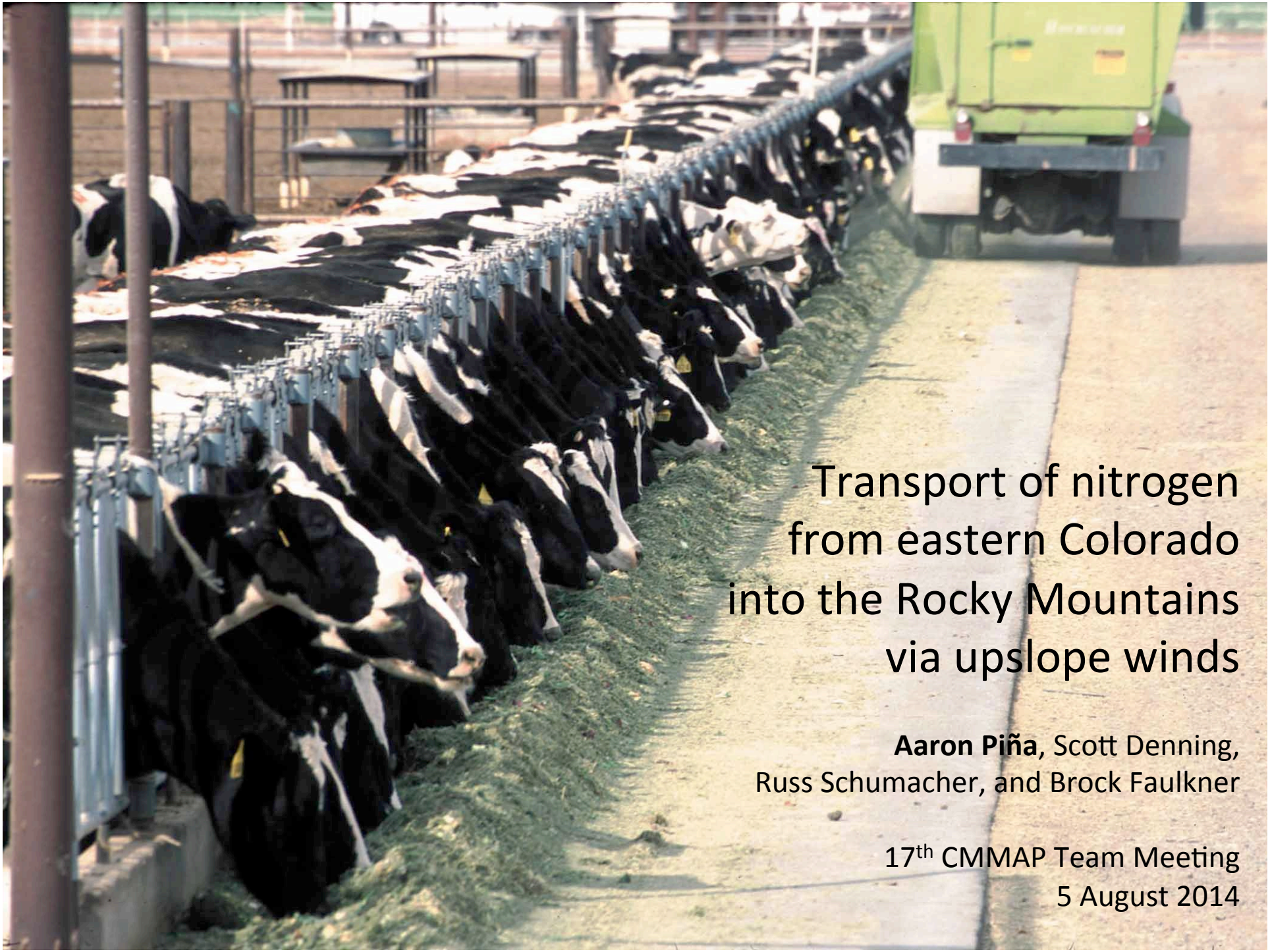


Transport of nitrogen from eastern Colorado into the Rocky Mountains via upslope winds

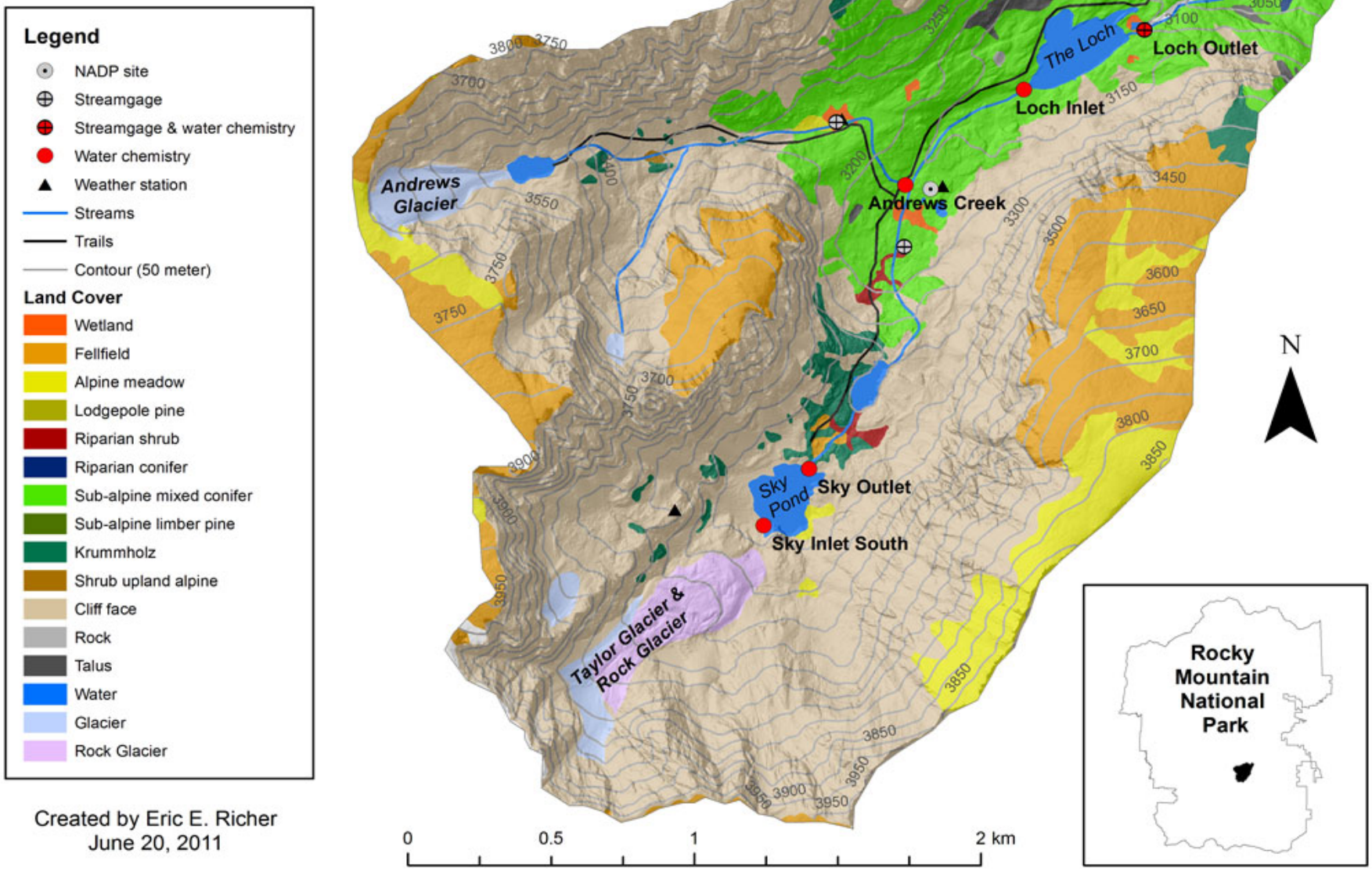
Aaron Piña, Scott Denning,
Russ Schumacher, and Brock Faulkner

17th CMMAP Team Meeting
5 August 2014

RMNP—a pristine environment receiving pollution

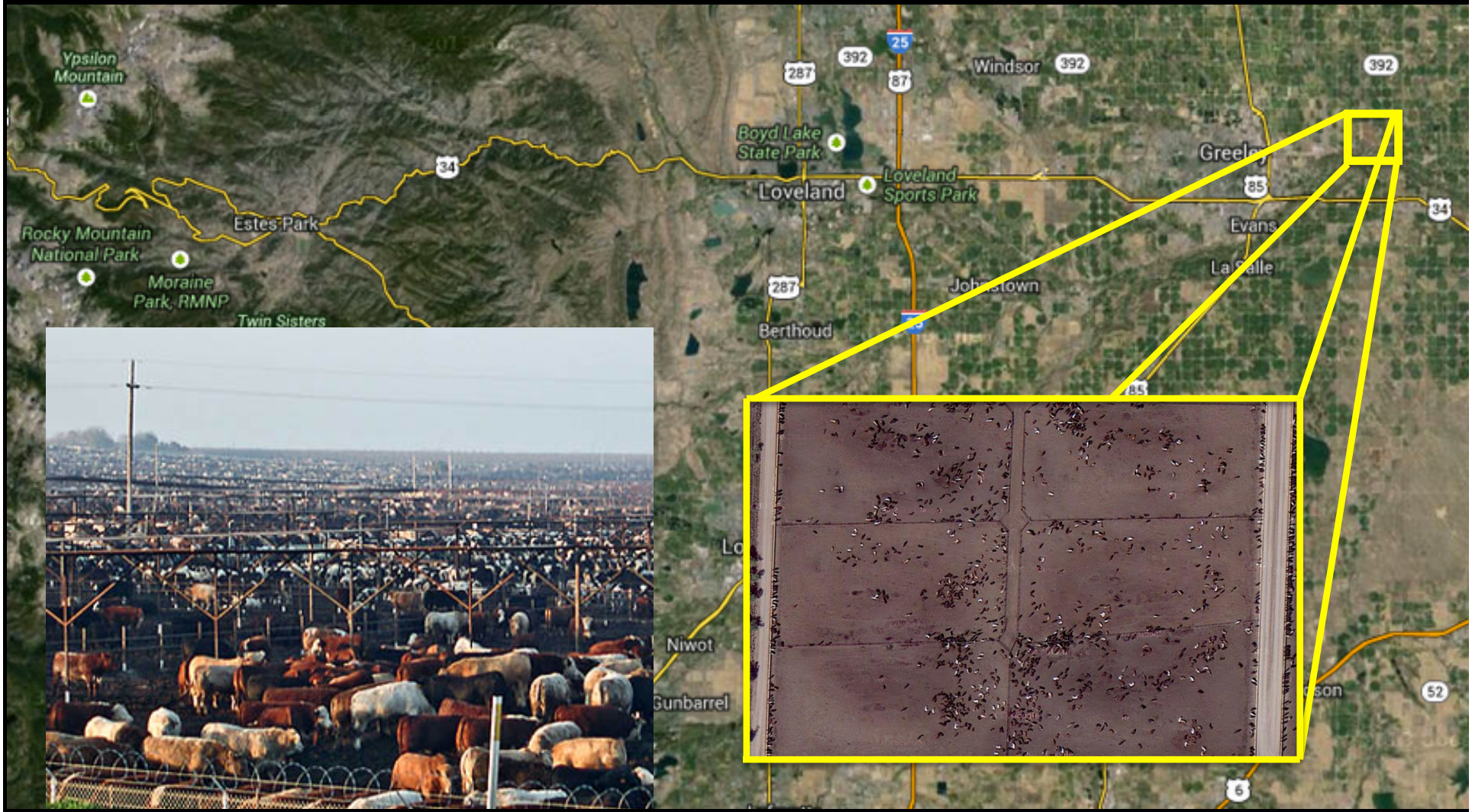
Loch Vale Watershed

Rocky Mountain National Park, Colorado



Created by Eric E. Richer
June 20, 2011

Livestock is an important source of NH_3



Concentrated Animal Feeding Operation (CAFO) Facts

- CAFOs → 0.5 Gt manure per year
- 1 head of cattle : 5 Colorado residents
- Cattle on feedlots in Weld County, Colorado produce as much manure as the sewage from New York City and Chicago combined.

Front Rap

We got a trough from the west,
They callin' for baroclinicity,
Don't know what that is?
It's part of vorticity.

Don't have to ask,
Just walk outside,
Make sure you layered,
And don't you dare drive.

The roads will be covered,
With snow and ice,
Just wait a few days,
And it will be nice.

But if there's a chance,
Of a wind from the easties,
Plug up your nose,
You're smellin' cow feces

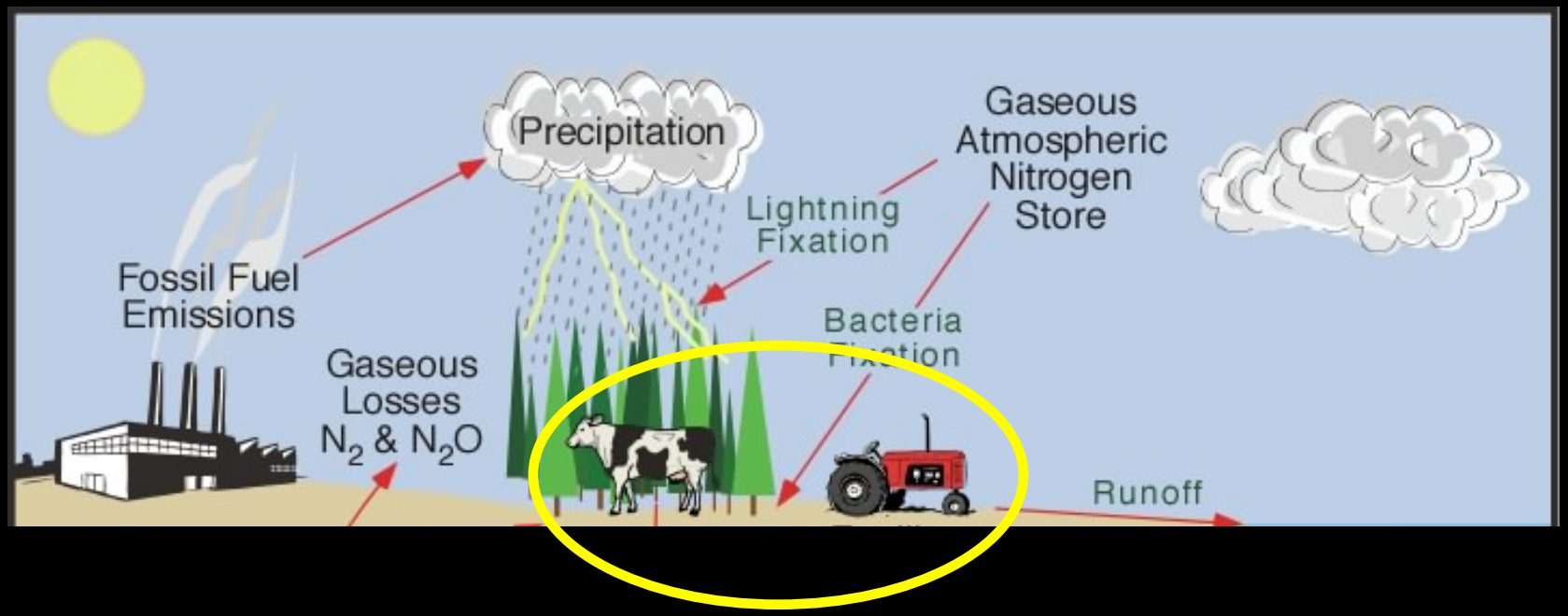
I digress…

Meteorologists will be smiling,
As mother nature delivered,
What the east don't know,
Models say a blizzard.

Outline

- Background
  - Deposition pathways
  - Mountain-valley circulation
- Convective transport case study
  - National Atmospheric Deposition Program
  - North American Regional Reanalysis
  - Weather Research & Forecasting Model
- Probabilistic prediction tool

Many N reservoirs → Atmosphere is a key transport mechanism



Source: http://www.physicalgeography.net/fundamentals/images/nitrogencycle.jpg

Atmospheric Processing of NH_x

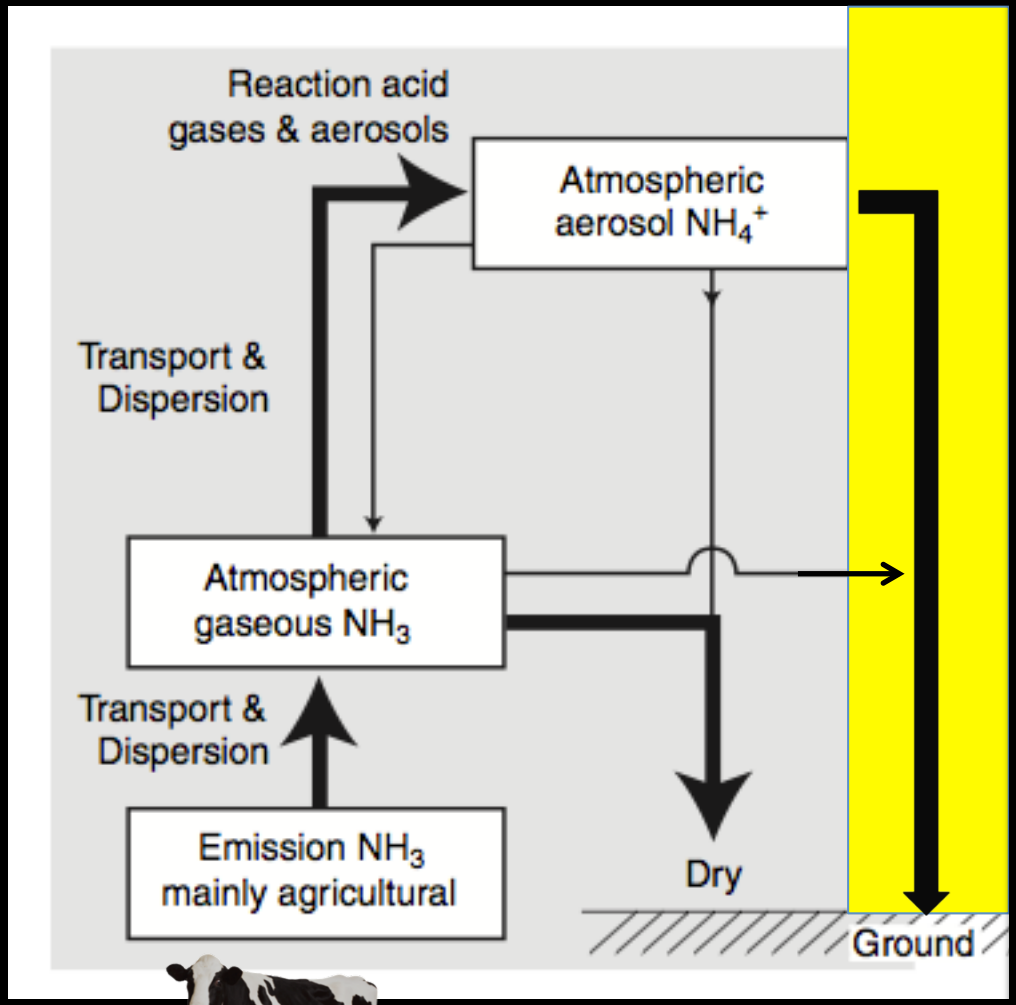


Figure source: Courtesy of Emily Fischer

Effects of N deposition in the Rockies

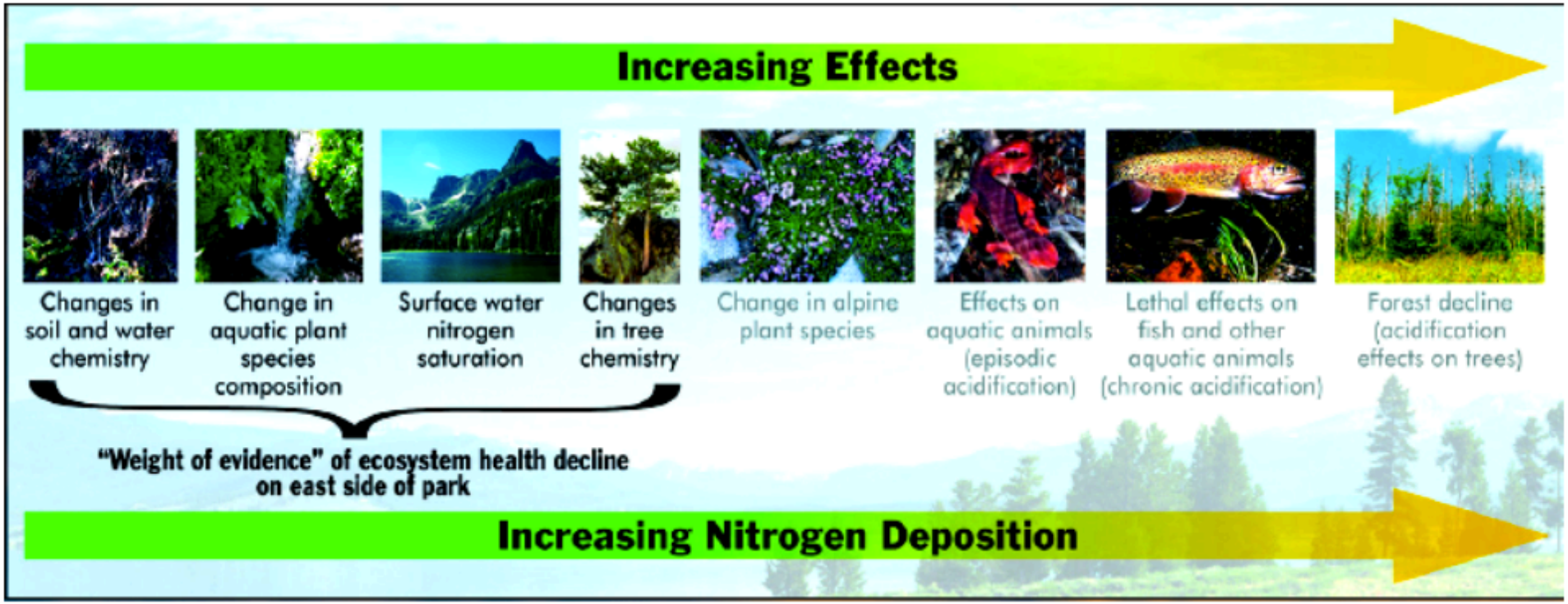
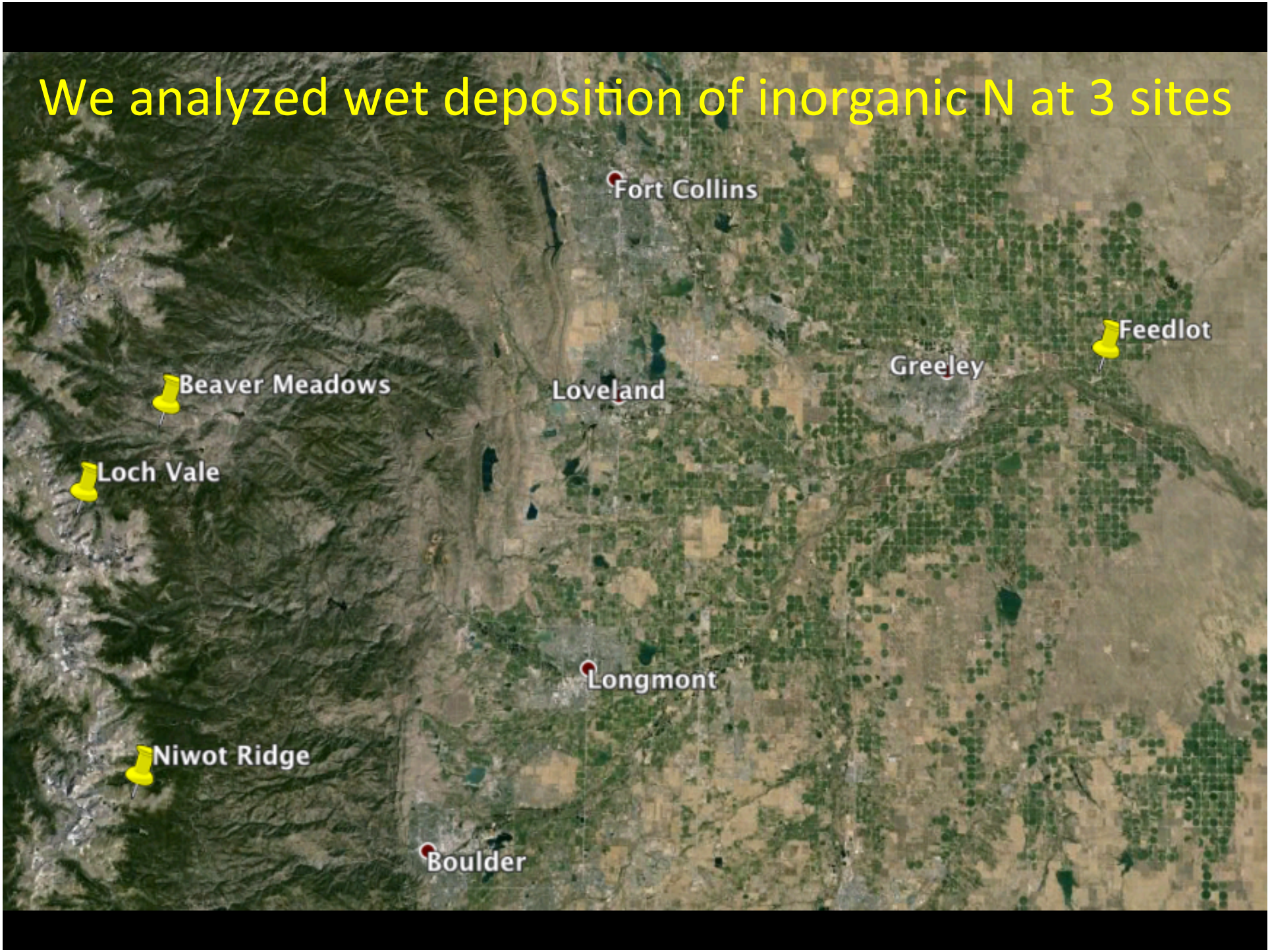
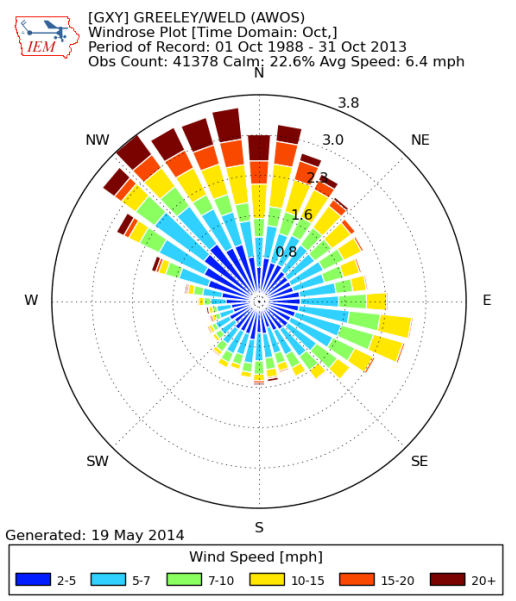


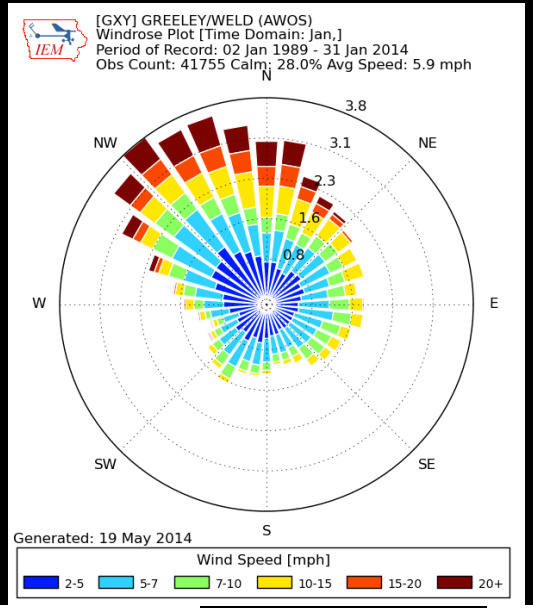
Figure source: National Park Service


We analyzed wet deposition of inorganic N at 3 sites
Fort Collins
Feedlot
Greeley
Beaver Meadows
Loveland
Loch Vale
Longmont
Niwot Ridge
Boulder

Wind climatology in Greeley, CO

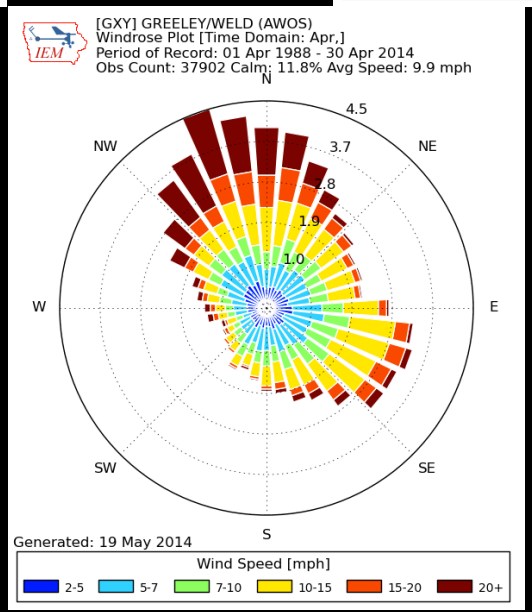


October
1988-2013

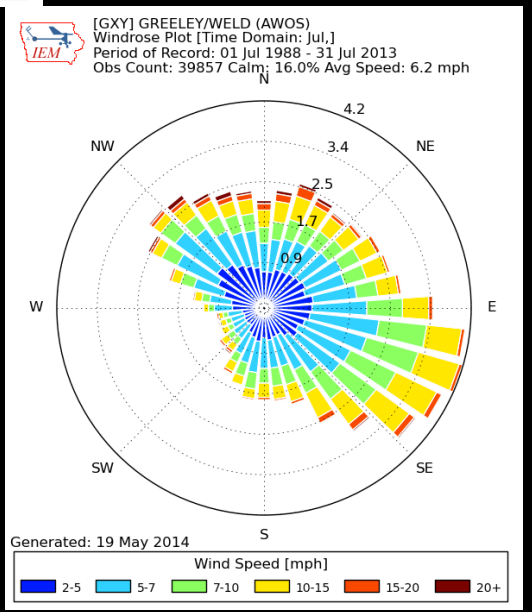


January
1989-2014

April
1988-2014

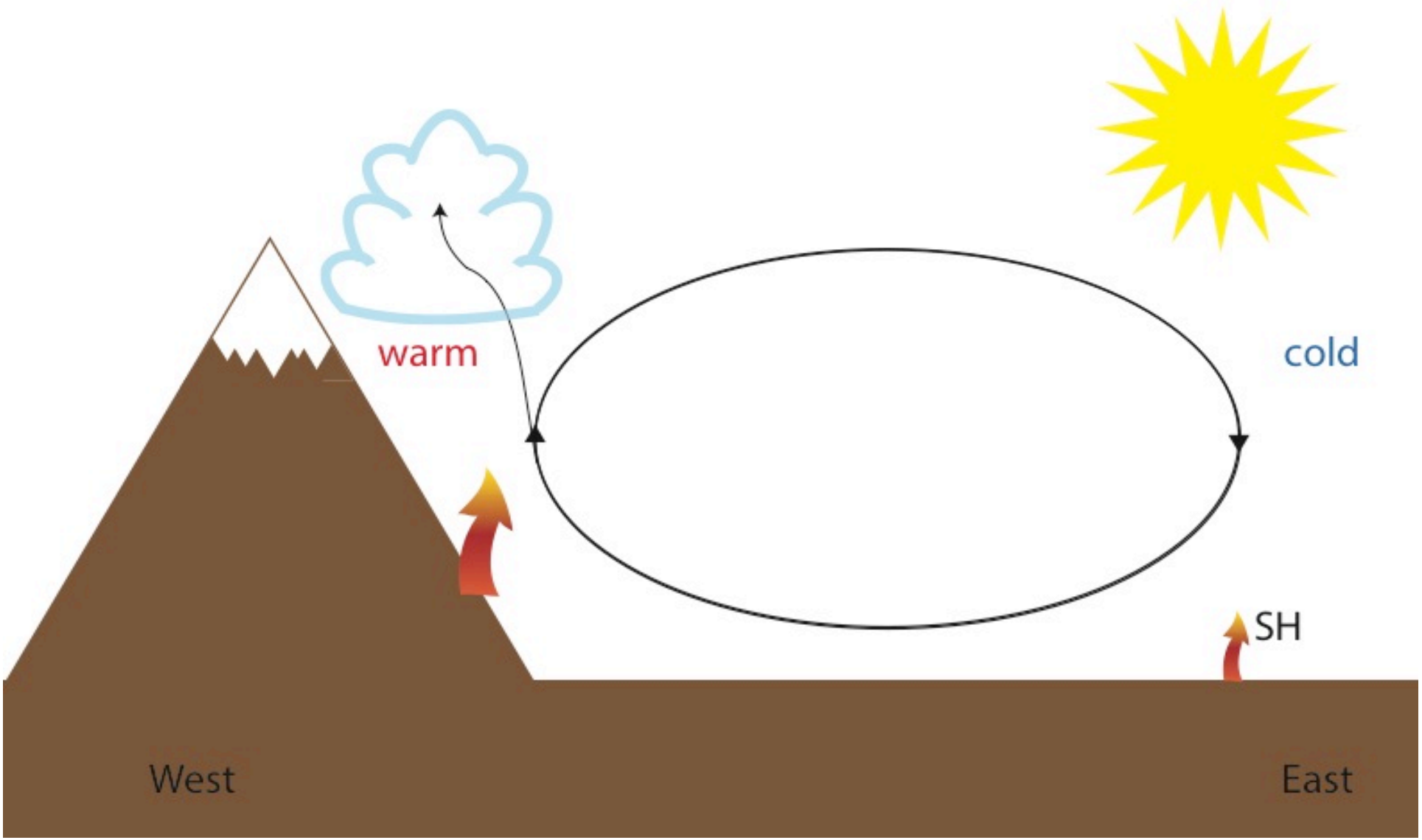


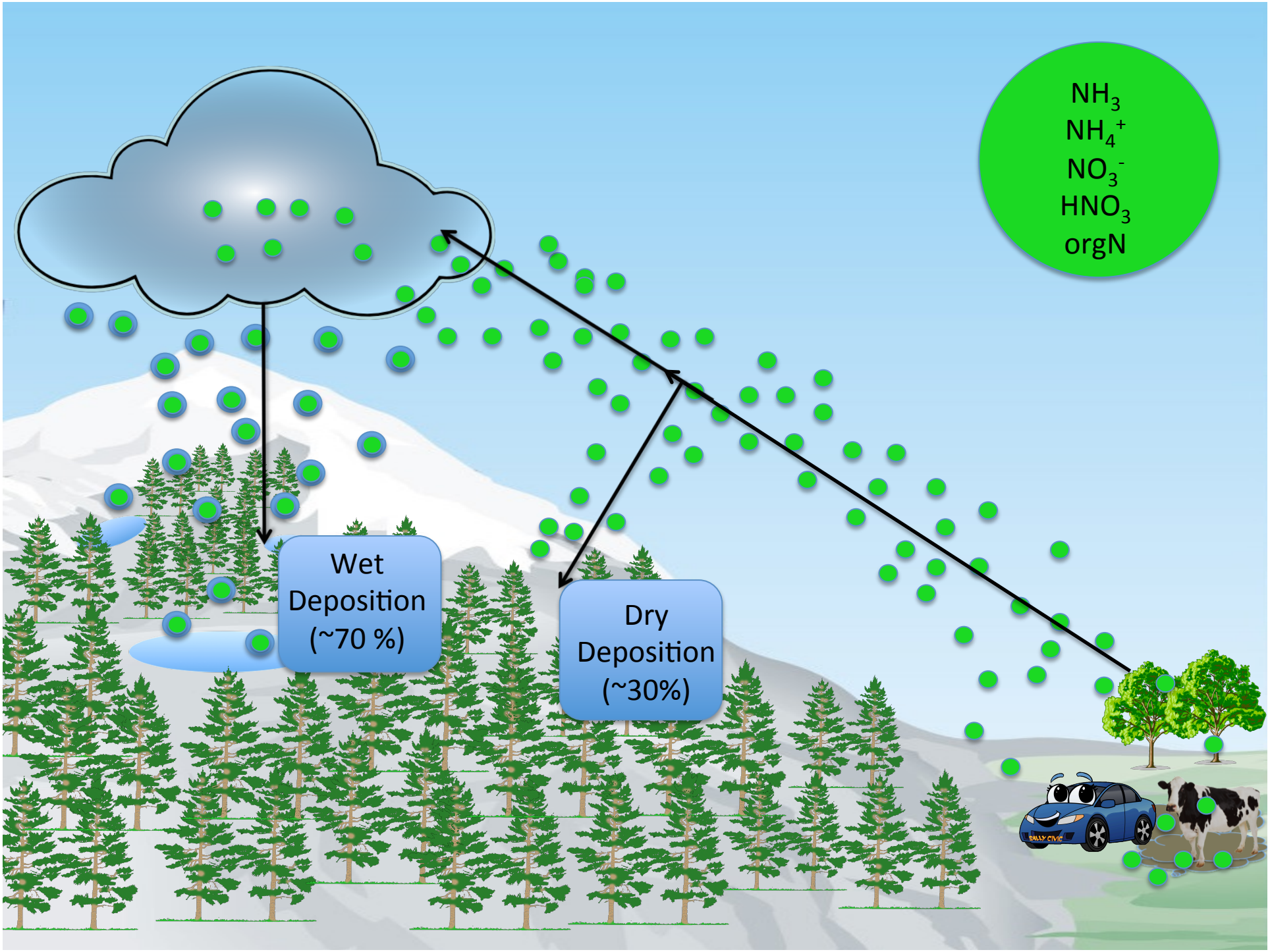
June
1988-2013



http://mesonet.agron.iastate.edu/

Mountain-Valley Circulation




NH_3
NH_4^+
NO_3^-
HNO_3
orgN
Wet Deposition (~70 %)
Dry Deposition (~30%)

National Atmospheric Deposition Program National Trends Network

- Provides a long-term record of precipitation chemistry at over 300 rural sites across the U.S.
- Weekly samples of constituents in wet deposition
- Samples sent to Central Analytical Lab at the IL State Water Survey

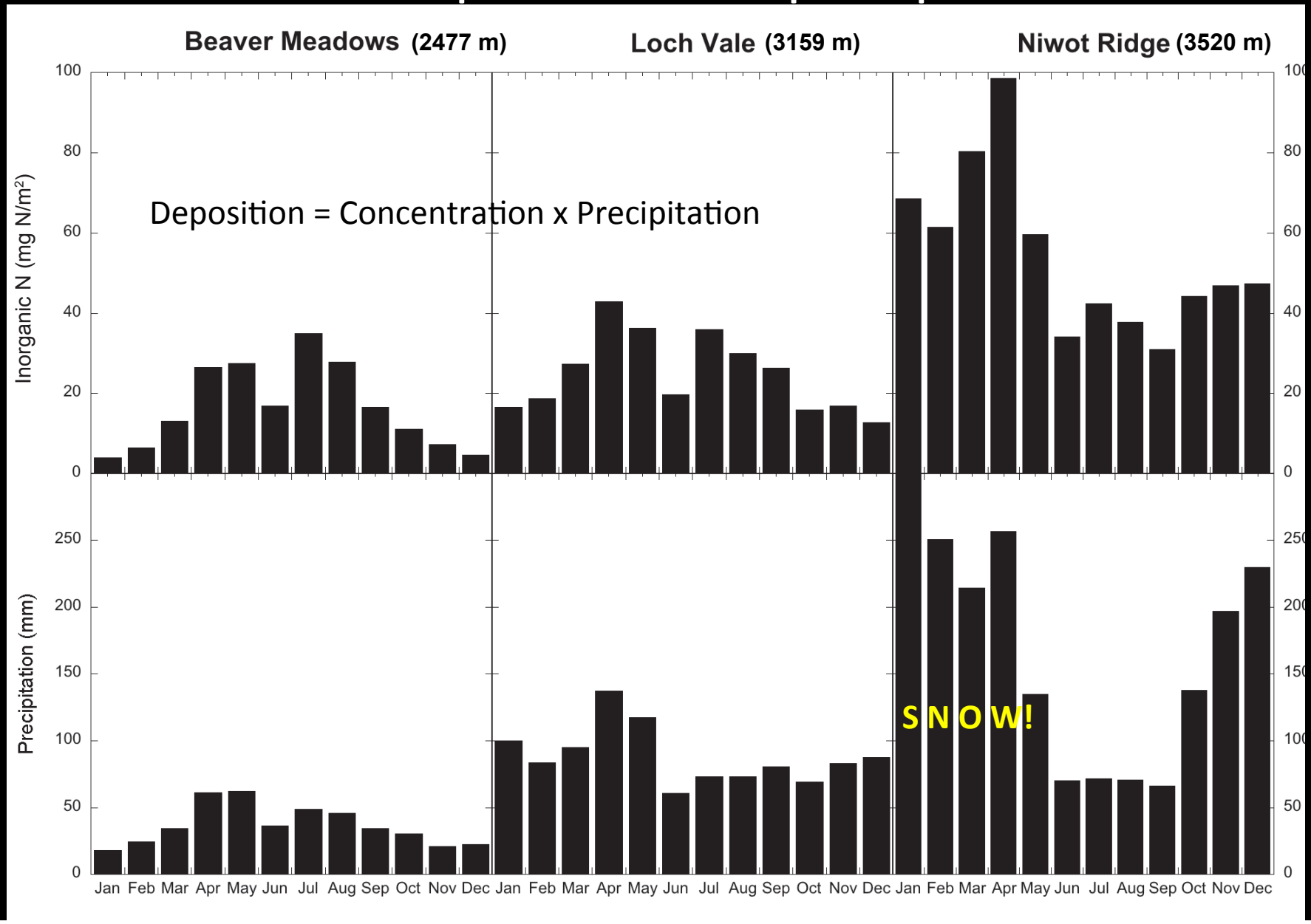
National Atmospheric Deposition Program (NRSP-3) (2007); Peden (1986)

Beaver Meadows

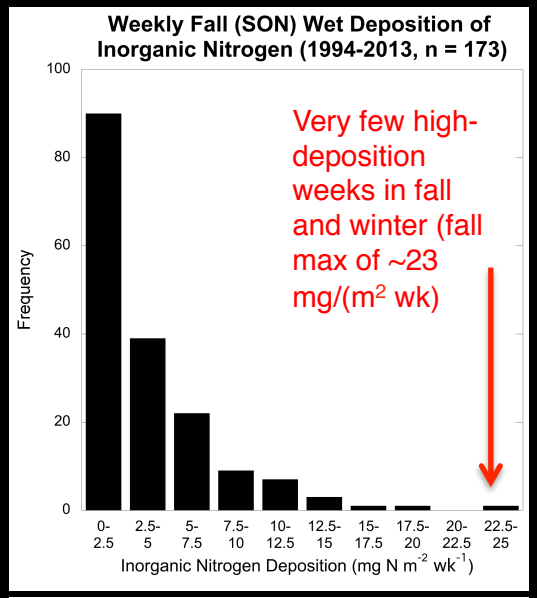
Loch Vale

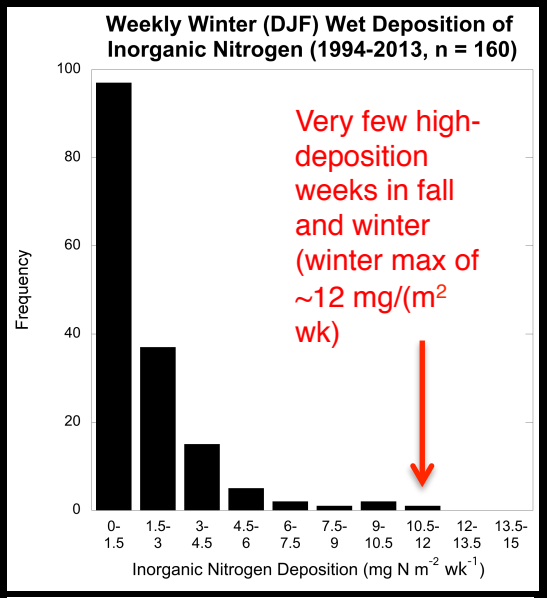
Niwot Ridge

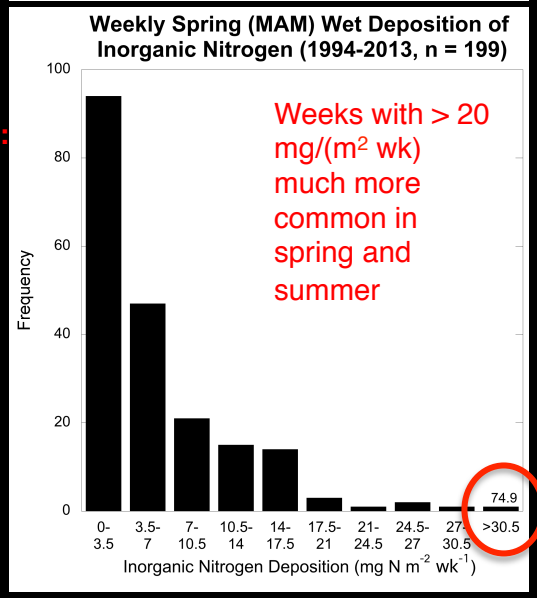
Monthly averages (1994-2013) of N deposition and precipitation

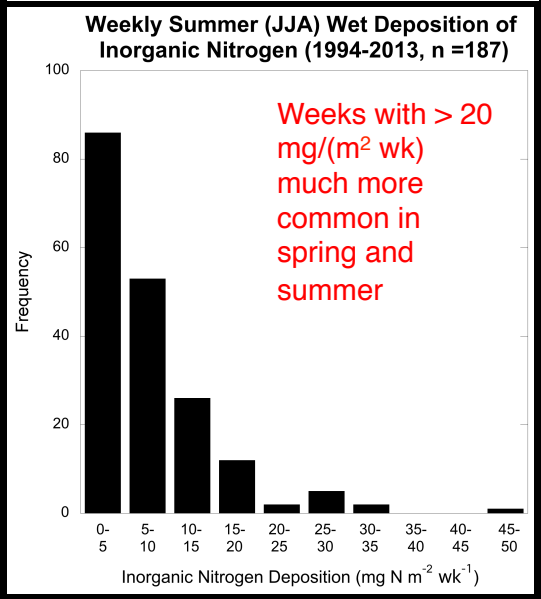


Beaver Meadows: histograms of weekly deposition









Overall maximum: 74.9 mg/(m² wk): 30 March-6 April 2004

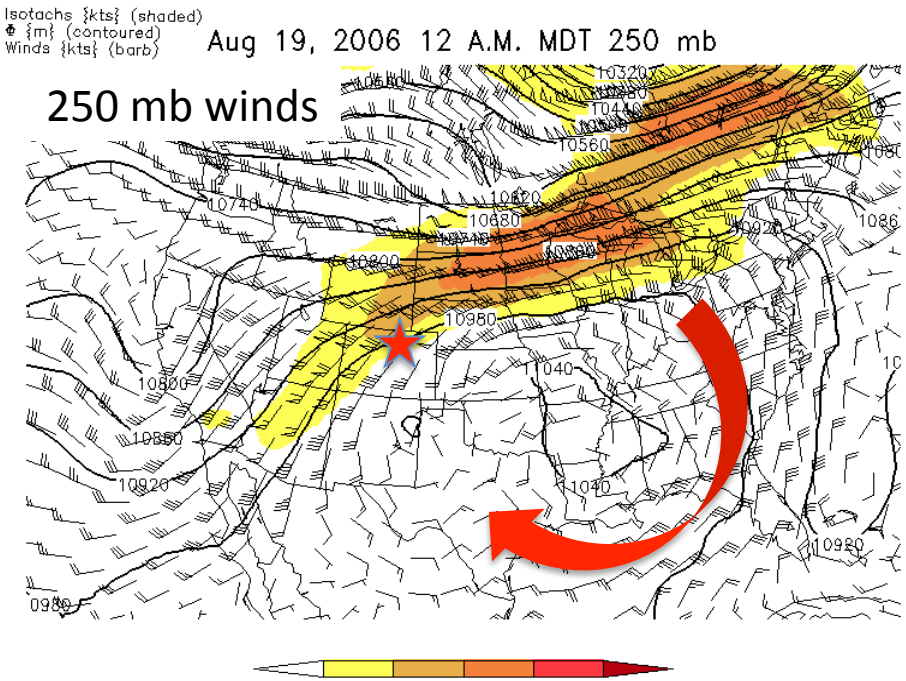
This week contributed over 6% of the total spring deposition in this ~20 year period

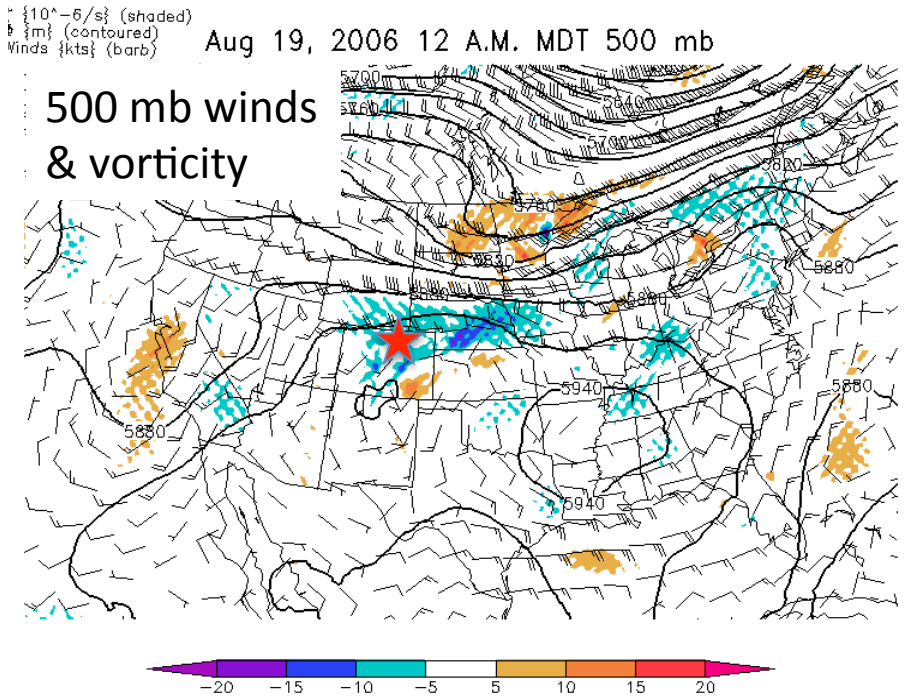
North American Regional Reanalysis

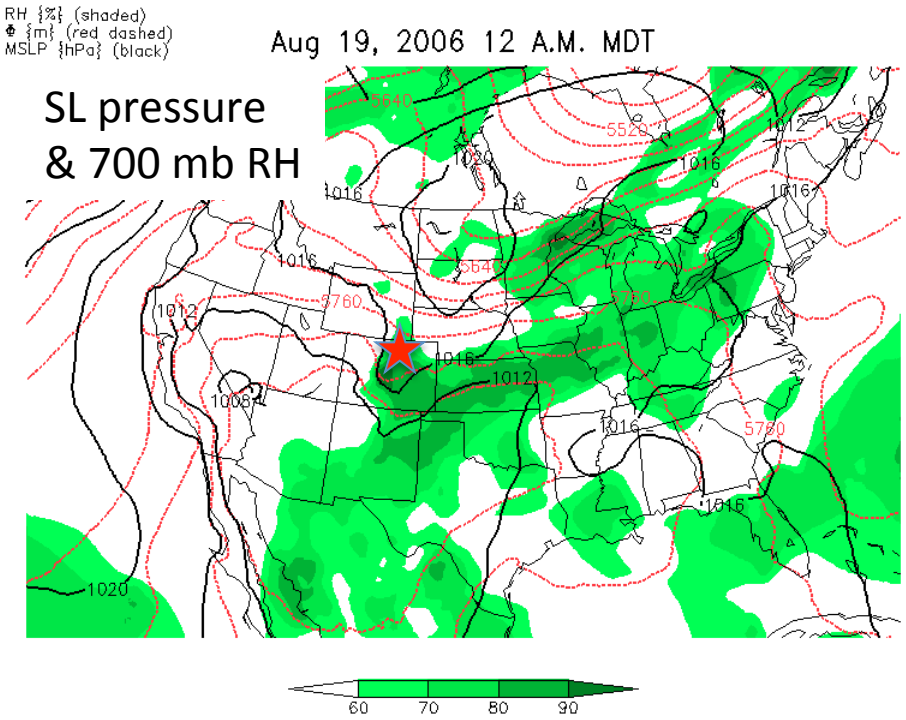
- Meteorological data from 1979 – present
- Data every 3 hours
- 32-km/45 vertical layers

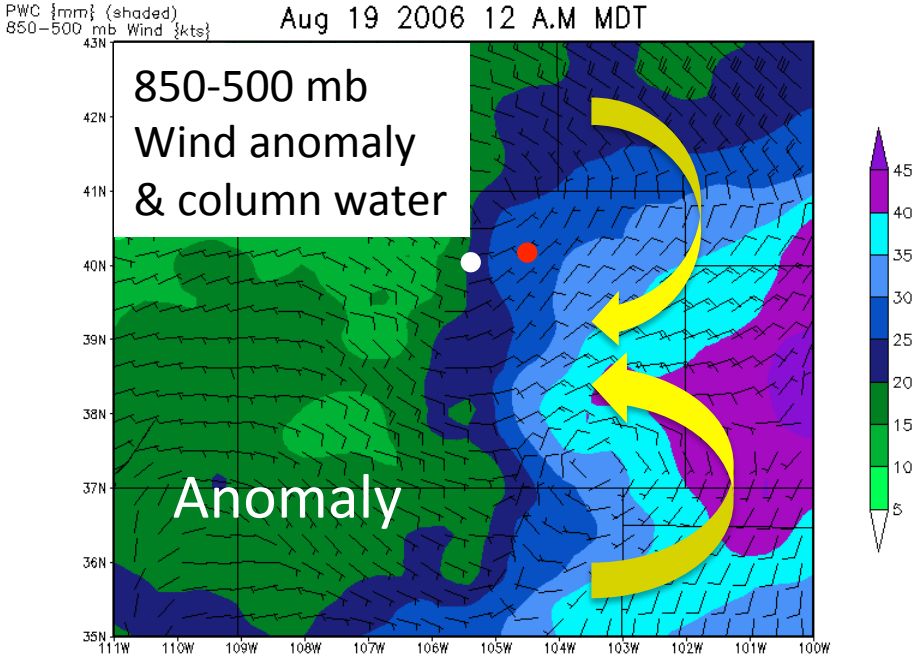
We used NARR to analyze synoptic circulation pattern of the 18-20 August 2006 case study

Mesinger and Coauthors (2006)


Isotachs {kts} (shaded)
Φ {m} (contoured)
Winds {kts} (barb)
Aug 19, 2006 12 A.M. MDT 250 mb
250 mb winds

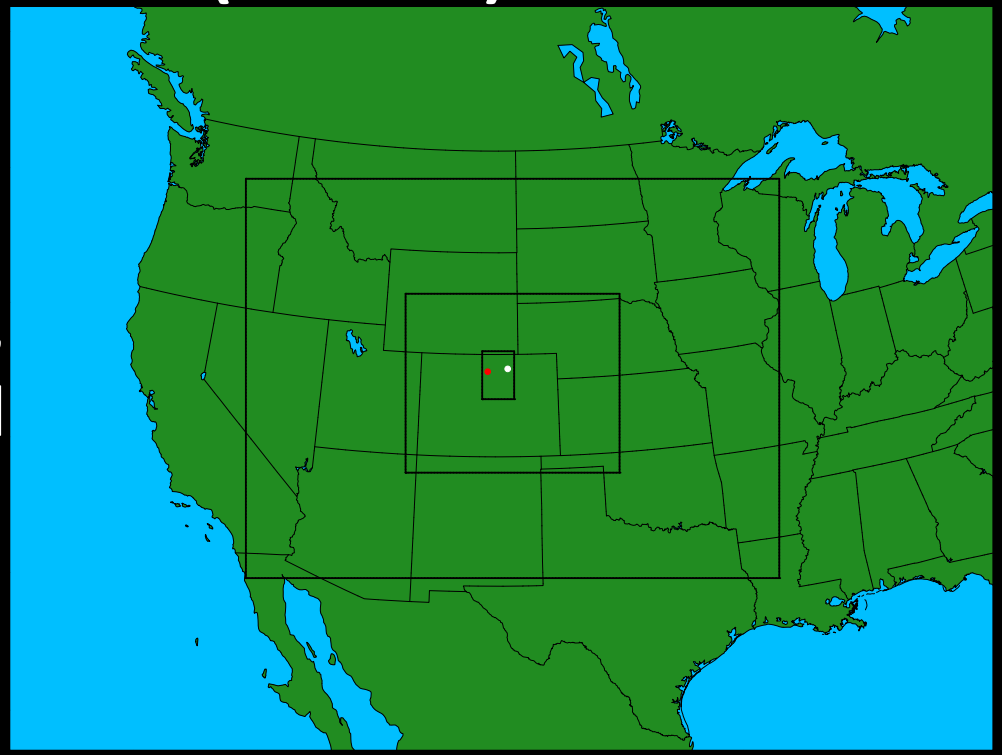

{10^-6/s} (shaded)
{m} (contoured)
Winds {kts} (barb)
Aug 19, 2006 12 A.M. MDT 500 mb
500 mb winds
& vorticity
−20 −15 −10 −5 5 10 15 20


RH {%} (shaded)
Φ {m} (red dashed)
MSLP {hPa} (black)
Aug 19, 2006 12 A.M. MDT
SL pressure
& 700 mb RH
60 70 80 90


PWC {mm} (shaded)
850-500 mb Wind {kts}
Aug 19 2006 12 A.M MDT
850-500 mb
Wind anomaly
& column water
Anomaly
45 40 35 30 25 20 15 10 5

Weather Research and Forecasting Model (WRF)

- Initialized with GFS FNL Analysis (1º)
- 4 domains (27 km, 9 km, 3 km, 1 km); 50 vertical levels
- Output variables every 10 min for 48 hours
- Included passive tracer



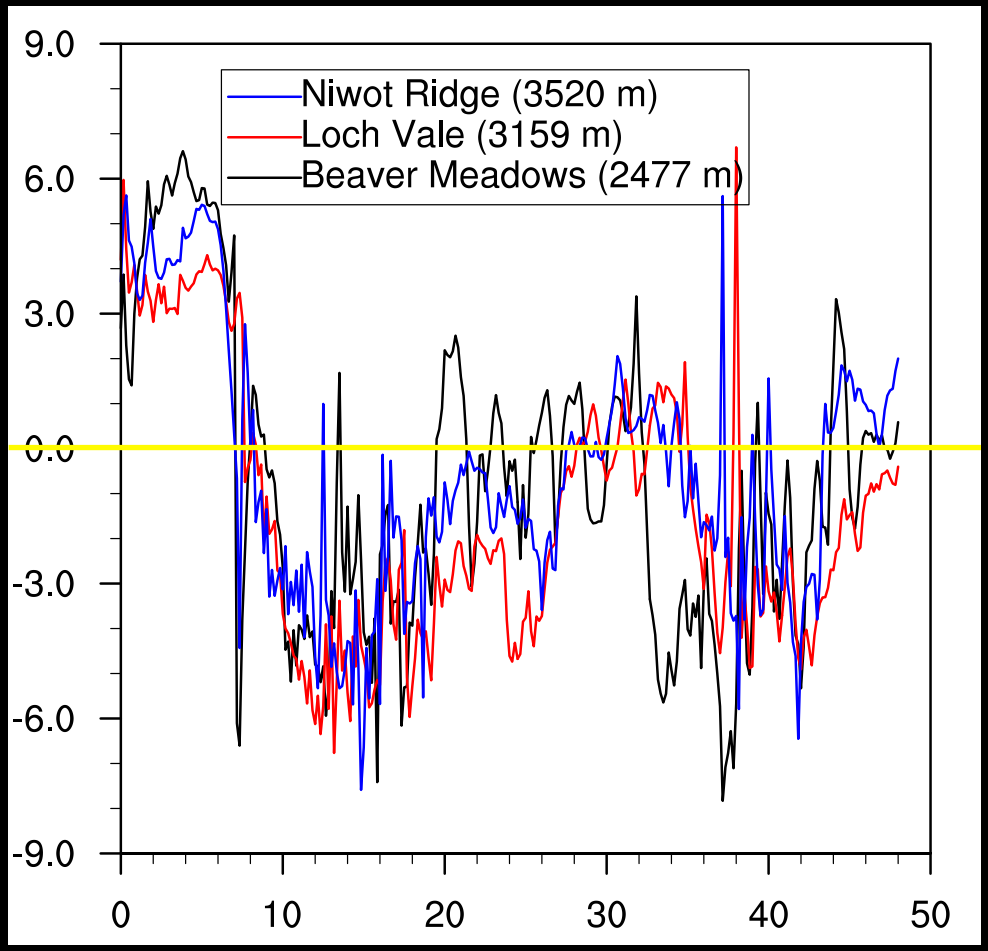
We used WRF to simulate cloud-scale convection

WRF captured expected diurnal cycle of winds

Downslope

u (m/s)

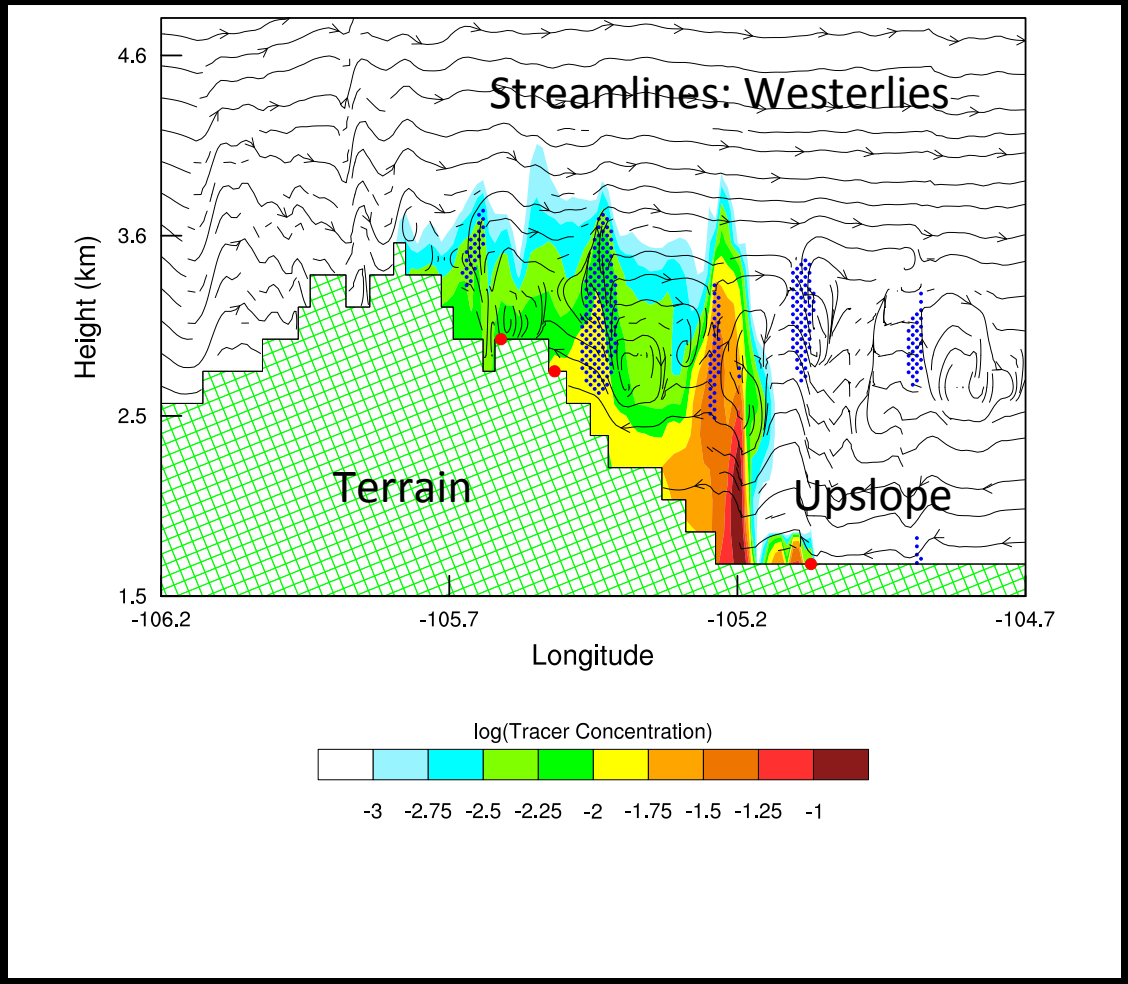
Upslope



Hours since 12 A.M. August 18, 2006

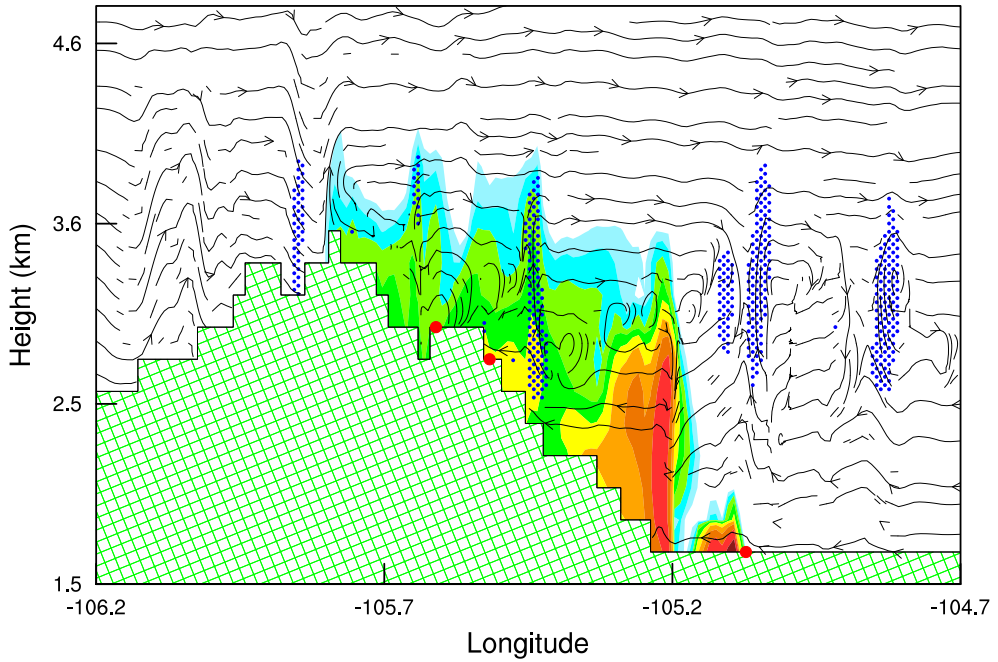
WRF output

12:40 MDT August 19, 2006



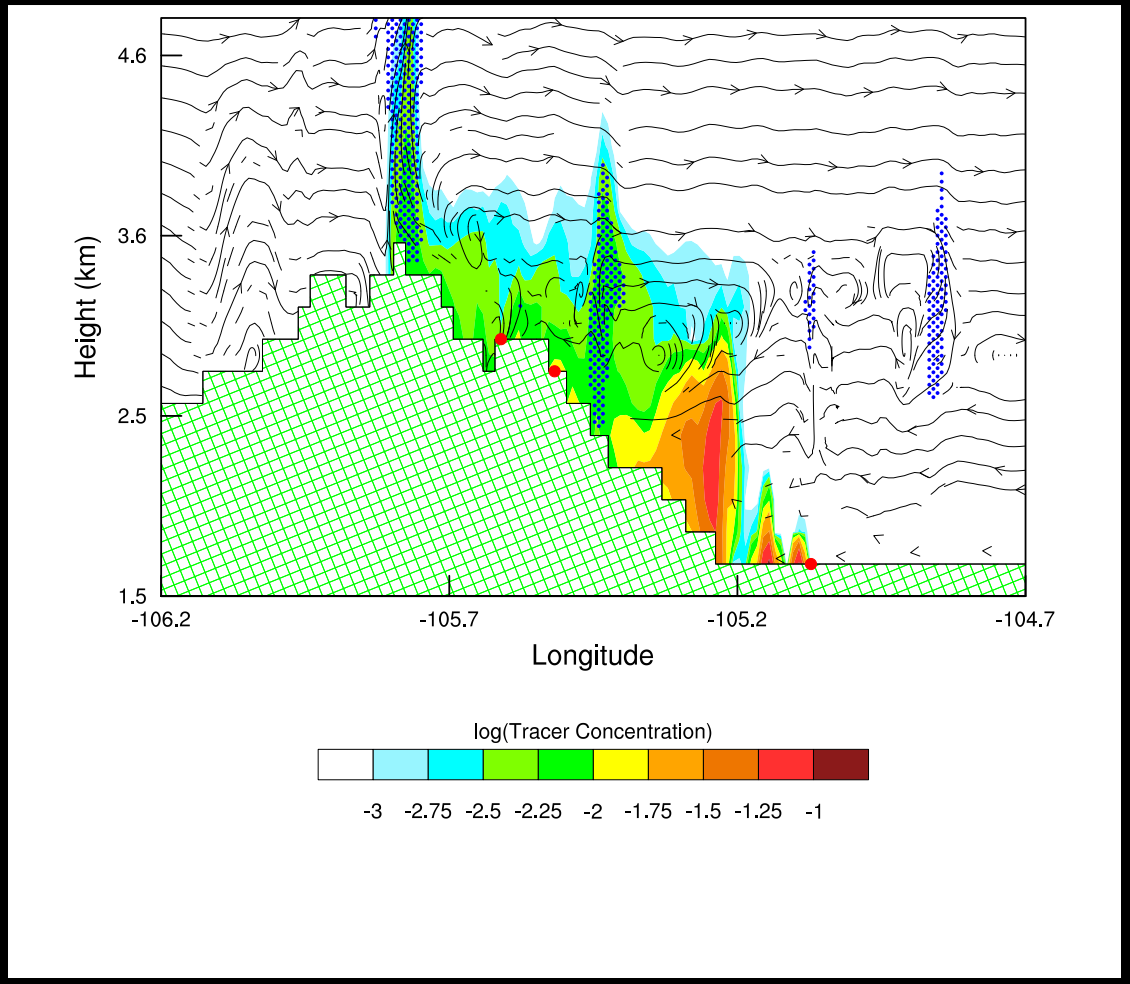
WRF output

12:50 MDT August 19, 2006



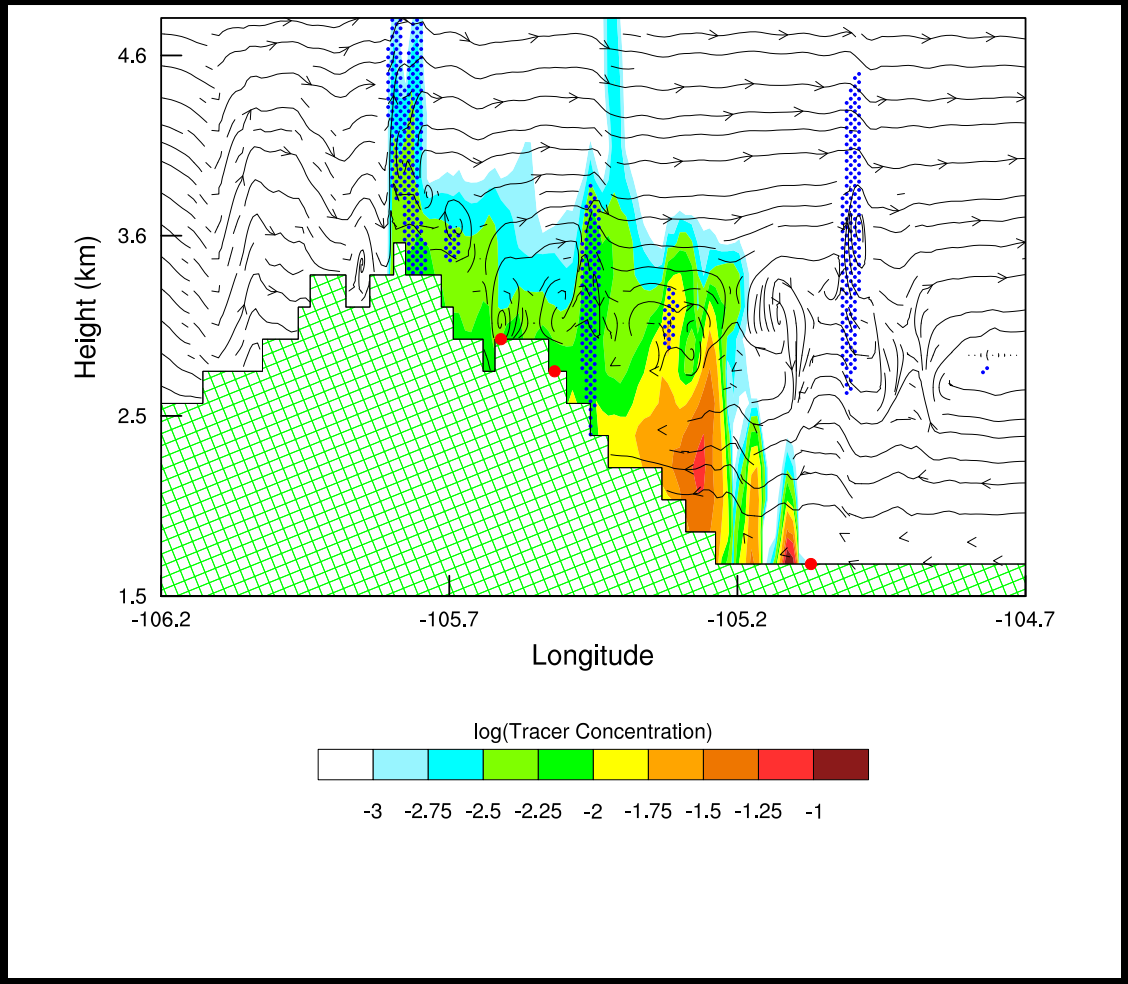
WRF output

13:00 MDT August 19, 2006



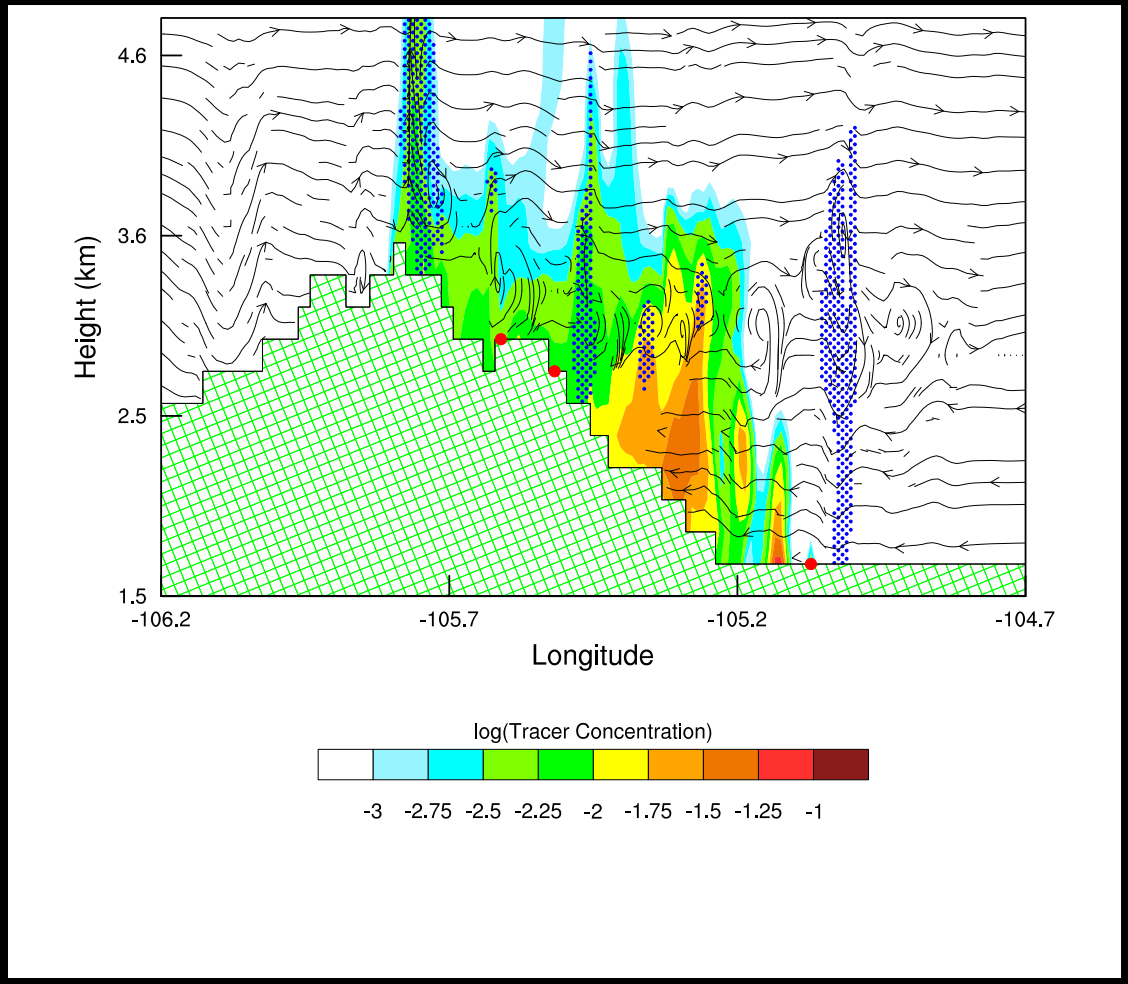
WRF output

13:10 MDT August 19, 2006



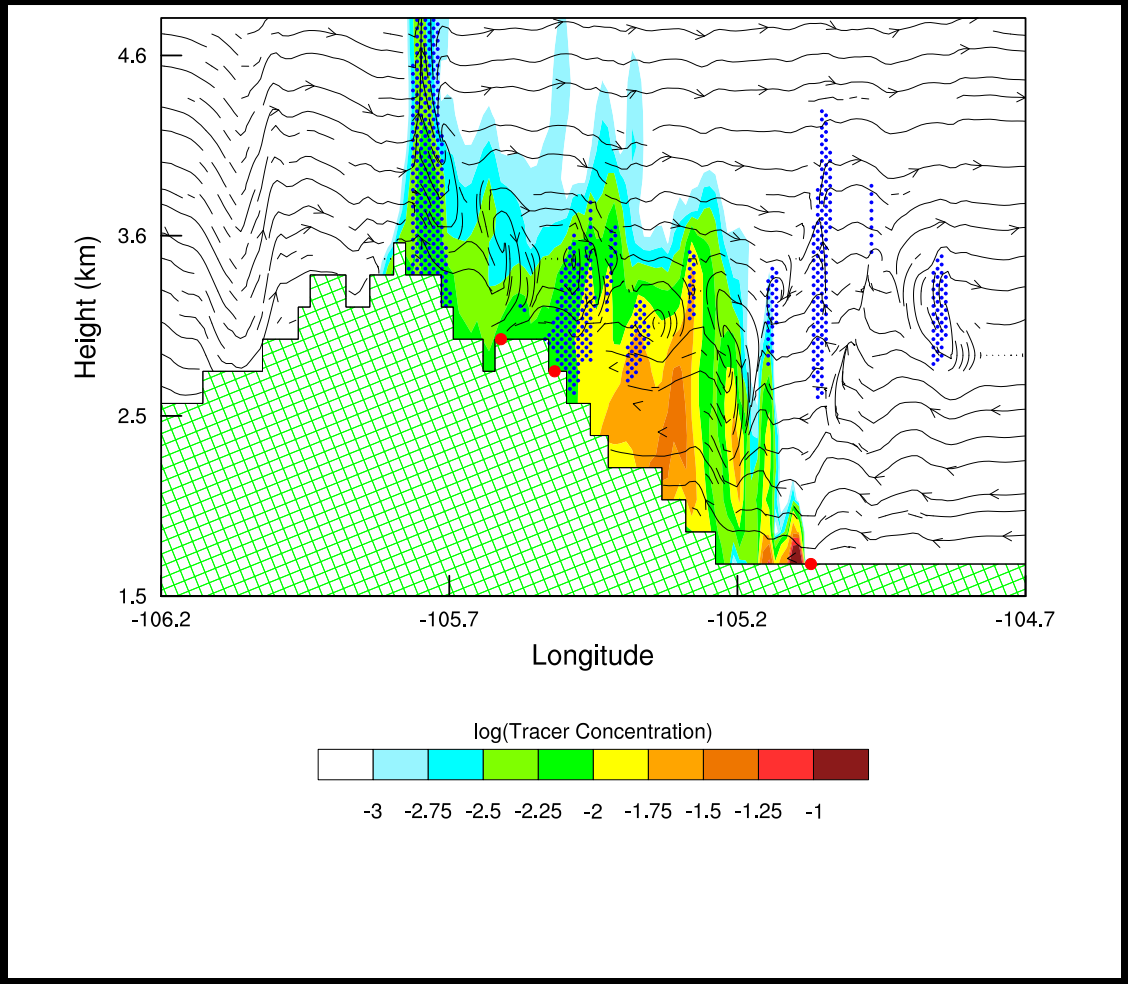
WRF output

13:20 MDT August 19, 2006



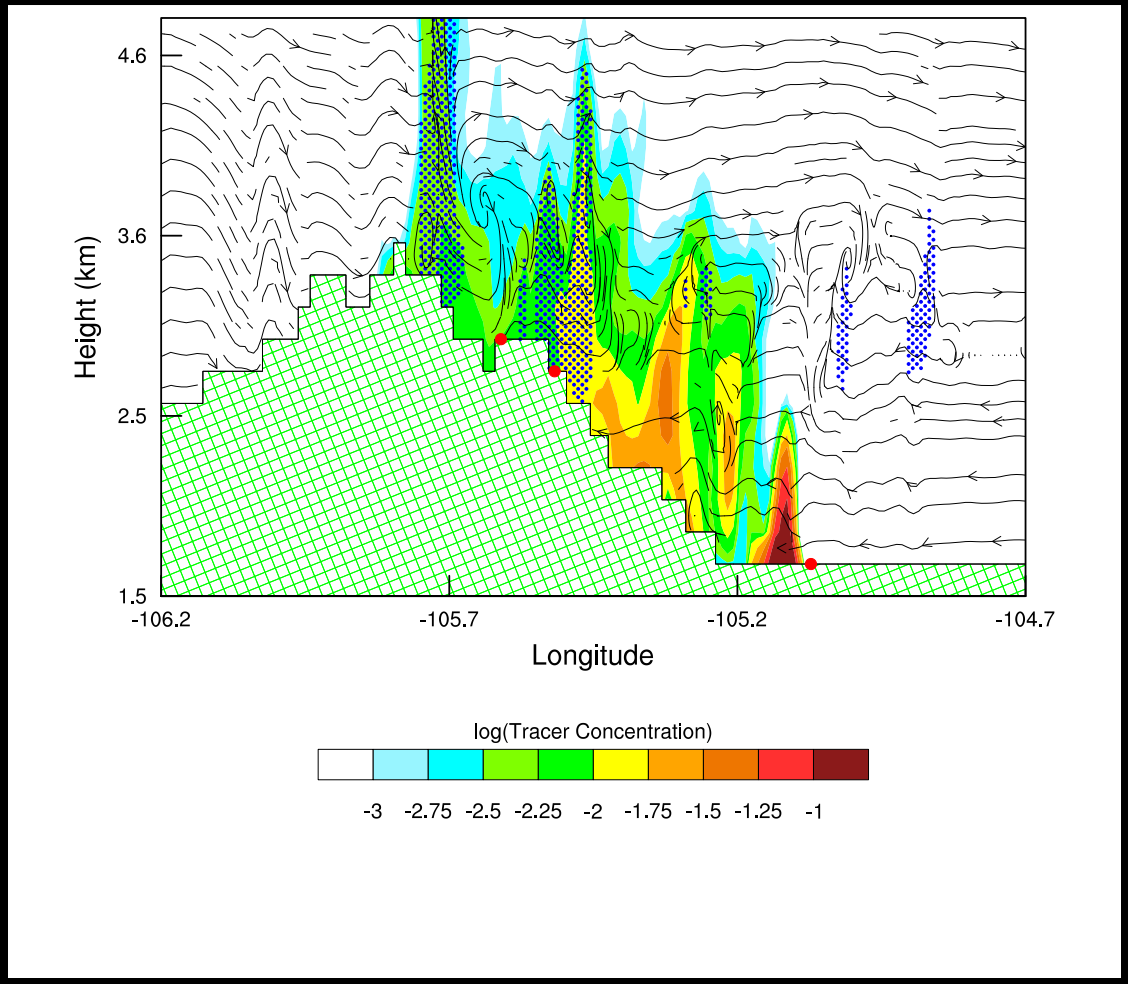
WRF output

13:30 MDT August 19, 2006



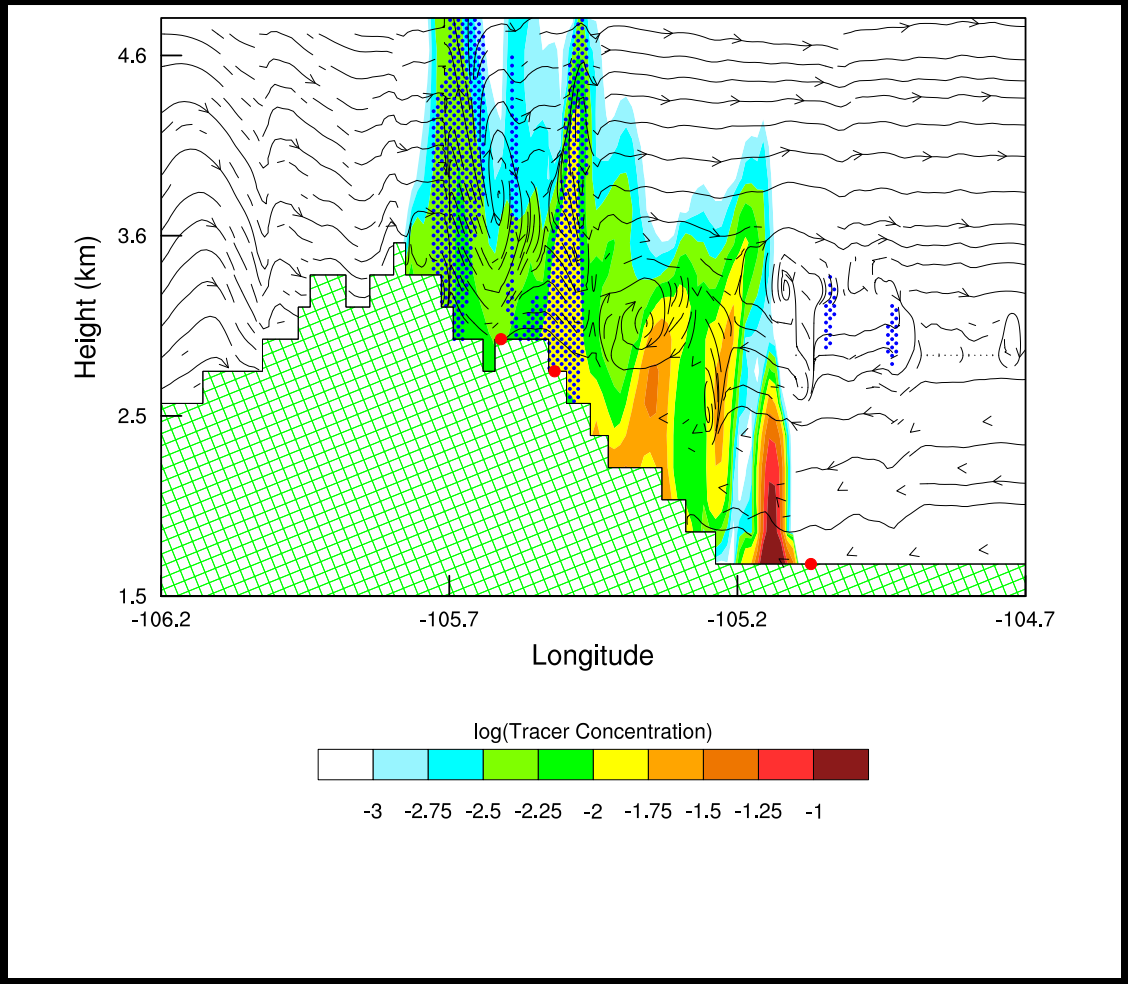
WRF output

13:40 MDT August 19, 2006



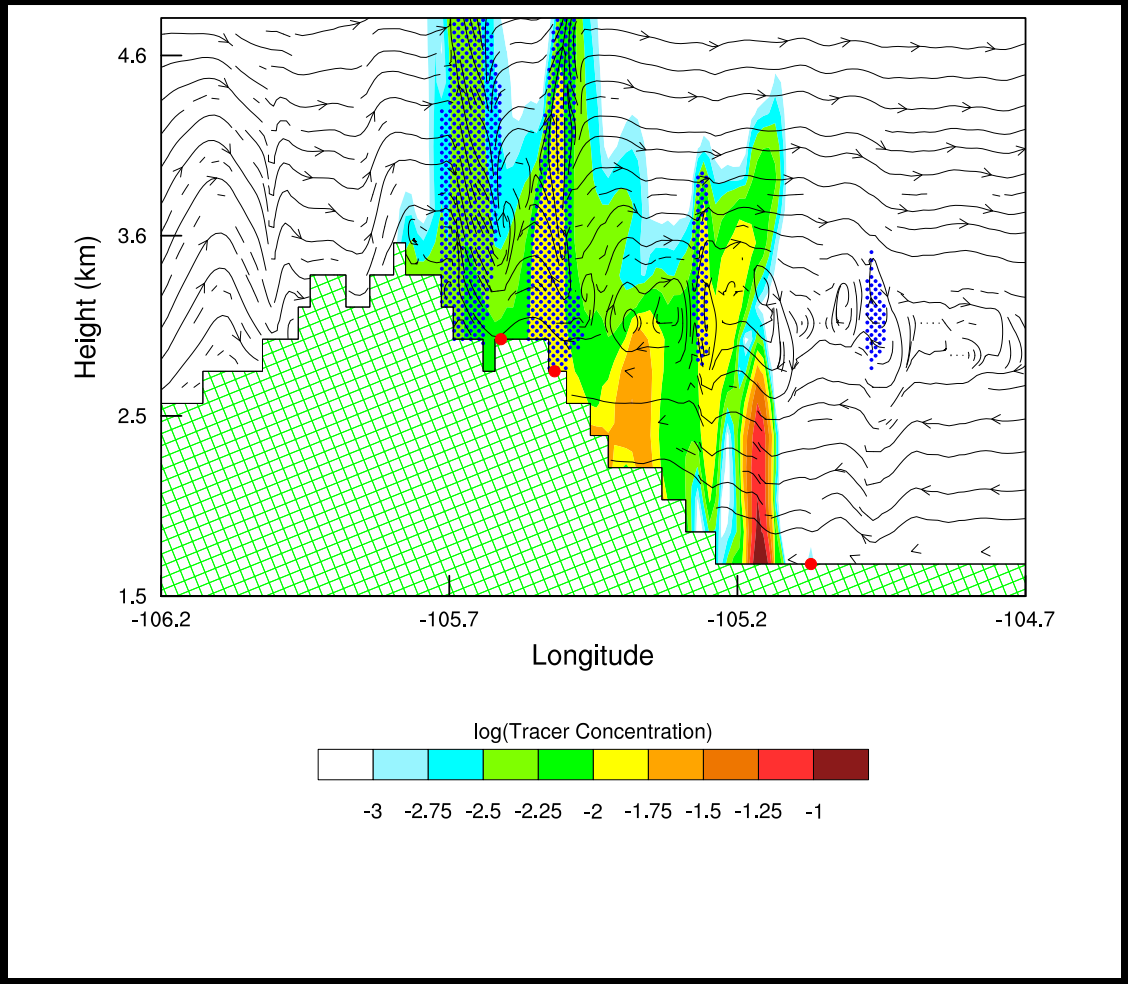
WRF output

13:50 MDT August 19, 2006



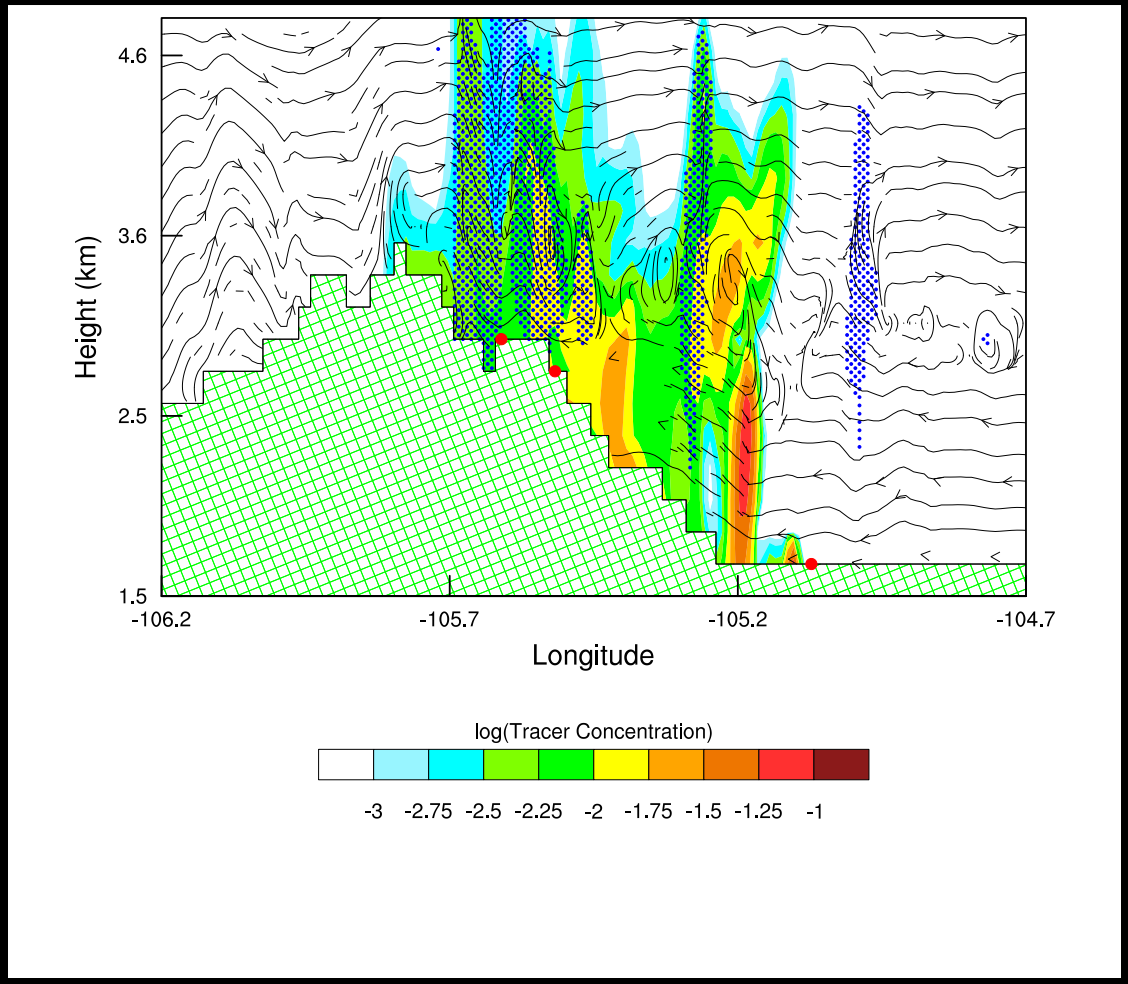
WRF output

14:00 MDT August 19, 2006



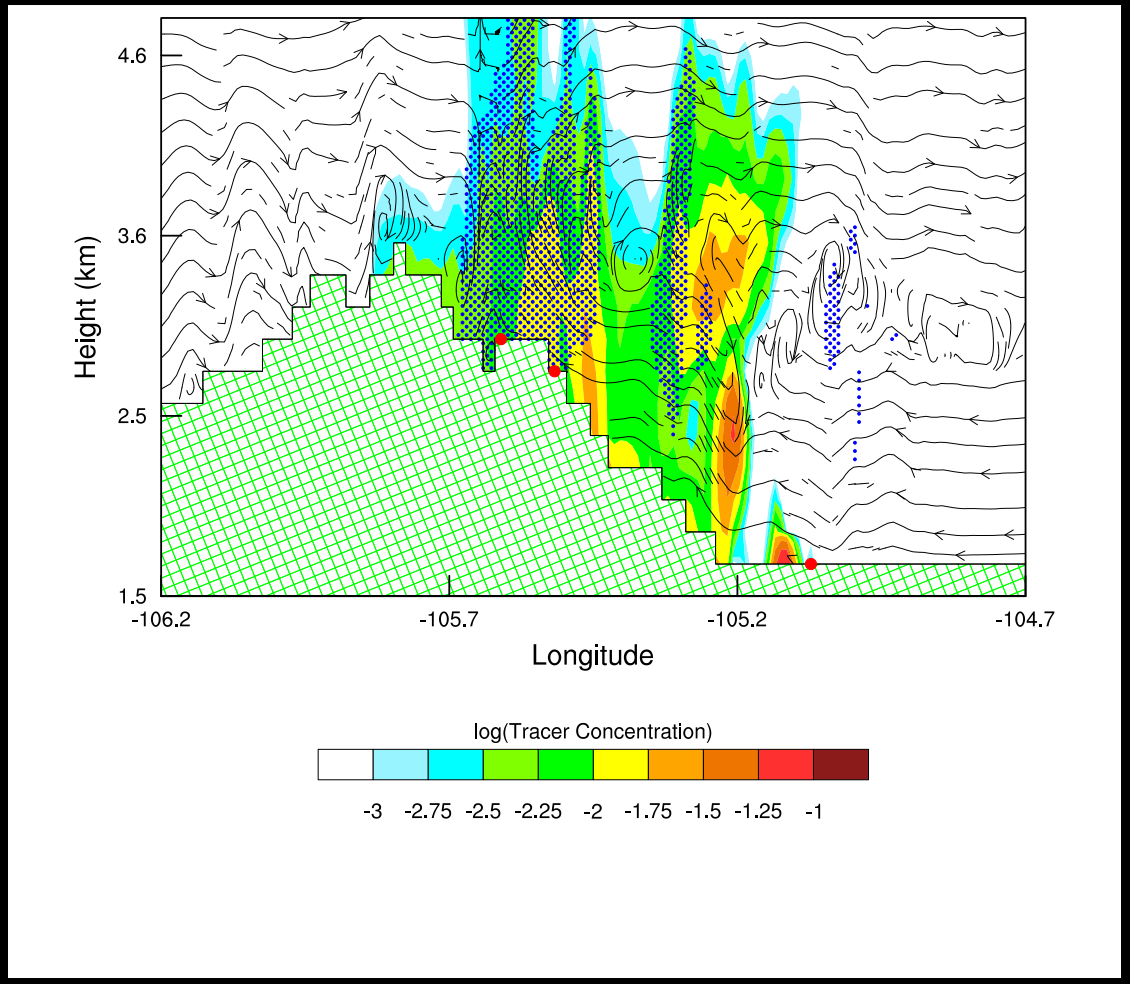
WRF output

14:10 MDT August 19, 2006



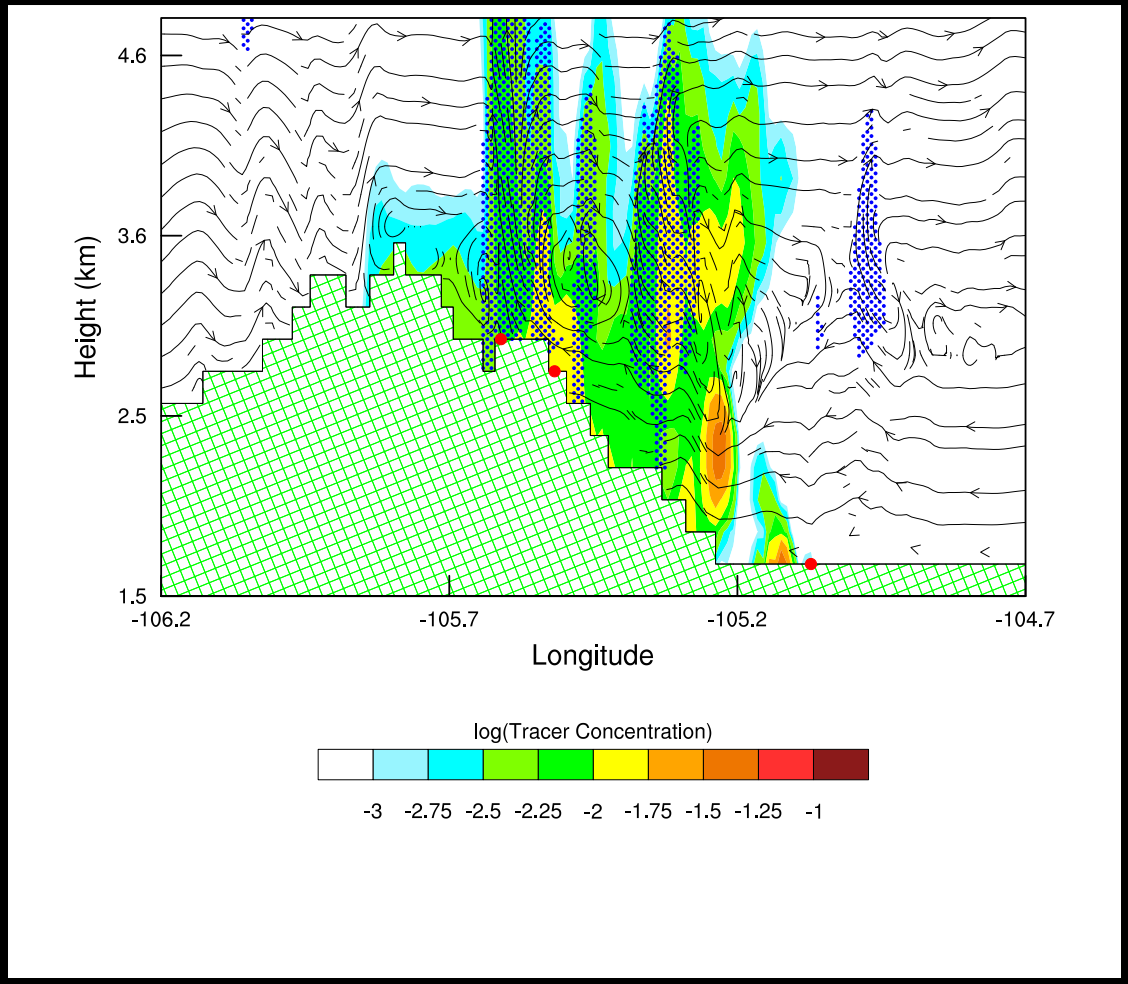
WRF output

14:20 MDT August 19, 2006



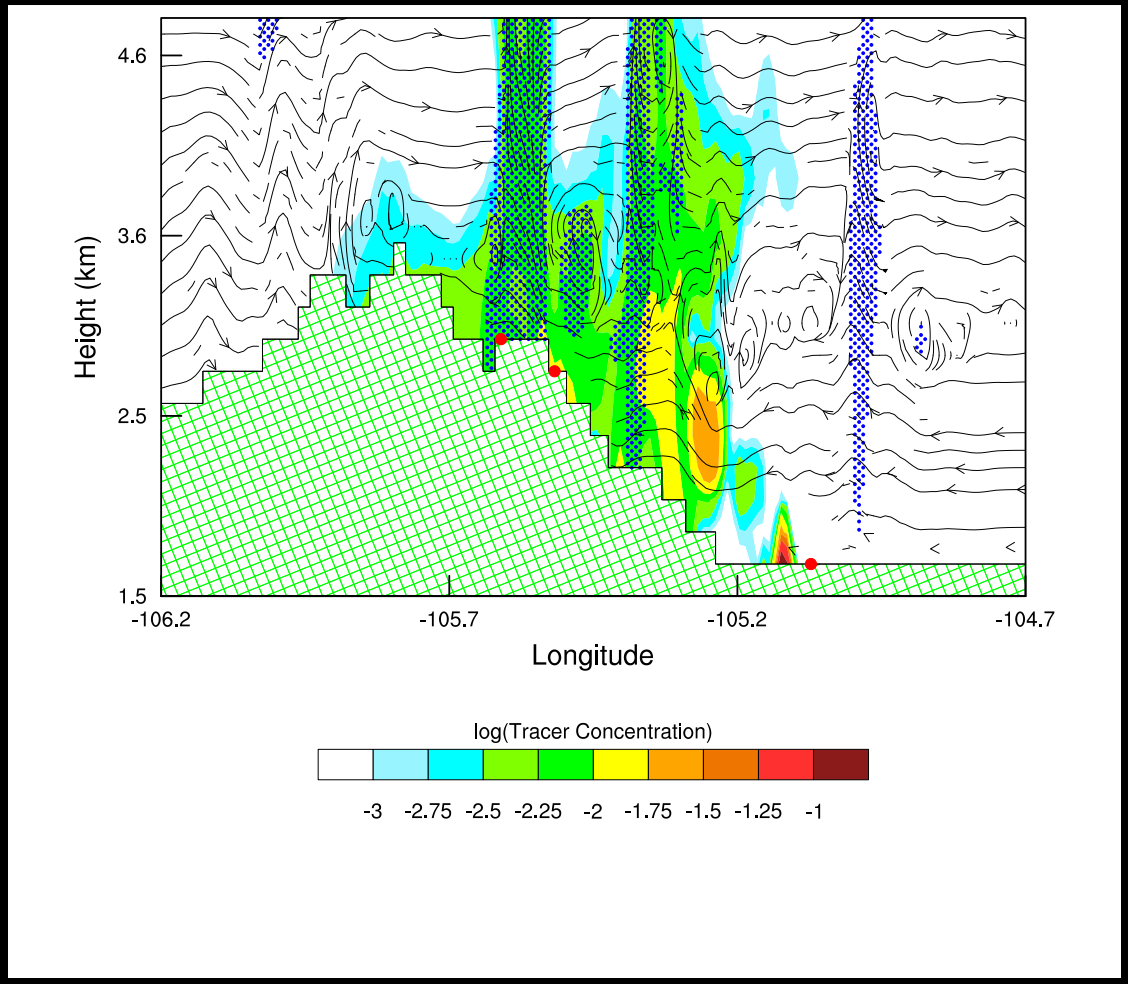
WRF output

14:30 MDT August 19, 2006



WRF output

14:40 MDT August 19, 2006



WRF output

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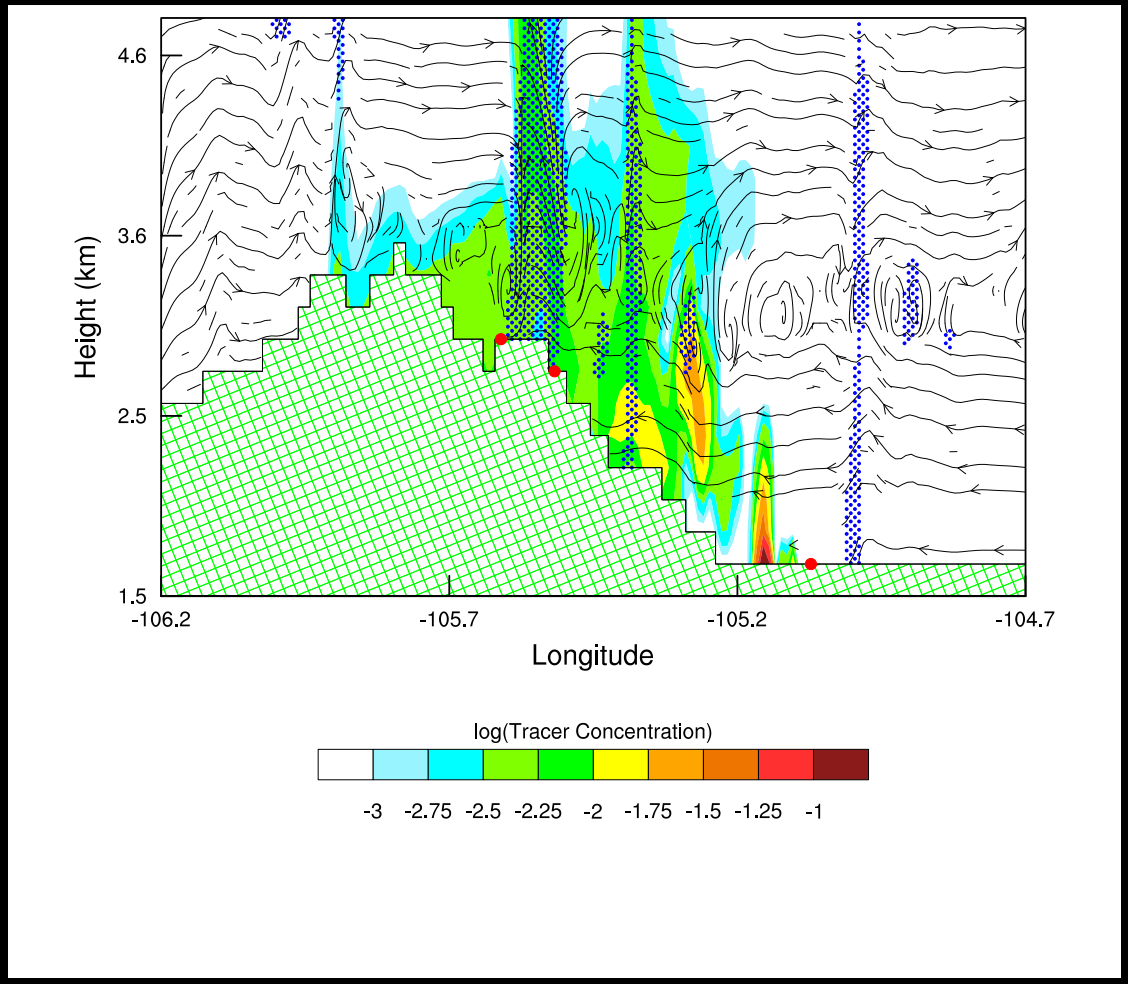
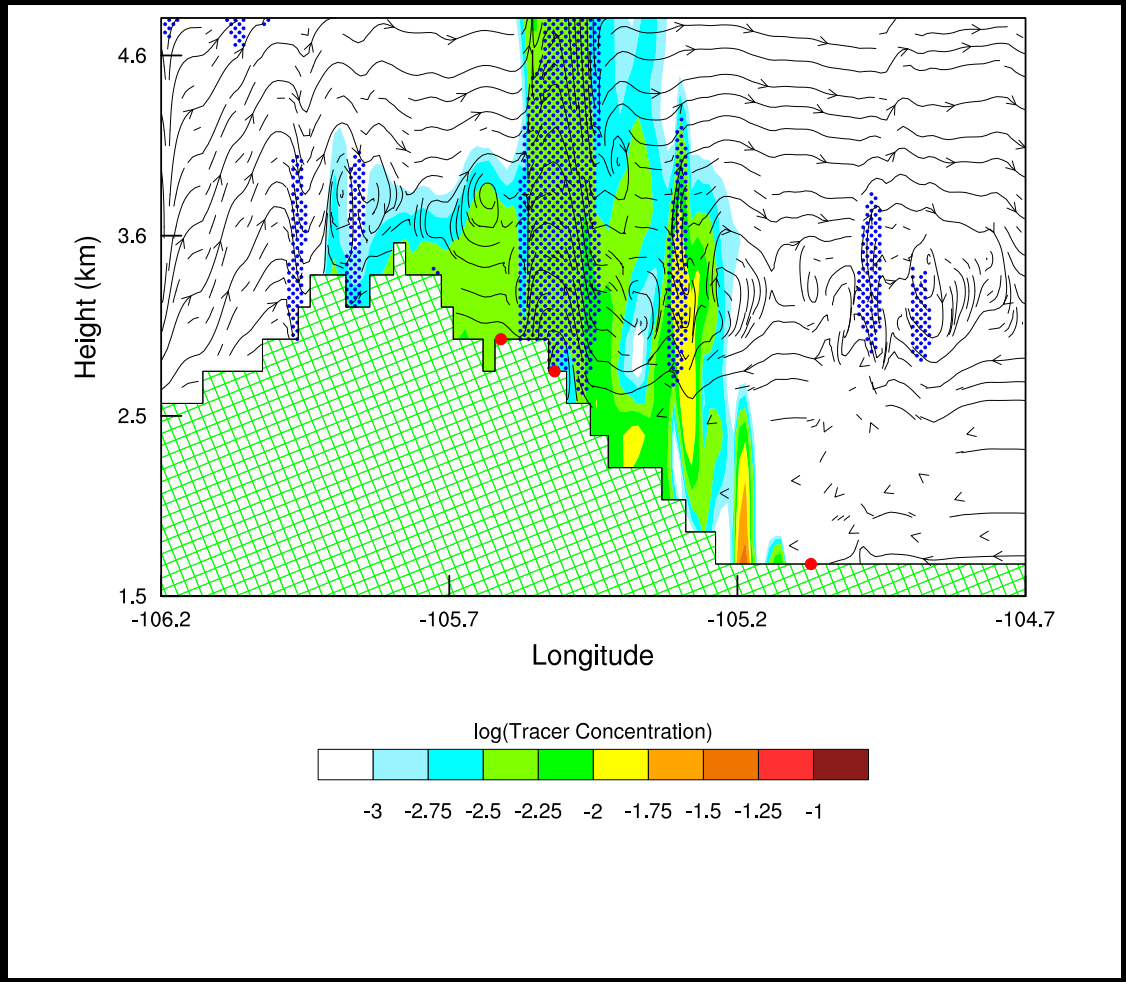


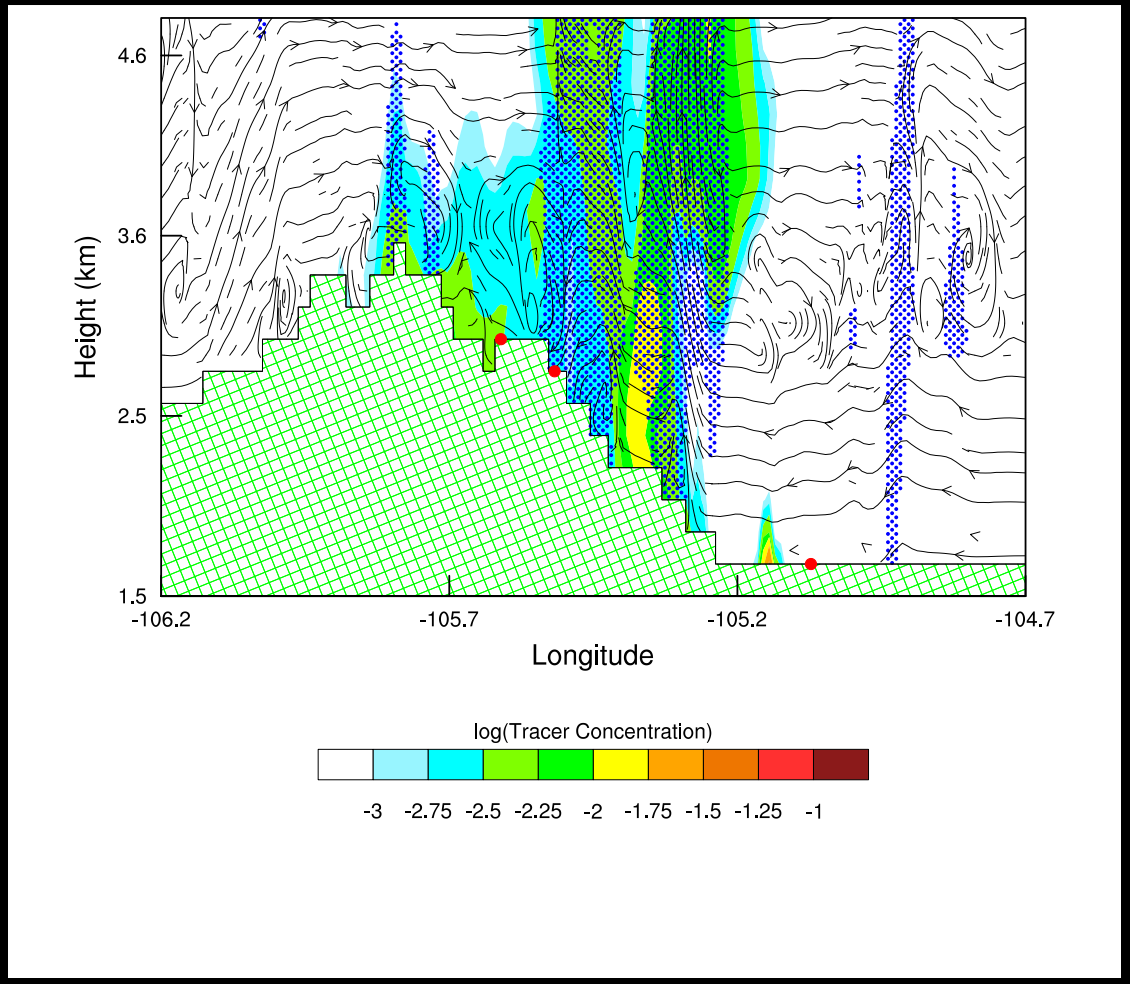
WRF output

15:00 MDT August 19, 2006



WRF output

15:10 MDT August 19, 2006



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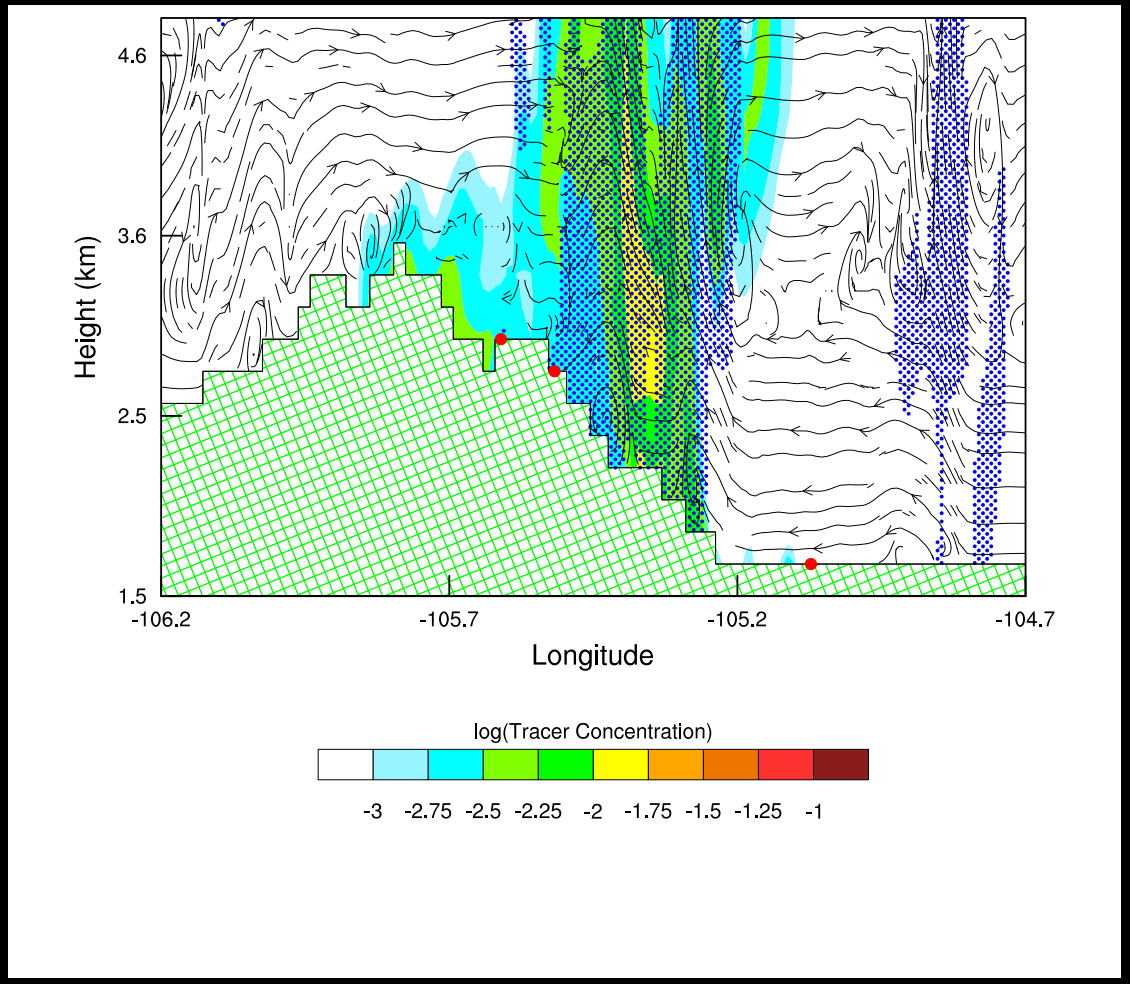
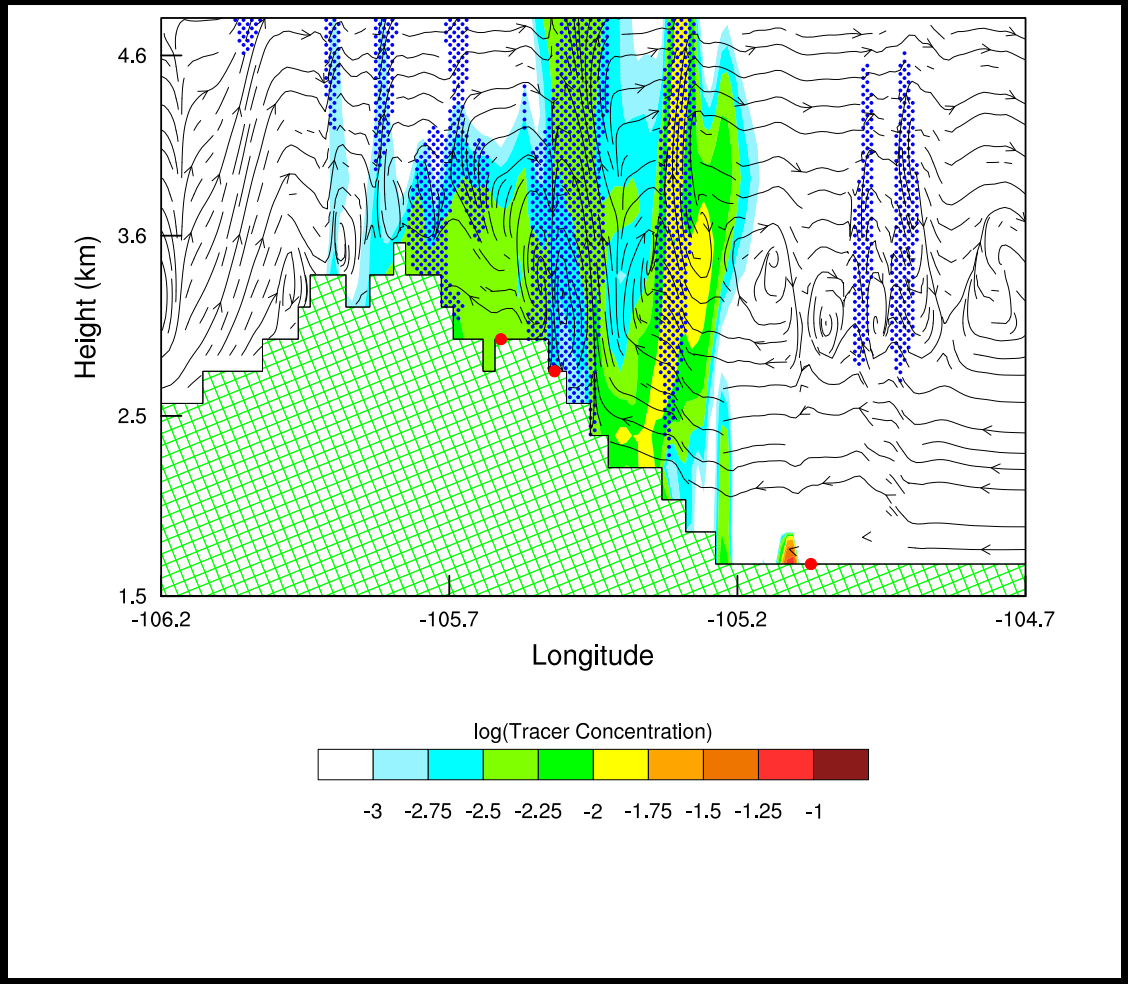


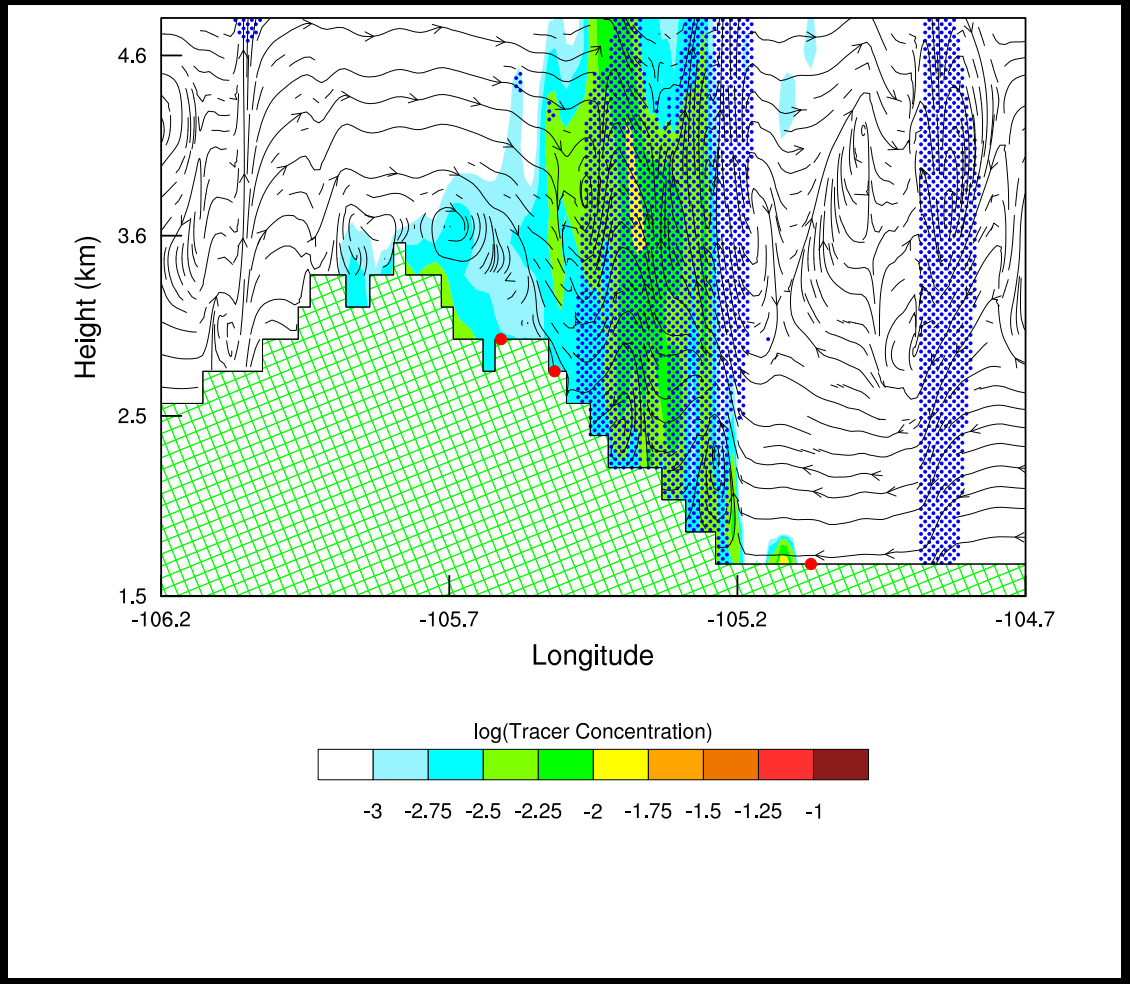
WRF output

15:30 MDT August 19, 2006



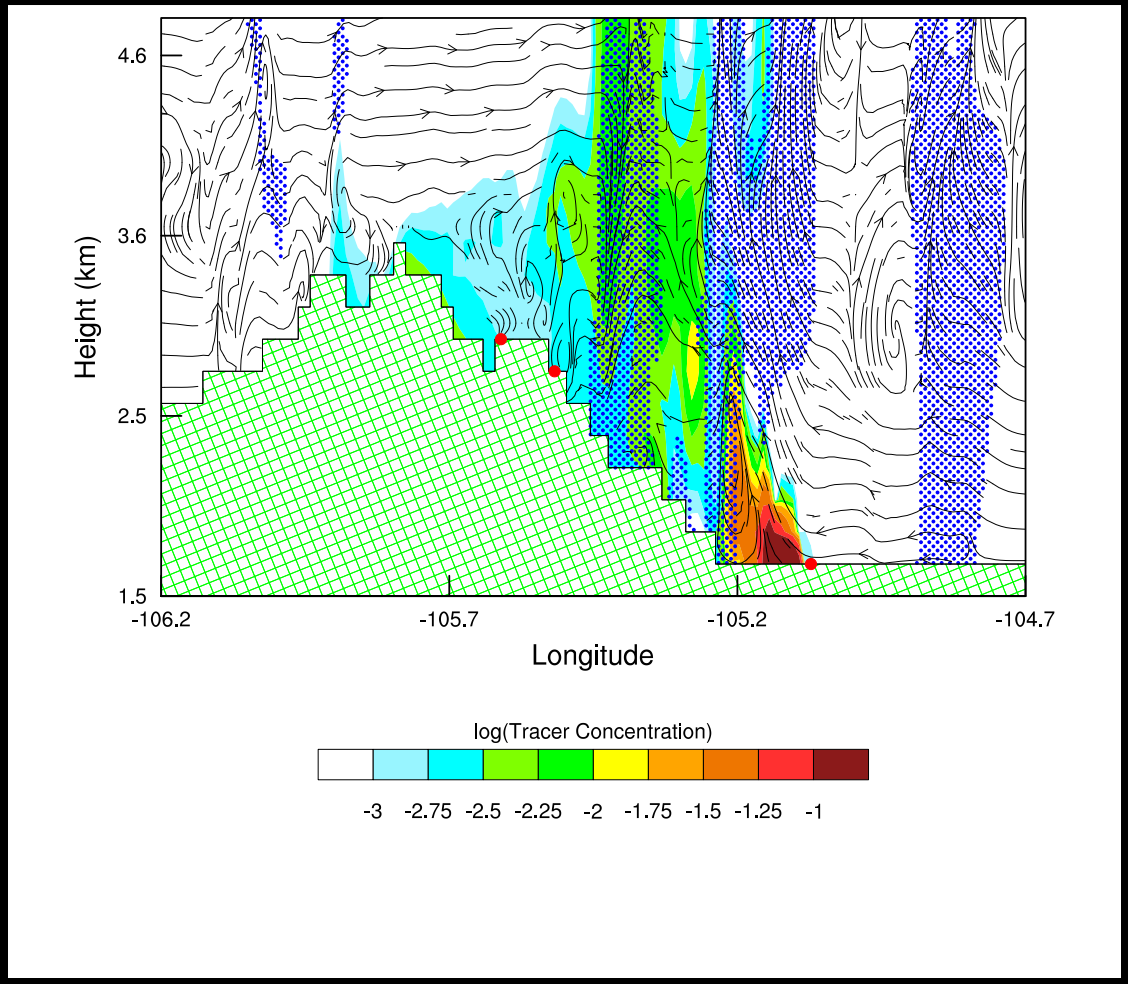
WRF output

15:40 MDT August 19, 2006



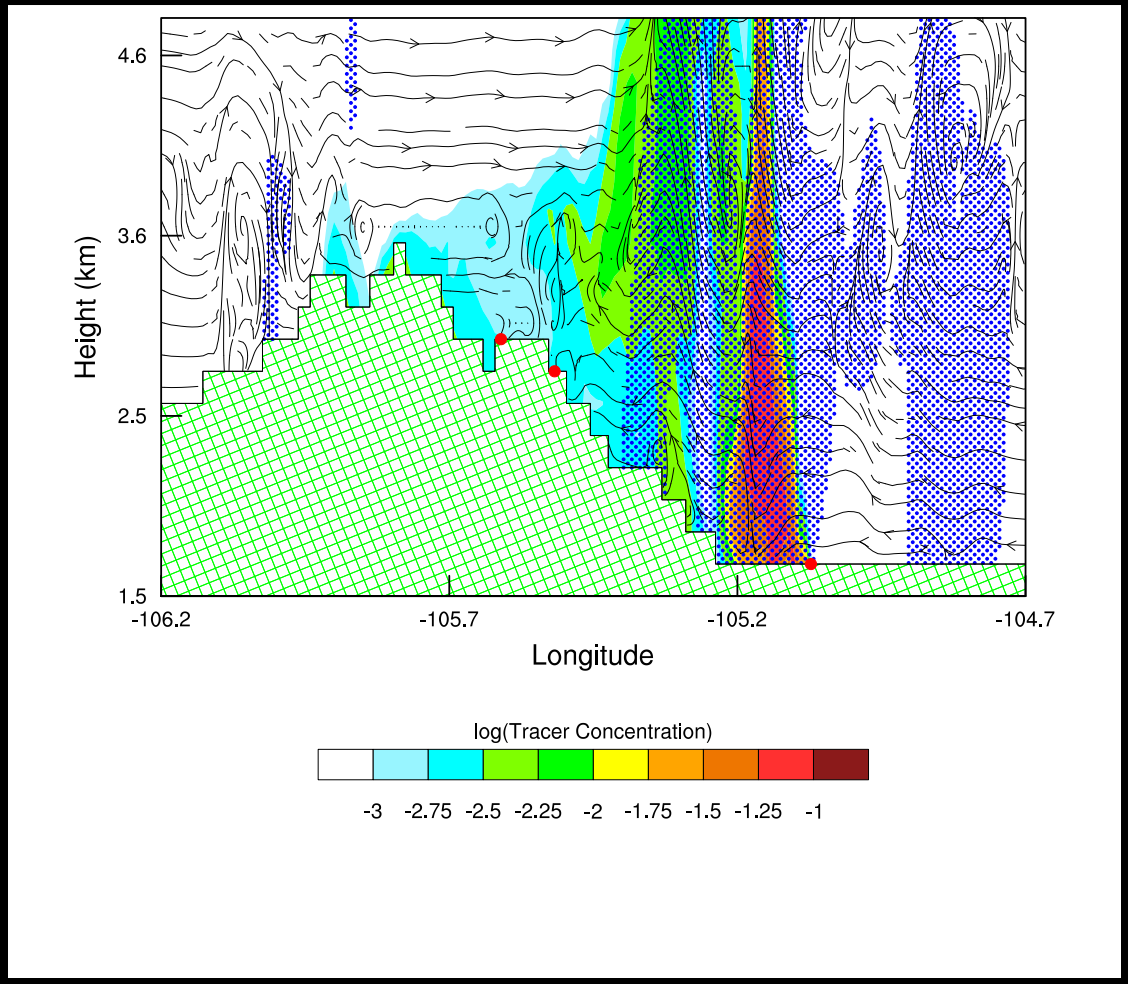
WRF output

15:50 MDT August 19, 2006



WRF output

16:00 MDT August 19, 2006



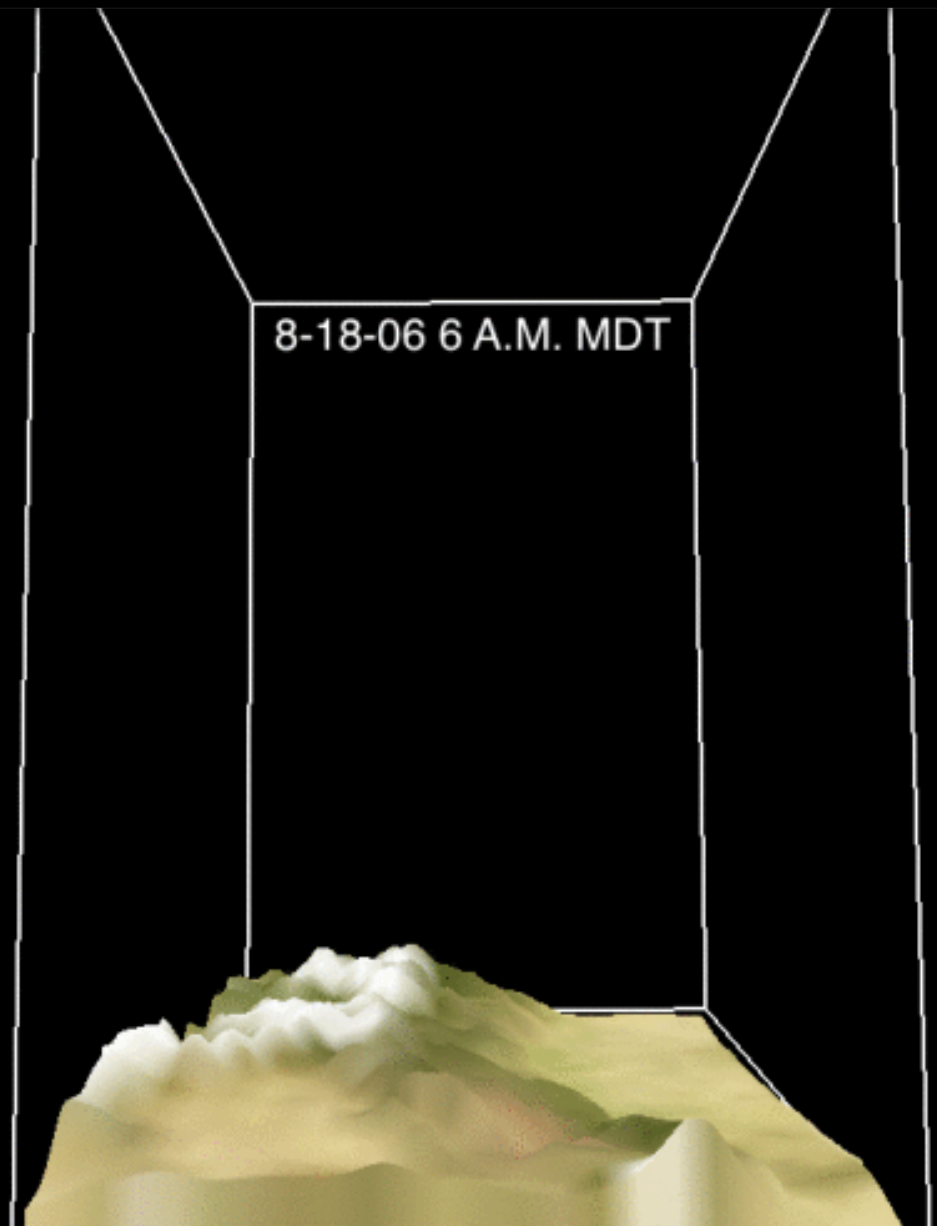
Summary until now:

- Spring and summer have the most wet deposition events
- High wet deposition is caused mostly by moist, upward transport

Next steps:

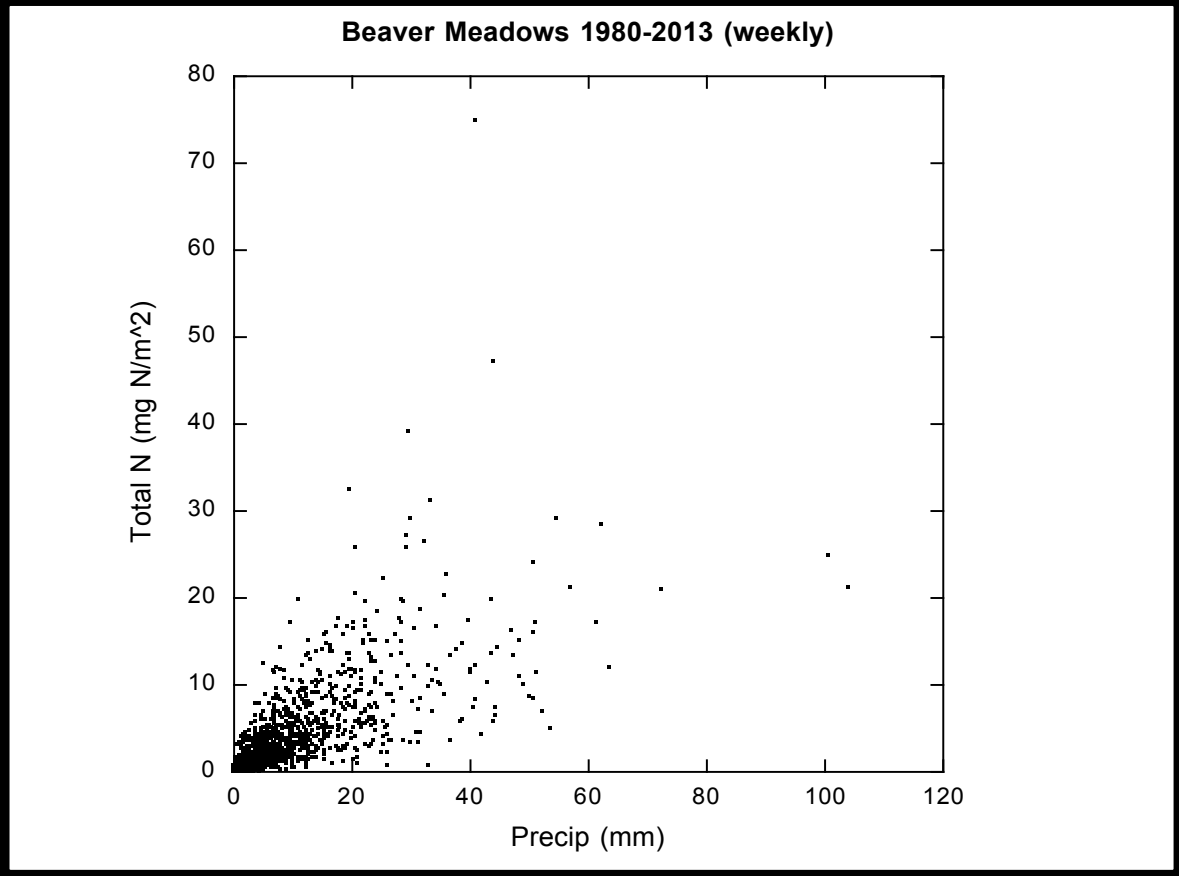
- Work towards a probabilistic prediction tool for future deposition events
- Connect transport, precip, and deposition

3D field of WRF output



Probabilistic prediction tool for nitrogen deposition in RMNP

Precip vs. deposition at Beaver Meadows



A general relationship exists between them, but it's certainly not a perfect correlation

Simple attempts at a "metric" that is associated with high deposition events

- High-deposition weeks tend to have strong easterly upslope flow with lots of moisture, generally after the passage of a cold front
- As a very simple test, let's look at a metric that combines precipitable water (i.e., column-integrated water vapor) and easterly low-level winds, with both normalized by "high" values:

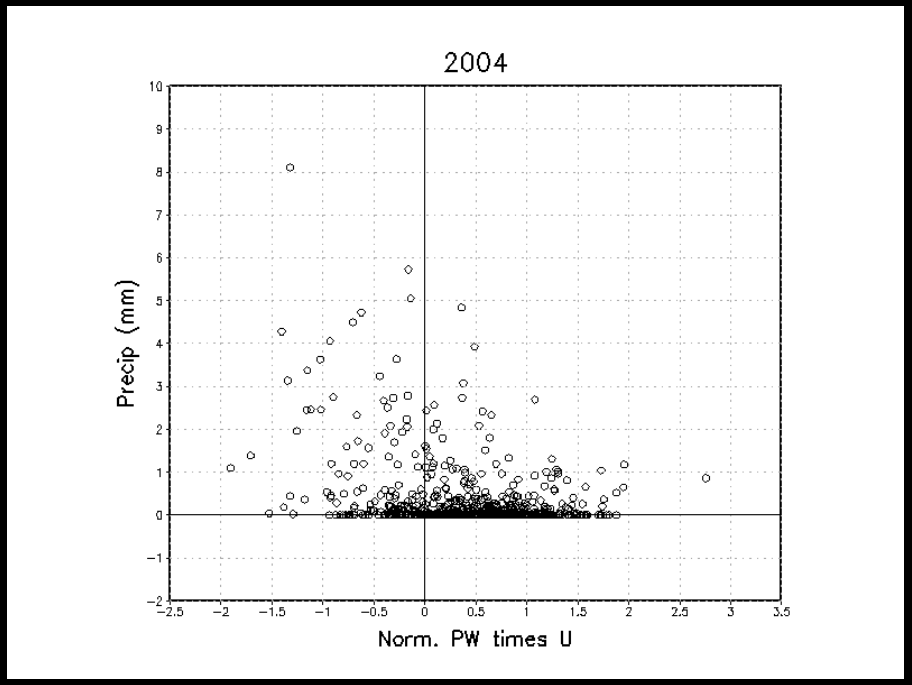
$$Q = \frac{PW}{25\ mm} * \frac{u_{850-700}}{2.5\ m\ s^{-1}}$$

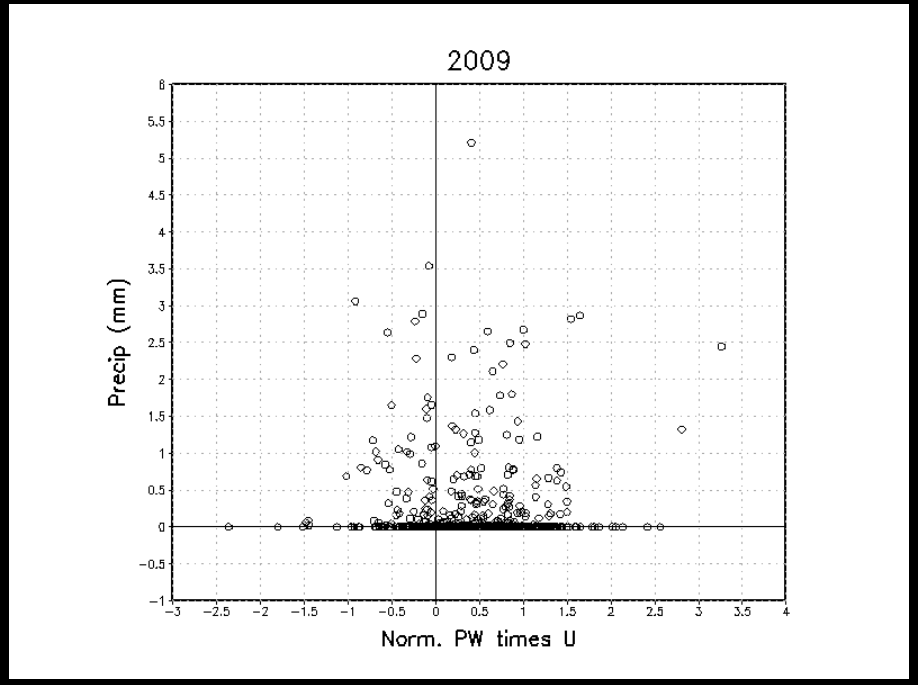
- Where values of this quantity are large in magnitude and negative, there is strong upslope flow and ample moisture, which should account for both transport of emissions and likelihood of precipitation

Remember! Upslope flow = negative u

How well does this predictor do generally?

In terms of predicting precipitation along the northern Front Range, it appears to do ok, but could be better



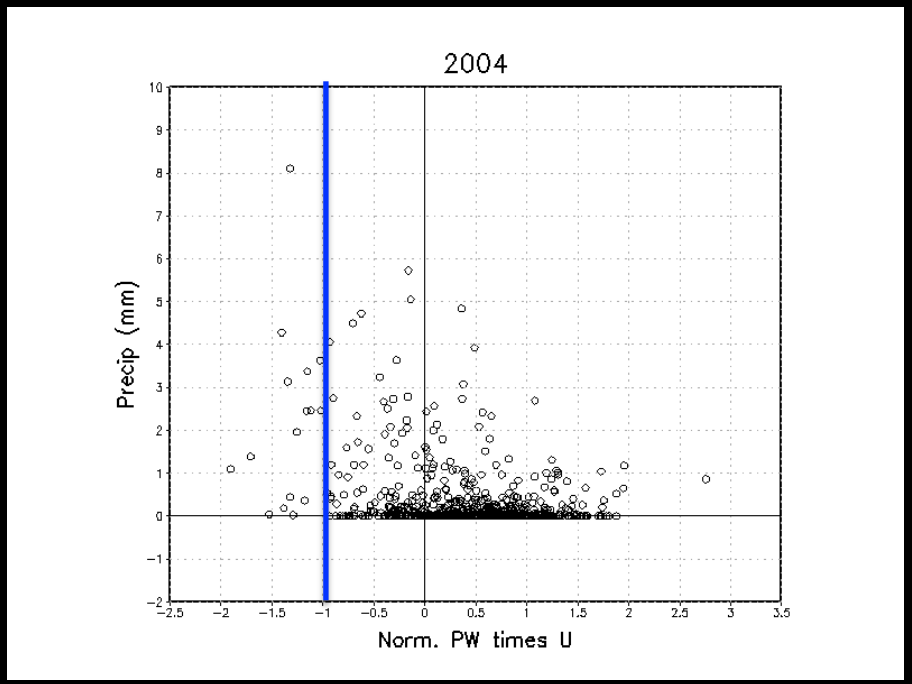


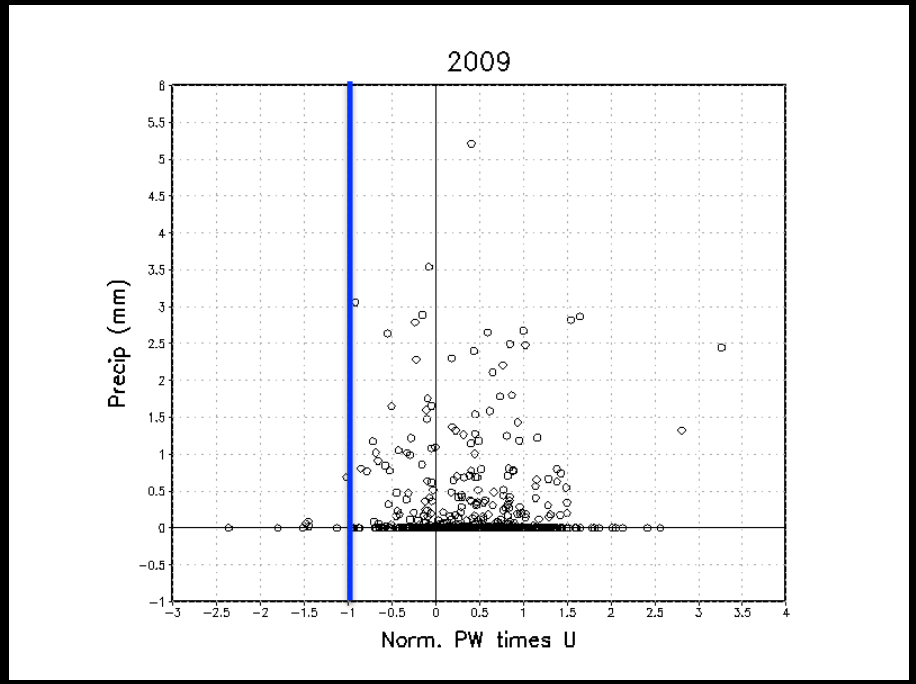
2004: strong correlation between negative "Q" and precip;
there were several high-deposition events that matched up well, though also a few false alarms

2009: not much correlation, though there were only a few periods with high Q and no major rain events (or deposition events)

How often do we see these conditions?

- 12 out last 20 years had trends up to the left
- On average, there are ~15 three-hour periods each summer with Q < -1 over northern CO, many of them consecutive
- This suggests that the “early warnings” would not need to be issued on that many days, but thresholds for these warnings still need to be determined

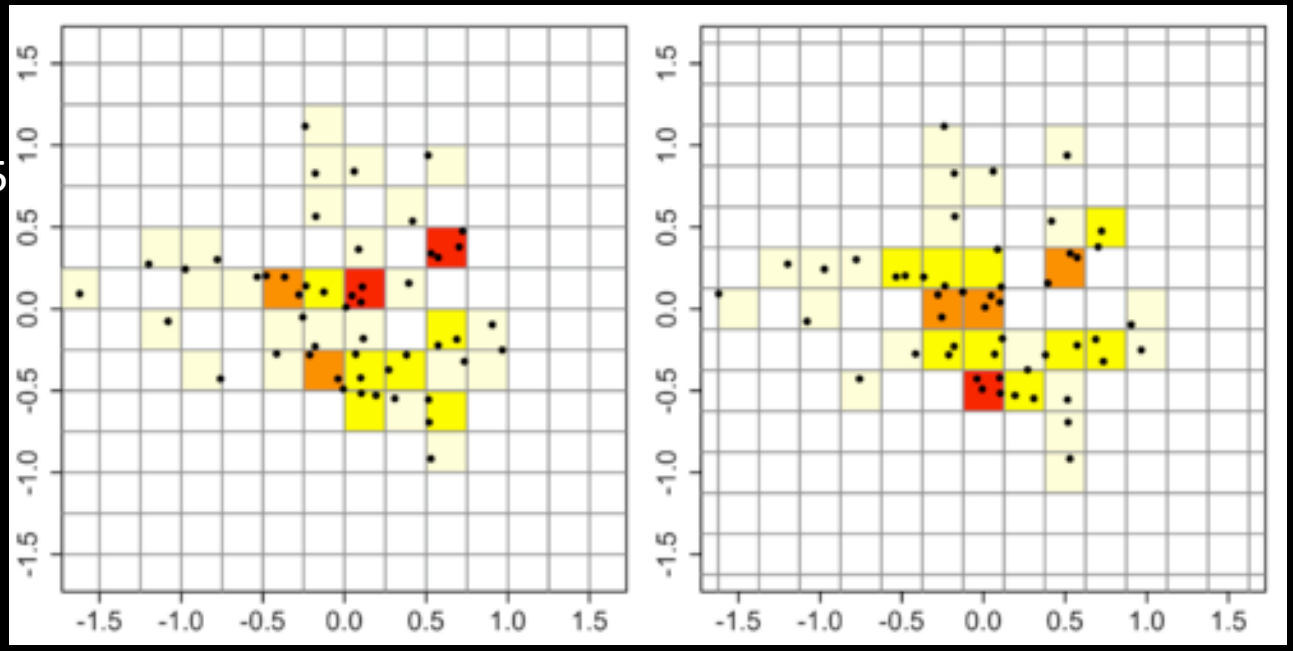




Density Estimation

- Histogram is the most widely known form of density estimation
- Histograms are biased by starting point and bin width

Anchor point:
(-1.5, -1.5)
Binwidth: 0.25

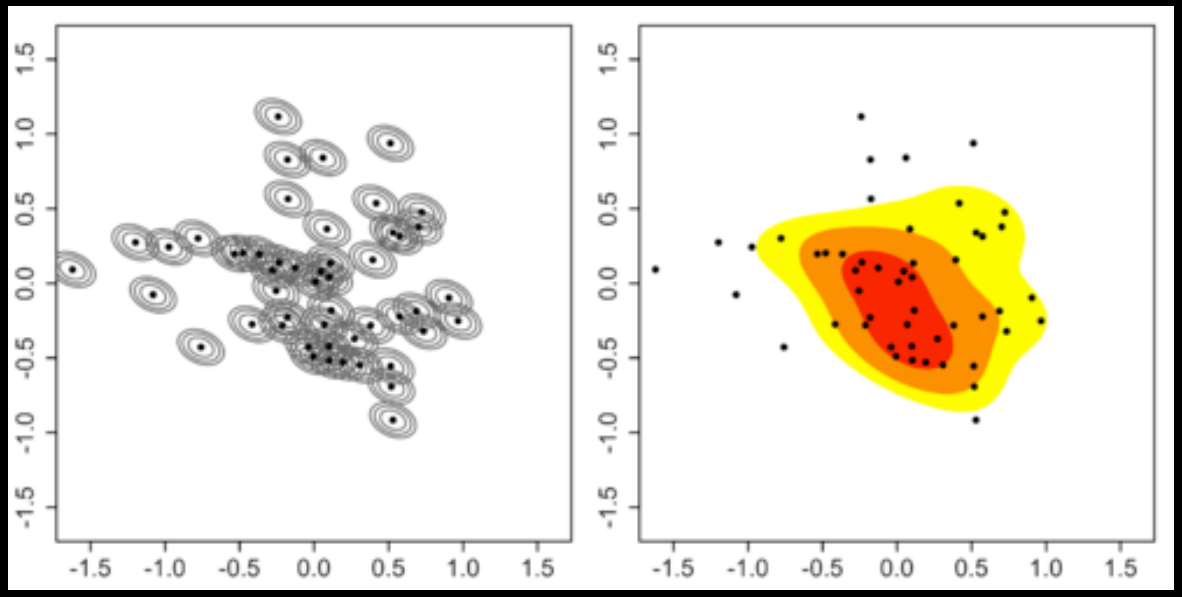


Anchor point:
(-1.625, -1.625)
Binwidth: 0.25

http://en.wikipedia.org/wiki/Multivariate_kernel_density_estimation

Kernel Density Estimation

- Finite sample → PDF everywhere, including where no data are observed
- Each point is smoothed into a space surrounding it



Probability mass:

Red = 25%

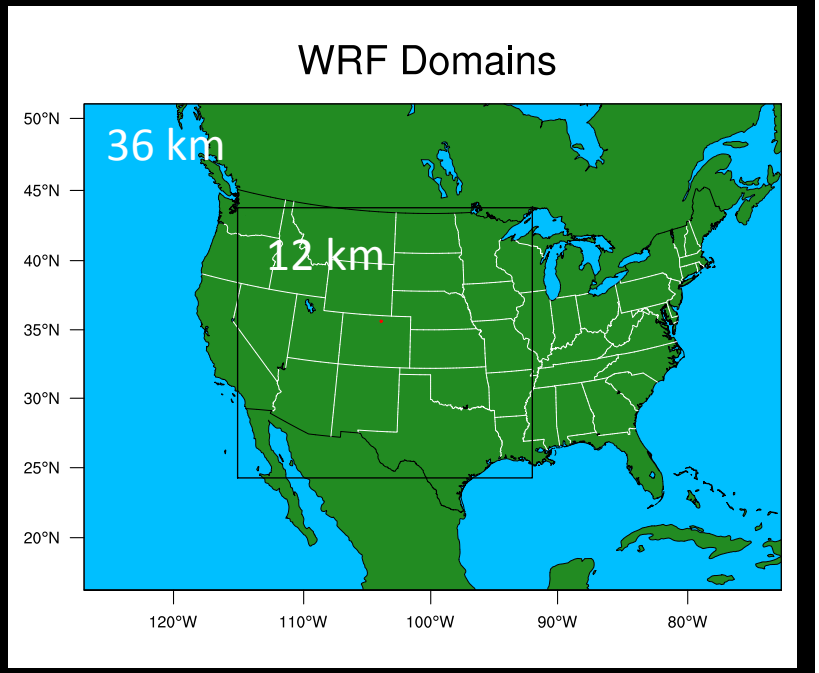
Red+Orange = 50%

R + O + Y = 75%

http://en.wikipedia.org/wiki/Multivariate_kernel_density_estimation

Back to WRF

- WRF-ARW v3.3.1
- Operational: 0z run every day
- 5 runs with 12-km grid spacing

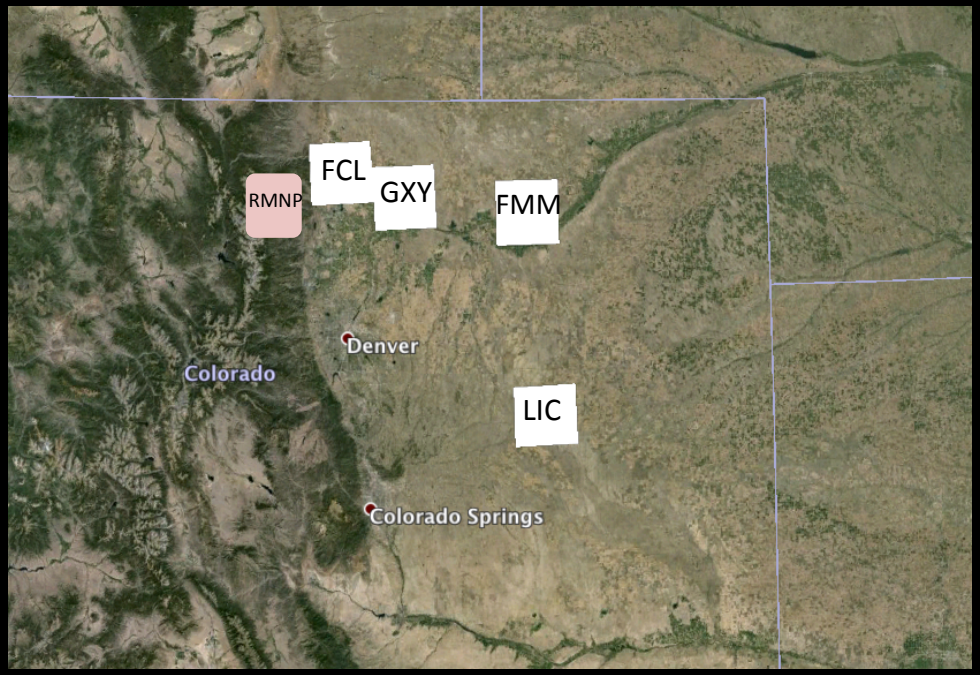


WRF physics options

	Member 1	Member 2	Member 3	Member 4	Member 5
Initial/Boundary conditions	0.5 degree GFS, BCs updated every 3 hours	0.5 degree GFS, BCs updated every 3 hours	40-km NAM, BCs updated every 3 hours	40-km NAM, BCs updated every 3 hours	ICs come from a cycled WRF/WRF-VAR forecast and assimilation system, BCs come from the 6-hours earlier 0.5-degree GFS forecast
Cumulus	Kain-Fritsch	Grell-Devenyi 3 (G3)	Betts-Miller-Janjic	Kain-Fritsch	G3
Boundary layer	MYJ	YSU	MYJ	MYJ	YSU
Microphysics	WSM 6-class	Thompson	Goddard	Thompson	Goddard
Land surface	Noah	Noah	Noah	Noah	Noah
Shortwave radiation	Dudhia	Dudhia	Goddard	Dudhia	Goddard
Longwave radiation	RRTM	RRTM	RRTM	RRTM	RRTM

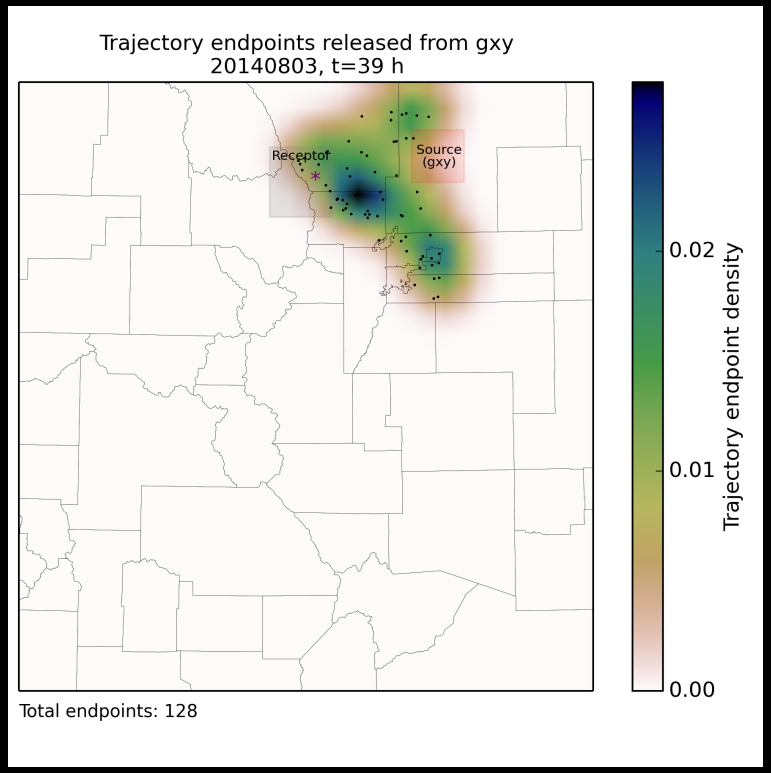
WRF trajectories

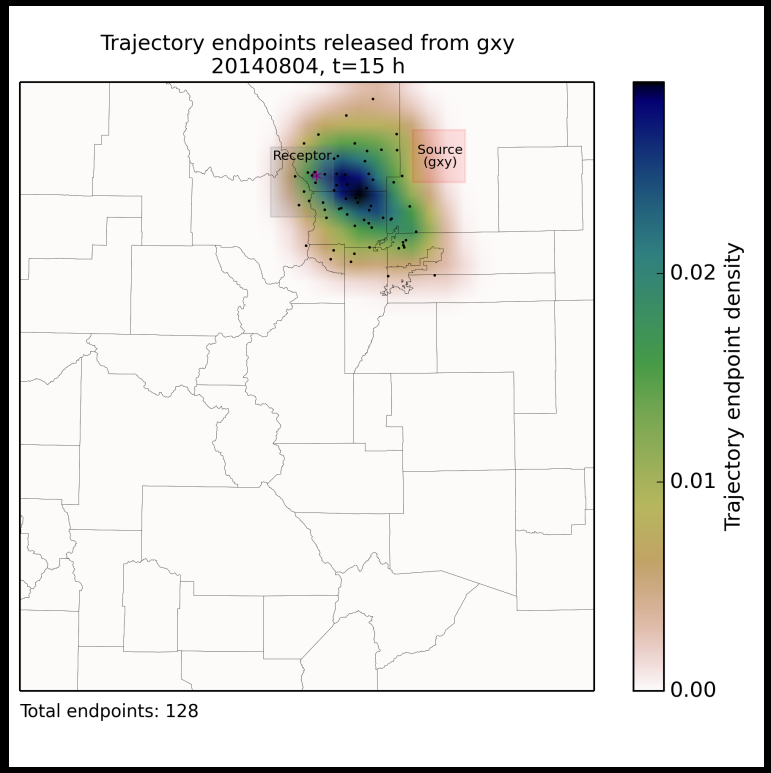
- 32 grid points per run released every 3 hours from FCL, GXY, FMM, and LIC
- Saved endpoints from 6-hour forward trajectories



Applying KDE to trajectory endpoints

Monday, 04 Aug 2014 9 AM local time





Limitation! Will need to verify collocated precipitation

Next steps

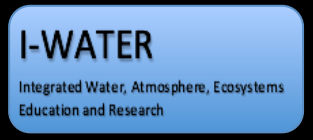
- Collocation with rain
- Concentration vs precipitation
- Setting a threshold for KDE
- Forecast skill
  - NADP reports
  - Complexity added with ranchers changing management

Summary

- Seasonality in precipitation and deposition (NADP)
- Cloud-scale convection is just as important as mesoscale mountain-valley circulation
- Probability prediction tool is operational but we still have some tuning to do

Acknowledgements

- This research was supported by the National Science Foundation under Grant No. 0966346 and the National Park Service under award P13AC00599, project number CSURM-273.
- Matt Bishop for computing help
- Russ Schumacher, Cameron Homeyer, and Gus Alaka for help with WRF
- Denning biocycle group
- I-WATER program
- CMMAP & SOARS



Questions?

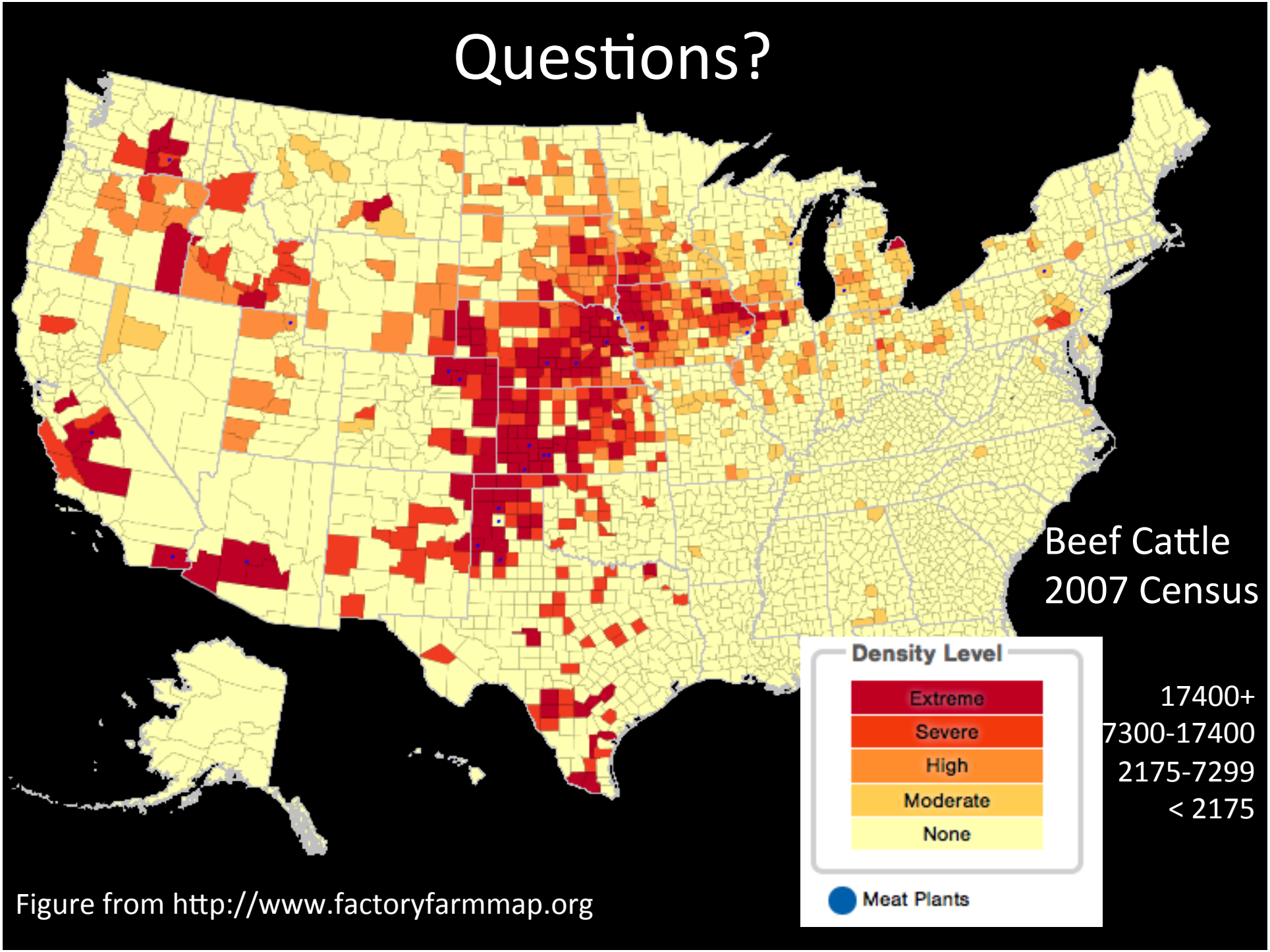
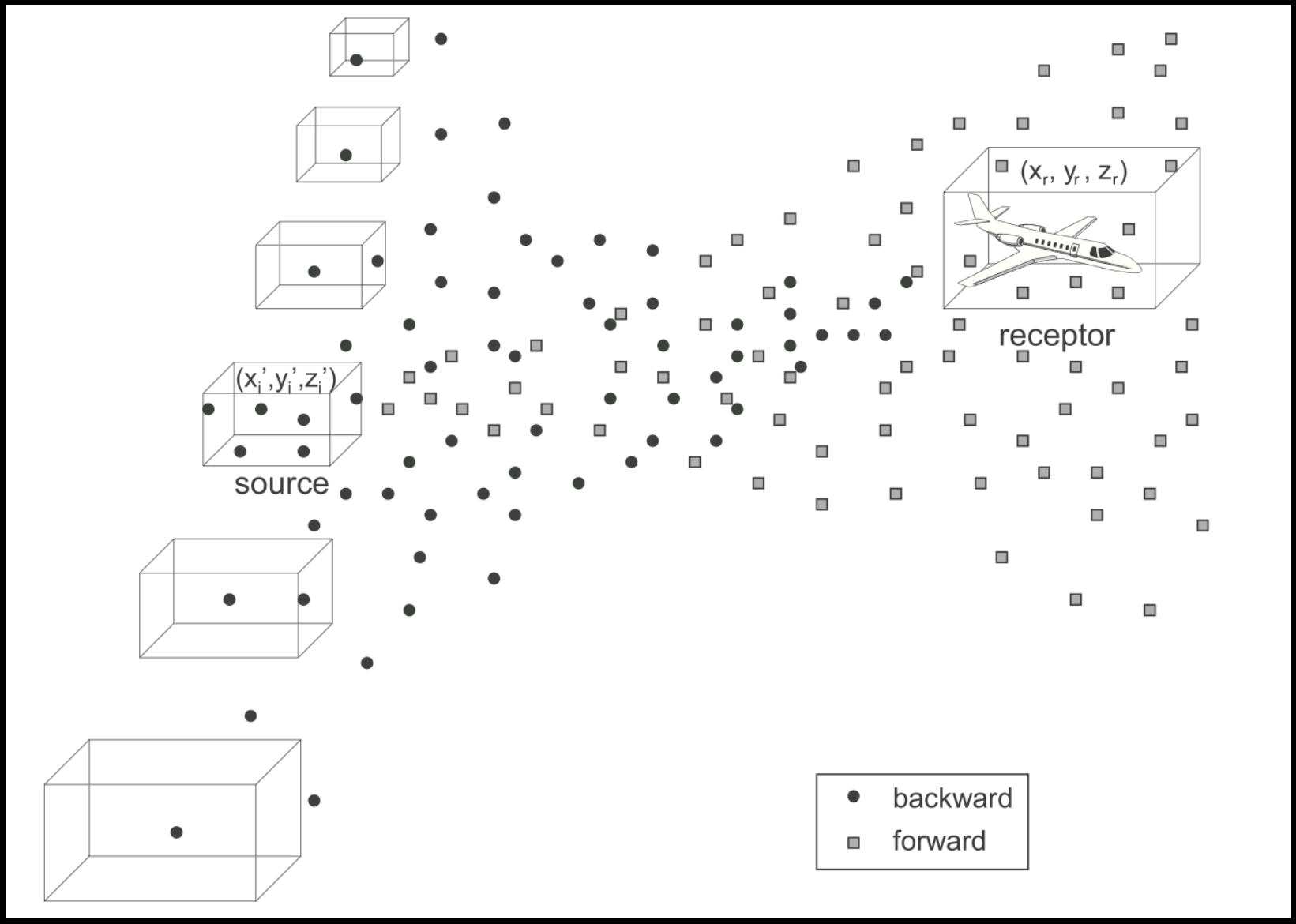


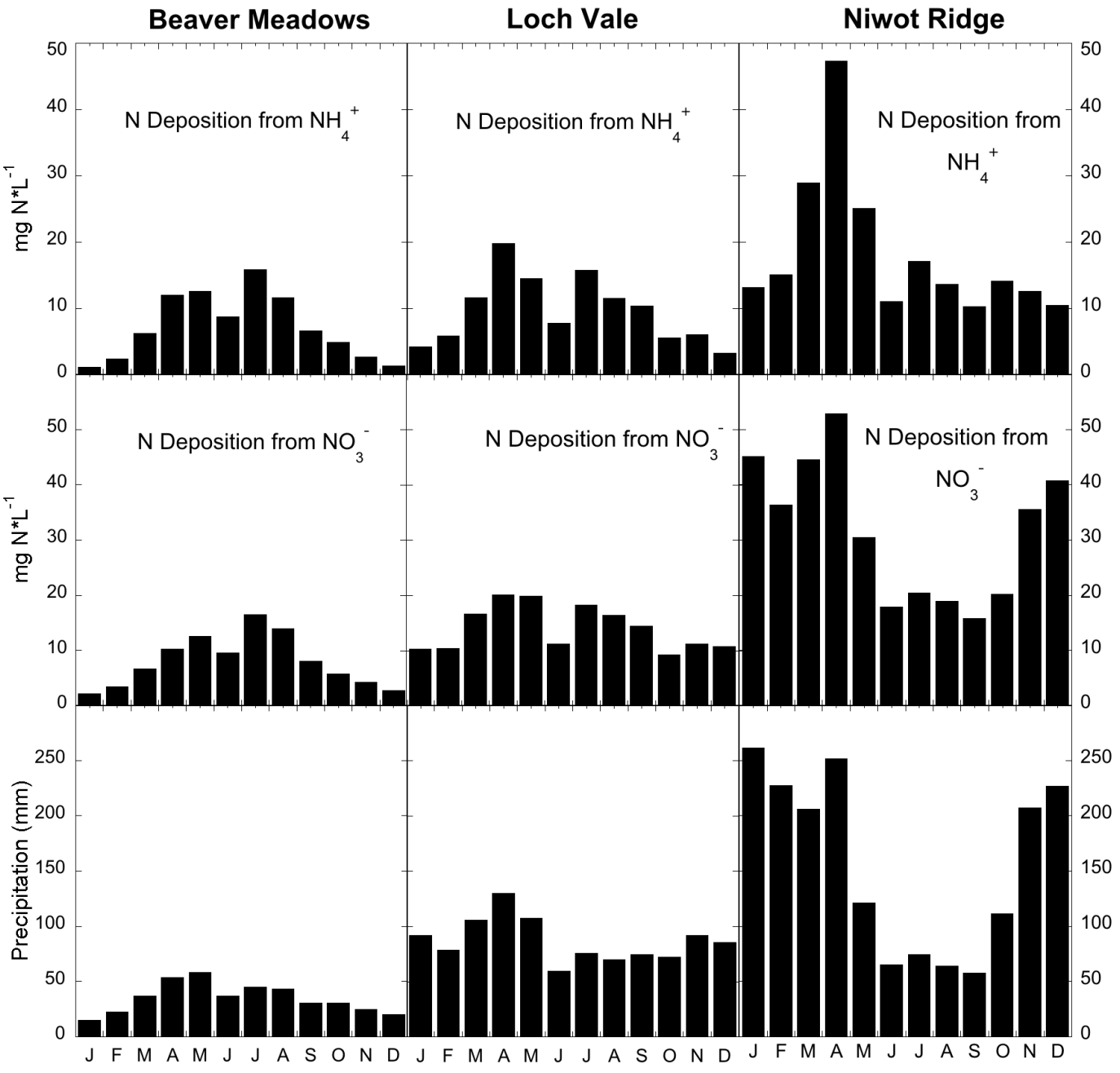
Figure from http://www.factoryfarmmap.org

Future Work – STILT

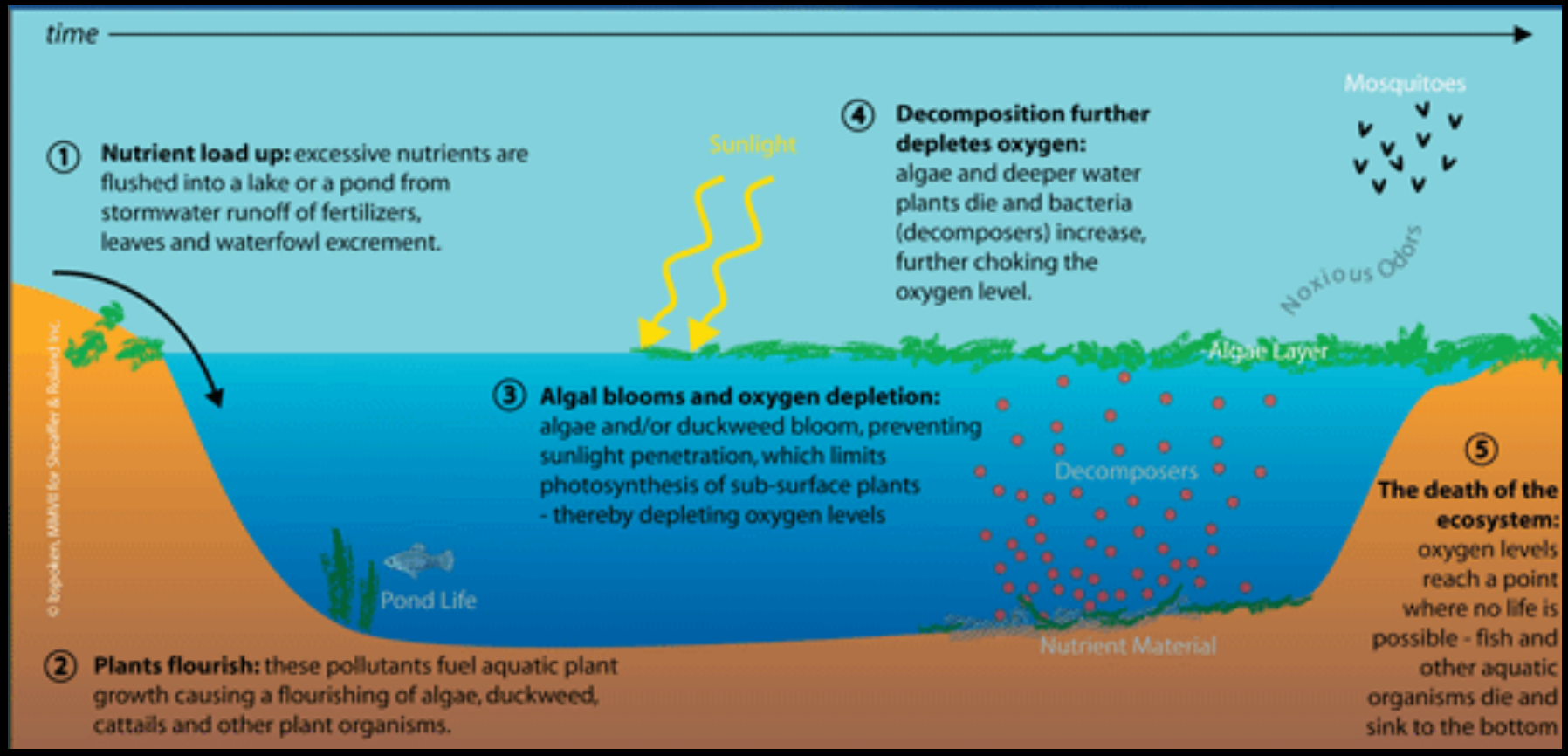


Lin et al. (2003)

Mt. Elbert

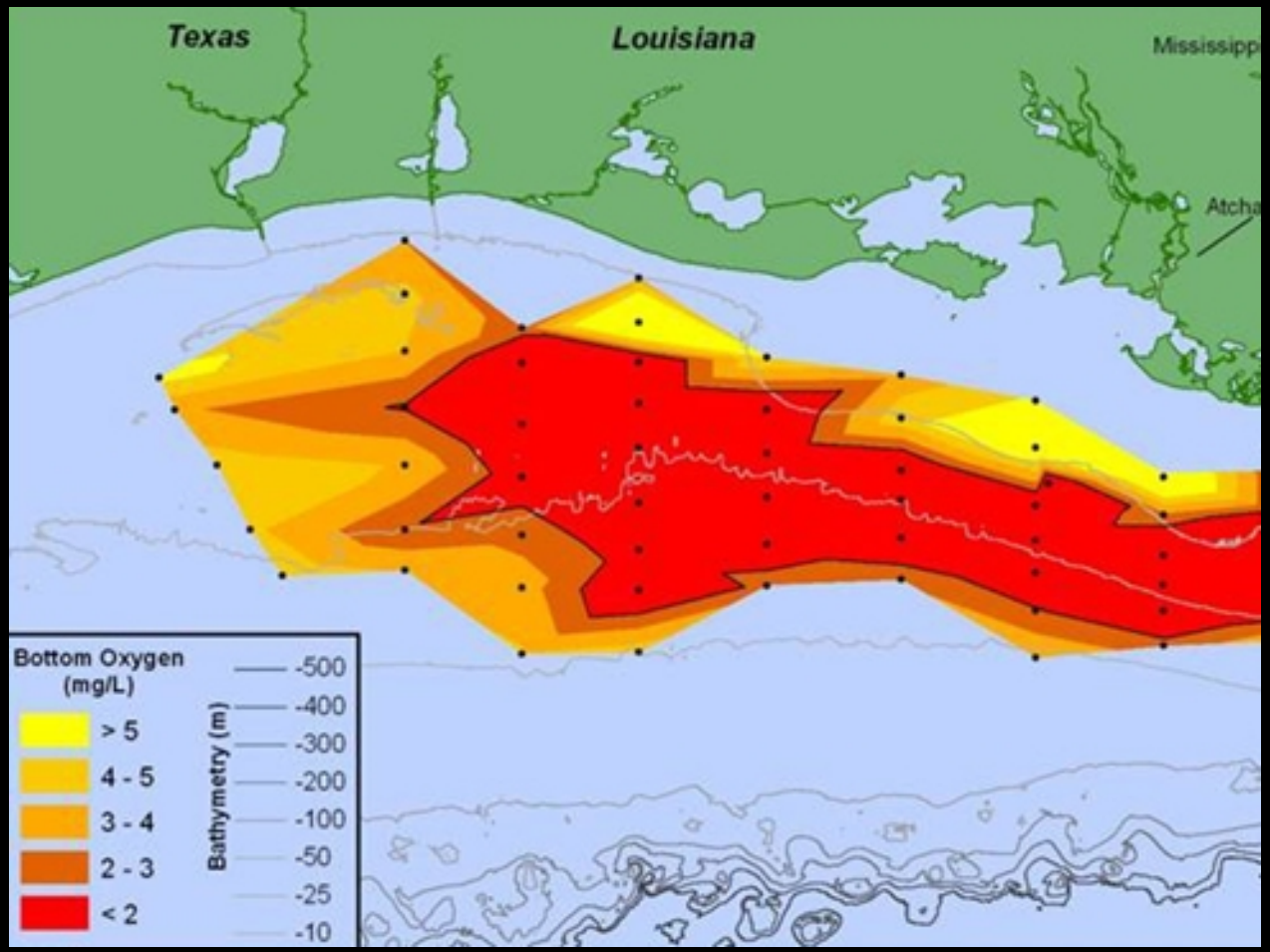

Beaver Meadows
Loch Vale
Niwot Ridge
N Deposition from NH4+
N Deposition from NO3-
mg N*L-1
Precipitation (mm)
0
10
20
30
40
50
0
50
100
150
200
250
J F M A M J J A S O N D

Effects of Nitrogen-loading



Recently in the news…

Gulf Coast



Recently in the news…

Forget the lottery, invest in climate change solutions

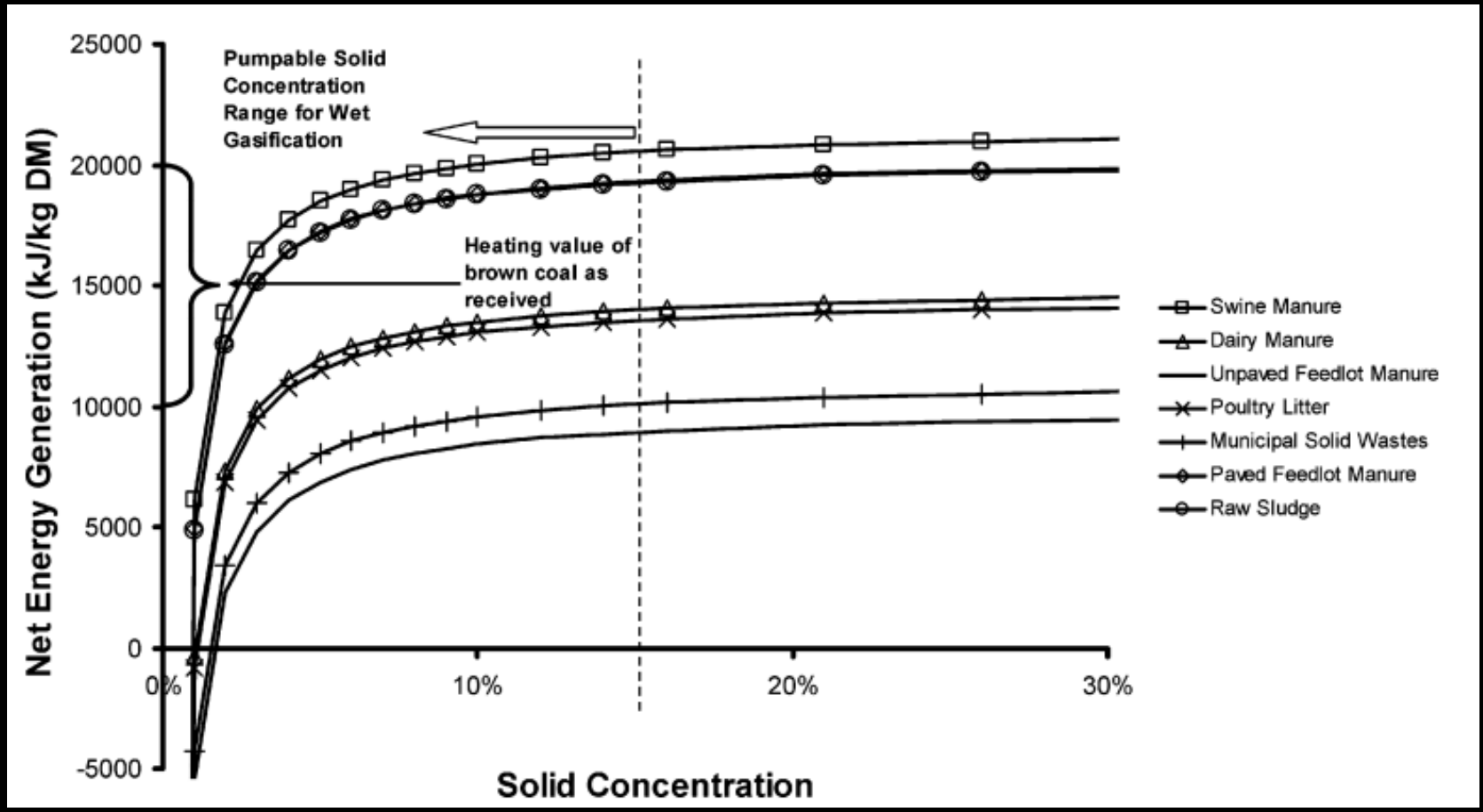
CNBC

Published: Thursday, 5 Sep 2013 | 3:58 PM ET

By: Terry Tamminen | President, Seventh Generation Advisors

Each hog produces about 300 gallons of manure over the course of its life, and all that waste could be converted to electricity and diesel fuel using modern gasification technology. Imagine the economic benefits versus **oil**—which hit record highs again last week—and the far-lower carbon footprint of that feedstock for producing domestic, renewable energy.

Cows Emissions → Energy



Feedlot Cow Emissions → Energy

Feedlot cows:

- Produce 12 tons of manure per year per 1000 lbs
- Live 2 years
- Are slaughtered at 1000 lbs

Manure and energy

- ~14 MJ/kg (from previous plot)

So how much energy?

Solving the Problem

Manure per year	*	Life expectancy	*	Energy per unit weight	*	Weight conversion
$\frac{12 \text{ tons}}{1 \text{ year}}$	*	2 years	*	$\frac{14 \text{ MJ}}{1 \text{ kg}}$	*	$\frac{907.18 \text{ kg}}{1 \text{ ton}}$

$$= \quad 304.8 \text{ GJ}$$

6.1 GJ ≈ potential chemical energy stored in 1 barrels of oil

∴ 1 cow ≈ 50 barrels of oil!!!