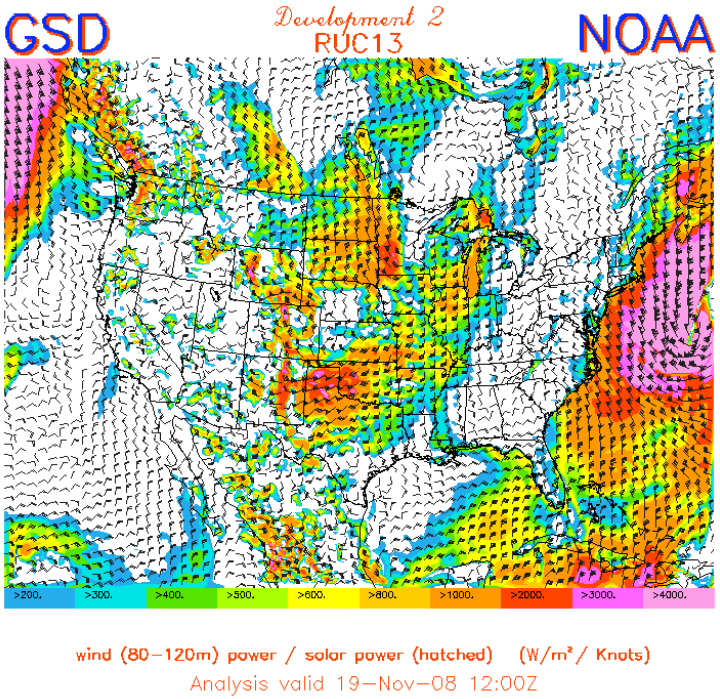


Challenges and Directions for NOAA's Weather Modeling and Implications for Renewable Energy

Stan Benjamin
Research Meteorologist
Chief, Assimilation and Modeling Branch http://ruc.noaa.gov/amb
NOAA Earth System Research Laboratory, Global Systems Division
Boulder, CO

NOAA/ESRL- Kevin Brundage, John Brown, Jian-Wen Bao, Jim Wilczak, Joe Olson, Wayne Angevine

NOAA/NCEP - Geoff DiMego

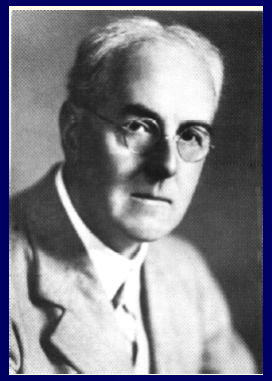
Current Surface
LT RAIN/DRIZZLE
MOD/HVY RAIN
FRZ RAIN/SLEET
LT SNOW/FLUR
MOD/HVY SNOW
FOG
H
L
L
L
L
L
H
H
THE WEATHER CHANNEL
23 Feb 2001 14:52 GMT / 23 Feb 2001 09:52 AM EST

Where weather forecasting was in 1940

- Based largely on surface observations
- Little information on conditions above surface
- Weather disasters in first half of 20th century - essentially unforecast
  - Galveston hurricane – 1900
  - New England hurricane – 1938
  - Miami hurricane – 1926 – 600 killed
    - Estimated $75 billion if same storm hit today
  - Tri-State Tornado – 1921 – 600 killed
  - Tornadoes – Flint, Mich; Worcester, Mass - 1953

What happened to cause change

- New ideas - understanding atmospheric motion with fundamental physics
  - Vilhelm Bjerknes – 1905
  - Lewis Richardson – 1919



- World War II
  - Dominant role of aviation in warfare
- Development of commercial aviation

What is different now

- Improved understanding of weather phenomena – development of meteorology programs in major universities starting in 1940s
- Improved observations – weather balloons, satellites, radar, commercial aircraft
- Development of numerical weather prediction (NWP) – computer models of atmosphere
- Development of high-speed computers
- Public understanding of importance of weather forecasts for economic activity as well as for protection of life and property

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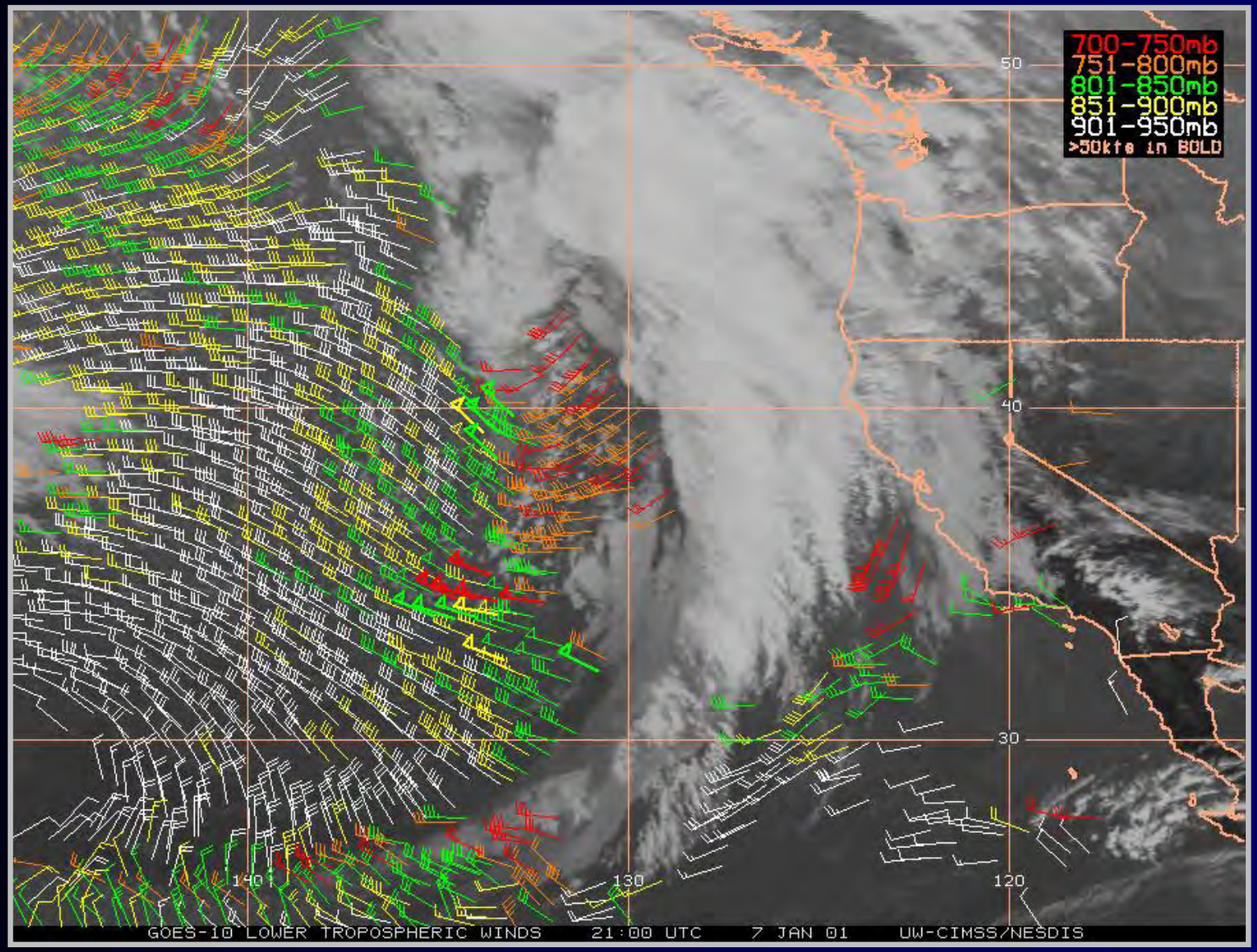
Weather balloons

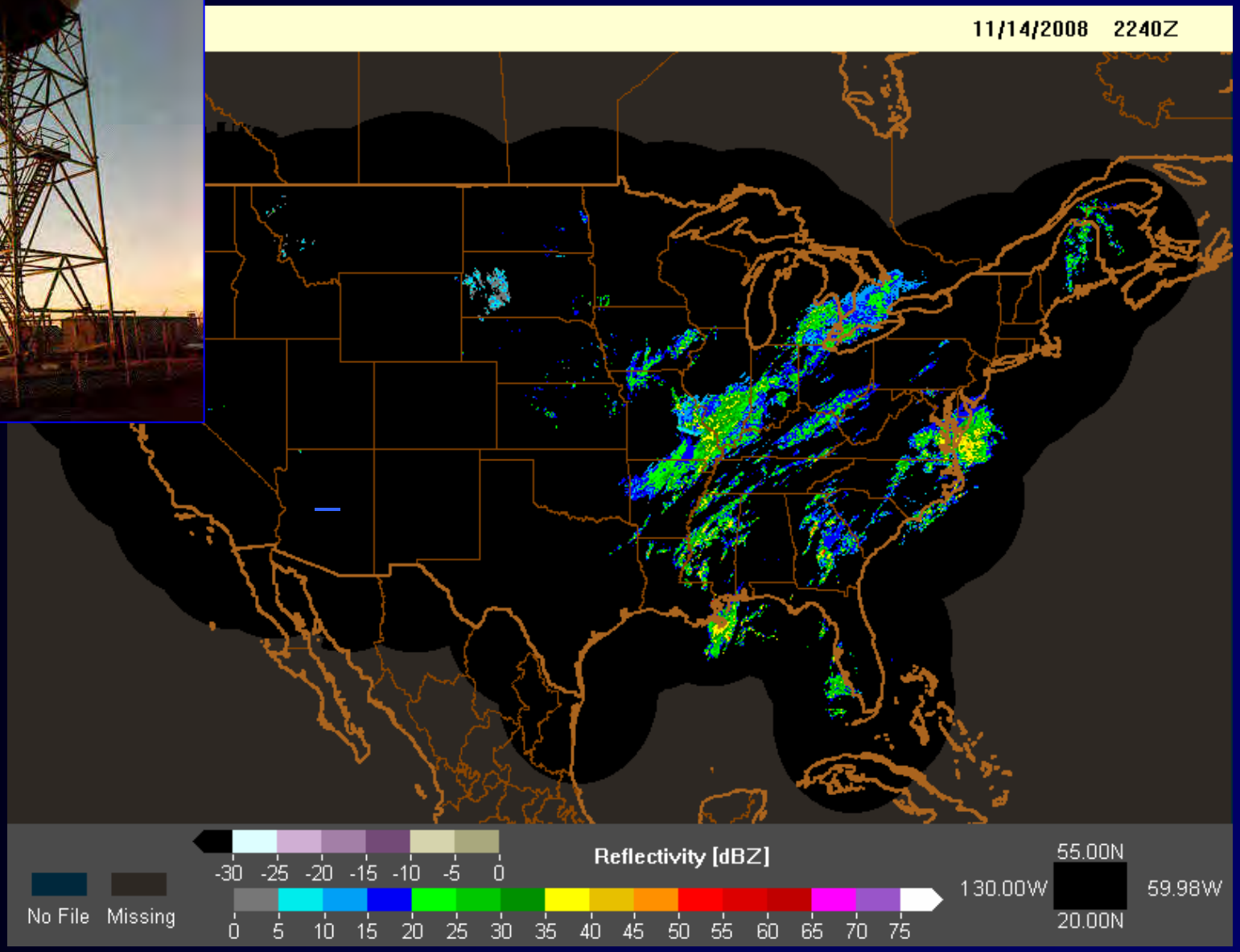
Wind profilers

Satellite clouds, estimated winds, radiances



Commercial aircraft observations
- winds and temperature
- recently – water vapor, turbulence

Radar – 120-station Doppler radar network in US



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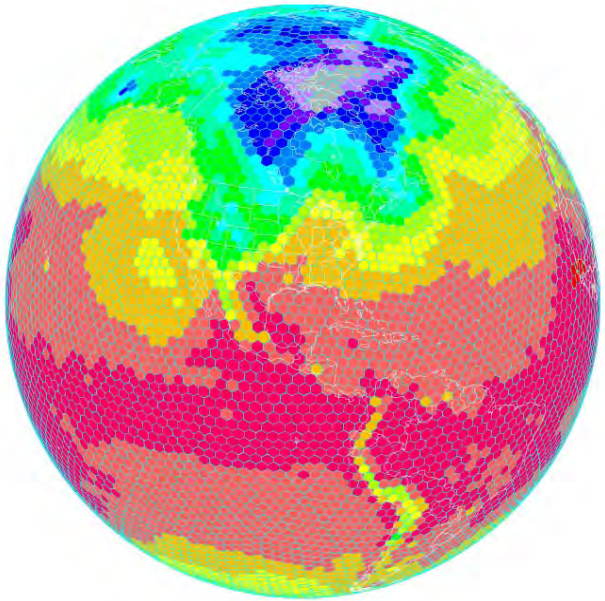
Two main points:

1. Atmospheric forecasts from weather models for **both** **wind energy** and **solar energy** are outputs from the **same** model.
   - Improved cloud/sun forecasts improves near-surface wind forecasts, and conversely,
   - Improved forecasts of "boundary layer" winds is related to forecasts feeds back into clouds, precipitation, and even winds *above* the PBL.

   Good thing: **Consistent forecasts for both wind energy and solar energy generation potential are from the same physical atmospheric system.**

2. Equally complicated problems: Development of
a. Weather model and
b. Data assimilation (to initialize model)
Both are important for 1h to 15-day forecasts

Numerical weather prediction



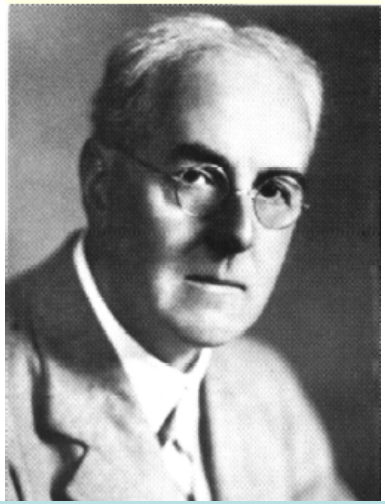
solutions to partial differential equations for

fluid dynamic flow on
unevenly heated rotating sphere

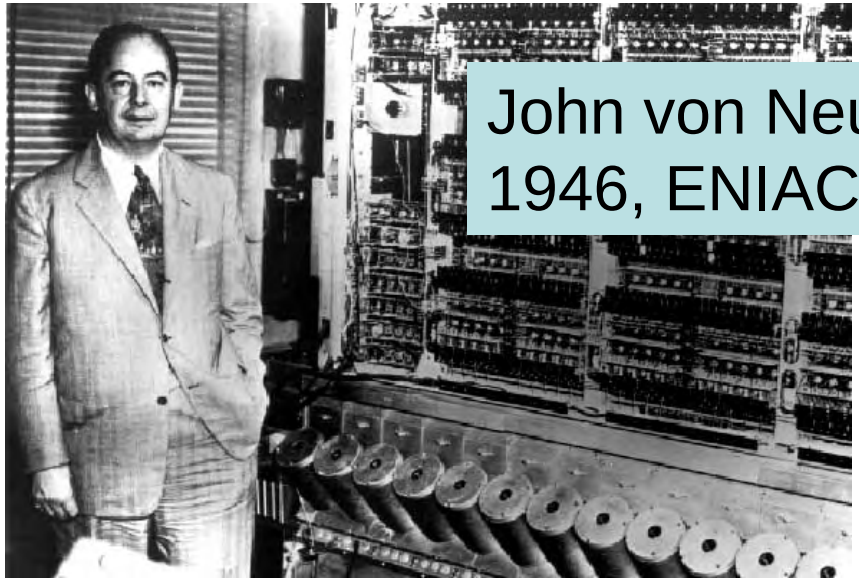
Tendency-in-time equations for
horizontal wind components, pressure, temperature,
moisture variables – e.g., $\frac{\partial u}{\partial t} = \ldots$

Finite difference representation of atmosphere

- *cover area to be forecast with 3-d grid of points at which equations will be solved*
- *produce short prediction over short time step (0.5 – 5 min) at each grid point*
- *repeat process until desired forecast length is complete*

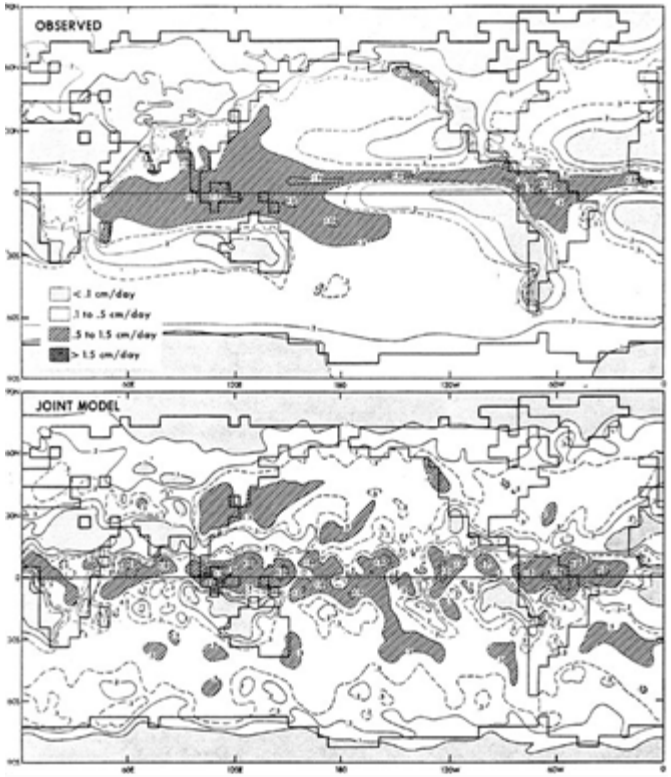


Lewis Richardson
1919

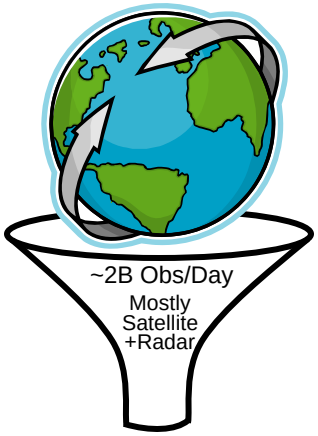


John von Neumann
1946, ENIAC

Jule Charney, Norm Phillips
1952, Princeton, MANIAC



NOAA's NWS Model Production Suite



Global Data Assimilation

Climate CFS

MOM3

Hurricane

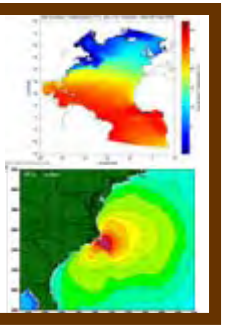
GFDL
HWRF

Coupled

Oceans

HYCOM

WaveWatch III



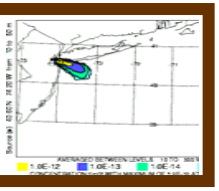
Global Forecast System

North American Mesoscale

WRF NMM

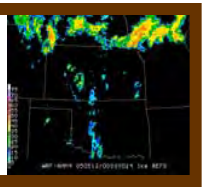
Dispersion

ARL's HYSPLIT



Severe Weather

WRF NMM
WRF ARW



Short-Range Ensemble Forecast

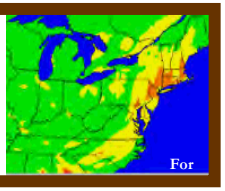
WRF: NMM+ARW
ETA, RSM

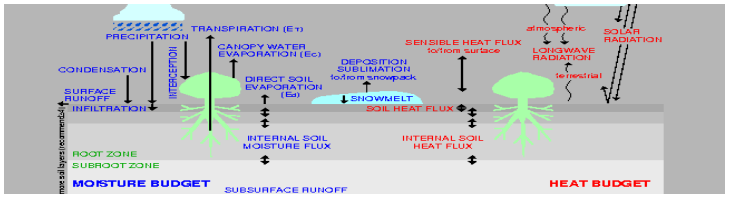
North American Ensemble Forecast System

GFS, Canadian Global Model

Air Quality

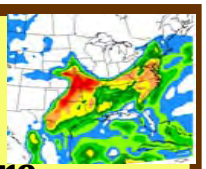
NAM+CMAQ

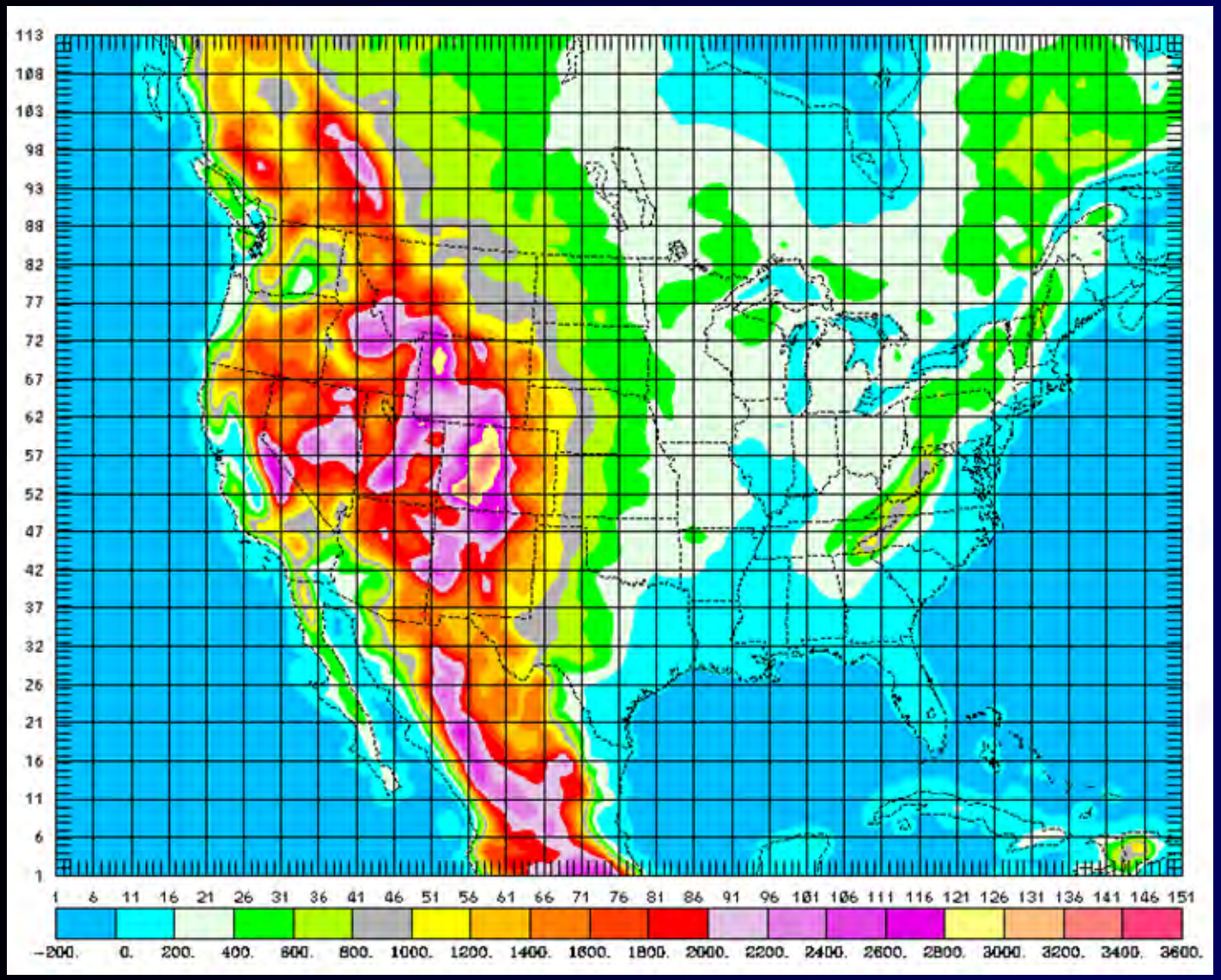




NOAH Land Surface Model

Rapid Update for Aviation, Severe

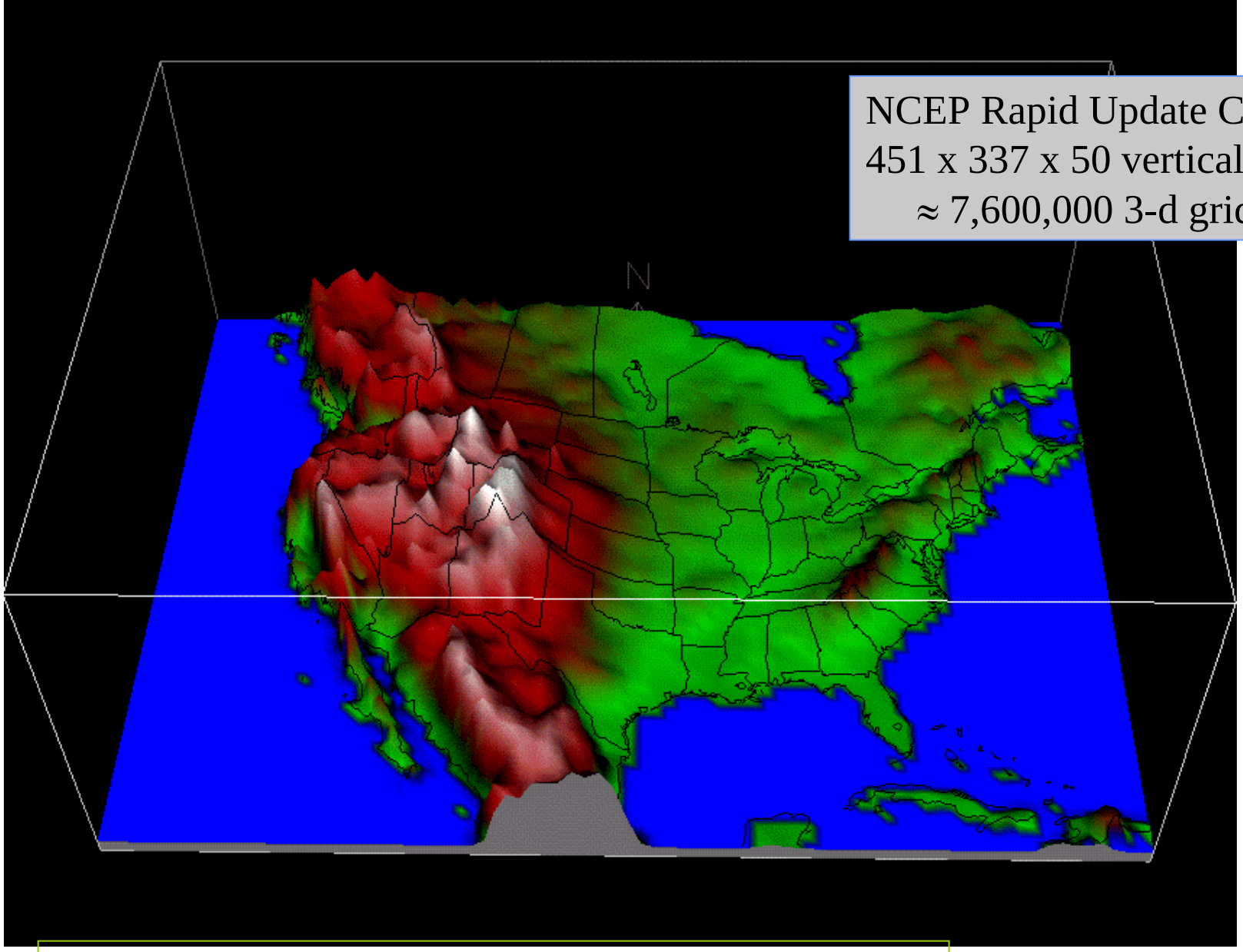




NWS
Rapid Update Cycle
(RUC)
forecast model
- 13 km resolution

-451 x 337 grid pts
= 151,987 grid pts

Place 2-dimensional grid of “forecast grid points”
over area to be forecast



NCEP Rapid Update Cycle
451 x 337 x 50 vertical levels
≈ 7,600,000 3-d grid pts

Add a vertical dimension to create a 3-d grid

Key components of weather models

Component

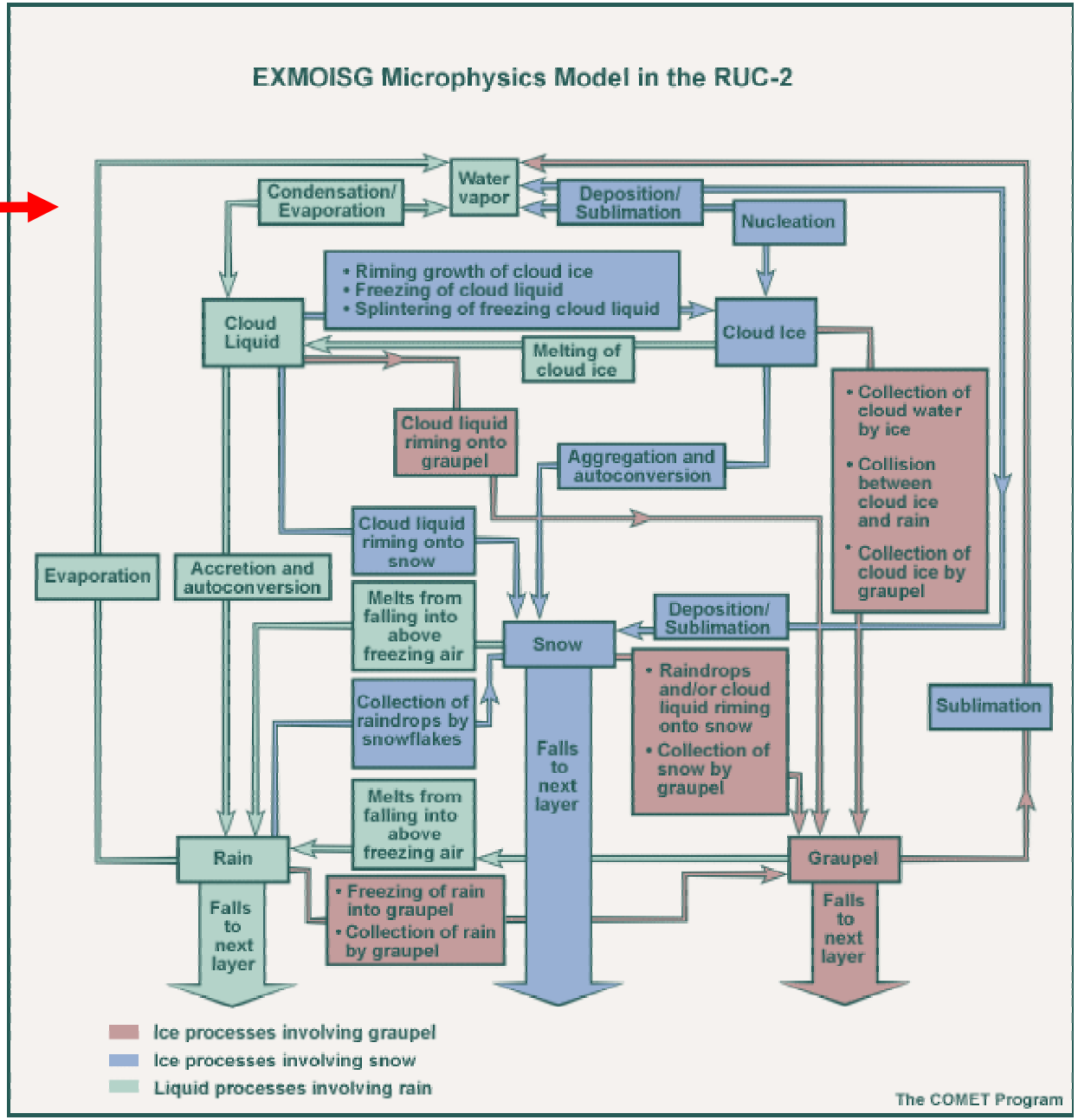
- Dynamics - wind, pressure
- Physics - clouds, radiation, land surface, etc.
- Chemistry

No. of 3-d prognostic variables	RUC
4	4
4-30+	11
18- >400	0

Cloud forecasting in weather models

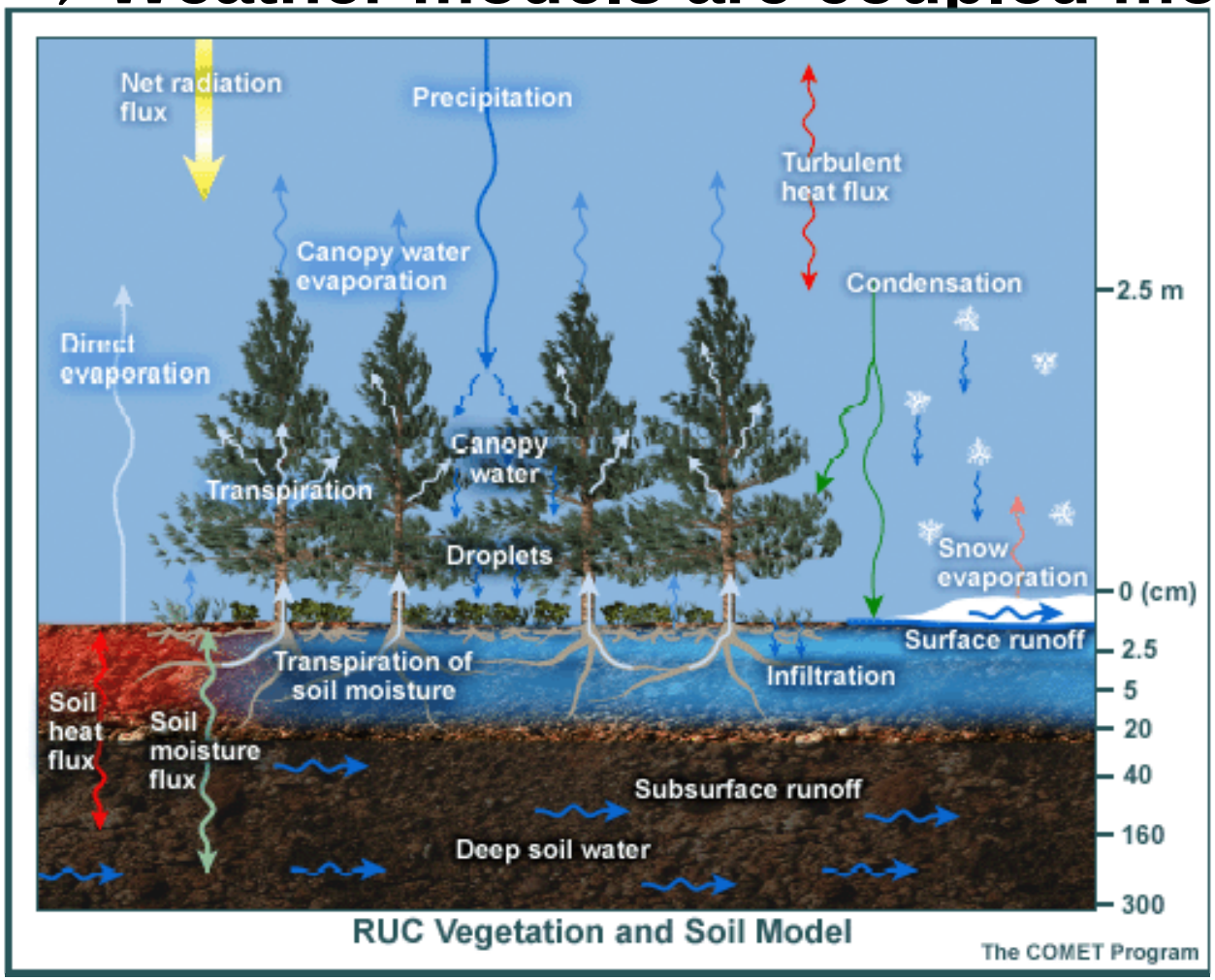
In 2002-09 RUC model.

For improved cloud/solar accuracy, need to forecast separately:
- different sizes of cloud droplets
- different ice crystals
- aerosols



Atmospheric models are typically coupled with land-surface (soil, vegetation, snow) models with 4-10 soil layers + 1-10 level snow model

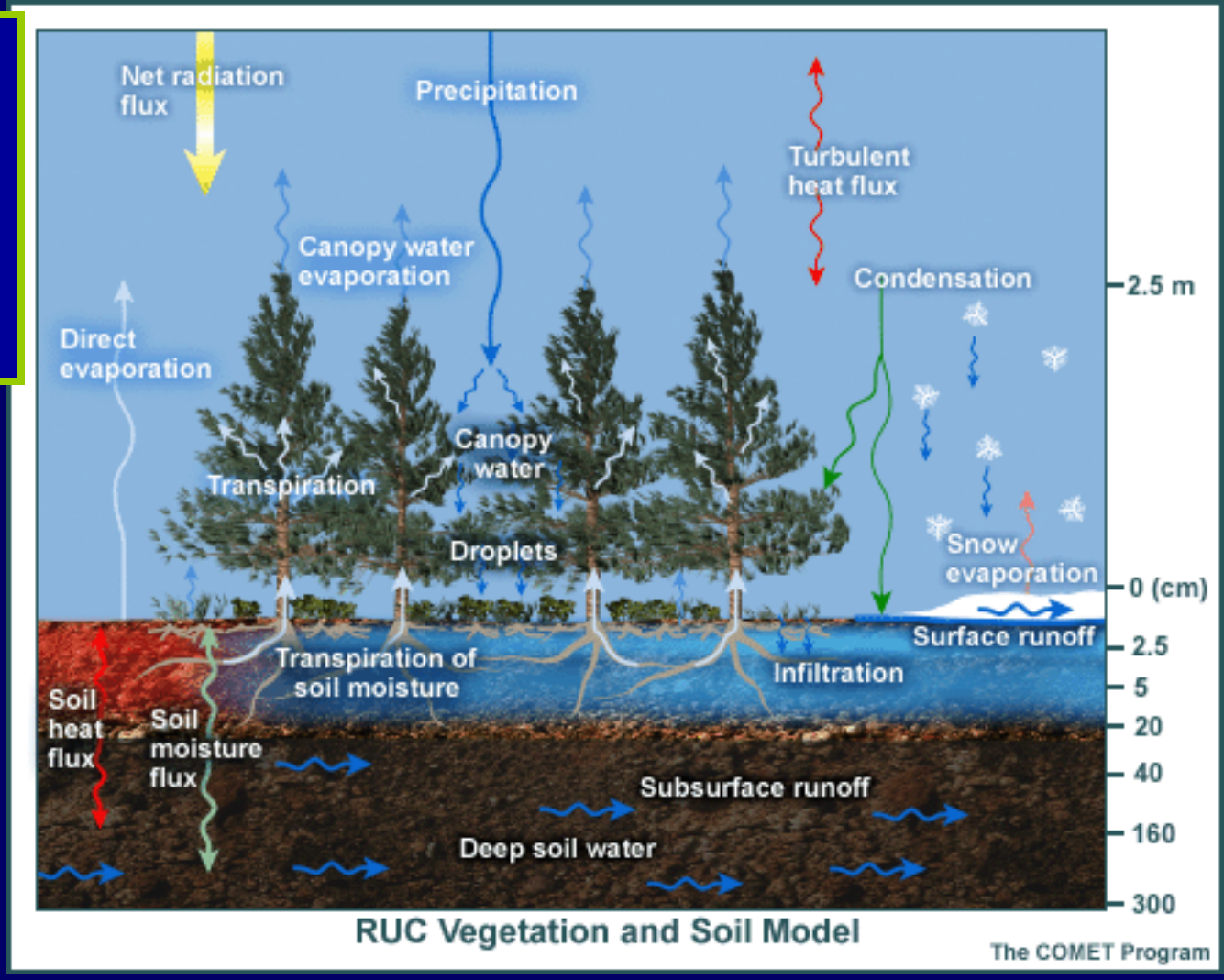
→ **Weather models are coupled models**



* All of these processes are in weather models

The COMET Program

RUC Land-surface Process Parameterization



Purpose – Calculate air-surface transfer of moisture, heat, momentum.

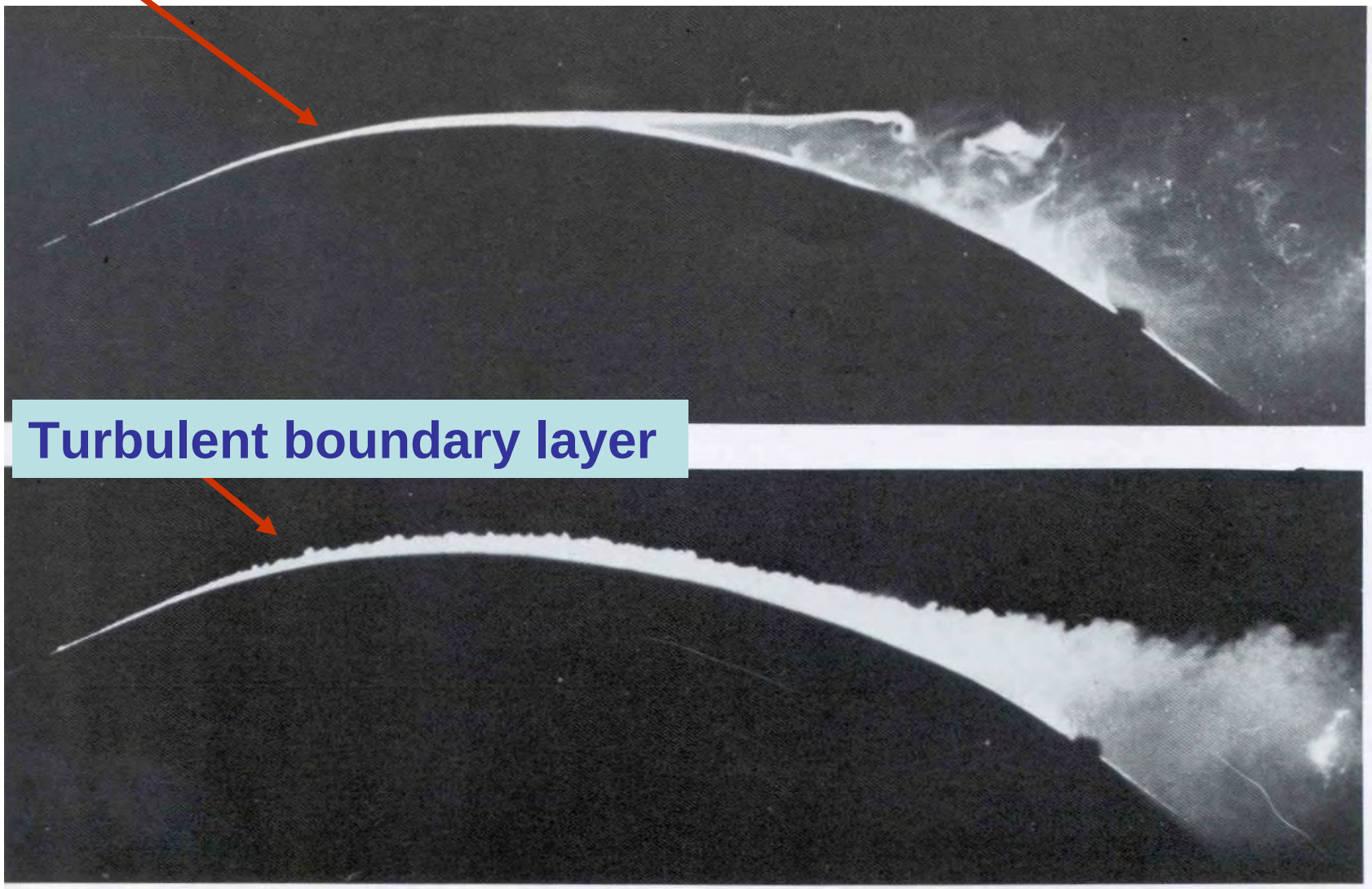
Coupled atmosphere/land-surface models improve near-surface wind forecasts

July 2001

PBL top

Griffith Observatory

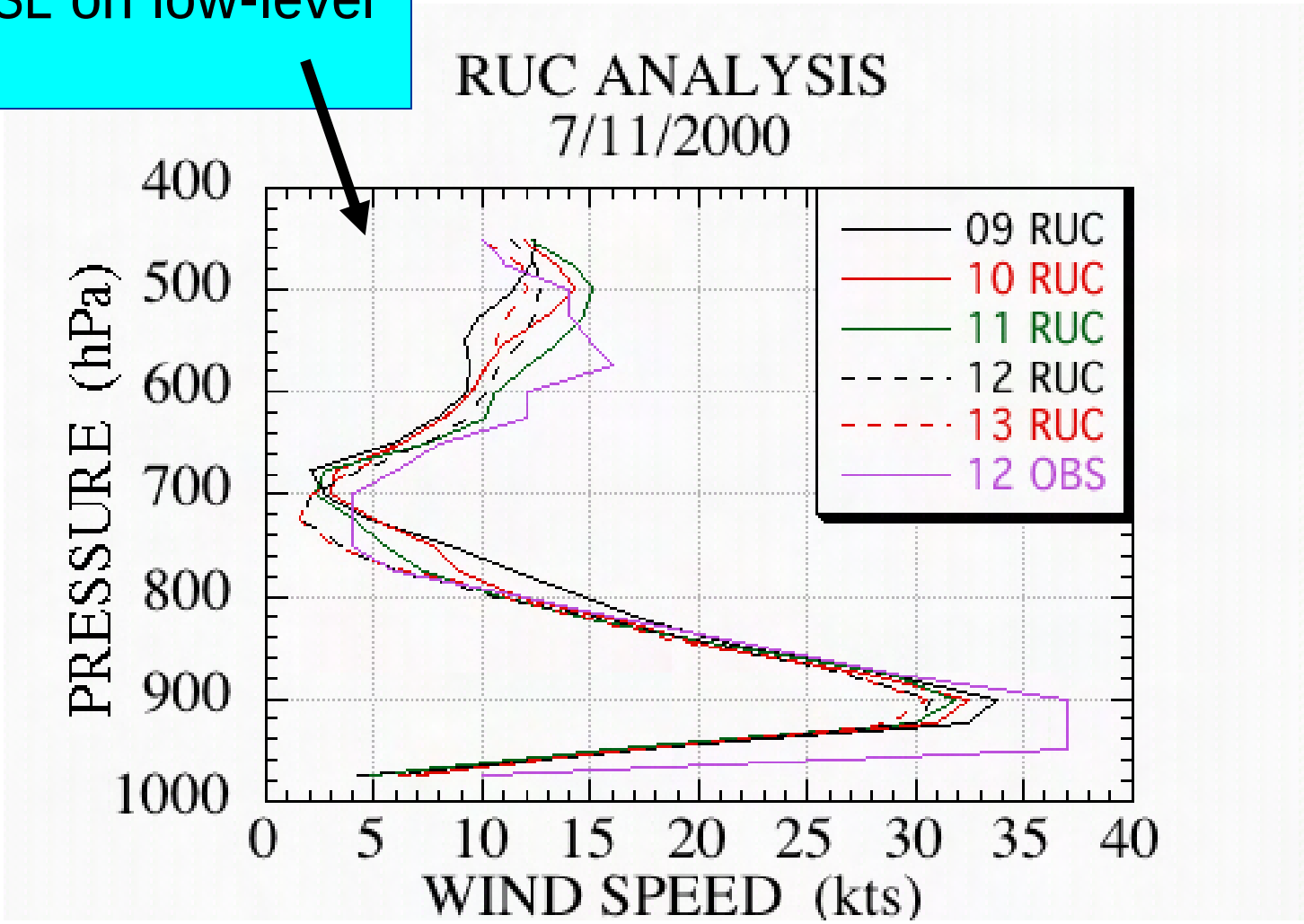
Laminar boundary layer (in wind tunnel)



156. Comparison of laminar and turbulent boundary layers. The laminar boundary layer in the upper photograph separates from the crest of a convex surface (cf. figure 38), whereas the turbulent layer in the second photograph remains attached; similar behavior is shown below for a sharp corner. (Cf. figures 55-58 for a sphere.) Titanium tetrachloride is painted on the forepart of the model in a wind tunnel. *Head 1982*

Research between NOAA/ESRL and NOAA/NSSL on low-level jet biases

Extensive work at ESRL on nocturnal boundary layer, LLJs, lidar/sodar observational studies (R. Banta) - NREL/NOAA project



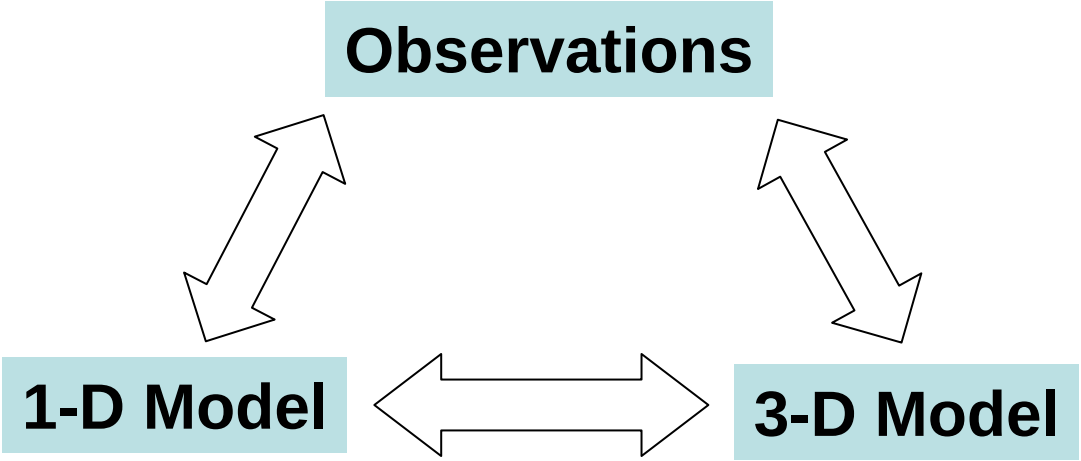
Research Challenge

As horizontal grid spacing (Δs) decreases and becomes smaller than the depth of the ABL, how to parameterize the turbulence mixing on the subgrid scale becomes a challenging research problem. When Δs is so small that the assumption of scale separation between horizontal and vertical mixing is no longer valid, conventional 1-D parameterizations for subgrid mixing used in operational NWP models is probvlematic and the use of parameterizations for 3-D subgrid mixing is required.

But, how to evaluate and validate the 3-D subgrid mixing?

(from Jian-Wen Bao and Jim Wilczak - NOAA/ESRL)

A Paradigm for the ABL Physics Improvement



Short-Term Goal: Continue evaluating and improving current parameterizations in research and operational models

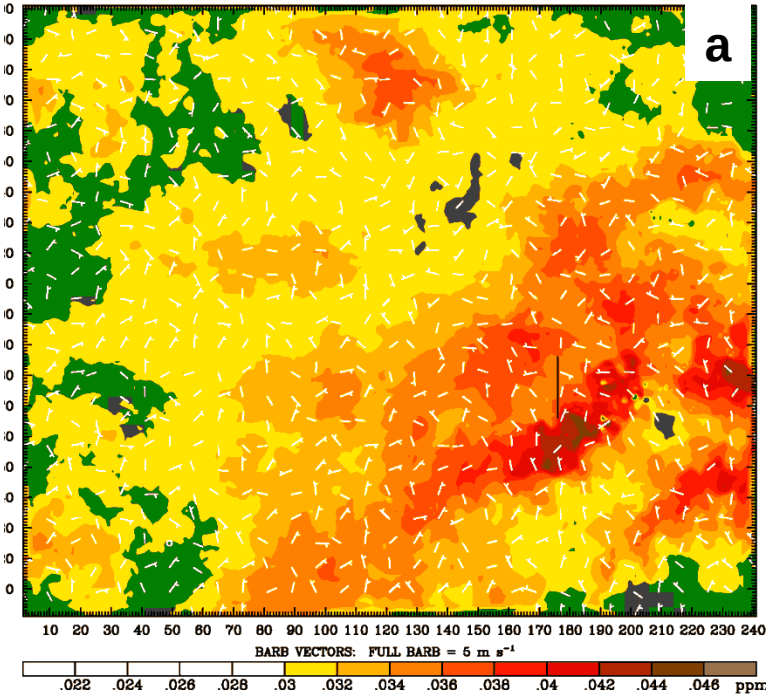
Long-Term Goal: Take up the challenge of the ABL modeling in the “Terra Incognita”

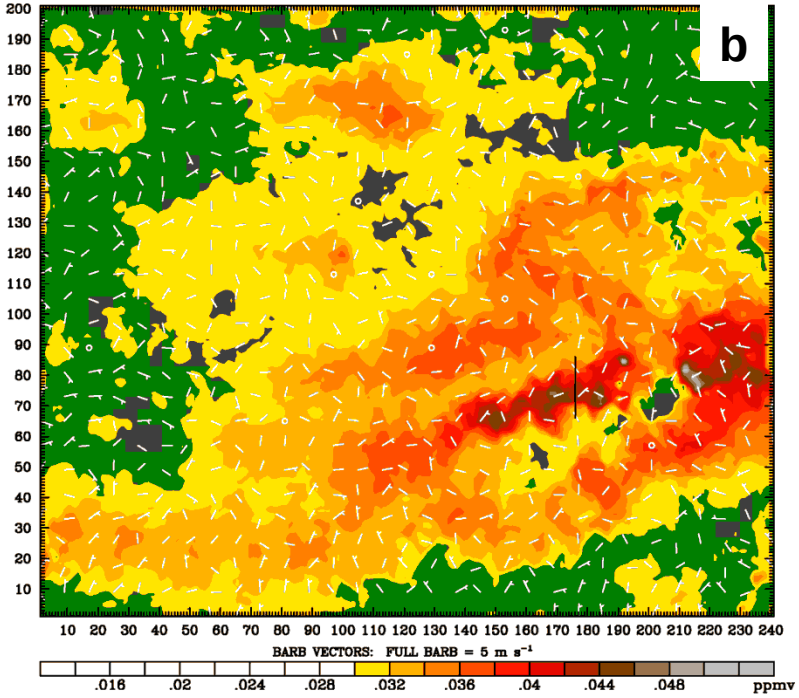
A WRF-CHEM Example to Demonstrate the Challenge

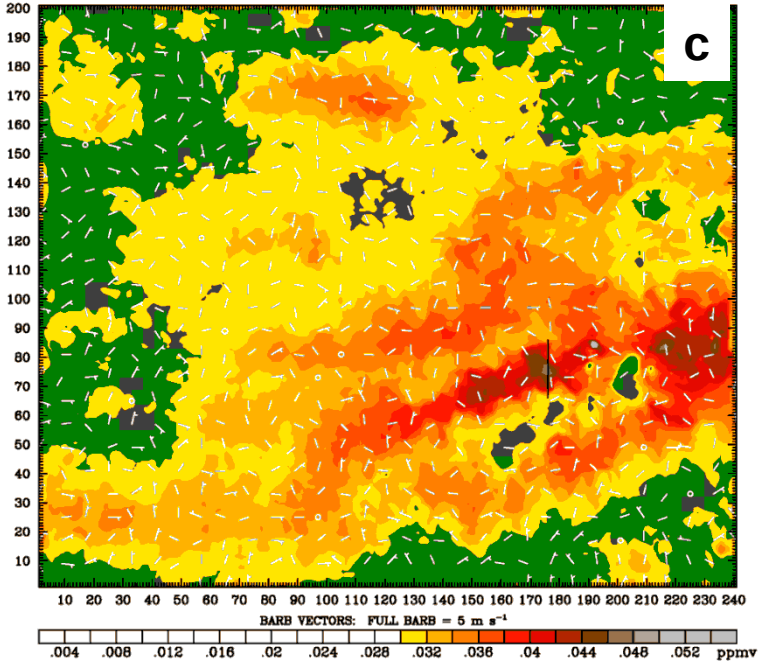
- One-way nested grid: 36, 12, 4, 1, and 0.2 km
- Noah Land-Surface Model
- Monin-Obukhov surface layer scheme
- Chemistry option: RADM2
- Emissions: anthropogenic point sources only
- Vertical levels: 50
- 241 x 201 grid points for the 0.2 km grid
- Length of forecast:
  - 24h for coarser meshes, initialized at 00 UTC on 25 Aug 2000
  - 10h for 0.2km mesh, initialized at 12 UTC on 25 Aug 2000

Options for subgrid turbulence mixing:

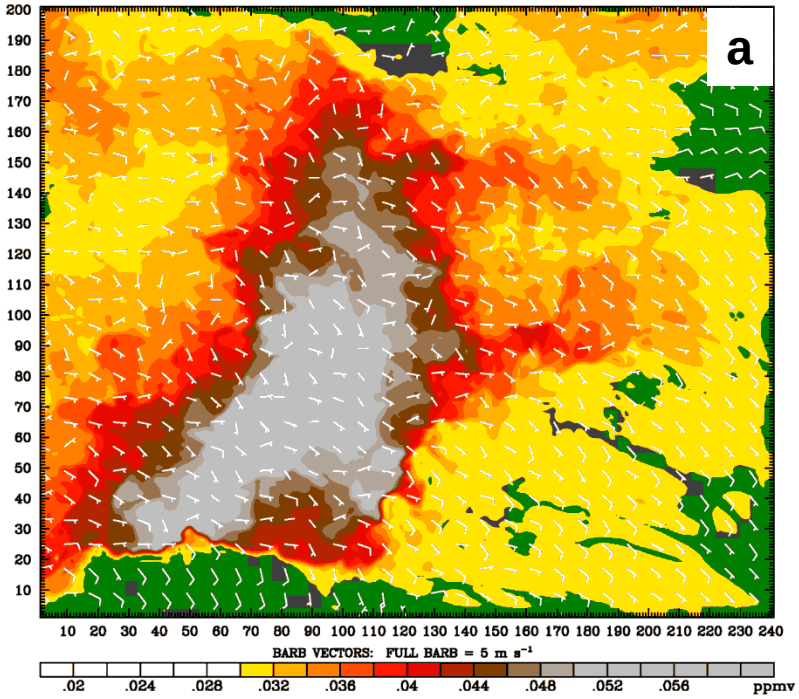
- the Mellor-Yamada-Janjic (MYJ) boundary layer scheme
  - the 3-D Smagorinsky closure
  - the 3-D turbulent kinetic energy (TKE) closure

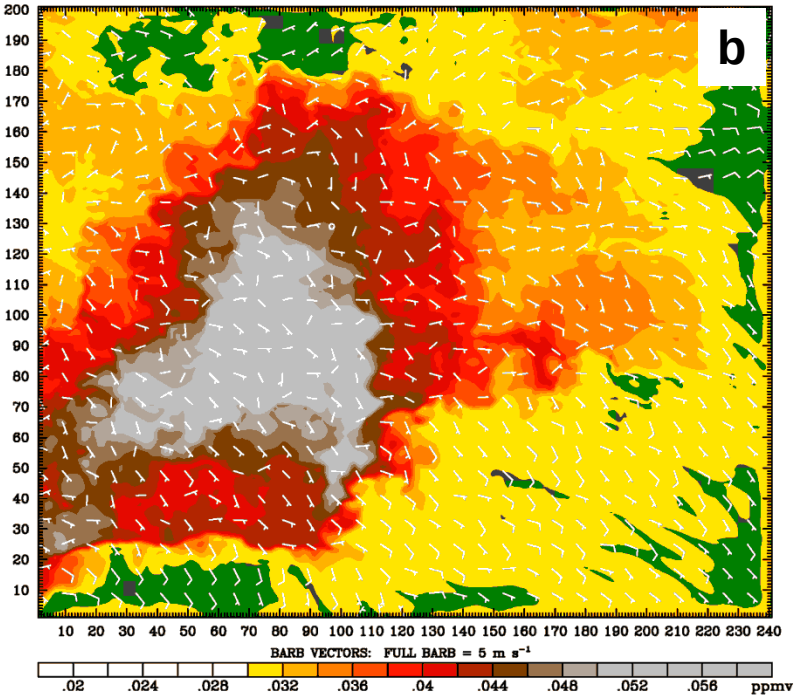


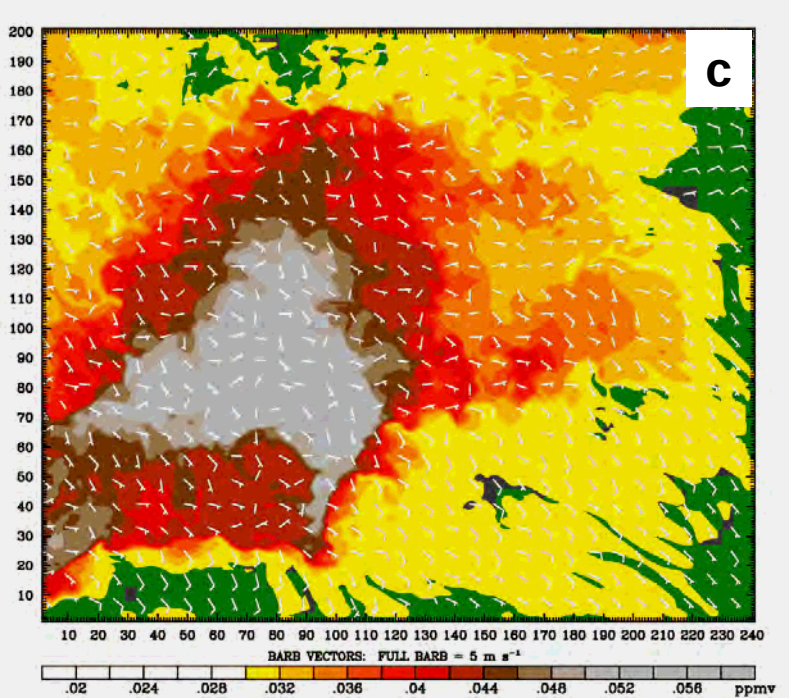




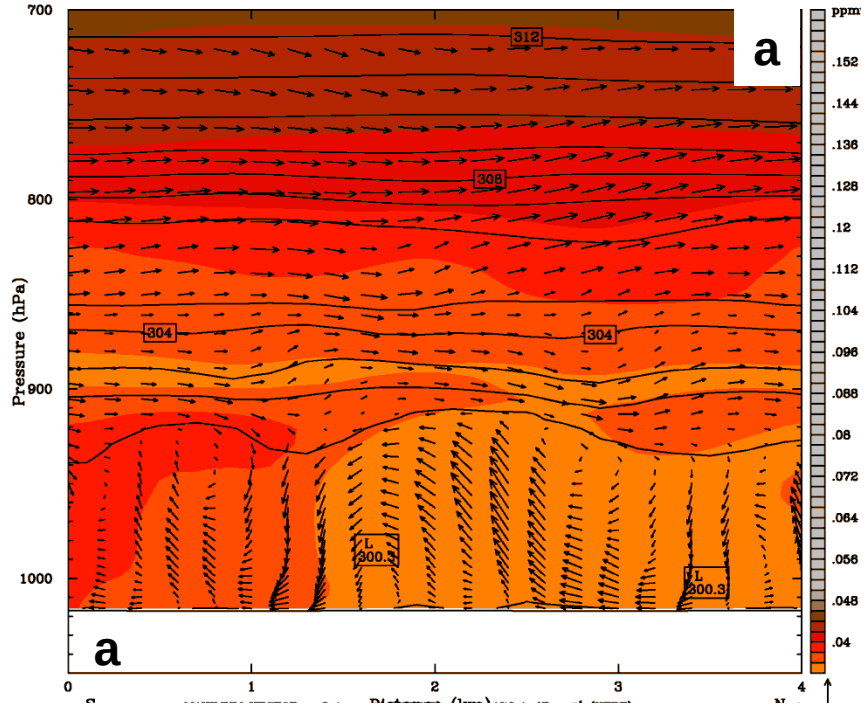
Ozone concentrations at the lowest model level at 1700 UTC (noon local time) for the simulations using a) MYJ parameterization, b) Smagorinsky closure, and c) TKE closure. The line indicates the position of the cross sections.

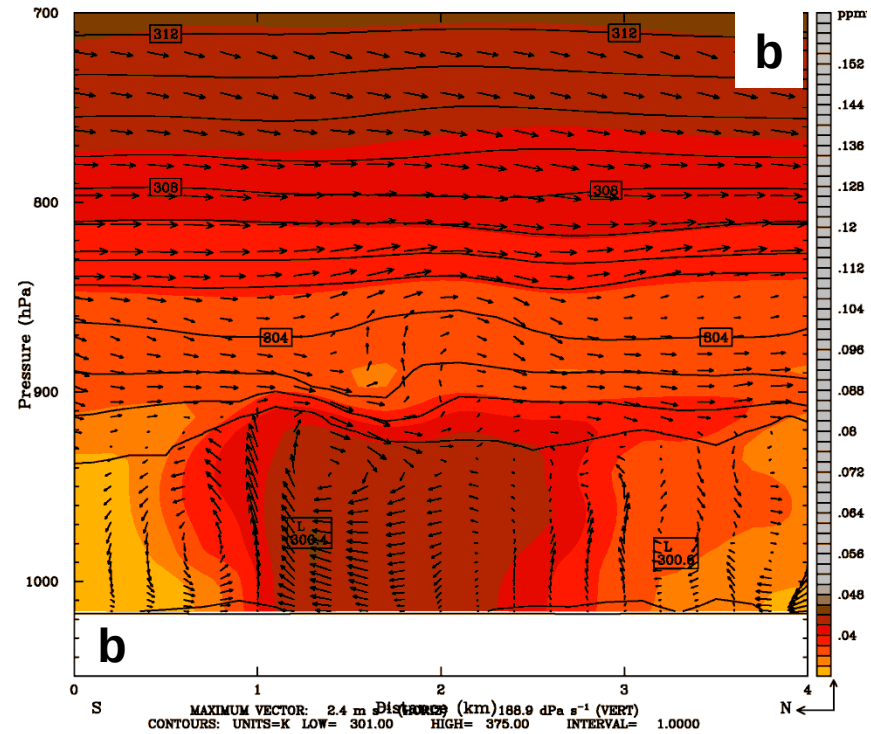


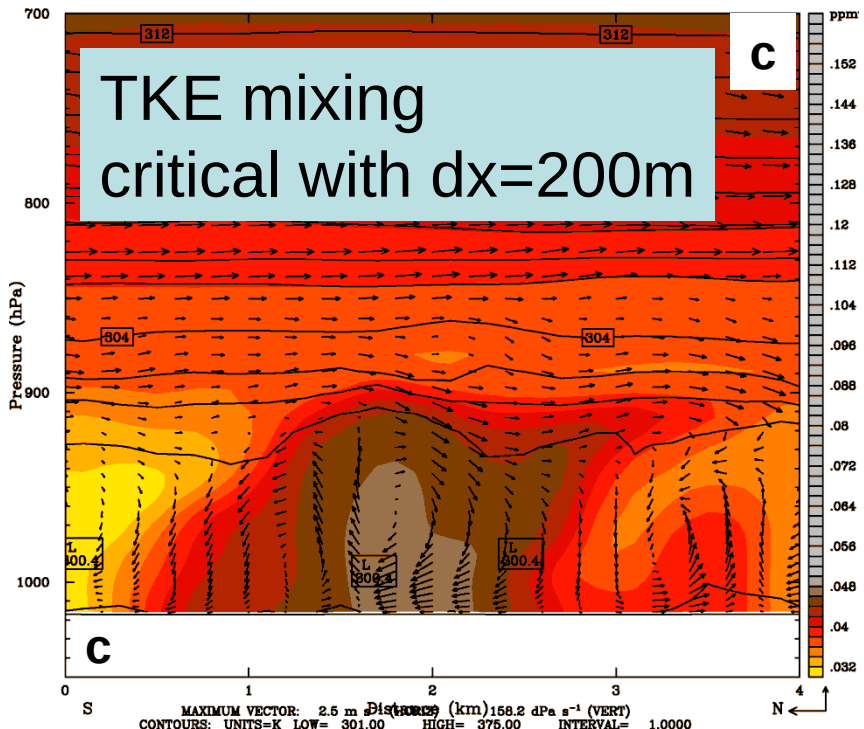




Ozone concentrations as the previous figure, but 4 hours later, at 2100 UTC (4 pm local time).



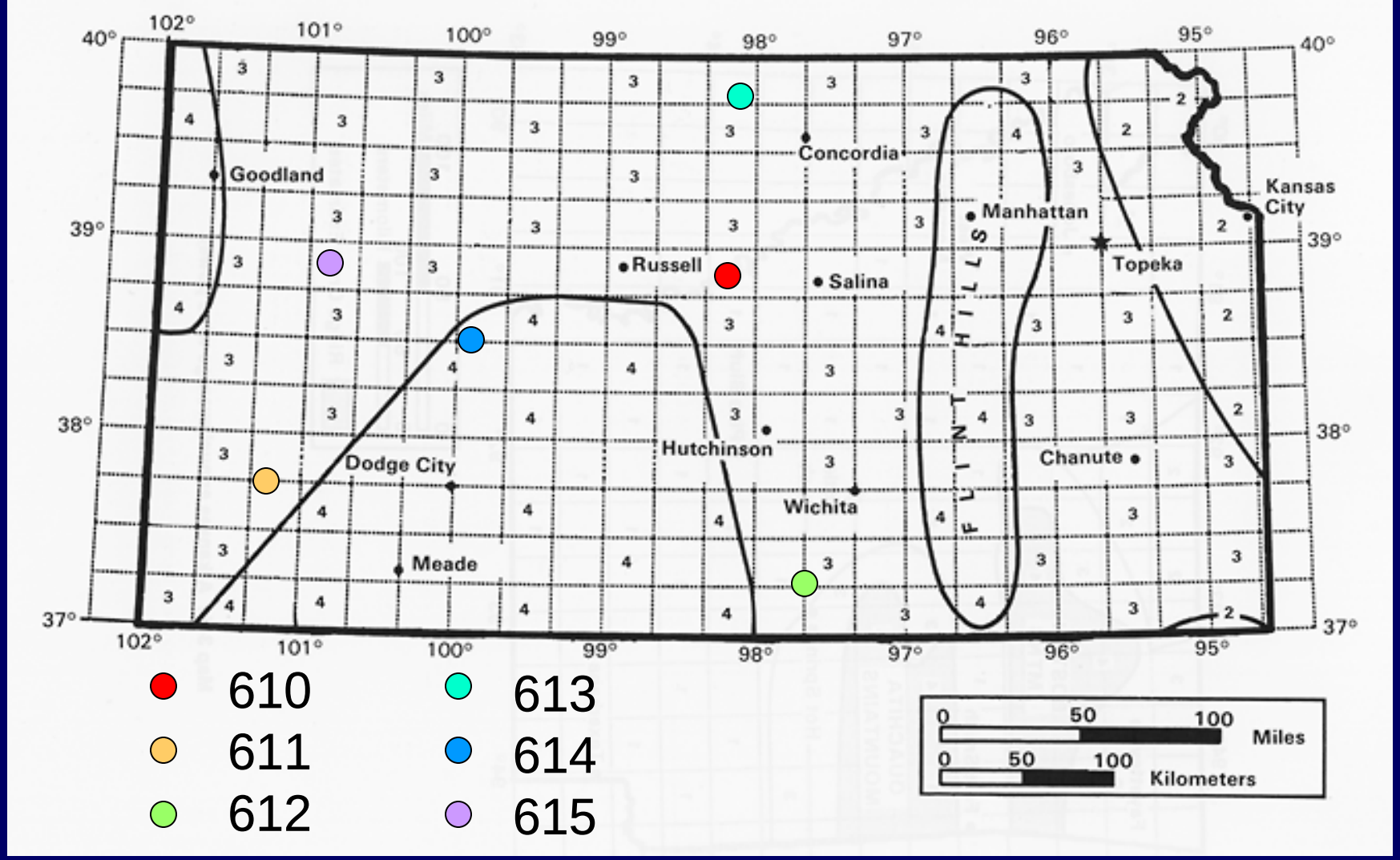




South-north cross sections of ozone concentrations at 1700 UTC through the lines shown above for the simulations using the a) MYJ parameterization, b) Smagorinsky closure, and c) TKE closure.

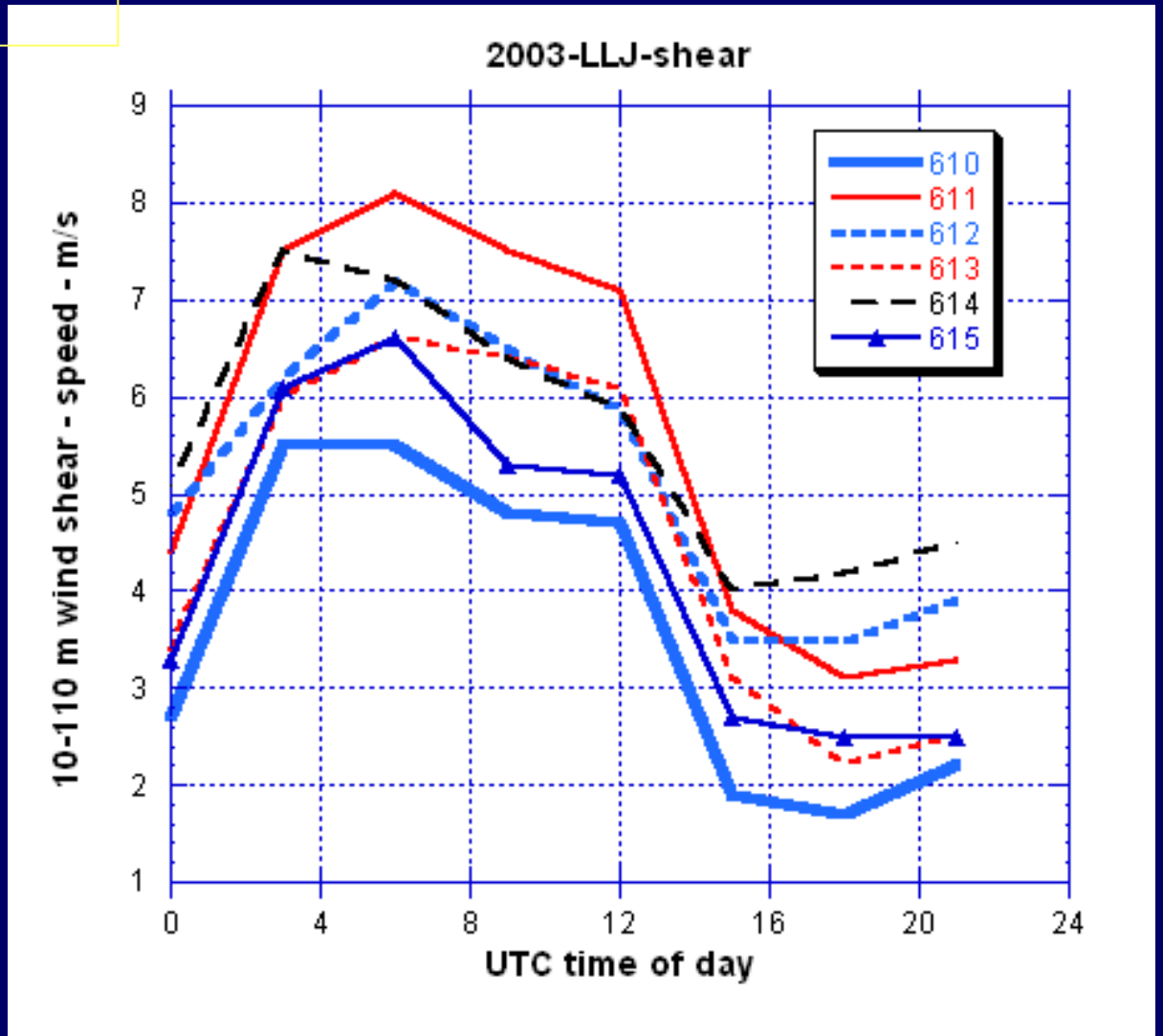
From another NOAA/NREL study - 10-110m wind forecasting - Brundage, Benjamin (NOAA), Schwartz (NREL)

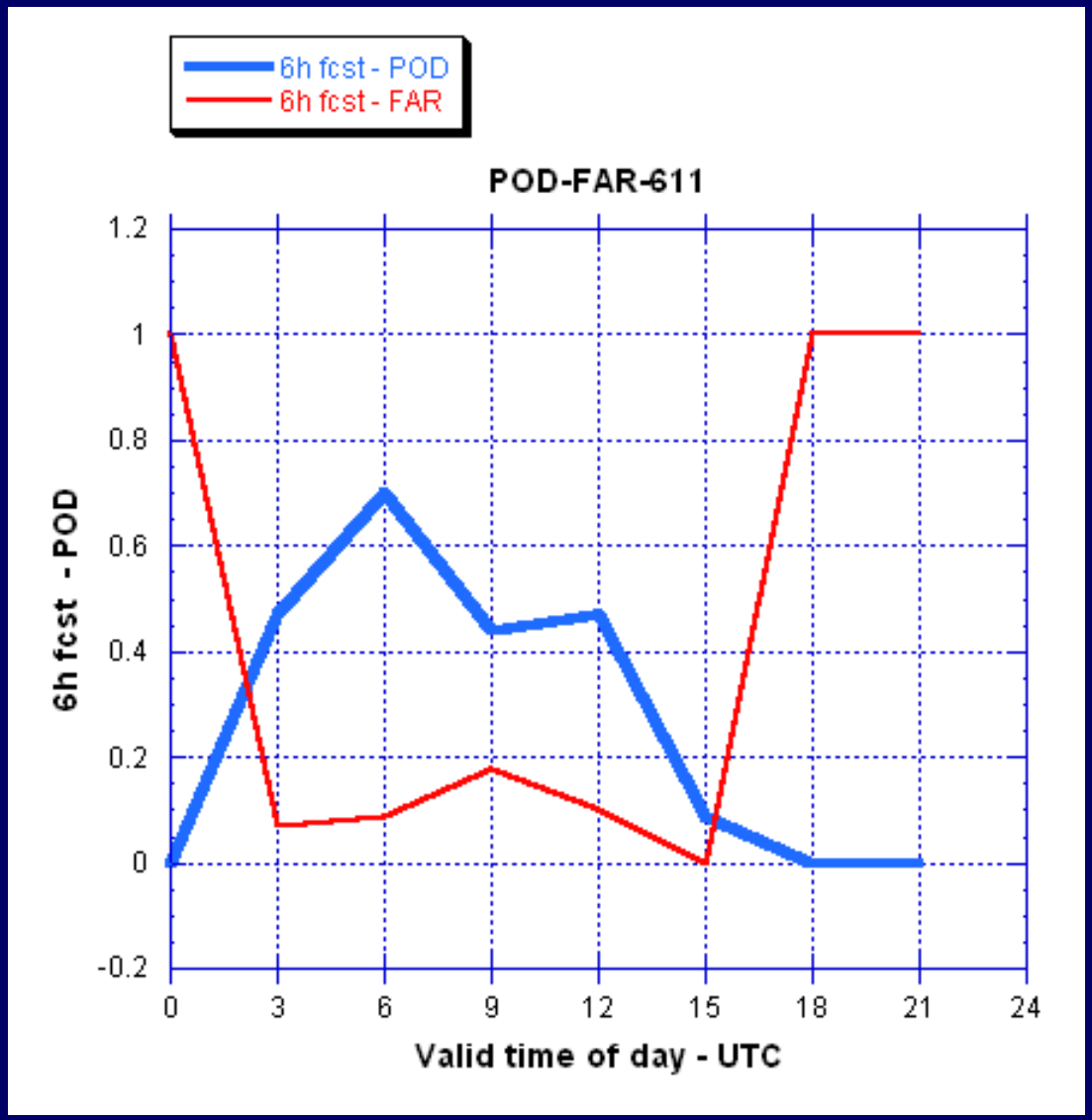
---tower----		---mesonet station--	
lat	lon		dist(km)
38.85	-98.19	K5ELW	10.3
37.74	-101.20	KUHES	21.4
37.27	-97.76	KARES	0.0
39.78	-98.12	KBBEJ	34.3
38.45	-99.85	K5NES	22.6
38.96	-100.85	K5OK7	17.5



Observations
-Summer 2003
- Tower 110m wind combined with 10m mesonet wind

10-110m wind shear - Kansas Summer 2003





LLJ shear event
- defined as 5 m/s vector difference in 110-10 m layer

Site 611
E. of Russell, KS
“Typical station”

POD
- probability of LLJ shear

RUC underforecasts nighttime LLJ shear events
- main problem – nighttime warm bias – overforecasting at 10m

RUC upgrade – 2008
Implemented at NCEP Mon 17 Nov 08

NOAA/ESRL/GSD/AMB
Stan Benjamin
Steve Weygandt
... many others

NCEP/EMC – Geoff Manikin

NCO/PMB – Xiaoxue Wang

Major components to RUC13 change package

- assimilation - radar reflectivity, TAMDAR (regional aircraft), mesonet winds
- model physics – longwave radiation, convection, land-surface model

NCEP

Earth System Research Laboratory
SCIENCE, SERVICE & STEWARDSHIP

RRTM Longwave Radiation in RUC Upgrade
Effect on 2-m temperature forecasts

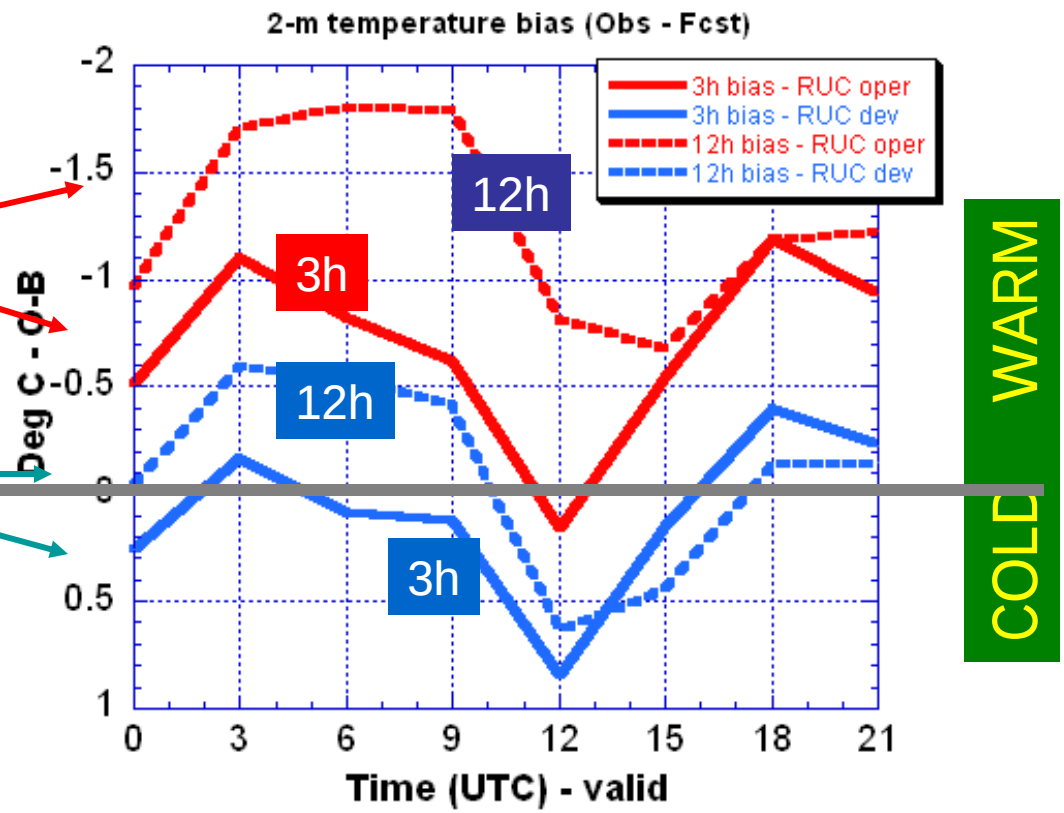
- Much decreased warm bias near surface

1-month comparison
14 May –13 June 07
Eastern US only

2-m temp bias (obs – forecast)

RUC oper – Dudhia LW

RUC para – RRTM LW



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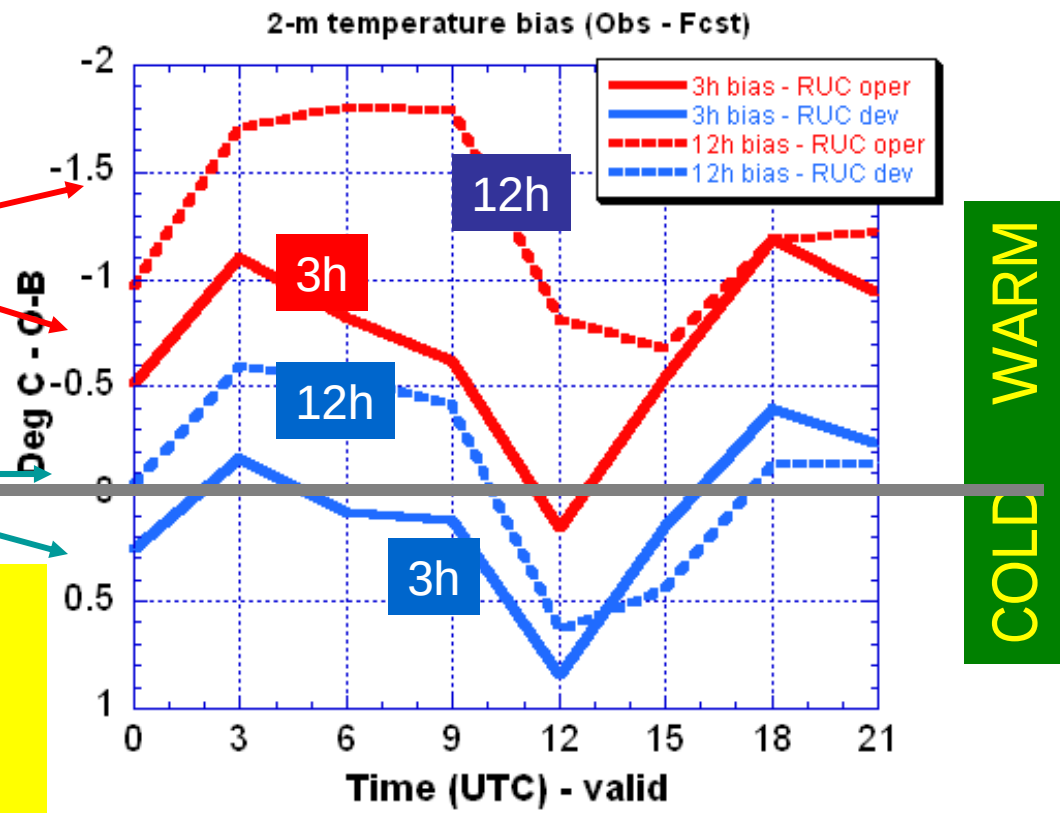
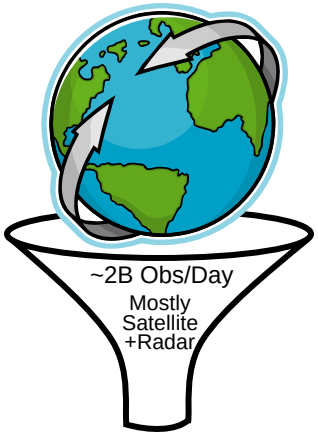


Change to oper RUC resulted in part from previous NREL-NOAA research

NOAA's NWS Model Production Suite



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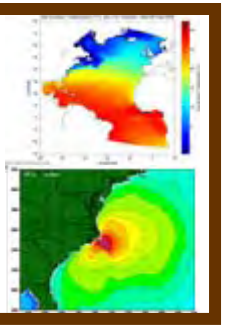

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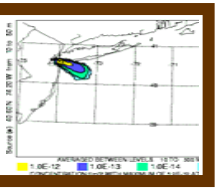
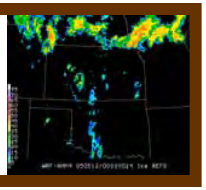
ARL's HYSPLIT



Severe Weather

WRF NMM
WRF ARW



Short-Range Ensemble Forecast

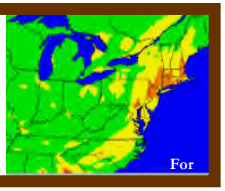
WRF: NMM+ARW
ETA, RSM

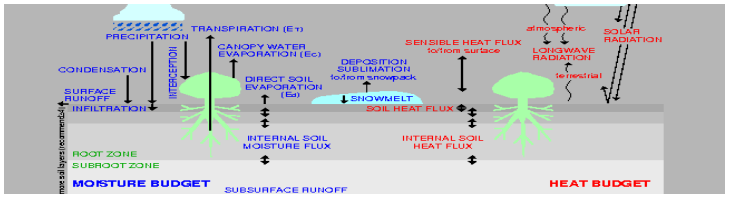
North American Ensemble Forecast System

GFS, Canadian Global Model

Air Quality

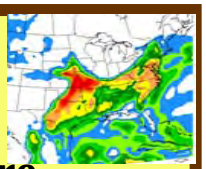
NAM+CMAQ





NOAH Land Surface Model

Rapid Update for Aviation, Severe



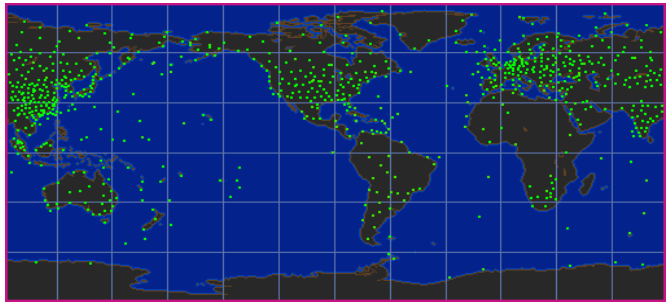
Atmospheric Models I

Model application	CFS Climate	GFS Global/Wx	GEFS Global Ensembles	NAM Regional/ SevereWx	SREF Regional Ensembles
Domain	Global	Global	Global	No. Am.	No. Am.
Resolution	T62 (~200km) 64 levels MOM3 1 deg/40l	T382(~35km) to 7.5days T190(~70km) to 16 days 64 levels	T126 (~105km) 28 levels	12 km 60 levels	32-45 km/ 28-60 lvls
Forecast length	9 months 4/day	16 days 4/day	16 days 4/day	84 hrs 4/day	87 hrs 4/day
# of Members	120/month	N/A	84/day	N/A	84/day

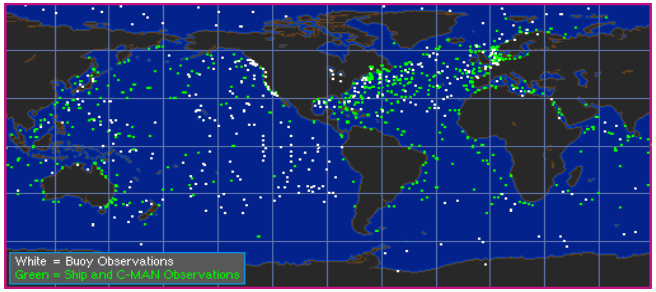
Atmospheric Models II

Model	RUC Domestic Aviation & Severe Wx	Air Quality Domestic Sfc Ozone [Smoke]	HiRes-Window Severe Weather	Fire Wx/ IMET Support [Homeland Security]	Hurricane track & intensity
Domain	CONUS	CONUS [CONUS & Alaska]	2/3 CONUS Alaska Hawaii & PR	Selectable 4-8 State [1-3 state]	Storm Movable nest
Resolution	13 km 50 levels	CMAQ 12 km / 22 levels [HYSPLIT off the 12 km NAM]	WRF-NMM 4.0 km 35 lvls WRF-ARW 5.1 km 35 lvls	NMM [+ HYSPLIT] 8 [4] km 50 lvls	HWRF & GFDL 9 km 42 levels
Forecast length	18 hours 24 / day	12-48 hours 2 / day [4/day]	48 hours 1 large nest + 1 small nest 4/day when no hurricanes	48 [30] hrs 4/day	120 hrs 4 storms 4/day

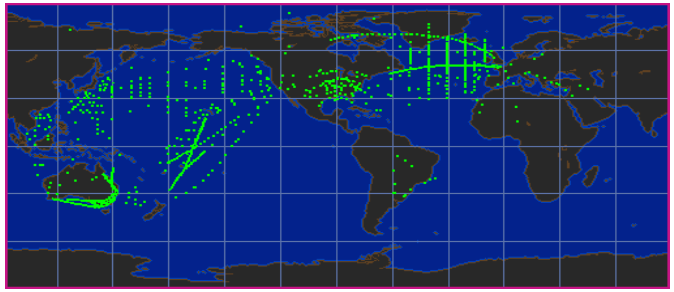
Global Observations 12 UTC
6 hour window



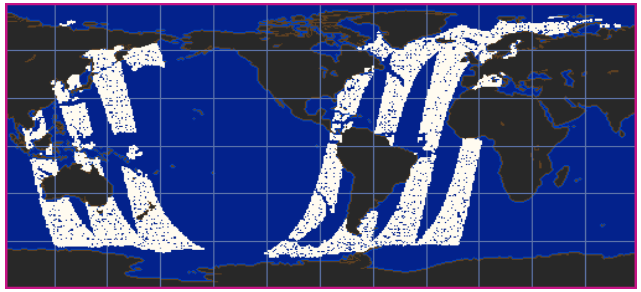
Global Rawinsondes



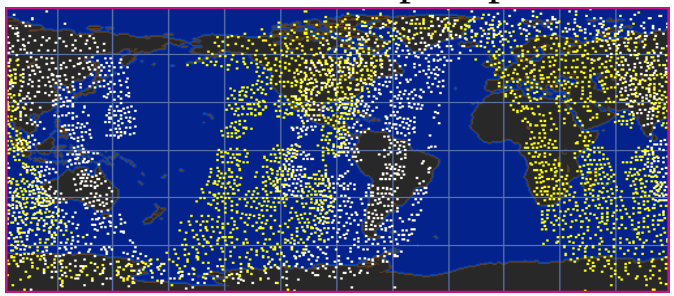
Marine Obs -- 12 Hour Total



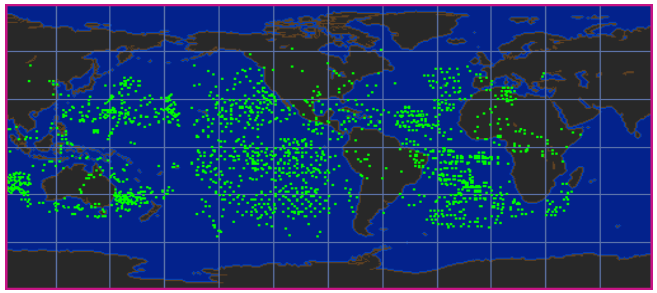
Aircraft Wind/Temp Reports



DMSP Imager – Sfc winds/PW



Polar Satellite Radiances (just 2 sat)

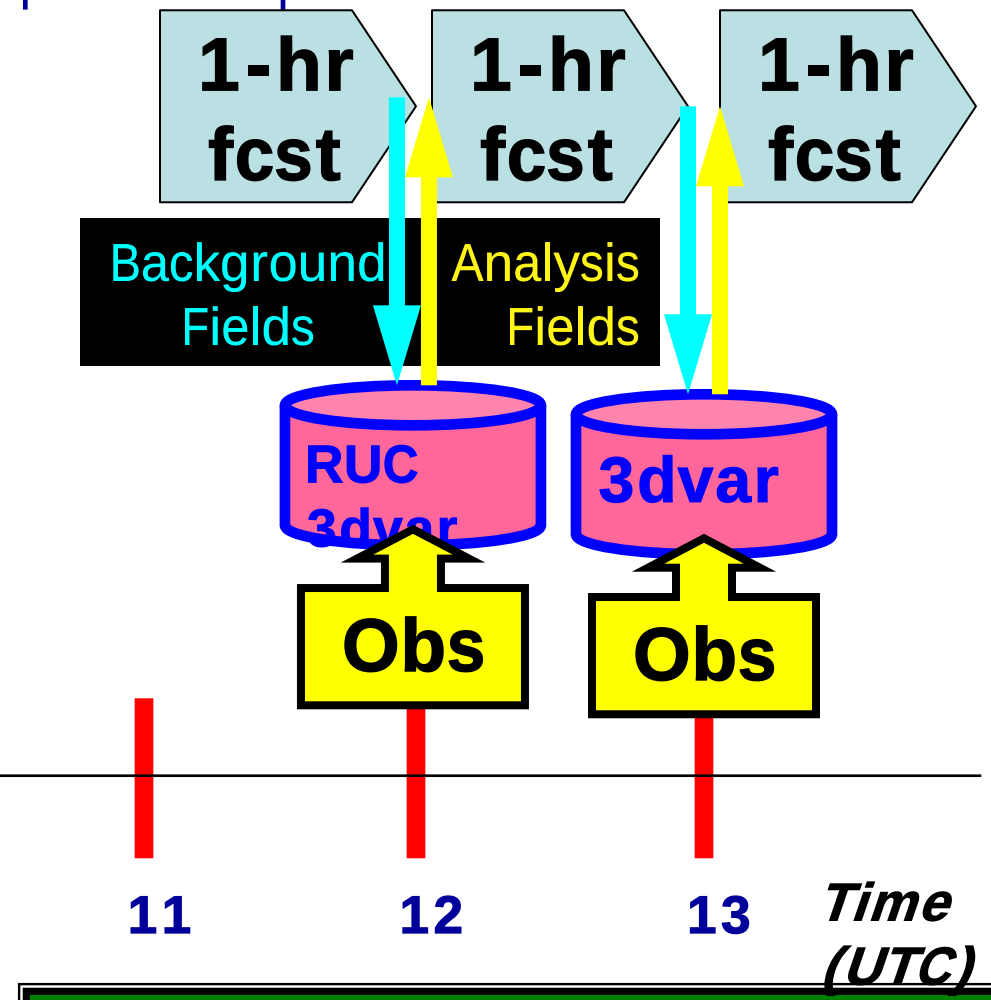


Satellite Winds from Geostationary Satellites

2 billion obs each day

New observations assimilated -- RUC upgrade

Cycle hydrometeor, soil temp/moisture/snow plus atmosphere state variables

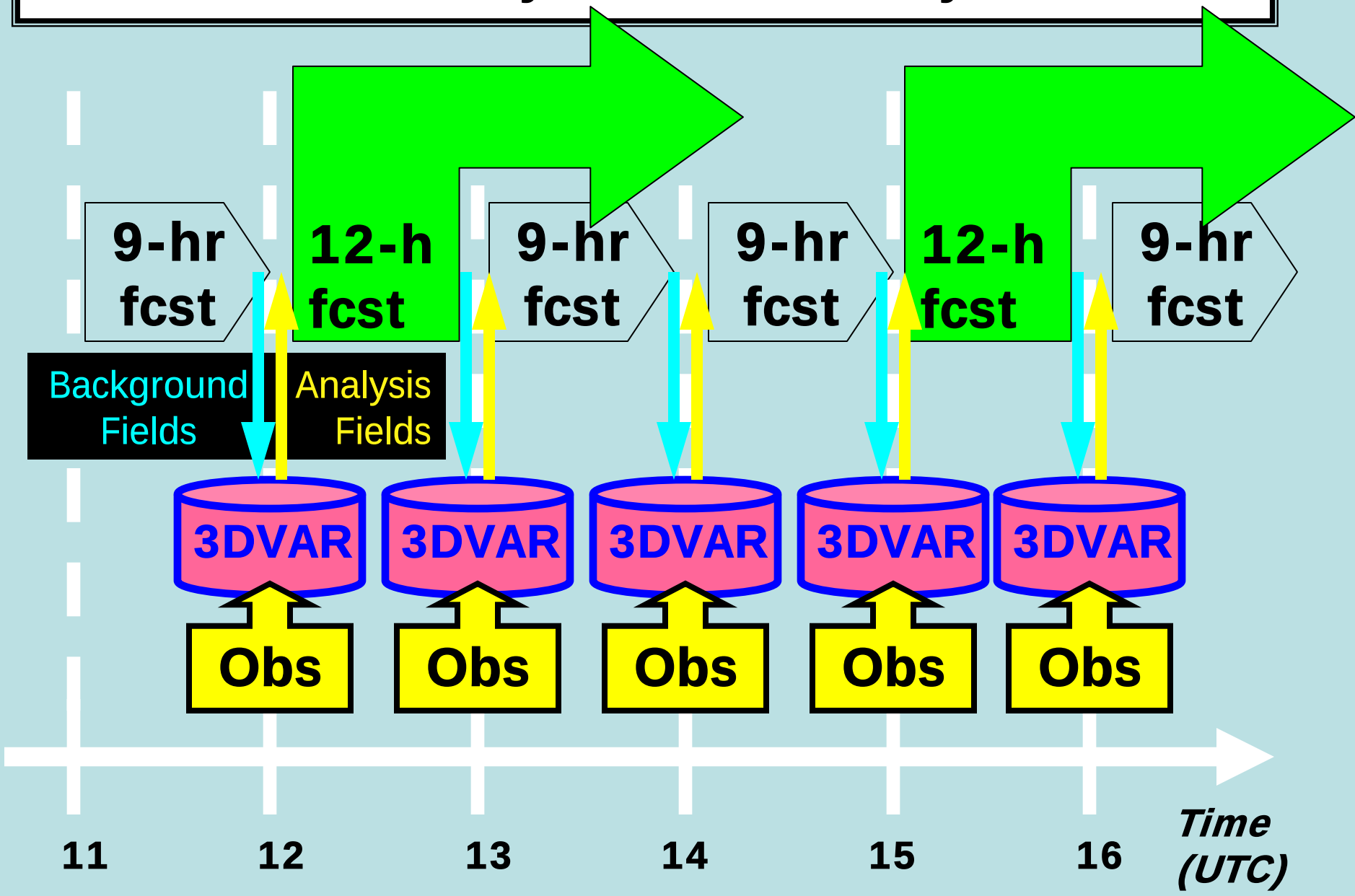


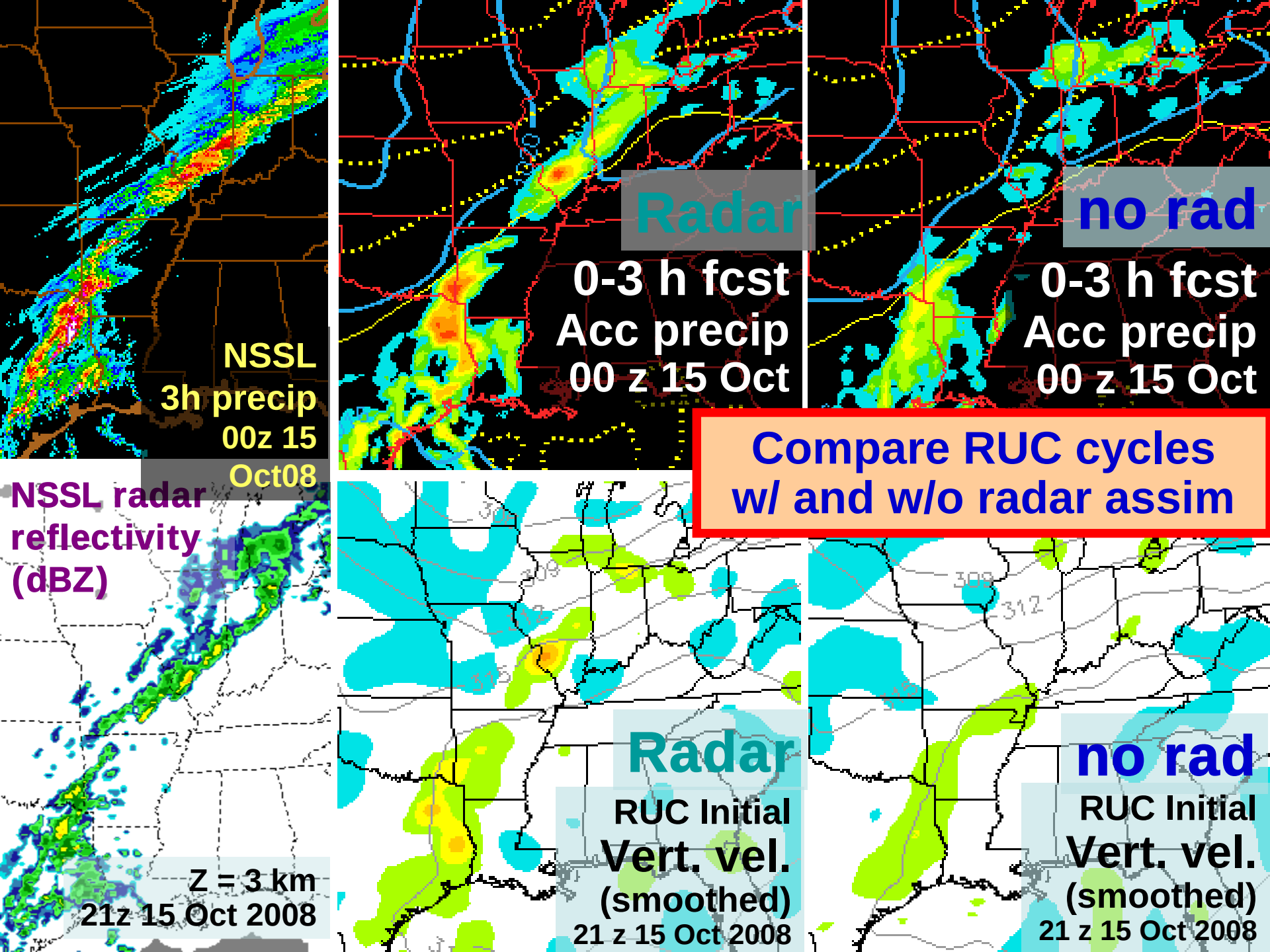
Hourly obs in 2008 RUC

Data Type	~Number
Rawinsonde (12h)	80
NOAA profilers	30
VAD winds	110-130
PBL – prof/RASS	~25
Aircraft (V,temp)	1400-7000
TAMDAR (V,T,RH)	0 - 800
Surface/METAR	1800-2000
Buoy/ship	100- 200
GOES cloud winds	1000-2500
GOES cloud-top pres	10 km res
GPS precip water	~300
Mesonet (temp, dpt)	~7000
Mesonet (wind)	2000-4000
METAR-cloud-vis-wx	~1600
Radar reflectivity	2km

RUC Hourly Assimilation Cycle

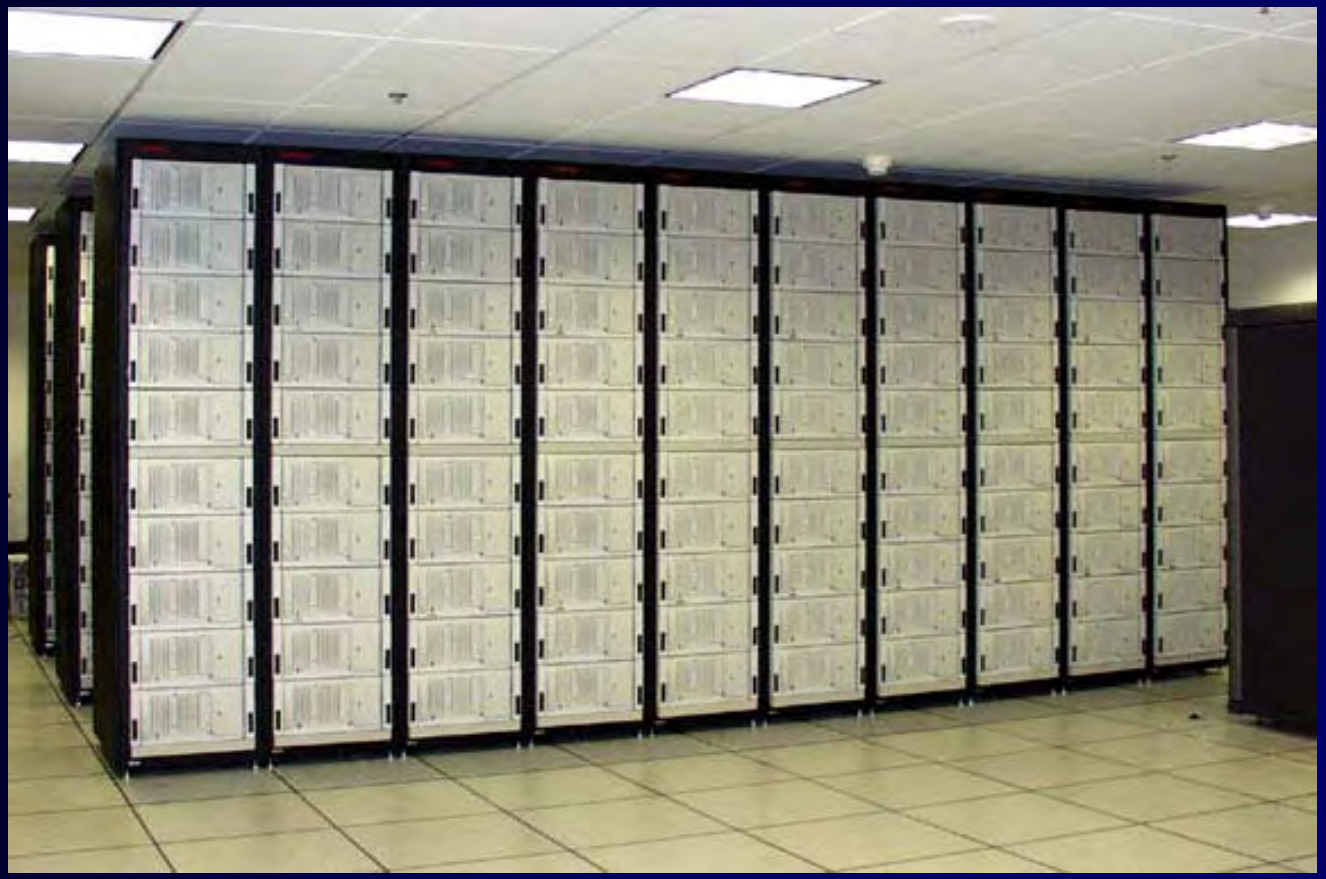
RUC Hourly Assimilation Cycle



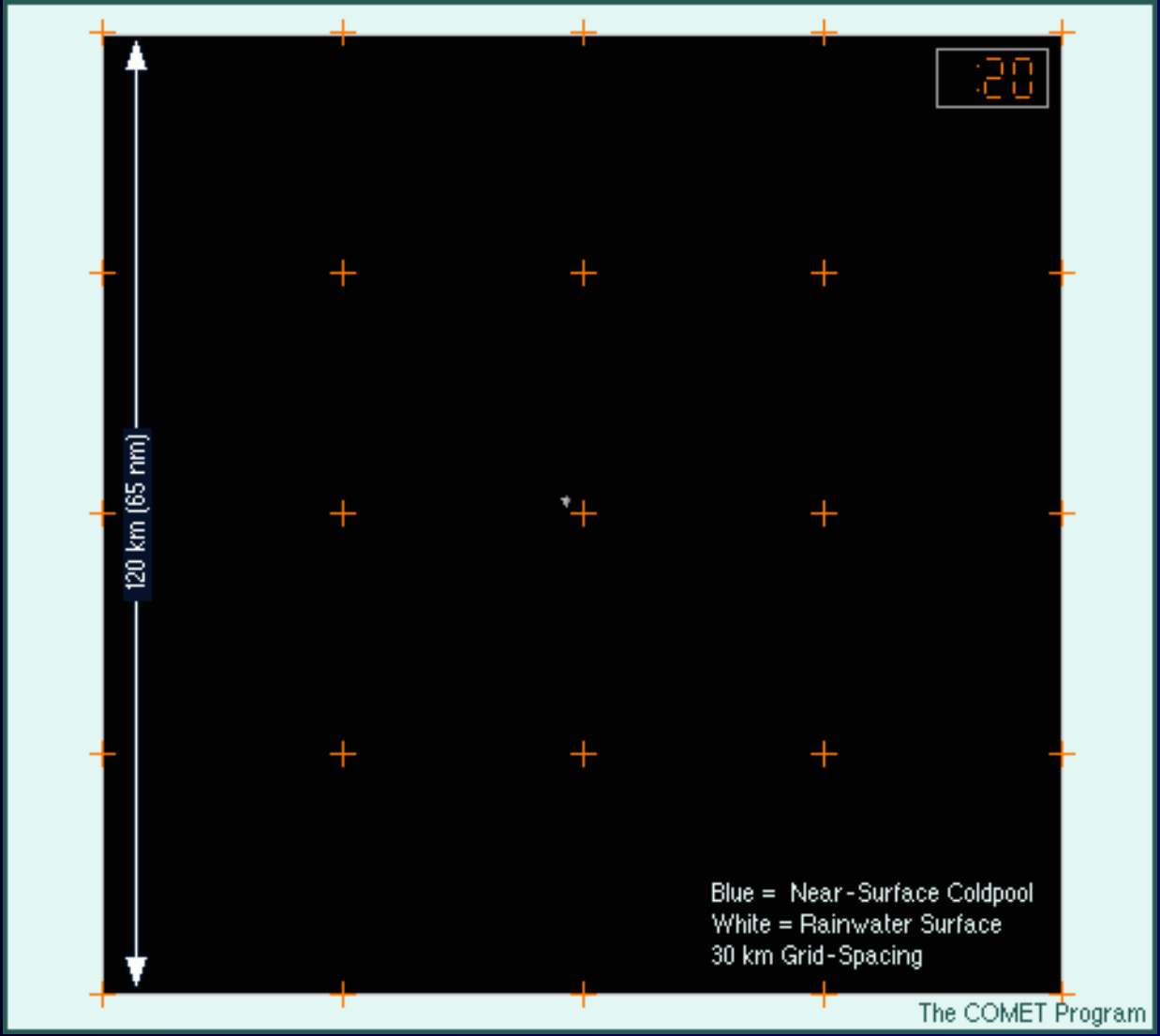

NSSL
3h precip
00z 15
Oct08
Radar
0-3 h fcst
Acc precip
00 z 15 Oct
no rad
0-3 h fcst
Acc precip
00 z 15 Oct
Compare RUC cycles
w/ and w/o radar assim
NSSL radar
reflectivity
(dBZ)
Z = 3 km
21z 15 Oct 2008
Radar
RUC Initial
Vert. vel.
(smoothed)
21 z 15 Oct 2008
no rad
RUC Initial
Vert. vel.
(smoothed)
21 z 15 Oct 2008

What is different now

- Improved observations – weather balloons, satellites, radar, commercial aircraft
- Improved understanding of weather phenomena – development of meteorology programs in major universities starting in 1940s
- Development of numerical weather prediction (NWP) – computer models of atmosphere
- Development of high-speed computers
- Public understanding of importance of weather forecasts for economic activity as well as for protection of life and property

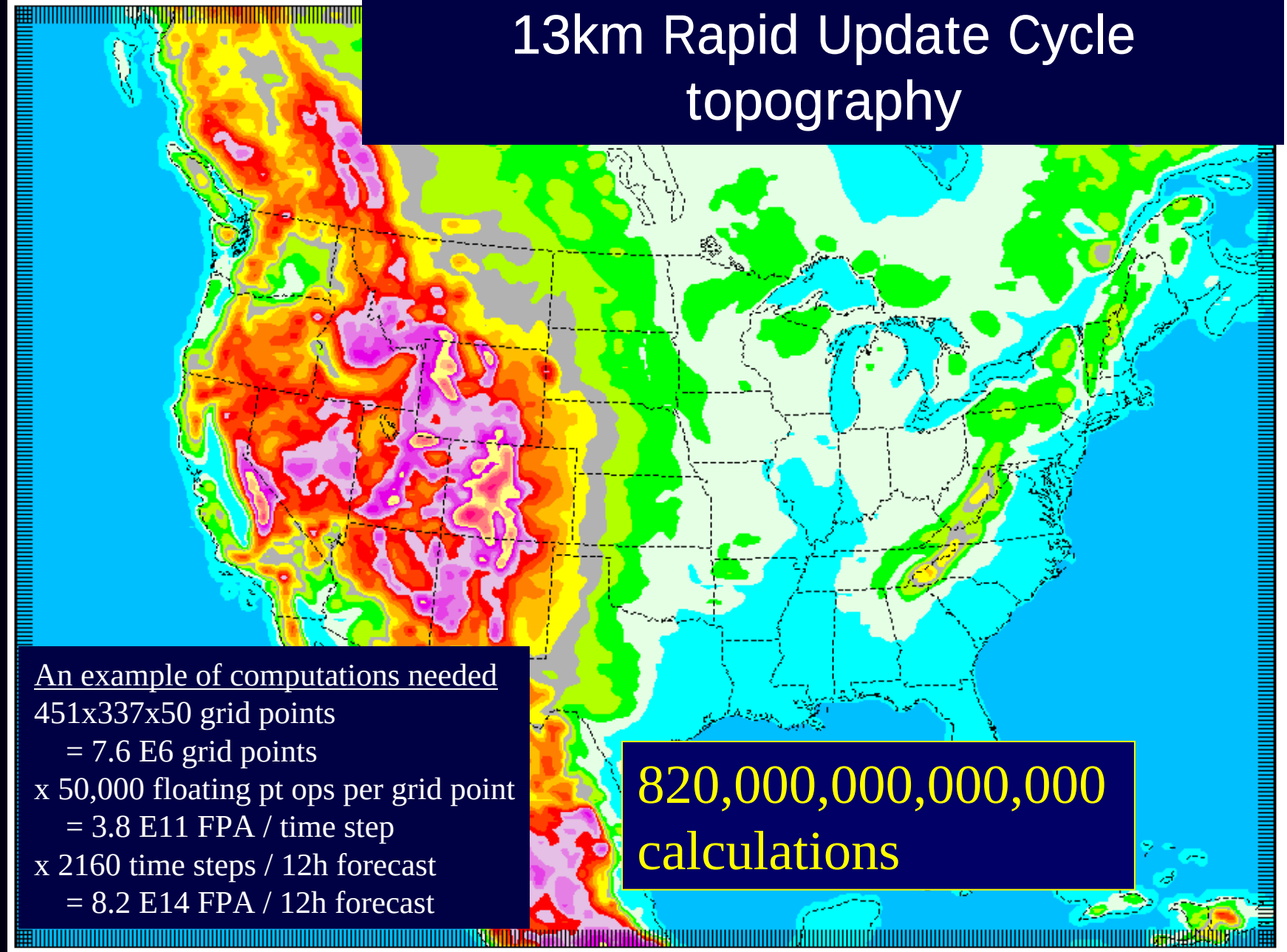


NOAA/ESRL Linux cluster computer - 2002- ancient
- 277 Compaq EV67 PCs
linked by high-speed interconnect



The importance of horizontal resolution in weather prediction models

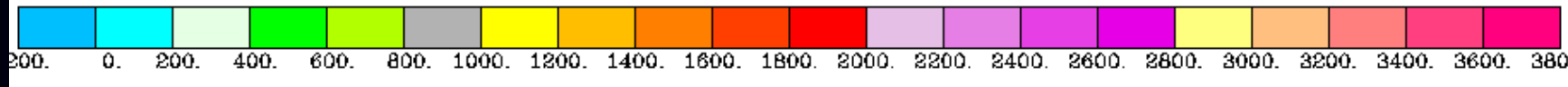
13km Rapid Update Cycle topography



<u>An example of computations needed</u>

451x337x50 grid points
= 7.6 E6 grid points
x 50,000 floating pt ops per grid point
= 3.8 E11 FPA / time step
x 2160 time steps / 12h forecast
= 8.2 E14 FPA / 12h forecast

820,000,000,000,000 calculations



Subset of full domain

NOAA/ESRL FIM global model

15km - horizontal resolution

(highest yet resolution real-time global model runs in NOAA)

2.5M horizontal points

X 64 levels = 160M 3-d points

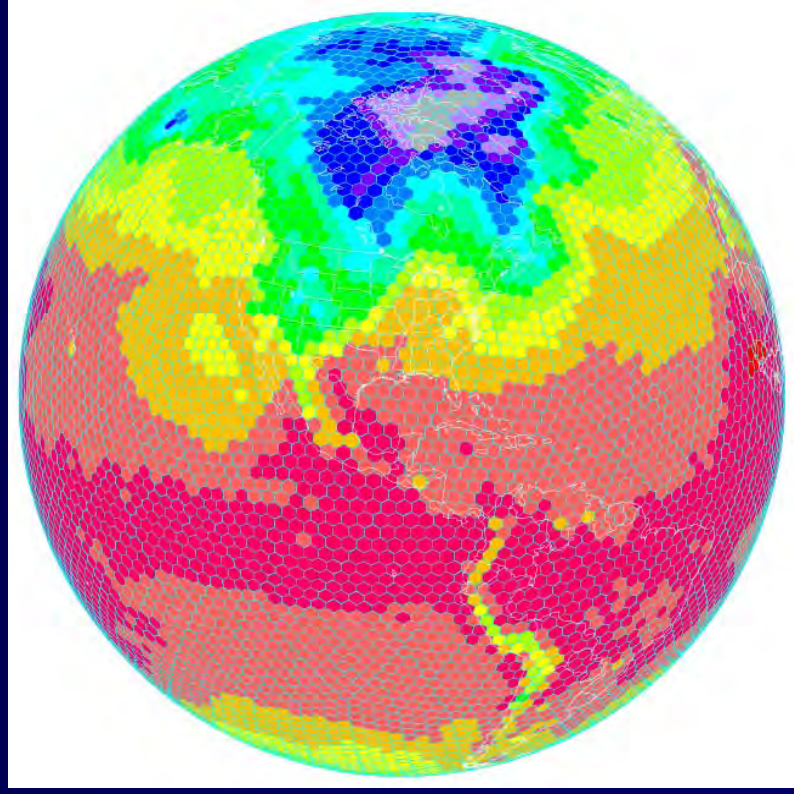
X 30,000 floating pt ops (FPA)

per grid pt = 5 trillion FPA

X 3840 time steps/day

= 19 E15 FPA/24h

X 10 days = 190E16 FPA



15km FIM global model runs out to 10 days 2x daily on 1680 processors in 4 hours on Texas supercomputer since Aug 2008 - NOAA experimental hurricane forecast program

What is different now

- Improved understanding of weather phenomena – development of meteorology programs in major universities starting in 1940s
- Improved observations – weather balloons, satellites, radar, commercial aircraft
- Development of numerical weather prediction (NWP) – computer models of atmosphere
- Development of high-speed computers
- Public understanding of importance of weather forecasts for economic activity as well as for protection of life and property

Two main points:

1. Atmospheric forecasts from weather models for **both** **wind energy** and **solar energy** are outputs from the **same** model.
   - Improved cloud/sun forecasts improves near-surface wind forecasts, and conversely,
   - Improved forecasts of "boundary layer" winds is related to forecasts feeds back into clouds, precipitation, and even winds *above* the PBL.

   Consistent forecasts for both wind energy and solar energy generation potential are from the same physical atmospheric system.

2. Equally complicated problems: Development of

a. Weather model and

b. Data assimilation (to initialize model)

Both are important for 1h to 15-day forecasts

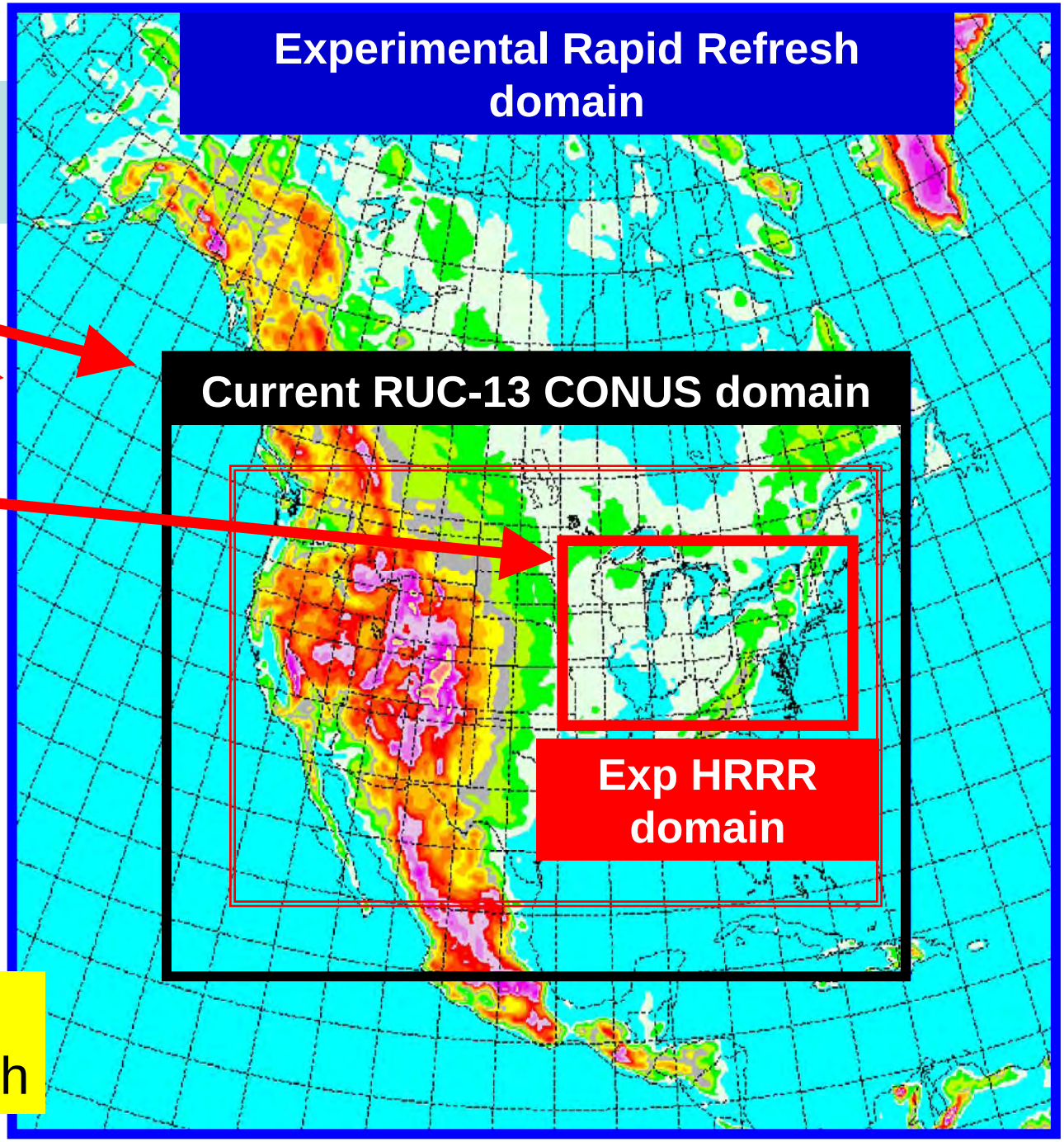
Hourly updated NWP for NOAA

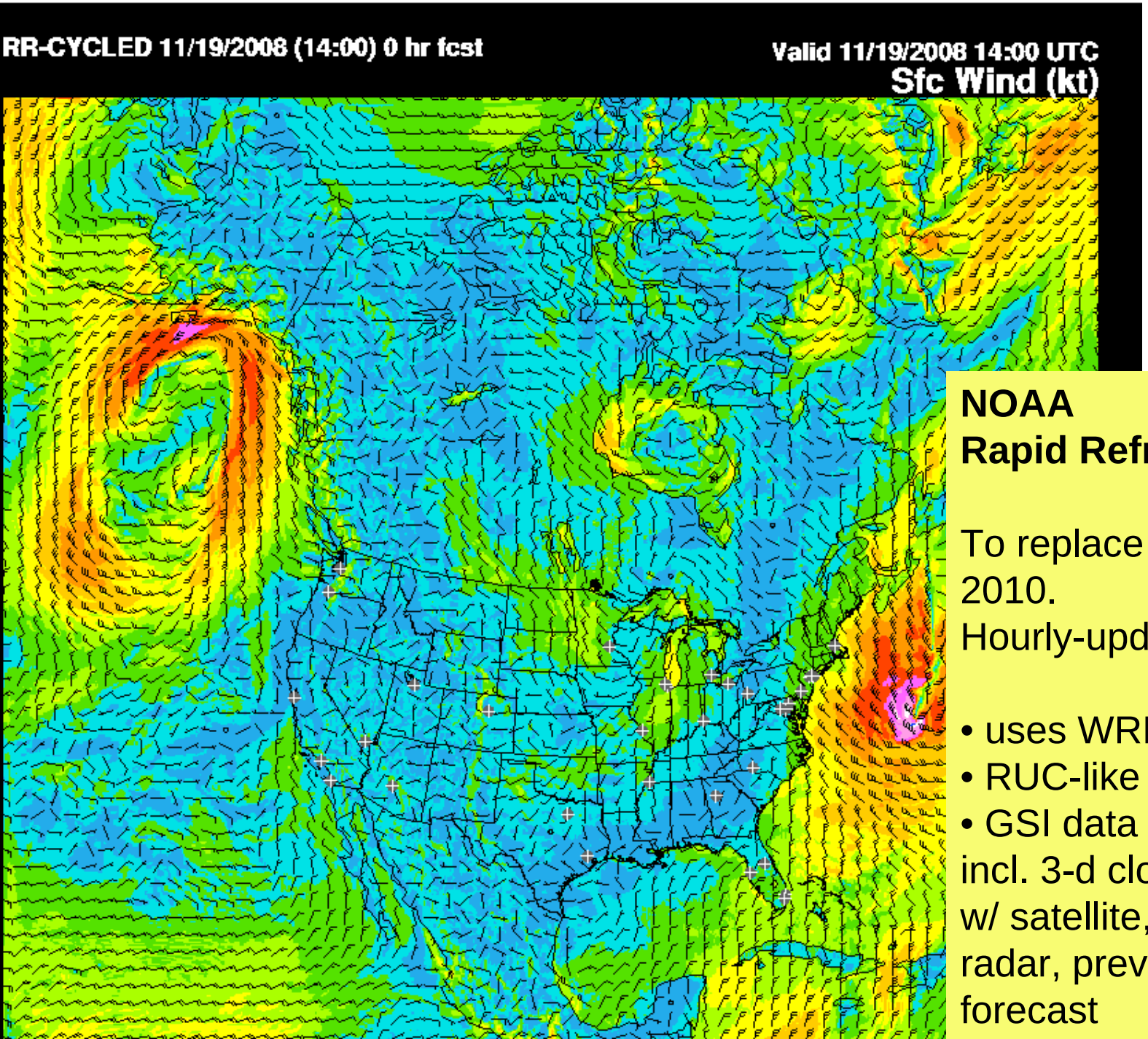
- 13km RUC
- 13km Rapid Refresh
- 3km Hi-Res Rapid Refresh

Storm-resolving (3-km) model init from radar-enhanced RUC or RR

For aviation, severe weather, energy, fire weather, emergency situations, etc.

By 2016,
Global Rapid Refresh



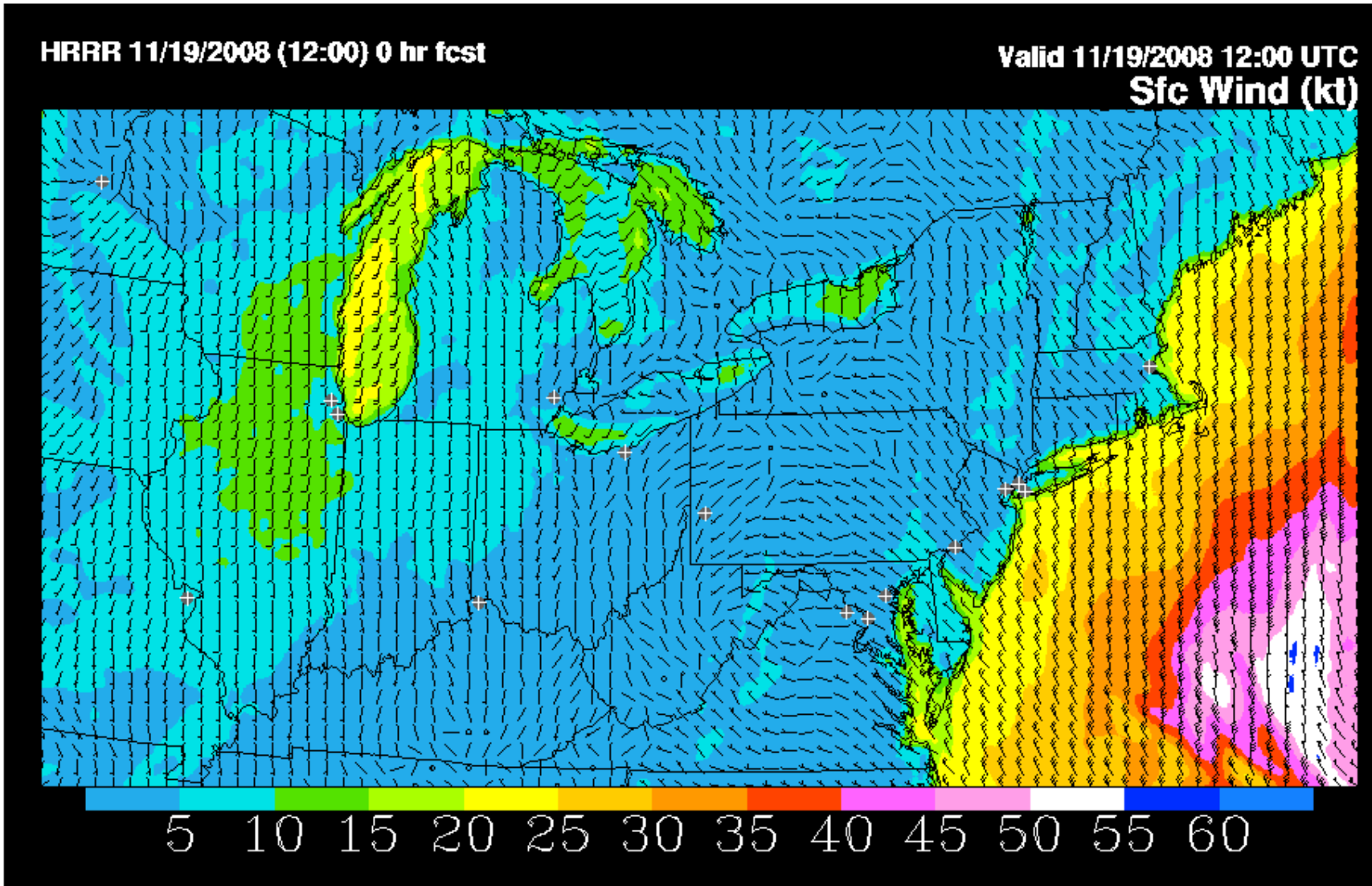


NOAA
Rapid Refresh (RR)

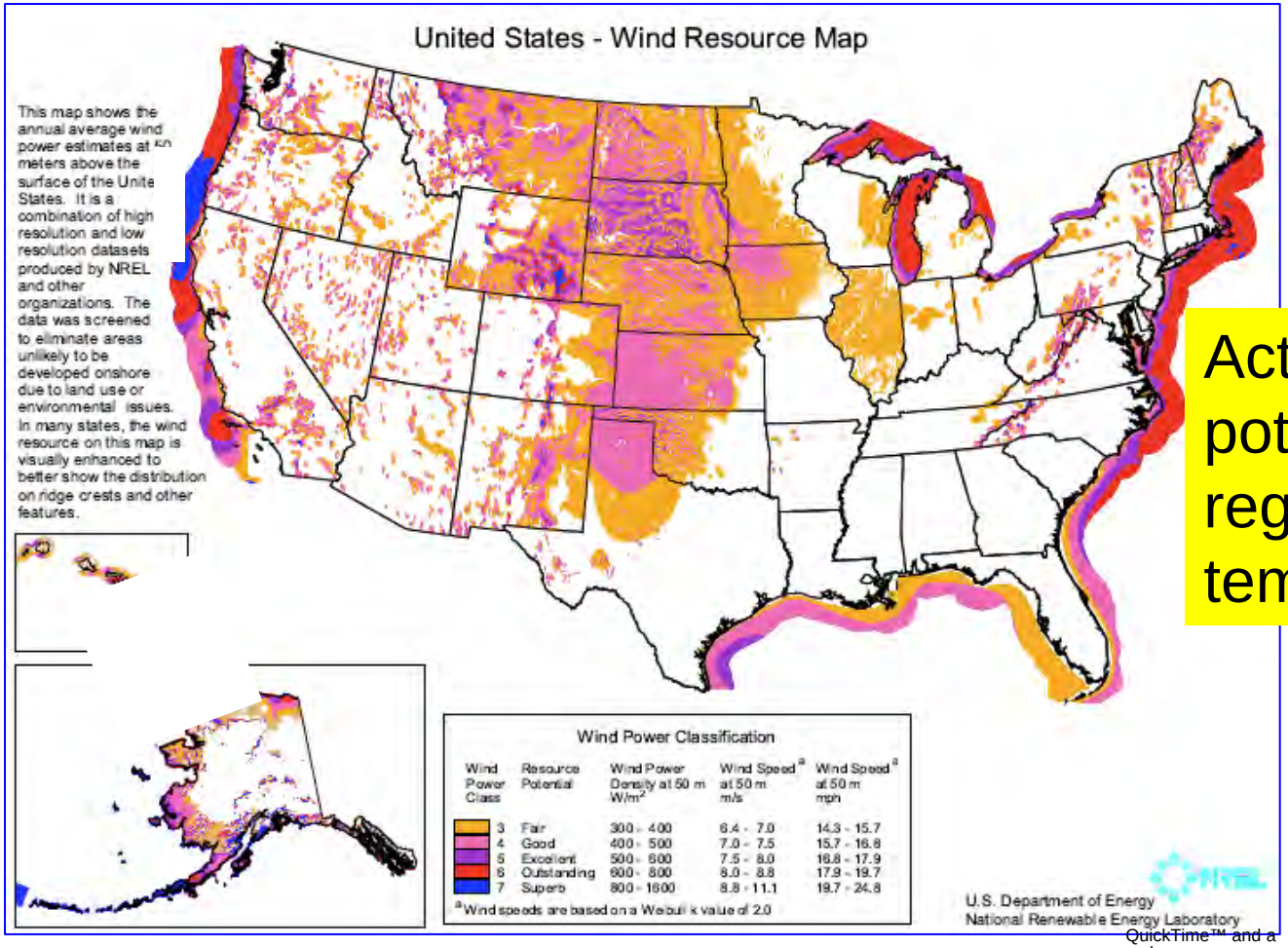
To replace RUC by 2010.
Hourly-update cycle

- uses WRF-ARW
- RUC-like physics
- GSI data assimilation incl. 3-d cloud analysis w/ satellite, METAR, radar, previous 1h forecast

HRRR - High-Resolution Rapid Refresh - 10m winds
-3km hourly updated nest inside RUC/ Rapid Refresh
- also includes radar reflectivity assimilation (and other obs



Wind



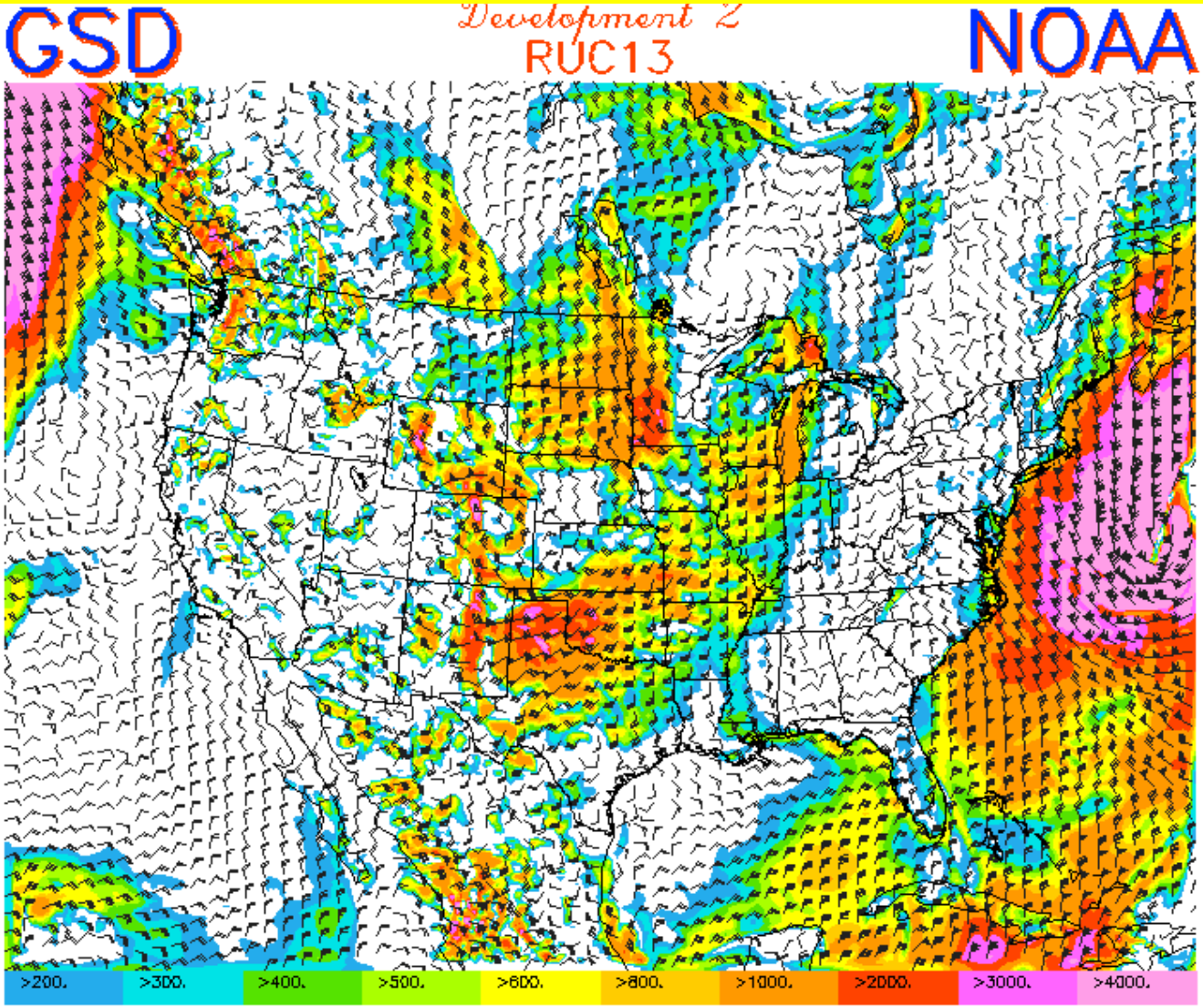
QuickTime™ and a decompressor are needed to see this picture.

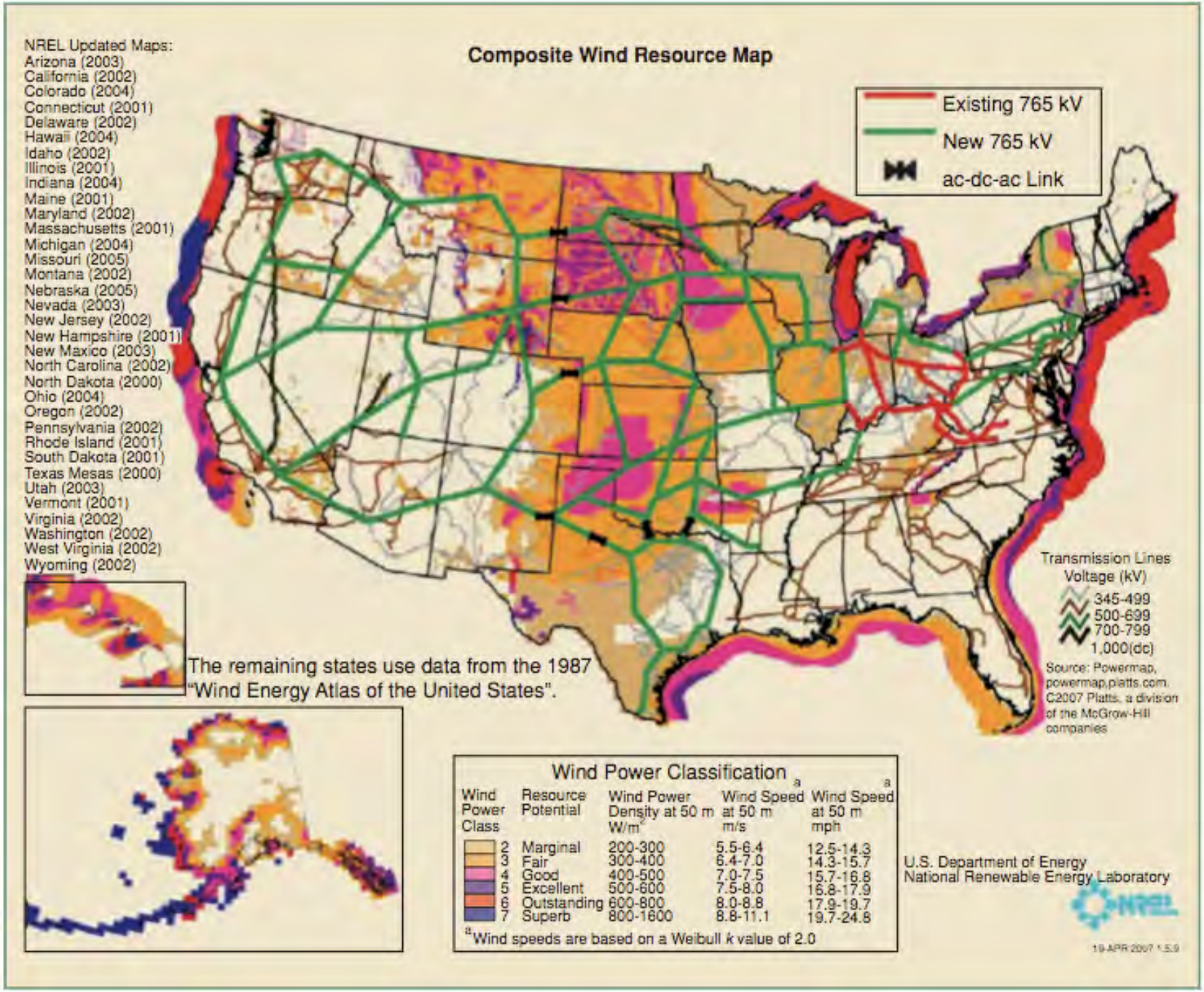
Actual wind energy potential - strong regional and temporal variations

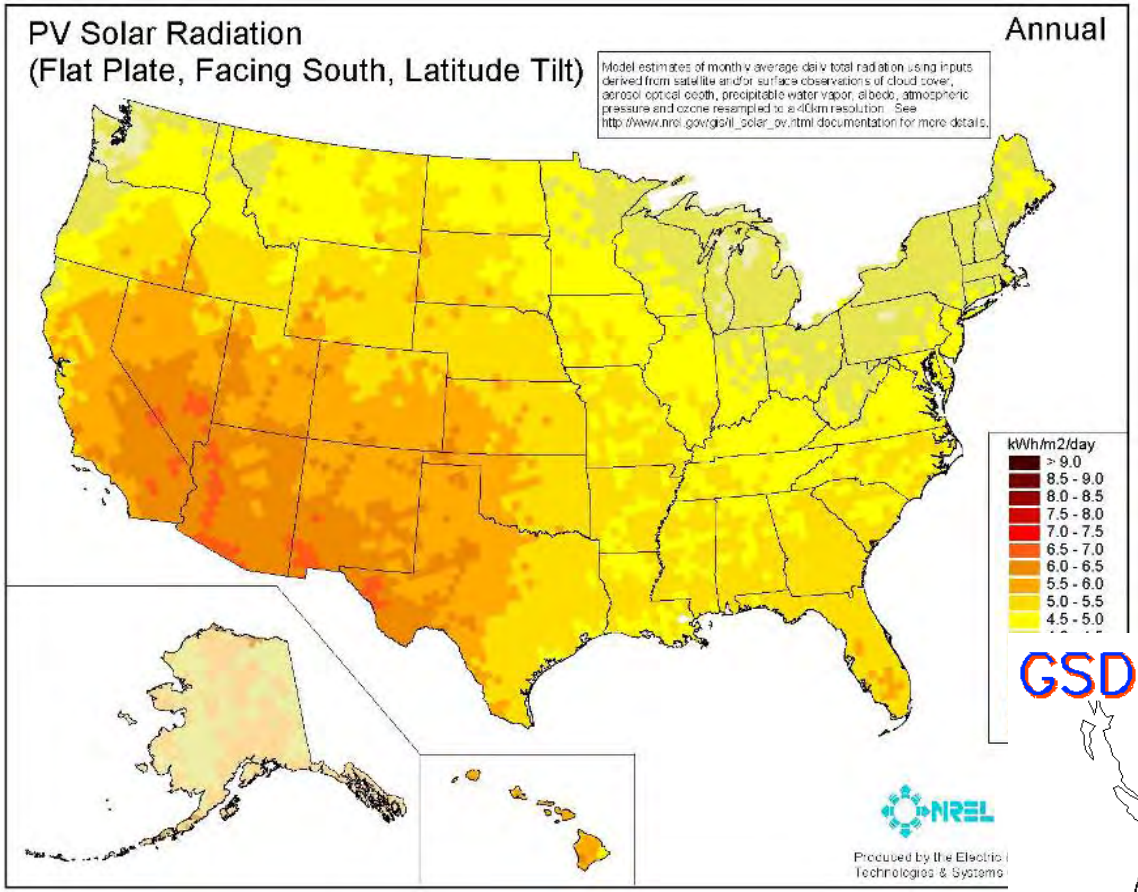
Outstanding

RUC 1h fcst
80-120m wind energy
Valid 23z Wed 12 Nov 08

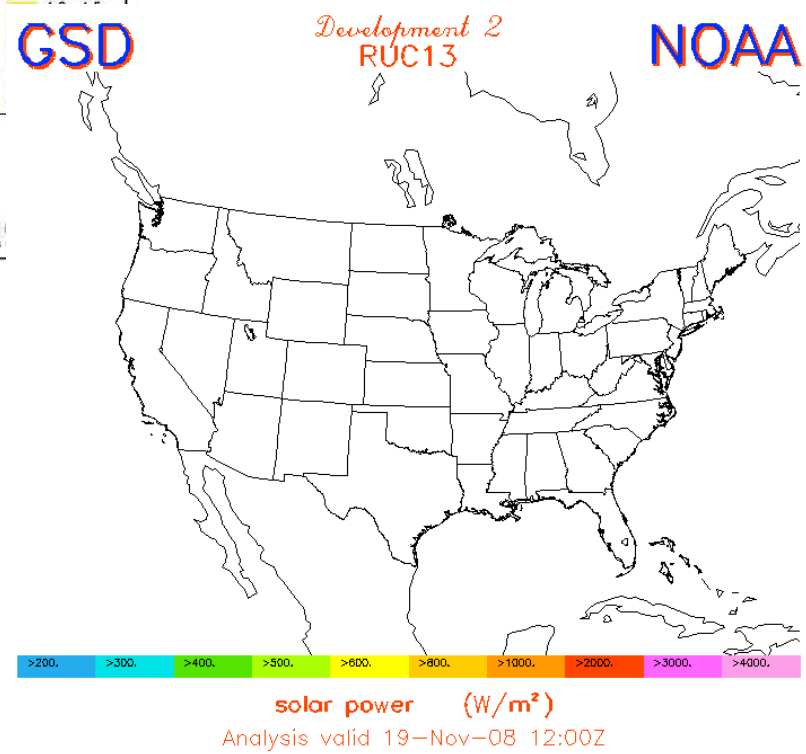
Wind energy - ρV^3 - 80-120m wind / Solar energy (shaded)
RUC forecast - initialized 12z Wed 19 Nov 2008




Composite Wind Resource Map
NREL Updated Maps:
Arizona (2003)
California (2002)
Colorado (2004)
Connecticut (2001)
Delaware (2002)
Hawaii (2004)
Idaho (2002)
Illinois (2001)
Indiana (2004)
Maine (2001)
Maryland (2002)
Massachusetts (2001)
Michigan (2004)
Missouri (2005)
Montana (2002)
Nebraska (2005)
Nevada (2003)
New Jersey (2002)
New Hampshire (2001)
New Maxico (2003)
North Carolina (2002)
North Dakota (2000)
Ohio (2004)
Oregon (2002)
Pennsylvania (2002)
Rhode Island (2001)
South Dakota (2001)
Texas Mesas (2000)
Utah (2003)
Vermont (2001)
Virginia (2002)
Washington (2002)
West Virginia (2002)
Wyoming (2002)
Existing 765 kV
New 765 kV
ac-dc-ac Link
Transmission Lines
Voltage (kV)
345-499
500-699
700-799
1,000(dc)
Source: Powermap, powermap.platts.com. ©2007 Platts, a division of the McGraw-Hill companies
The remaining states use data from the 1987 "Wind Energy Atlas of the United States".
Wind Power Classification
Wind Power Class
Resource Potential
Wind Power Density at 50 m W/m²
Wind Speed at 50 m m/s [a]
Wind Speed at 50 m mph [a]
2 Marginal 200-300 5.5-6.4 12.5-14.3
3 Fair 300-400 6.4-7.0 14.3-15.7
4 Good 400-500 7.0-7.5 15.7-16.8
5 Excellent 500-600 7.5-8.0 16.8-17.9
6 Outstanding 600-800 8.0-8.8 17.9-19.7
7 Superb 800-1600 8.8-11.1 19.7-24.8
[a] Wind speeds are based on a Weibull k value of 2.0
U.S. Department of Energy
National Renewable Energy Laboratory
NREL
19-APR-2007 1:5:9



Actual hourly variation of solar energy potential
- accurate forecasts are essential



Ensemble Forecasting
- probabilistic forecasts

- **Goal for NCEP - global and regional ensembles already running**

- **Hourly updated ensemble also needed - initial convective probabilistic forecast with RUC - used for FAA air traffic management (counterpart to real-time energy management)**
  - **http://ruc.noaa.gov/rcpf**

- **Initial work from NOAA/ESRL and NREL on ensemble-based wind forecasts**

- **Demonstration on 30km global ensemble from ESRL FIM model (operational GFS is at ~100km)**

NOAA Short-Range Ensemble Forecast (SREF) - 30 members - Prob fields

Means/Spreads

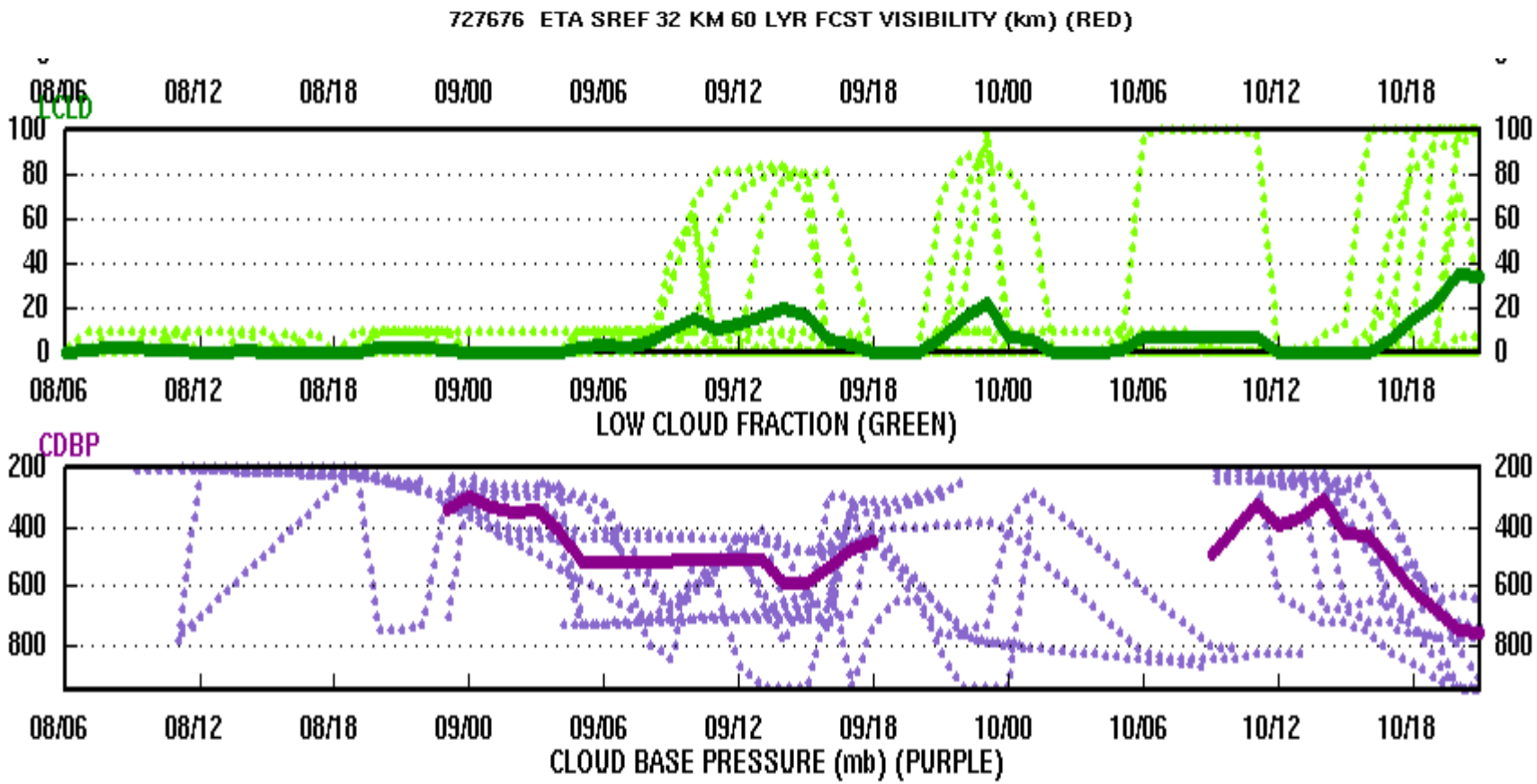
- Heights at 1000, 850, 700, 500, 250 mb
- U+V at 1000, 850, 700, 500, 250 mb & 10 m
- Temperature 850, 700, 500 mb & 2 m
- Dew Point (RH) 850, 700, 500 mb & 2 m
- QPF at 3, 6, 12 and 24 hour totals
- 12-hr Snowfall
- Sea Level Pressure
- Precipitable Water

Probabilistic Fields

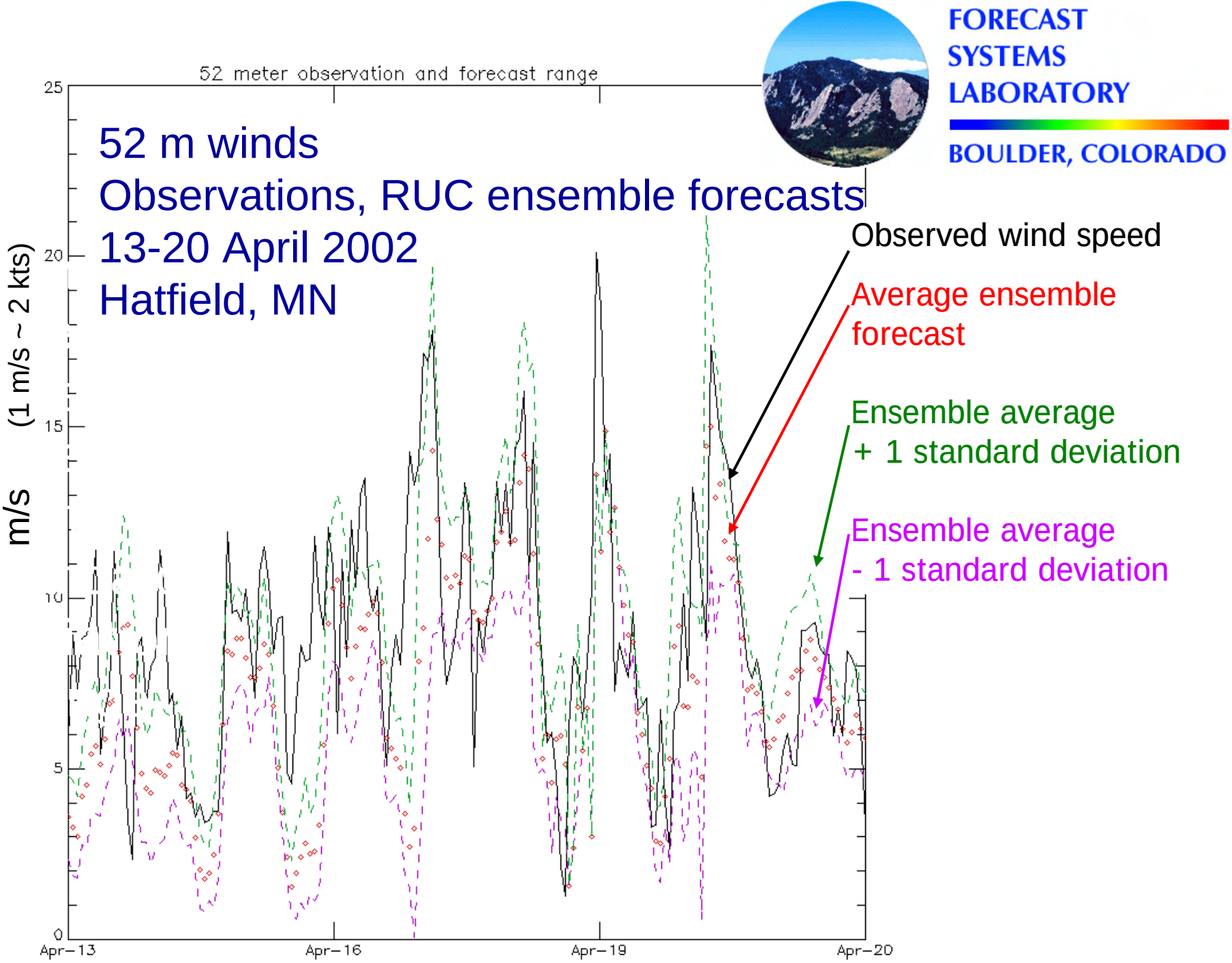
• 3-hr/6-hr QPF	GE .01”, .25”, .50”, 1.0”
• 12-hr/24-hr QPF	GE 01”, .25”, .50”, 1.0”, 2.0”
• 12-hr Snowfall	GE 1”, 4”, 8”, 12” (have 2.5, 5, 10, 20”)
• Temperature at 2 m & 850 mb	LE 0°C
• 10 m Wind	GE 25 kt, 34 kt, 50 kt
• CAPE	GE 500, 1000, 2000, 3000, 4000
• Lifted Index	LE 0, -4, -8
• Surface Visibility	LE 1 mi, 3 mi
• Cloud Ceiling	LE 500 ft, 1000 ft, 3000 ft

- Probability of precipitation types (rain, frozen, & freezing)
- 6-hr/12-hr/24-hr QPF Best Category

Example of SREF Meteogram



727676 MINOT INTL AIRPORT ND


52 meter observation and forecast range
52 m winds
Observations, RUC ensemble forecasts
13-20 April 2002
Hatfield, MN
m/s (1 m/s ~ 2 kts)
25
20
15
10
5
0
Apr-13
Apr-16
Apr-19
Apr-20
Observed wind speed
Average ensemble forecast
Ensemble average + 1 standard deviation
Ensemble average - 1 standard deviation
FORECAST SYSTEMS LABORATORY
BOULDER, COLORADO

Main Points of this Informational Presentation

1. An overview of NOAA weather models - regional vs. global, different u
   frequencies, users
2. Demonstrate how models depict rapid temporal and spatial variations in potential generation of wind and solar energy.
3. Demonstrate errors in models, how they increase in time, how they exist even at very short time scales (e.g., RUC - 250hPa wind, HRRR, FIM global)
4. How models work, dynamics and physical processes that are treated.
5. How to initialize models - use of observations to correct previous forecasts. Kinds of observations that are assimilated.
6. Key modeling and assimilation effects for near-surface wind and solar radiation forecasts.
7. Improvements in models upcoming - higher resolution (all models incl. HRRR, FIM), better physics (e.g., RUC - RRTM, cloud physics, PBL physics, land-surface, chemistry)
8. Improvements in NOAA's atmospheric observations, models, and forecasts could be used to save the nation many billions of dollars.
9. Improvements in data assimilation - aircraft, satellite radiance assimilation, profiler, cloud assimilation (METAR, satellite, radar)
10. Examples: RUC to RR to HRRR, FIM (15km global runs now done)

Opportunities for improving renewable energy forecasts

1. Precise weather forecasts (esp. wind and solar) will allow precise forecasts of transmission and storage needs, carbon-based power, etc.
   a. Current costly imprecision in forecasts of all scales (1h to 15 days) for energy.
2. What's needed:
   a. Better models, especially in treatment of 10-200m winds, clouds, addition of chemistry/aerosols
   b. Better global models for 1h-15d+ forecasts (and climate). Everything pivots on global models.
   c. Better observations above surface to initialize models - winds, moisture, temperature, clouds.
   d. Higher-resolution models.
   e. Much improved data assimilation - model initialization
   f. Interaction between NOAA and NREL/energy industry

http://ruc.noaa.gov/amb