NWS Nashville Presents

Weather 101

Numerical Weather Models

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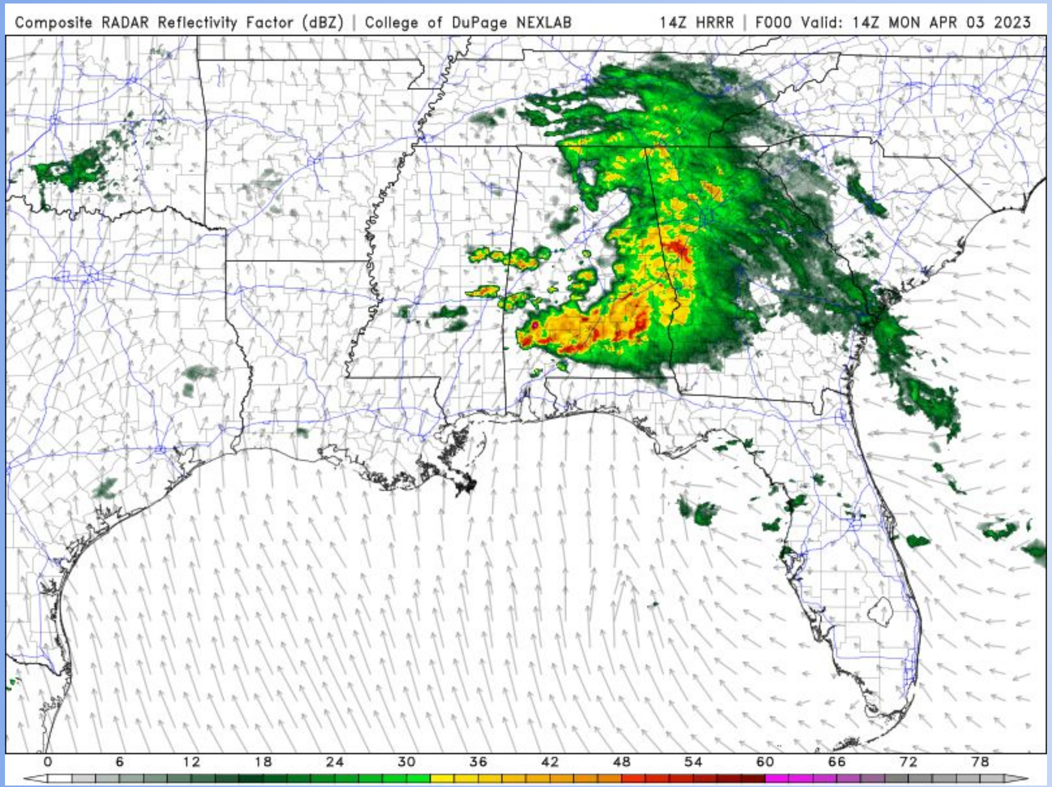
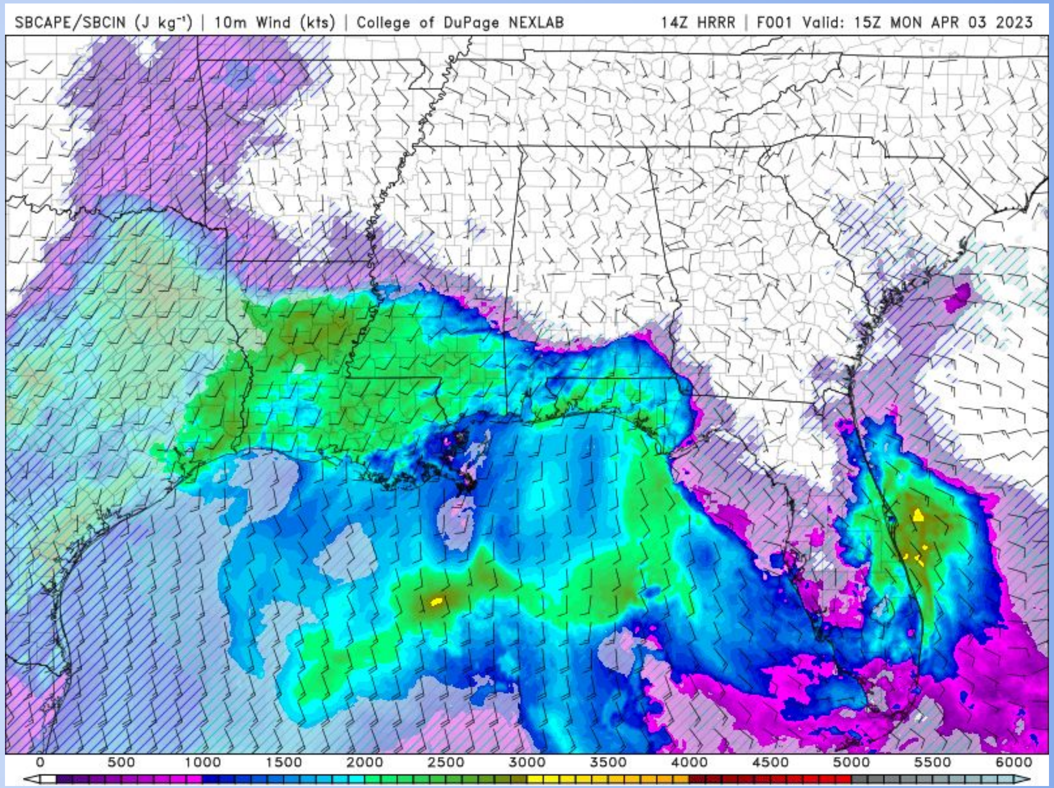
What are Numerical Weather Models?



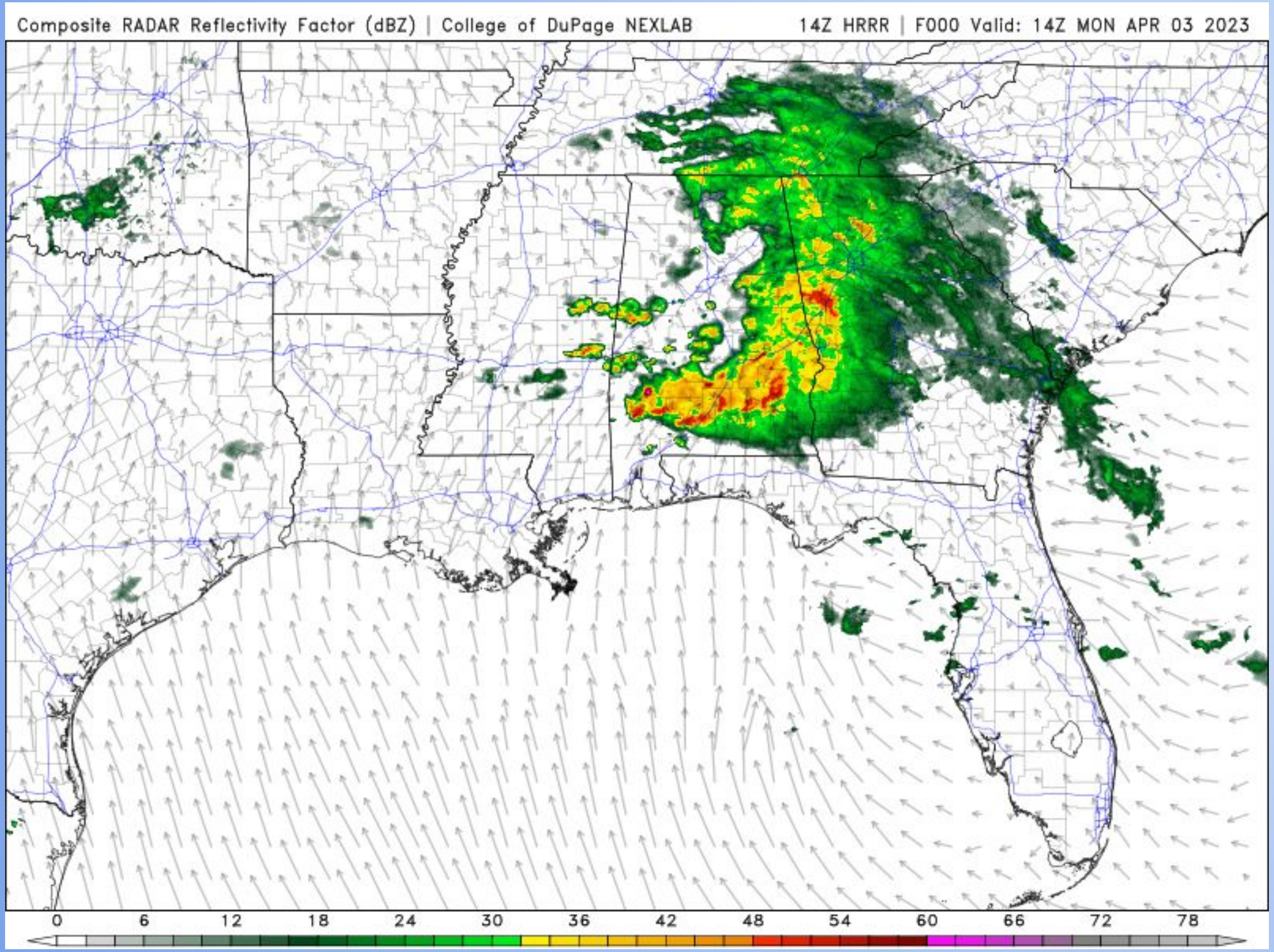


Computational physics and mathematical simulations to predict the future weather!

Overview

- How do weather models work?
- What types of weather models are there?
- How we use them in forecasting & limitations
- The future?

Background



- What will this HRRR simulated radar image look like next hour?
  - Well it's based on the wind speed at low & upper levels, cooling from rain, heating from the sun **& how the wind changes because of these other changes!**

Background

Just going to do a brief run through of some of the physics and math behind weather models. No worries if your not a math or physics person!

Background - Newton's 2nd Law

- We can't really avoid some math in a discussion about models...but at the most simple level, Newton's Second Law provides what we need.

Force = Mass * Acceleration

↓

Acceleration = Change in Velocity over Time

↓

So we can relate how air velocity changes over time to the forces acting on the air!

Background - Newton's 2nd Law Example

$$\sum F = ma$$

$$a = \frac{\sum F}{m} \quad (solve\ for\ the\ acceleration\ of\ the\ air)$$

$$a = \frac{dv}{dt} = \frac{\sum F}{m} = PGF + Coriolis + Gravity + Friction$$

Pressure Gradient Force (air flows from high to low pressure)

Earth's rotation accelerates the wind by deflecting horizontally

Gravity always accelerates towards Earth

Frictions always decelerates wind

Background - Predictive Equations

- **Don't worry about specifics here!** To make an accurate forecast, these equations quickly get very complicated & complex when you start adding moisture, temperature gradients, etc.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{v}{r}\frac{\partial u}{\partial \lambda} + w\frac{\partial u}{\partial z} - \frac{v^2}{r} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial r}, \quad (2.1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + \frac{v}{r}\frac{\partial v}{\partial \lambda} + w\frac{\partial v}{\partial z} + \frac{uv}{r} + fu = -\frac{1}{\rho r}\frac{\partial p}{\partial \lambda}, \quad (2.2)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial r} + \frac{v}{r}\frac{\partial w}{\partial \lambda} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g, \quad (2.3)$$

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial \rho r u}{\partial r} + \frac{1}{r}\frac{\partial \rho v}{\partial \lambda} + \frac{\partial \rho w}{\partial z} = 0, \quad (2.4)$$

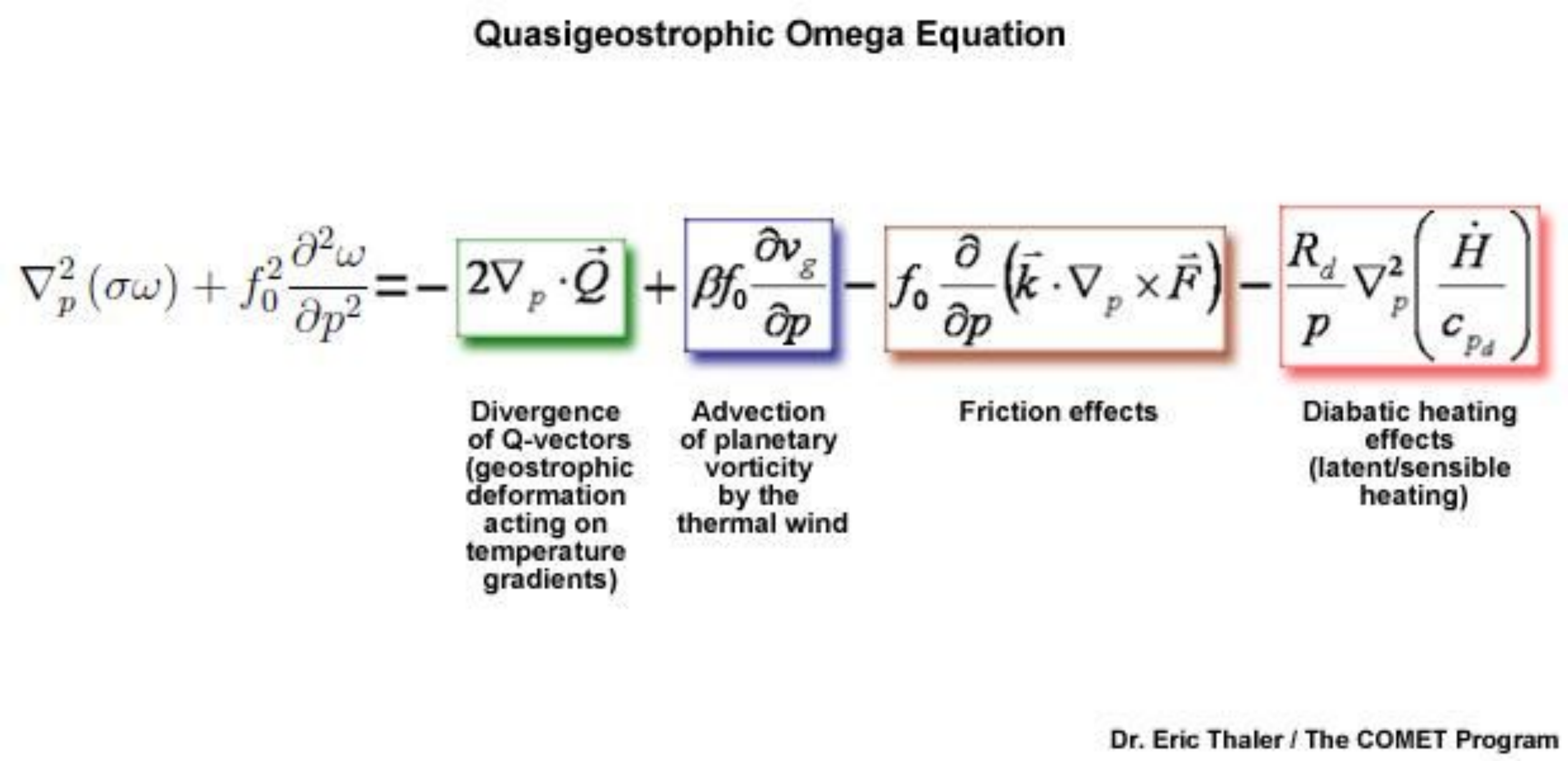
$$\frac{\partial \theta}{\partial t} + u\frac{\partial \theta}{\partial r} + \frac{v}{r}\frac{\partial \theta}{\partial \lambda} + w\frac{\partial \theta}{\partial z} = \dot{\theta} \quad (2.5)$$

$$\rho = p_* \pi^{\frac{1}{\kappa}-1}/(R_d\theta) \quad (2.6)$$

https://www.meteo.physik.uni-muenchen.de/~roger/TCLecs/Tropical%20Cyclones_Dynamics.html

Background - Predictive Equations

- **Again don't worry about specifics here!** But some simplifications and clever physics can develop an equation like this which predicts vertical motion in the atmosphere.



History lesson time!

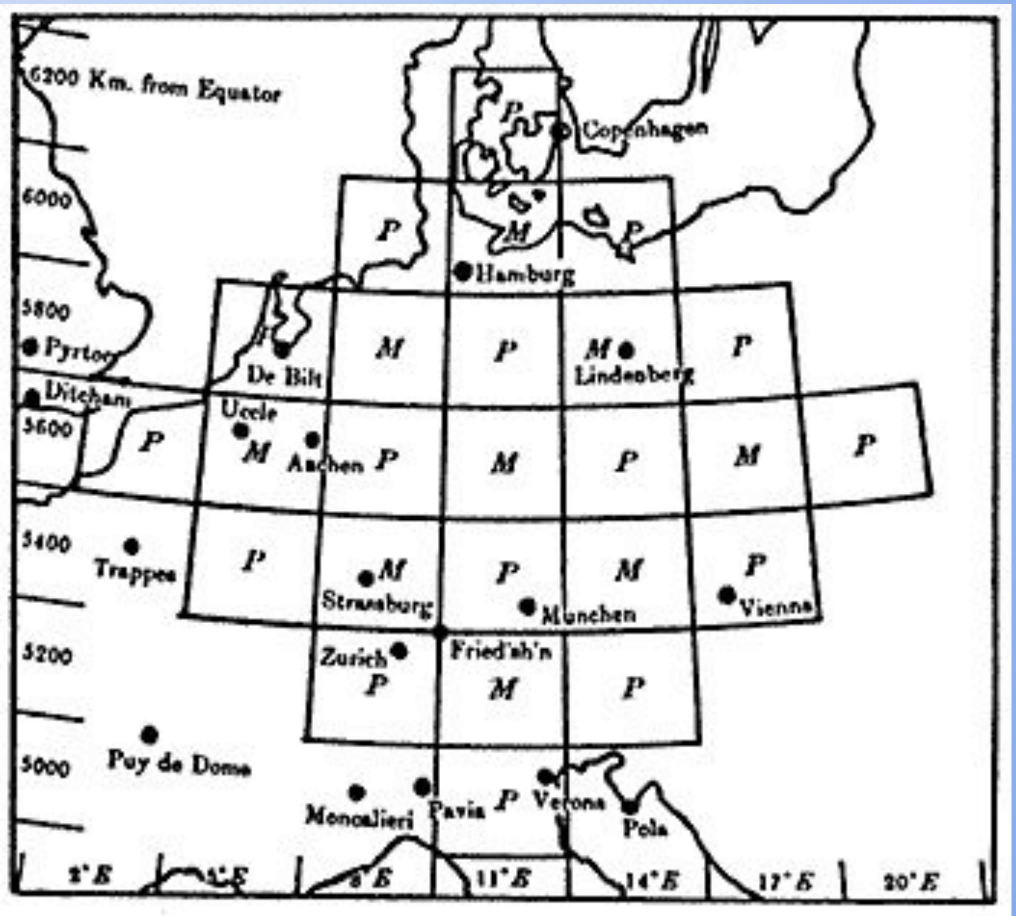
History of NWP

Lewis Fry Richardson in the early 1900's is credited with the first Numerical Weather Prediction purely following these sets of equations.

He used a simplified full set of those equations to predict the pressure map for 6 hours in the future.

This took Richardson 6 weeks (!) to calculate by hand.

Forecast Map of Europe by Richardson



How do they work?

Computers, particularly modern supercomputers, can now do this type of calculation in microseconds.

So we know can use those equations to predict future weather extremely fast, multiple times per day.

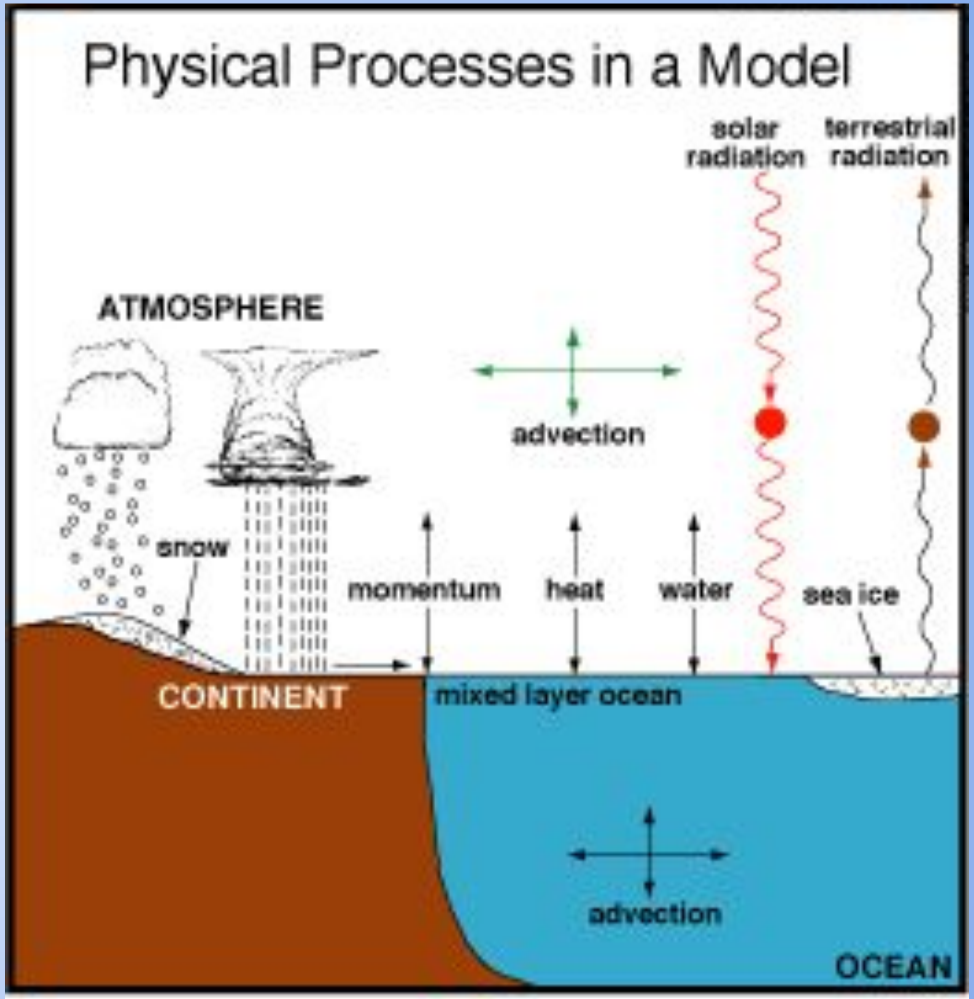
NOAA supercomputer that supports all modeling operations. One of the fastest computers in the world!

How do they work?

How do they work?

Models are essentially a compilation of smaller models, each handling their own portion of the earth-atmosphere.

Boundary layer, ocean-atmosphere, free atmosphere, cumulus-cloud, microphysics, radiation, etc.

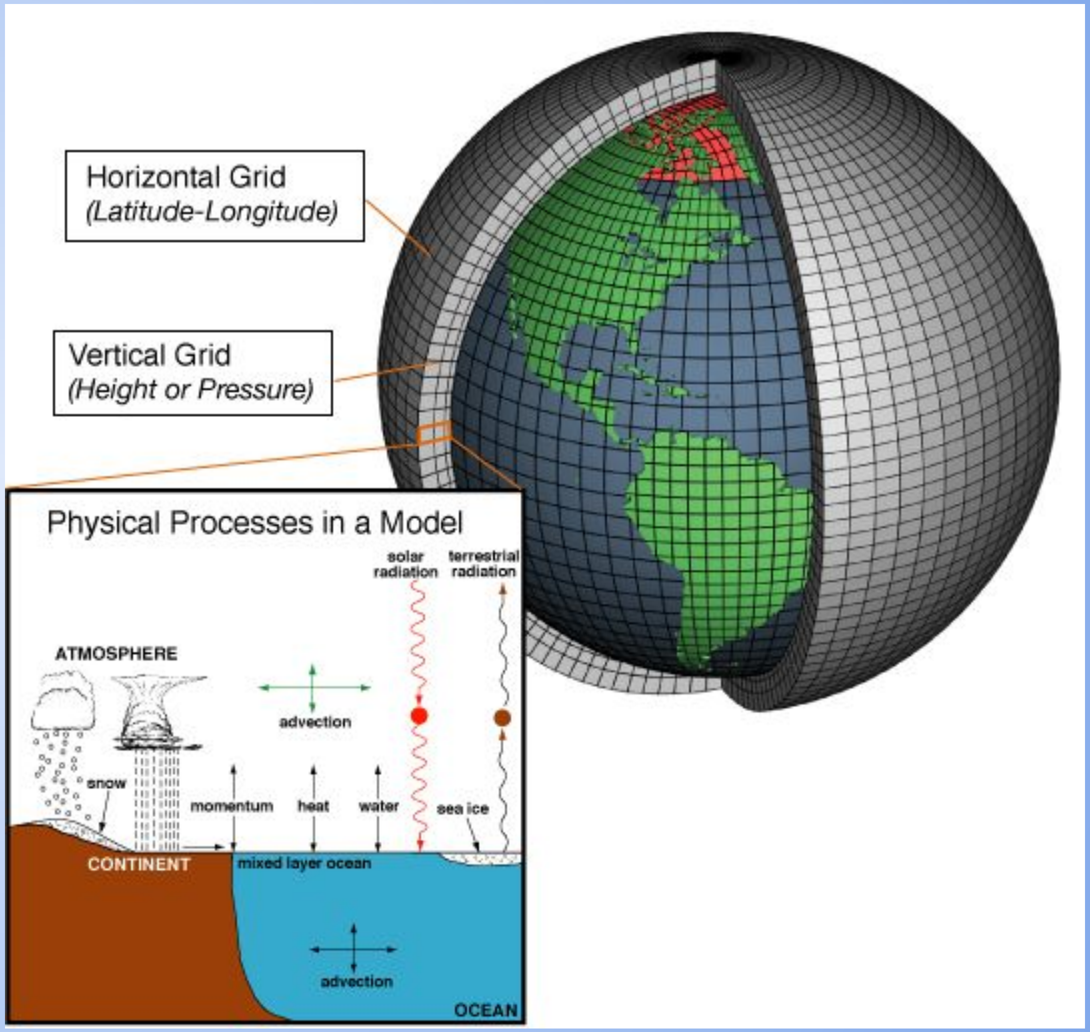


Examples of the processes in weather models.

How do they work?

The equations previously shown all correspond to some to process (wind acceleration, moisture transport, temperature changes, etc.)

The equations are then **solved on a grid** using some numerical mathematical methods.

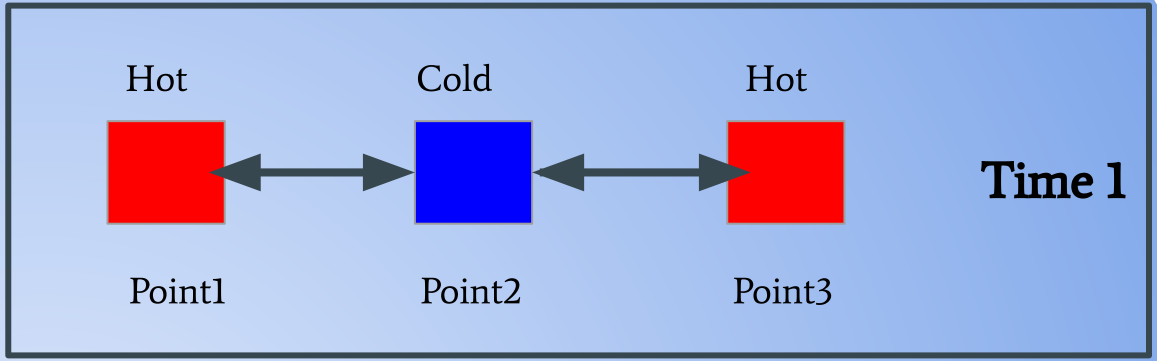


<u>Example:</u> These processes are all solved within each of the grid cells.

Solving on a Grid

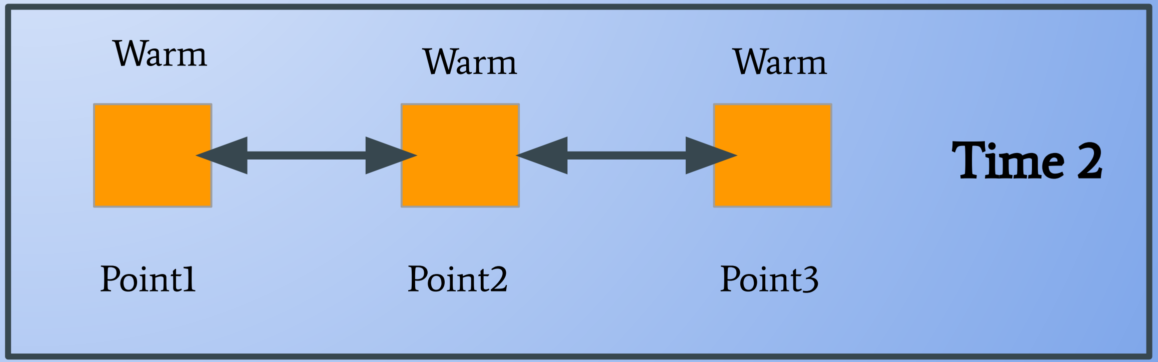
At the most fundamental level, the equations we discussed answer the question...

How does the temp (or any parameter) at a point influence the surrounding points and future times?



With this setup, how will temperature change over time?

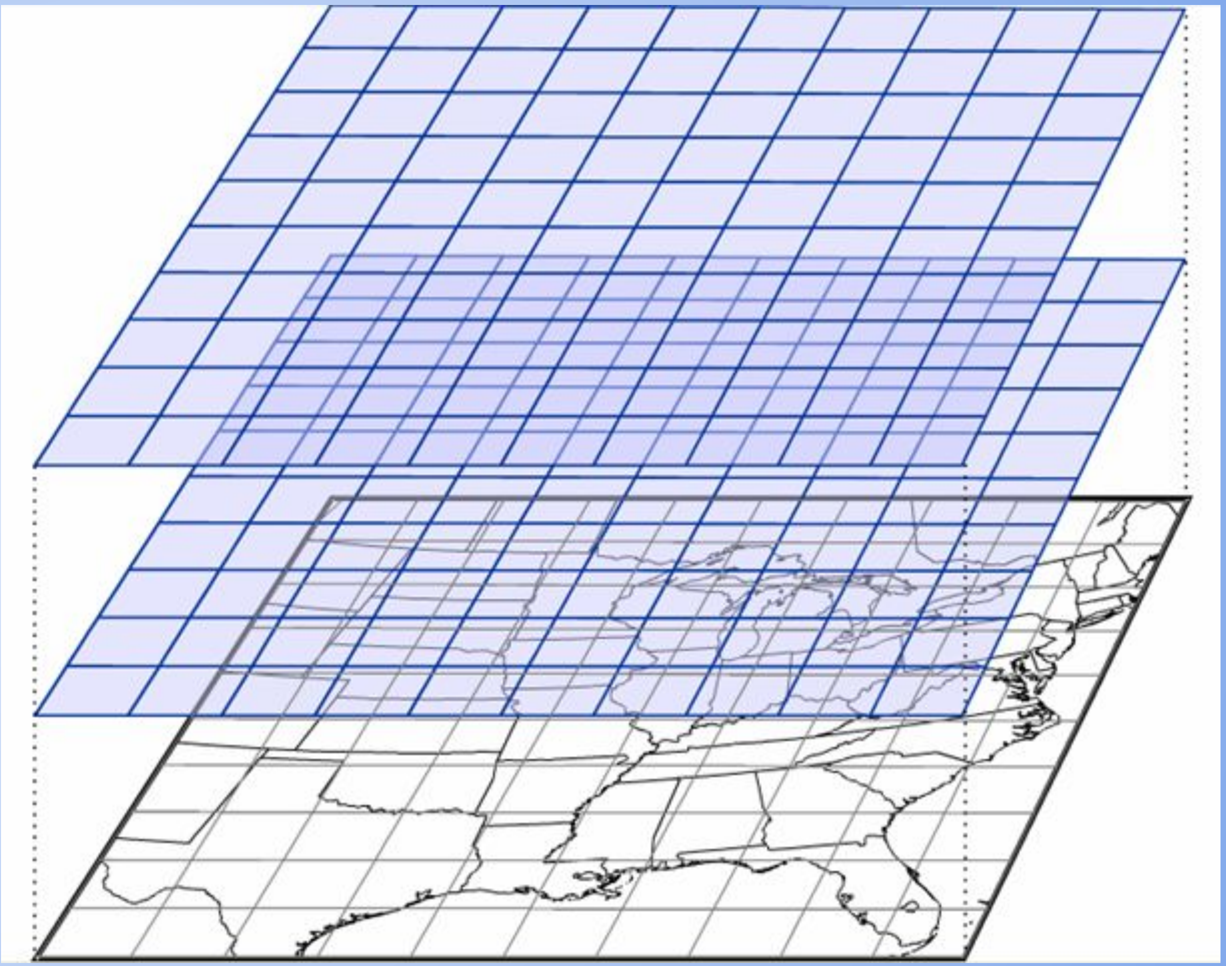
The equations basically describe how higher temps “flow” to colder areas and eventually the blocks will settle to common temp.



Grid Spacing

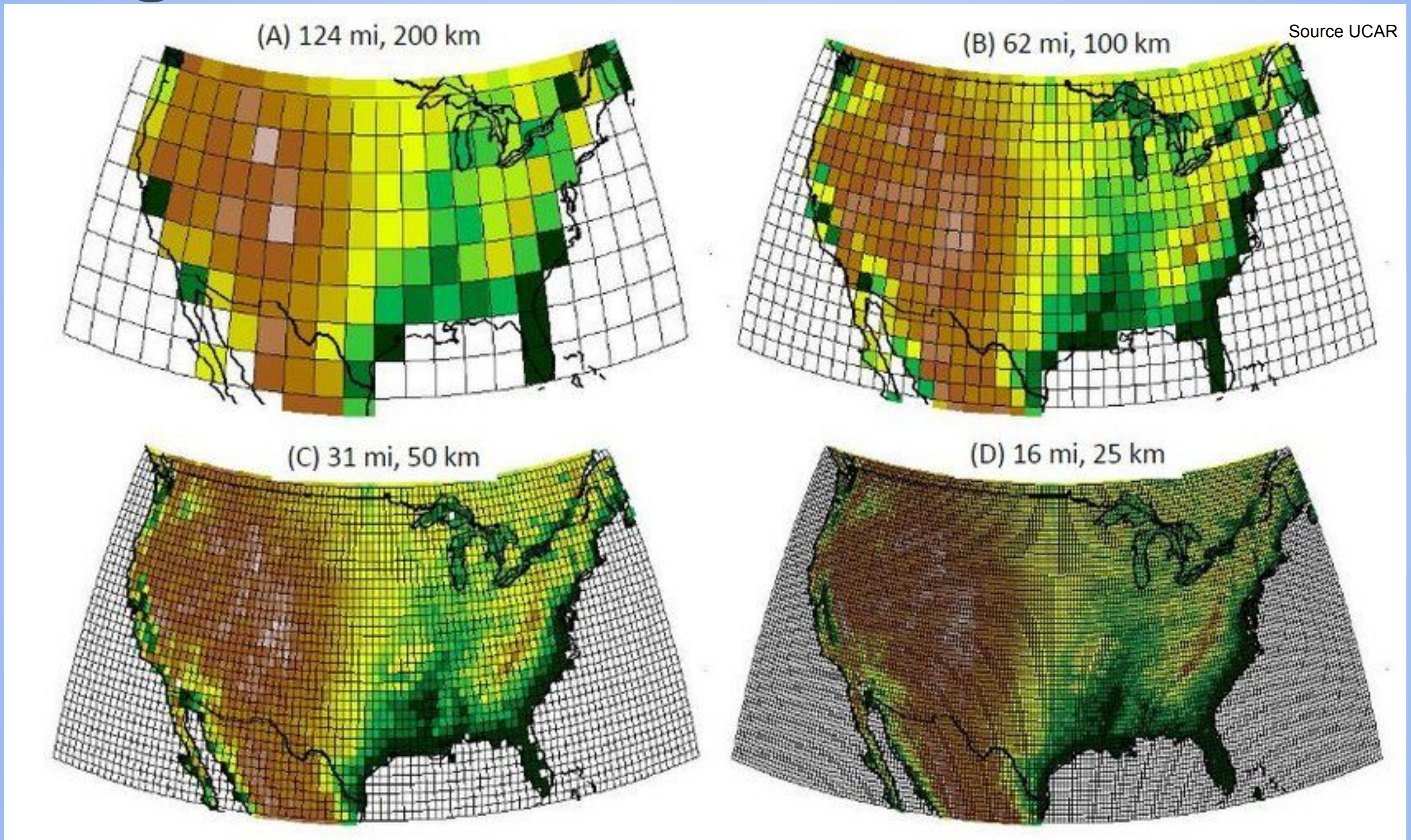
This process is done on millions of grid points horizontally and vertically in the atmosphere. Pressure, temperature, wind speed, dew point, height above ground, etc. within each grid cell (horizontally and vertically) are sent into the equations.

Layers of grids are stacked throughout the atmosphere.



https://www.e-education.psu.edu/worldofweather/node/2029

Grid Spacing & Resolution

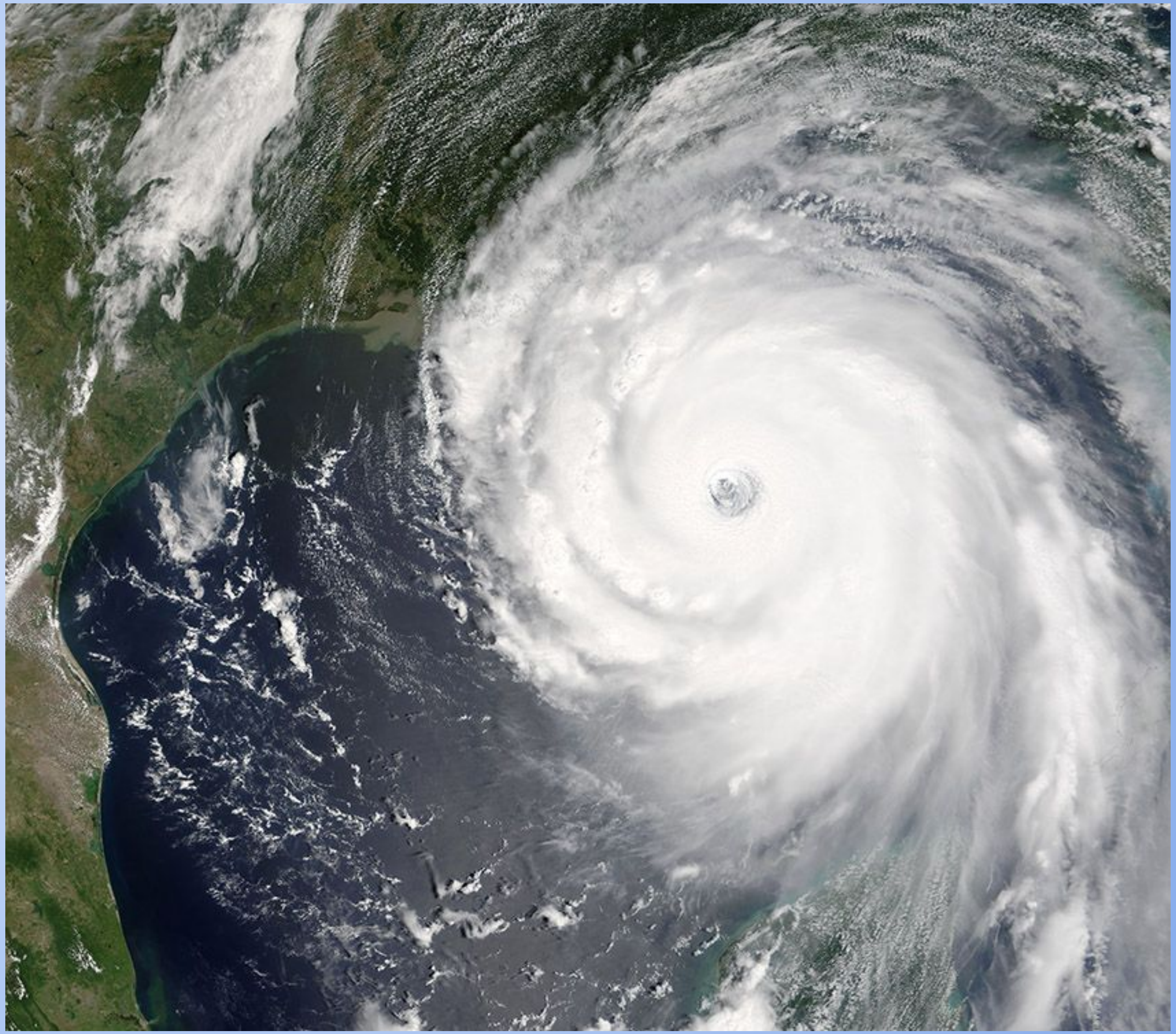


A key difference between weather models are their grid spacing. Modern weather models generally run from around 1km up to 20km.

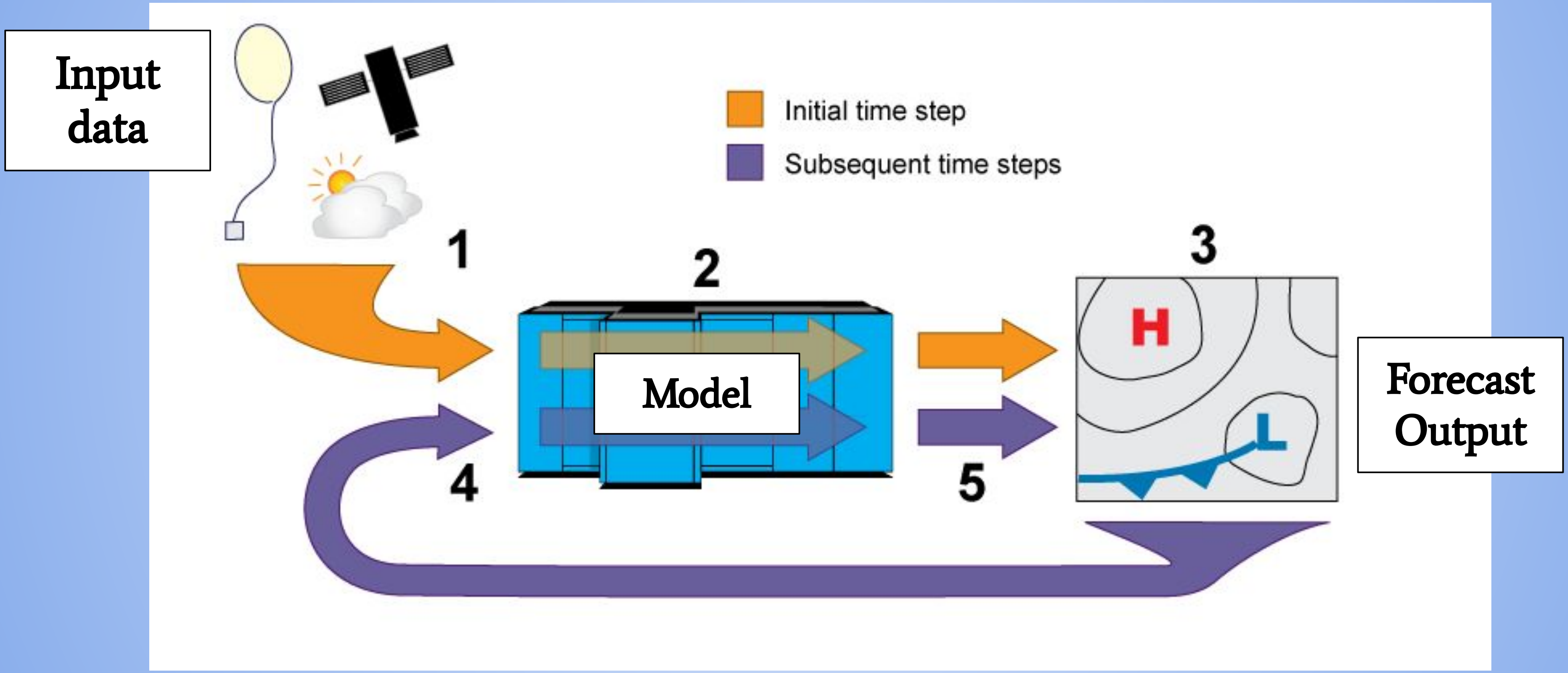
Grid Spacing & Resolution

A key difference between weather models are their grid spacing. Modern weather models generally run from around 1km up to 20km.

Some models would fit tons of grid points inside a hurricane, others maybe just a few.



From Start to Finish Process

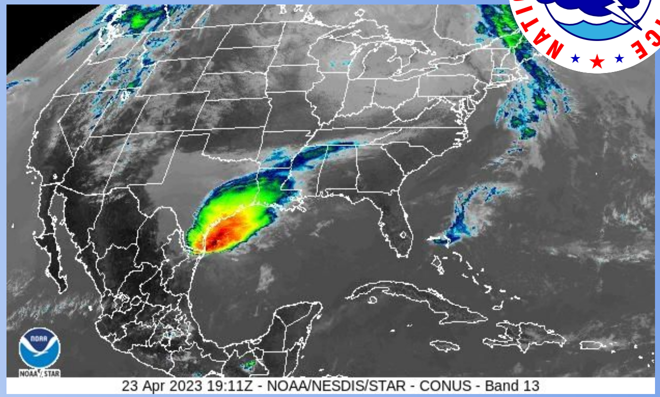


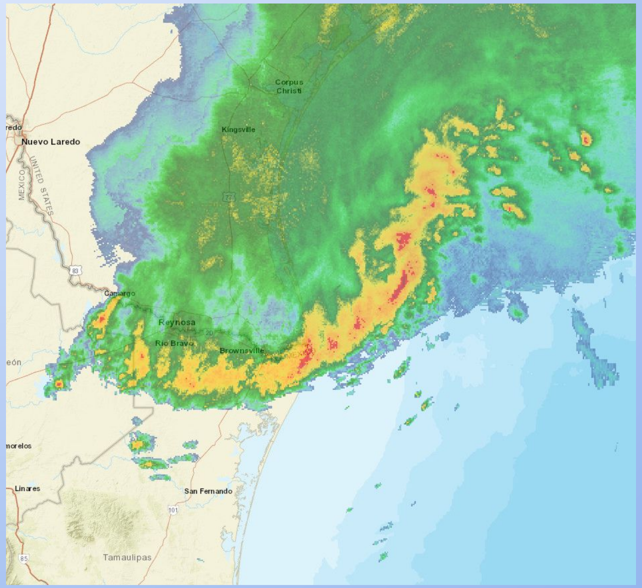
Start to Finish Processes - Input

Input: Satellite, old model data, land stations, sounding balloons, radar, airplanes, etc.

Input data is inherently imperfect is part of the reason models are not perfect.

This step is extremely important and complex.

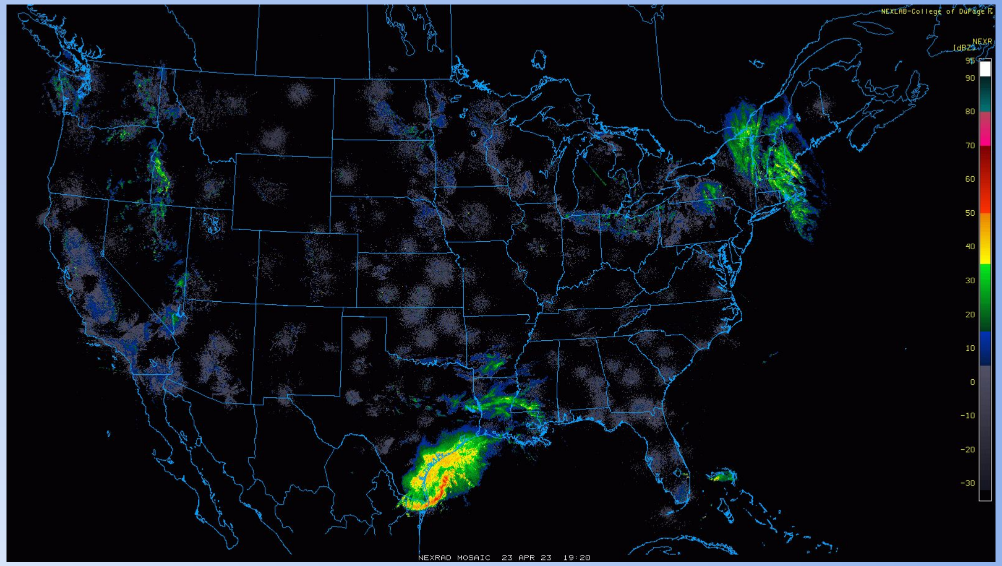




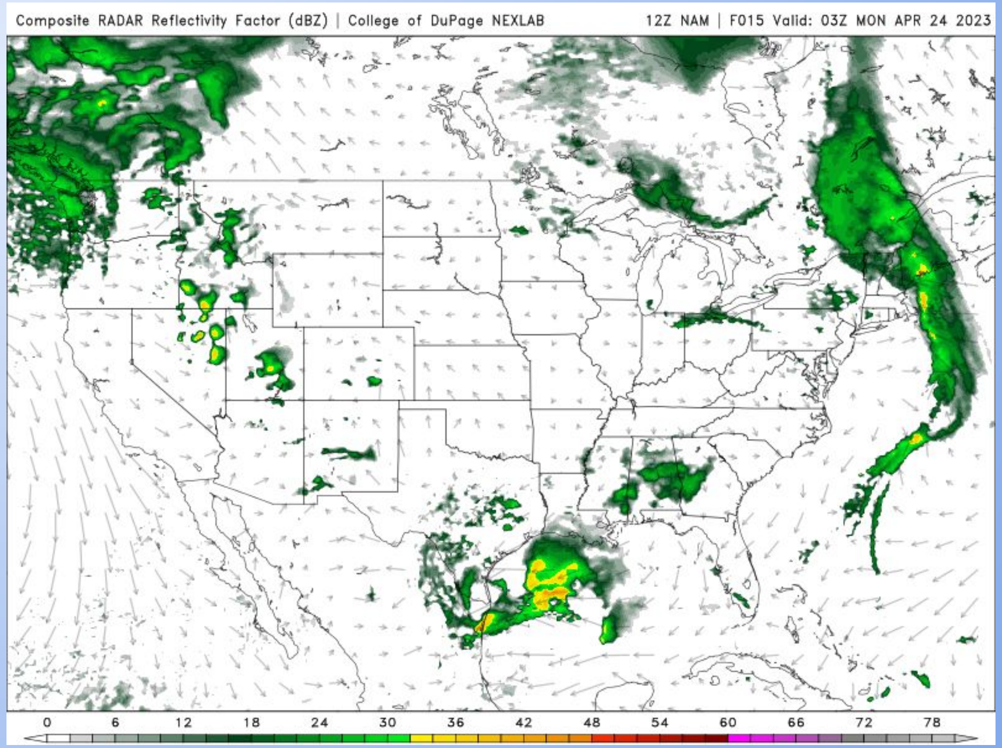
Start to Finish Processes

NWP: the input goes into a model and from here a prediction is made. The prediction is then fed back into the model has next set of inputs.

We talked a bit about how these models work, so now let's discuss different types.



Observation



12 hour forecast

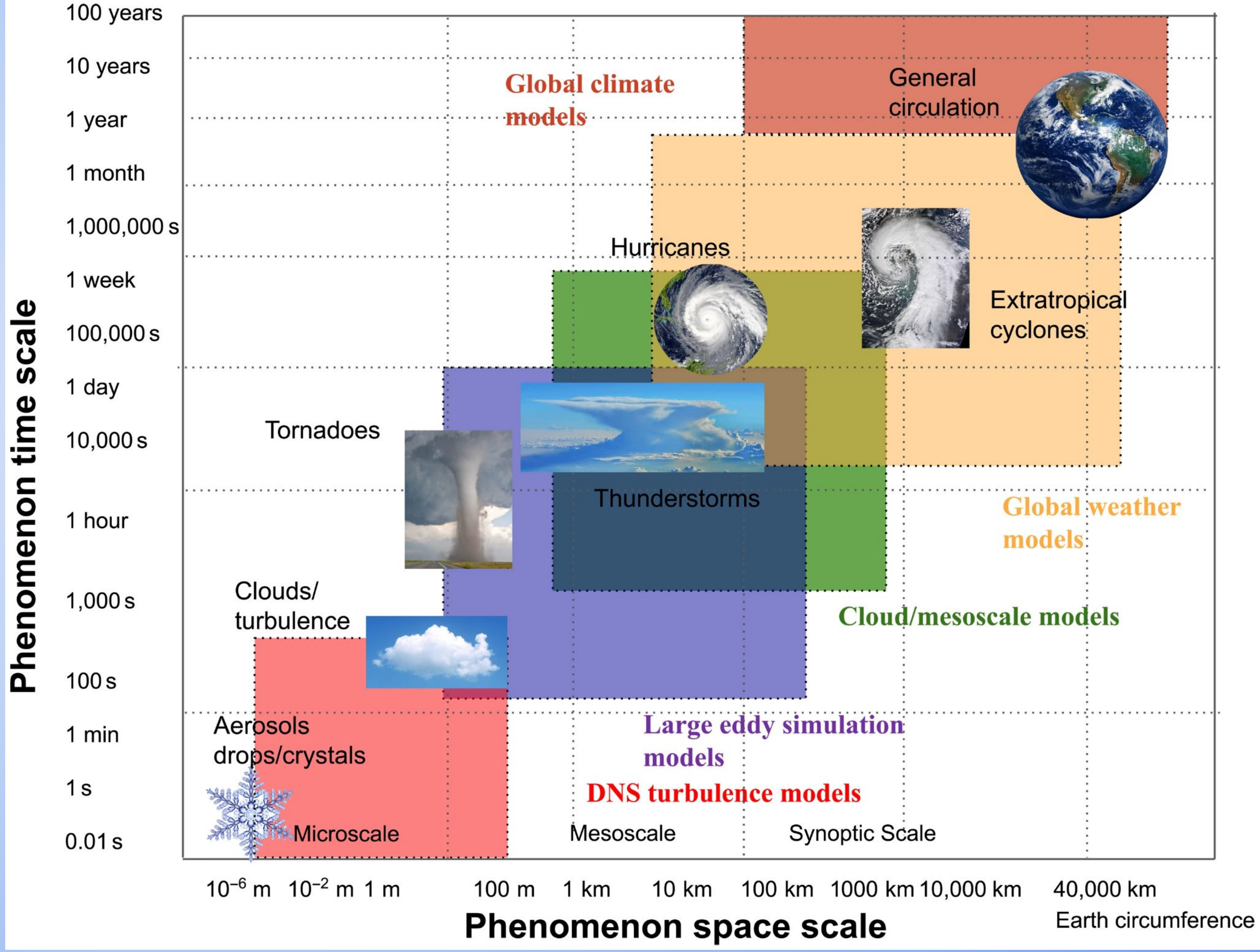
Any Questions?

Types of Weather Models

Two Primary Categories:

Global Models

High-Resolution
(Convective Allowing)



https://www.science.org/doi/10.1126/sciadv.abn3488

Types of Weather Models

If we wanted to predict thunderstorms for the afternoon, would we prefer hi-res or global?

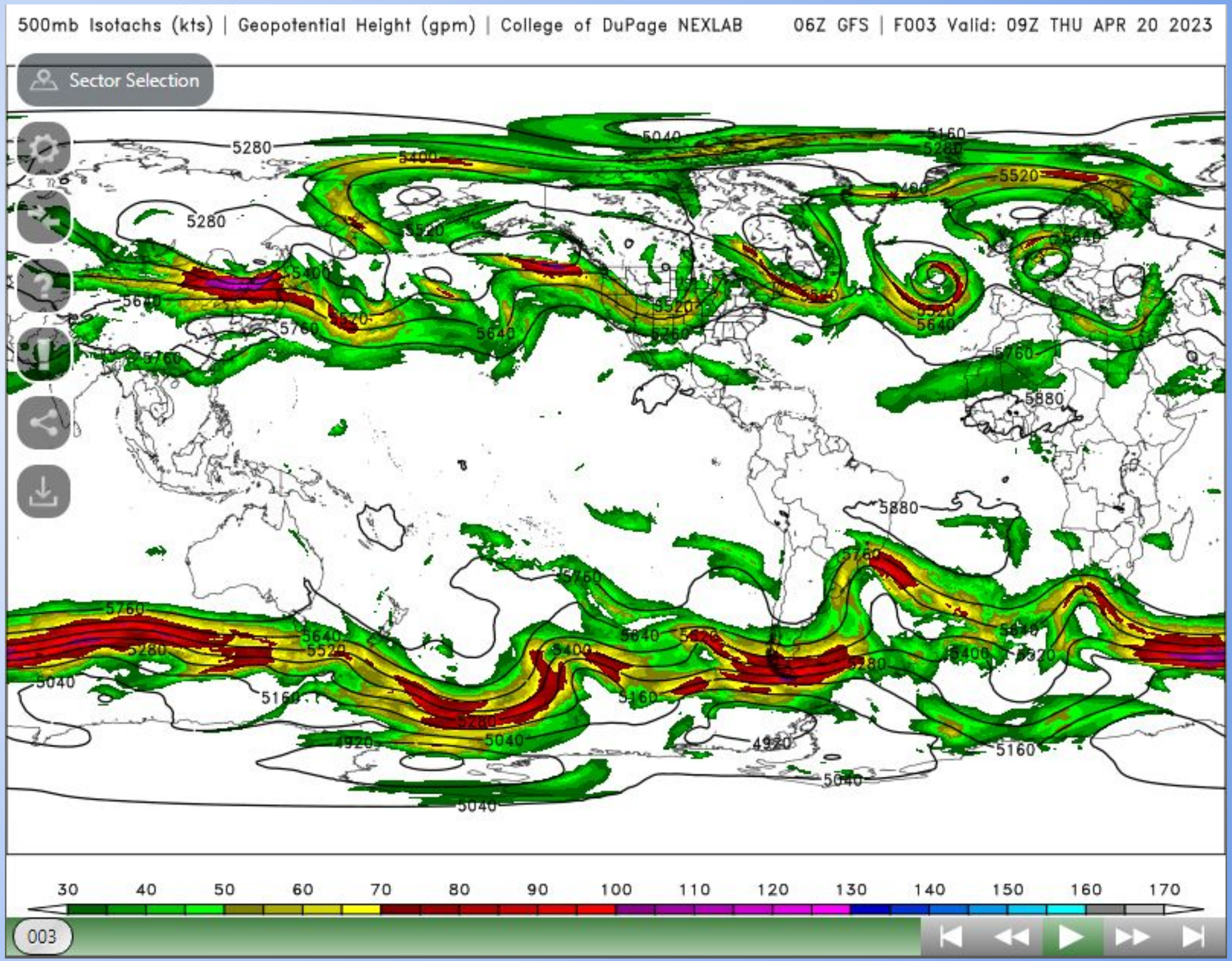
If we wanted to simulate a cold front passage early next week?

Types of Weather Models - Global

Global Models - Global Forecast System (GFS), ECMWF ("Euro Model") & Canadian (CMC), UKMET, etc.

These global models forecast for the entire global and have grid spacing of roughly ~10km.

These run into the future about 1-2 weeks.

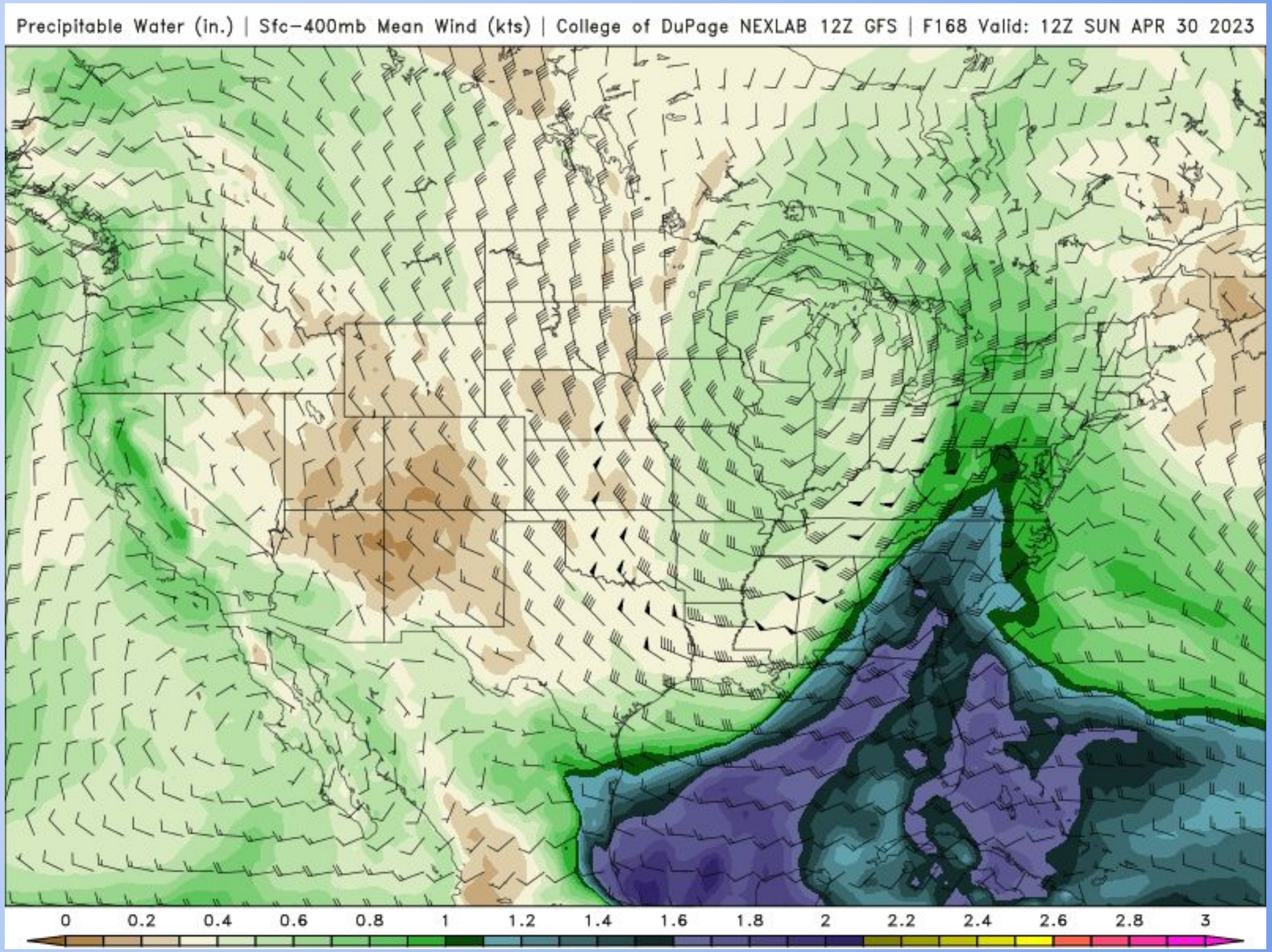


Types of Weather Models - Global

Global Models:

Most useful when forecasting at longer time periods and larger scale features.

Looking for general changes in patterns, cold fronts, etc.



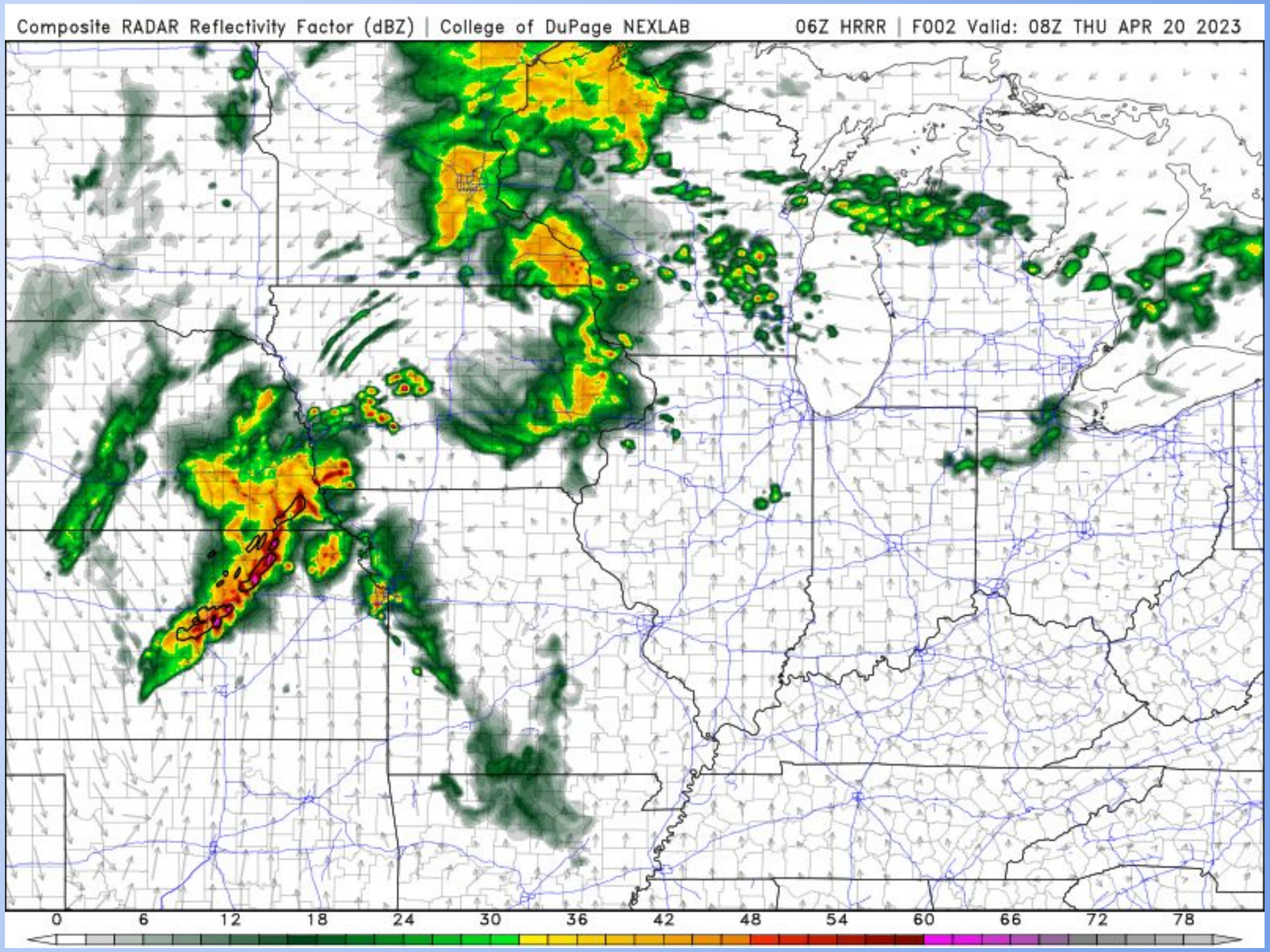
Types of Weather Models - HiRes

High-Resolution (Convective Allowing):

High Resolution Rapid Refresh (HRRR), North American Model (3km NAM), HRW WRF, RRFS, etc.

These range in grid spacing from 1km to 4km all with some ability to depict convection explicitly.

These usually have small coverage areas and short time future run times.



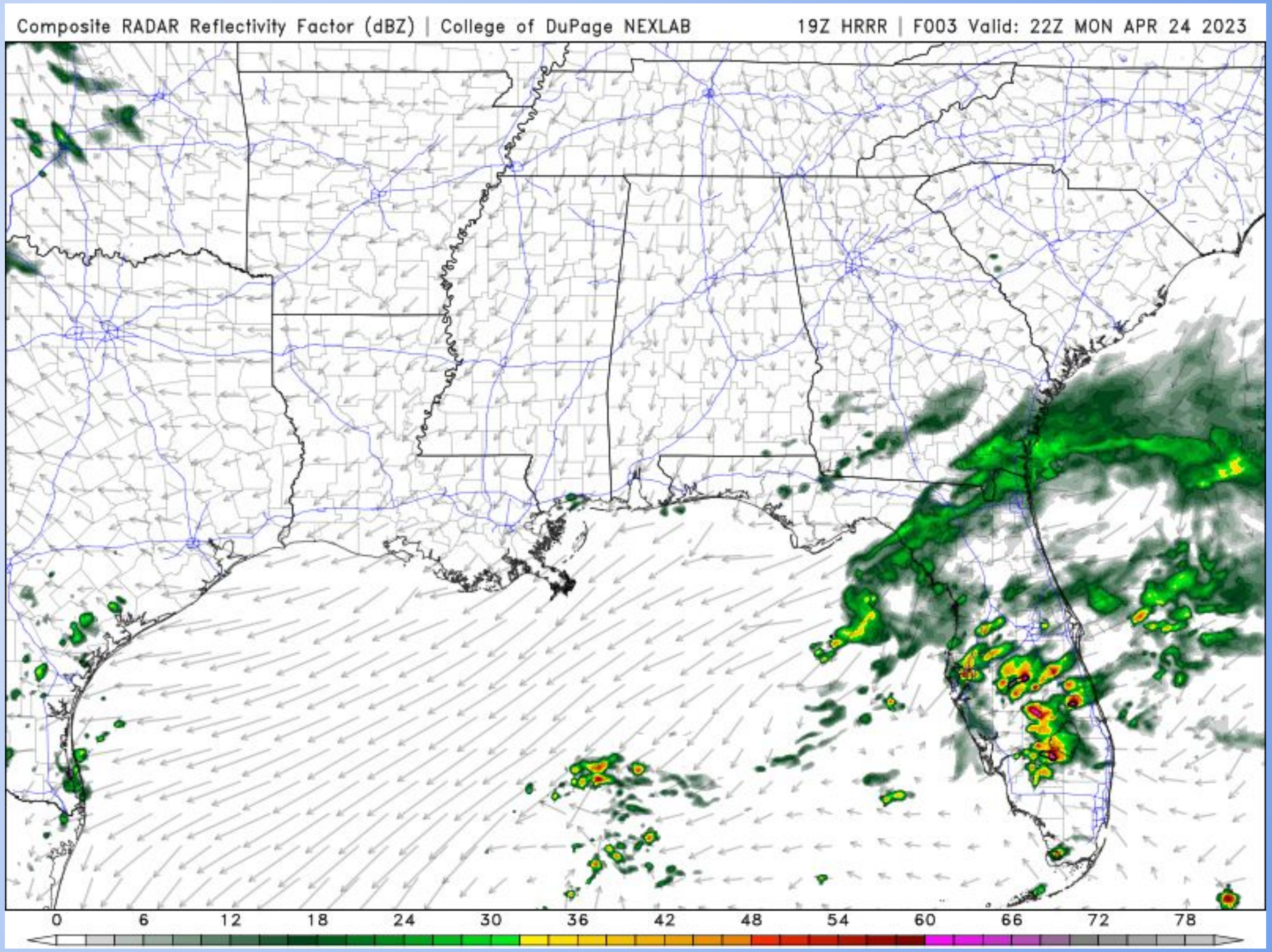
Types of Weather Models - HiRes

High-Resolution (Convective Allowing):

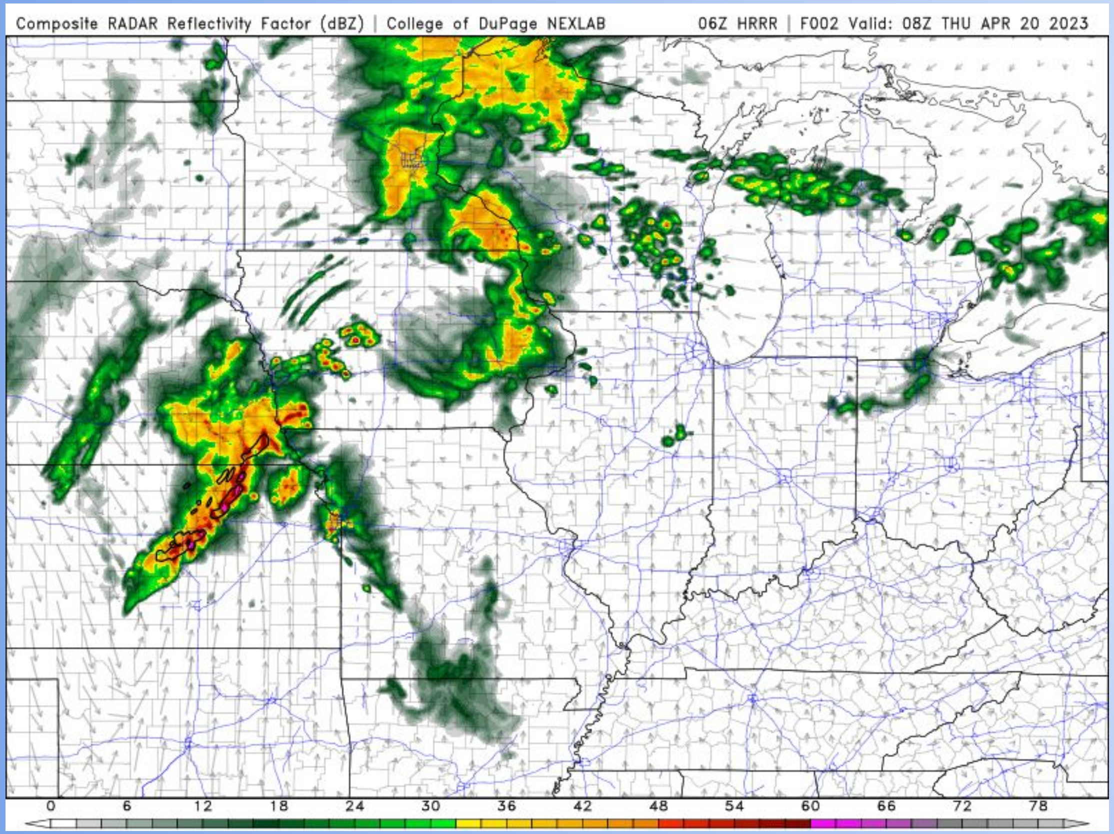
These models explicitly resolve convection since their grid spacing allows for it.

Models like the HRRR and RAP are run very quickly, only out 18 hours. But this provides hourly updates.

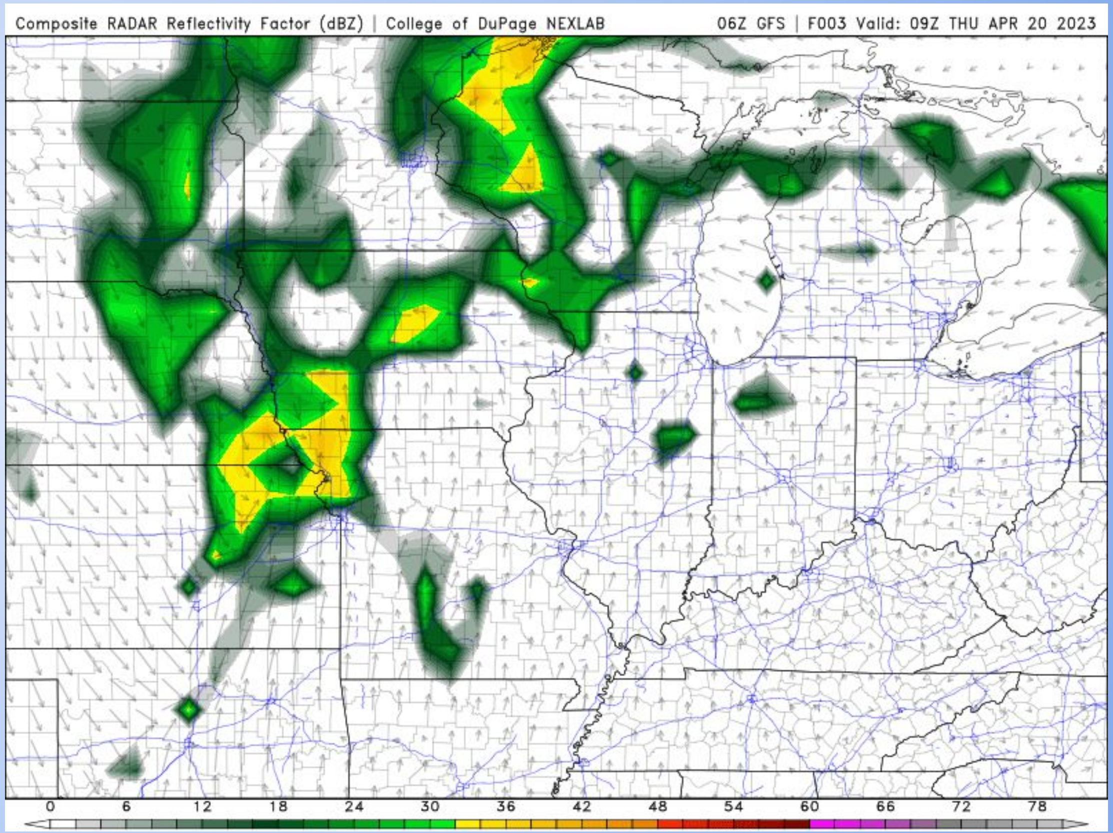
These models can physically resolve thunderstorms but nothing smaller like tornadoes!



Types of Weather Models - HiRes vs Global

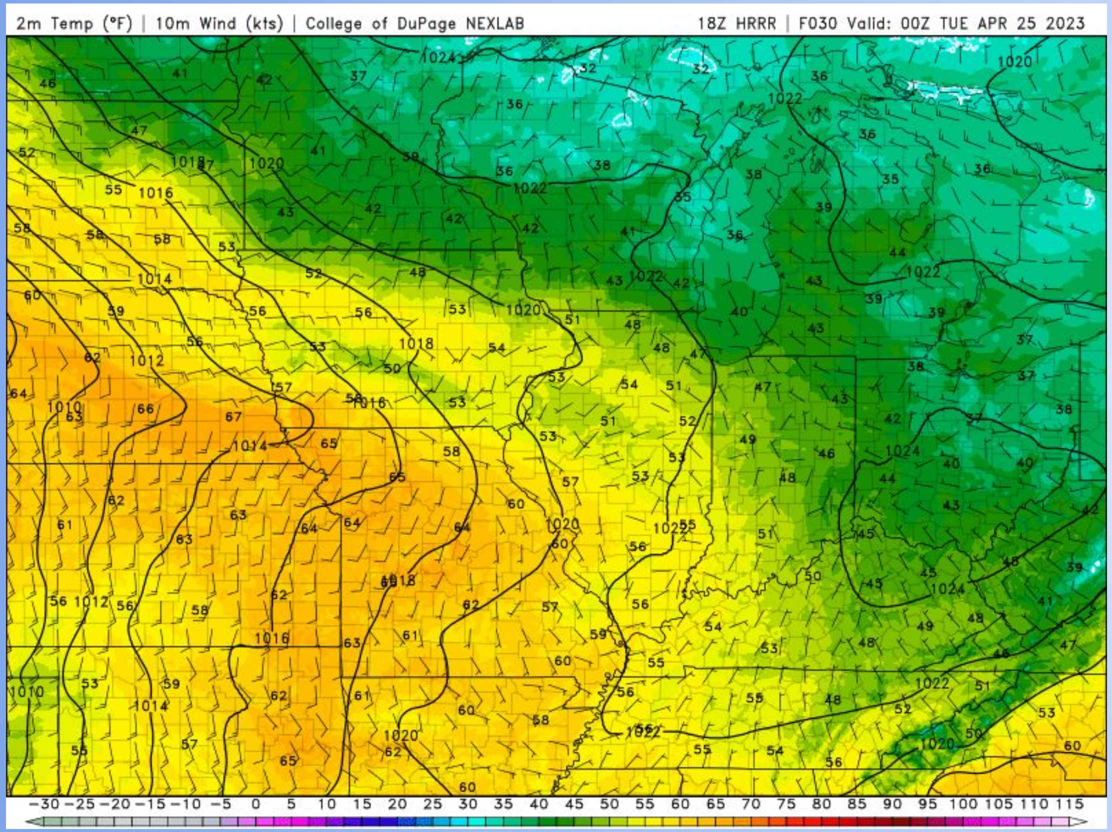


High Resolution HRRR (3km) - Simulated Radar

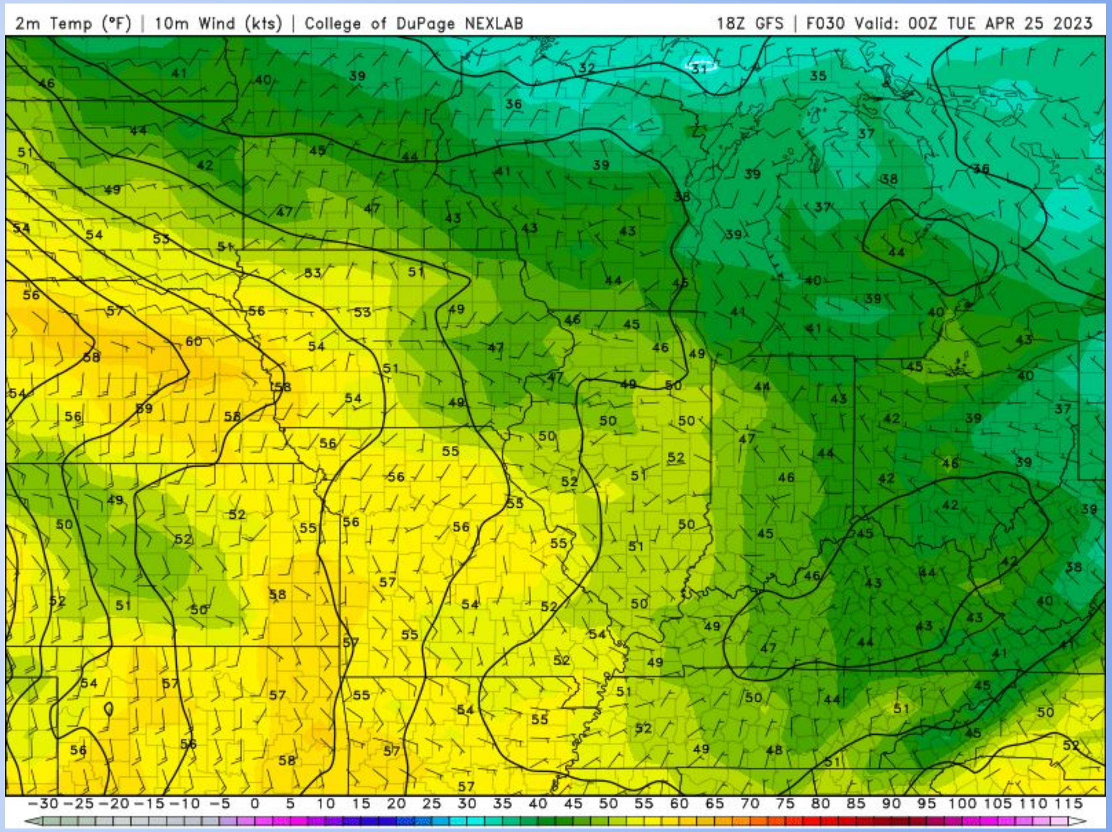


GFS (13km) - Simulated Radar

Types of Weather Models - HiRes vs Global



High Resolution HRRR (3km) - Dew Point, pressure, winds



GFS (13km) - Dew Point, pressure, winds

Types of Weather Models

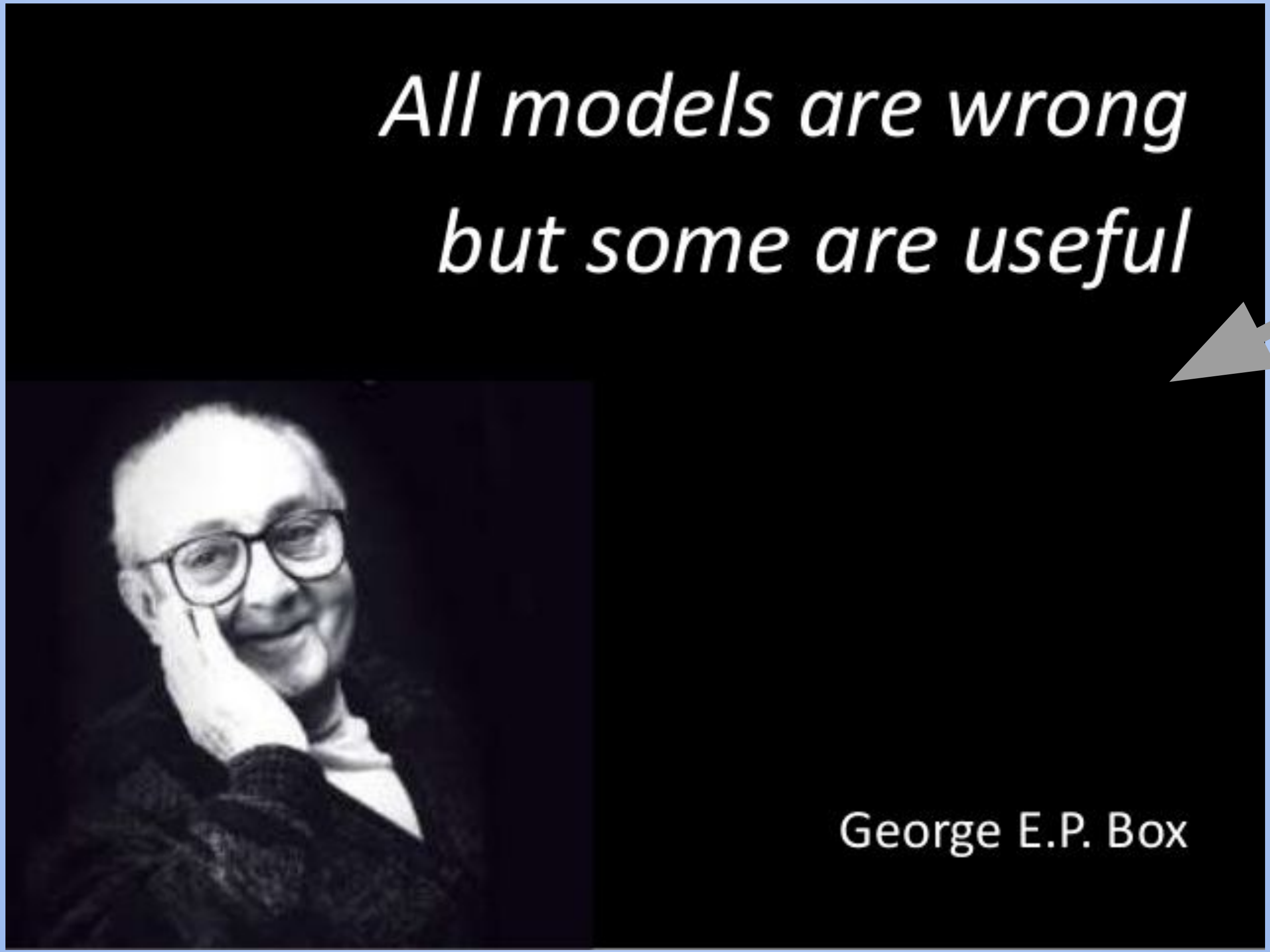
Why don't we just run the global models at smaller grid spacing?

For example, run the GFS at 1km grid spacing?

The computational time and resources would be outrageous and the model would quickly become very noisy!

Any Questions?

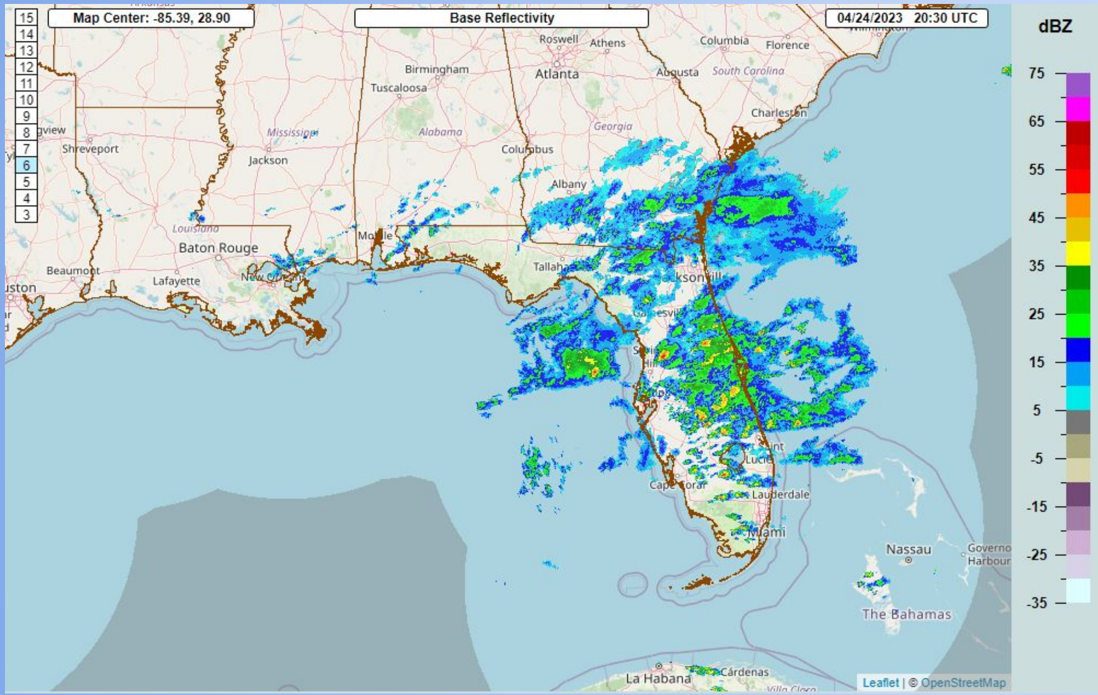
How we use models - Limitations

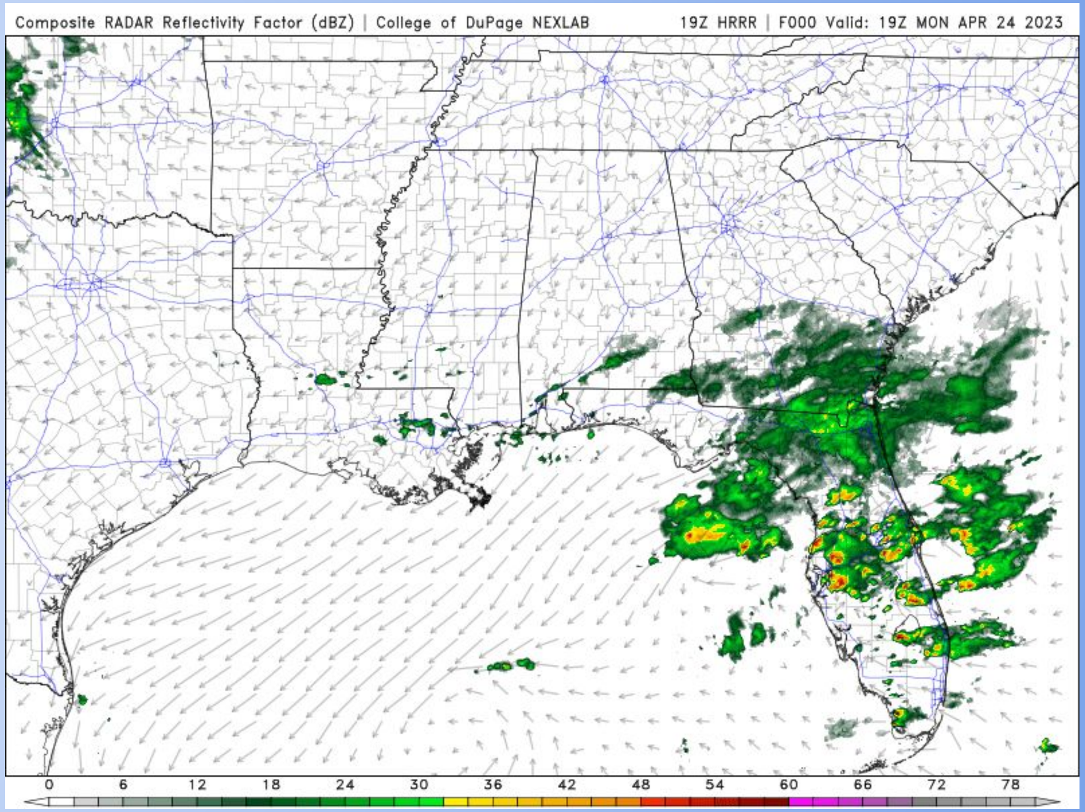


He was actually referring to statistical models, not weather models, but it still applies!

https://www.lacan.upc.edu/admoreWeb/2018/05/all-models-are-wrong-but-some-are-useful-george-e-p-box/

How we use models - Limitations





The model here has a pretty good handle on the initial conditions, so it could be a useful run!

How we use models - Limitations

Models are pretty much always “wrong”! It’s just a matter of how wrong.

Models simply solve a set of equations that are given, but input values do not represent the true atmosphere.

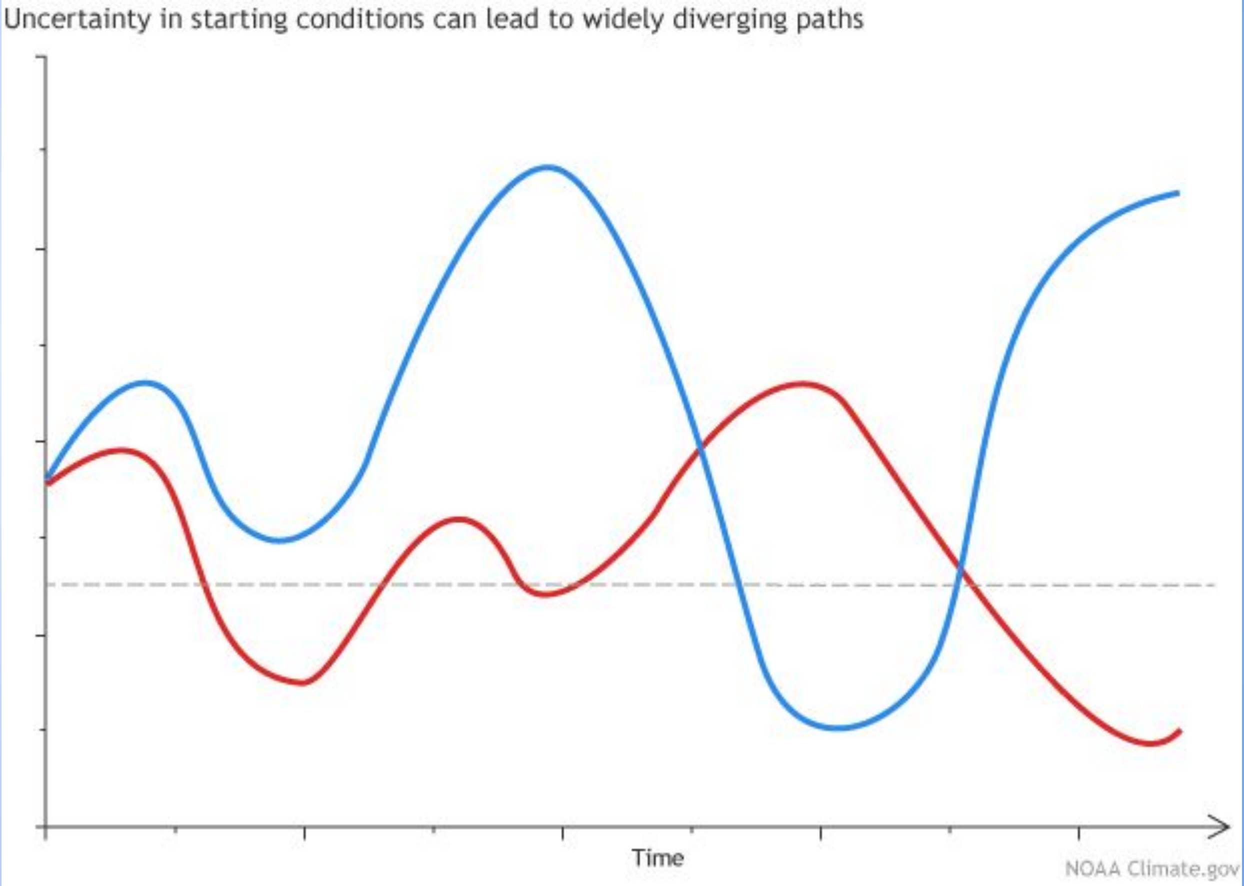
So it's up to meteorologists to identify when, where, and which models should be used in a given situation.

How we use models - Limitations

Chaos theory or the Butterfly Effect:

Small changes in the initial conditions can lead to widely varying outcomes!

Given how spaced out observations are, we can't ever achieve perfect initial conditions so we will always fight against chaos theory.



How we use models - Limitations

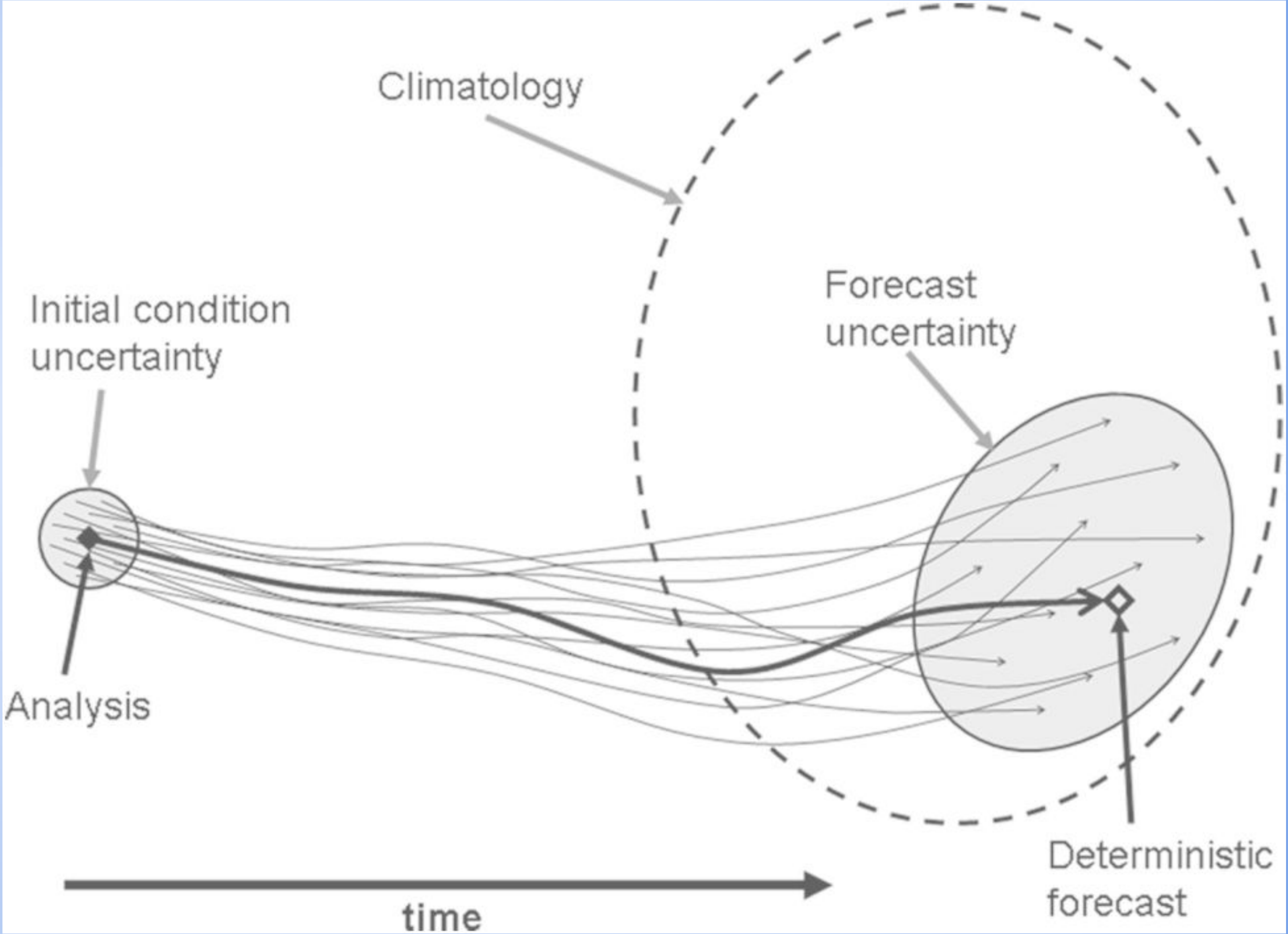
So what can we do to mitigate these issues?

How we use models - Ensembles

<u>Ensembles:</u> Quite simply just a whole bunch of the models run at once.

Each individual model has its initial conditions or some other portion of the model tweaked.

This produces a range of possible outcomes.



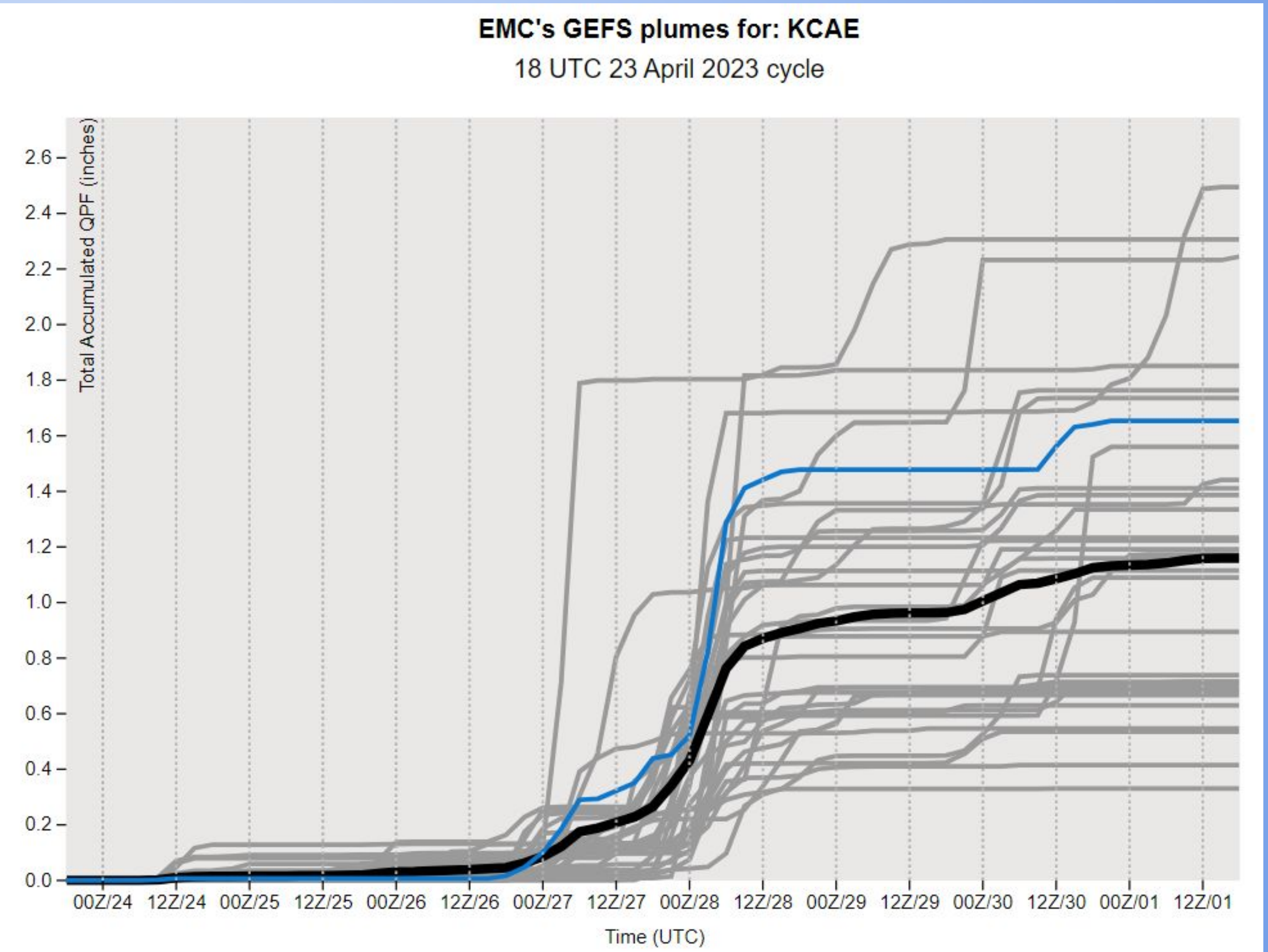
https://www.cambridge.org/core/books/abs/dynamics-and-predictability-of-largescale-highimpact-weather-and-climate-events/forecasting-highimpact-weather-using-ensemble-prediction-systems/47FB69AB9790A44555463F30B5F5AB23

How we use models - Global Ensembles

<u>Global Ensembles:</u> Quite simply just a whole bunch of the models run at once.

Each individual model has its initial conditions or some other portion of the model tweaked.

This produces a range of possible outcomes.

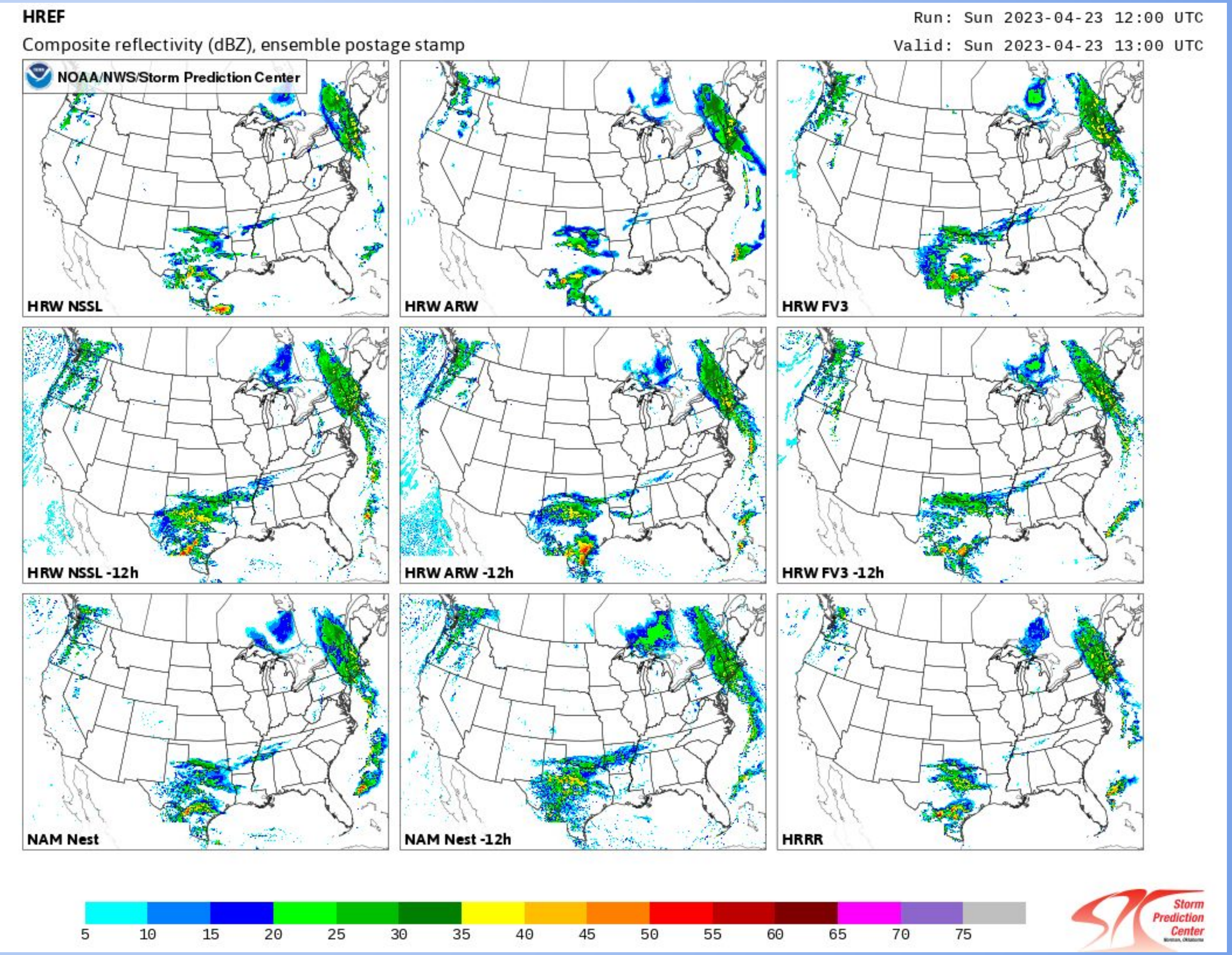


How we use models - HiRes Ensembles

Hi-Res Ensembles: Known as the HREF.

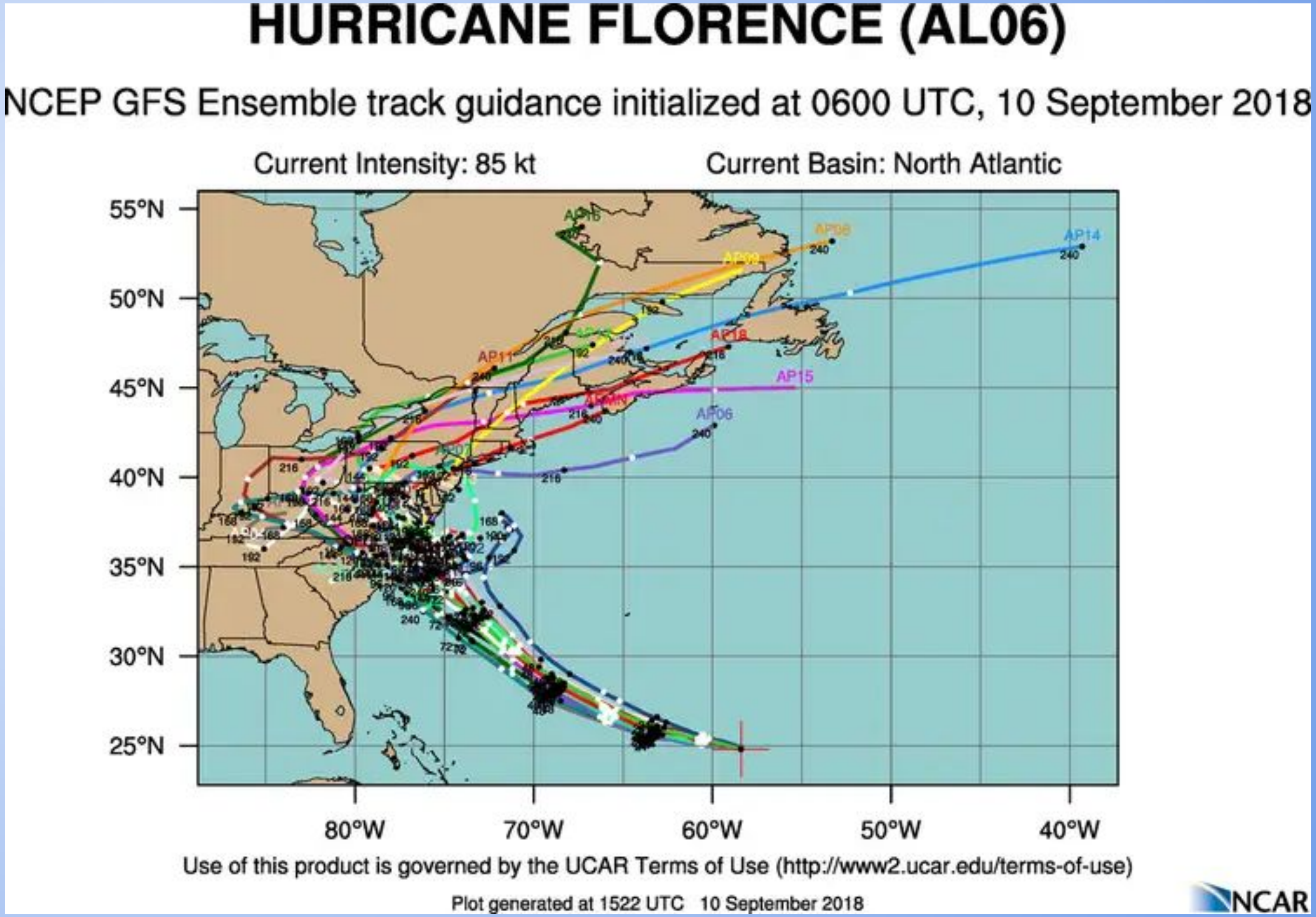
Four different hi-res models with different grid spacing, parameterizations, initializations, etc.

Can give a range of possibilities of possible severe weather types.



How we use models - Specialized Ensembles

<u>Spaghetti Plots:</u> Commonly seen with hurricane forecasting.



Quick review of some model websites to wrap up

Thanks for Listening!

For more information: https://www.weather.gov/ohx/weather101

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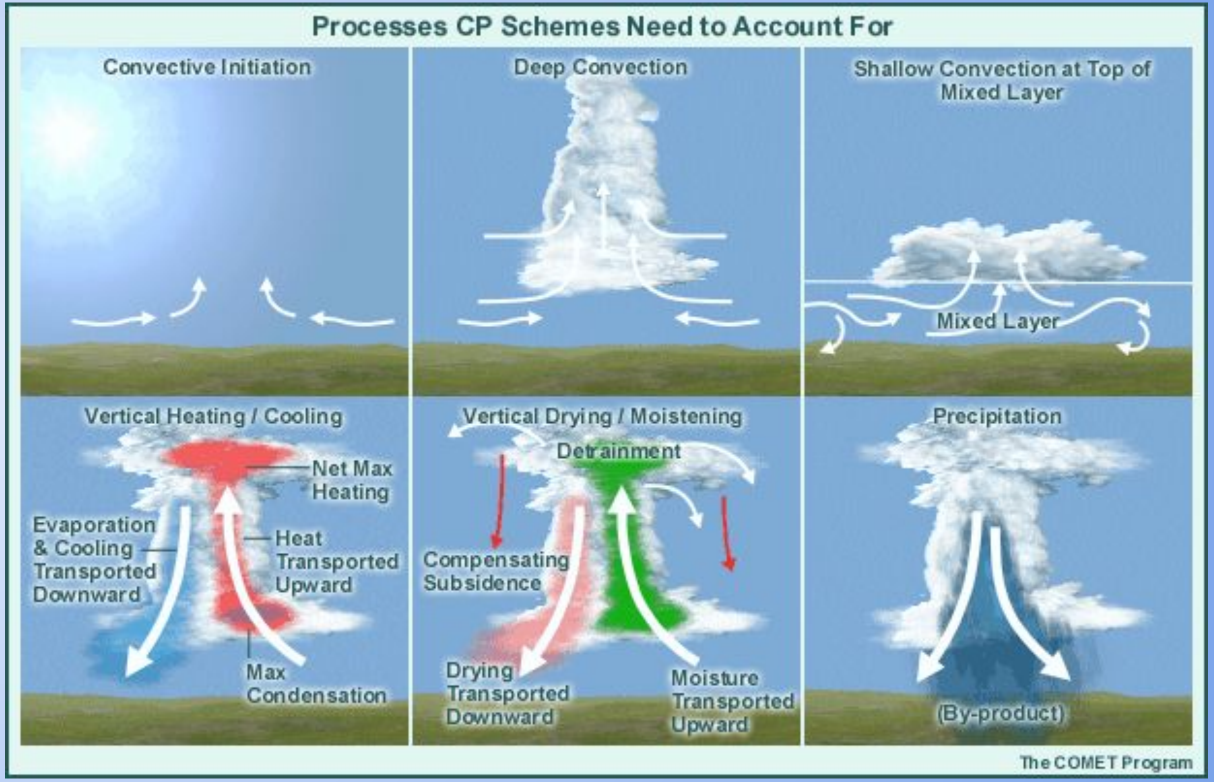
Extra Information
Sub Grid Spacing Processes

We won't dive into too much detail but models use **parameterizations** to deal with processes that are unable to be resolved.

Parameterizations are a key difference between models and handle things like snow growth, cumulus clouds, etc.



https://www.meted.ucar.edu/nwp/model_precipandclouds/navmenu.php?tab=1&page=3-1-0&type=flash

Extra Information
Sub Grid Spacing Processes

For example, if enough moisture and instability converge, you would get a thunderstorm. But the thunderstorm is smaller than grid scale, so the parameterization estimates the impact that the thunderstorm would have on the surrounding environment.