The Colorado Great Front Range Flood of 2013-Lessons for Alberta

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National Center for Atmospheric Research

The National Center for Atmospheric Research

Contributions:

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National Center for Atmospheric Research: Kyoko Ikeda, Rita Roberts, Jim Wilson

NOAA Earth Systems Research Laboratory: Kelly Mahoney

FEMA confirms 262 homes destroyed in Boulder County as 9 more rescued

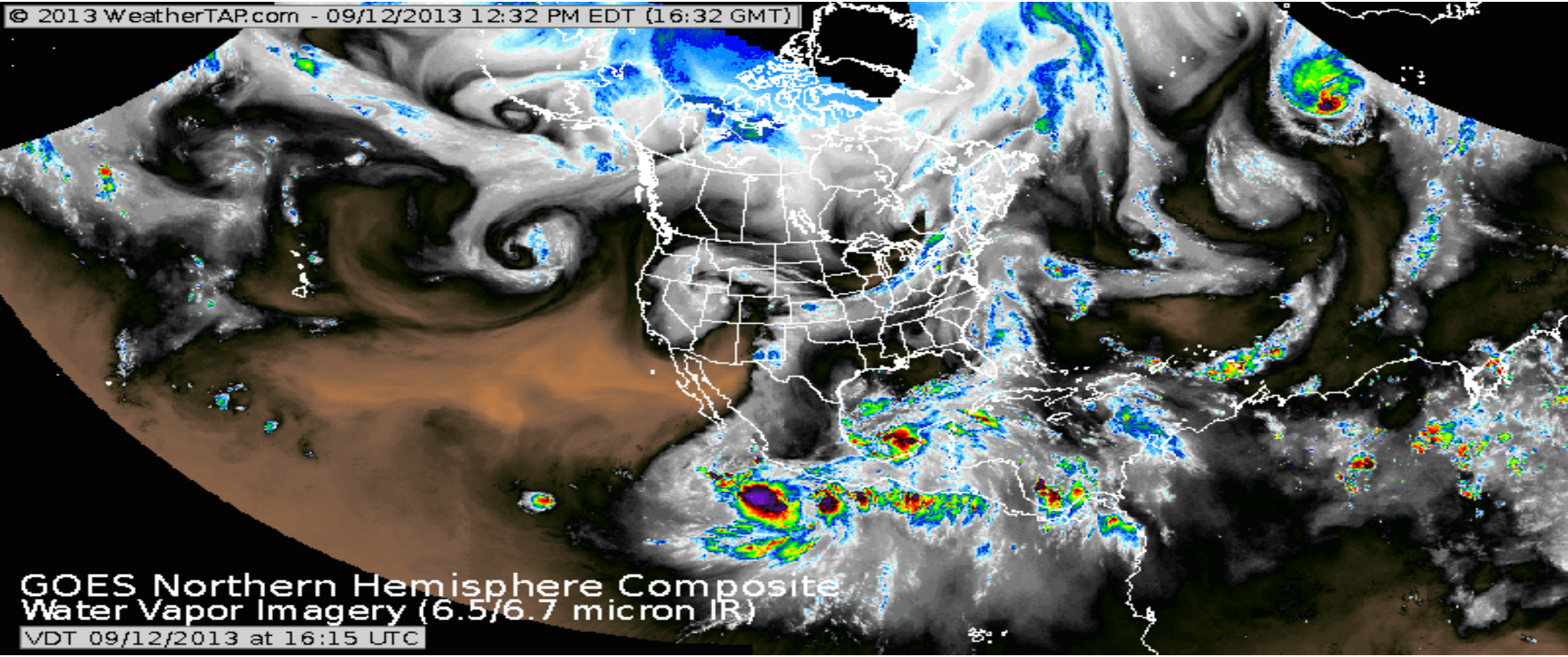
- **Boulder open space flood damage 'horrendous'**
- City promises to restore trails as quickly as possible but asks for patience
- Small rivers run where hikers once walked, and massive debris fields now block major trails.
- The McClintock fire road at Chautauqua Park is blocked by a debris field 20 to 30 feet high and twice as long. A brand-new trailhead at Thomas Lane for the South Boulder Creek Trail is wiped out.
- Every trail that you can think of is in horrendous shape

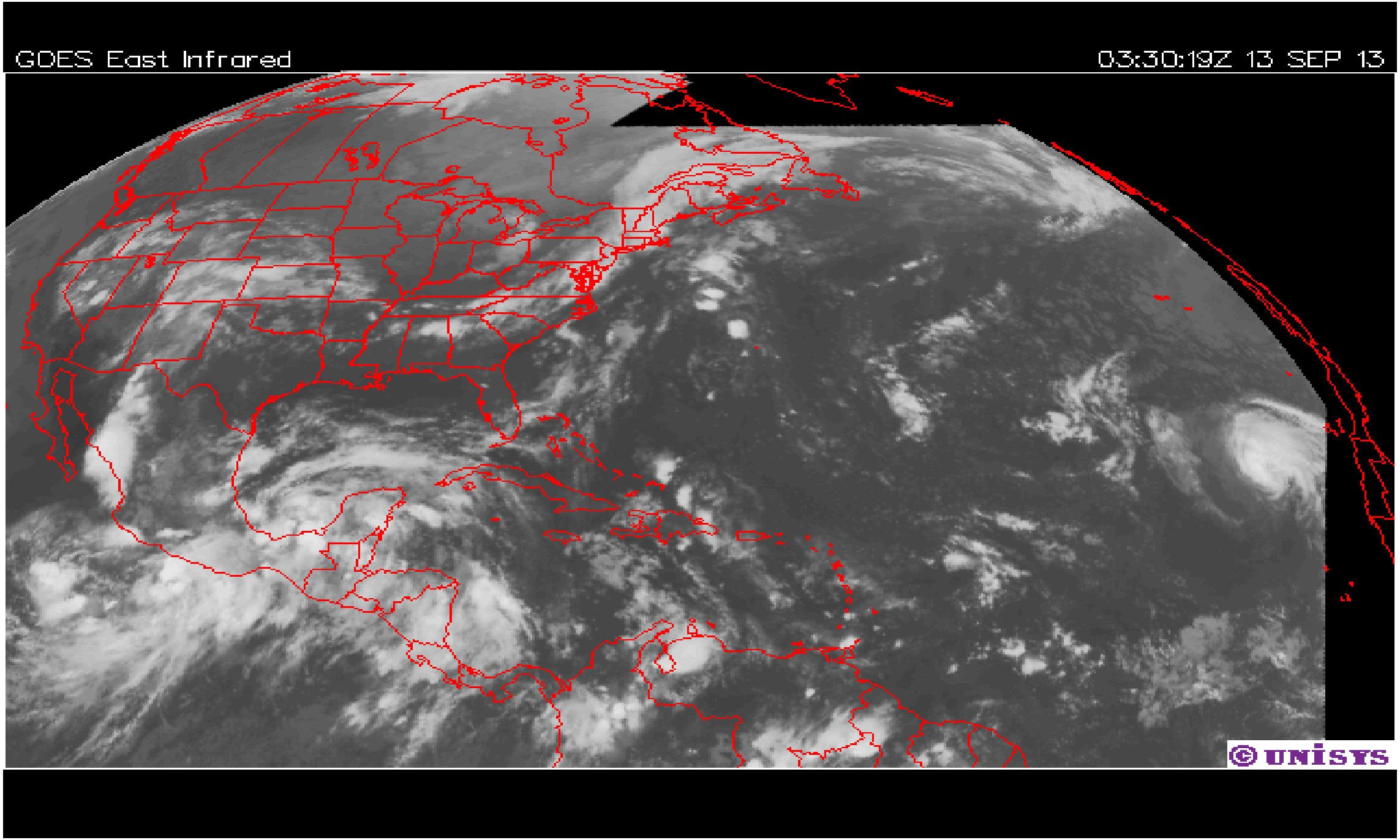
as of 17 Sept

Daily Camera

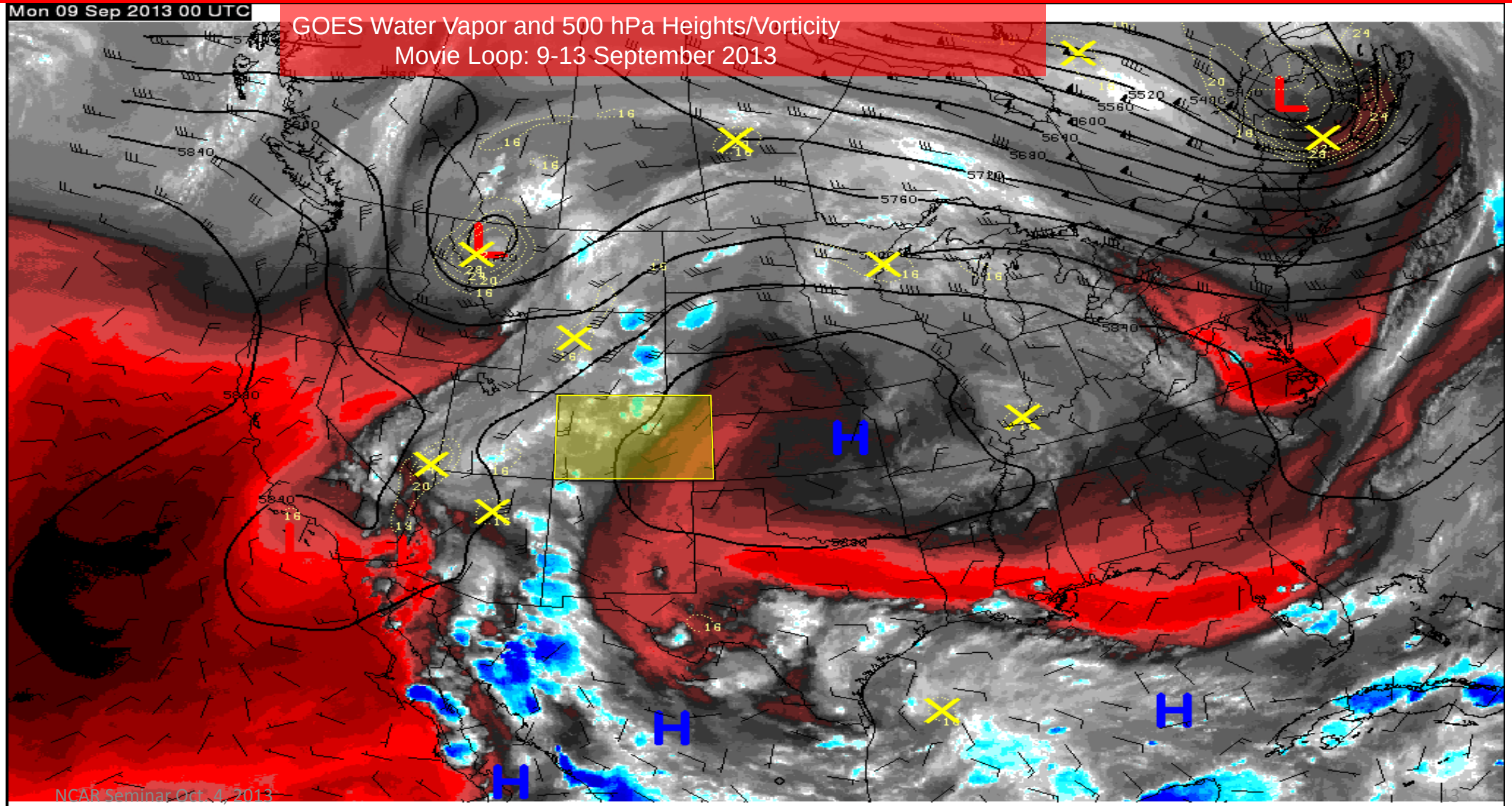
Boulder Flooding September 2013

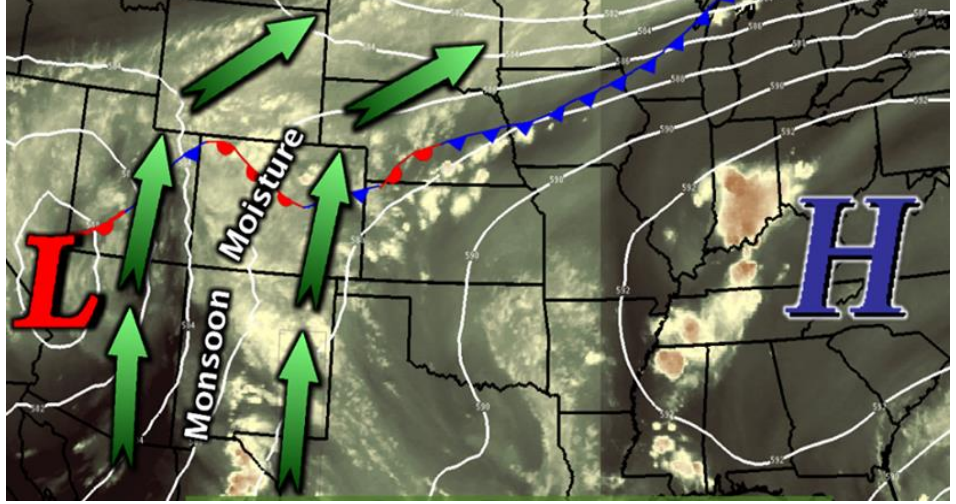
Composite satellite imagery

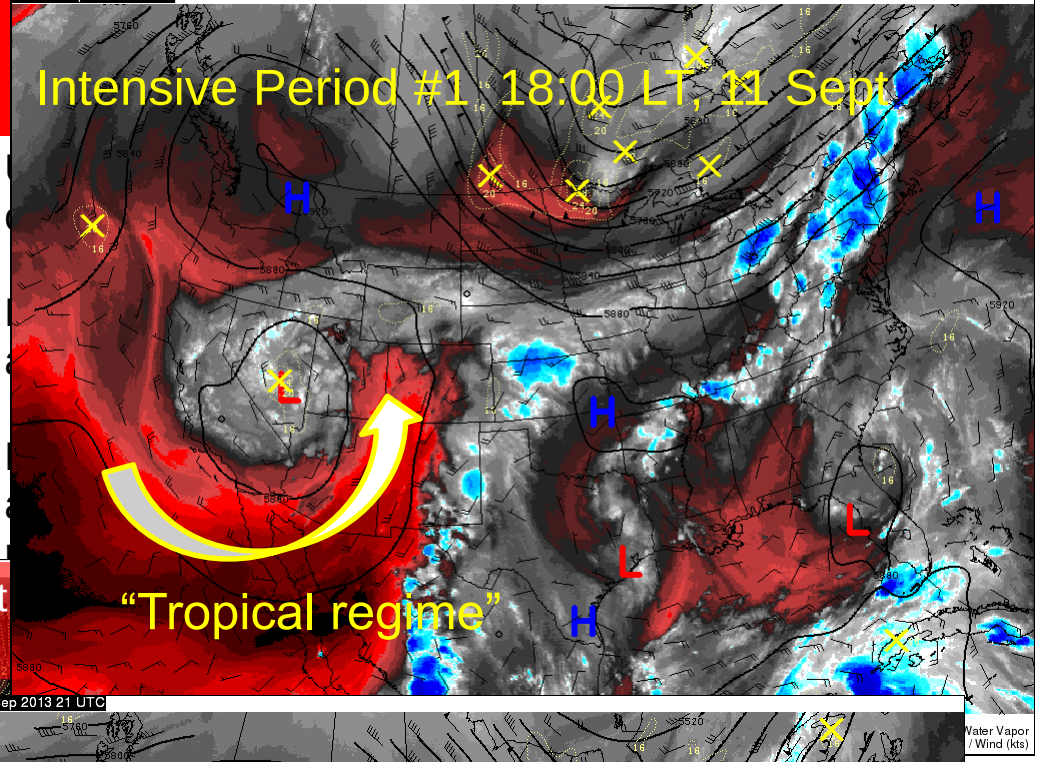


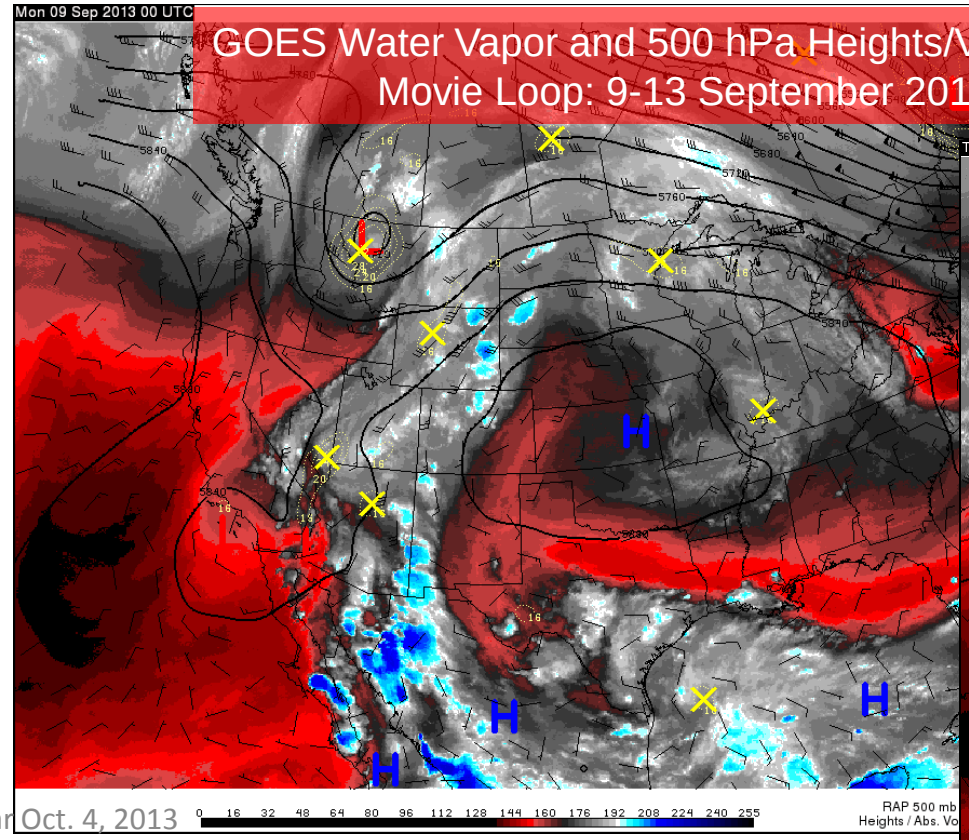

GOES East Infrared
03:30:19Z 13 SEP 13
©UNISYS

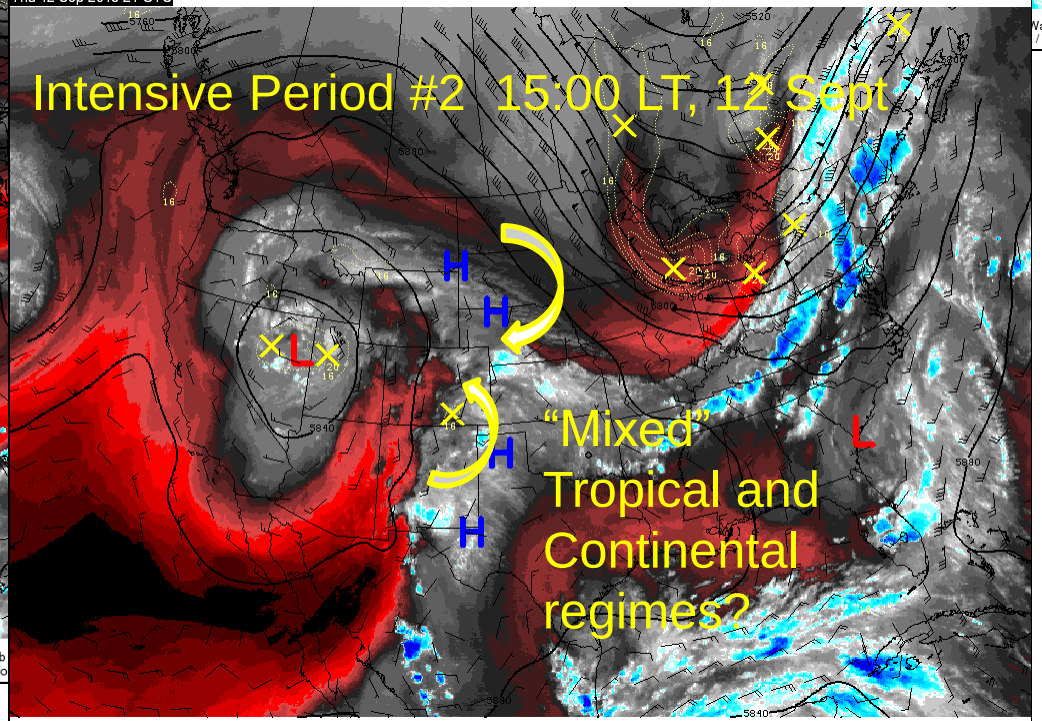
Northeastern Colorado Flash Floods 9-13 September 2013

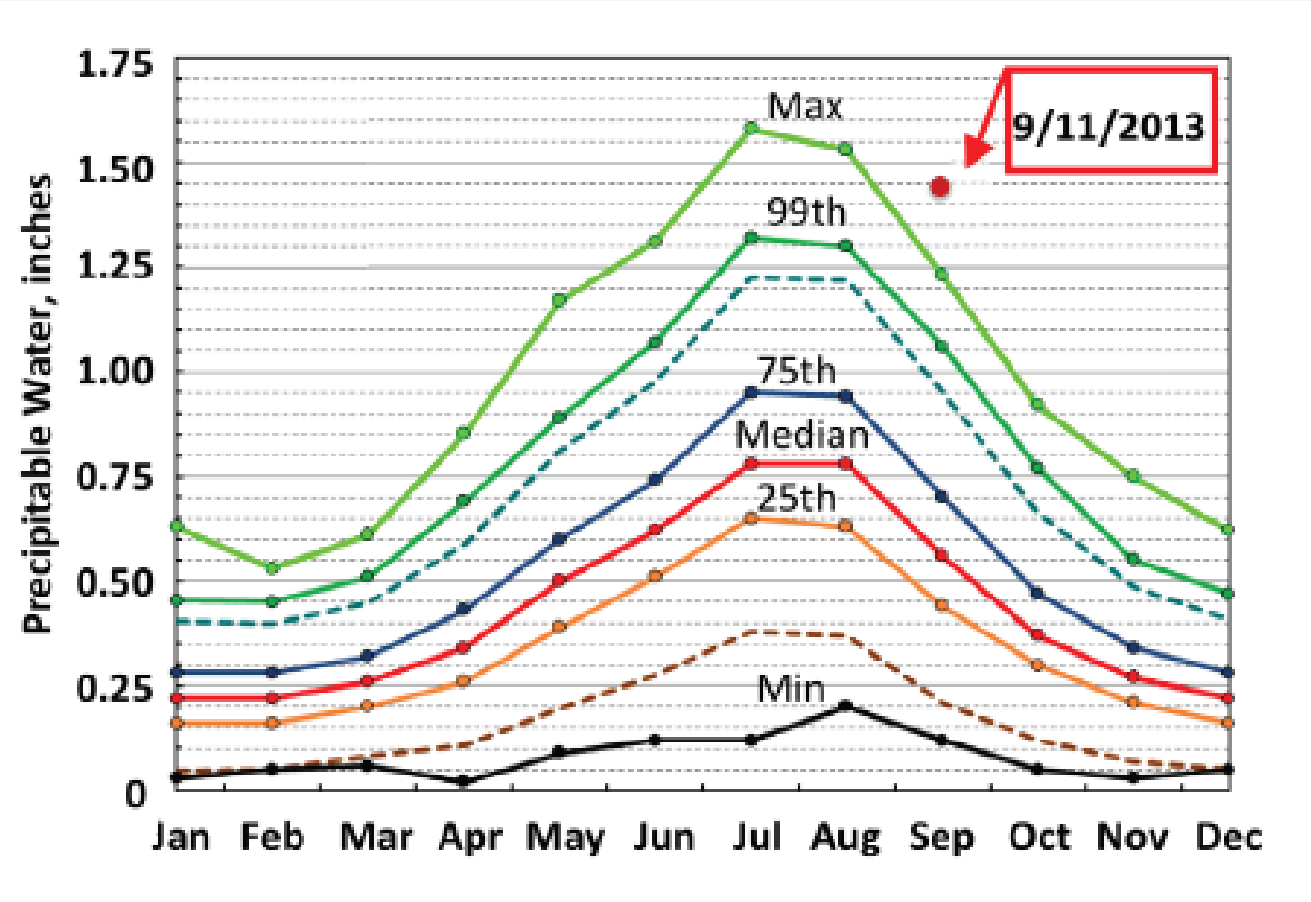



L
Moisture
Monsoon
H


Intensive Period #1 18:00 LT, 11 Sept
H
L
"Tropical regime"


Mon 09 Sep 2013 00 UTC
GOES Water Vapor and 500 hPa Heights/Vort
Movie Loop: 9-13 September 2013
H
L
RAP 500 mb
Heights / Abs. Vo


Thu 12 Sep 2013 21 UTC
Intensive Period #2 15:00 LT, 12 Sept
H
L
"Mixed"
Tropical and
Continental
regimes?
RAP 500 mb Analysis and Water Vapor

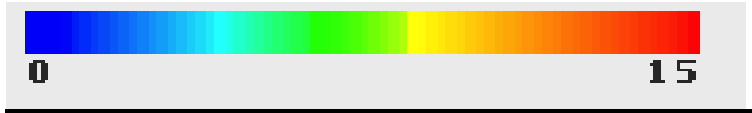


The range of total atmospheric precipitable water (PW) over Denver from 1948-2012, as measured by balloon soundings at Denver. The measurement on September 11, 2013 (red dot) was higher than any previous September reading. The prominent seasonal curve reflects that warmer air is able to contain more water vapor. (Plot adapted from NOAA NWS.)

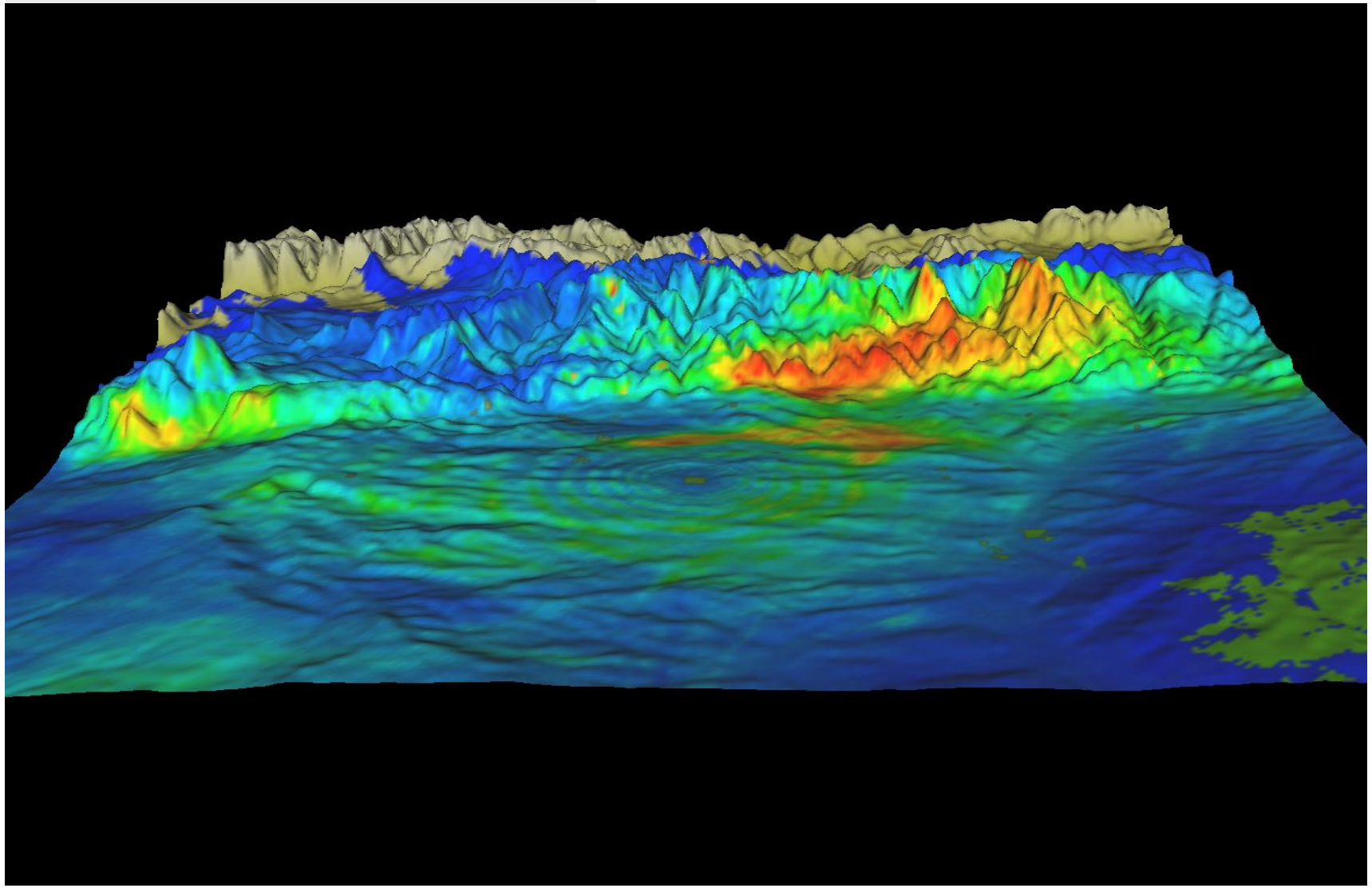
NOAA/CU-CIRES/WWA, Col. Climate Center Report

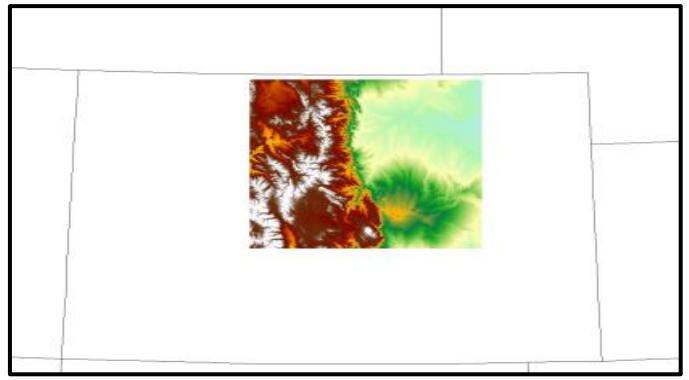
Radar Precipitation

NEXRAD ‘tropical’ approximation



inches



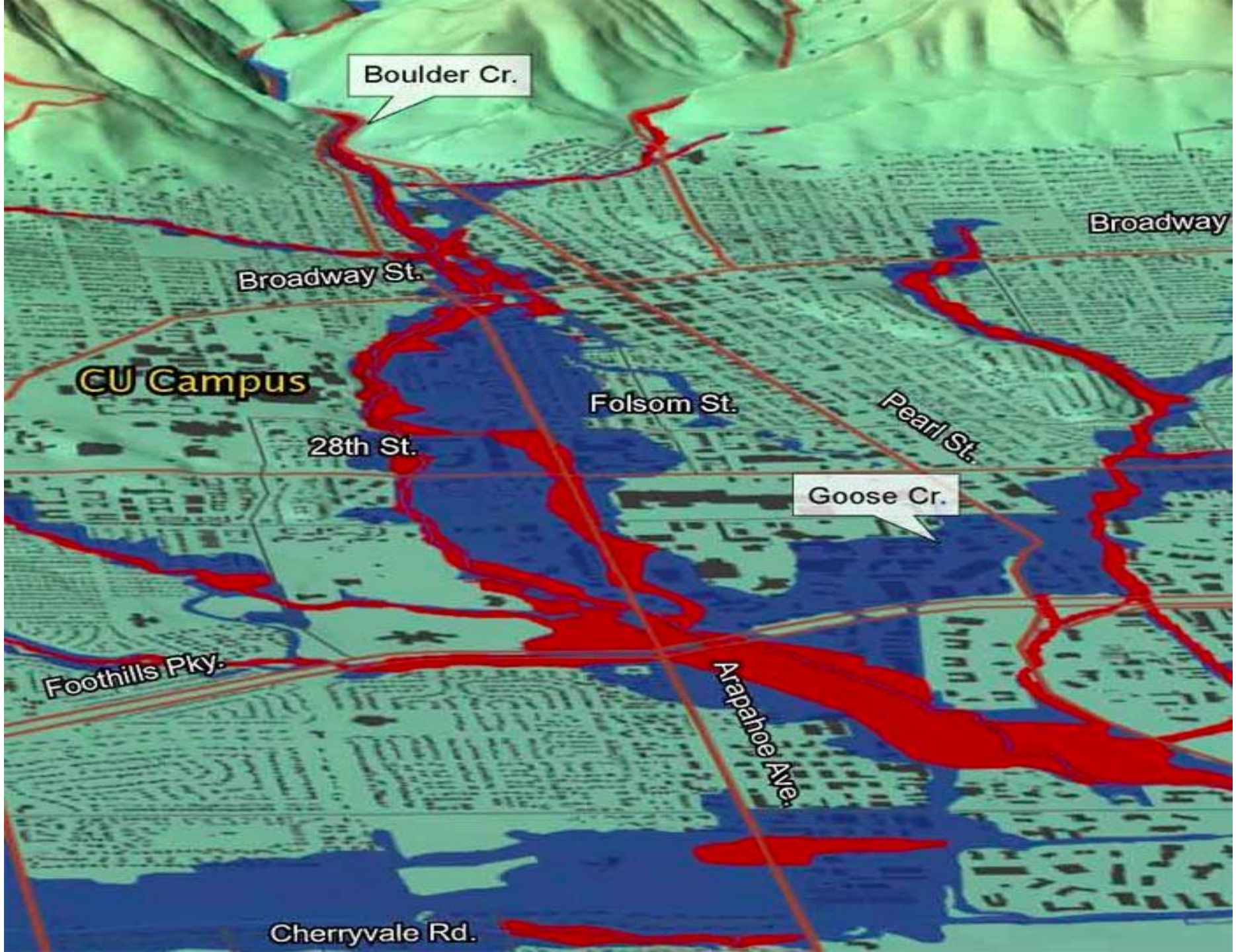


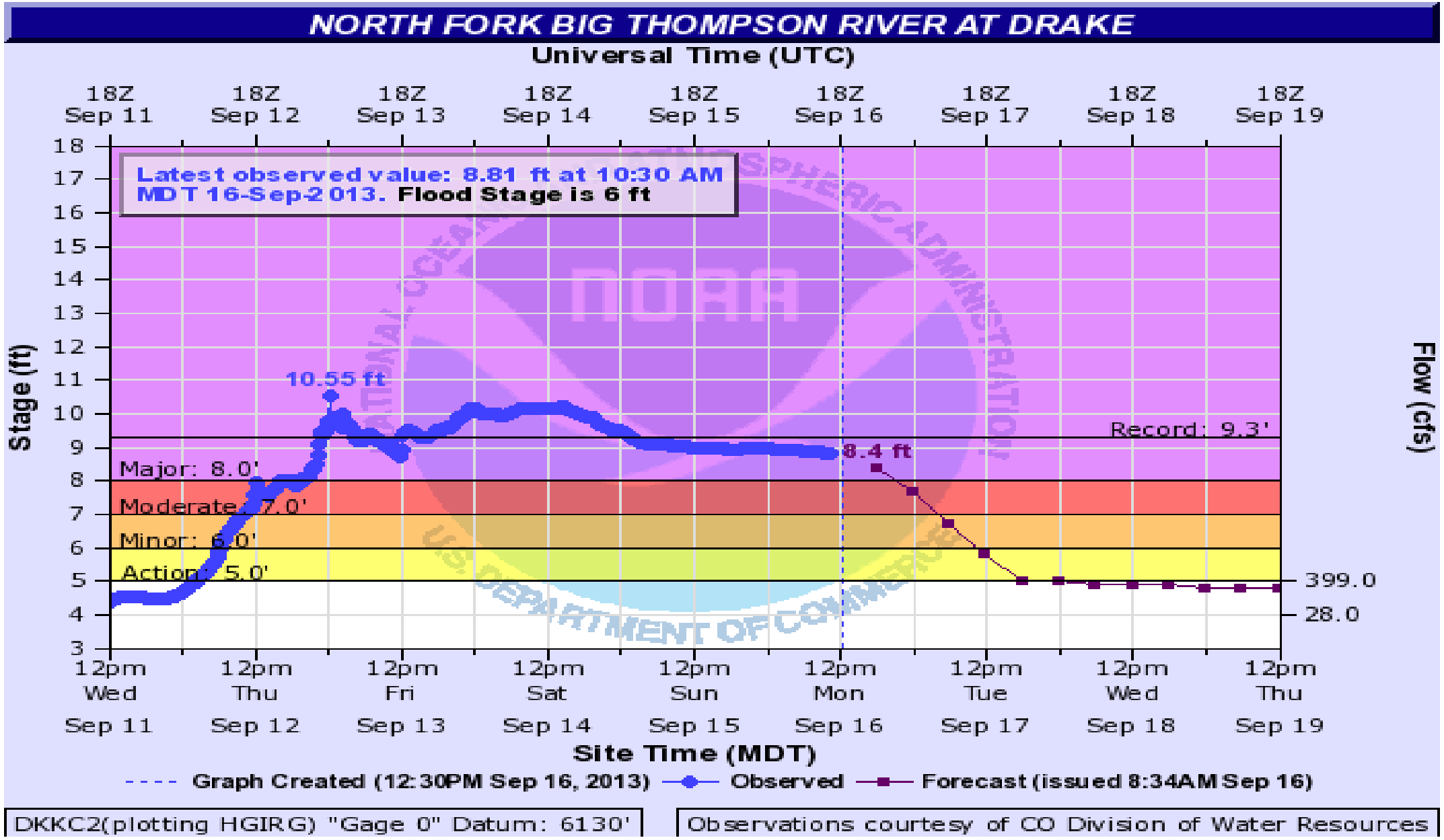
Radar ‘reflectivity’-rainfall relationship:
Z=32R^1.6

Precipitation Records:

- Boulder
  - Daily record (24 hr) of 9.08", previous record was 4.80" set on July 31, 1919
  - Monthly record for September of 17.18", previous record was 5.50" set on September 30, 1940
  - Monthly record for rainfall in any month of 17.18" so far in September 2013, previous record was 9.60" set in May 1995
  - Annual record of 30.14" so far in 2013, previous record was 29.47" in 1995
- DIA
  - 24 hr rainfall for September 14, 2013 of 2.01", previous record was 1.48" set back on September 26, 2012

NOAA NWS Denver Boulder Online Summary


Boulder Cr.
Broadway
Broadway St.
CU Campus
Folsom St.
Pearl St.
28th St.
Goose Cr.
Foothills Pky.
Arapahoe Ave.
Cherryvale Rd.


NORTH FORK BIG THOMPSON RIVER AT DRAKE
Universal Time (UTC)
18Z Sep 11
18Z Sep 12
18Z Sep 13
18Z Sep 14
18Z Sep 15
18Z Sep 16
18Z Sep 17
18Z Sep 18
18Z Sep 19
Latest observed value: 8.81 ft at 10:30 AM MDT 16-Sep-2013. Flood Stage is 6 ft
10.55 ft
8.4 ft
Record: 9.3'
Major: 8.0'
Moderate: 7.0'
Minor: 6.0'
Action: 5.0'
Stage (ft)
Flow (cfs)
399.0
28.0
12pm Wed Sep 11
12pm Thu Sep 12
12pm Fri Sep 13
12pm Sat Sep 14
12pm Sun Sep 15
12pm Mon Sep 16
12pm Tue Sep 17
12pm Wed Sep 18
12pm Thu Sep 19
Site Time (MDT)
Graph Created (12:30PM Sep 16, 2013)
Observed
Forecast (issued 8:34AM Sep 16)
DKKC2(plotting HGIRG) "Gage 0" Datum: 6130'
Observations courtesy of CO Division of Water Resources

Year-To-Date Rainfall Totals

Boulder

Source: RCC-ACIS.org - Applied Climate Information Systems
Boulder Station USC00050848

CLIMATE CENTRAL

Colorado Water Conservation Board Analysis of Front Range Flood Return Period by Water Shed

Location	Drainage Area (sq. mi)	2013 Peak Discharge Estimate (CFS)	2013 Estimated Frequency
South Platte River at Kersey	9,659	55,000	500 year
Boulder Creek at 28th Street	136	5,300	25 year
St. Vrain below confluence N and S branches	211	19,600	< 500 year
Little Thompson river below West Fork	43.2	12,300	> 500 year
Big Thompson below Drake	274	29,500	> 500 year

Courtesy of Ron Stewart

Alberta Flood

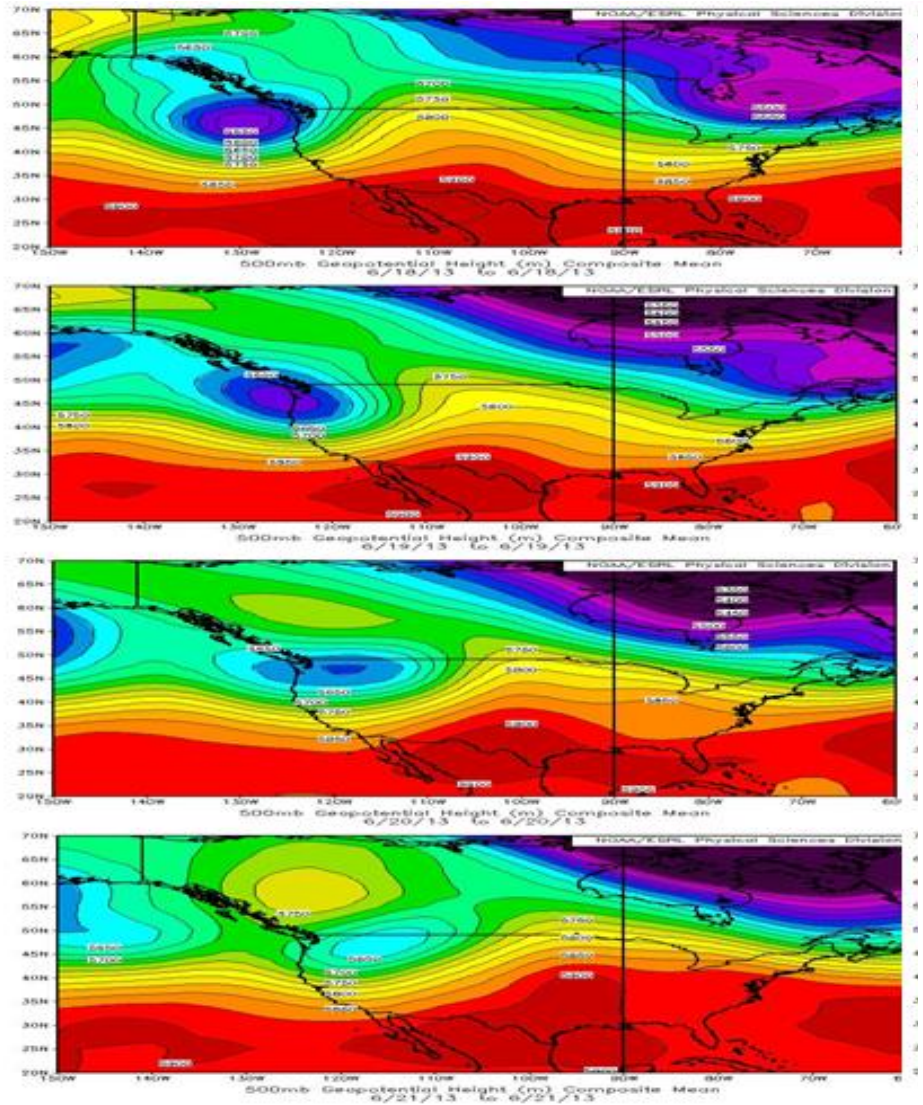
500 mb Heights

June 18

June 19

June 20

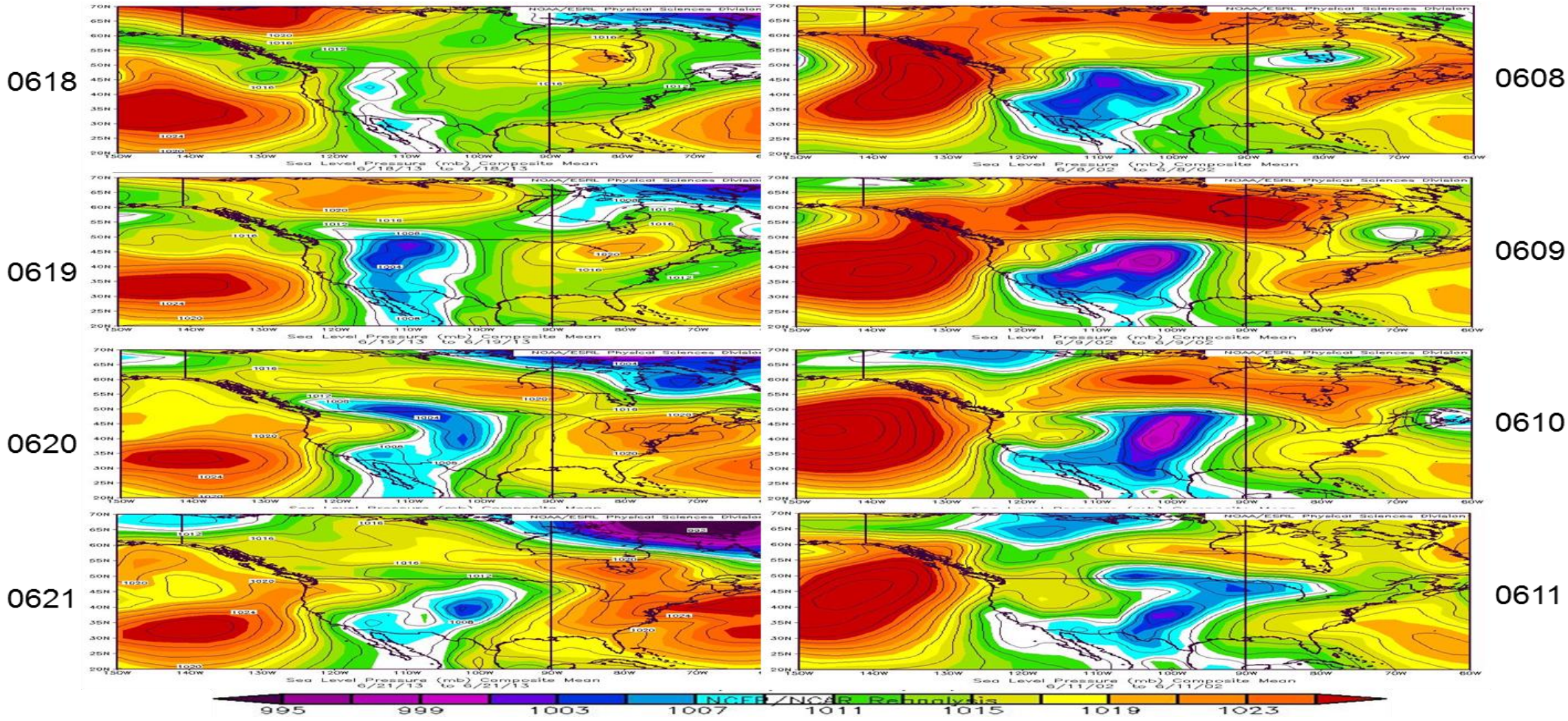
June 21



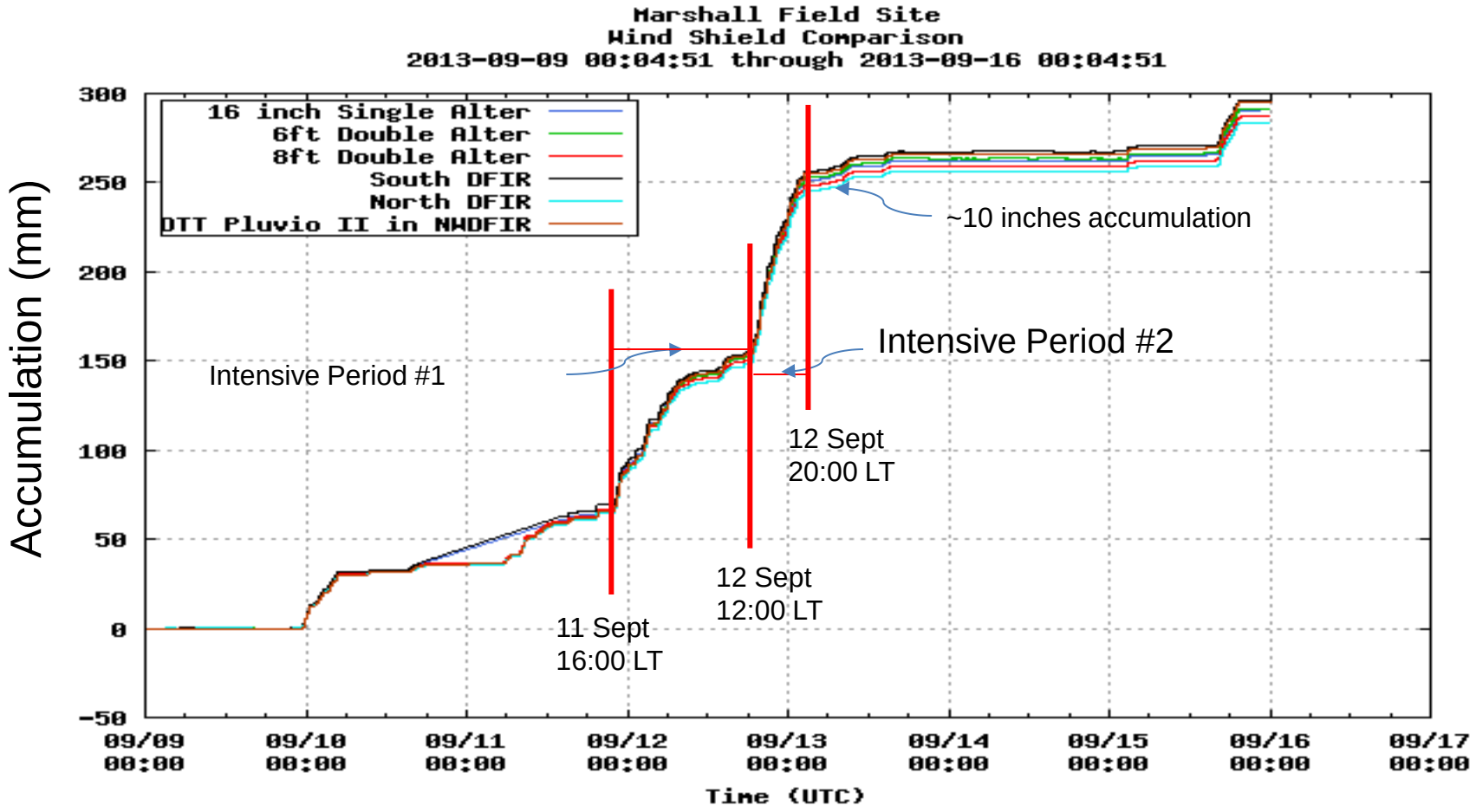
Courtesy of Ron Stewart

Alberta Flood

Surface Pressure

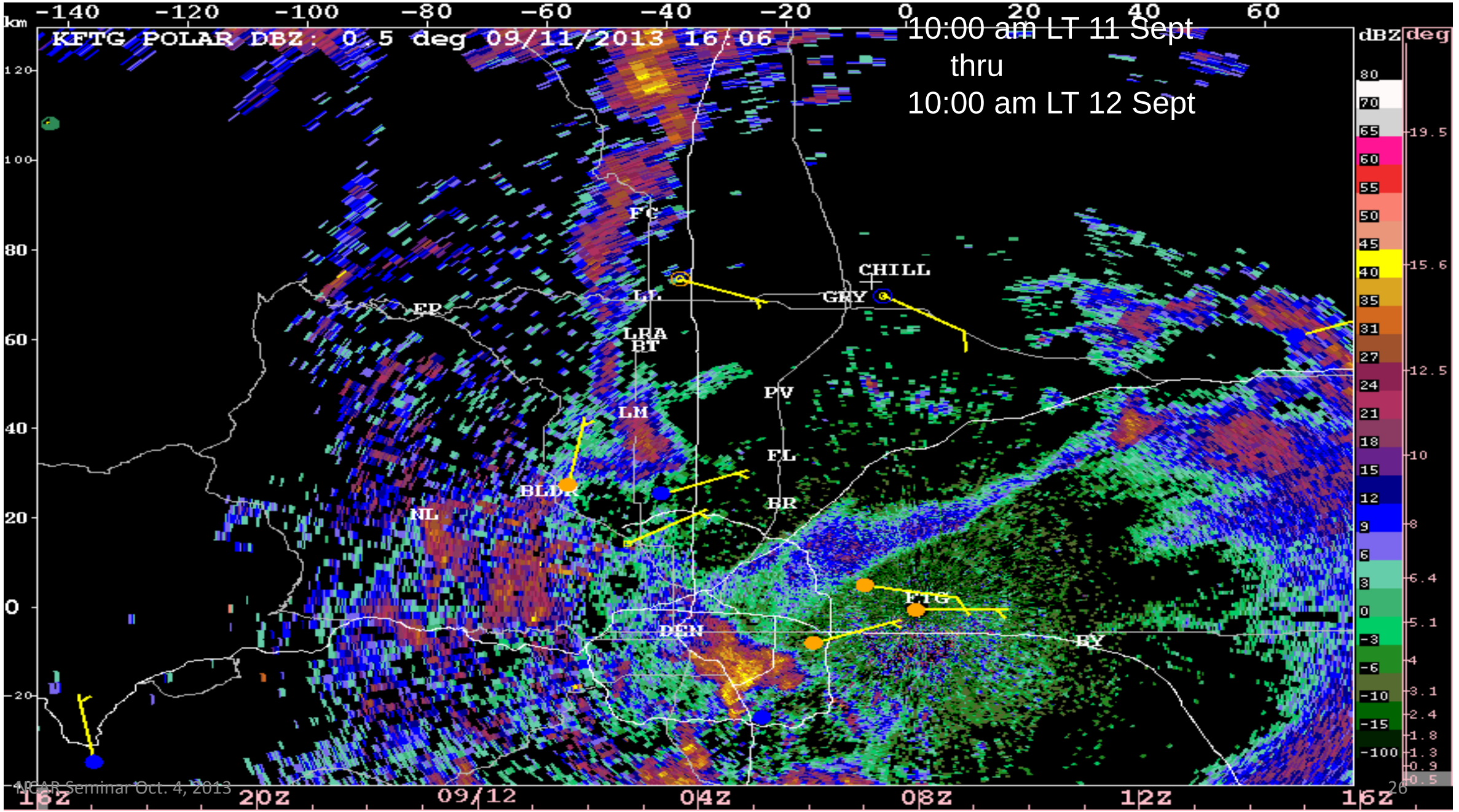


Surface Station Testbed at NCAR's Marshall Field Site – rain gauge measurements



Courtesy of Roy Rasmussen

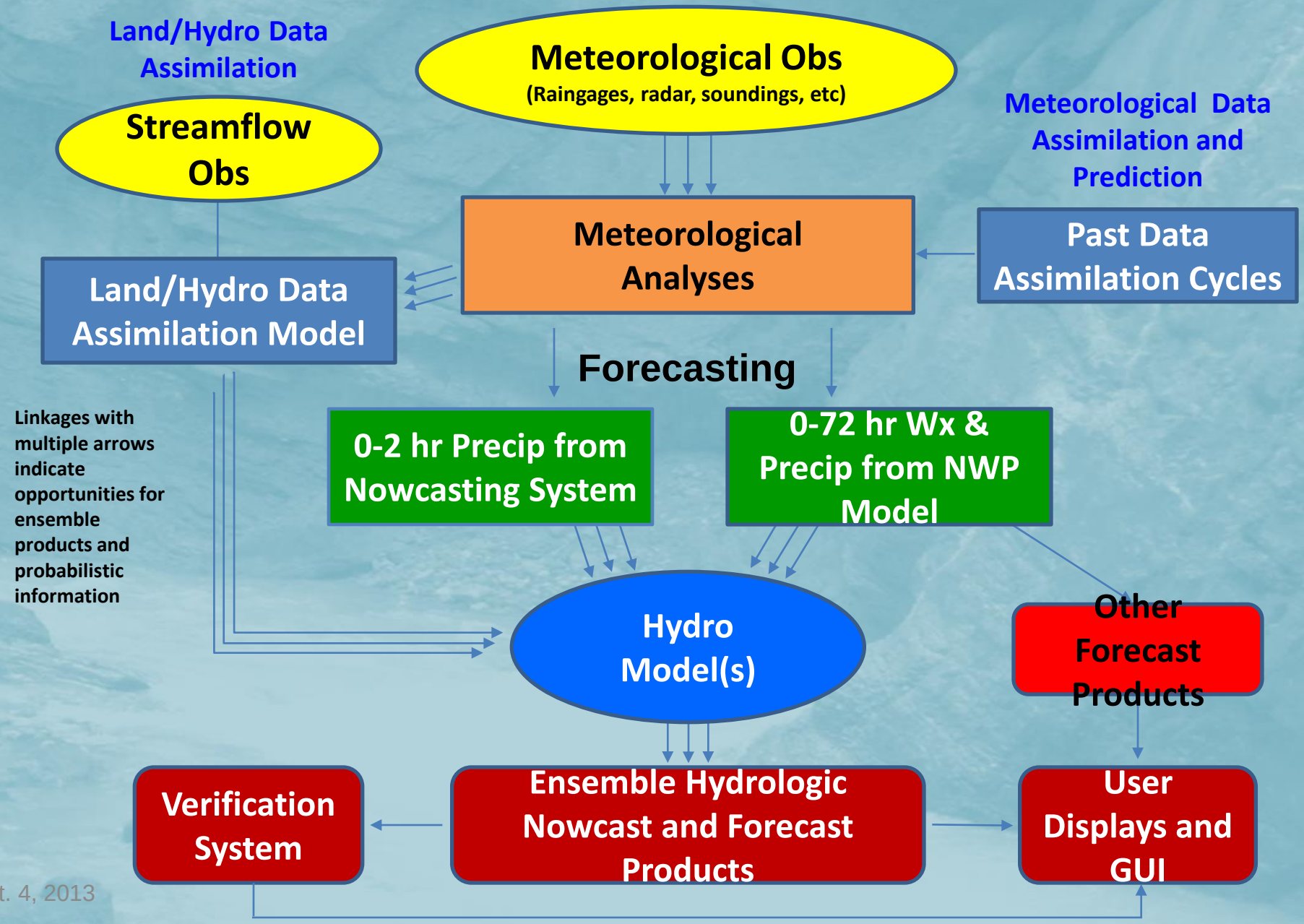
24 hour Loop of Denver KFTG Radar Reflectivity



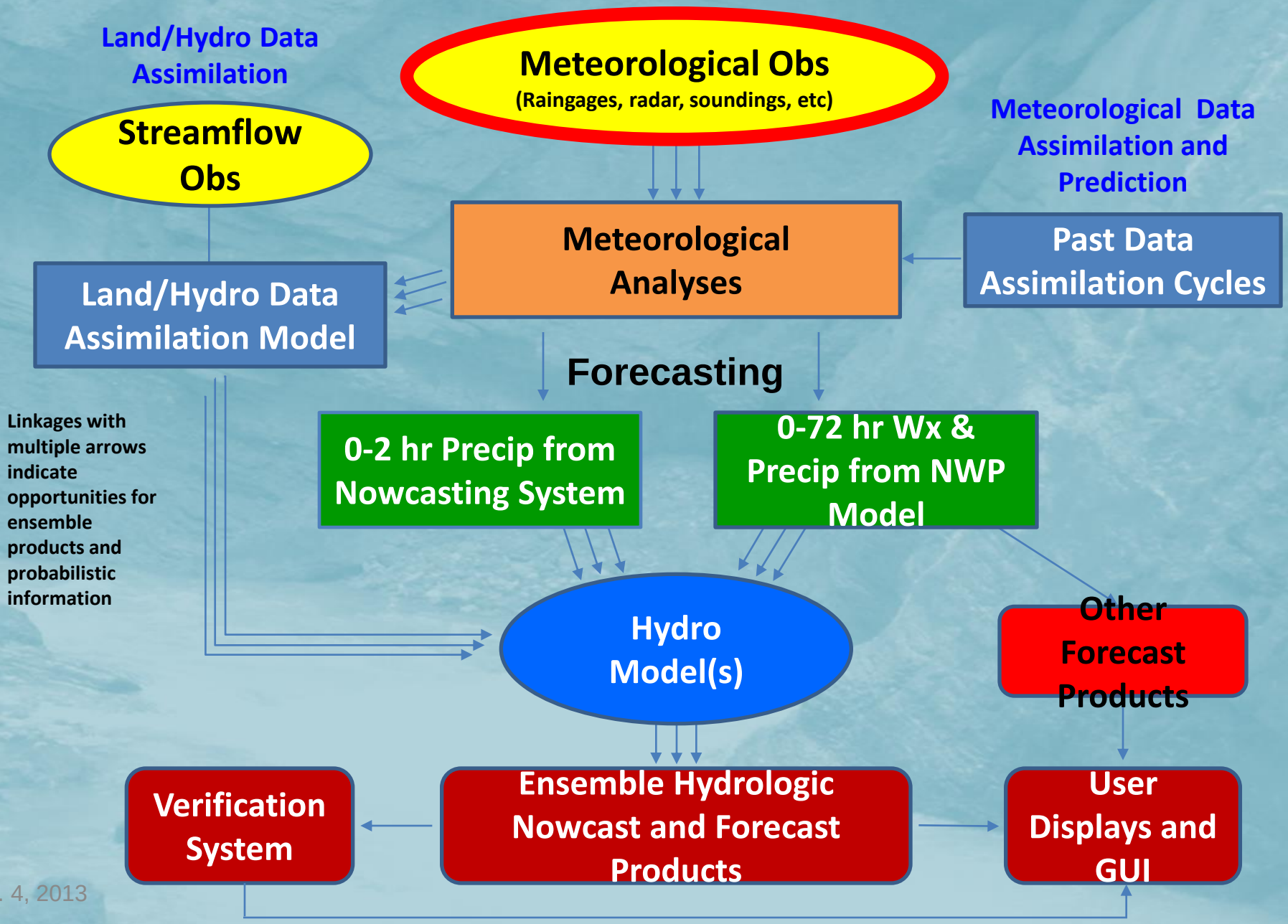
Real Challenges in Real-time:

- Weather forecast models were not verifying well
- Surface instrument networks were being destroyed
- Communications were in/out
- Meteorological processes were atypical
- Hydrologic models were operating out of calibrated ranges, channels were changing, structures were failing
- Hazards were widely distributed (1,300 landslides in addition to flooding)

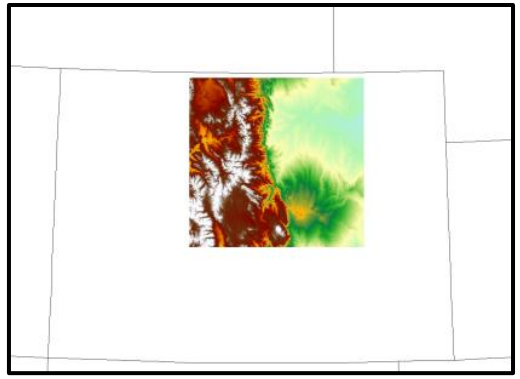
Hydrometeorological Warning System

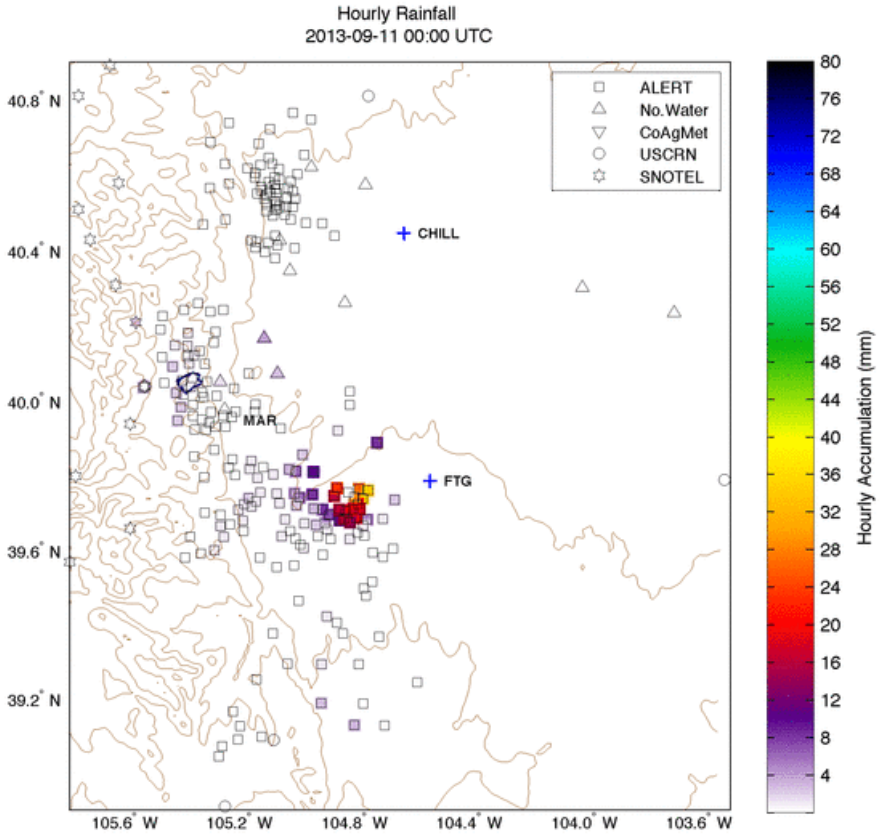


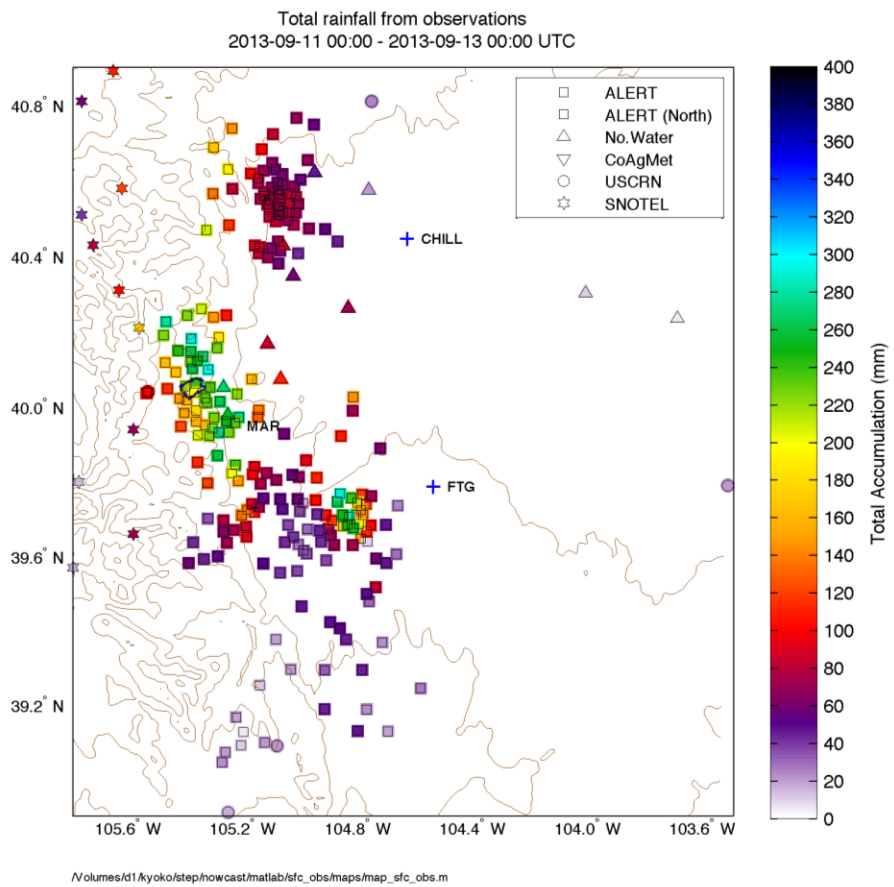
Hydrometeorological Warning System



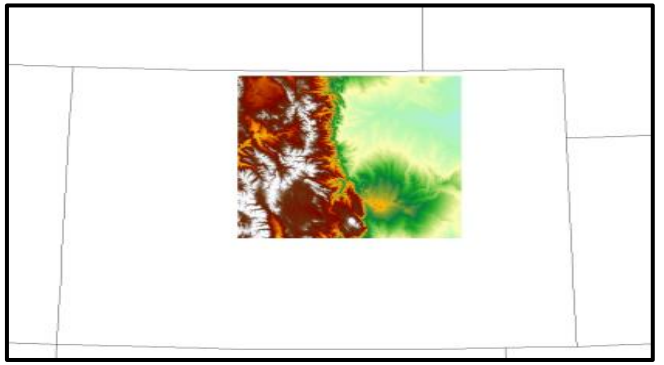
Automated, high time resolution rainfall gauge stations:



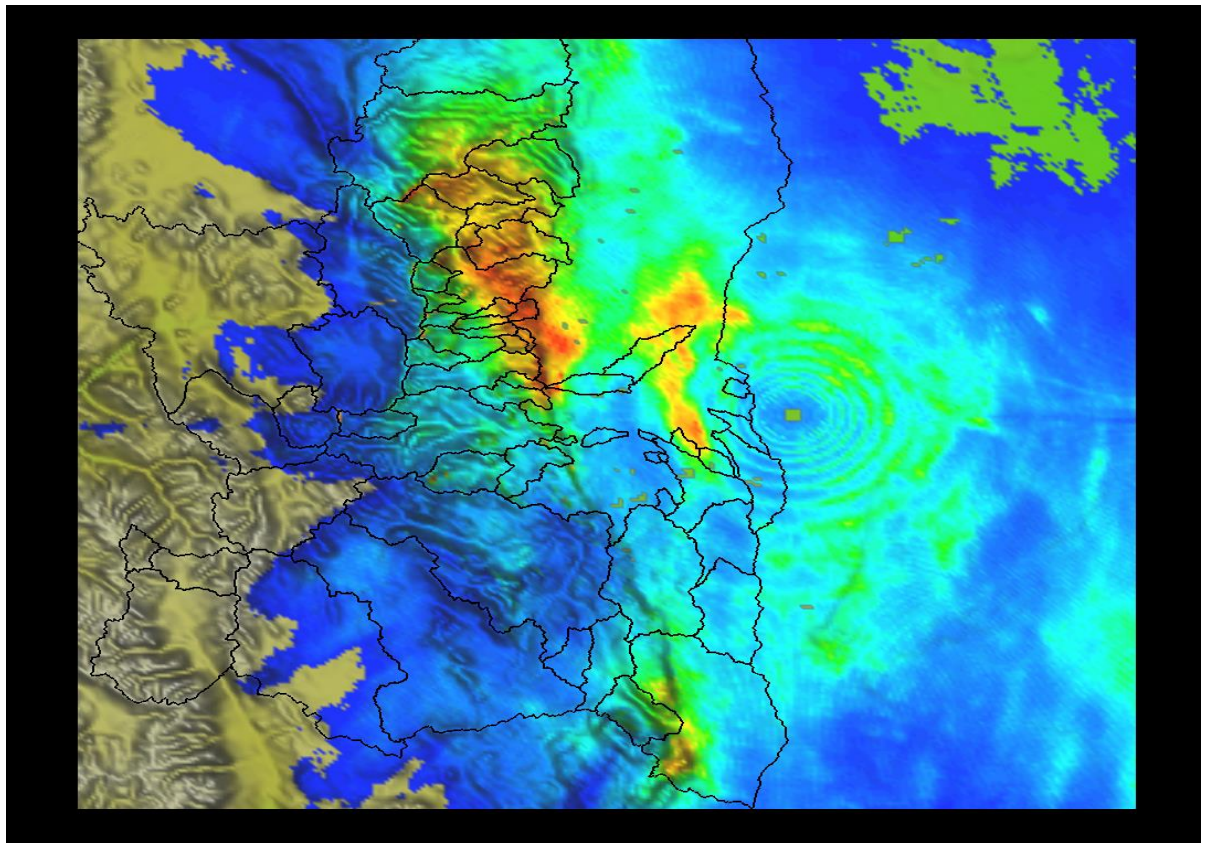


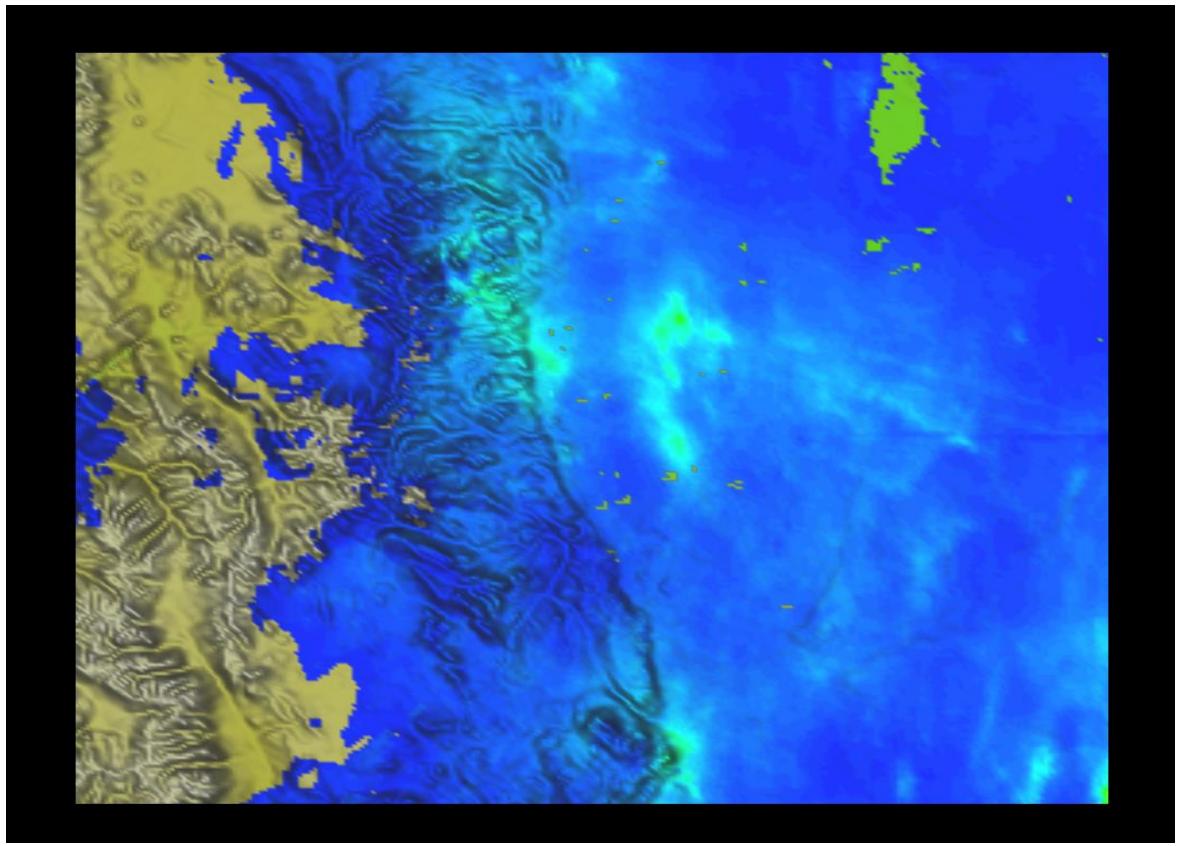


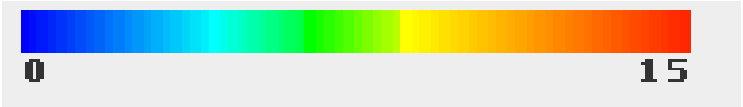
Radar Quantitative Precipitation Estimate (QPE) results:



NEXRAD Z=32R^1.65 versus Z=300I NSSL Q3 Radar-only

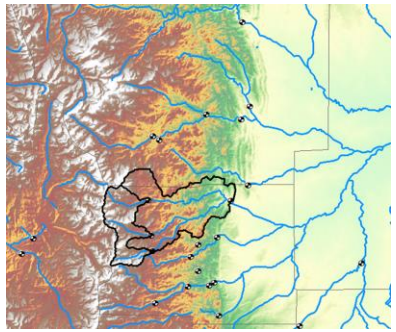


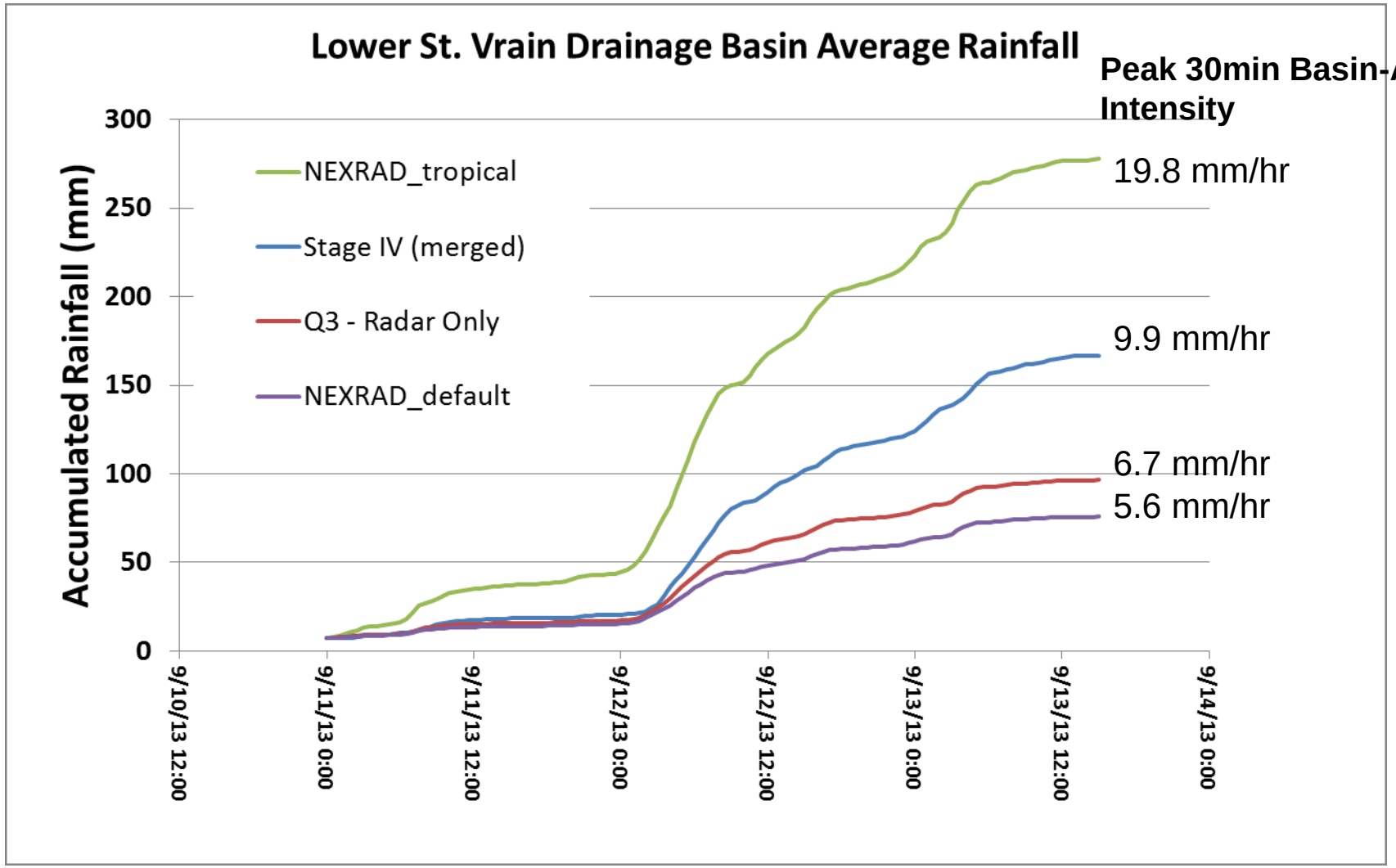




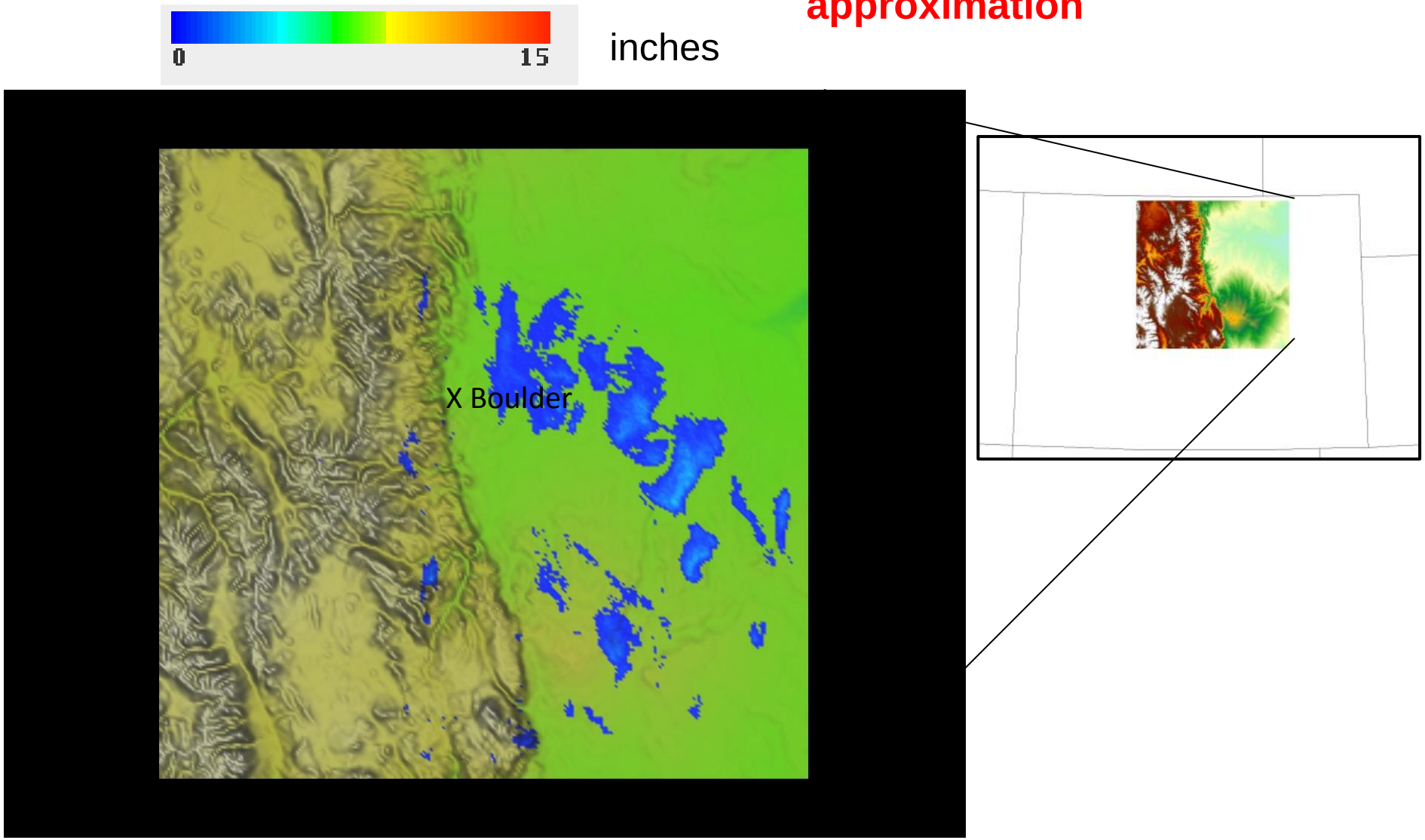
inches

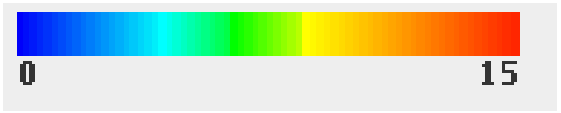
Precipitation Estimate Uncertainty
Basin Accumulations:
Ex: Lower St. Vrain basin





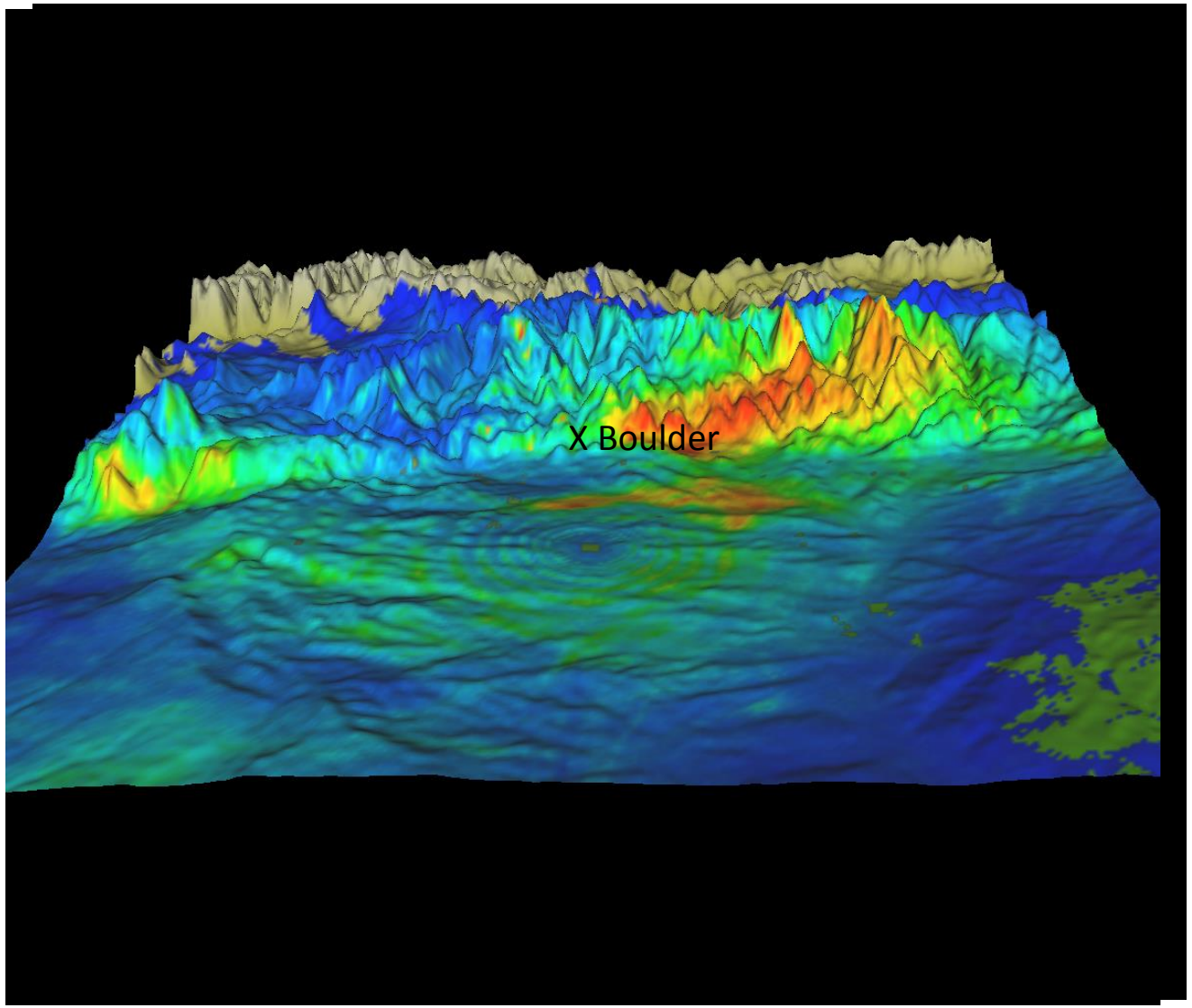
Radar Precipitation Estimate results NEXRAD 'tropical' approximation

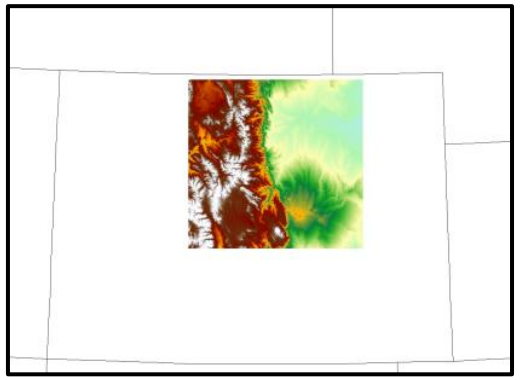




inches

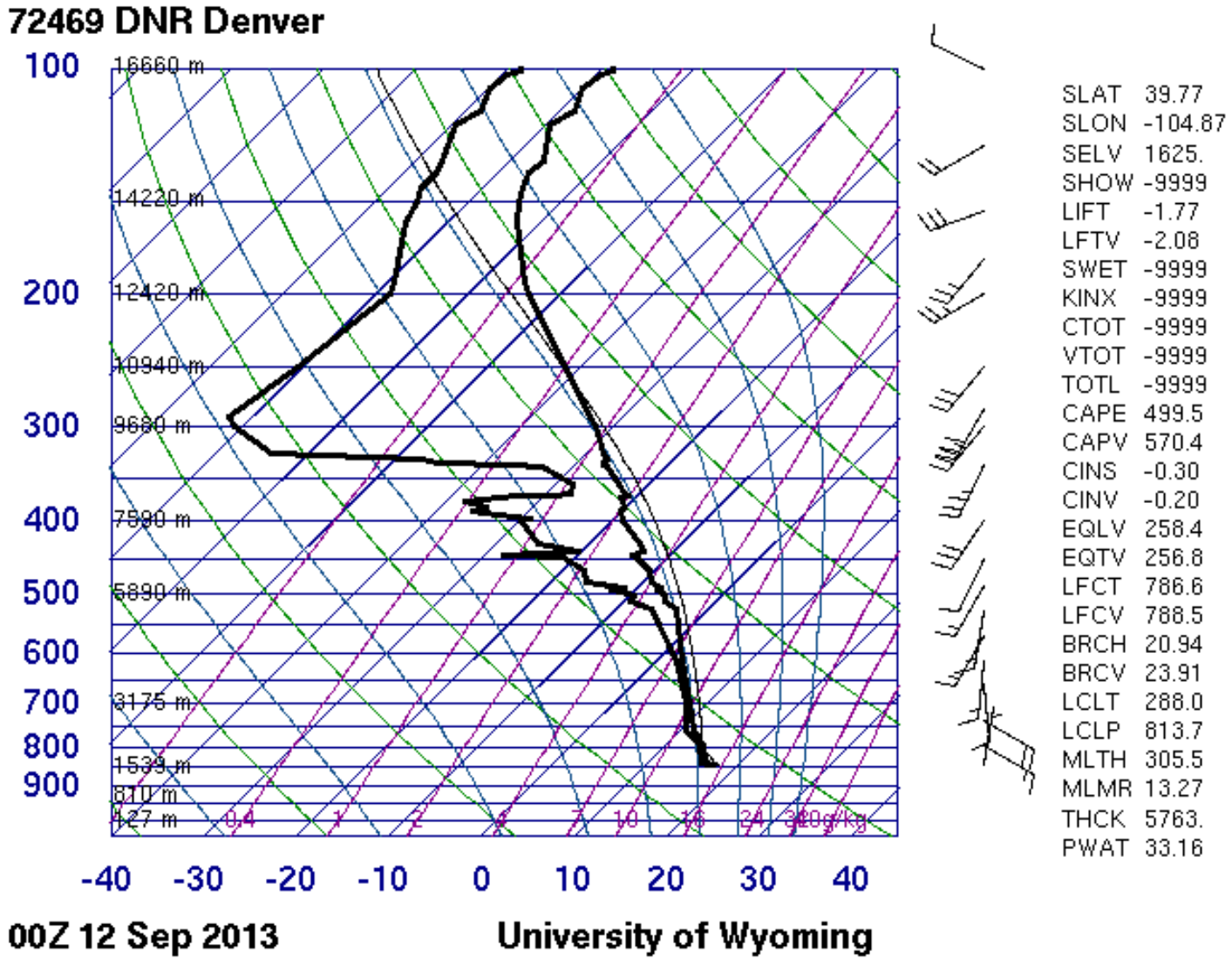
Radar Precipitation Estimate results NEXRAD 'tropical' approximation



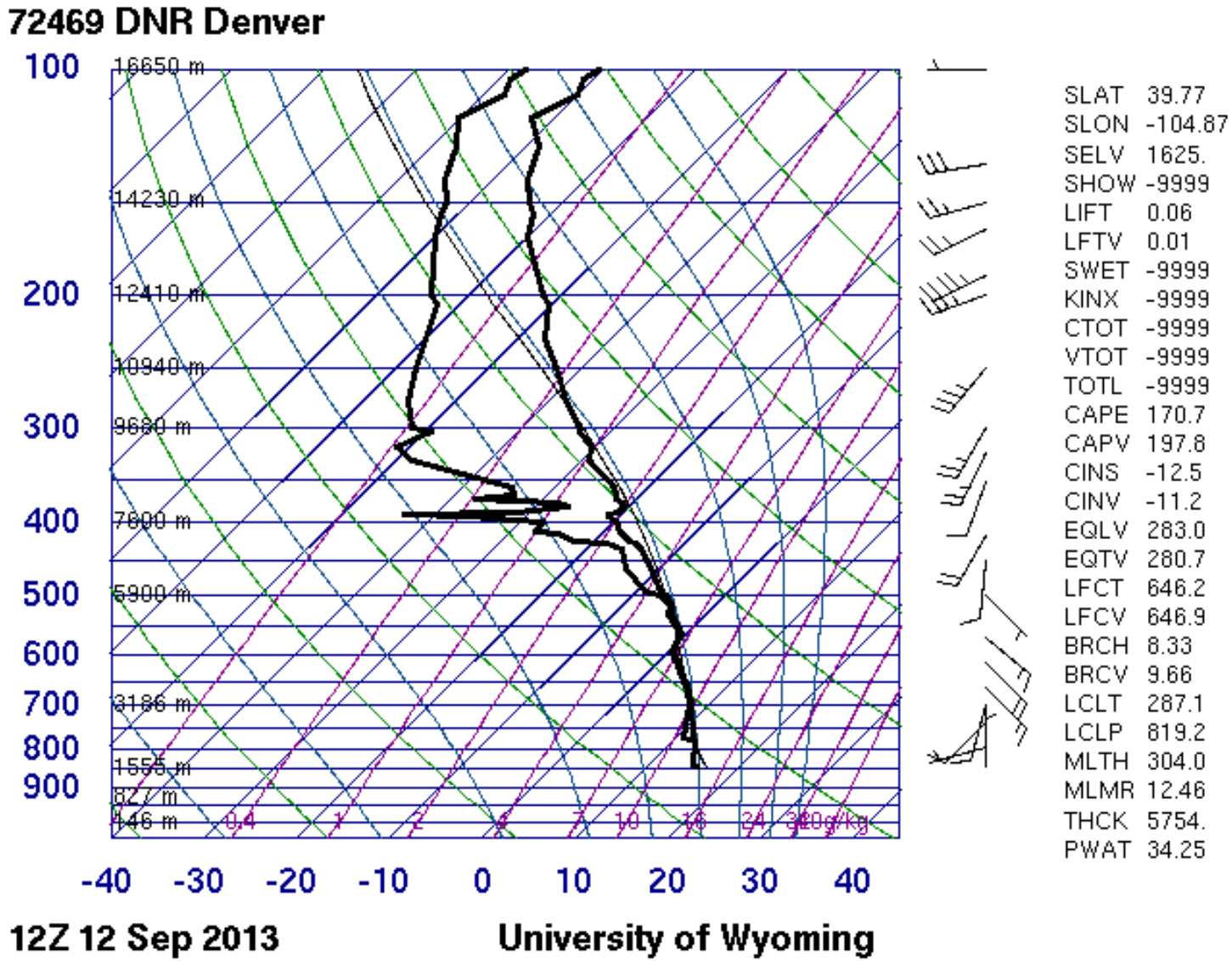


Radar 'reflectivity'-rainfall relationship:
Z=32R^1.6

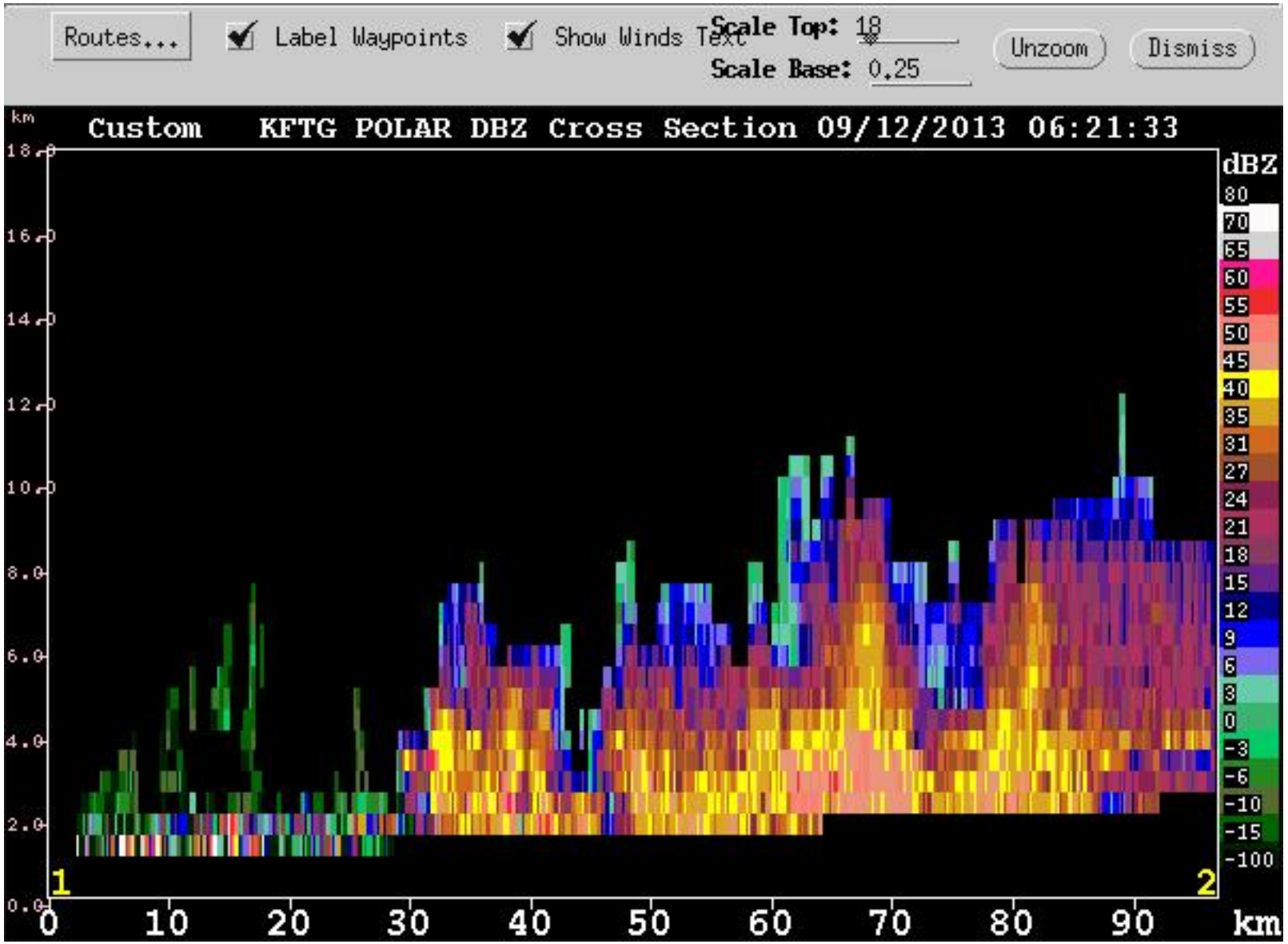
Denver sounding at 00 UTC (6:00 p.m. LT) on September 12, 2013



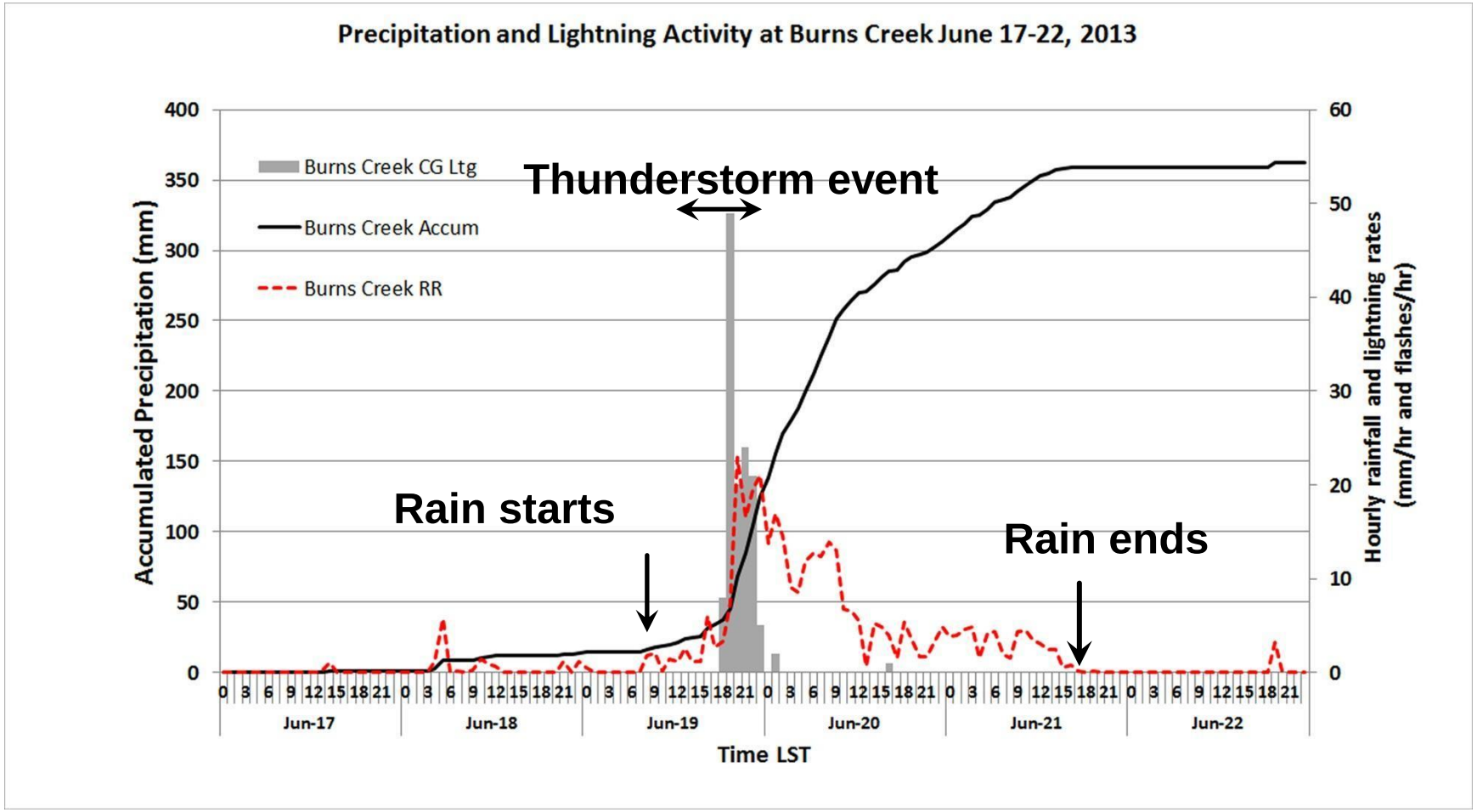
Denver sounding at 12Z (6:00 a.m. LT) on September 12, 2013



Vertical Cross Section of Radar Reflectivity at 9/12/2013 at 06 UTC at 300 degrees radial



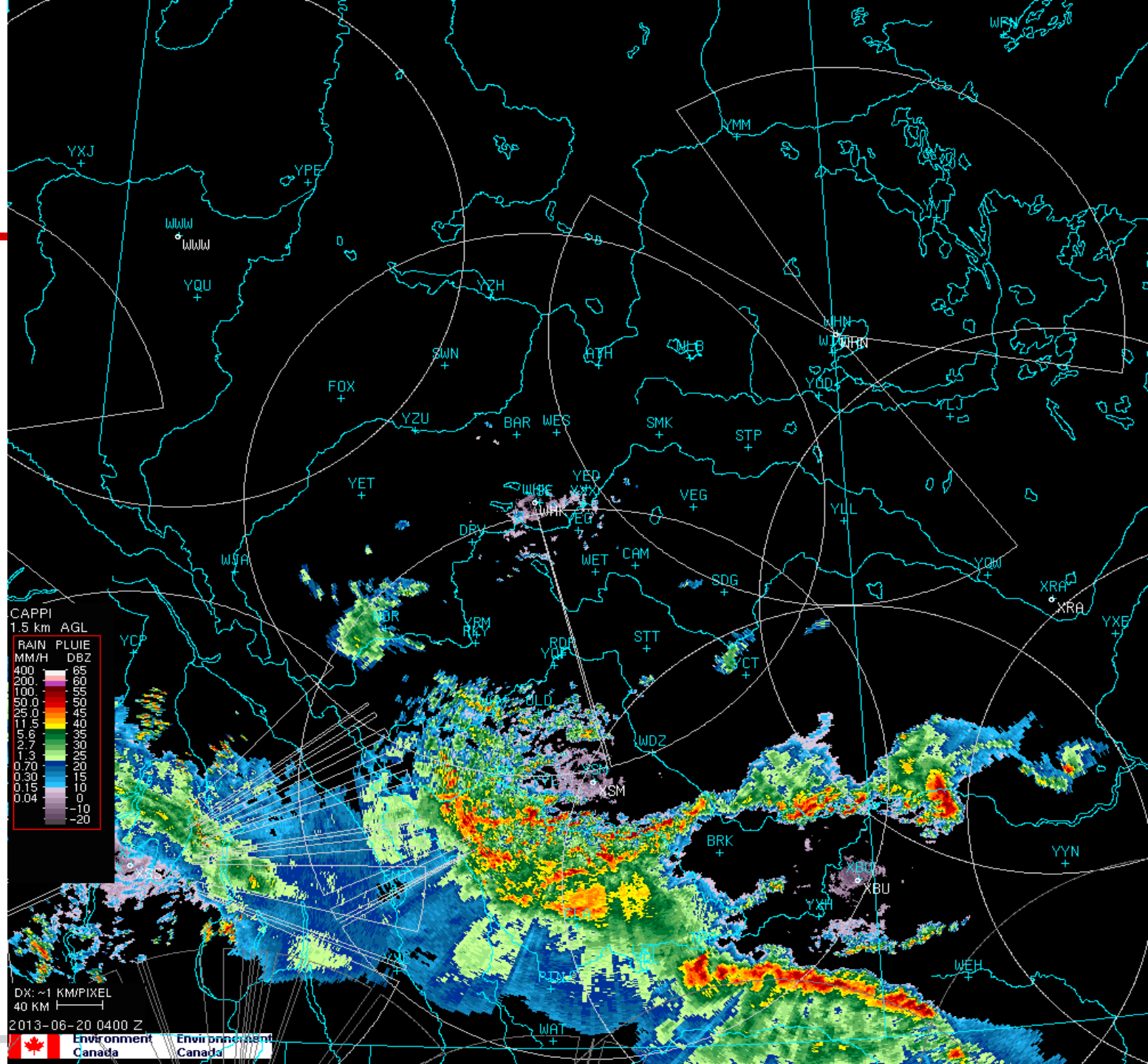
Rainfall and thunderstorm Activity
Burns Creek station



Composite

04 UTC
June 20

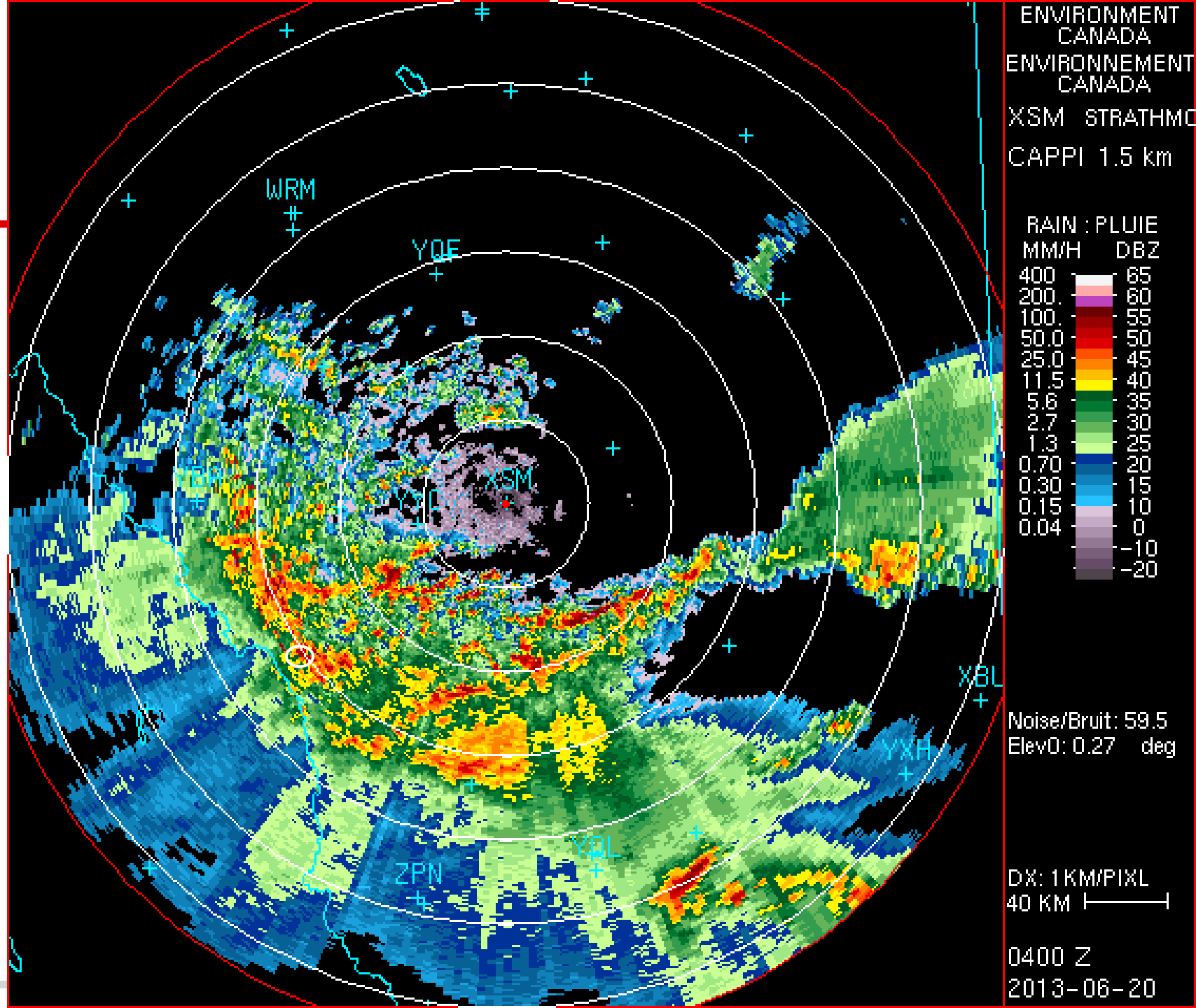
around time of highest precipitation rate - Burns Lake



Strathmore

04 UTC

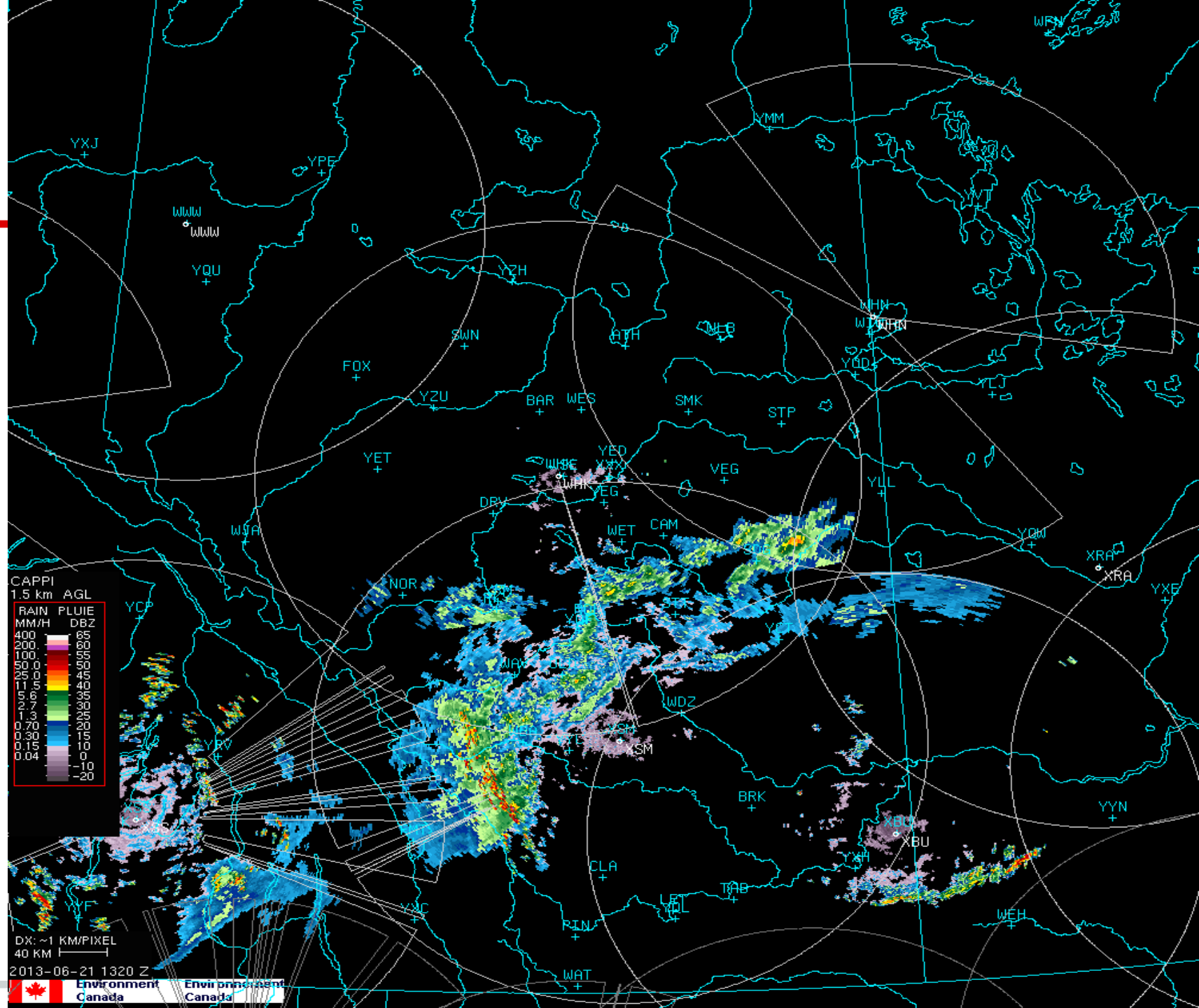
June 20



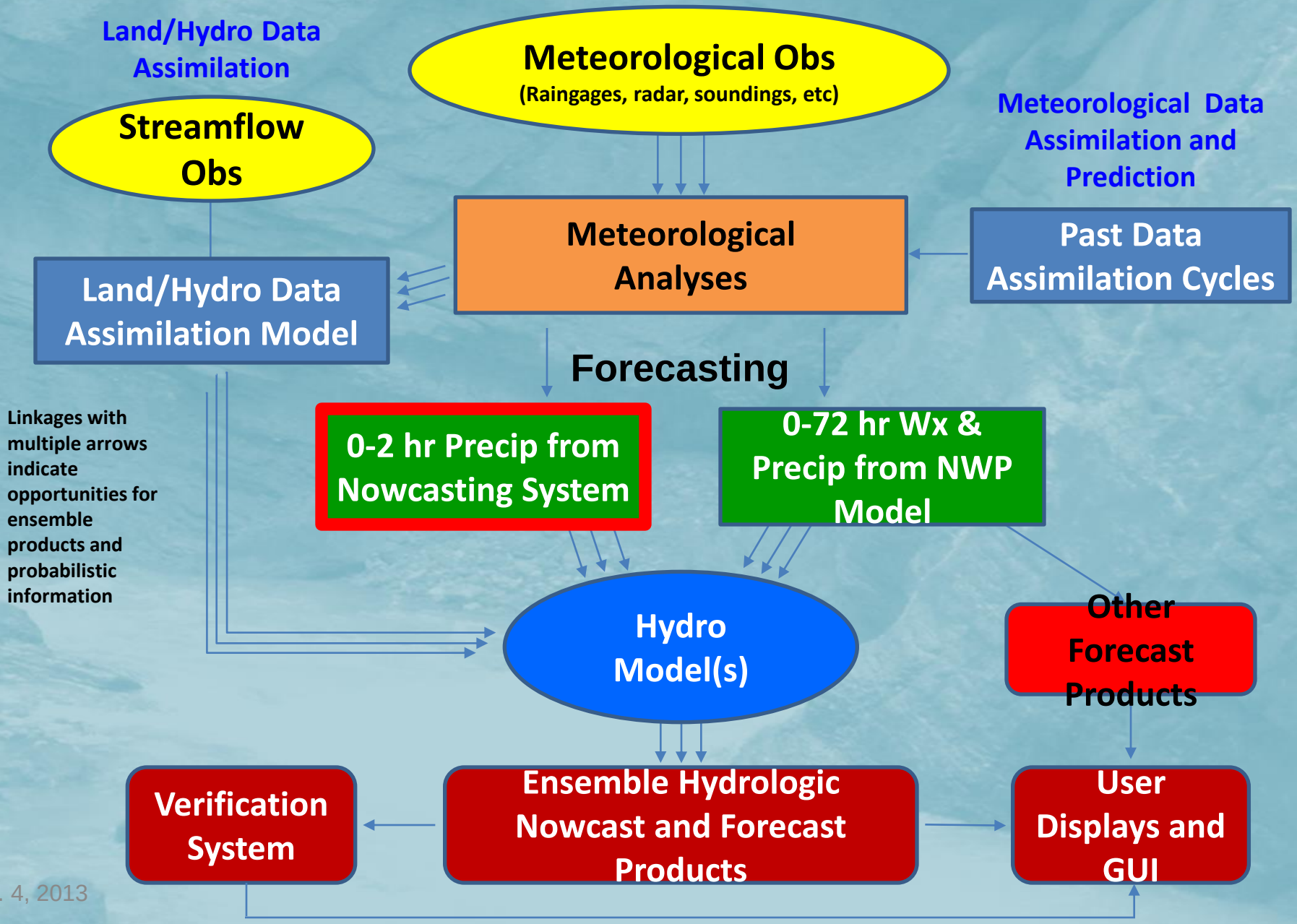
Composite

1320 UTC

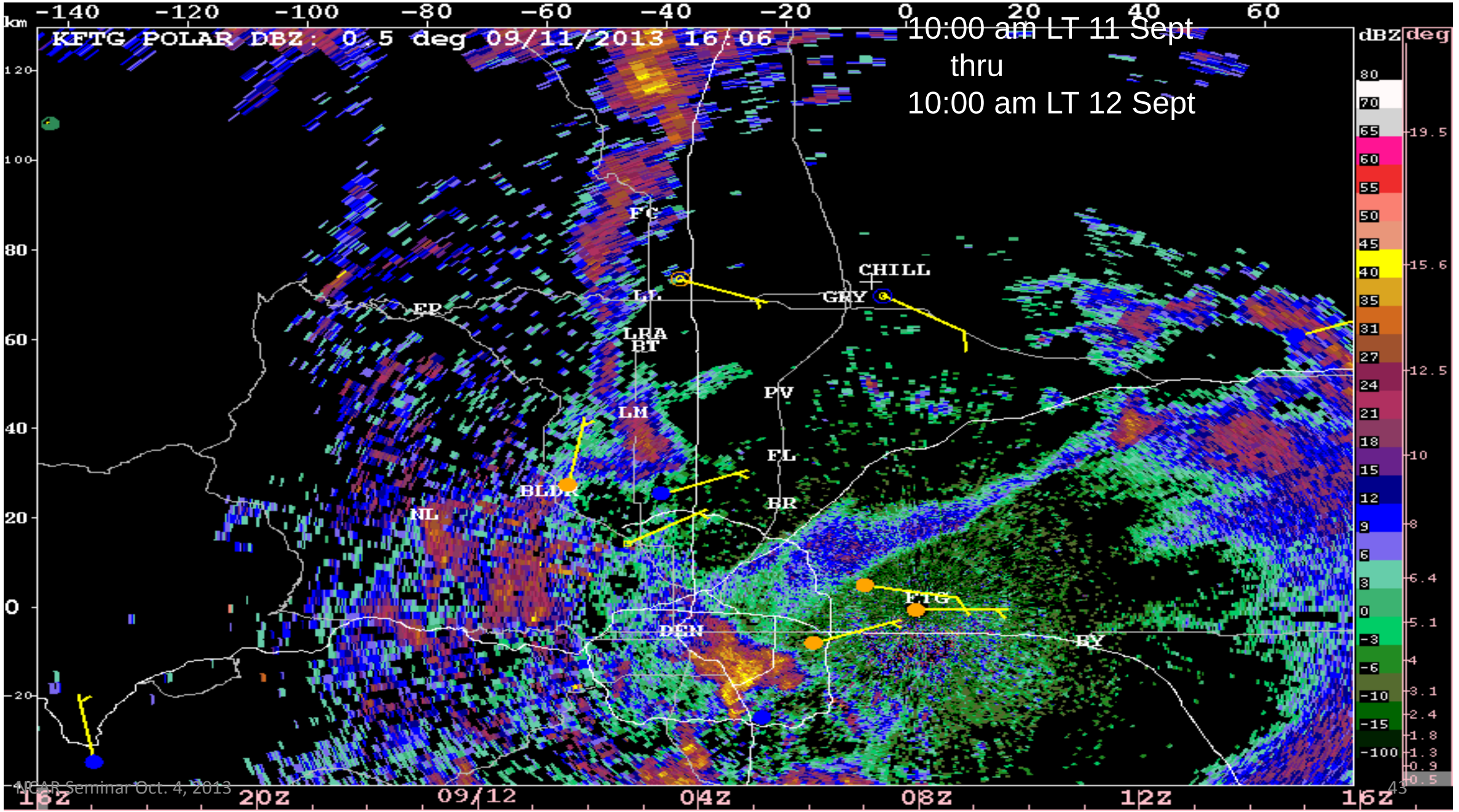
June 21



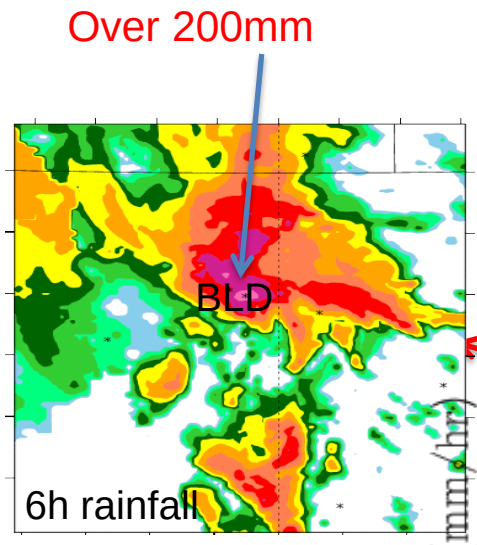
Hydrometeorological Warning System



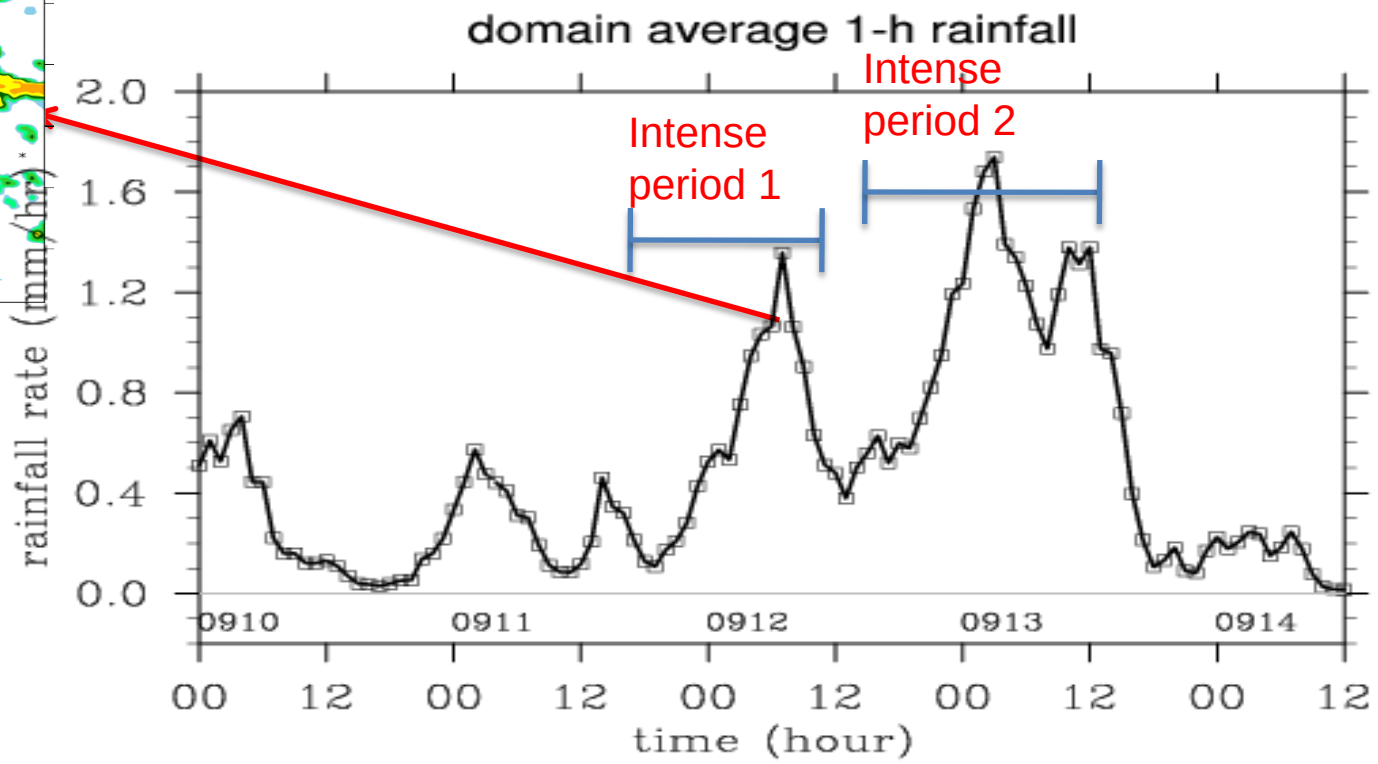
24 hour Loop of Denver KFTG Radar Reflectivity



NWP is an important component of the end-to-end system, but its performance depends on the scale and type of weather systems



Average hourly rainfall from Stage 4 (combined radar and rain gauge precipitation) over the Boulder/Denver area



- Forecasting the heavy precipitation in the intense periods is challenging for NWP models

24h (091200-091300) accumulated rainfall

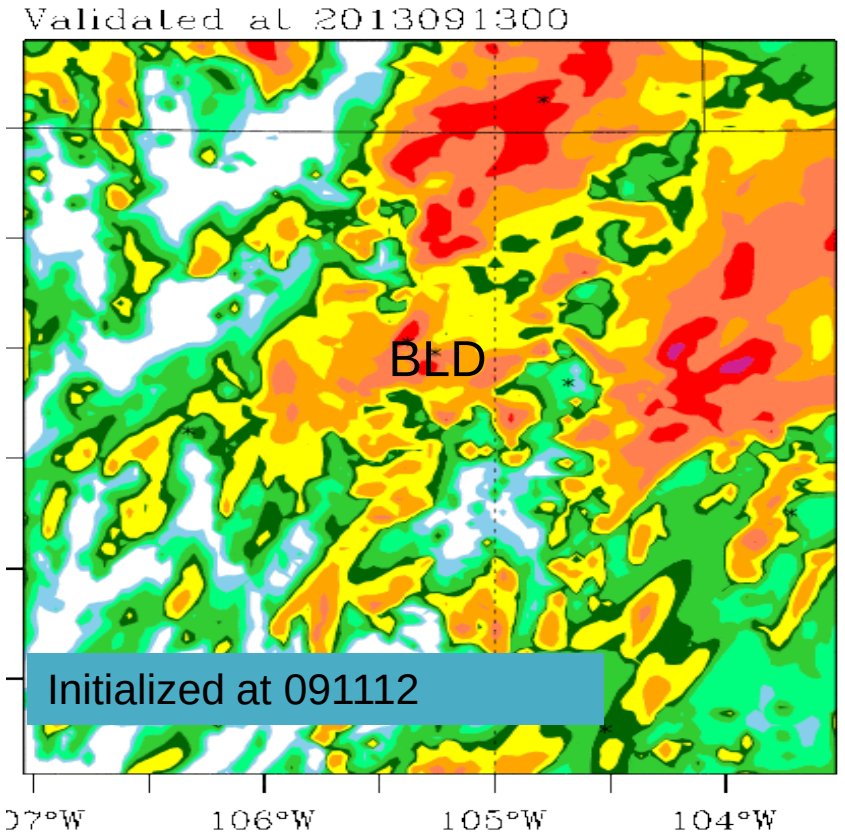
The WRF model rerun

- 15km/3km nested grids
- initialized by GFS analysis at 091112

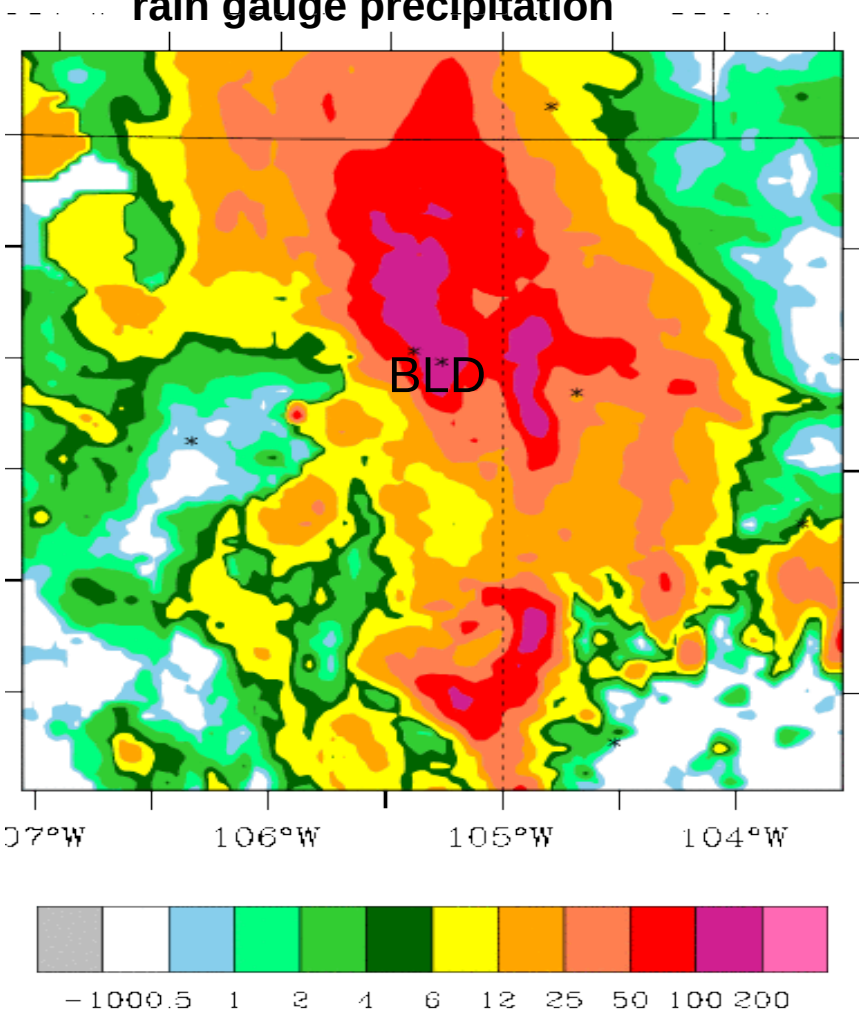
- WRF is able to forecast the large-scale rainfall patterns – useful for guidance 1-2 days ahead

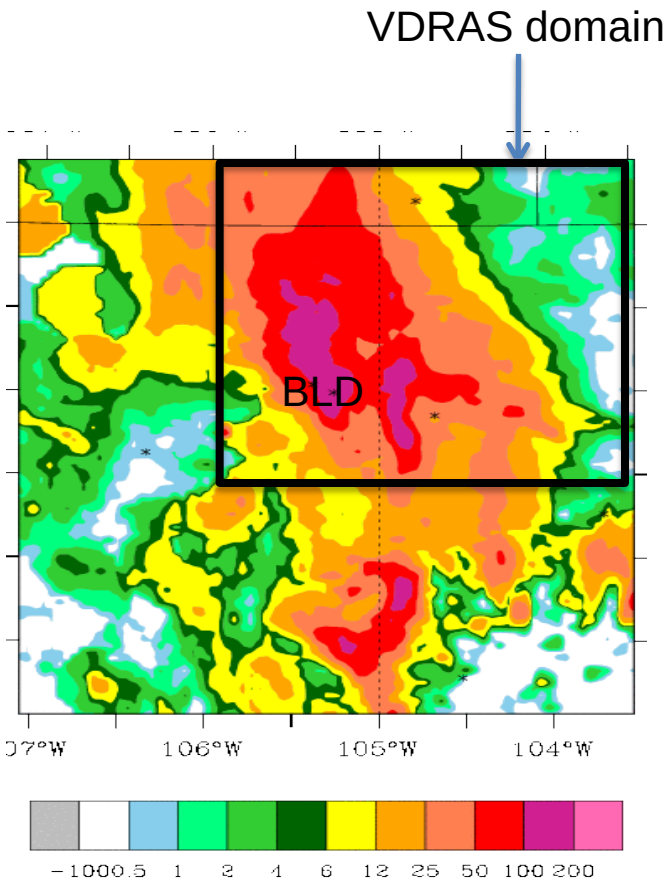
- But it misses small-scale details that are responsible for the heavy rainfall and flash floods

WRF 3km forecast



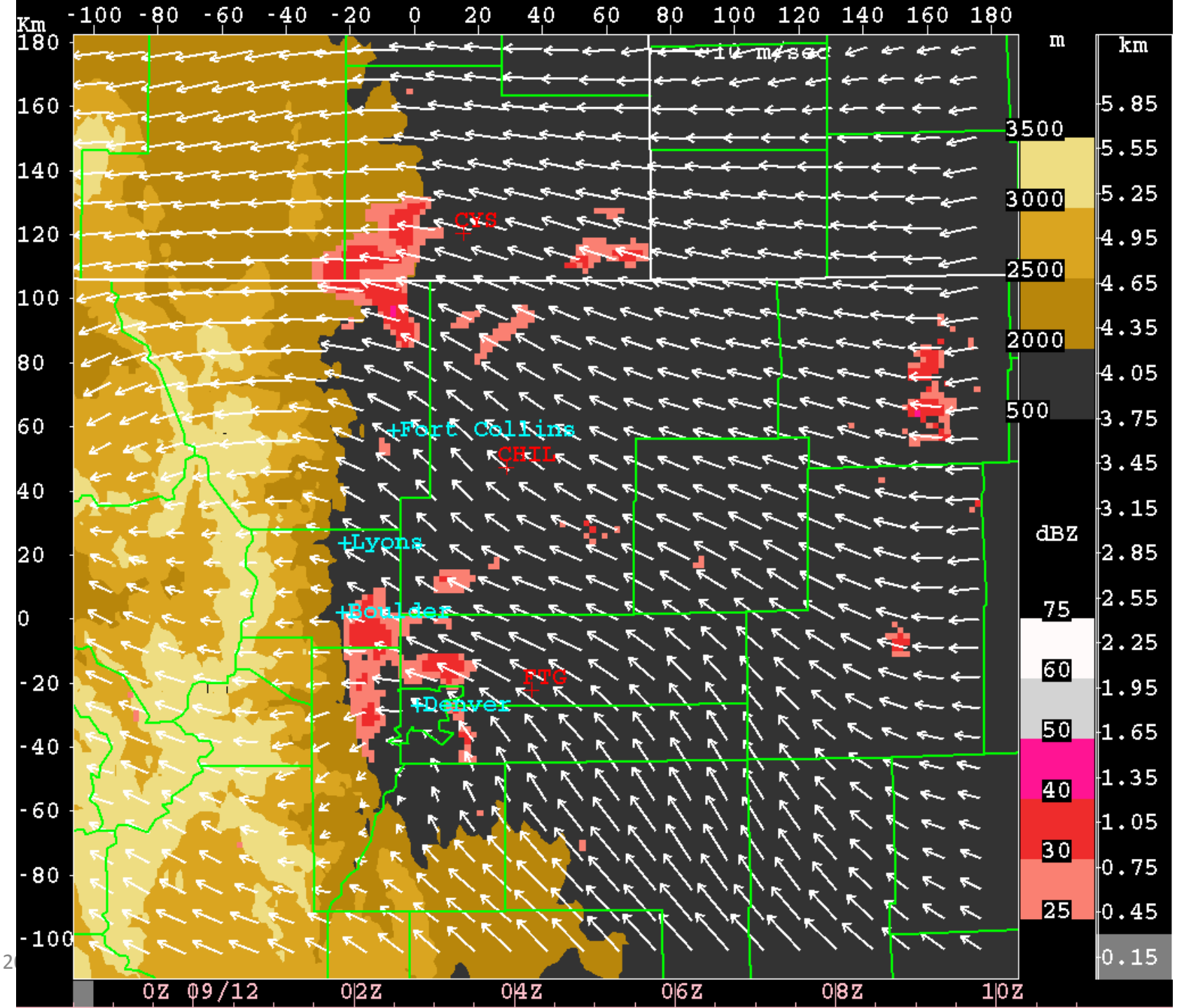
Combined radar and rain gauge precipitation





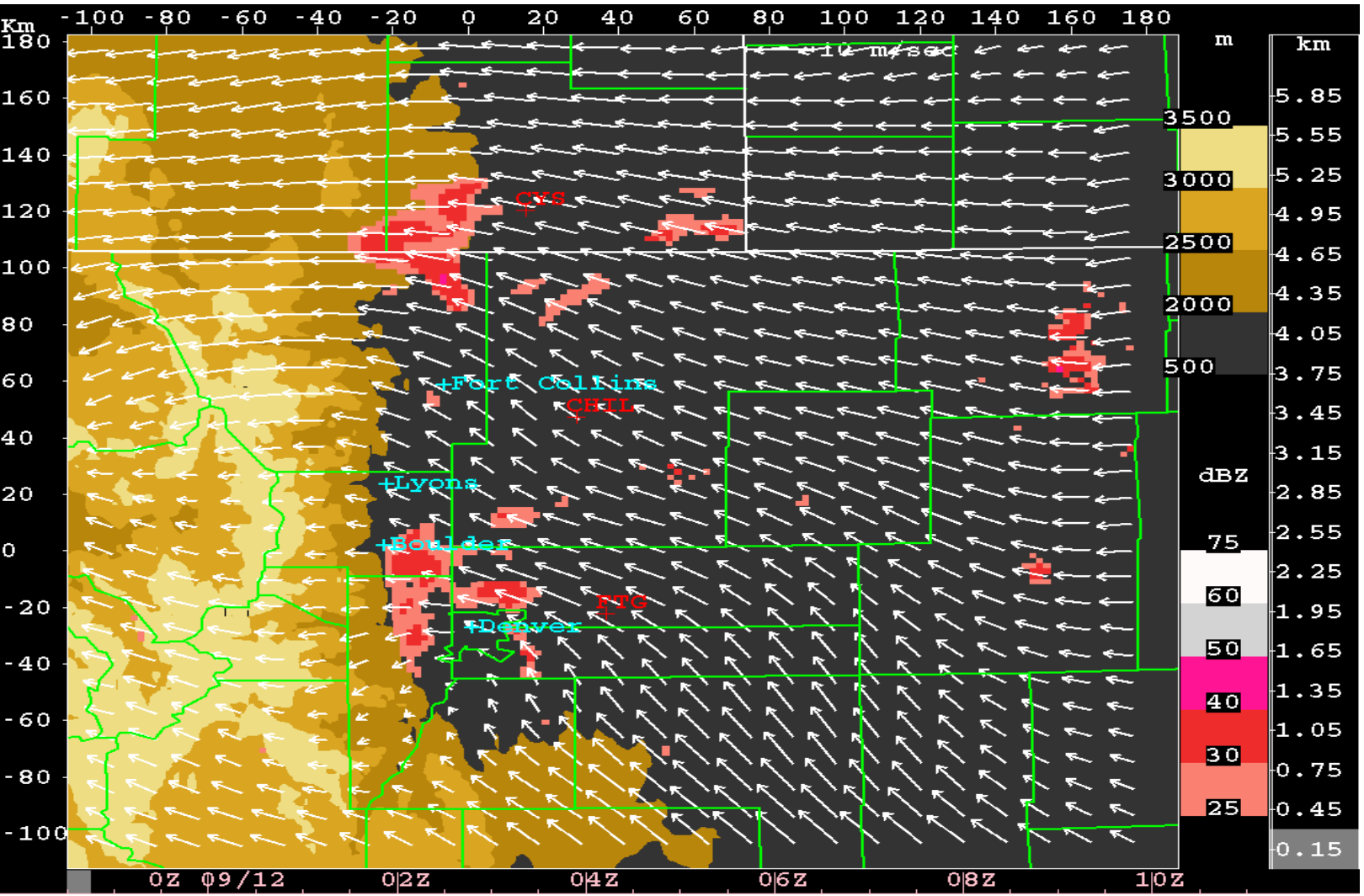
What are the mesoscale-scale features that might have been missed by the NWP models?

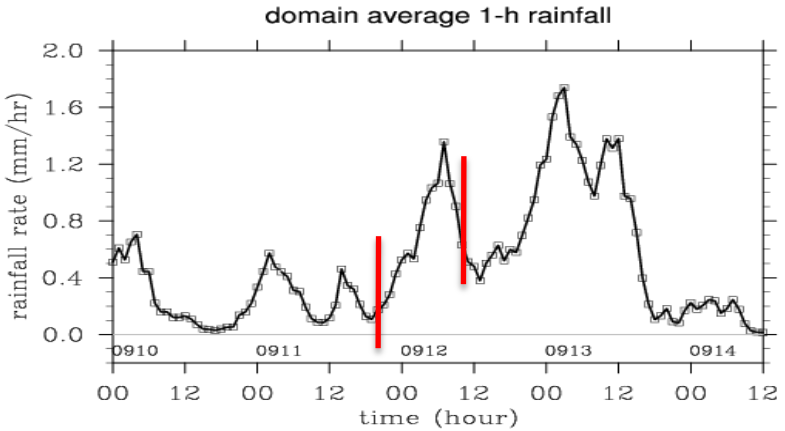
- VDRAS (Variational Doppler Radar Analysis System) was run from 091000 to 091400 with a 2km resolution assimilating KFTG and KCYS radar data.
- VDRAS is a 4DVar system producing high-resolution and high-frequency (15min) analyses based on radar observations
- VDRAS analyses can provide vital information for observation-based nowcasting and model initialization

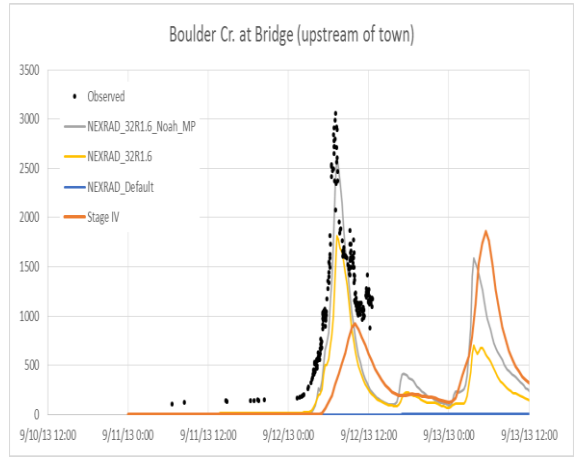

Km
-100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180
180
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
10 m/sec
CYS
Fort Collins
CHIL
Lyons
Boulder
PTG
Denver
m
3500
3000
2500
2000
500
dBZ
75
60
50
40
30
25
km
5.85
5.55
5.25
4.95
4.65
4.35
4.05
3.75
3.45
3.15
2.85
2.55
2.25
1.95
1.65
1.35
1.05
0.75
0.45
0.15
0Z 09/12
02Z
04Z
06Z
08Z
10Z

VDRAS wind at z=150m overlaid with reflectivity (>25 dBZ)

4:30pm, 9/11 – 2:30am, 9/12, intense period 1

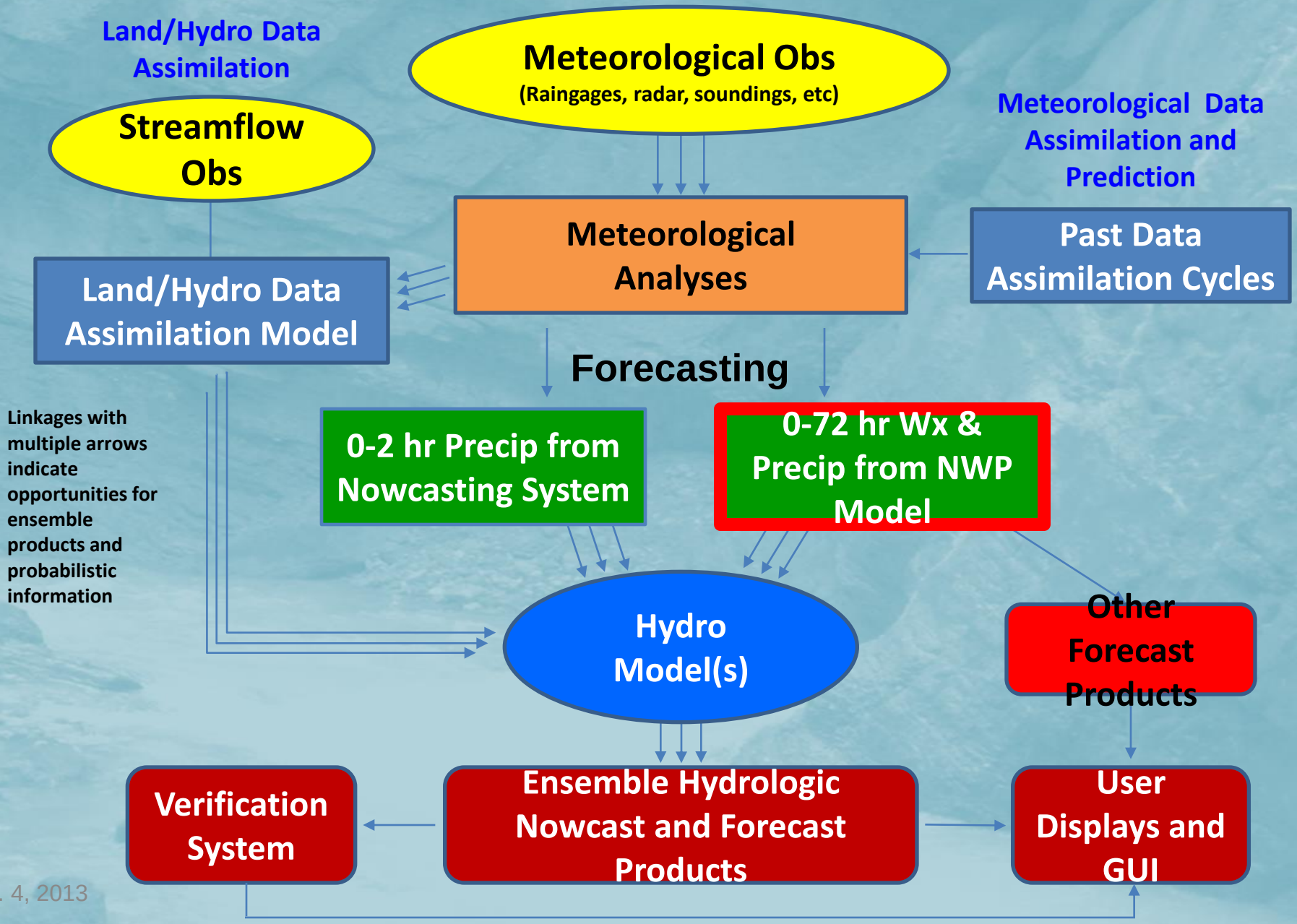




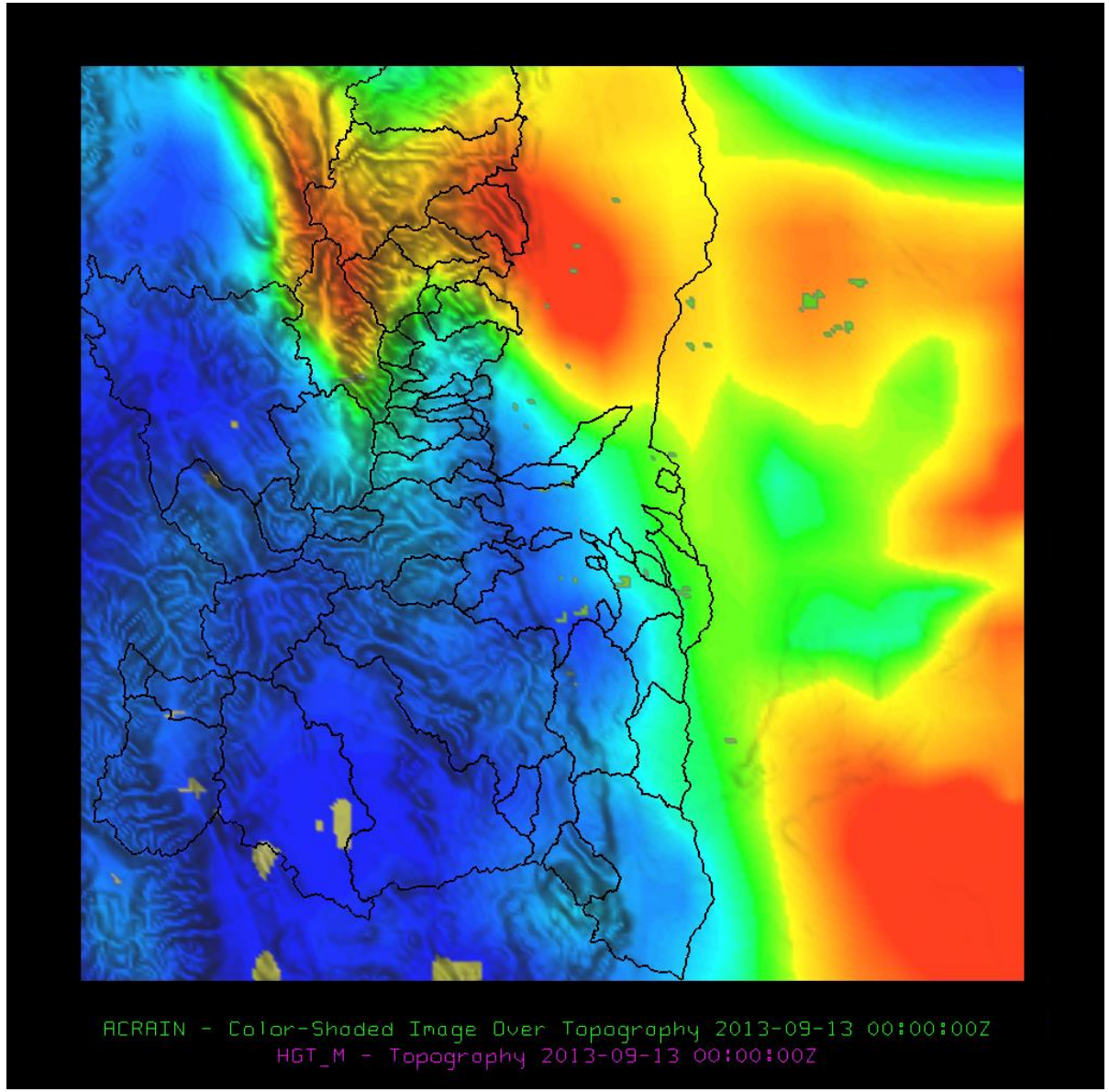


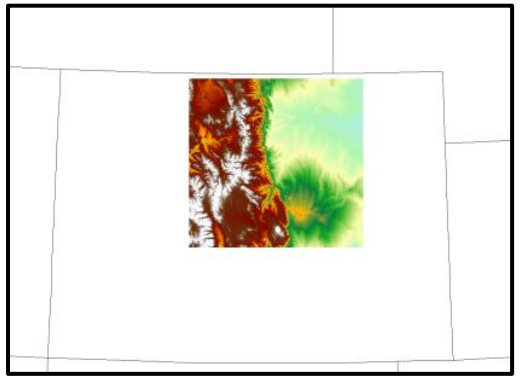
Few hour delay in the Boulder flood wave after the increase of precipitation

Hydrometeorological Warning System



The model forecast dilemma:



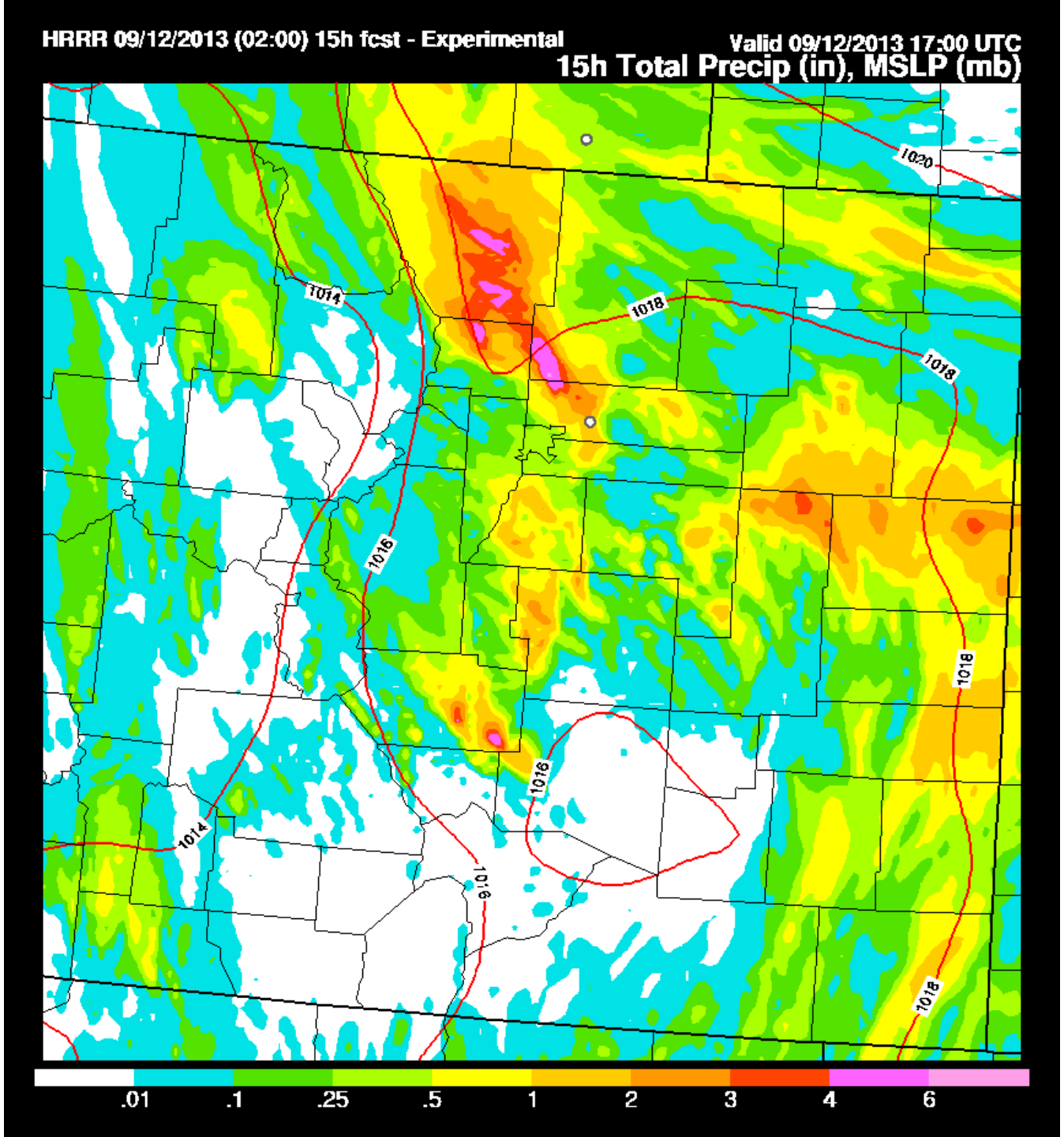


24-hr Accumulated rainfall from the NOAA/NCEP North American Model

12 km grid spacing

Sep 12 6pm

millimeters (0-2 inches)



15-hr Accumulated rainfall from the HRRR model

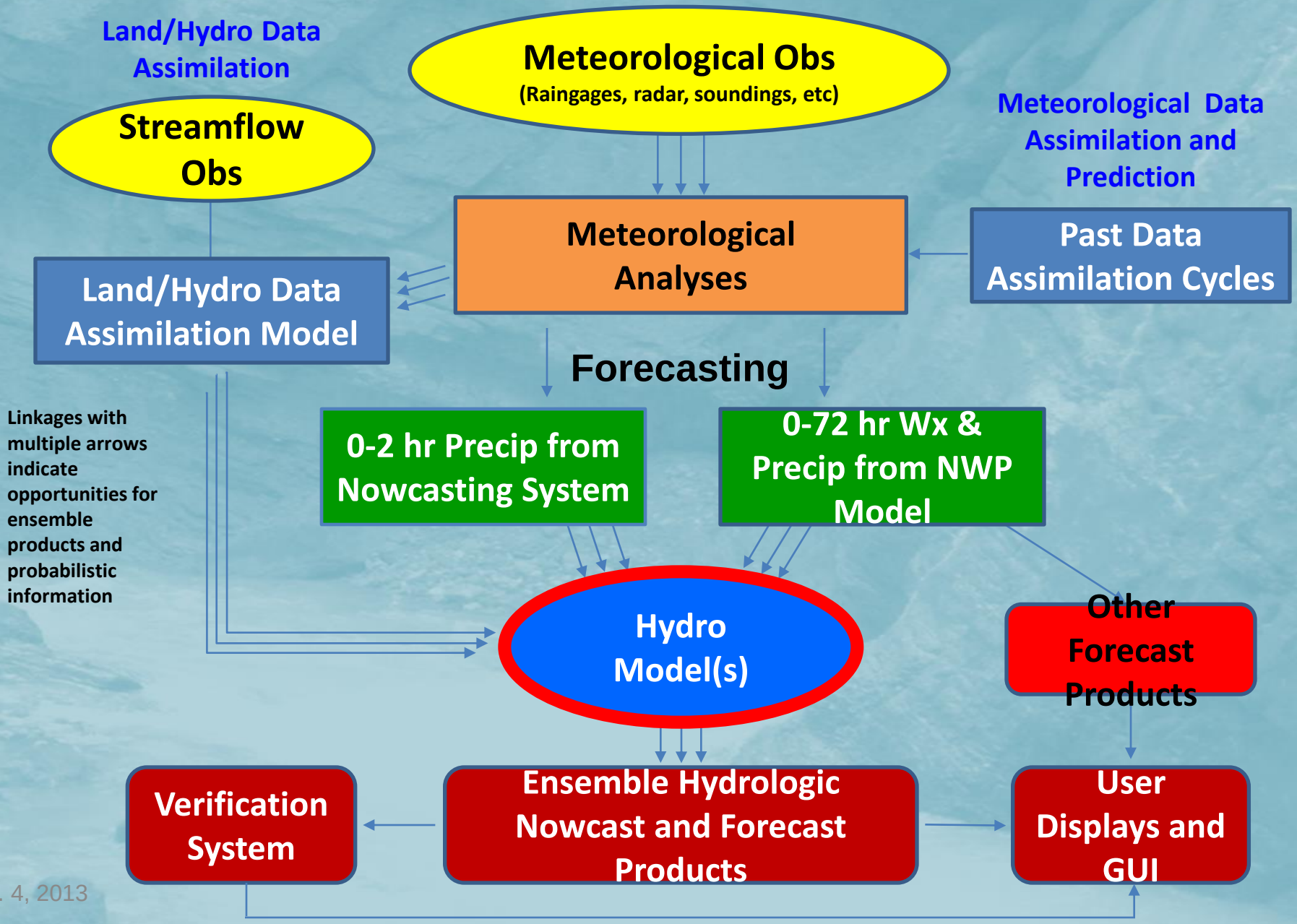
Initialization:

Sep 11 8pm (LT)

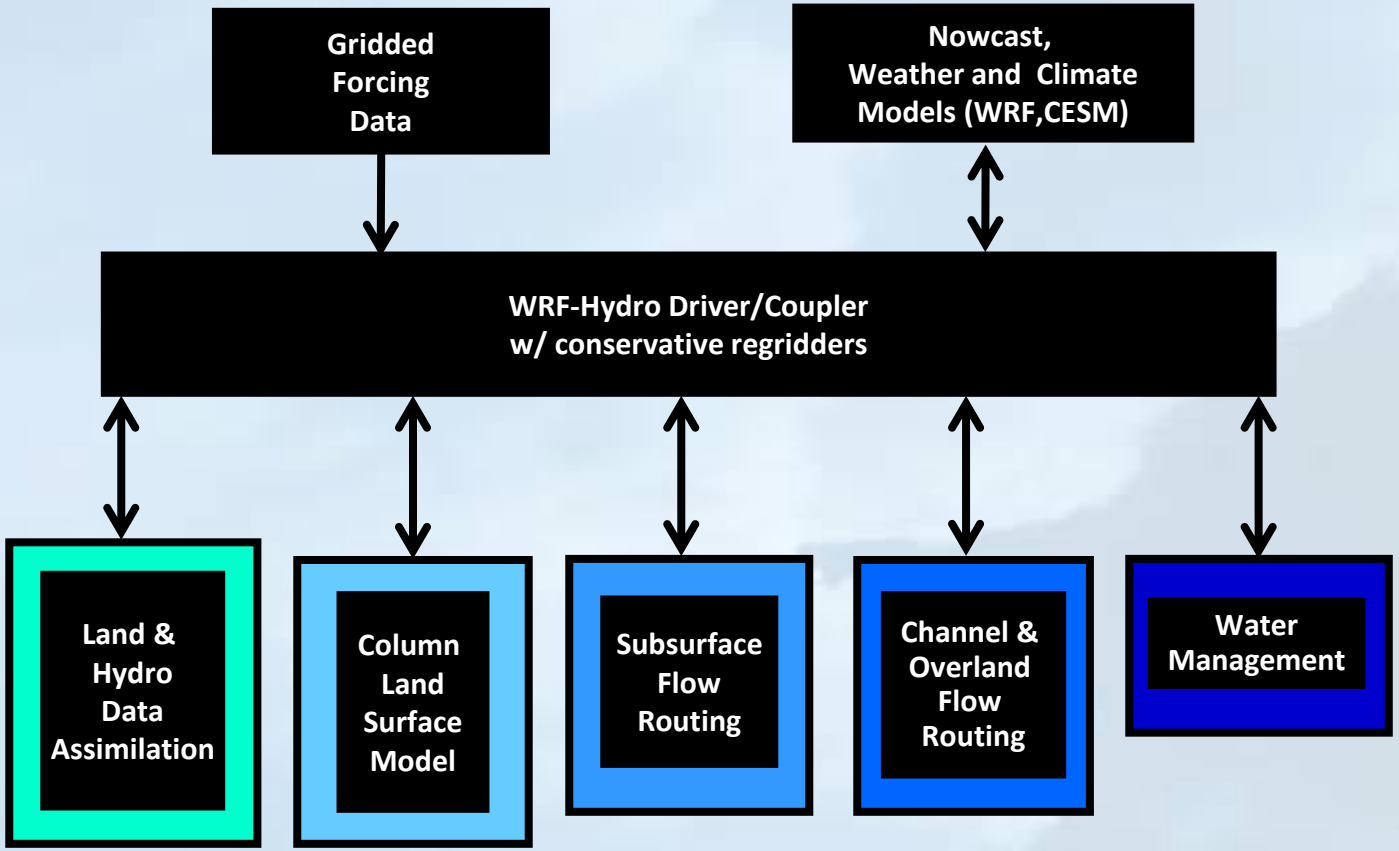
Rainfall in inches

Maps created by Kelly Mahoney, NOAA/ESRL

Hydrometeorological Warning System



WRF-Hydro Model

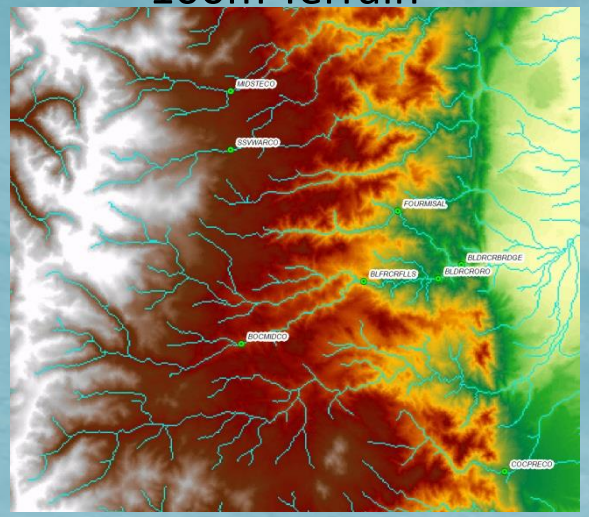


http://www.ral.ucar.edu/projects/wrf_hydro/

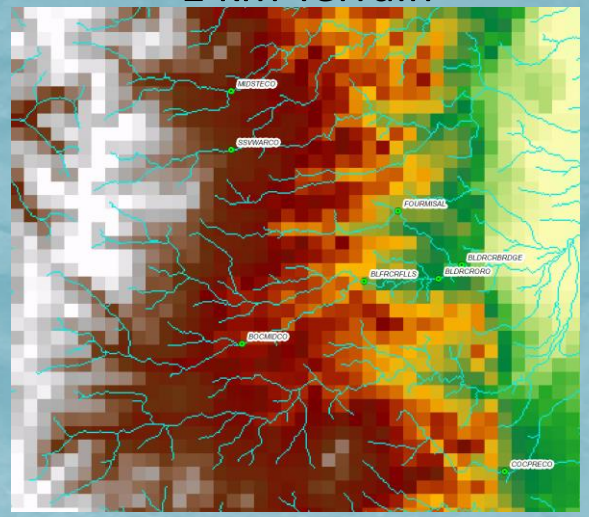
WRF-Hydro v1.0 Physics Components:

- Multi-scale aggregation/disaggregation:

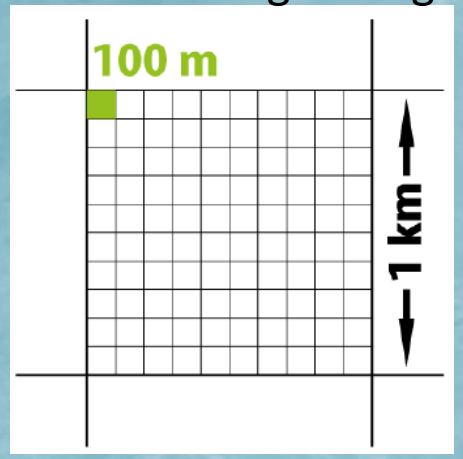
100m Terrain

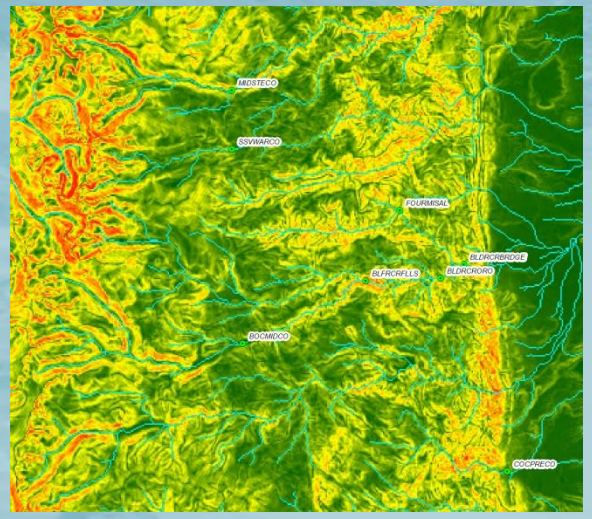


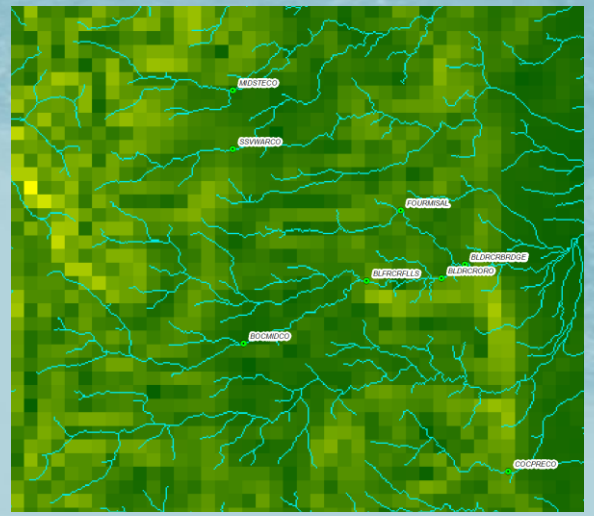
1 km Terrain



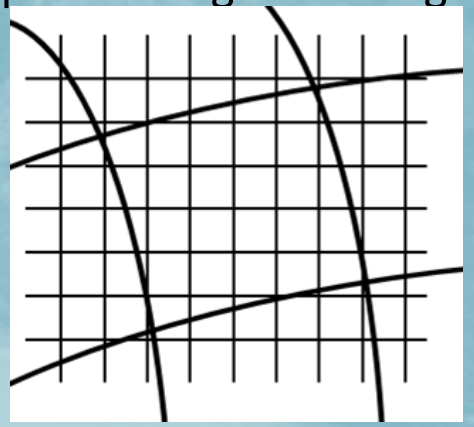
Current 'Regridding'







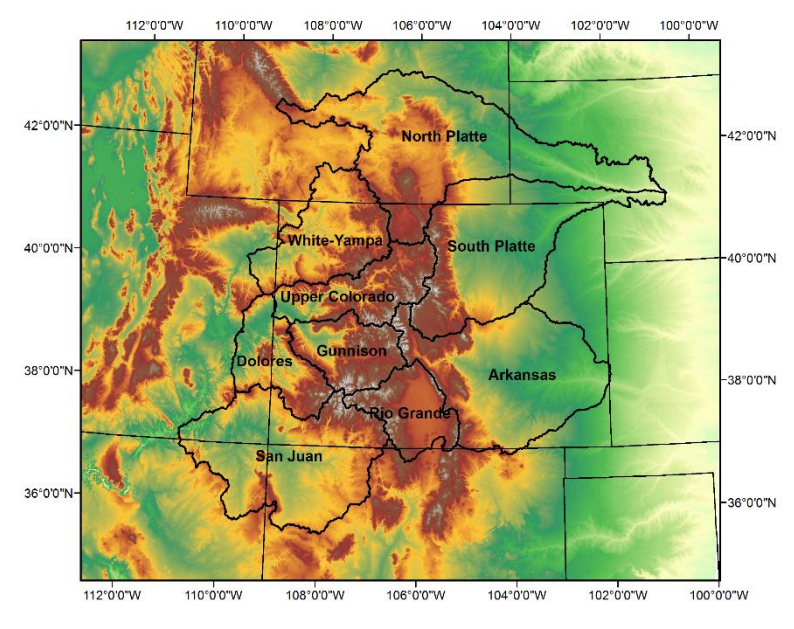
Implementing ESMF Regridders



Terrain slope (0-45

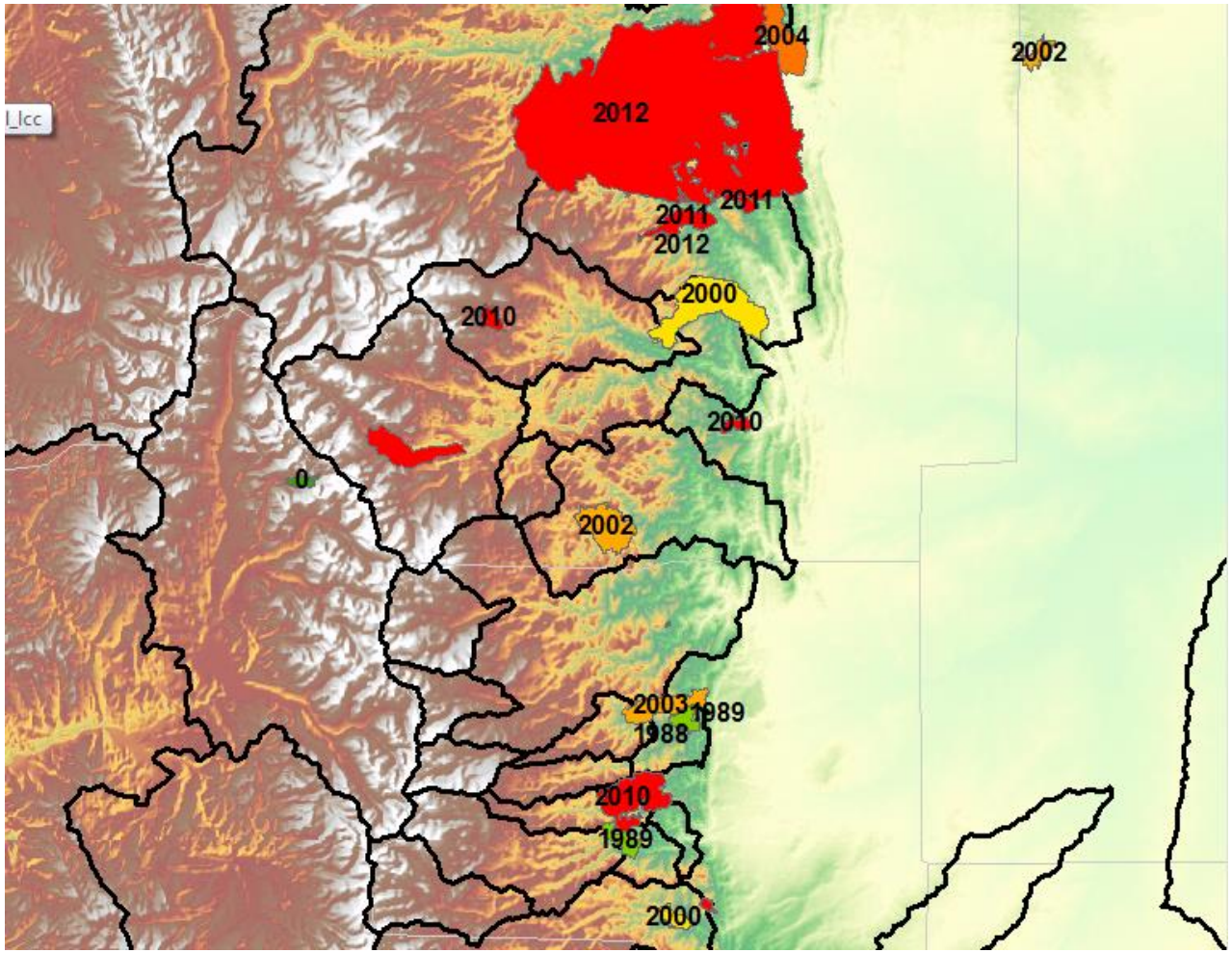
The National Center for Atmospheric Research

Multi-scale modeling and visualization:

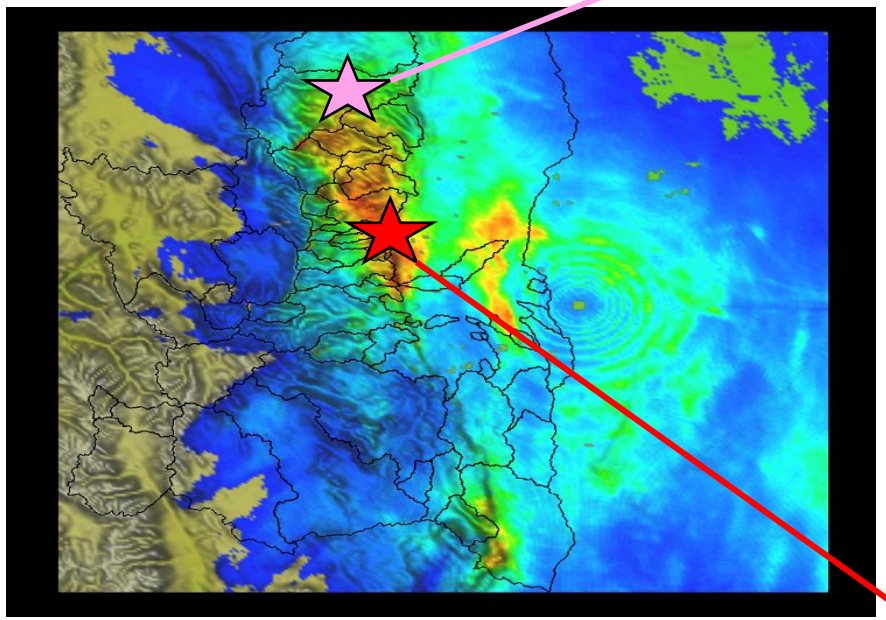


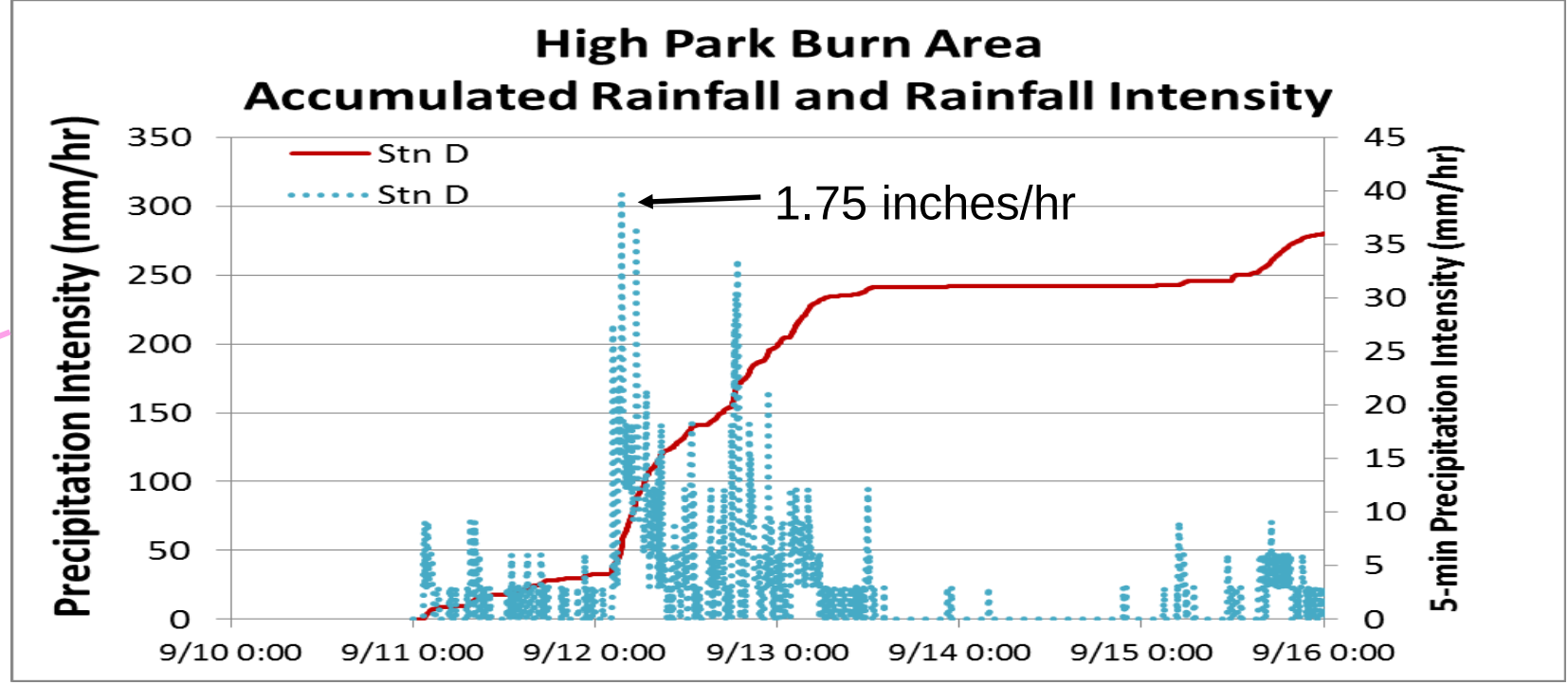
Burned Landscape Representation:

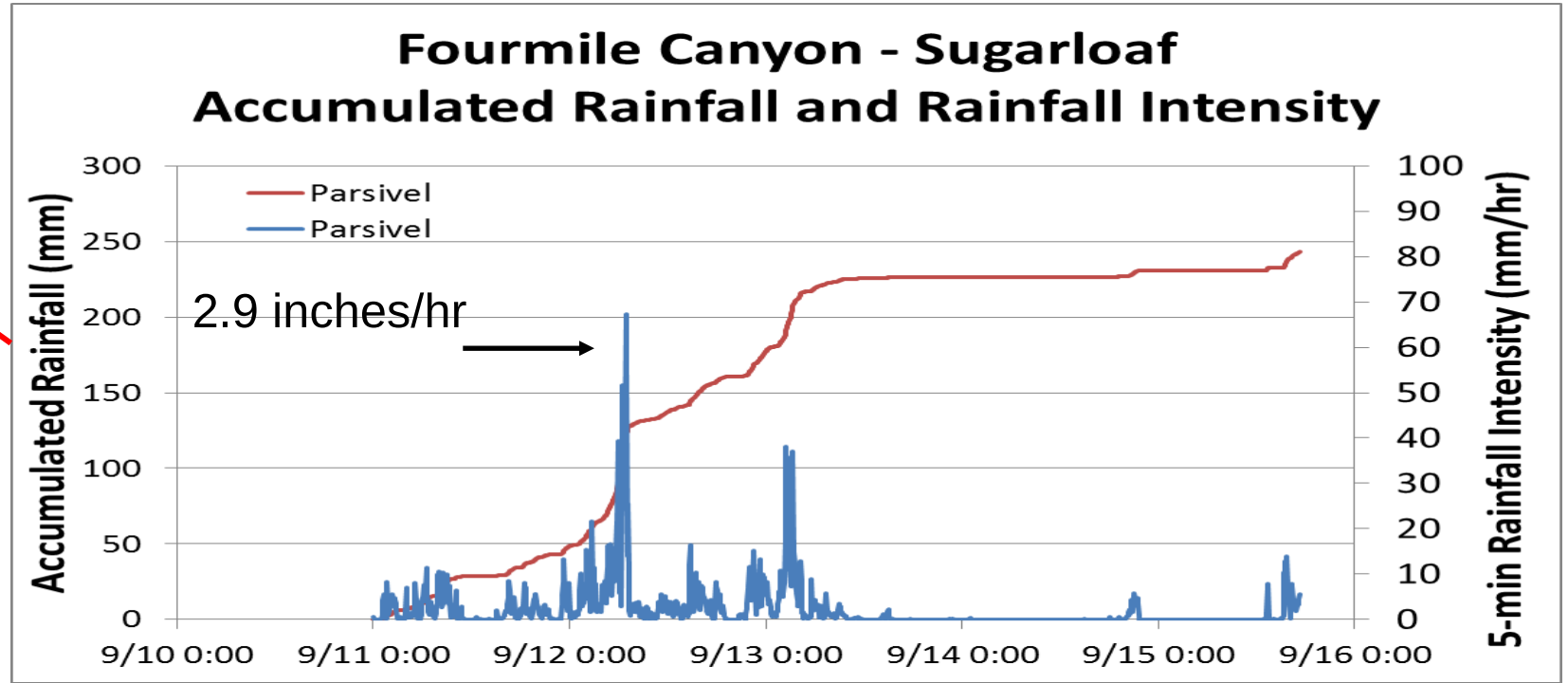
- Modifying land surface conditions based on past fire activity



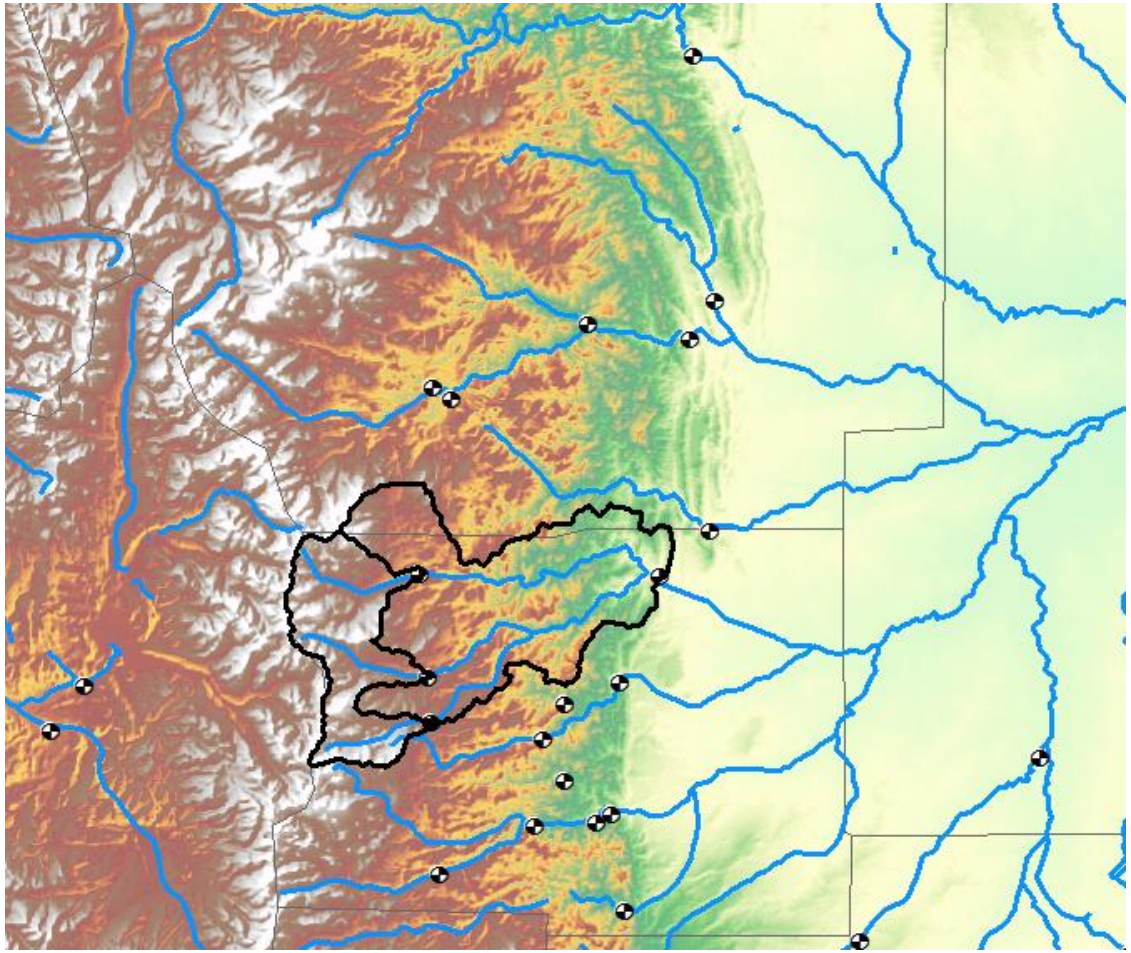
Peak Rain Rates in **Recent Burn** Areas







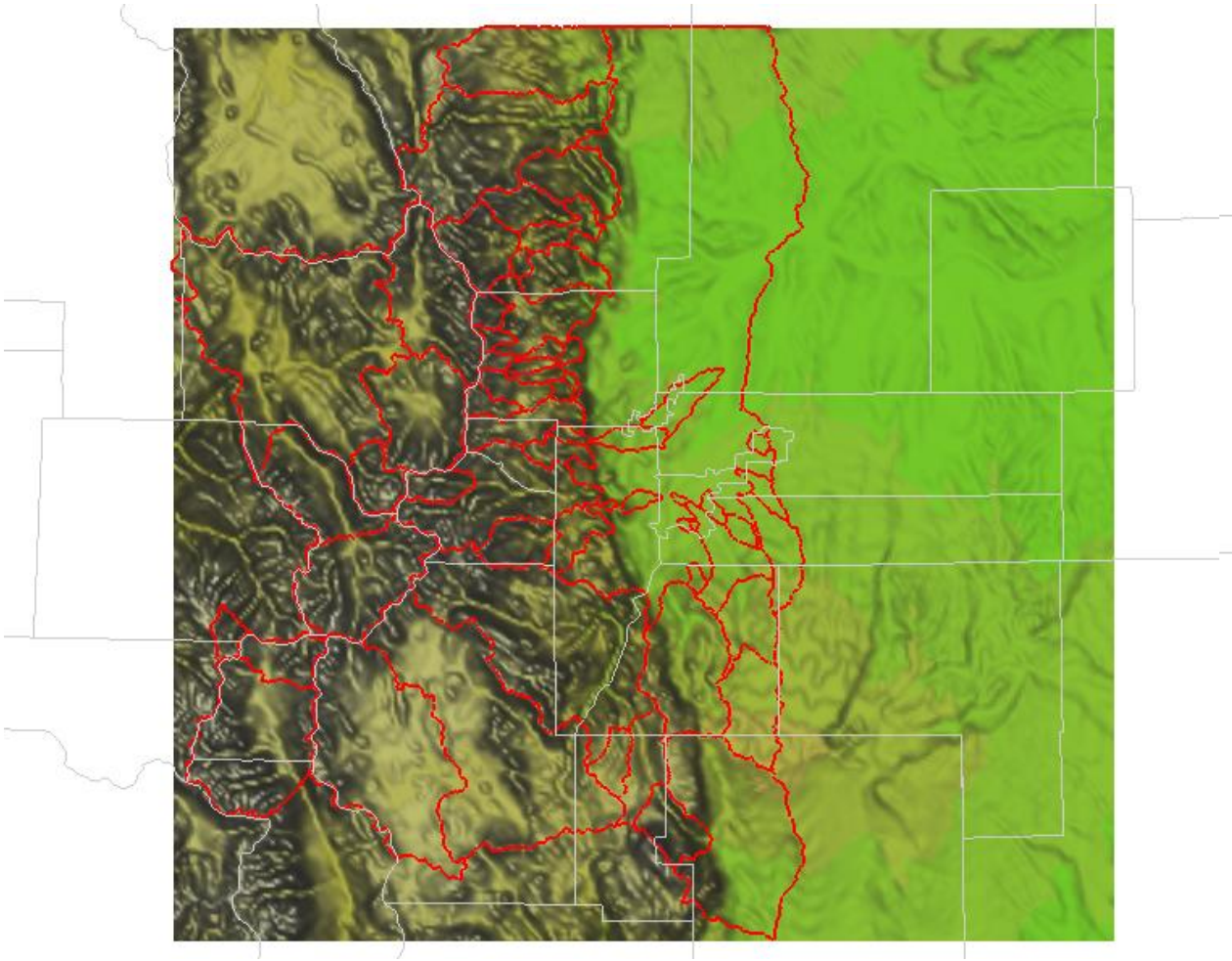
Hydrological Predictions:



NWS hydrologists had to set up more than 10 different instances of a ‘site specific’ model as the event was evolving

More efficient, continuous, spatially-resolving tools could significantly help with maintaining an accurate operating picture

Hydrological Predictions:

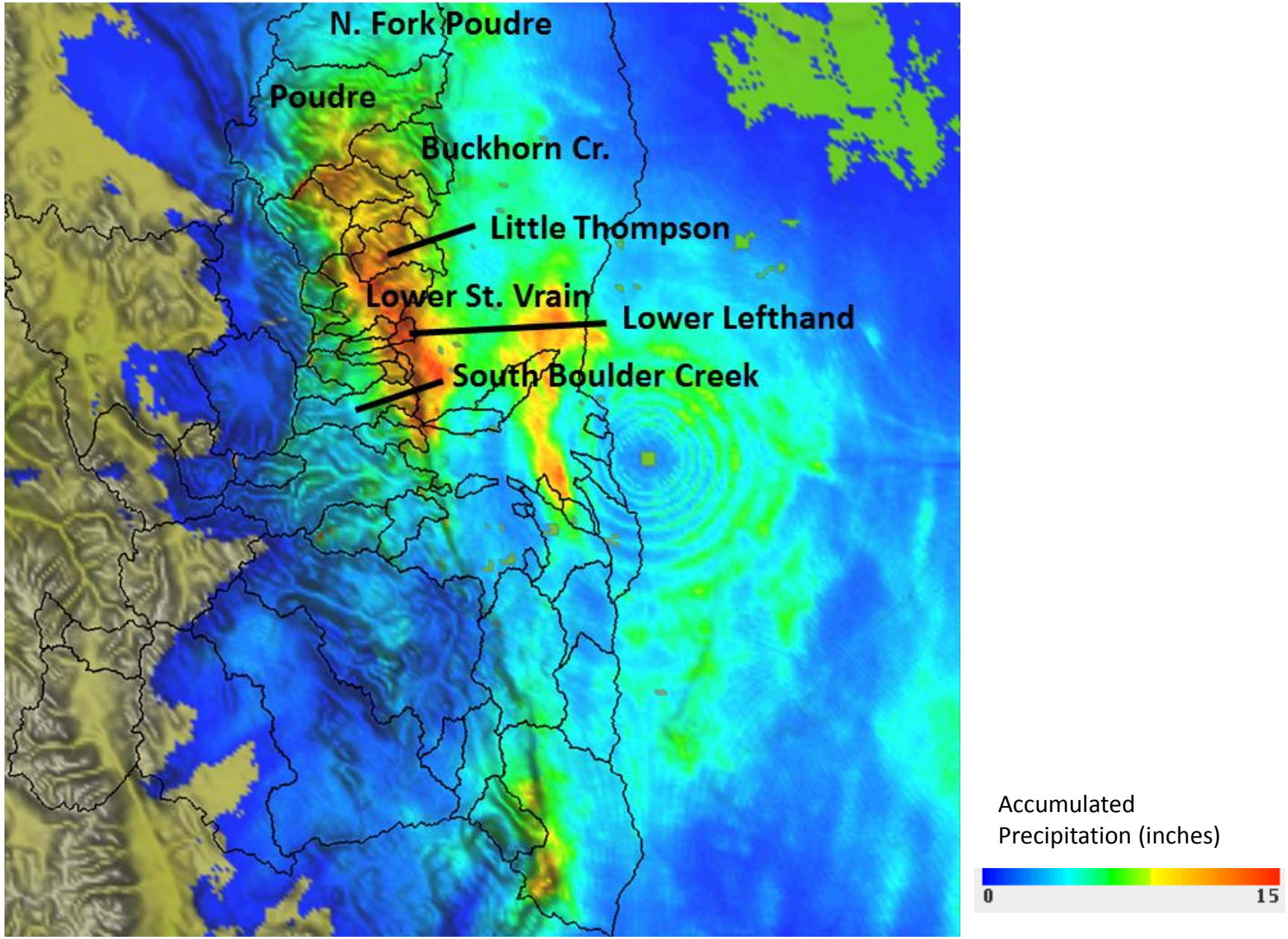


Front Range Operational Hydrological Modeling Domain (268x260 km)

Forcing applied at 1 km
Routing performed at 100m

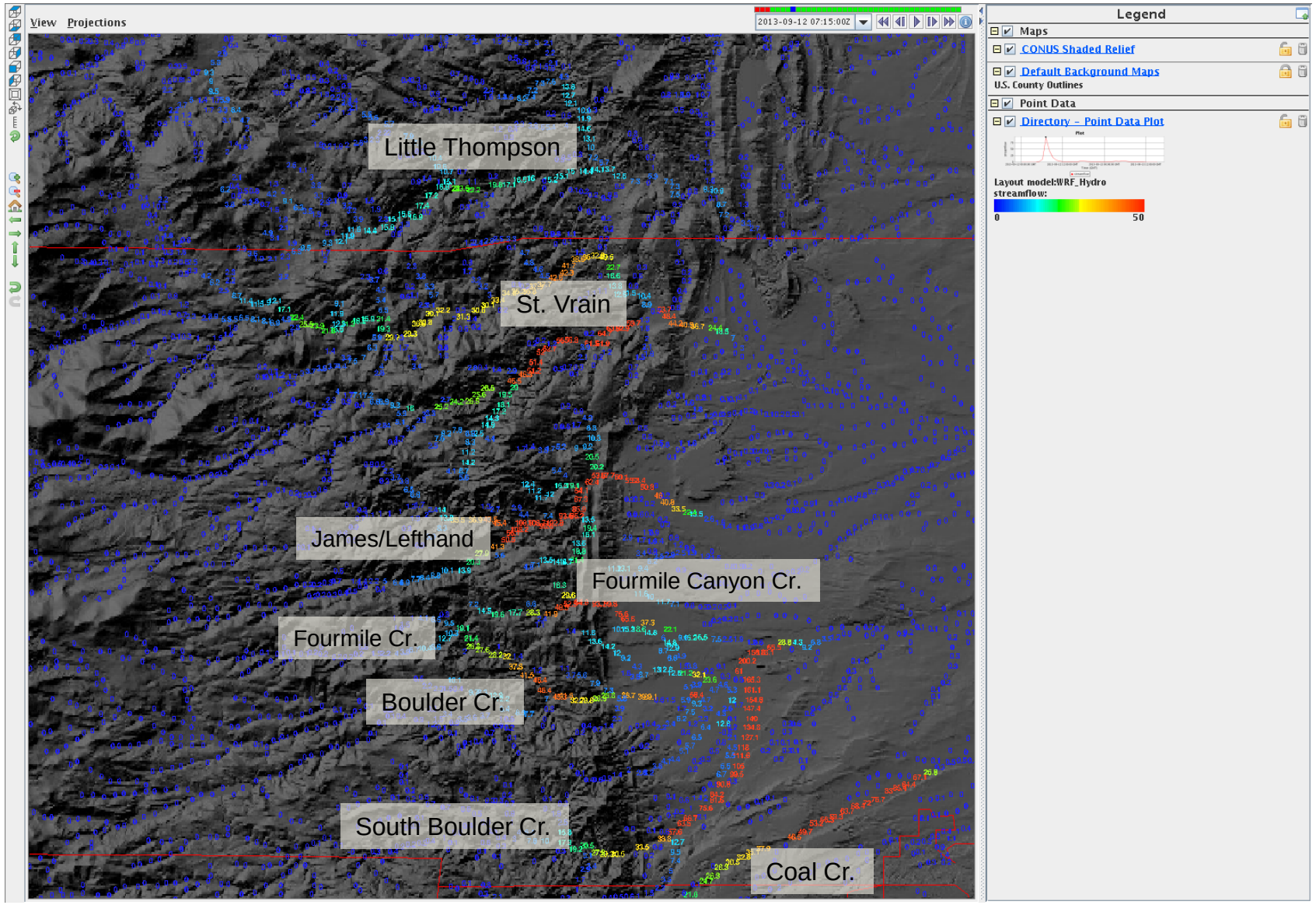
Initial channel contributing area = 1 sq km

Flows are analyzed at 61 gauging stations


N. Fork Poudre
Poudre
Buckhorn Cr.
Little Thompson
Lower St. Vrain
Lower Lefthand
South Boulder Creek
Accumulated
Precipitation (inches)
0
15

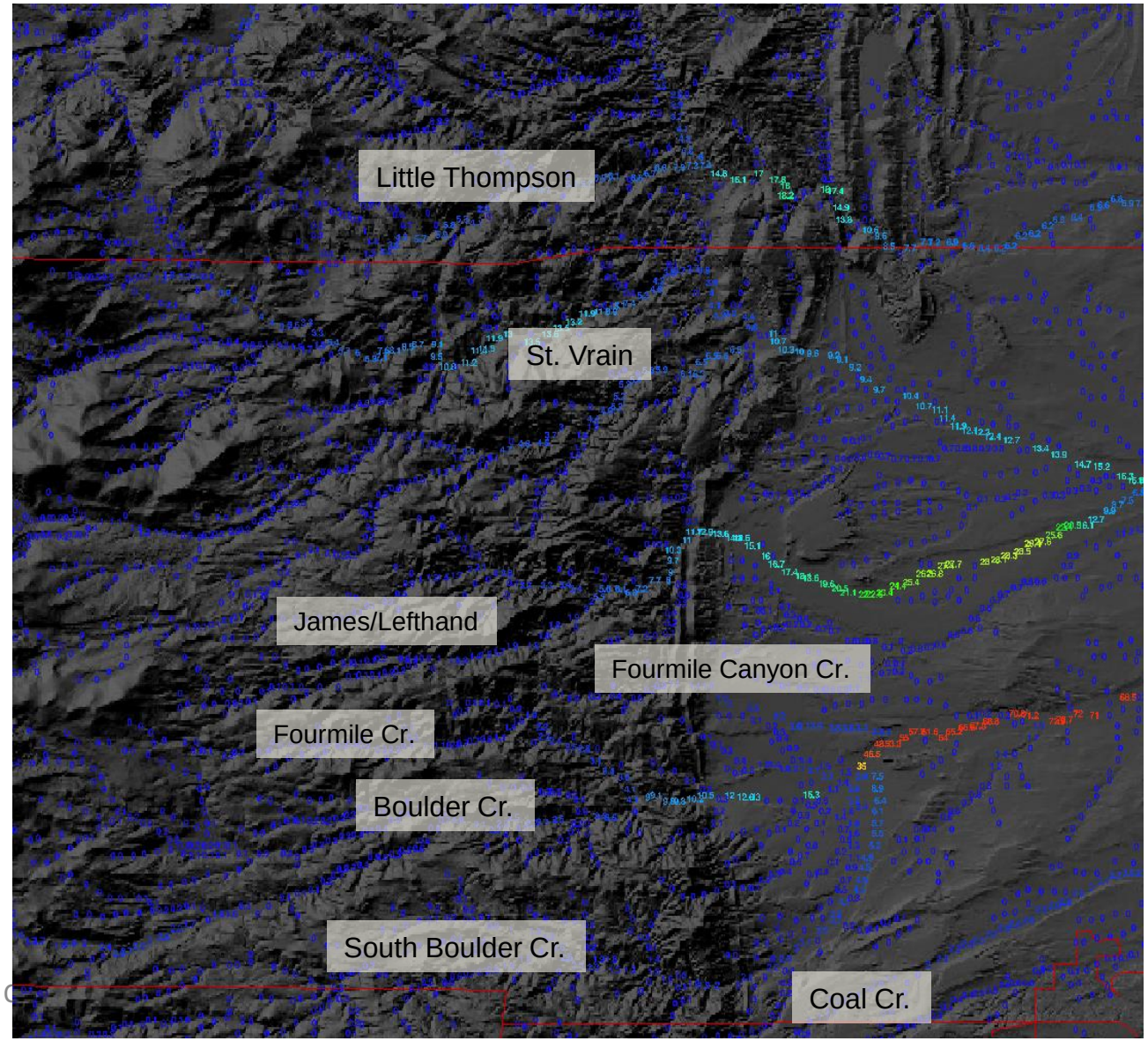
WRF-Hydro SIMULATED streamflow from NEXRAD (32R^1.65)

Valid: Sep 12 1:15 a.m. LT



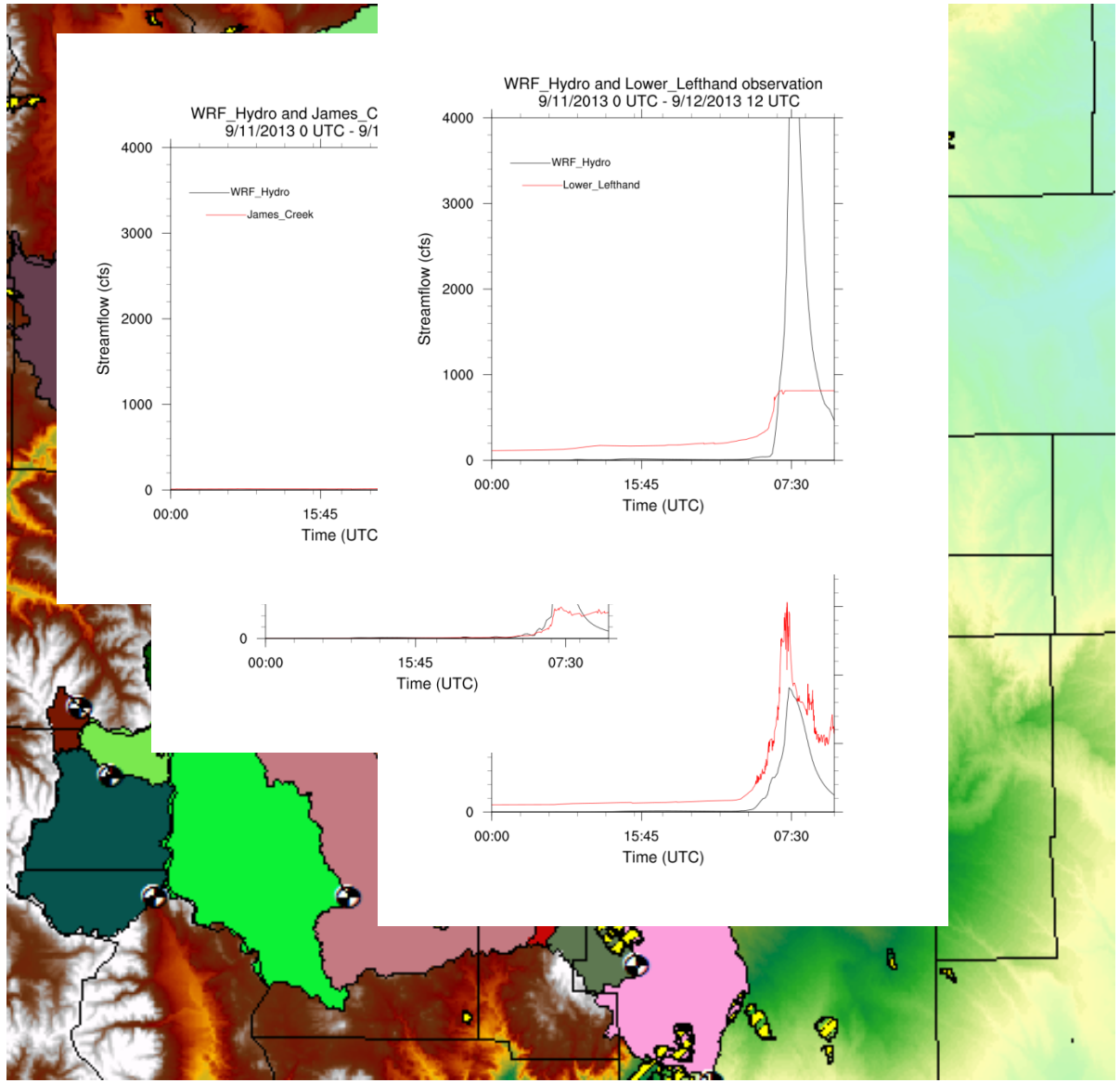
WRF-Hydro SIMULATED streamflow from NEXRAD (32R^1.65)

cms



Streamflow animation

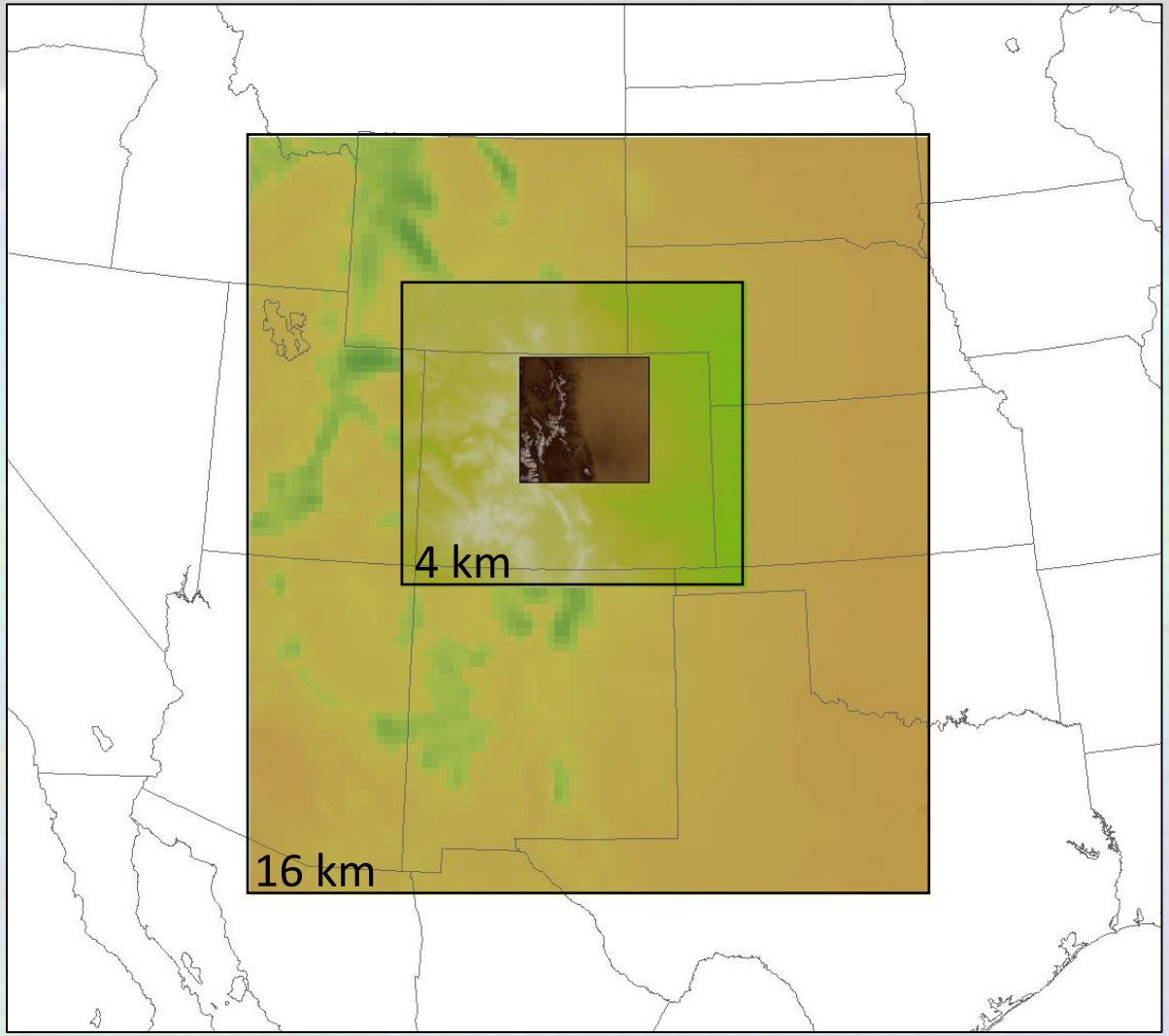
Validating Storm flow Simulations



Fully-coupled Hydrometeorological Prediction

- WRF v3.5:
  - 16, 4, 1 km nests
  - Thompson MP
  - Noah LSM w/ WRF-Hydro routing modules
  - Initialized 00z Sep. 11
  - 48 hour forecast
  - NOAA/NCEP GFS boundaries and initial conditions

- WRF-Hydro configuration:
  - 100m grid (active on 1km WRF grid)
  - Diff. wave overland and channel
  - Gridded Boussinesq GW
  - Simple ‘pass-through’ baseflow
  - Noah LSM (coupled)
  - Noah MP (uncoupled)



Forecasted accumulated rainfall:

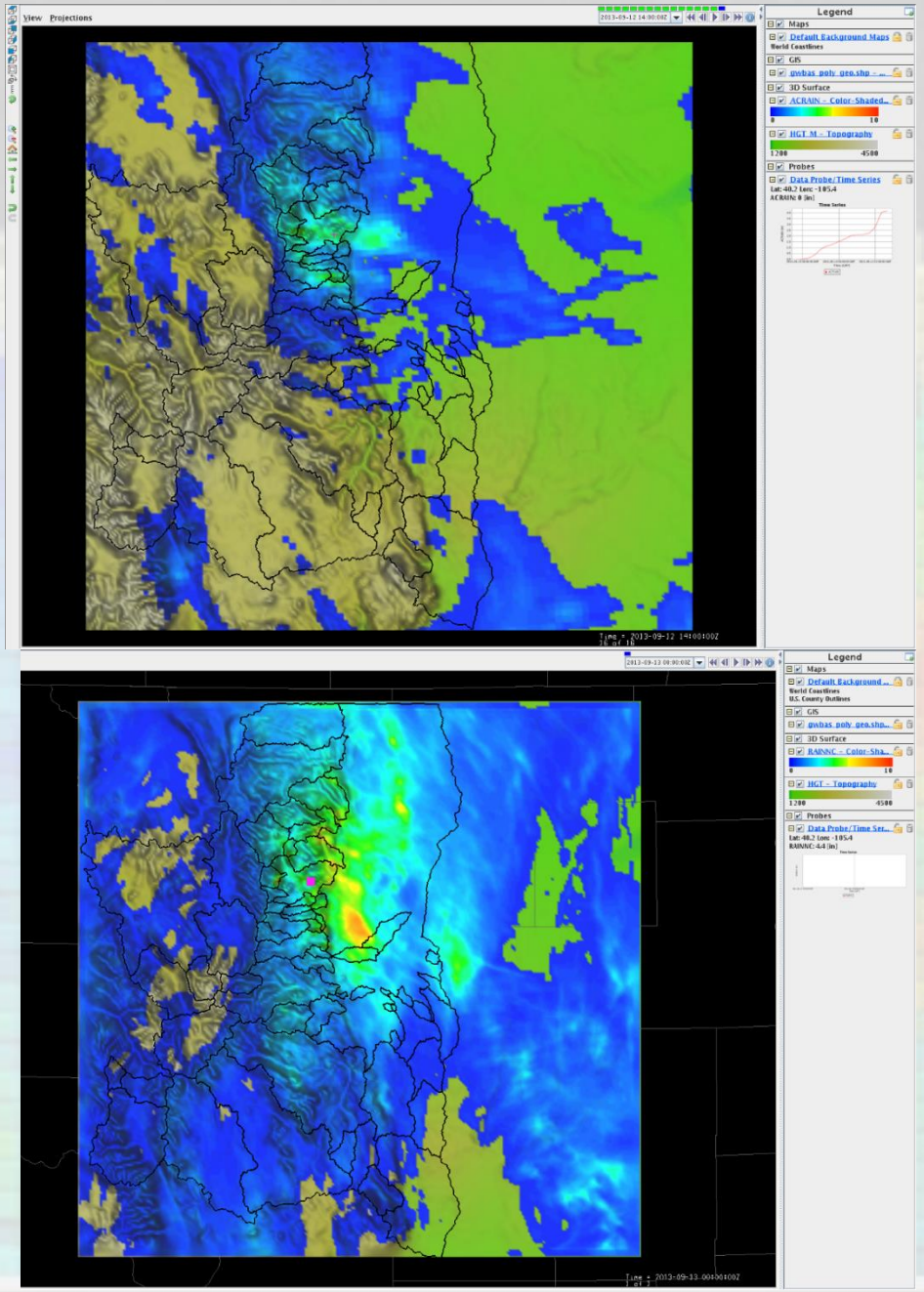
Uncoupled NOAA-ESRL HRRR:
15-hr Initialized:
9/11 23z (1700 LT)

Coupled WRF/WRF-Hydro model

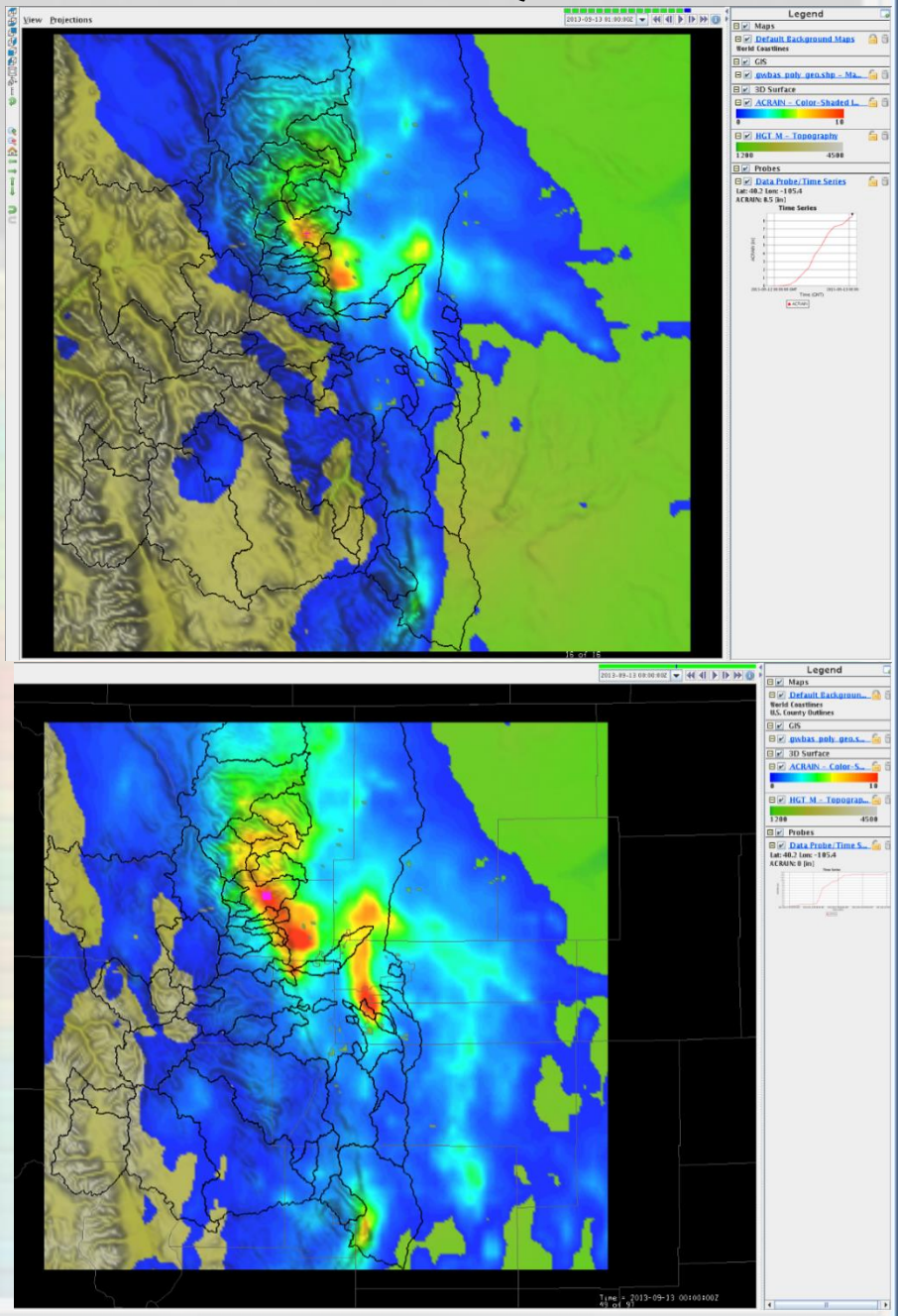
Initialization:
9/11 00z

Valid: 9/12 07z

Forecast



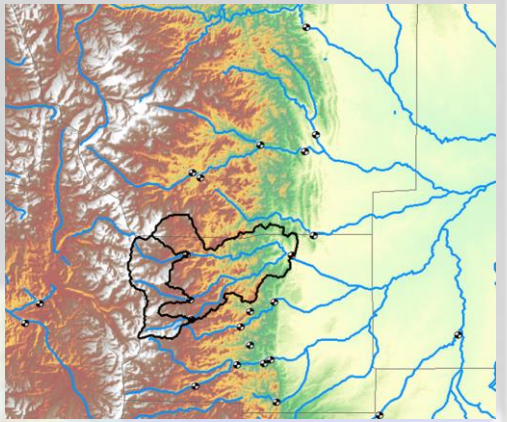
NEXRAD QPE

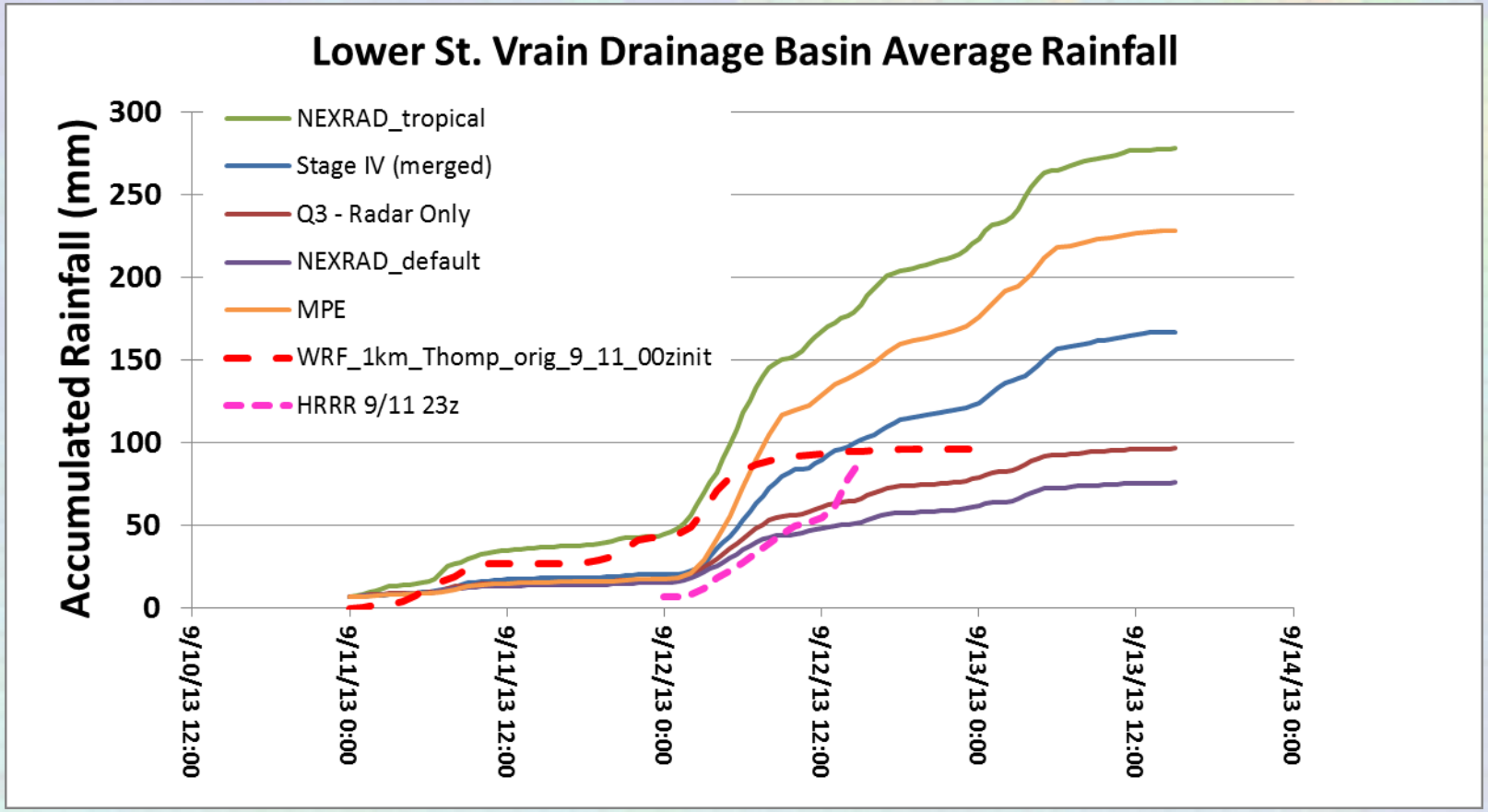


Forecasted accumulated rainfall coupled WRF/WRF-Hydro model

Initialization: 9/11 00z

Valid: 9/12 07z



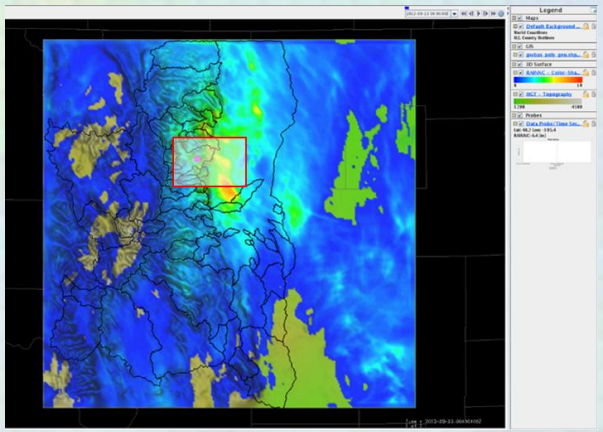


WRF model configuration:
3 domain 16, 4, 1 km
GFS init&LBC
Thompson MP

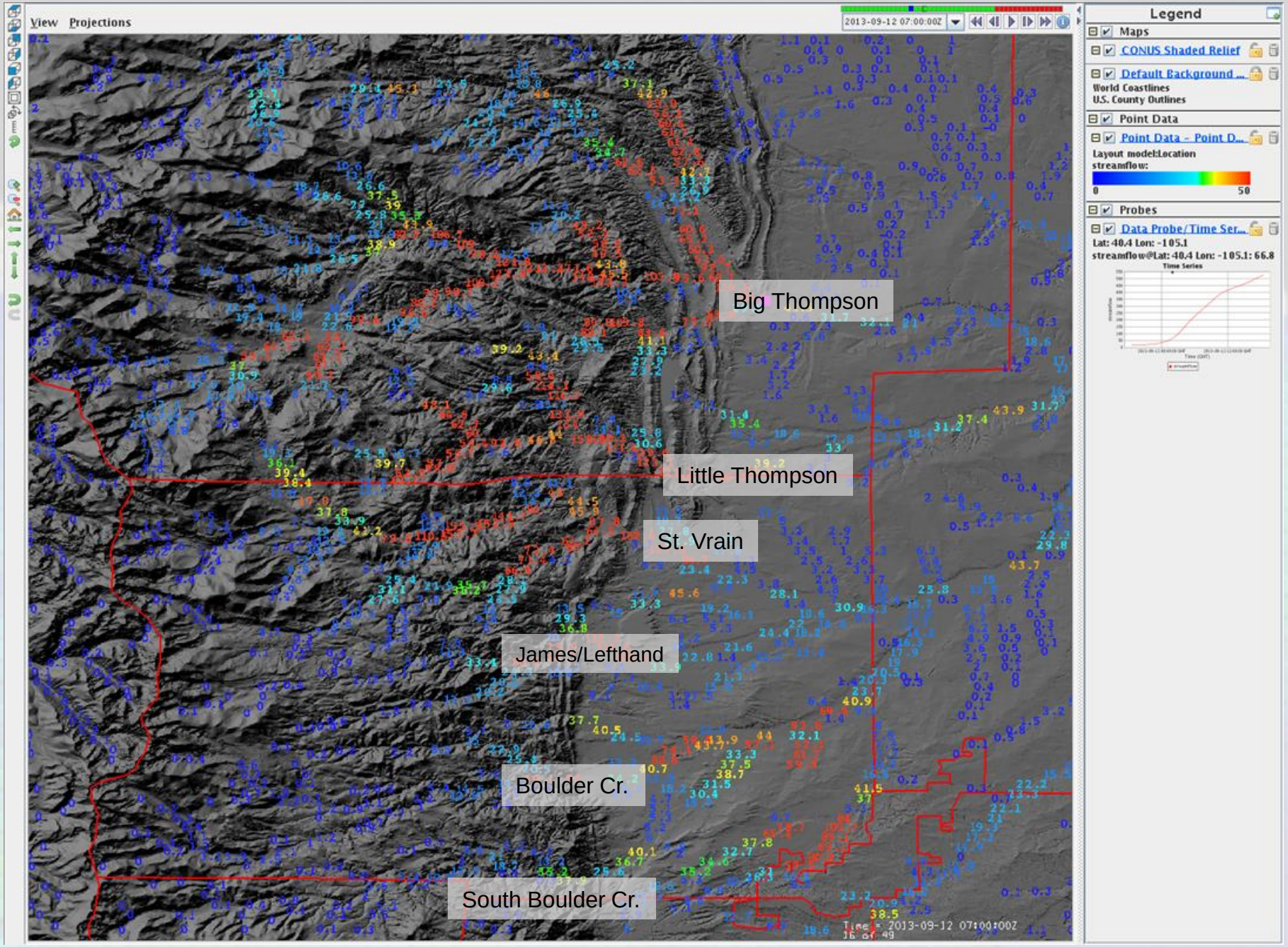
Forecasted streamflow coupled WRF/WRF-Hydro model

Initialization: 9/11 00z

Valid: 9/12 07z



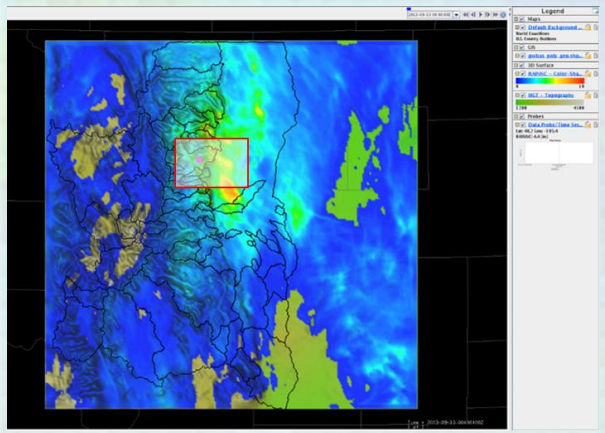
Streamflow in cms



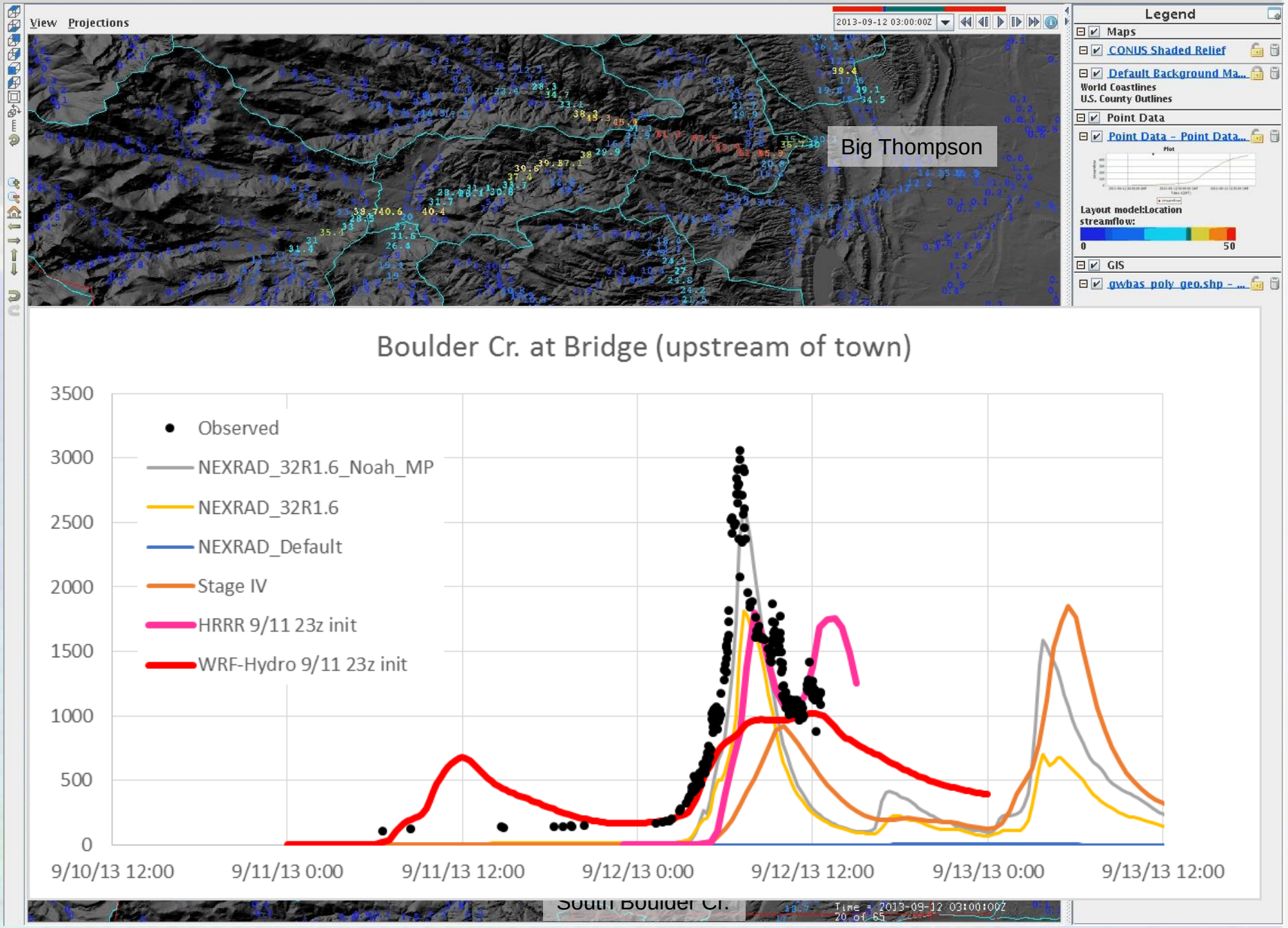
Forecasted streamflow coupled WRF/WRF-Hydro model

Initialization: 9/11 00z

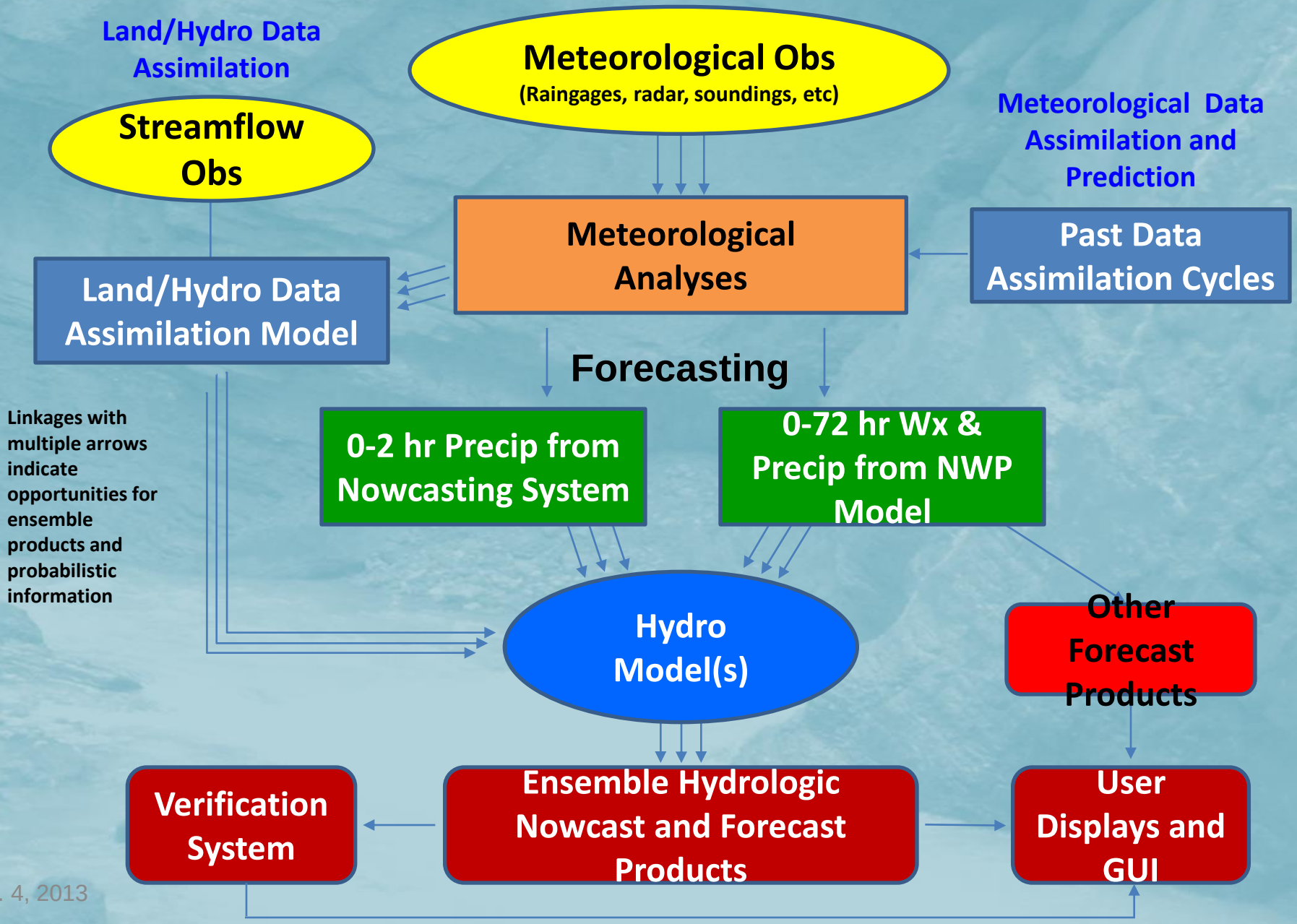
Valid: 9/12 07z



Streamflow in cms



Hydrometeorological Warning System



Similarities to the Alberta 2013 Flood

1. Slow moving upper level low to the west.
2. Long duration of heavy rainfall and widespread spatial extent of flooding.
2. Moisture advected in from the south.
3. Convective elements with likely warm rain process.

Differences from the Alberta 2013 Flood

1. No snow present on the ground.
2. Very little lightning, low levels of atmospheric instability, and deep levels of moisture.
3. Radar reflectivity levels lower than the Alberta flood.

Lessons for Alberta

1. High resolution weather forecasts with data assimilation (WRF with 3 km grid spacing for example) performed better than coarser resolution forecasts and show promise for improved precipitation forecasting.

2. Need to account for the moisture level in the conversion of radar reflectivity to rainfall rate (tropical versus continental size distribution).

3. The use of real-time distributed hydrological model (100m resolution) coupled to a high resolution atmospheric forecast model provides great potential to improve the lead time for the flood forecasts.

4. Coupling of current and nowcast radar estimates of rainfall with a real-time distributed model provides the ability to diagnose current flood conditions.

Summary:

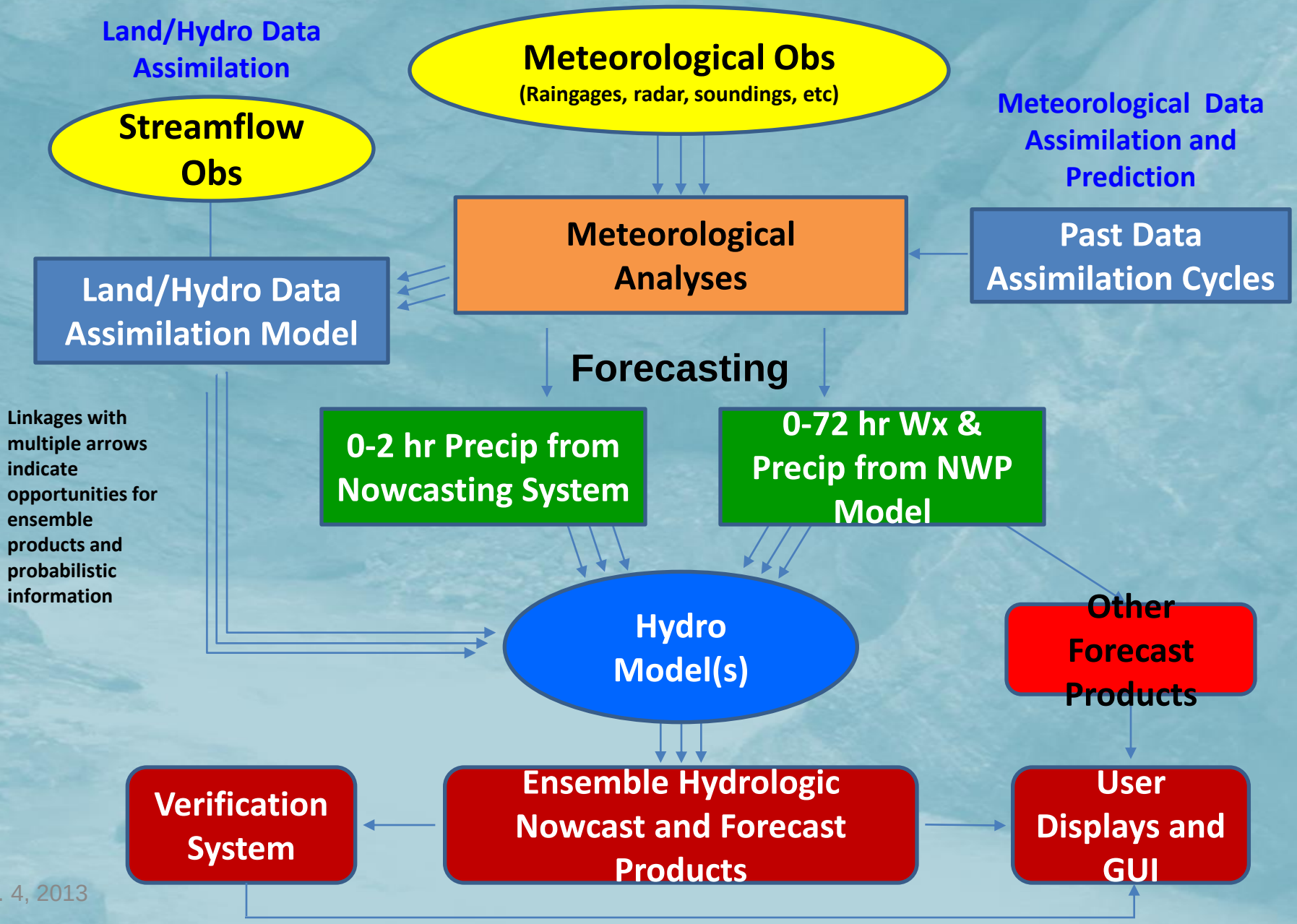
- **A lot of work remains to identify sources of error and opportunities for improvement in the forecasting chain…**

- **Operational Precipitation Estimates:**
  - **Existing operational QPE products exhibited large uncertainties and, in many cases errors. These errors significantly handicap forecasters…**

- **Operational Precipitation Forecasts:**
  - **Most precipitation forecasts captured the large-scale pluvial period in both time and general spatial extent but intensity and localization along mountain front was generally underestimated and displaced. Research models show promise…**

- **Hydrologic Prediction:**
  - **Errors and uncertainties in precipitation estimates and forecasts had *profound* impacts on hydrological simulations and predictions. This event also exhibited *strong groundwater* influences that are challenging for hydrological forecasting models.**

Hydrometeorological Warning System



The National Center for Atmospheric Research

Thank you.

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National Center for Atmospheric Research
Boulder, CO
rasmus@ucar.edu