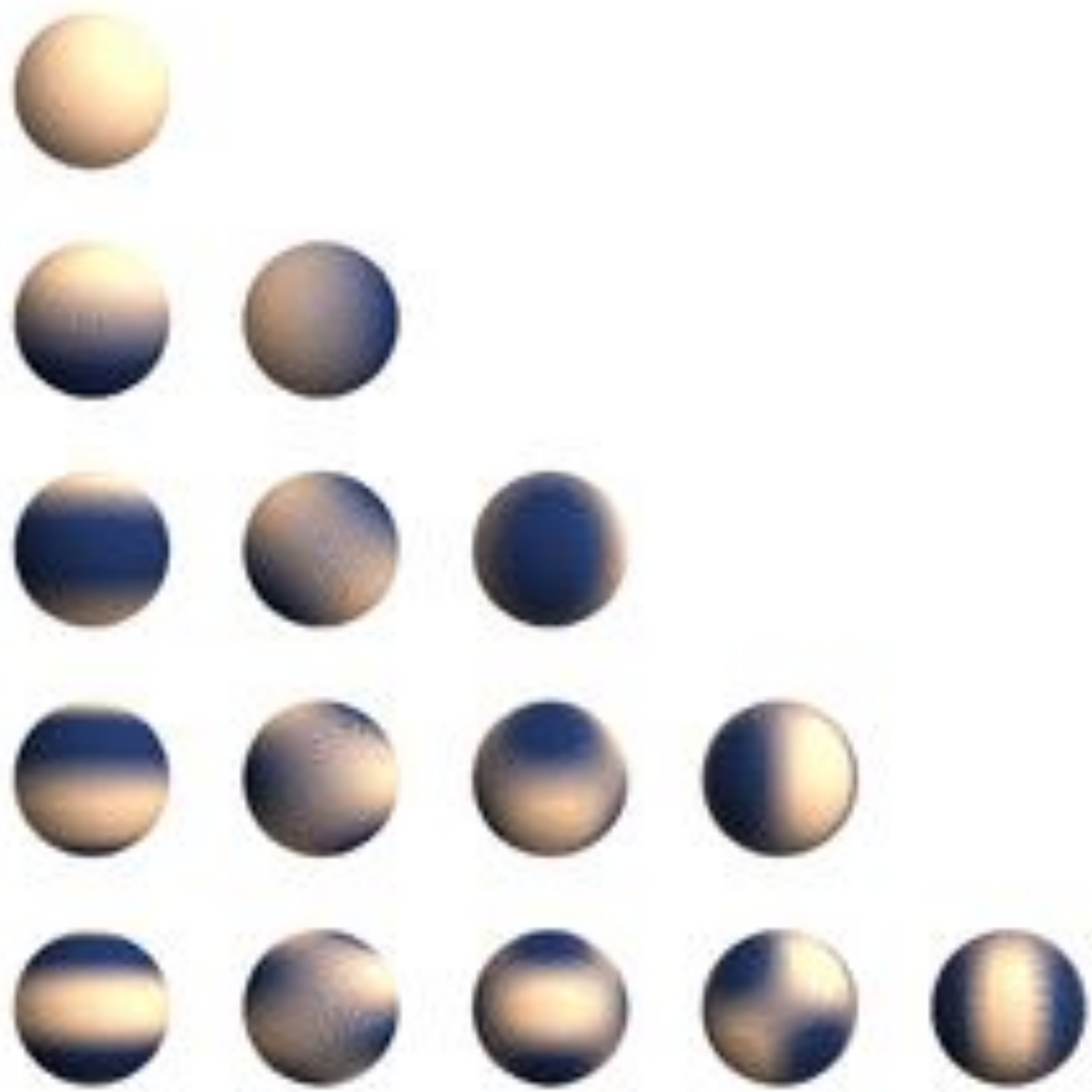
Numerical Weather Models

- **Dynamical Core**: discretizes equations of motion, resolving flow features to 4-6 grid-cells.
- Subgrid-scale features and unresolved processes are described by **physics parameterizations**.
- High-frequency waves such as sound waves and (sometimes) gravity waves are **filtered** out.

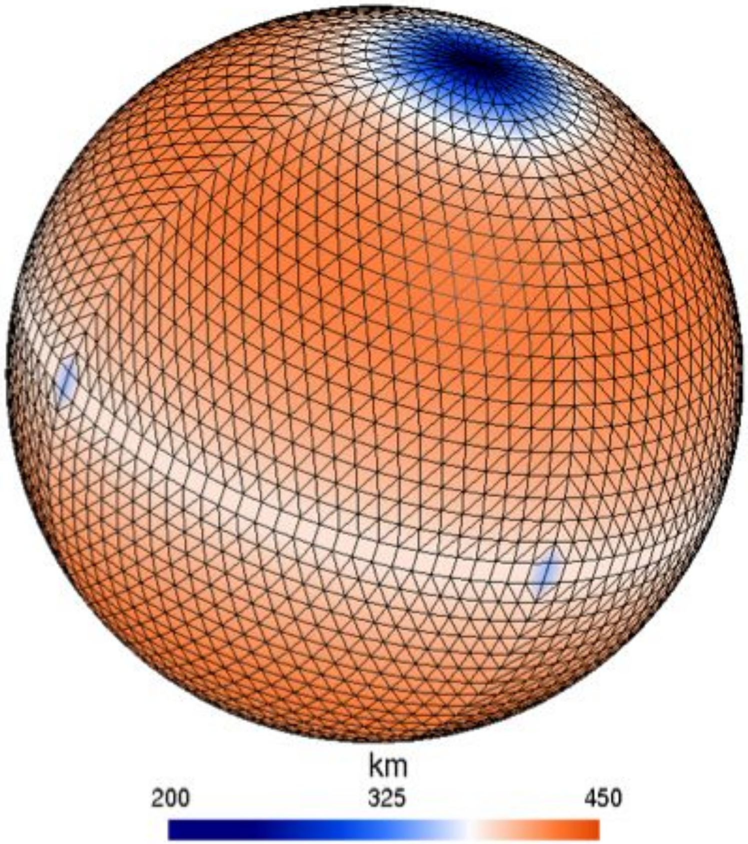
Model Grid


Horizontal grid
Latitude - longitude
Vertical grid
Height or pressure
Vertical exchange between layers
Horizontal exchange between columns
Physical processes in a model
Atmosphere
Snow
Advection
Solar radiation
Terrestrial radiation
Momentum
Heat
Water
Sea ice
Continent
Mixed layer ocean
Advection

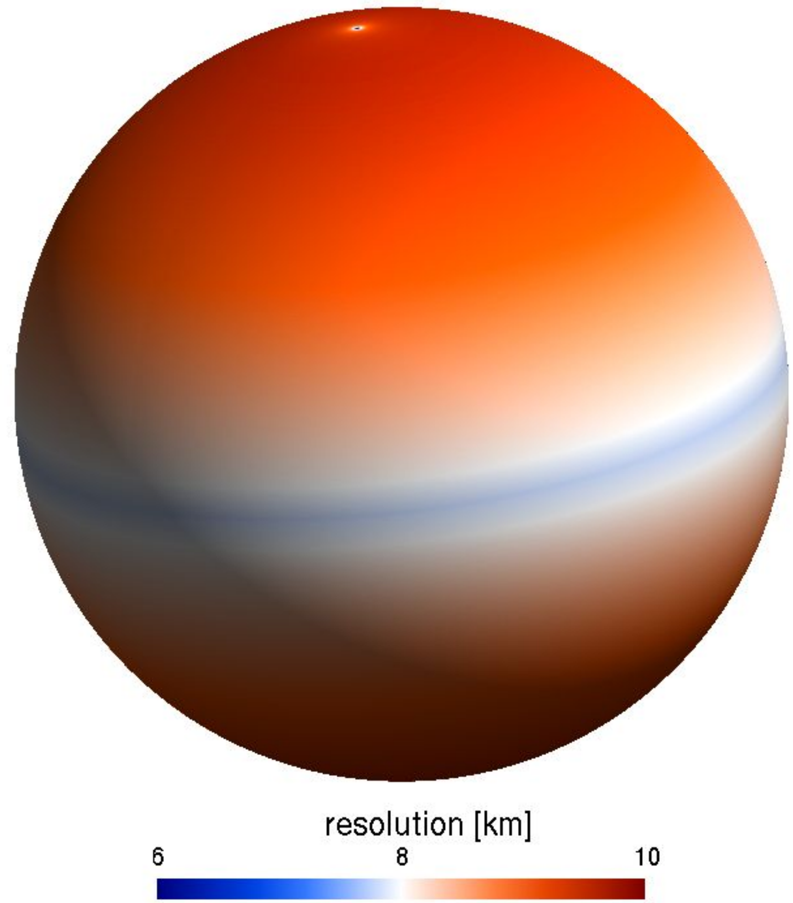
“Spherical Harmonics” increase efficiency!



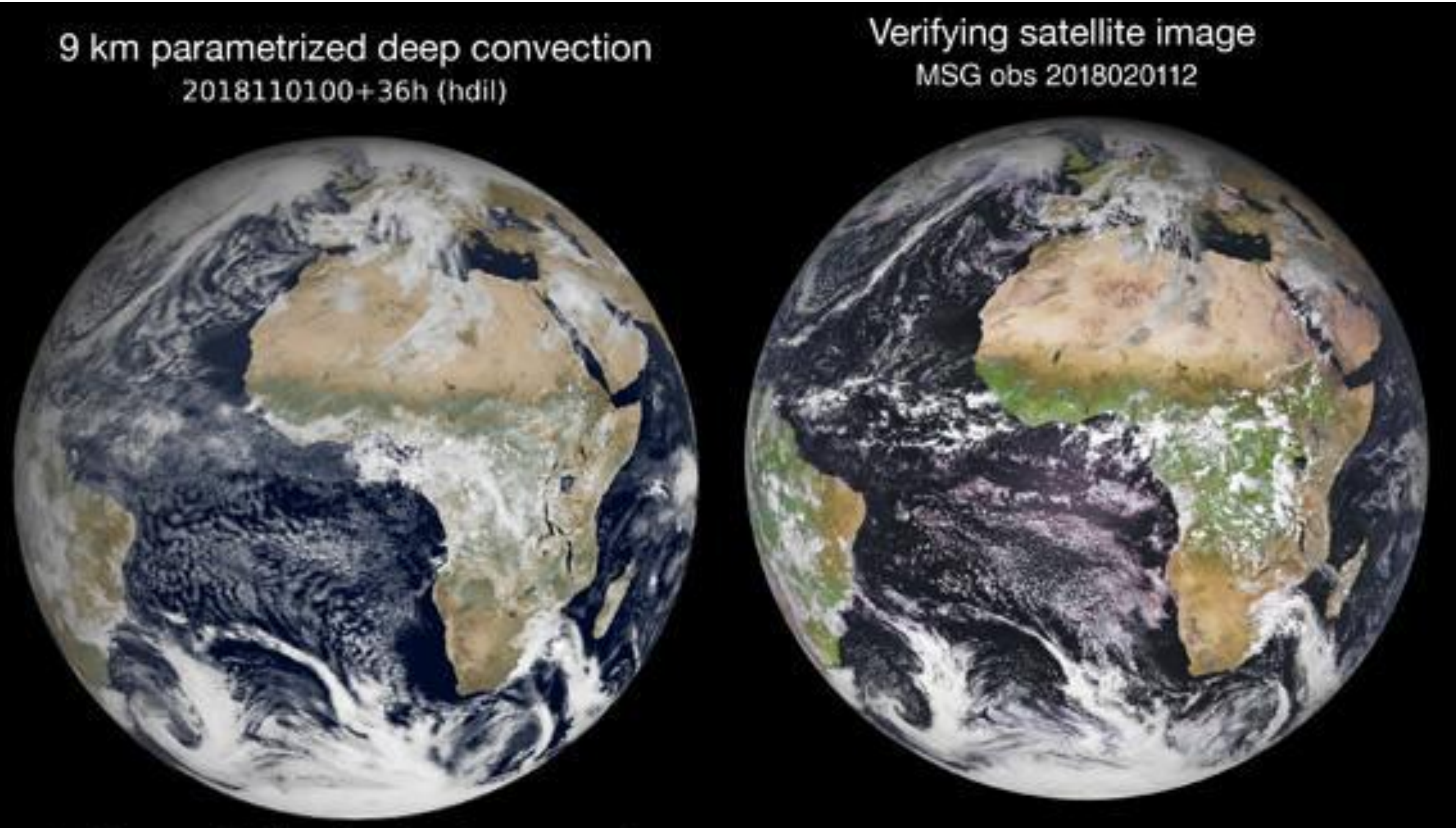
Horizontal Resolution (ECMWF)



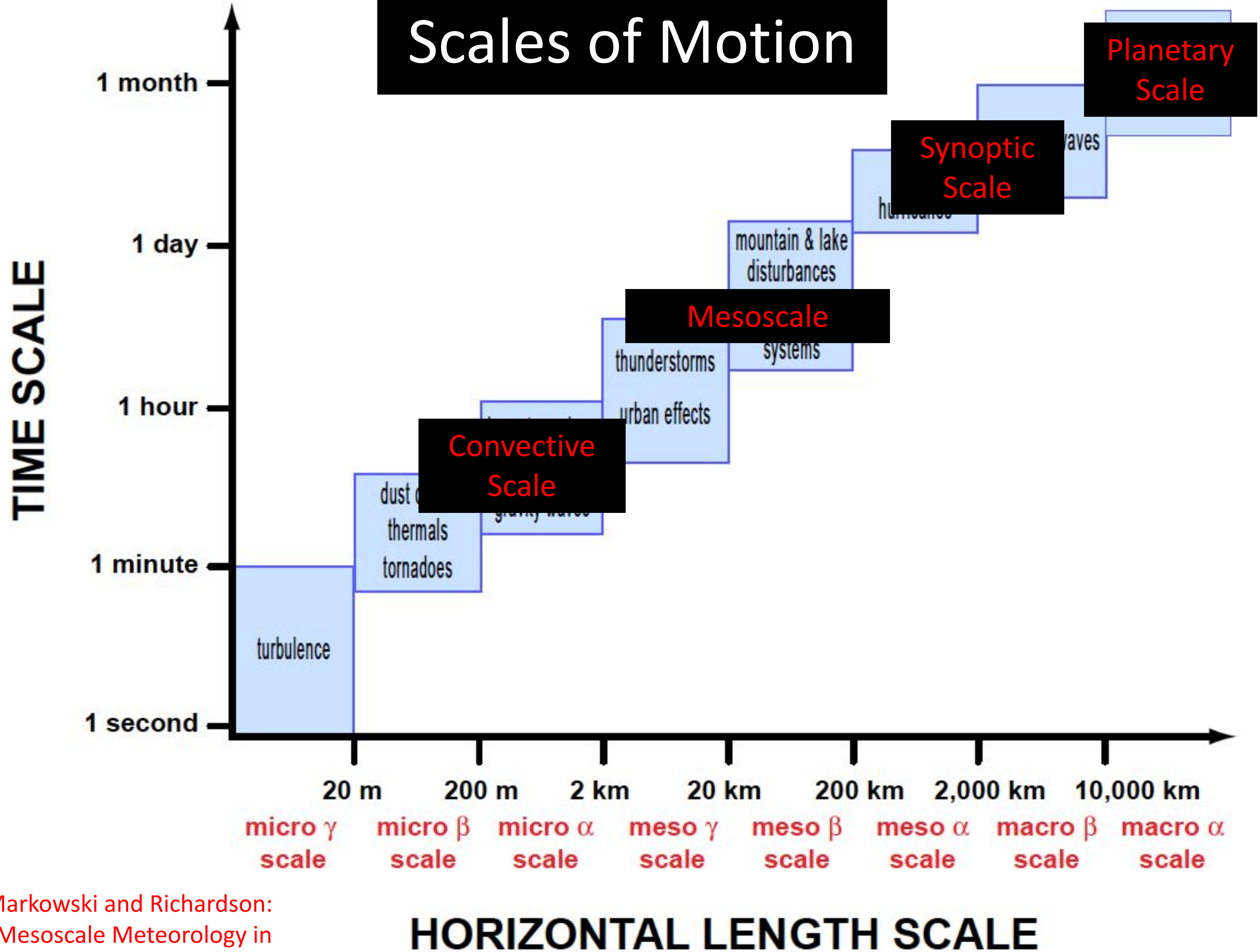
N24 octahedral Gaussian grid



ECMWF Model (left) vs Satellite (right)

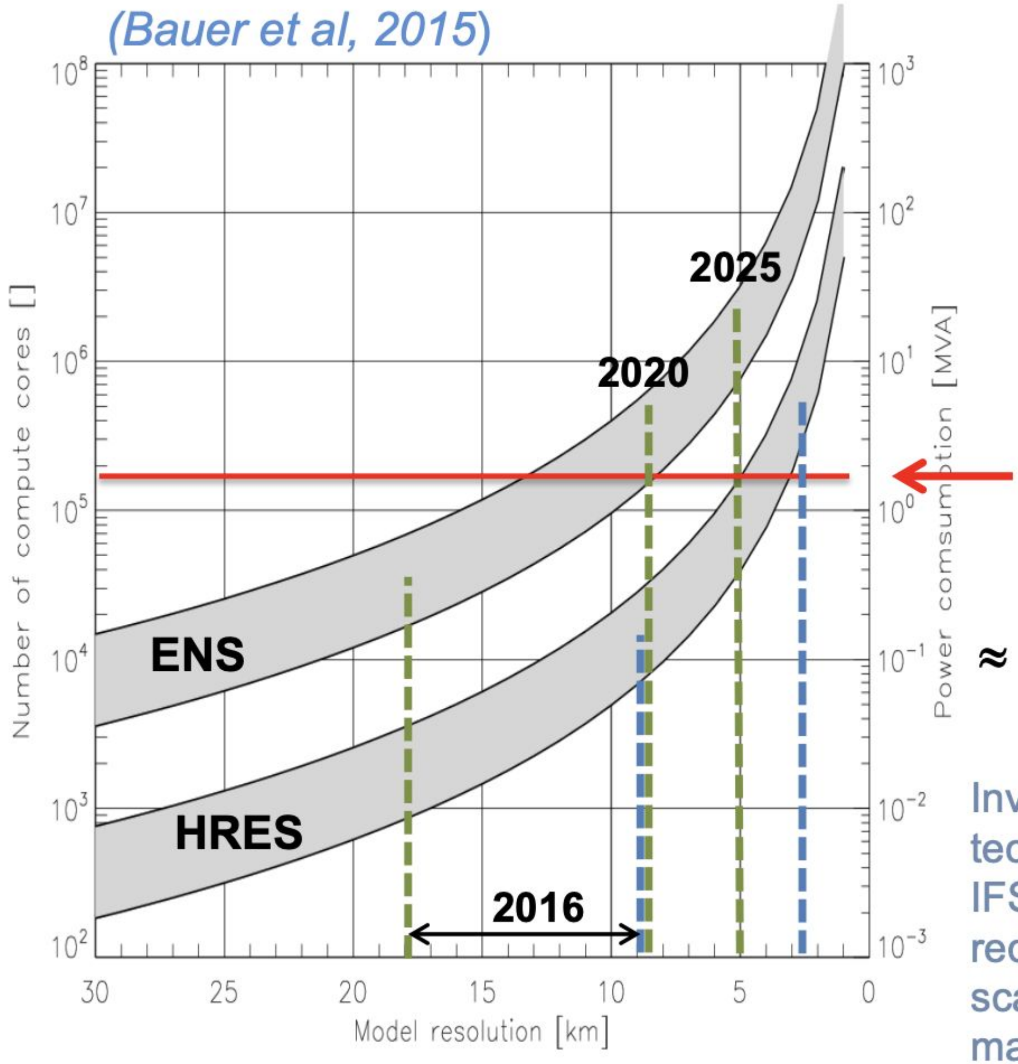


Scales of Motion



Markowski and Richardson: “Mesoscale Meteorology in the Mid-Latitudes”

How much does computing cost?



≈ M€ electricity/year

Investment in new hardware technology and continuous IFS model development required to move the energy scale down by one order of magnitude! *(see Aurora 180PF, HPCwire April 2015)*

Quiz 1/5

- How many atmospheric grid points do you think there are in the ECMWF global model?

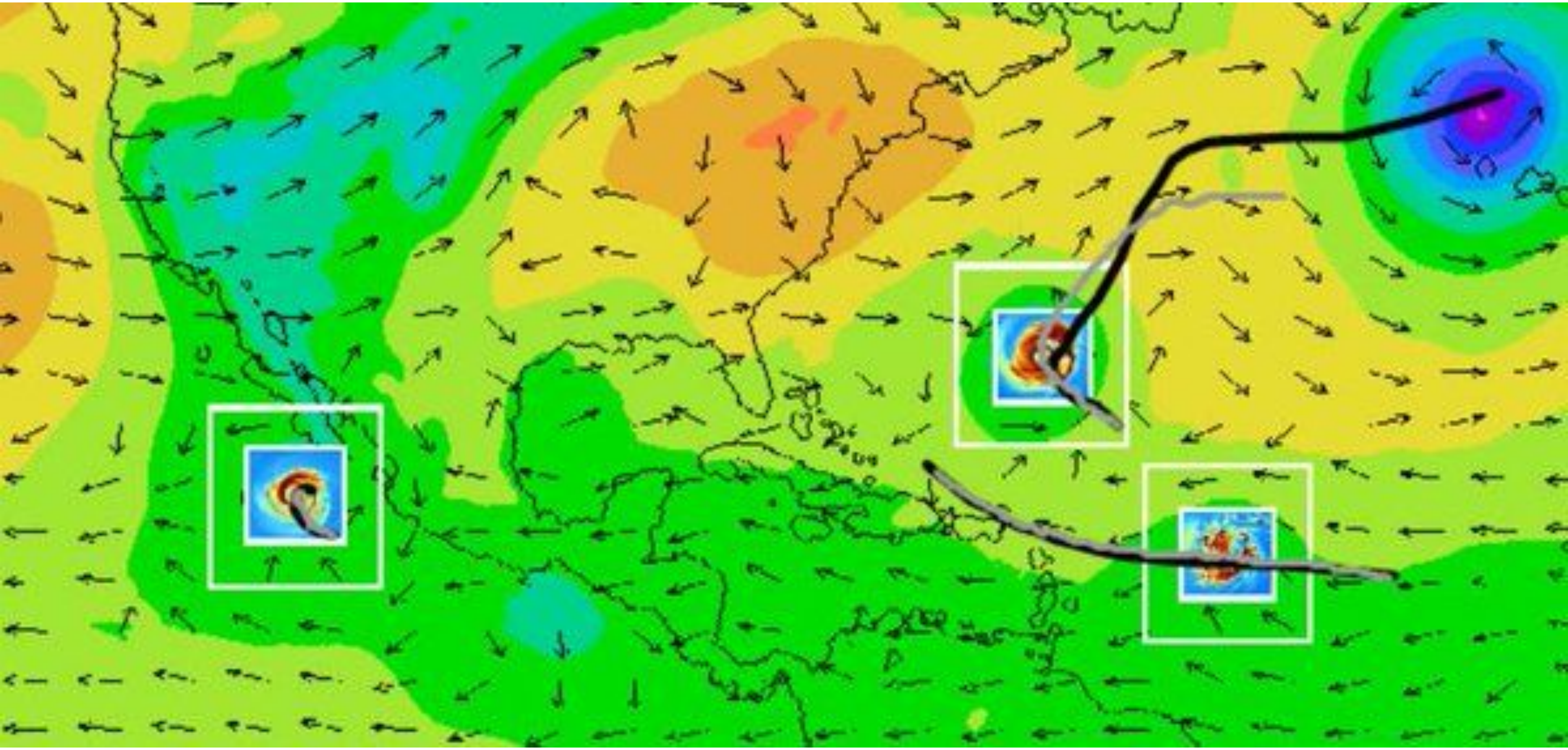
A. 1 million
B. 10 million
C. 100 million
D. 1 billion

Global vs Regional Models

- Global
  - Relatively coarse resolution (~10-15 km grid cells)
  - Normally hydrostatic (no vertical accelerations!)
  - “Parameterized” physics
  - Consistent dynamics and physics across globe
- Regional
  - Relatively high resolution nests (2 km in HWRF)
  - Can be nonhydrostatic (changes in vertical motion)
  - Explicitly resolving clouds and thunderstorms
  - Inconsistent physics with ‘parent’ domain

Regional Models: High-Resolution Moving Nests

Examples: HWRF, COAMPS-TC, HAFS ...



How to represent all these physical processes?

Incoming solar radiation

Absorption by the atmosphere

Condensation

Turbulence

Reflection / absorption at earth's surface

Soil water and snow melt

Scattering by aerosols

Emission from clouds

Deep convection (warming)

Rain (cooling)

Sensible heat flux

Surface Roughness

Snow / ice / water cover

Snow

Evaporation

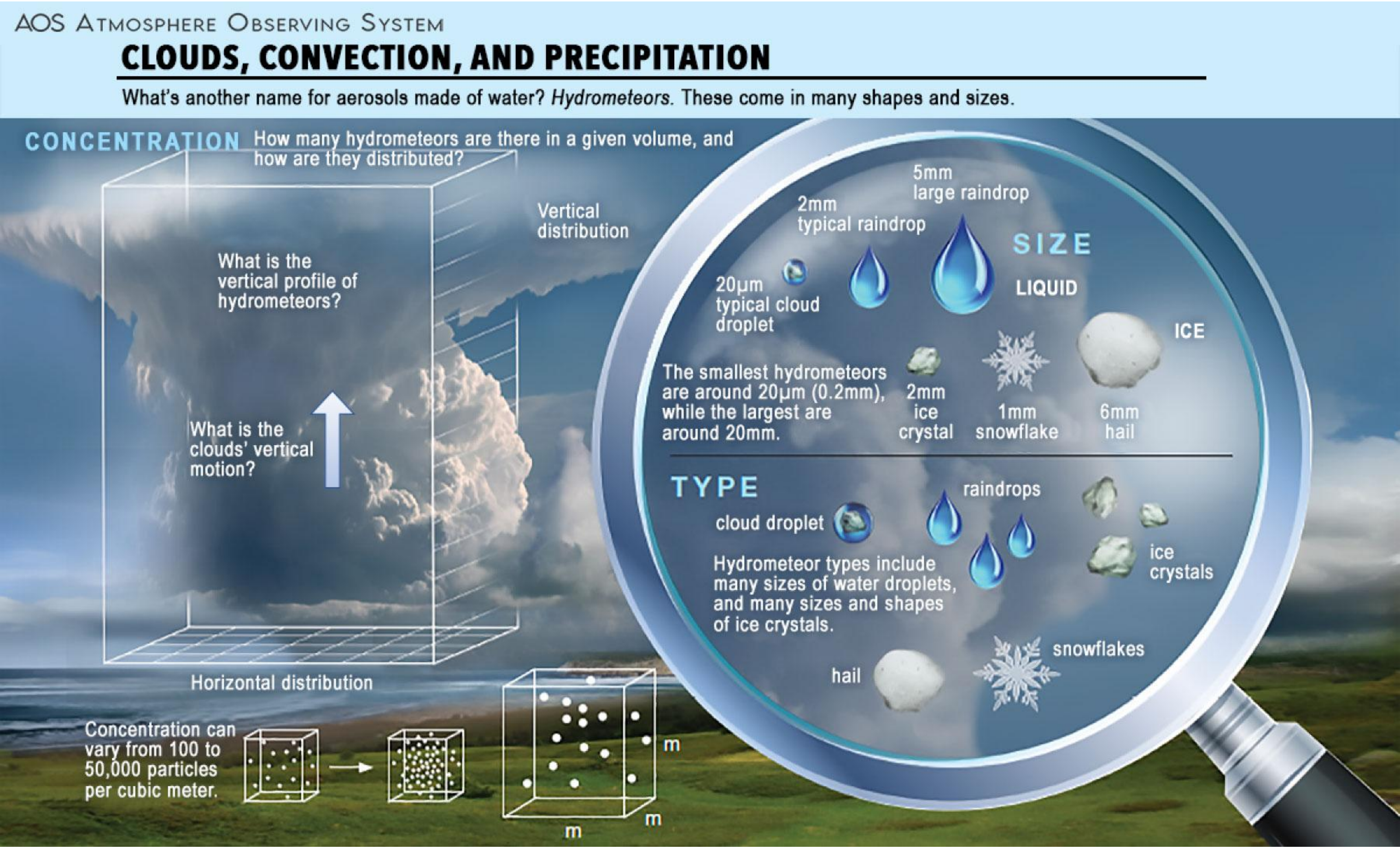
Vegetation

Soil Properties

Physics Parameterizations

- Land Surface
- Surface Layer
- Planetary Boundary Layer (PBL)
- Convection ("parameterized" vs "explicit")
- Microphysics – will introduce!
- Radiation
- Others …

Microphysics Parameterizations



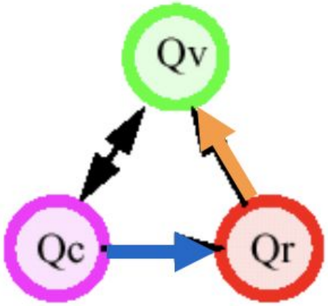
From NASA

Microphysics Parameterizations

- Obtain tendencies in temperature and moisture
- Microphysical processes
  - Aggregation, deposition, accretion, growth, condensation, freezing, melting, break up …
- Predict one or more **moments** of the distribution of hydrometeors
  - Vapor, cloud water, cloud ice, rain, snow (**5-class**)
  - Vapor, cloud water, cloud ice, rain, snow, graupel (**6-class**)
- **Single-moment**: mixing ratios of hydrometeors
- **Double-moment**: mixing ratios and number concentration of hydrometeors

Microphysics Parameterizations

Kessler

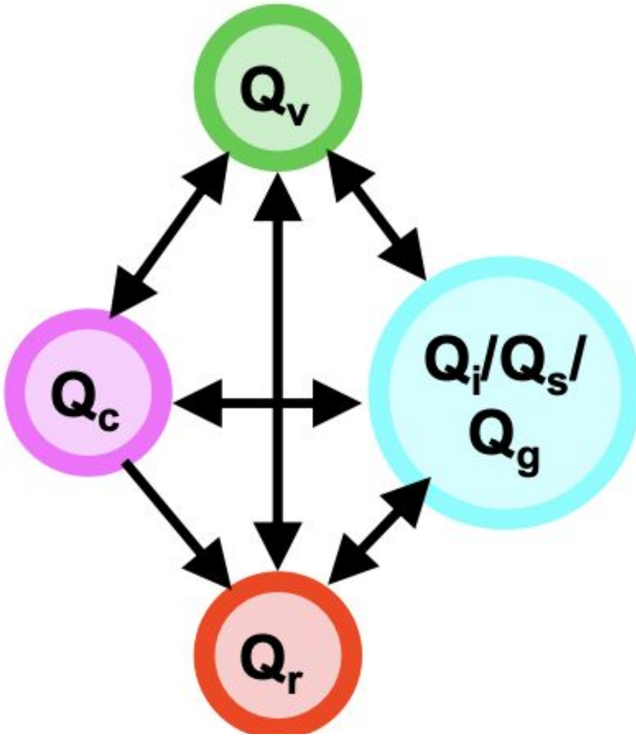


- **Kessler (1969) – simplest WRF MP scheme**
- **Key Processes:**
  - **Condensation to form cloud droplets; diffusional growth of cloud droplets**
  - **Autoconversion of cloud droplets to form rain**
  - **Coalescence of cloud droplets by falling rain**
  - **Evaporation of cloud or rain to vapor**

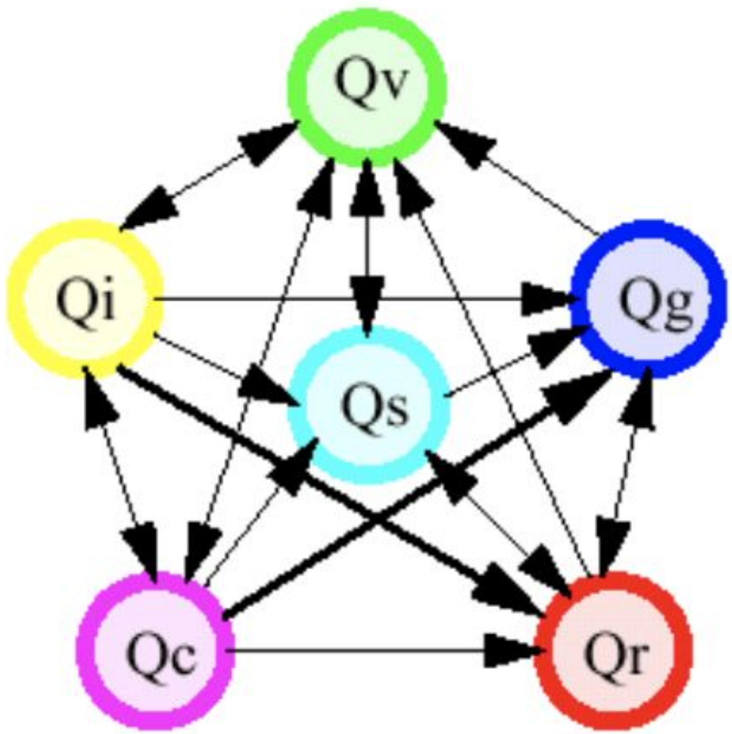
From Gary Lackmann

Microphysics Parameterizations

Ferrier (NOAA/NCEP)



Thompson
Double-moment, six-class



From Gary Lackmann

Quiz 2/5

- Which physical processes do NOT need to be “parameterized” in high-resolution, regional models?

A. Boundary Layer
B. Thunderstorms
C. Microphysics
D. Land Surface

End of Part I

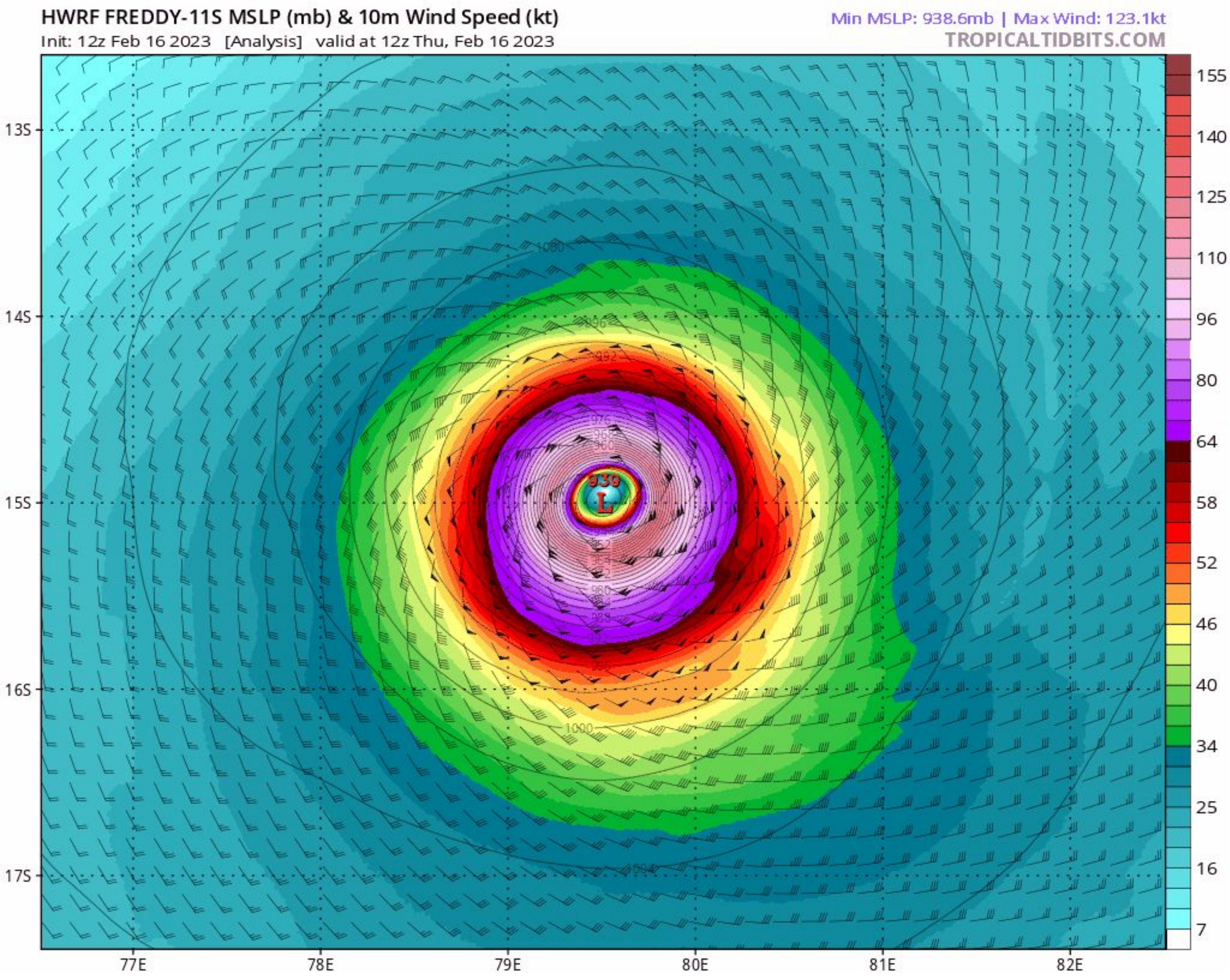
Start of Part II

What do TCs look like in numerical models?

- Global Models
  - Are they becoming realistic?
- Regional Models
  - Should be realistic
  - Need a realistic TC to accurately predict intensity

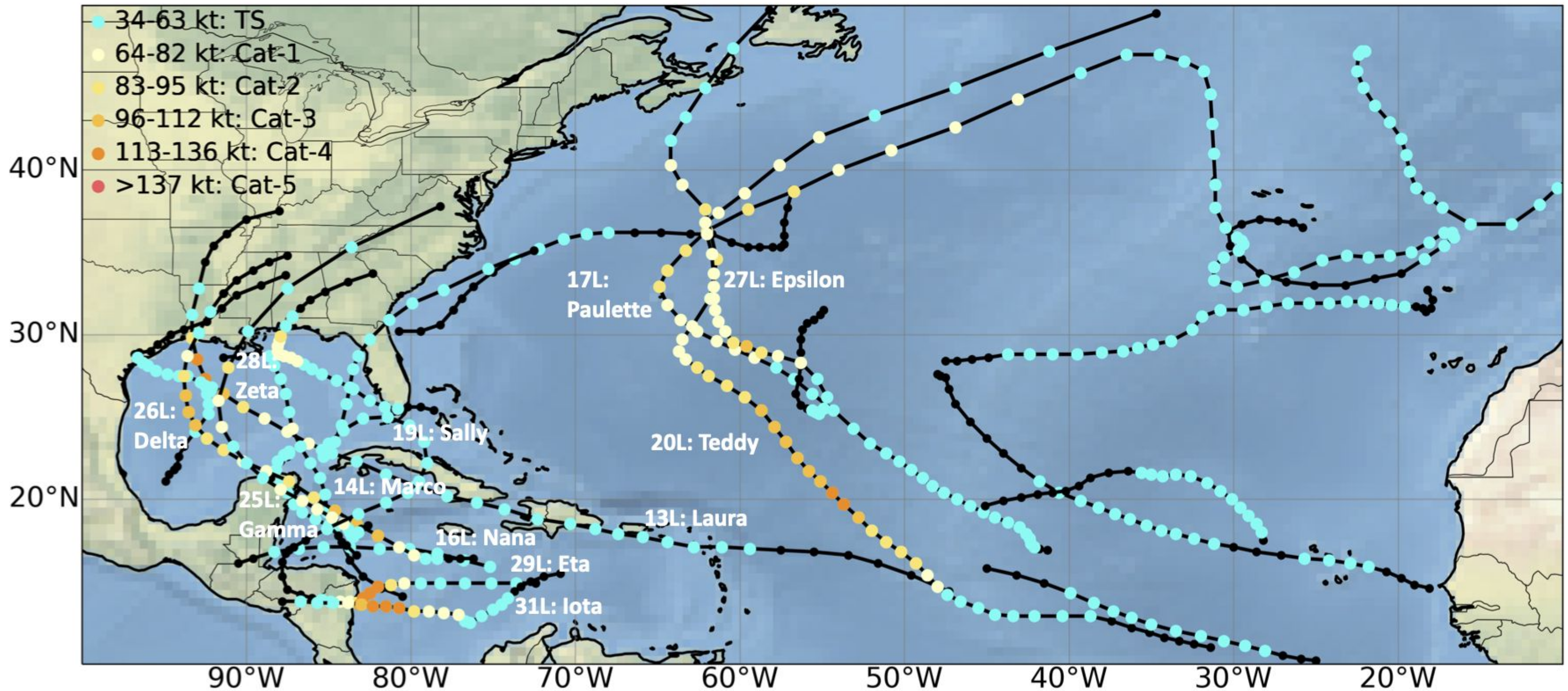
- Less emphasis on track and intensity here, and more emphasis on **3-dimensional structure**.

HWRF Surface Wind Forecasts of Cyclone Freddy (2023)



ECMWF and COAMPS-TC study

- Benchmark ECMWF in-house experimental forecasts versus a high-performing regional TC model (COAMPS-TC)
  - ECMWF
    - Designed and evaluated for many different metrics and applications
  - COAMPS-TC
    - Designed and tuned for TC performance



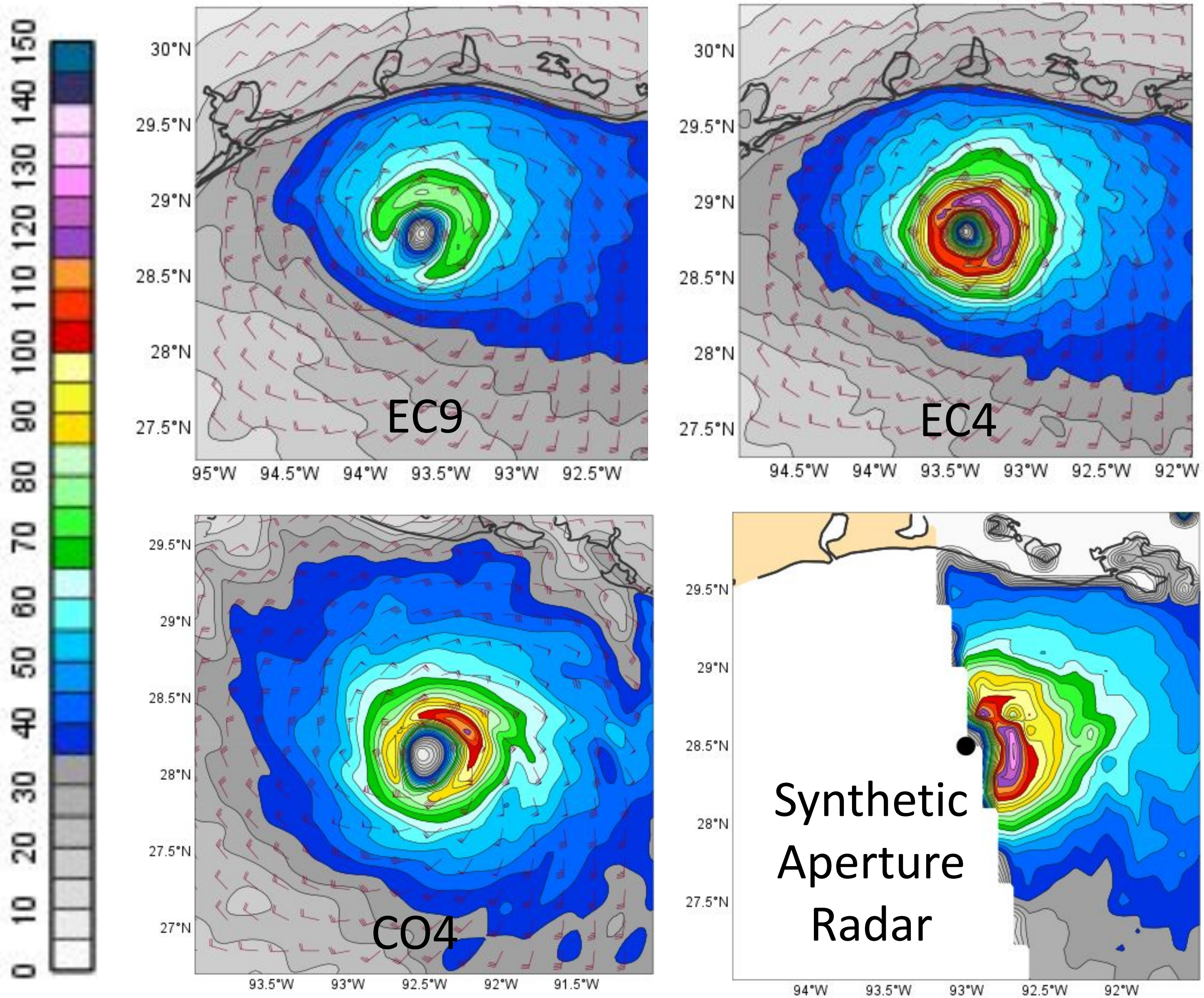
Majumdar et al. (2023)

Numerical Experiments

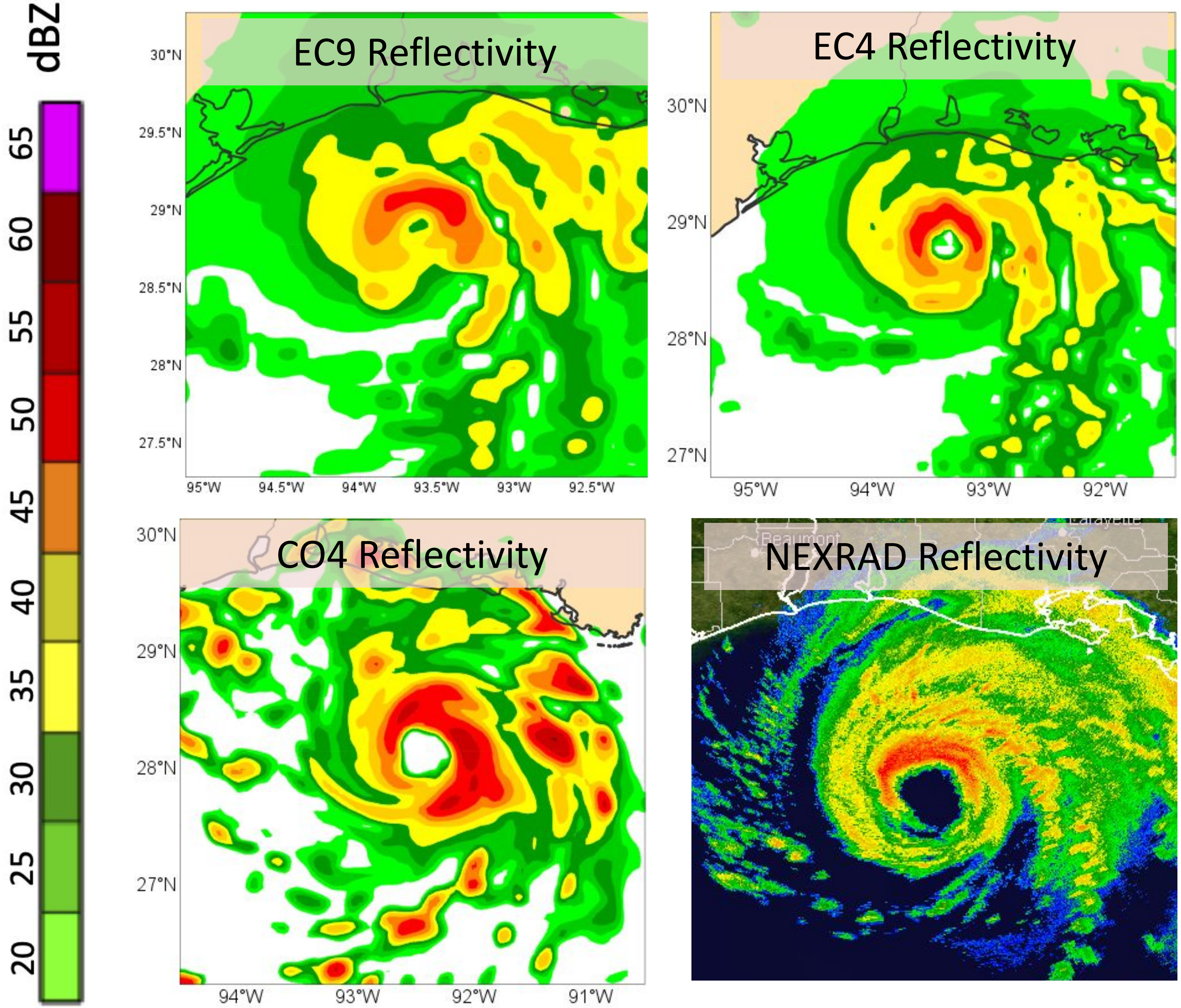
- 12-hourly ECMWF simulations (hindcasts) integrated from operational ECMWF analyses:
  - EC9 – 9 km, recently operational physics package
  - EC4 – 4 km, all else same as 9 km
- CO4 – Operational COAMPS-TC (2020 version)
- *Next: 60-hour forecasts of Hurricane Laura (2020)*

Majumdar et al. (2023)

Surface Winds (usually 10 m winds in models)

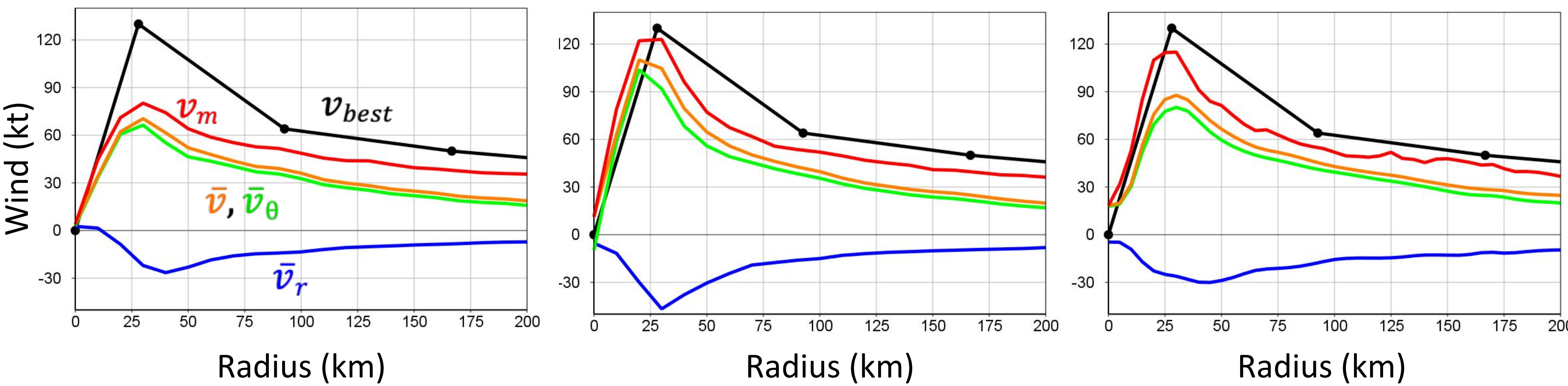


Radar Reflectivity



EC9 EC4 CO4

Radial Profile of Surface Winds



Evaluate model forecasts against NHC Best Track, including radii of 34-kt, 50-kt, and 64-kt wind.

Maximum wind speed at each radius is more realistic in 4 km models than in 9 km ECMWF.

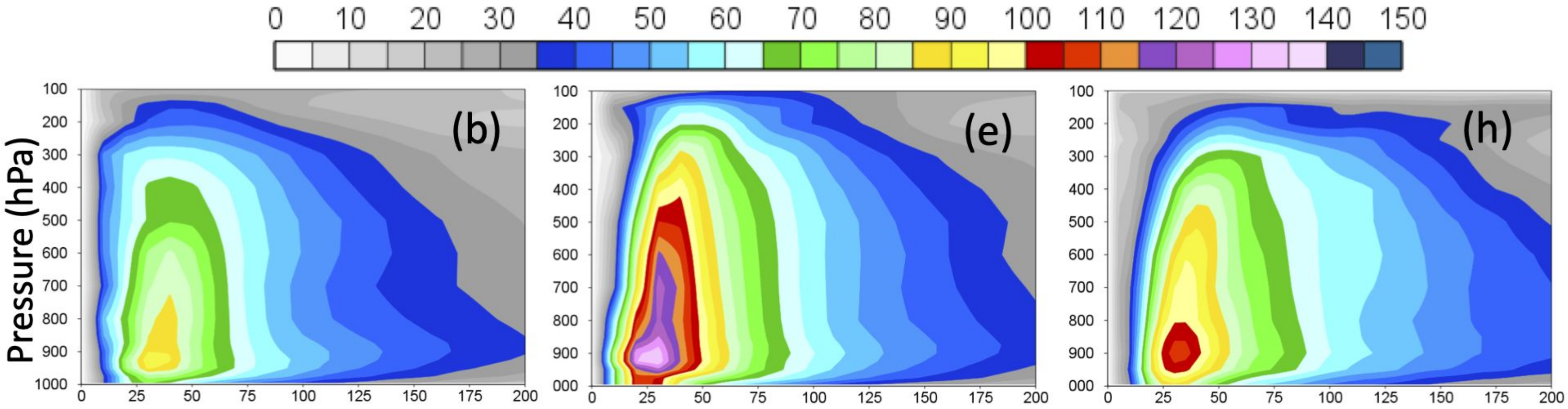
Radial inflow is strongest in EC4.

Wind speed is almost completely dominated by the swirling wind.

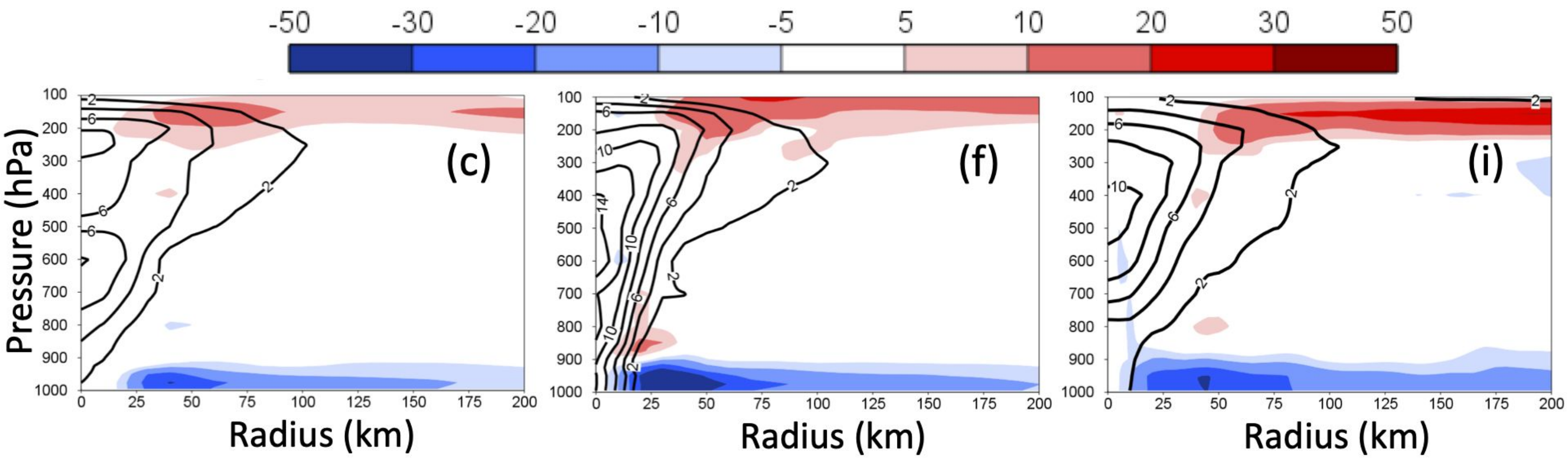
Radius of Maximum Winds is accurate in this example.

EC9 EC4 CO4

Total Wind



Radial Wind and Temperature Anomaly



EC4 simulates a deeper hurricane than EC9, stronger inflow and outflow, deeper warm core.

Quiz 3/5

- What is Hurricane Laura’s radius of maximum winds in the 4 km models?

A. 10 km
B. 30 km
C. 50 km
D. 100 km

Quiz 4/5

- How much warmer is the center of Laura than its environment in the 4 km models?

A. 1°C
B. 5°C
C. 10°C
D. 20°C

Summary

- **How to evaluate TCs in models?**
  - Conventionally ...
    - NHC Track and Intensity (maximum wind; minimum pressure)
  - Expand to **surface structural variables**
    - NHC Radius of Maximum Winds
    - NHC Radii of 34-kt, 50-kt, and 64-kt winds
  - Be careful about uncertainties in data!
  - Expand to **more advanced structural evaluations**
    - Compare against aircraft observations (where available): radar, dropsondes, flight-level obs, SFMR etc.
    - Simulated vs actual satellite observations (e.g. infrared)

End of Part II

Start of Part III

The next generation of model-based products

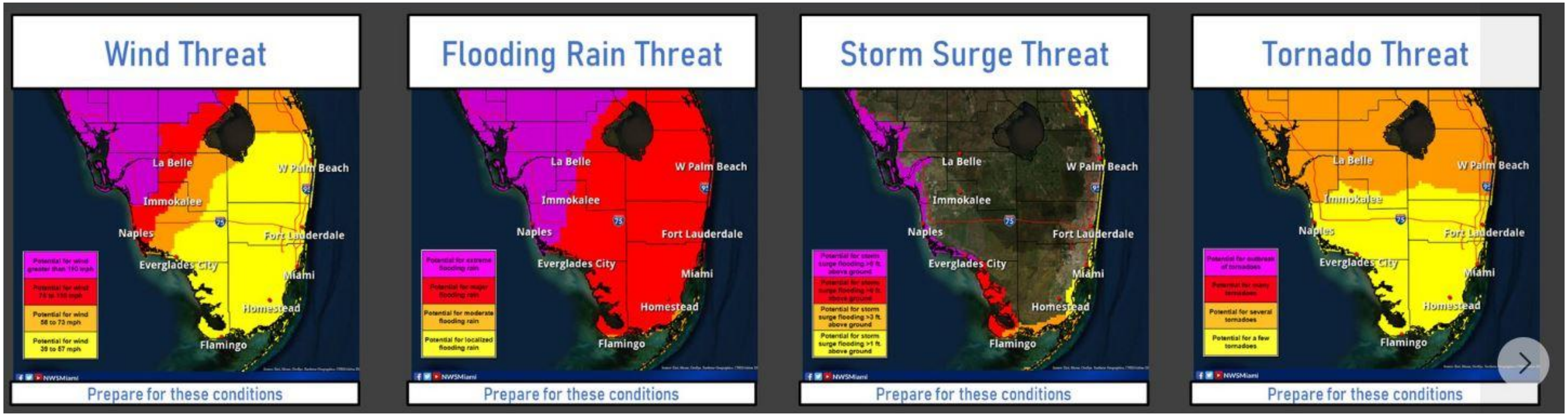
- A dream ... to make accurate forecasts of <u>impacts</u>

- “Will there be flooding in my street?”
- “Will my roof be damaged?”
- “Will there be public health impacts, and for how long?”
- “Will we have a better knowledge of when and how to evacuate hospital patients?”

- Main threats: storm surge, flooding rain, wind, tornados

Graphical Communication of Weather Risk

- Starting point: NOAA's Hurricane Threats and Impacts (HTI)
- Created by local NWS offices in USA



Graphical Communication of Weather Risk

- *More information about NOAA social science on Friday March 10th (Gina Eosco / Castle Williamsberg)*

- Our NOAA project employs a user-centered design approach
- Begin with “design charrettes”
  - To employ a participatory design process to provide a front-end analysis of users’ needs and preferences for effective risk communication.

- Reacting to graphics
- Map construction
- Identifying design priorities

- 4 charrettes
- 33 participants
- Local organizations

Design Charrettes: Feedback from Participants

MAP CONSTRUCTION

- Simplify **color coding** and highlight the **warning** information.
- Visualize the threat risk based on the **levels of impact and uncertainty**.
- Add **time-related information** while being aware of the uncertainty.
- Provide **localized** and **personalized** information.
- Provide an **overview** of the **hazard** situation.

LEGEND CONSTRUCTION

- Clarify the concept of “**storm surge**”.
- Design the legend with **visual**, **numerical**, and **real-scenario** explanations.

ACCESSIBILITY

- Design graphics available for **multiplatform** distribution.
- Consider the barriers of **seniors** and people with **disabilities**.

Graphical Communication of Weather Risk

- Next steps:
  - Online public experiments
  - Interviews with broadcast meteorologists and emergency managers
  - Test new prototype graphics
    - Legends and design characteristics
    - Information about timing
    - Multiple hazards
  - Develop a “Best Practices” guide on graphical design

Quiz 5/5

- Which threat / impact are **you** usually most concerned about?

A. Wind
B. Flooding Rain
C. Storm Surge
D. Tornadoes

Final Remarks

Final Remarks: Priorities

- **Resolve** hurricanes adequately in models
- Develop consistent model **physics**
- **Initialize** hurricanes in models more accurately with **assimilation of targeted satellite and aircraft observations**
- Model **holistically**: atmosphere / ocean / waves / land interactions
- Scientific challenges: **formation** and **rapid intensification**
- Develop **impact forecasting** in models
  - Storm surges, detailed wind structure, rainfall structure, hydrology, land use
- Improve prediction and management of **uncertainty**