Mesoscale Meteorology

Numerical Weather Prediction

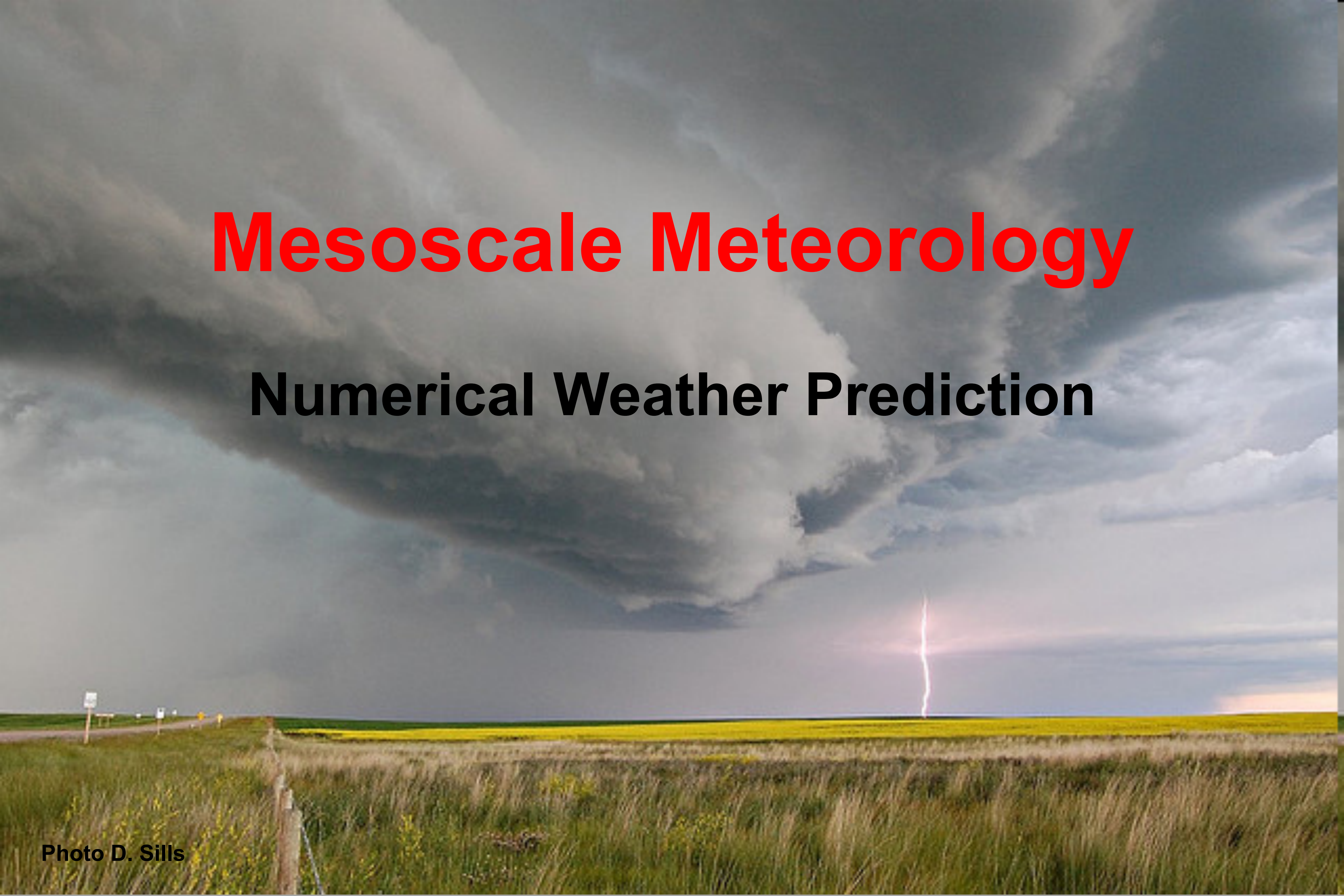
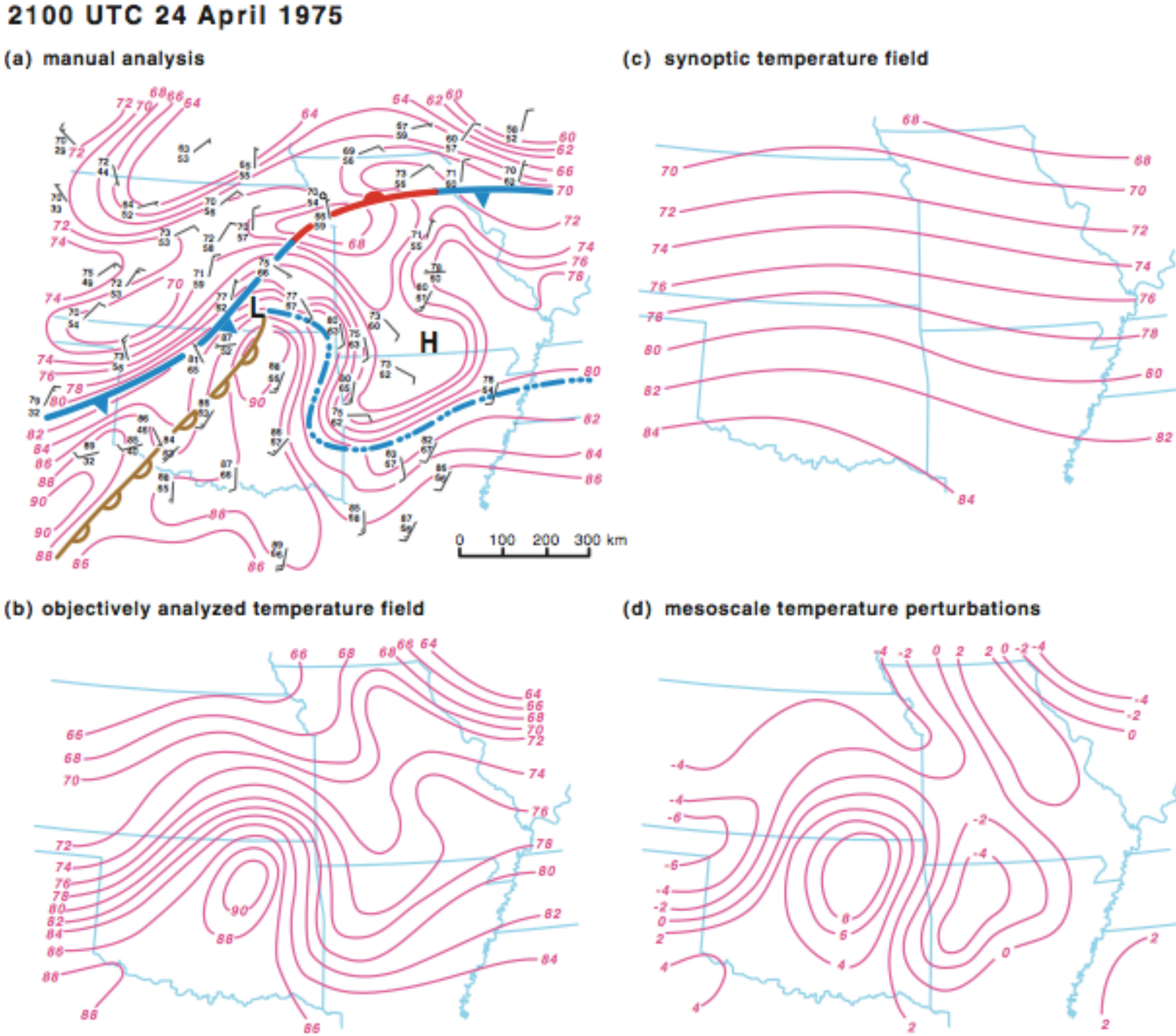


Photo D. Sills

Goals

- ➢ Understand scale separations and balance assumptions
- ➢ Discuss numerical weather prediction methods as they apply to storms and mesoscale weather systems
  - – Deterministic models
  - – Ensemble systems
  - – Derived parameters
    - In an operational setting
    - In a research setting

Scale Separations

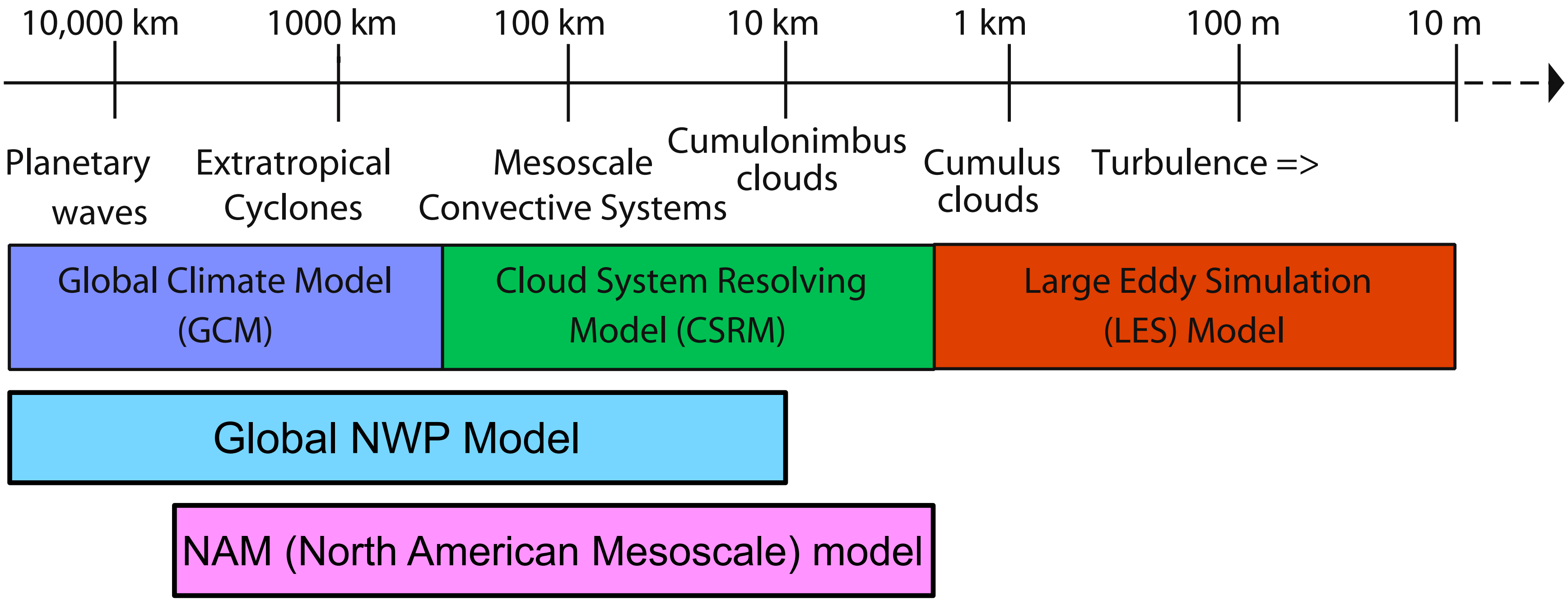


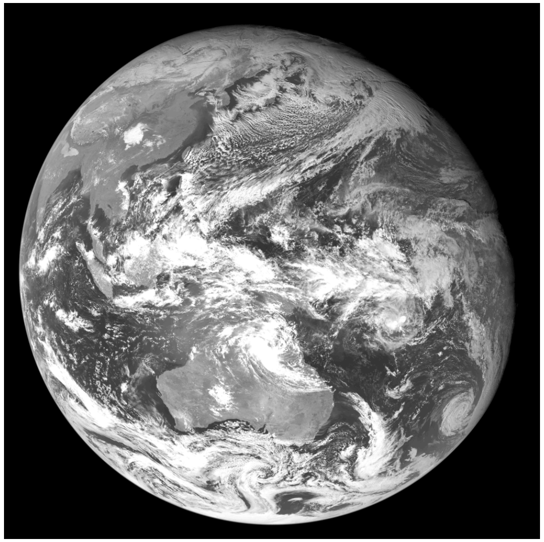
Ref: M&R Fig. 1.3

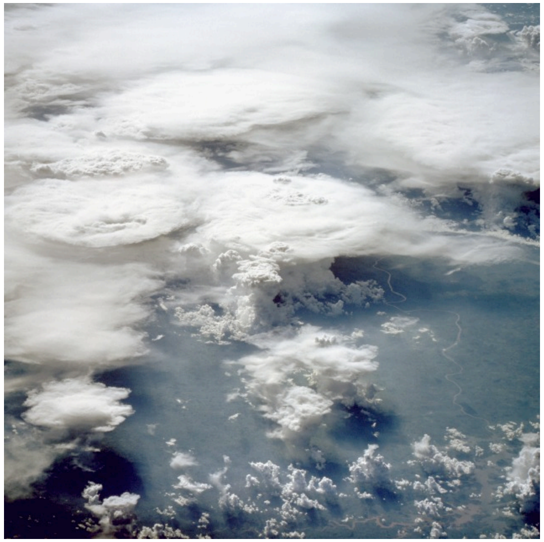
Dynamical NWP Models

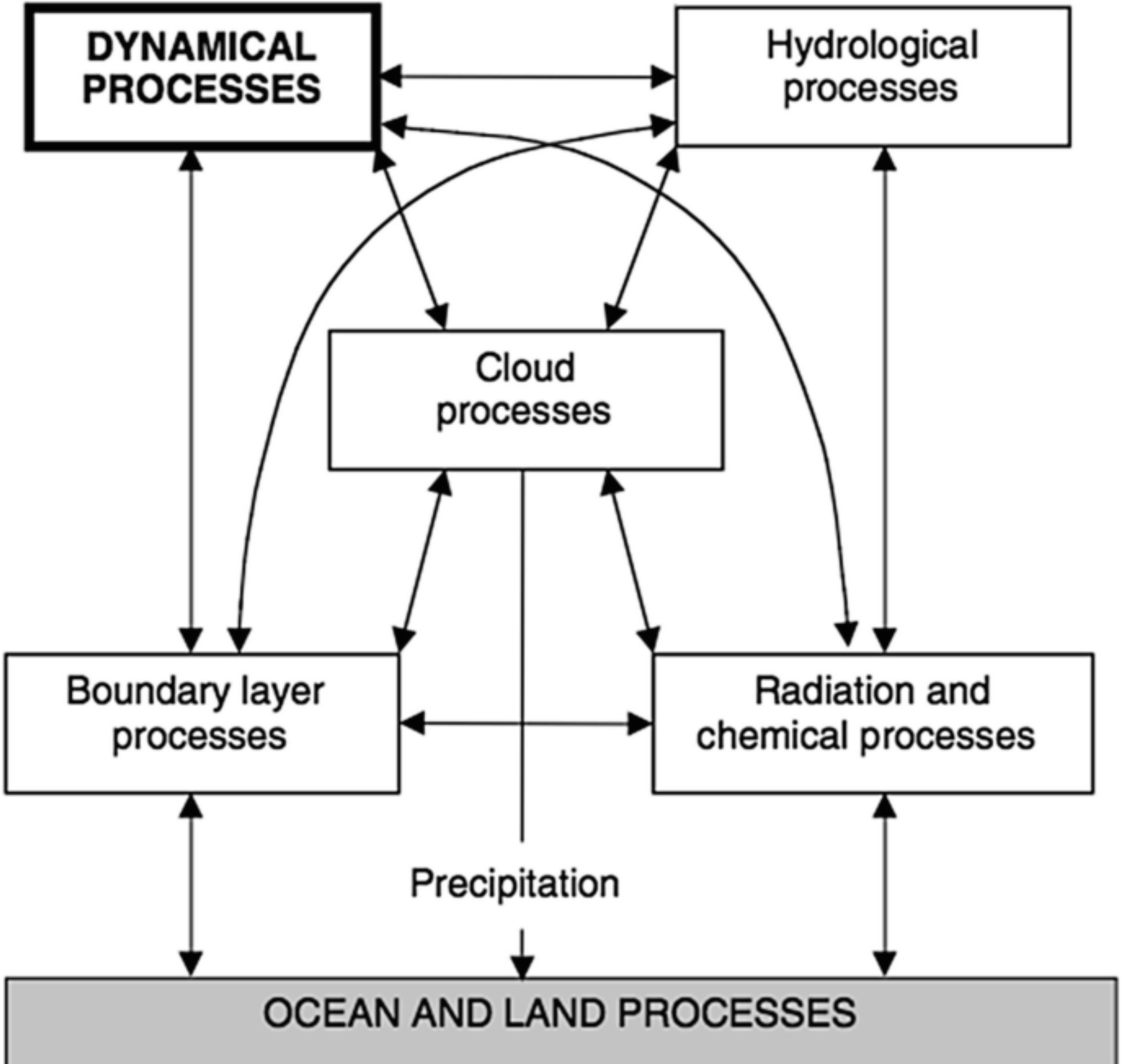
- ‘Primitive Equations’ – non-linear differential equations for:
  - Conservation of Momentum
  - Conservation of Thermal Energy
  - Conservation of Mass
- Calculations performed on 3D grid at pre-determined time intervals
- Provide a *deterministic* solution i.e. only one solution based on input to the model

Scales of Atmospheric Motion








DYNAMICAL PROCESSES
Hydrological processes
Cloud processes
Boundary layer processes
Radiation and chemical processes
Precipitation
OCEAN AND LAND PROCESSES

NWP - Parameterization

- Sub grid-scale processes are parameterized.
- Can be a physically based ‘model within a model’, empirical, or statistical.

NWP - Data Assimilation

- Data assimilation systems provide the initial conditions for NWP model runs.
- Very complex – would need an entire course to describe it properly!
- Combines observations and model output and their errors to get a best estimate of the atmospheric state
- There are too few observations available to define the initial model state, so the forecast from the previous model run is used as a first-guess and an 'analysis' is generated by minimizing differences between the model fields and the observations.
- Assimilated observations include radiosondes, wind profilers, surface station data, aircraft data, numerous types of satellite data, radar data, etc.

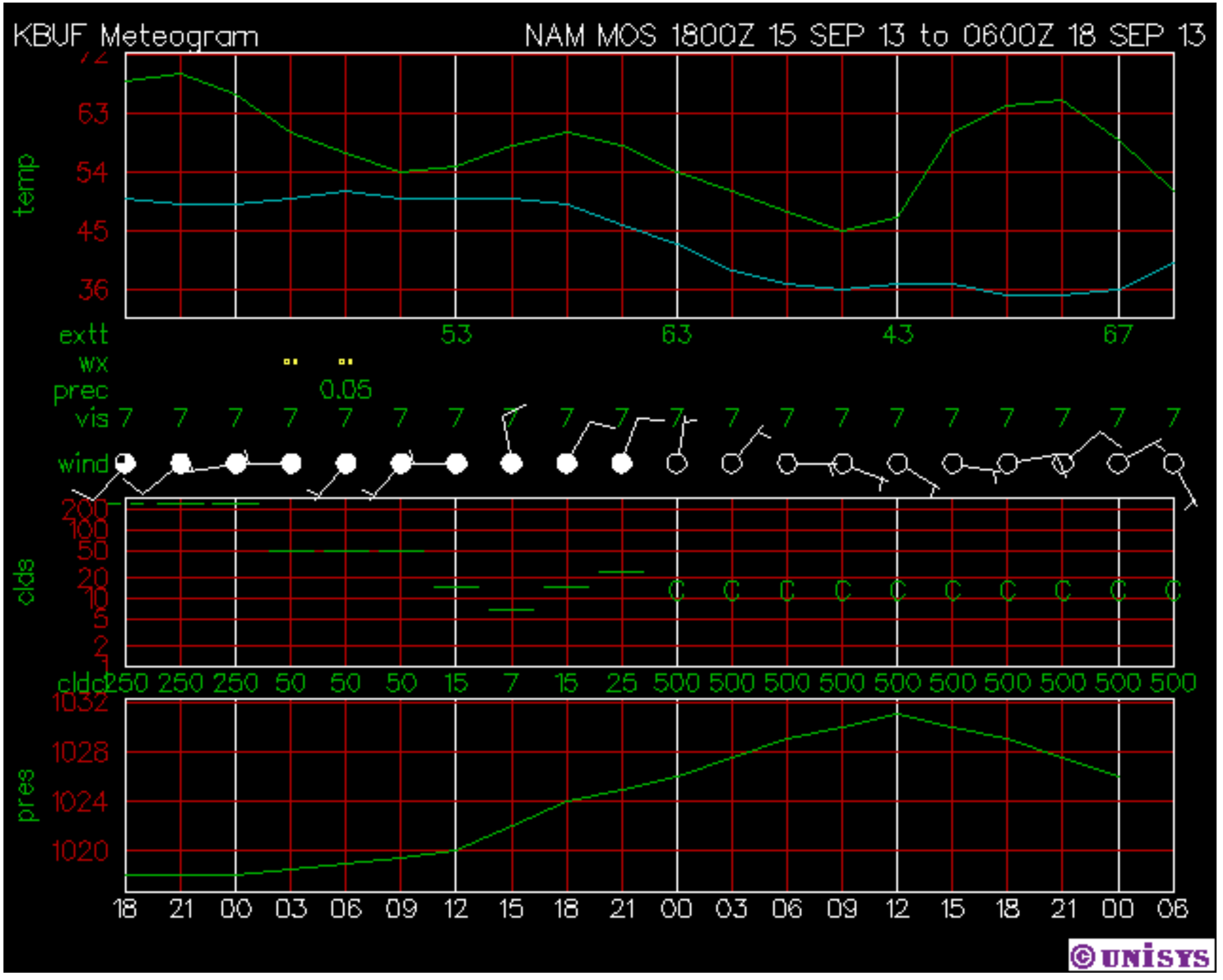
Deterministic Operational NWP Models Used Over North America

Model Name	Responsible Agency	Approximate Resolution	Approximate Domain	Range of Forecasts	Comments
North American Mesoscale Forecast System (NAM)	National Centers for Environmental Prediction (NCEP)	12 km (with regional nests of 4 km, 6 km, and 3 km, resolution) 1.3 km	North America	84 hr	Four runs per day: 00, 06, 12, 18 UTC
Global Forecasting System (GFS) UFS	NCEP	28 km (Days 1-7) 13 km	Global	16 days	22 Ensemble members also run at different resolutions
Global Environmental Multiscale (GEM/ RDPS)	Environment Canada	10 km regional 2.5 km regional	North America	48 hours 6 days	Regional has four runs per day: 00, 06, 12, 18 UTC, Global has runs at 00 and 12 UTC
European Center for Medium Range Forecasting (ECMWF) IFS	European Center in Reading, U.K.	16 km 9 km	Global	10 days	51 Ensemble members also run at 30-60 km resolution
Coupled Ocean Atmosphere Mesoscale Prediction System COAMPS	U.S. Navy	6/18/54 km 2.5 km	Regional	24 hours	Interactive ocean-atmosphere model

MOS - Model Output Statistics

- Statistical analysis can be used to predict weather at certain locations, but forecast quality deteriorates quickly
- NWP models often do poorly at representing local variations in surface weather
- With MOS, statistical regression equations are applied to NWP model output at points with surface weather stations to improve statistical forecasts
- MOS forecasts provide a large amount of the local forecast information that the public receives, especially in the longer term (> 48 h)

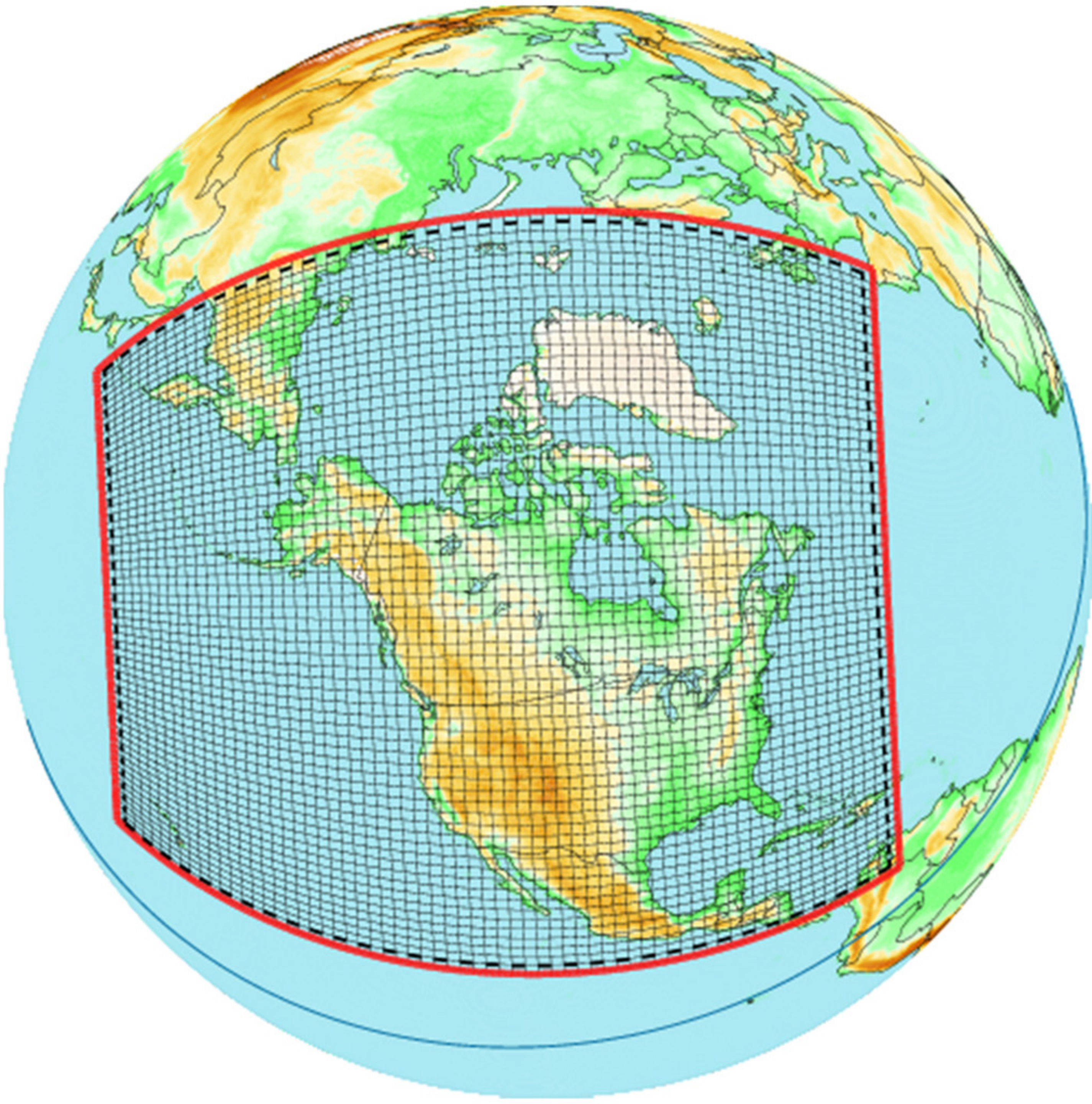
Model Output Statistics

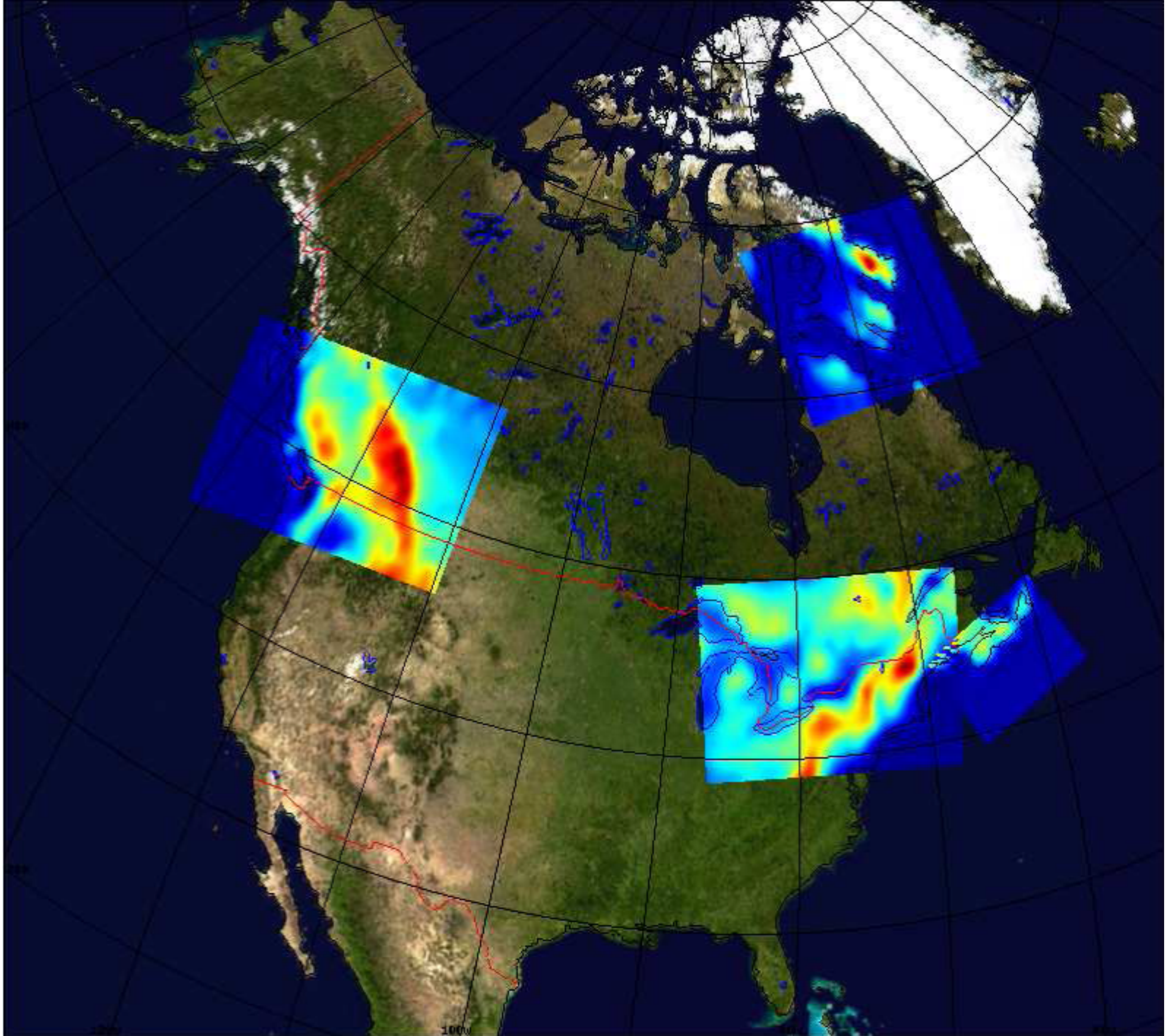


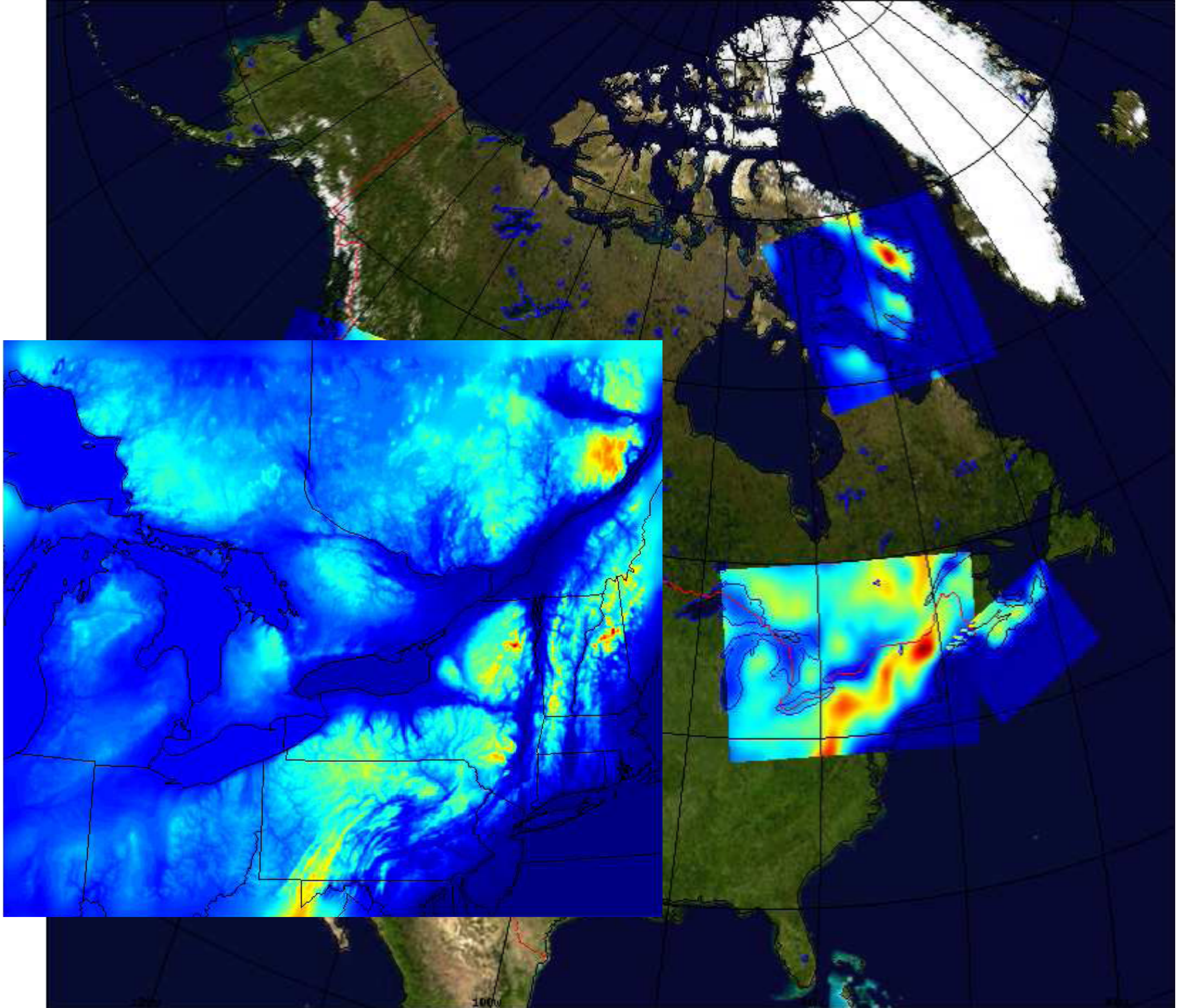
EC’s GEMLAM-2.5

(EC = Environment Canada)

- ‘Limited area’ version of GEM model
- 2.5 km horizontal grid spacing
- Run once per day at 12 UTC for several regions of Canada
- Forecasts out to 18 hours
- Advantage – higher resolution topography, ability to simulate smaller-scale atmospheric phenomena
- Now known at EC as HRDPS

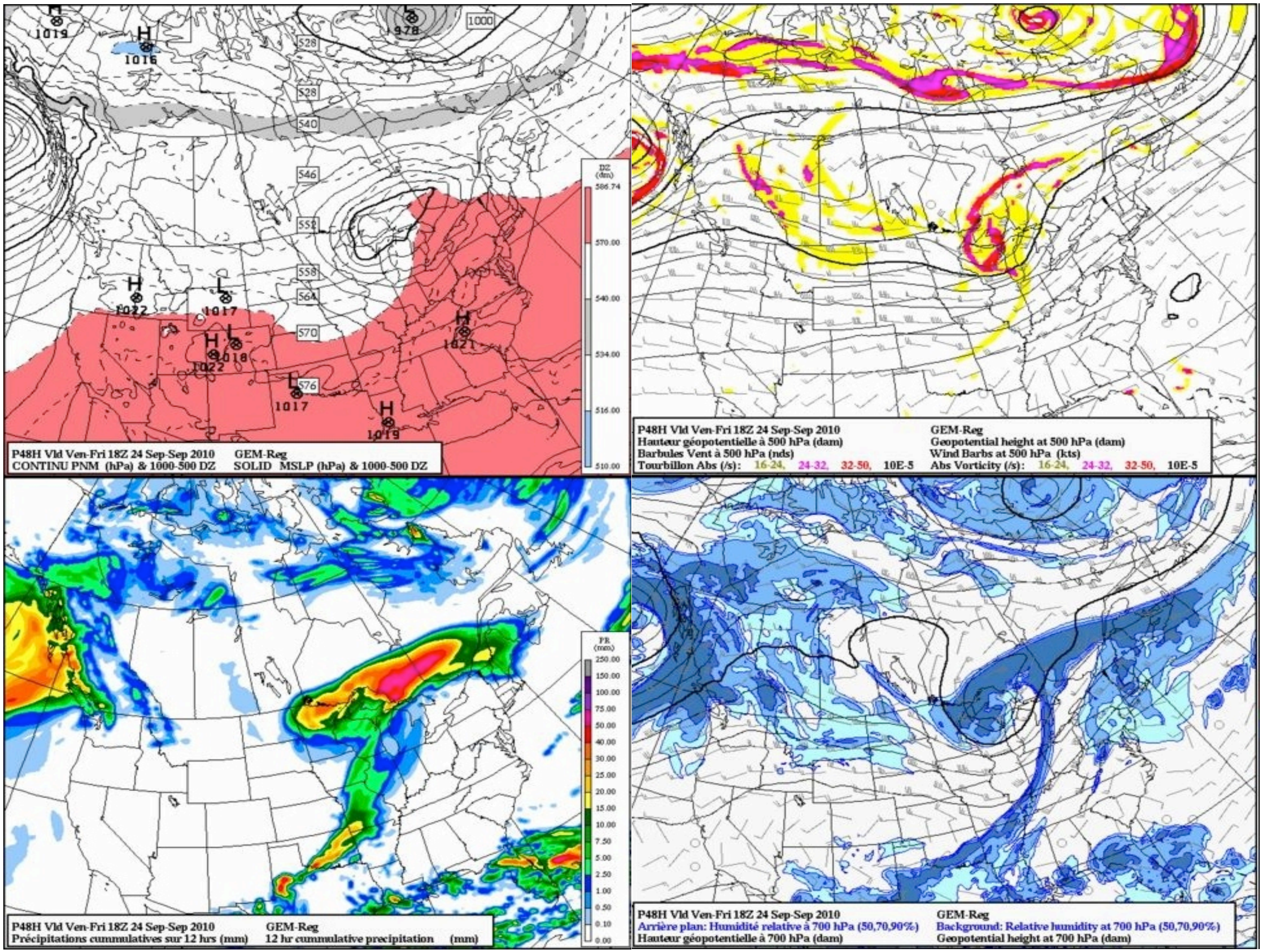






EC NWP

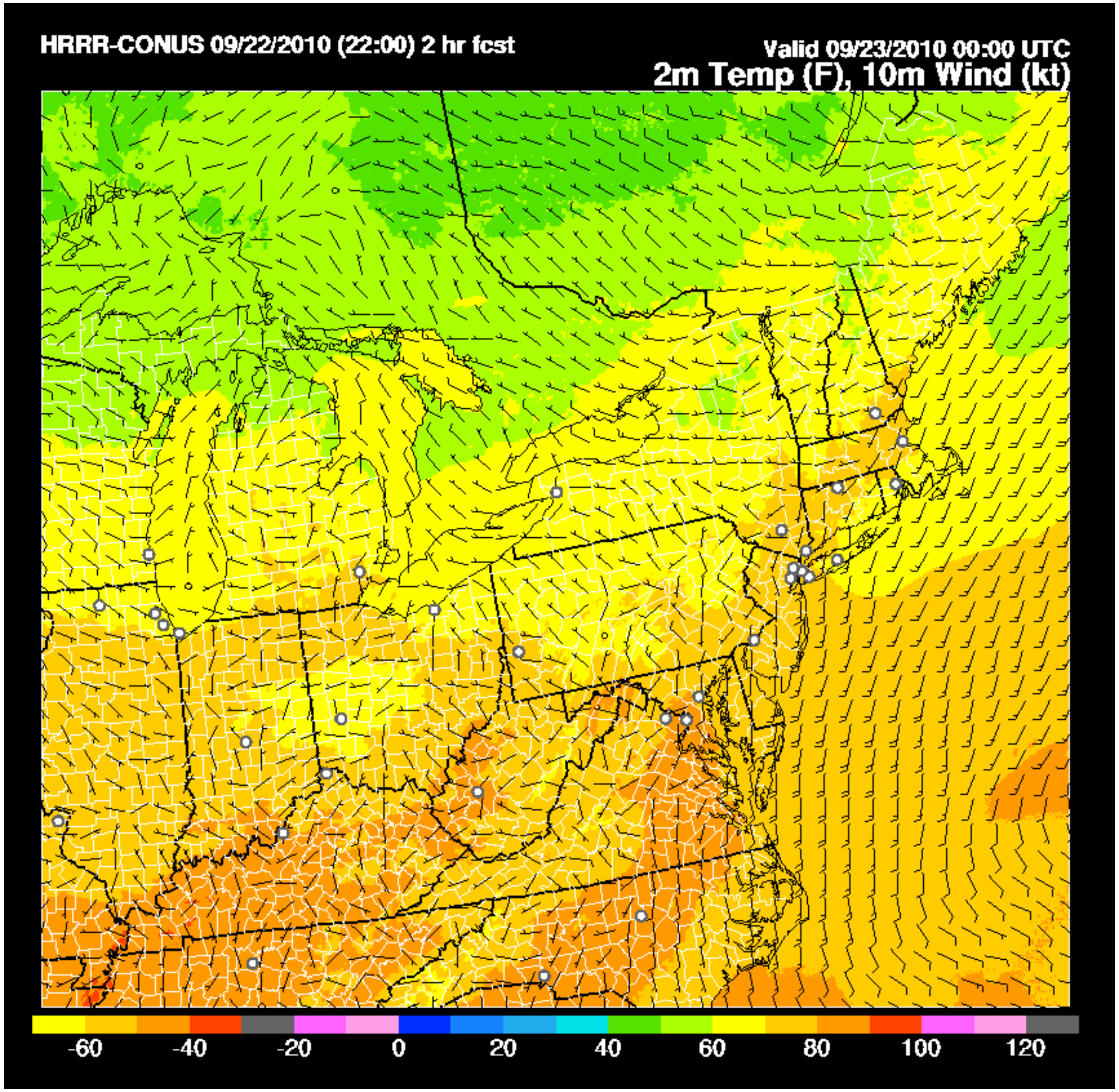
(EC = Environment Canada)



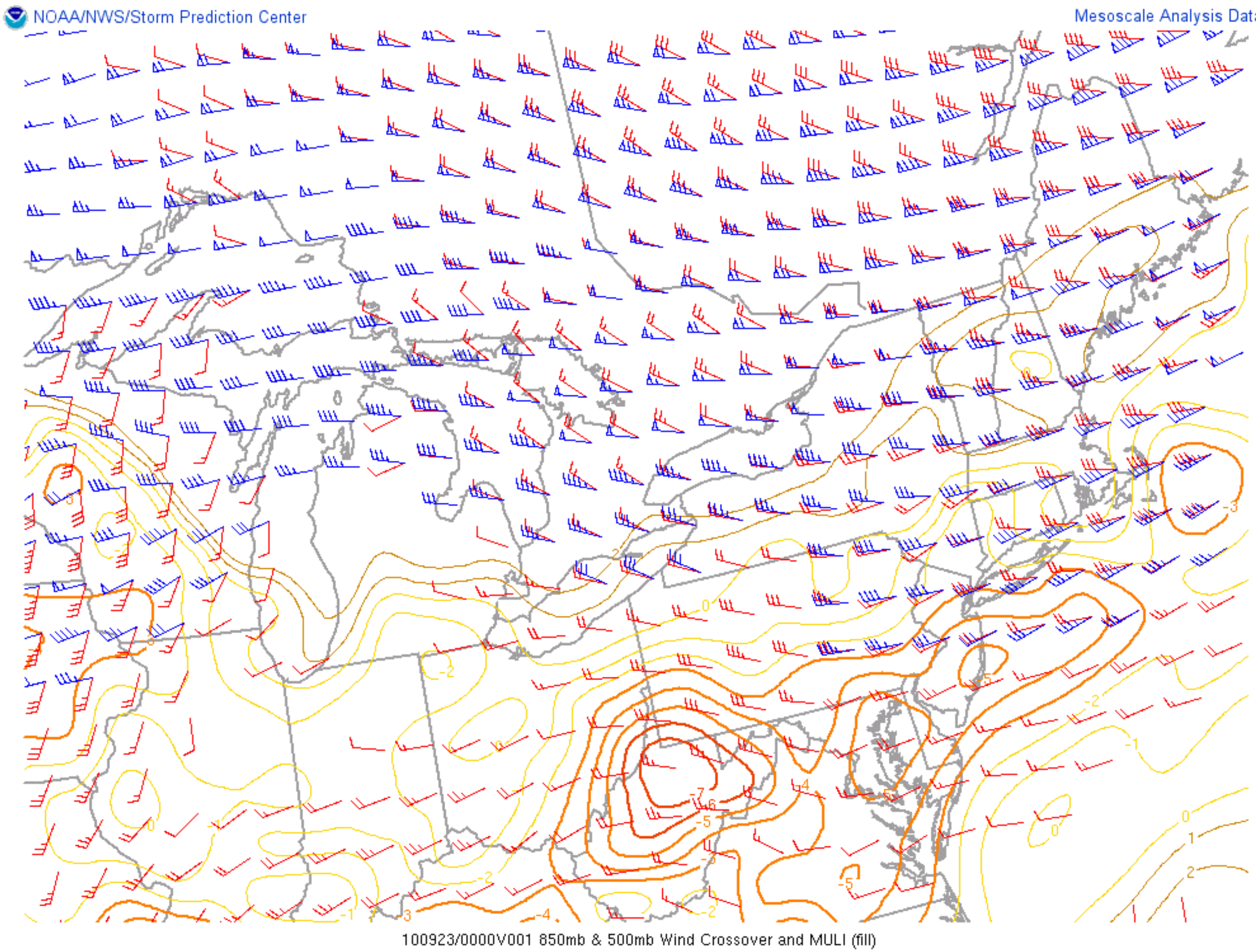
RAP / HRRR

- Rapid Refresh (RAP, 13 km) / High-Resolution Rapid Refresh (HRRR, 3 km)
- Run by NOAA's Earth System Research Lab
- Initial conditions updated hourly with surface observations, AMDAR, radar data, wind profiles, etc.
- Hourly forecasts out to 18 hours

HRRR


HRRR-CONUS 09/22/2010 (22:00) 2 hr fcst
Valid 09/23/2010 00:00 UTC
2m Temp (F), 10m Wind (kt)
-60
-40
-20
0
20
40
60
80
100
120

http://www.spc.noaa.gov/exper/mesoanalysis/new/viewsector.php?sector=16



Hi-Res Models - Issues

- Often large errors in location, timing, and/or intensity, inconsistency / flip-flops.
- However, often useful for guidance on range of possibilities and sensitivity to certain factors.
- Sometimes gives a good indication of ‘convective mode’ (type of storm).
- Rapid update cycles not always an improvement over longer forecast runs (latest run not always best!).
- Easy to get ‘sucked in’ by realistic-looking hi-res forecast fields.

Limitations of Deterministic NWP

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Limitations of Deterministic NWP

- Inexact Equations / Parameterizations
  - Equations in models and parameterizations are approximations and can have significant errors
- Errors in Initial Conditions
  - Impossible to measure the state of the atmosphere with no error
- Errors in Boundary Conditions
  - Errors entering model from lateral sides or geophysical fields at the surface
- Inadequate Resolution
  - Very high resolution is required to capture atmospheric phenomena at all scales
- Results: errors grow over model integration time

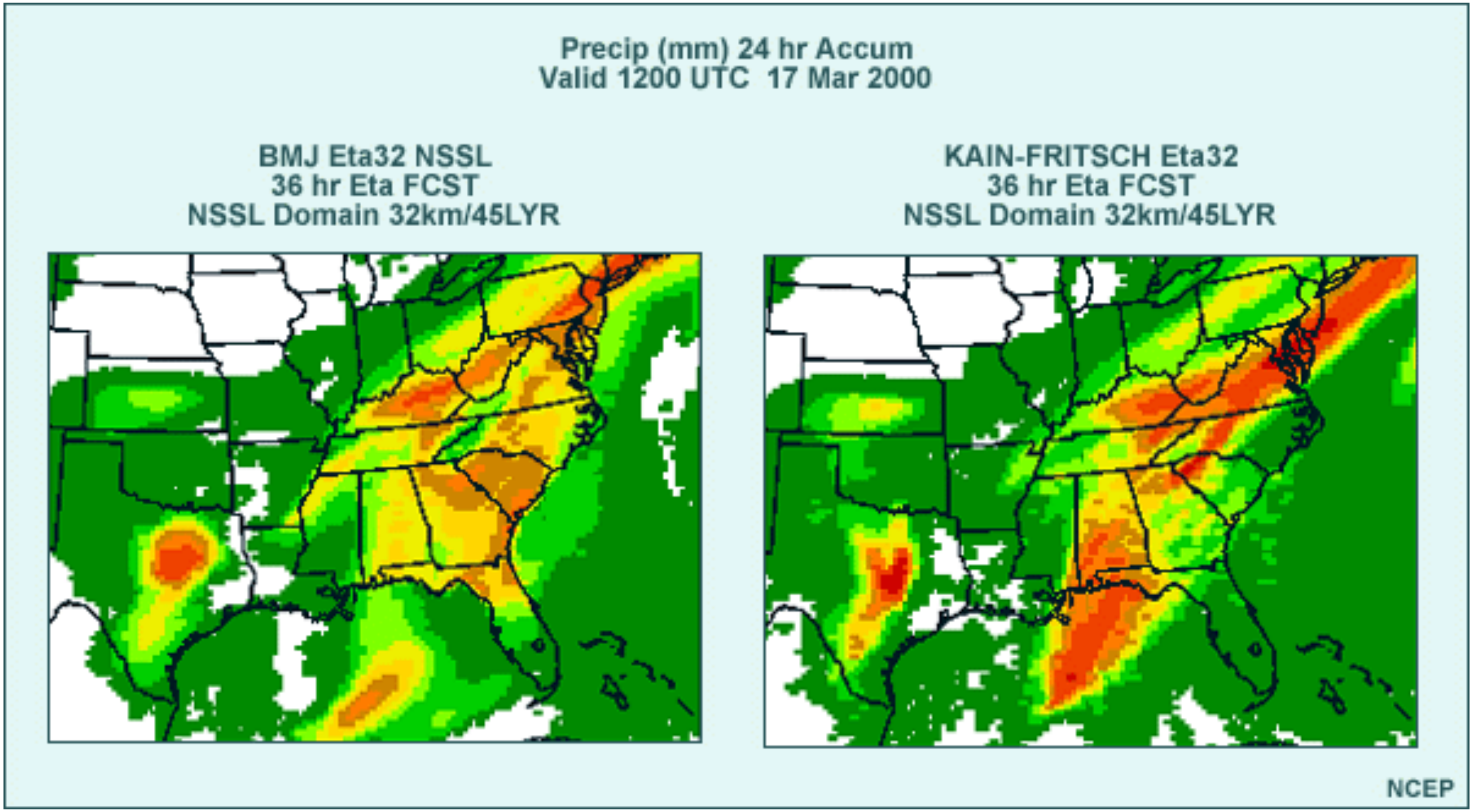
Ensemble Forecast Systems

- Edward Lorenz – in the 60’s, he discovered that very small errors in initial conditions (even due to rounding errors) can result in drastically different forecasts over time
- ‘Butterfly effect’ – “*Predictability: Does the Flap of a Butterfly’s Wings in Brazil set off a Tornado in Texas?”*
- Foundations of chaos theory
- Limit of predictability – he thought roughly 2 weeks but decades later is still not proven

Ensemble Forecasting

- An NWP method used to generate a representative sample of the possible future states of the atmosphere
- Can be a comparison between different models, or comparison between results from a variety of different parameterizations using a single model

Ensemble Forecasting



http://www.meted.ucar.edu

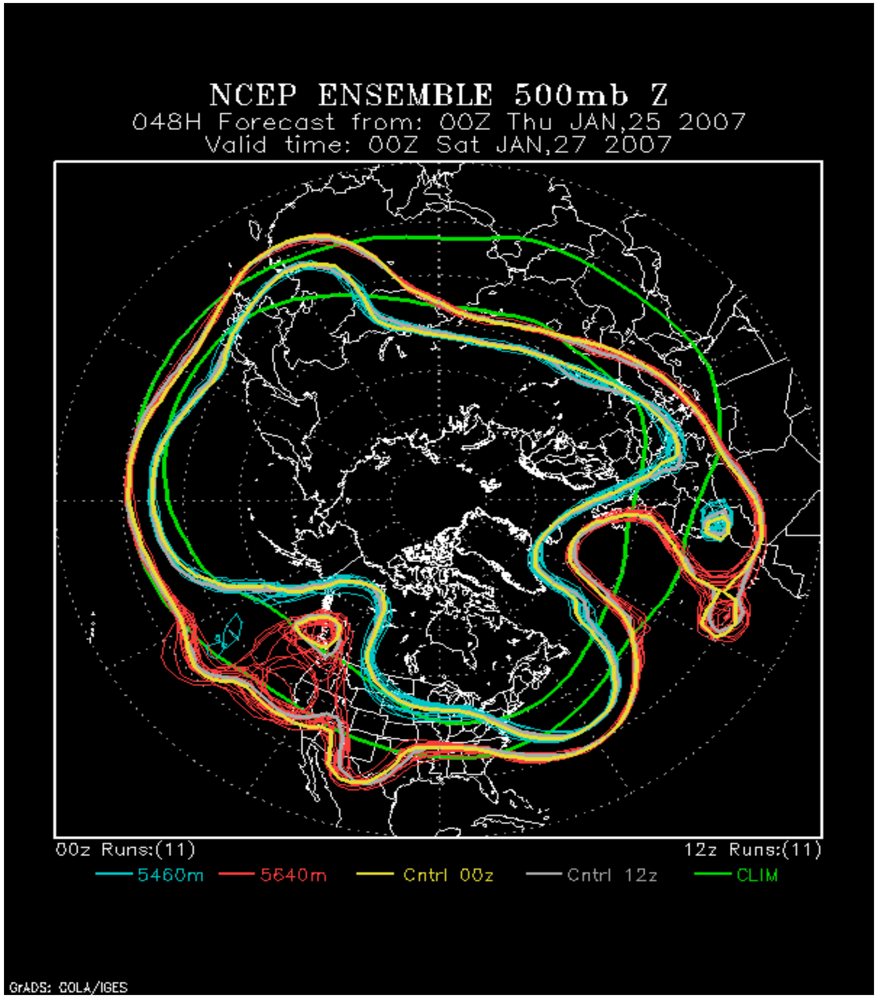
Ensemble Forecasting

- An NWP method used to generate a representative sample of the possible future states of the atmosphere
- Can be a comparison between different models, or comparison between results from a variety of different parameterizations using a single model
- Ensemble forecasting *systems* have been developed by:
  - Generating plausible perturbations for initial conditions or vary parameterizations in systematic way.
  - Running the model for each 'member' to generate probability statistics.

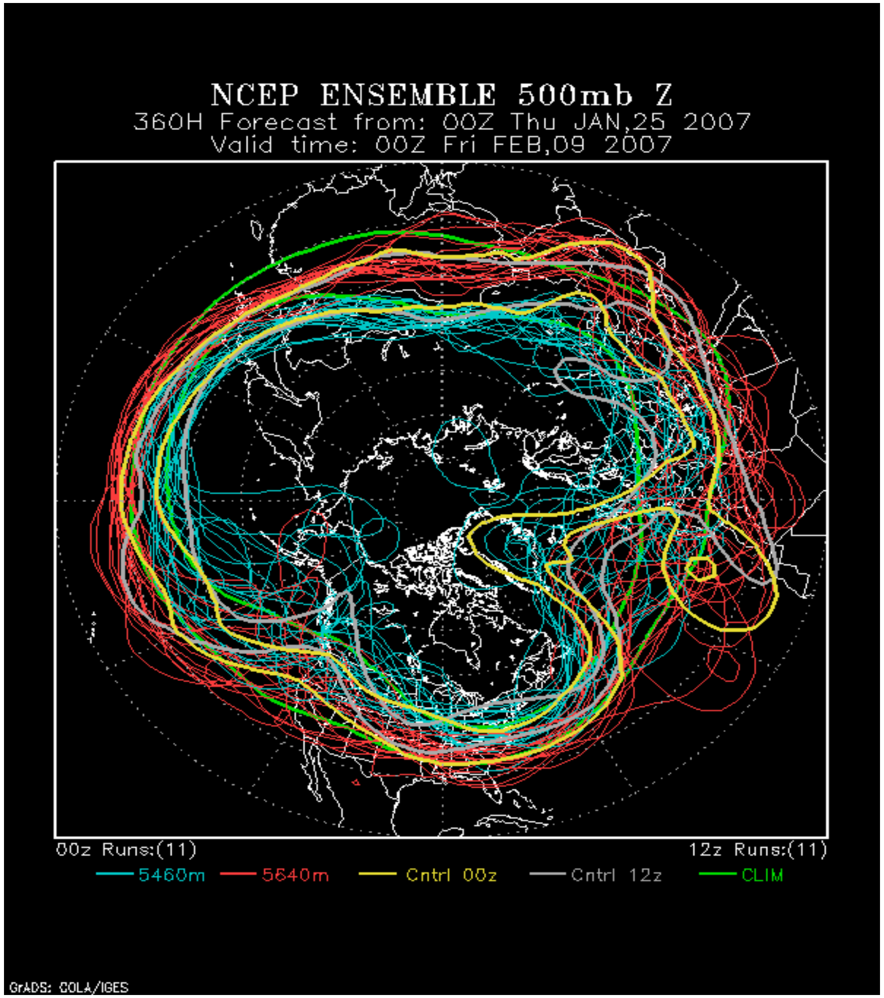
Ensemble Forecasting

- ECCC (Environment and Climate Change Canada) EPS (Ensemble Prediction System)
  - 20 ensemble GEM members run out to 16 days.
- US GEFS (Global Ensemble Forecast System) system
  - 21 GFS model ensemble members, + a control, run out to 16 days.
- NAEFS (North American Ensemble Forecast System)
  - Combined GEPS and GEFS ensembles run out to 16 days.
- ECMWF ensemble system
  - 51 ECMWF ensemble members run out to15 days.

‘Spaghetti’ Charts



48 h - low uncertainty



360 h - high uncertainty

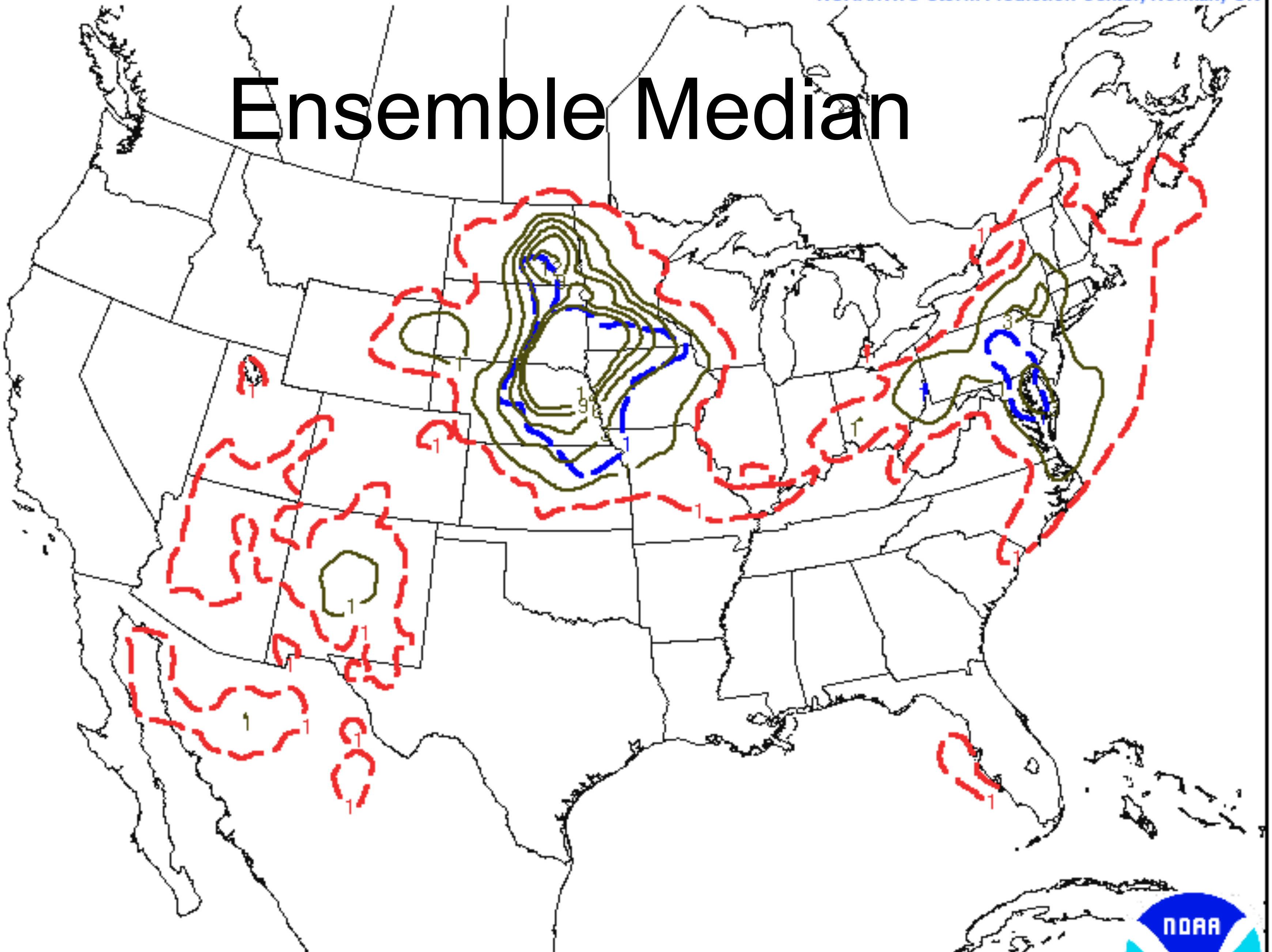
Regional Ensemble Forecasting

- Canadian Regional Ensemble Prediction System (REPS)
  - 10 to 30 members using GEM-MACH (2.5-km grid) out to Day 10. Uses more members for shorter lead times. (GEM-MACH = Global Environmental Multiscale - Modelling Air-quality and Climate-High Resolution Model.)
- NCEP SREF (Short Range Ensemble Forecast)
  - 21 members using WRF out to 3+ days (87 hrs).
  - Run 4x per day.
  - Grid size ~ 5 km.
  - SPC uses SREF output to generate severe weather-related products.

FCST: F000 VALID: Wed 20100922/2100 UTC

NOAA/NWS Storm Prediction Center, Norman, OK

Ensemble Median

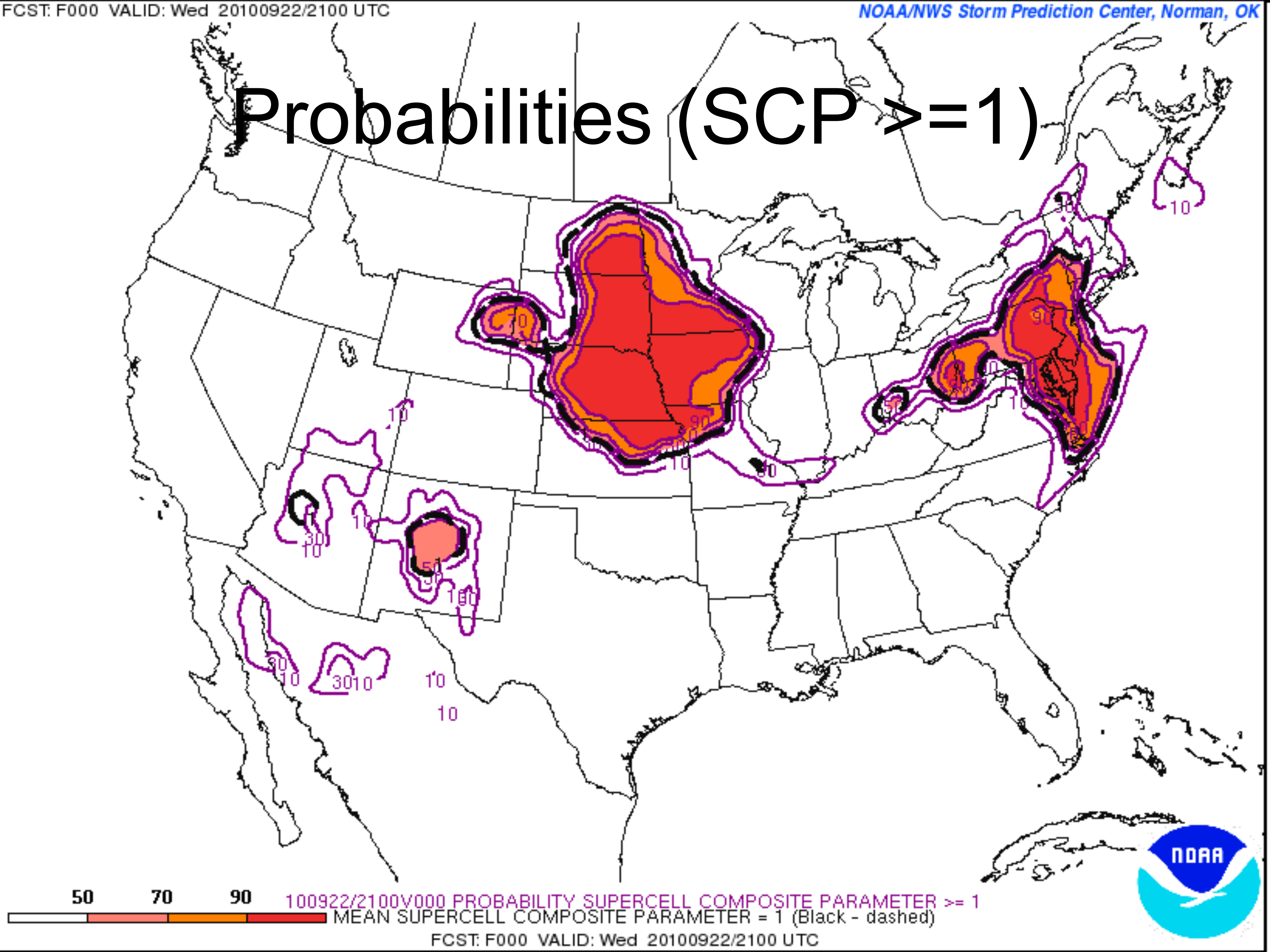


UNION (>=1 member; Red) and INTERSECTION (All members; Blue)

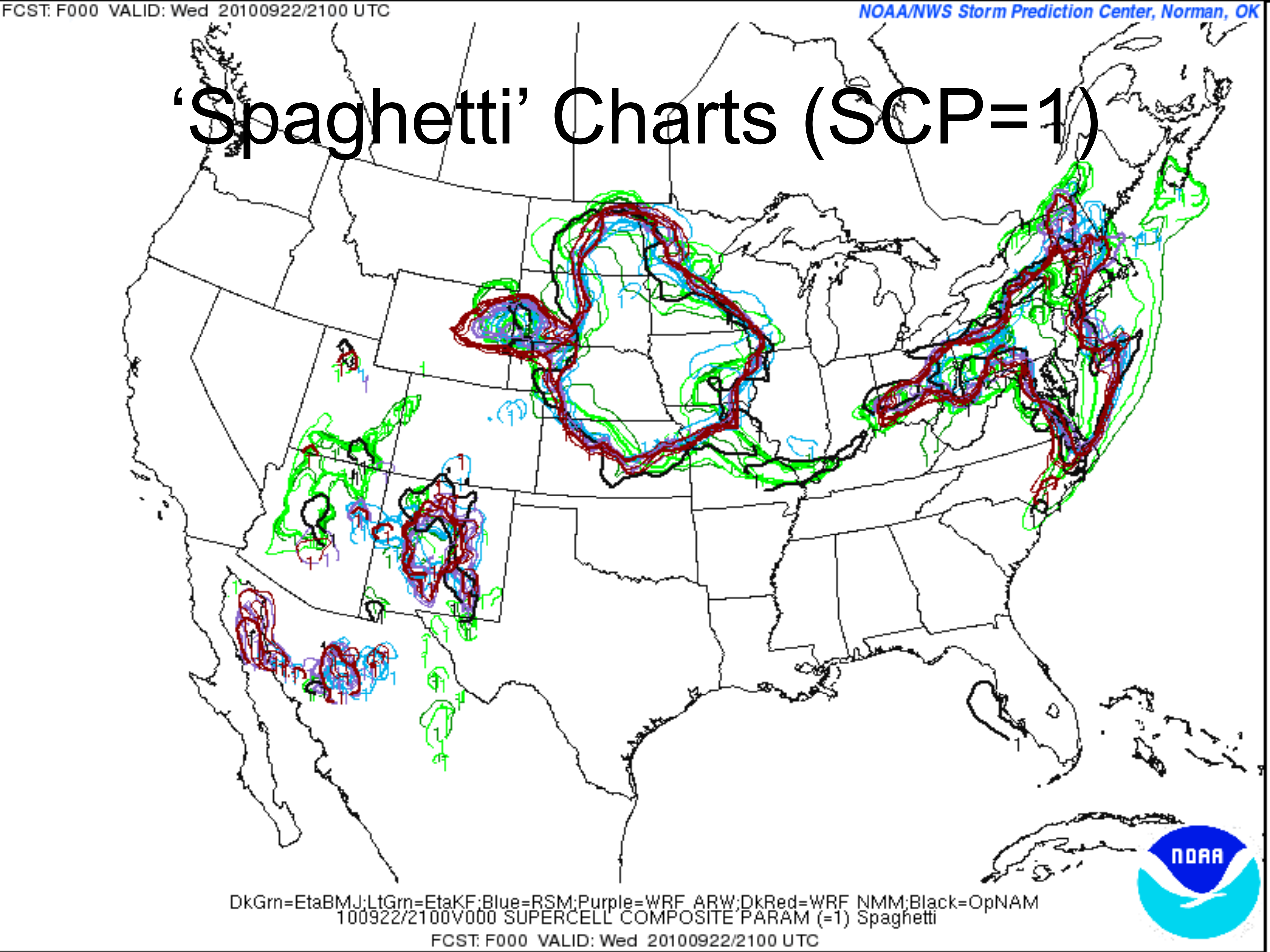
100922/2100V000 MEDIAN SUPERCELL COMPOSITE PARAMETER (Green)

FCST: F000 VALID: Wed 20100922/2100 UTC

Probabilities (SCP >=1)

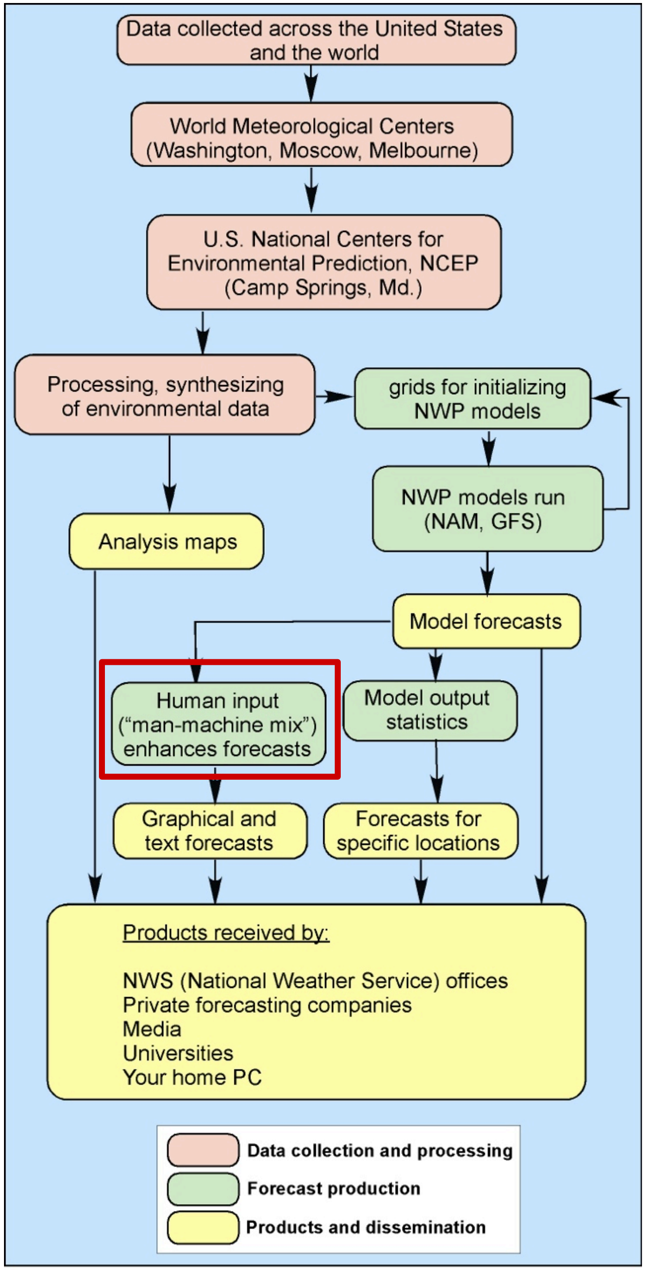


'Spaghetti' Charts (SCP=1)

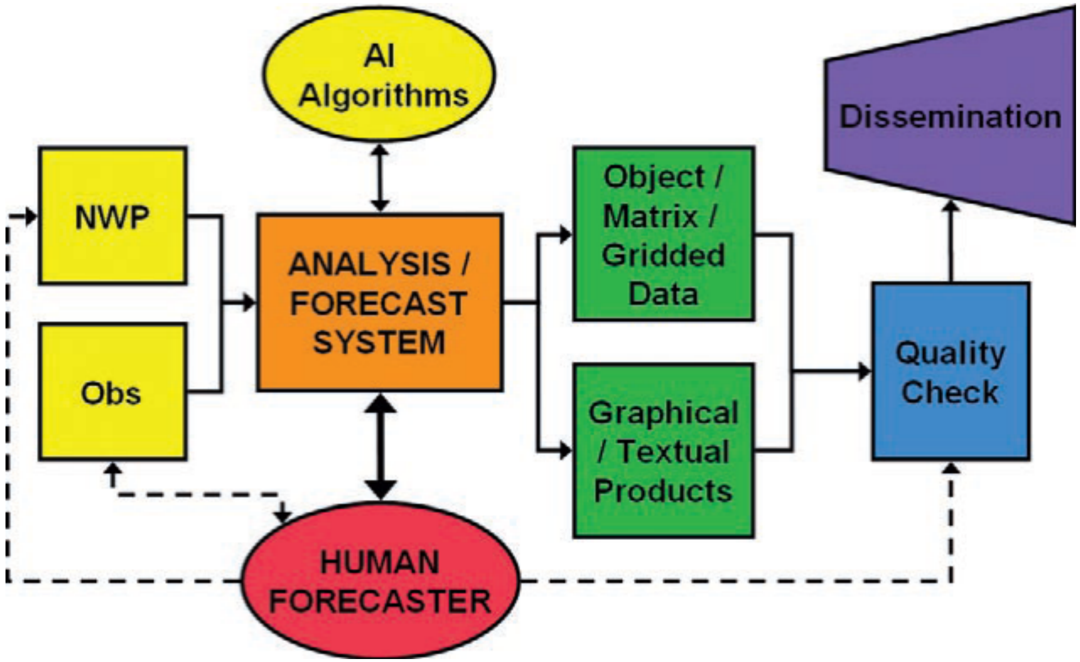


Limitations of Ensemble Forecasts

- More computational time / cost means lower horizontal resolution must be used.
- Interpretation – when is the mean / median the best solution, when is an outlier the best solution?
  - Especially important for extreme values (e.g. severe to climatologically extreme weather)
- What is the best choice of perturbations for ensemble members?
- How do users interpret probabilistic forecasts?
- Still a young science…



The Human-Machine Mix?



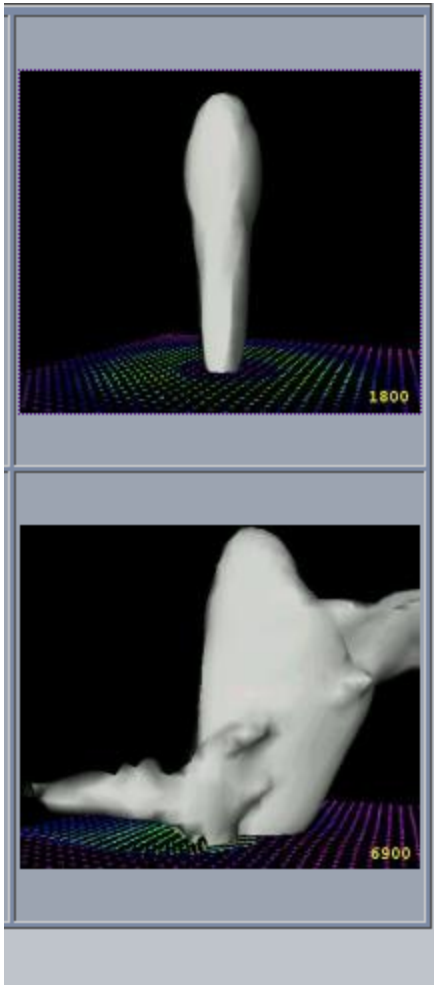
Research NWP

- Typically very high resolution
- Experimental parameterizations
- Highly adaptable to various problems

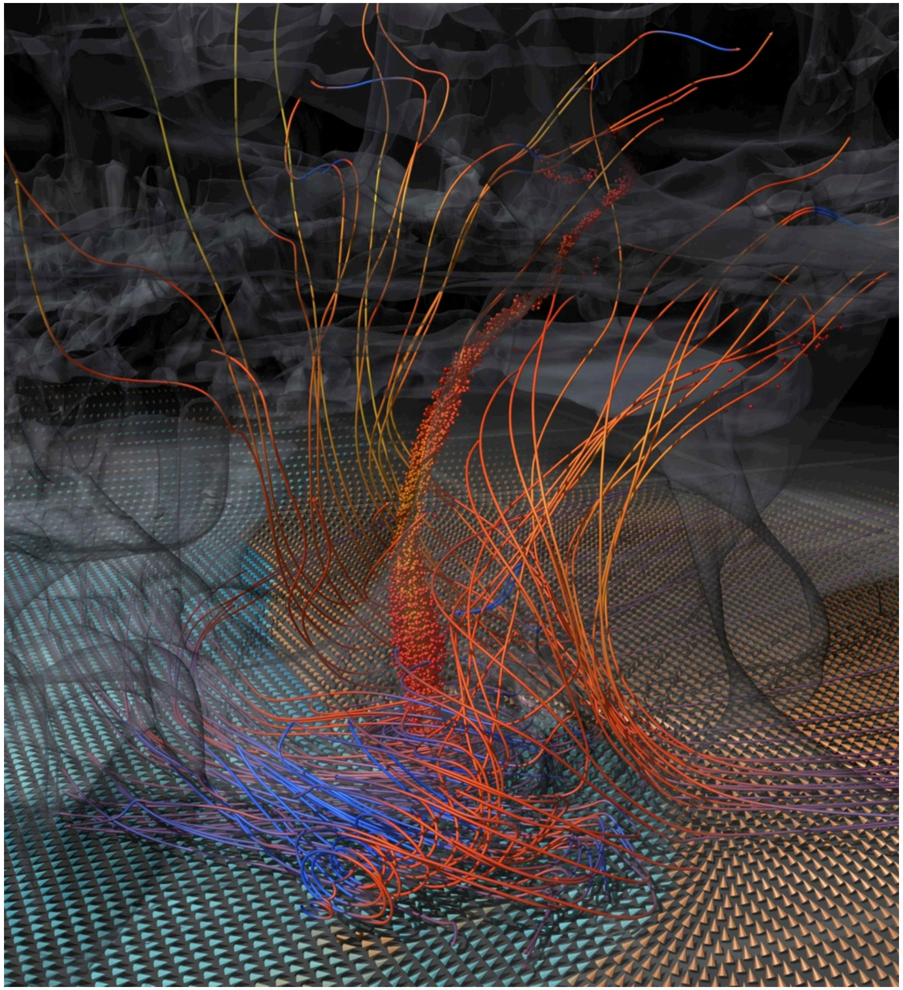
Models Used for Severe Weather Research

Model Name	Responsible Agency	Approximate Resolution	Approximate Domain	Range of Forecasts	Comments
Advanced Research Prediction System (ARPS)	University of Oklahoma	Adaptable	Regional	Adaptable	
Global Environmental Multiscale – Limited Area Model (GEM-LAM)	Environment Canada	Adaptable	Regional	Adaptable	Used in research – future operational model at EC
Weather Research and Forecasting Model (WRF)	Various U.S. Agencies	Adaptable	Regional	Adaptable	Used in research – future operational model at NCEP; also the basis of the North American Model
Cloud Model 1 (CM1)	NCAR	Adaptable	Regional	Adaptable	Research model used for very high resolution simulations of supercells and tornadoes.

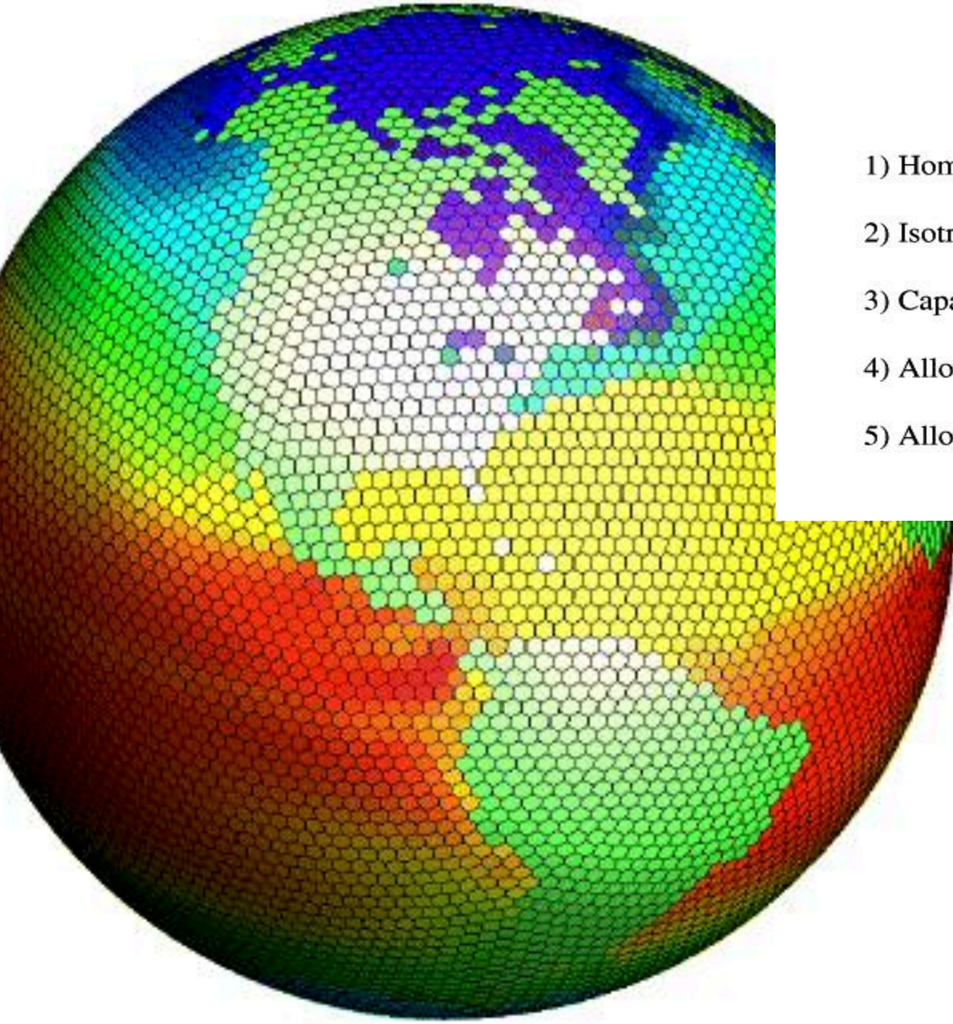
http://severewx.atmos.uiuc.edu/index.4.html



Storm simulations in two different shear environments



Simulating hurricanes, supercell thunderstorms and tornadoes



What are we looking for in a grid?

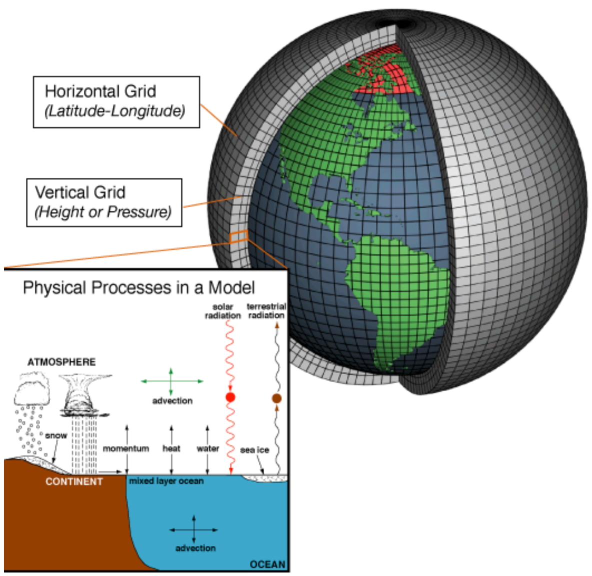
1) Homogeneity

2) Isotropy

3) Capability to increase resolution sufficient to resolve scales of interest

4) Allows the implementation of accurate finite-difference stencils

5) Allows the formulation of conservative finite-difference schemes



References

Effective use of high-resolution models (2010)
https://www.meted.ucar.edu/nwp/hires/index.htm

Limitations of High-Resolution NWP Models (2017)
https://www.meted.ucar.edu/training_module.php?id=1280

Operational Models Encyclopedia (date varies by model)
https://sites.google.com/ucar.edu/operational-models-encyclo/home