A Winter Season Physical Evaluation of the Effects of Cloud Seeding in the Colorado Mountains

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Introduction

In this research we apply the CSU Regional Atmospheric Modeling System (RAMS) to simulate cloud seeding operations supported by the Denver Water Department (DWD). The DWD's cloud seeding program is operated by Western Weather Consultants, LLC .

Hydrometeor Types

- Cloud droplets
- Rain
- Pristine ice (crystals)
- Snow
- Aggregates
- Graupel
- Hail

Ice Habits

Pristine ice and snow are allowed to have any of five different habits (shapes): columns, needles, dendrites, hexagonal plates, and rosettes. The dependence of mass and of fall velocity on diameter are different for each habit.

Microphysical Processes Represented in RAMS

- Cloud droplet nucleation in one or two modes
- Ice nucleation
- Vapor deposition growth
- Evaporation/sublimation
- Heat diffusion
- Freezing/melting
- Shedding
- Sedimentation
- Collisions between hydrometeors
- Secondary ice production

Natural Ice Crystal Nucleation

1. Deposition nucleation
   Condensation freezing

$$N_i = N_{IFN} \exp\left[12.96\,(S - S_o)\right]$$

$$S_o = 0.4$$

vapor $\longrightarrow$ IFN

$T < -5^{o}C$

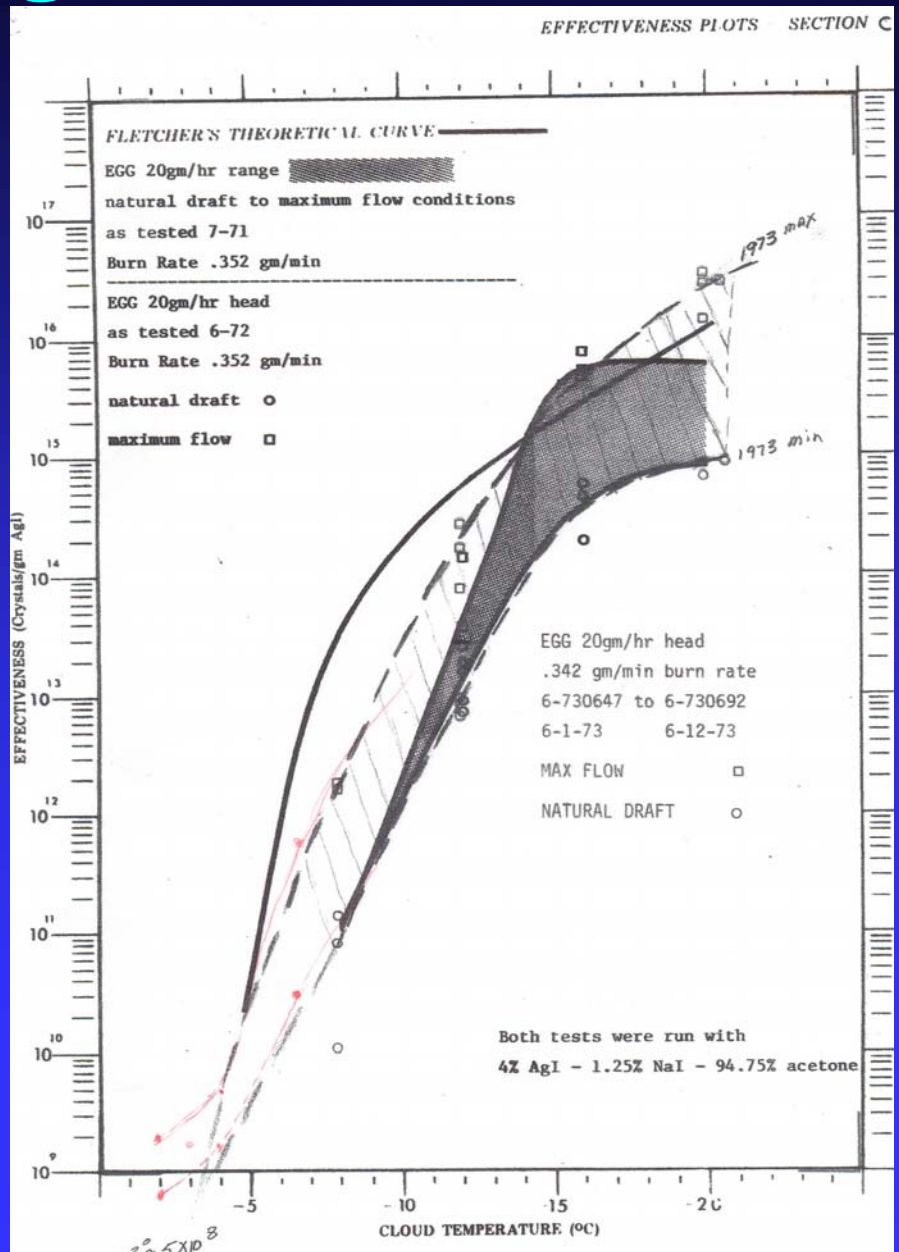
$r_v > r_{si}$ (supersaturation with respect to ice)

vapor $\longrightarrow$ CCN / IFN

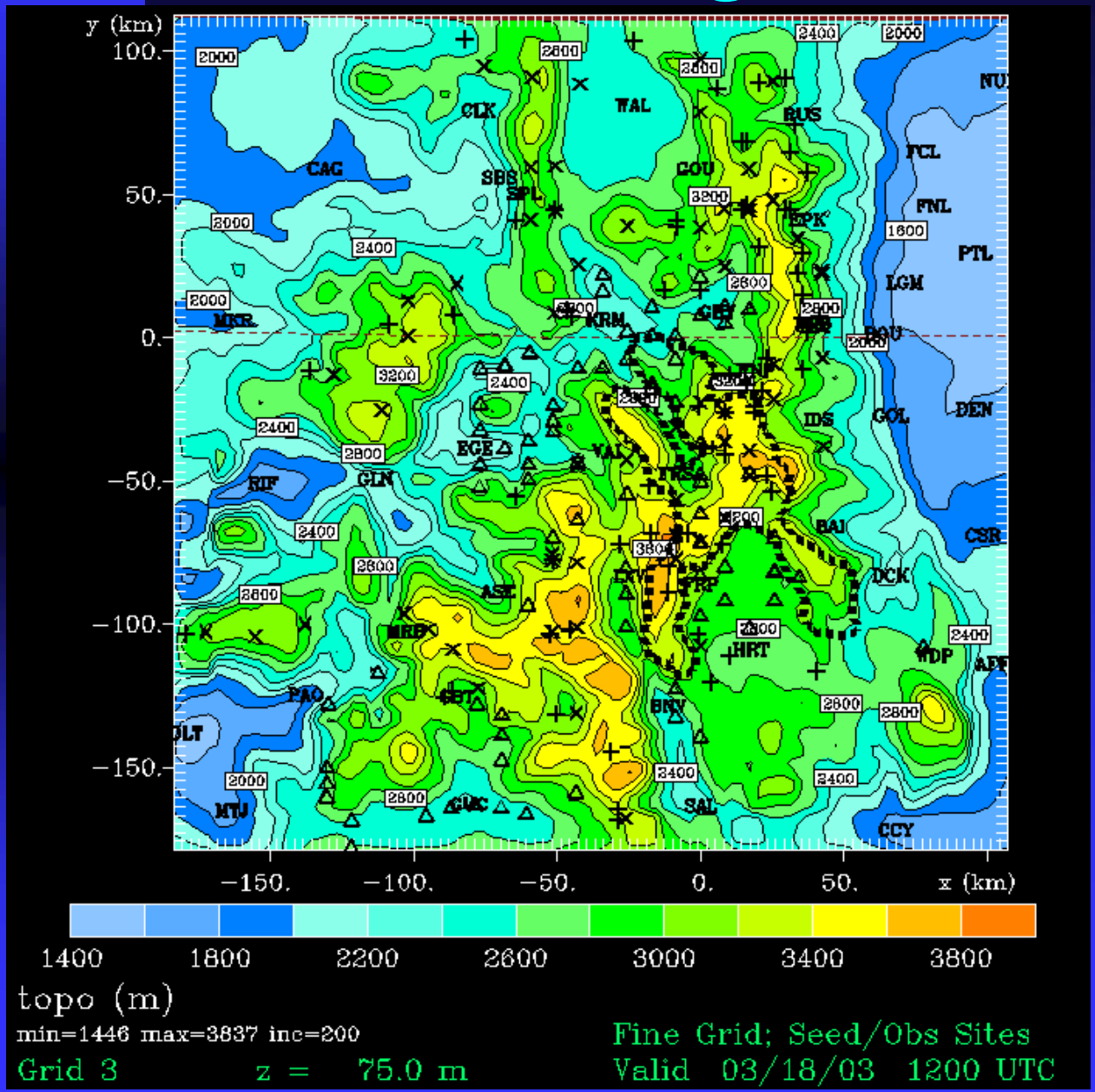
$T < -2^{o}C$

$r_v > r_{sl}$ (supersaturation with respect to liquid)

Seeding Activation curve for AgI



RAMS 3-km grid with Target Area

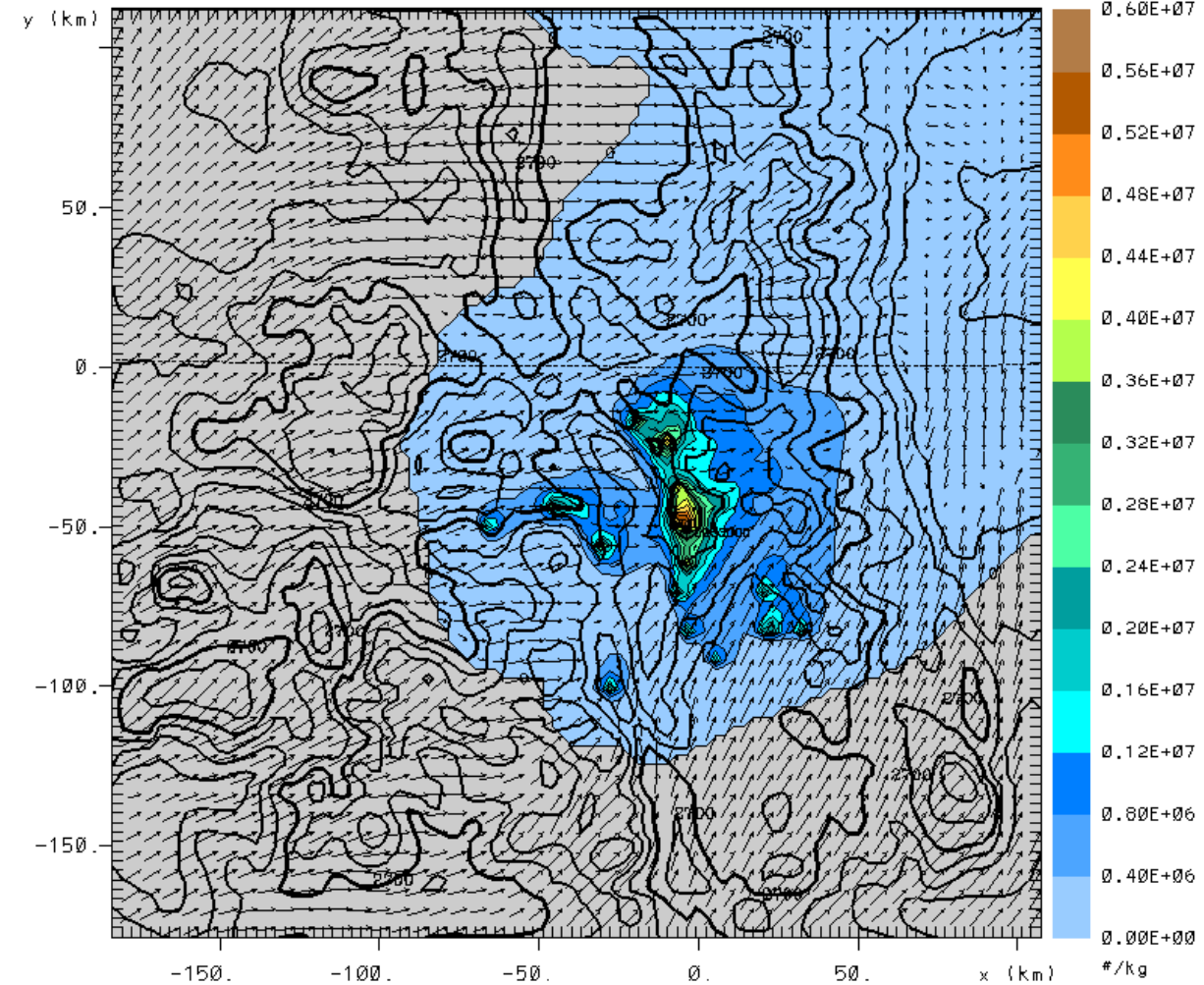


△ Seeding generator

x Snotel site

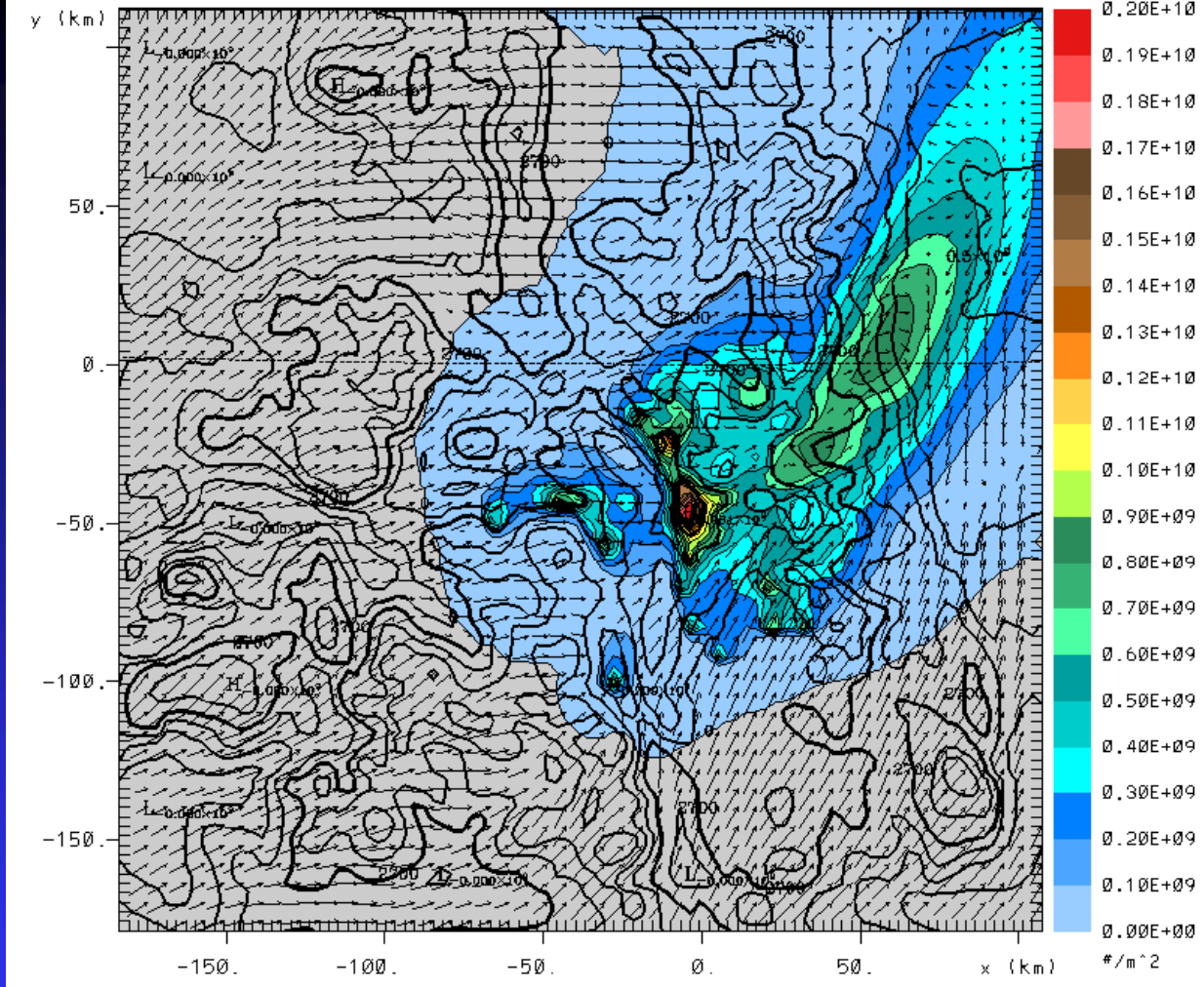
\+ Snowcourse site

···· Target area boundary



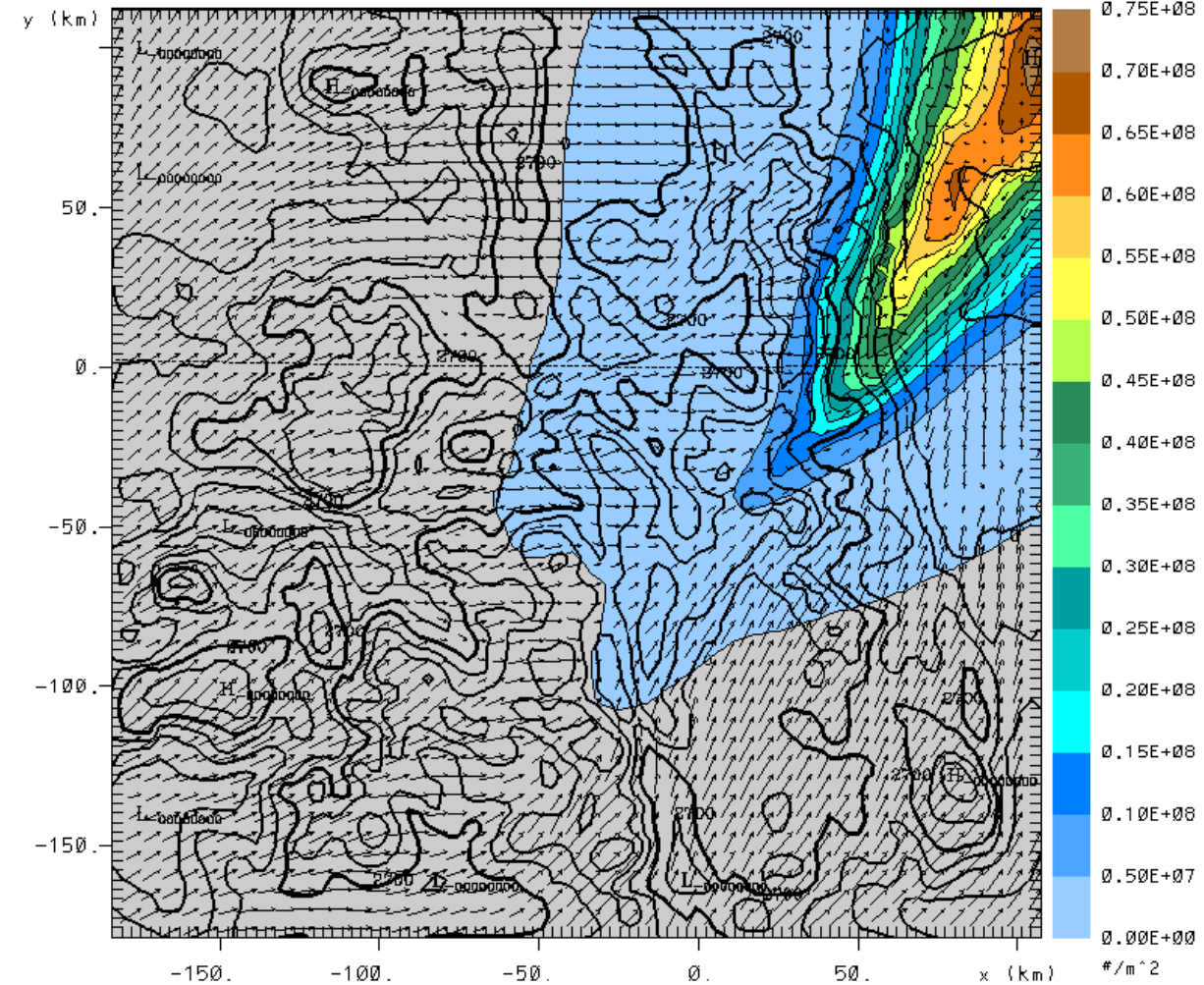
Init 11/03/03 0000 UTC seed		grid 3			
z = 146.4 m	2003-11-04-0000.00 UTC	min	max	inc	lab*
contours	ifn2-conc (#/kg)	-46.46	0.5953E+07	0.4000E+06	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0
vectors →	5 m/s horiz	0.1307	19.67		

Available seeded IFN concentration in lowest model level. The approximately 15 small maxima indicate the source grid points where active seeding generators are located.



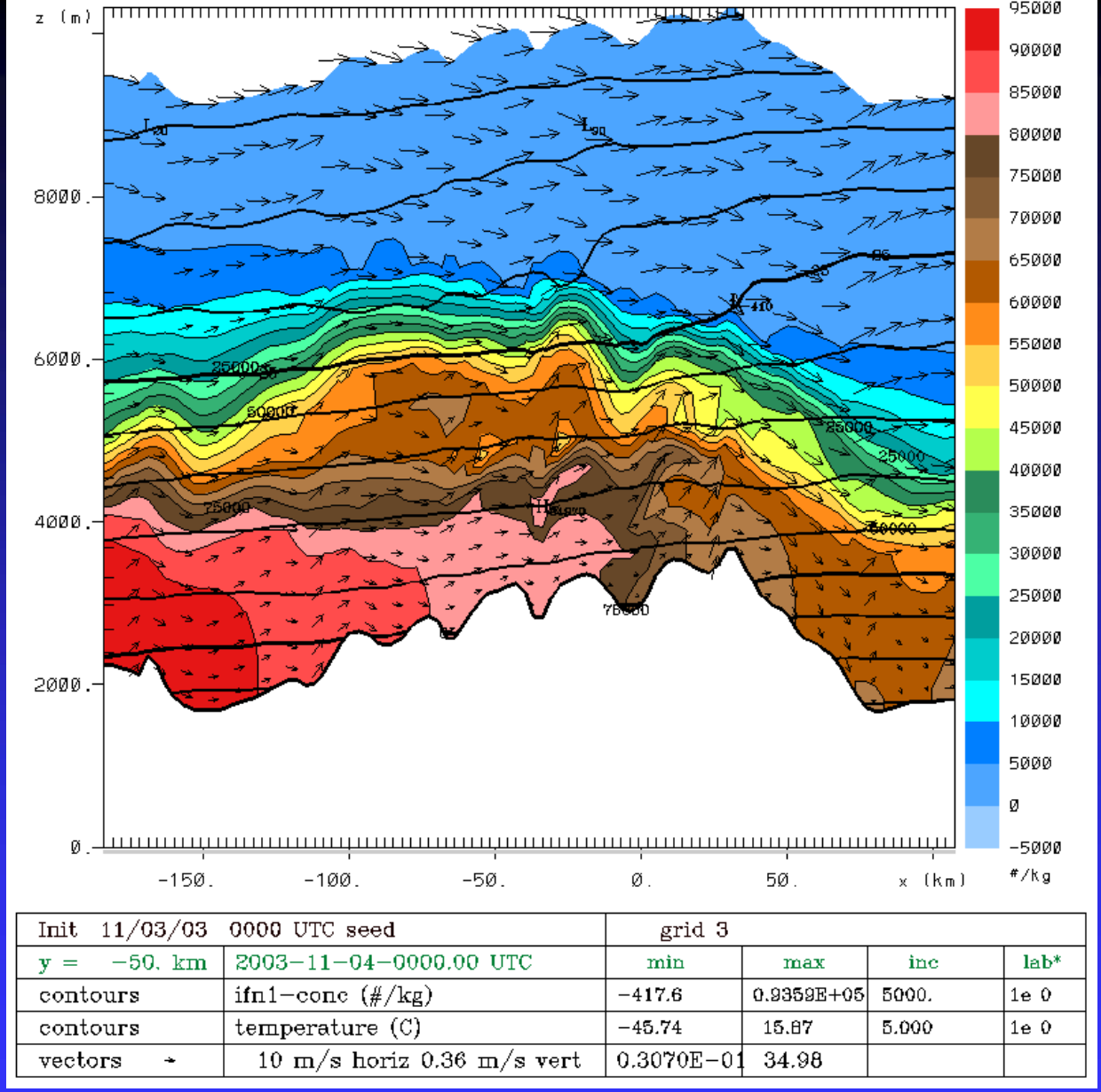
Init 11/03/03 0000 UTC seed		grid 3			
z = 146.4 m	2003-11-04-0000.00 UTC	min	max	inc	lab*
contours	vertint ifn2 (#/m 2)	-.2178E+06	0.1961E+10	0.1000E+09	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0
vectors →	5 m/s horiz	0.1307	19.67		

Vertically integrated available seeded IFN concentration. Shows both the generator sources and the advected downwind plume.



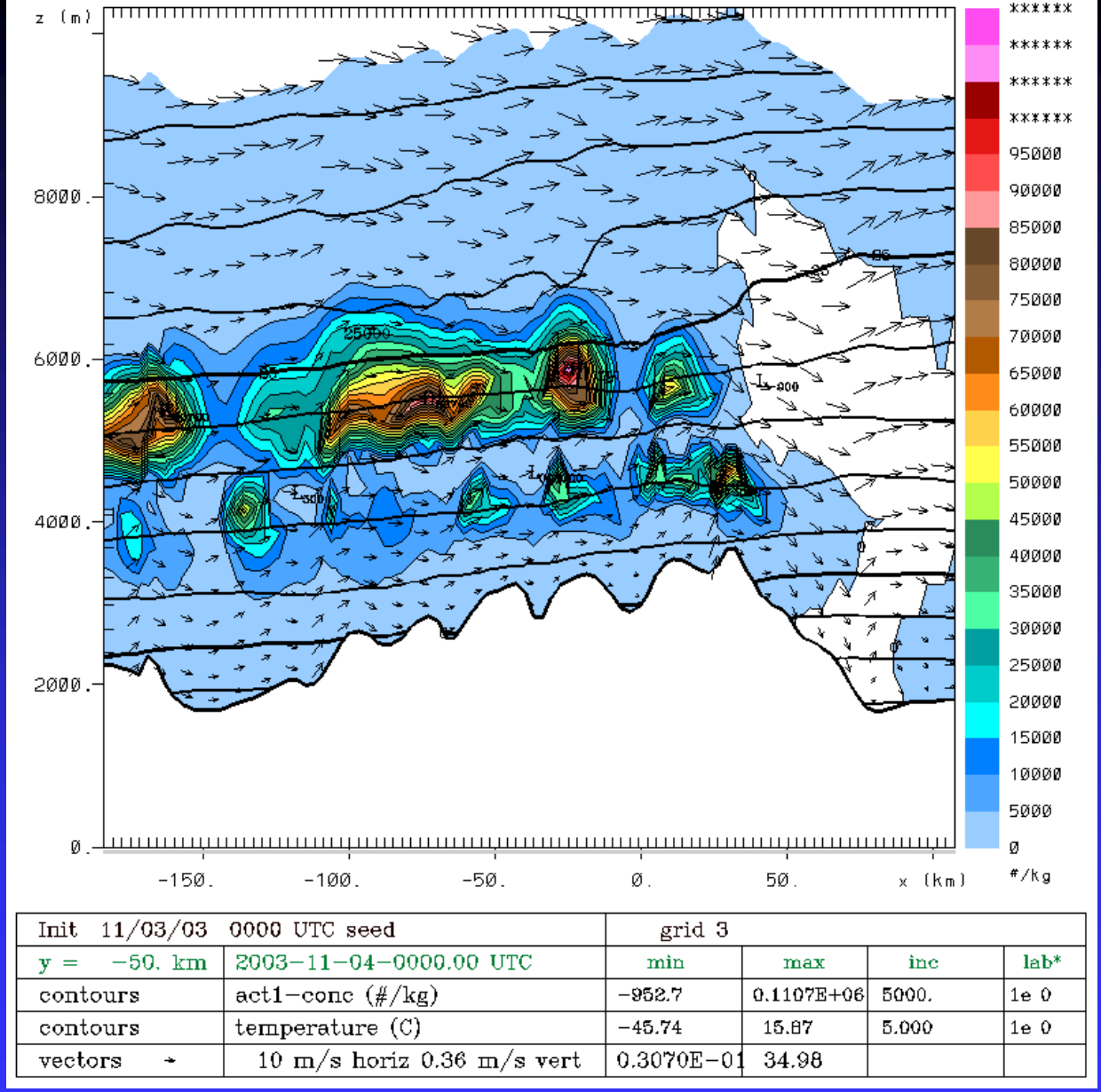
Init 11/03/03 0000 UTC seed		grid 3			
z = 146.4 m	2003-11-04-0000.00 UTC	min	max	inc	lab*
contours	vertint act2 (#/m 2)	-4806.	0.7262E+08	0.5000E+07	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0
vectors →	5 m/s horiz	0.1307	19.67		

Vertically integrated activated seeded IFN concentration (contributes to pristine ice concentration along with activated background IFN). The activated seeded plume is primarily downwind of the Target Area to the lee of the Front Range.



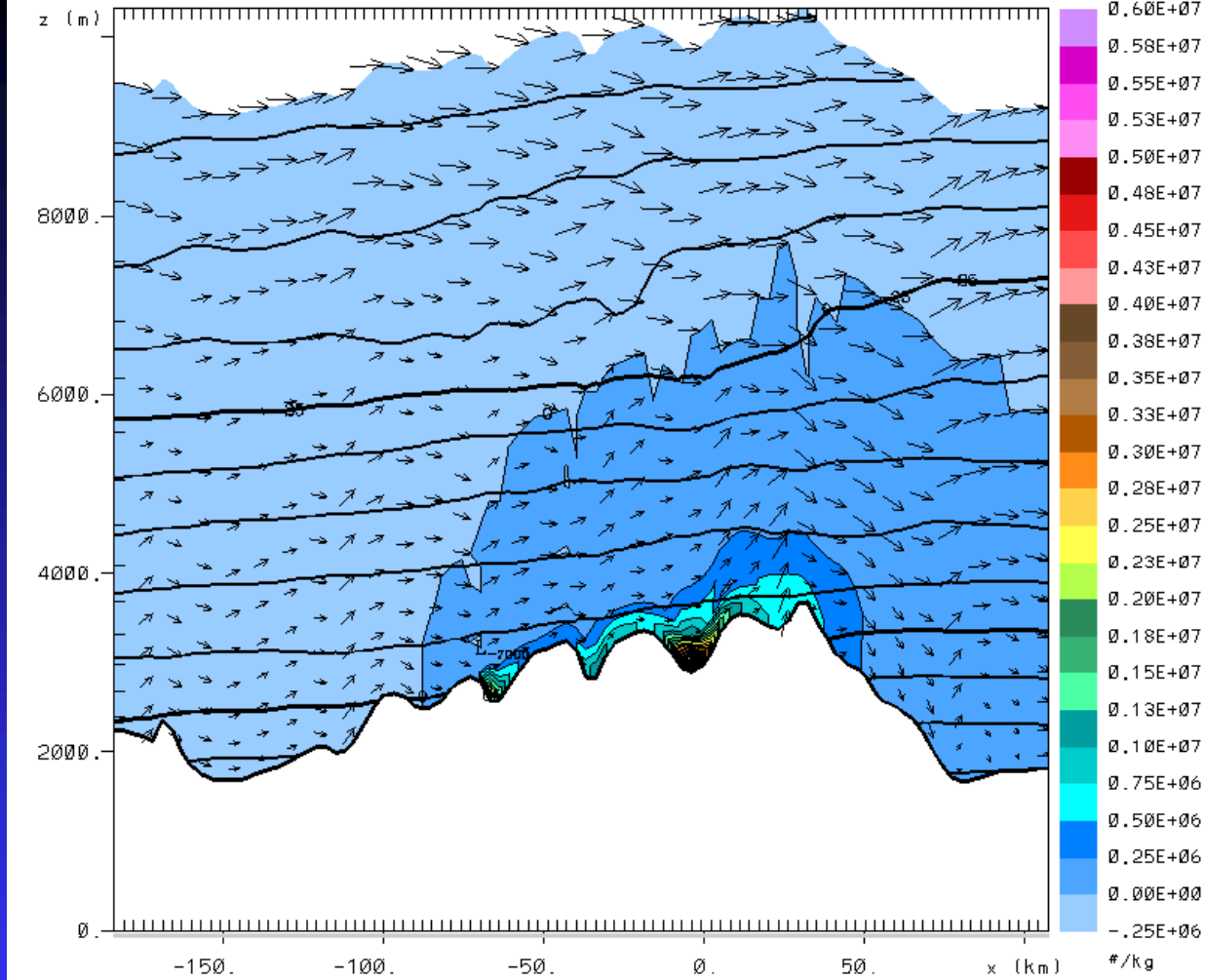
Init 11/03/03 0000 UTC seed		grid 3			
y = −50. km	2003−11−04−0000.00 UTC	min	max	inc	lab*
contours	ifn1−conc (#/kg)	−417.6	0.9359E+05	5000.	1e 0
contours	temperature (C)	−45.74	15.87	5.000	1e 0
vectors →	10 m/s horiz 0.36 m/s vert	0.3070E−01	34.98		

Available background IFN concentration. The initial field is largely a function of density, and is advected and diffused. There are no sources, and the only sink is when it is activated and becomes pristine ice.



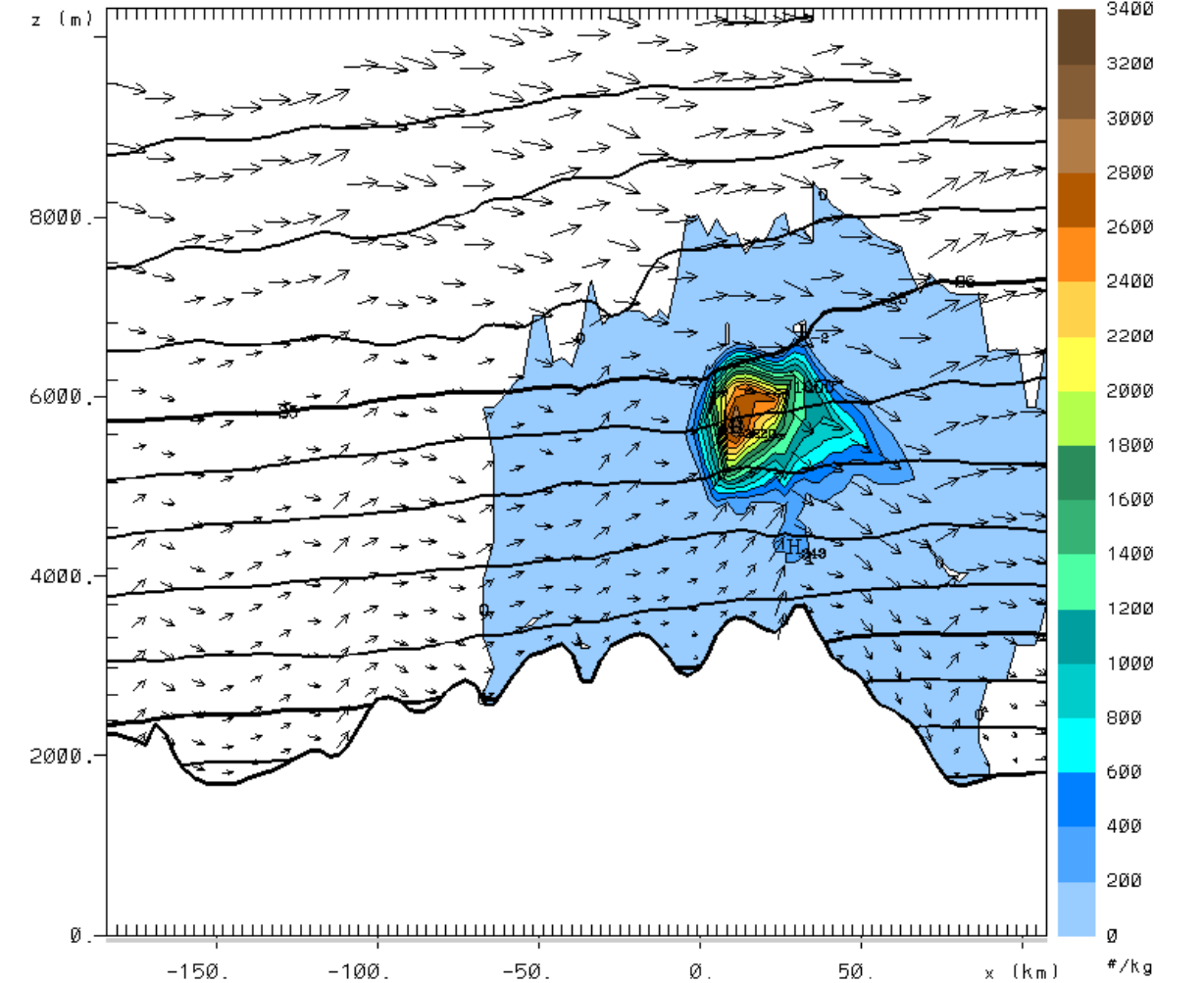
Init 11/03/03 0000 UTC seed		grid 3			
y = −50. km	2003−11−04−0000.00 UTC	min	max	inc	lab*
contours	act1−conc (#/kg)	−952.7	0.1107E+06	5000.	1e 0
contours	temperature (C)	−45.74	15.87	5.000	1e 0
vectors →	10 m/s horiz 0.36 m/s vert	0.3070E−01	34.98		

Activated background IFN concentration. Shows that natural pristine ice forms from the activation of background IFN in two primary temperature regimes, -10 to -12 C and -19 to -22C.



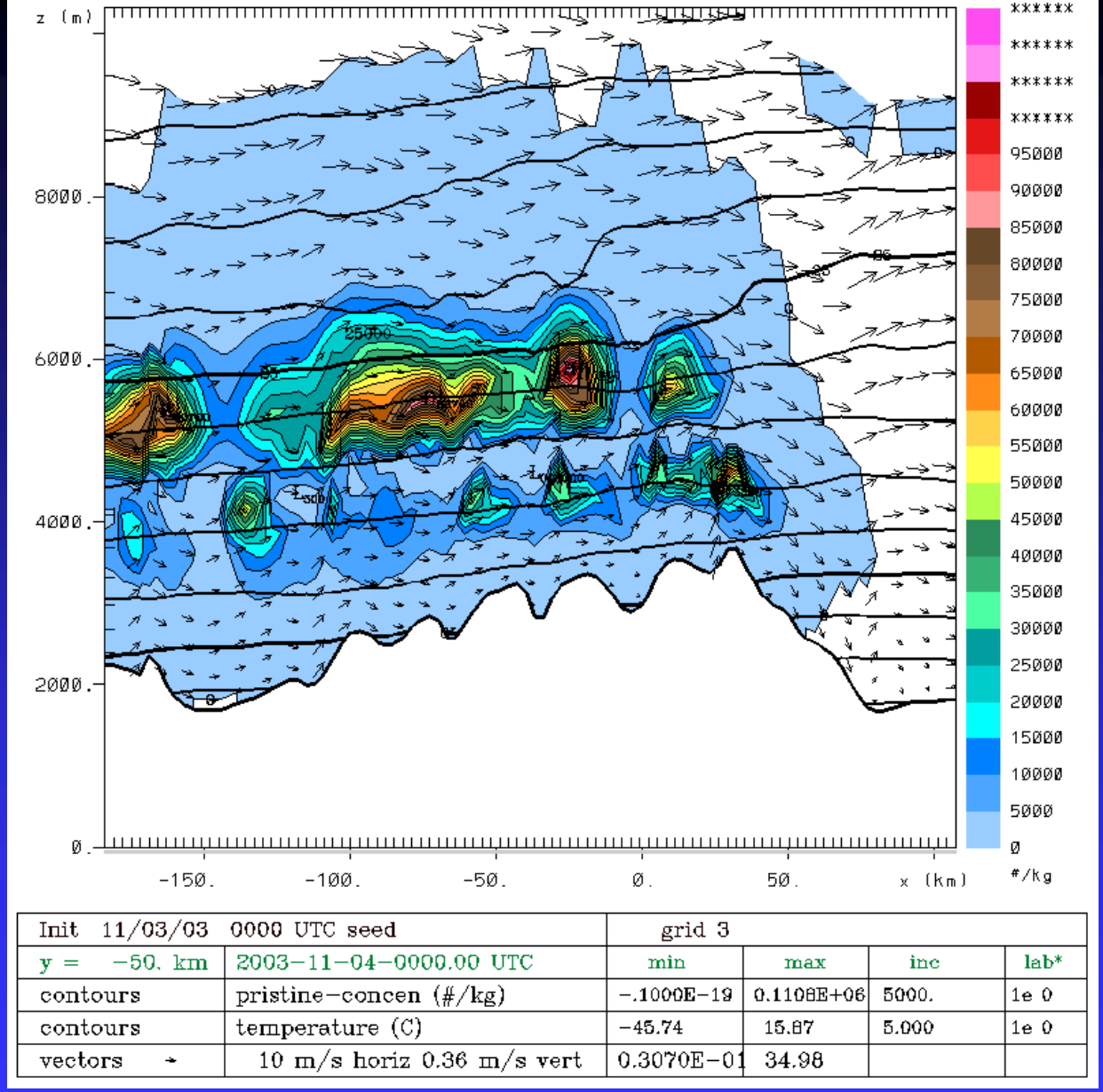
Init 11/03/03 0000 UTC seed		grid 3			
y = −50. km	2003−11−04−0000.00 UTC	min	max	inc	lab*
contours	ifn2−conc (#/kg)	−7959.	0.5953E+07	0.2500E+06	1e 0
contours	temperature (C)	−45.74	15.87	5.000	1e 0
vectors →	10 m/s horiz 0.36 m/s vert	0.3070E−01	34.98		

Available seeded IFN concentration. Shows the generator sources in the valleys within and adjacent to the Target Area.



Init 11/03/03 0000 UTC seed		grid 3			
y = −50. km	2003−11−04−0000.00 UTC	min	max	inc	lab*
contours	act2−conc (#/kg)	−2.776	3220.	200.0	1e 0
contours	temperature (C)	−45.74	15.87	5.000	1e 0
vectors →	10 m/s horiz 0.36 m/s vert	0.3070E−01	34.98		

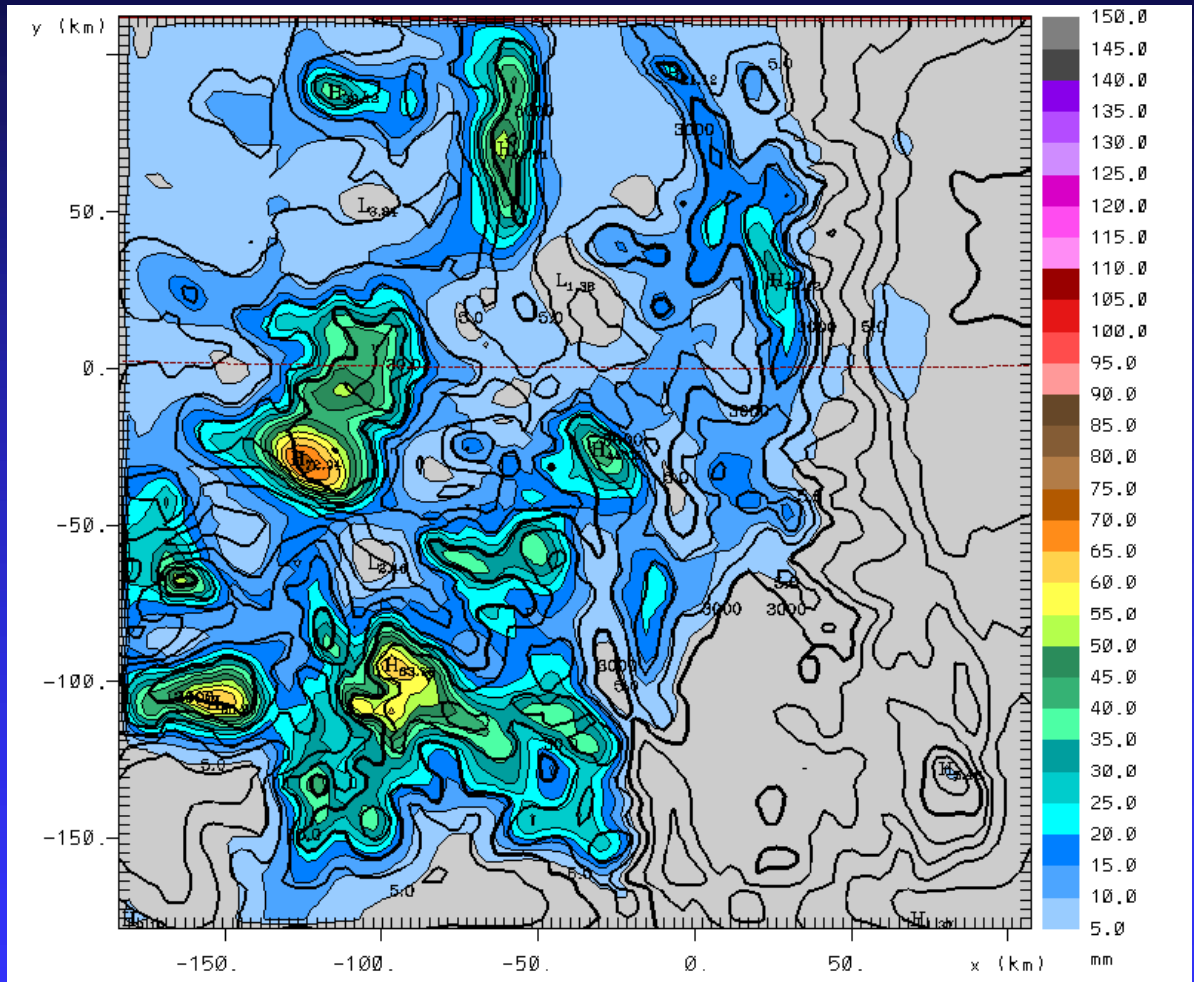
Activated seeded IFN concentration. Maximum at -19C. This maximum is two orders of magnitude less than the maximum activated background IFN concentration in the previous figure.



Init 11/03/03 0000 UTC seed		grid 3			
y = −50. km	2003−11−04−0000.00 UTC	min	max	inc	lab*
contours	pristine−concen (#/kg)	−.1000E−19	0.1108E+06	5000.	1e 0
contours	temperature (C)	−45.74	15.87	5.000	1e 0
vectors →	10 m/s horiz 0.36 m/s vert	0.3070E−01	34.98		

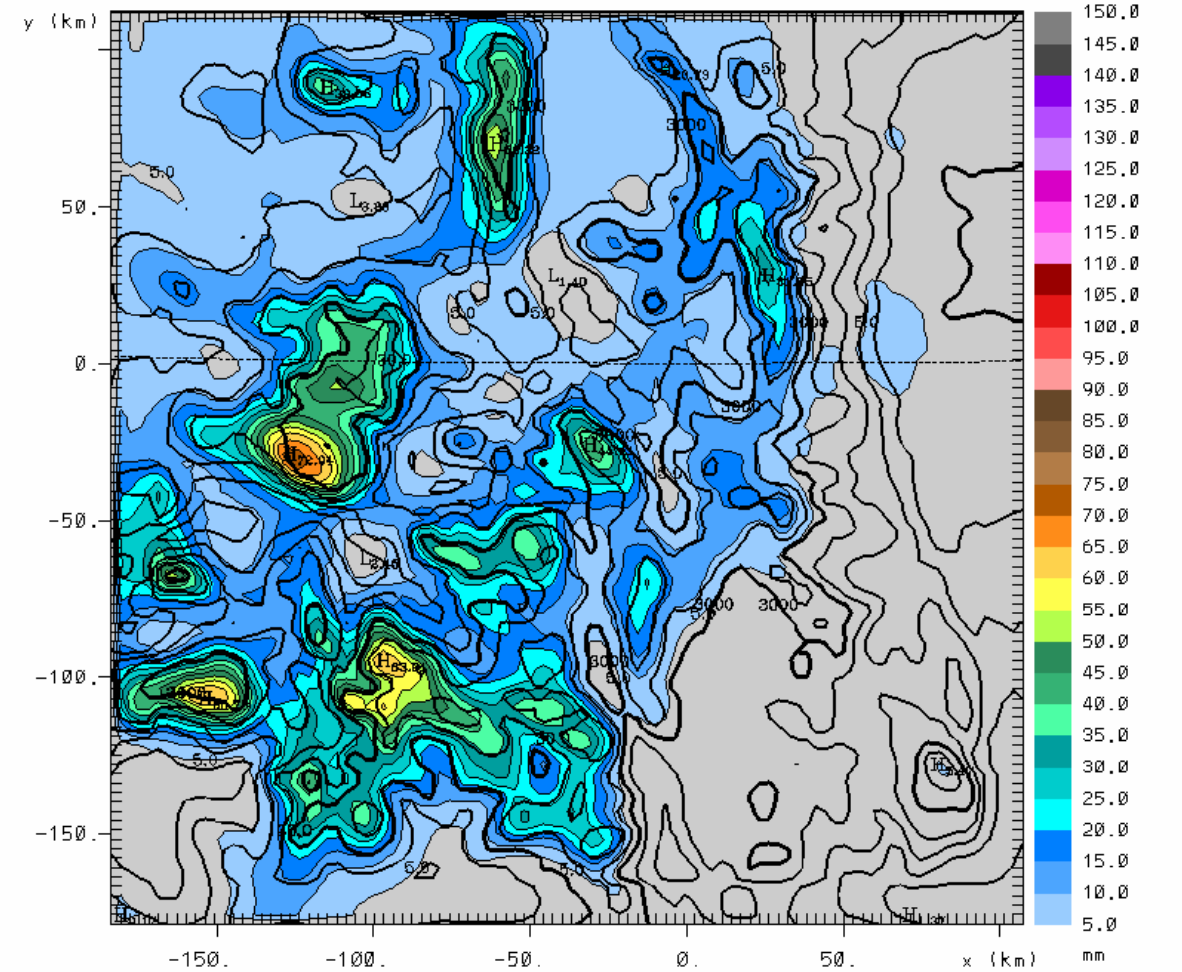
Total activated IFN concentration or pristine ice concentration. Because of the relatively low contribution from activated seeded IFN, this field is very similar to the activated background IFN concentration shown previously.

24h Precip, Control Run 3-4 Nov 2003



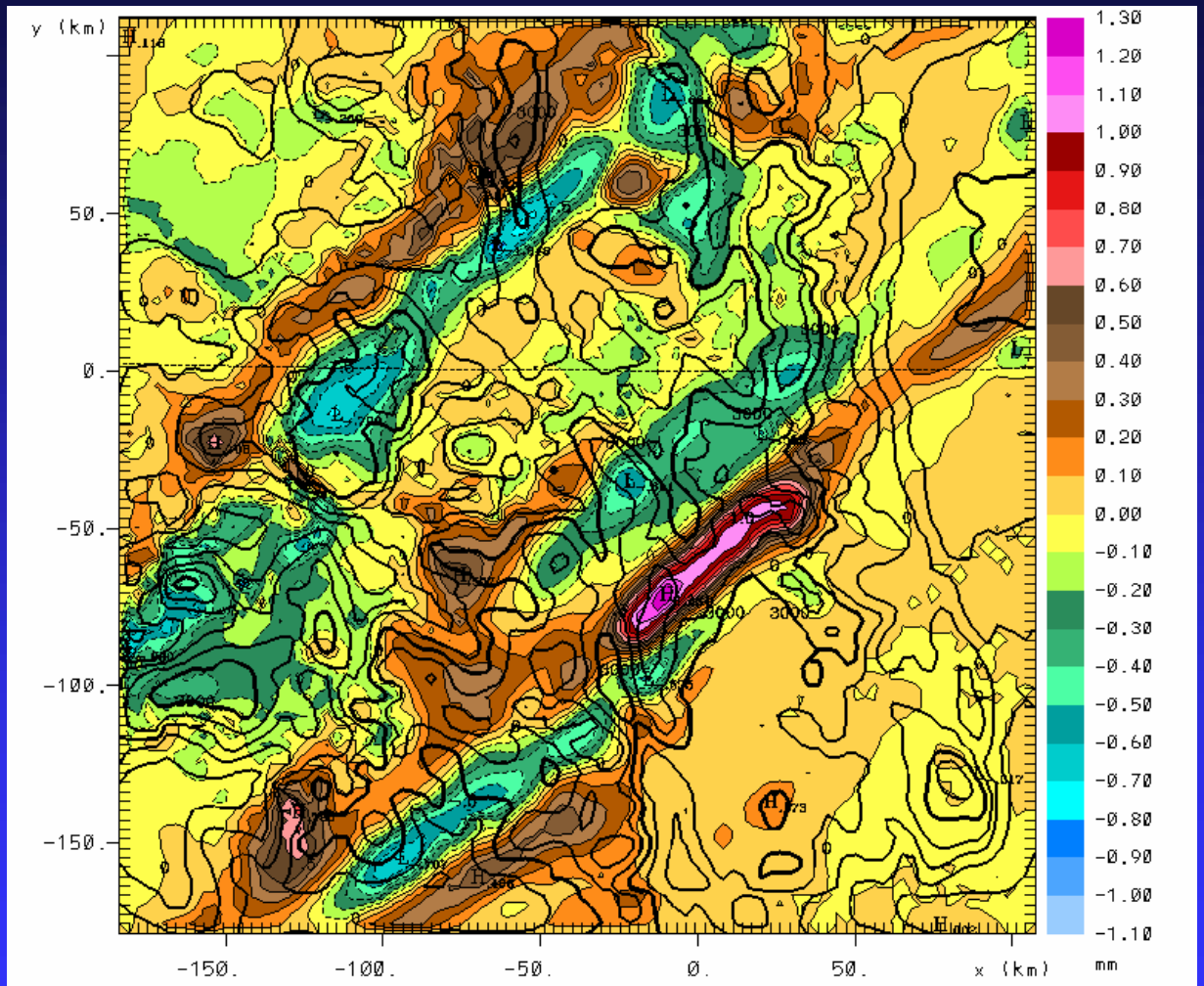
Init 11/03/03 0000 UTC contr		grid 3			
	2003-11-04-0800.00 UTC	min	max	inc	lab*
contours	precip 08-32h (mm)	0.000	72.94	5.000	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

24h Precip, Seed Run 3-4 Nov 2003



Init 11/03/03 0000 UTC seed		grid 3			
	2003-11-04-0800.00 UTC	min	max	inc	lab*
contours	precip 08-32h (mm)	0.000	72.94	5.000	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

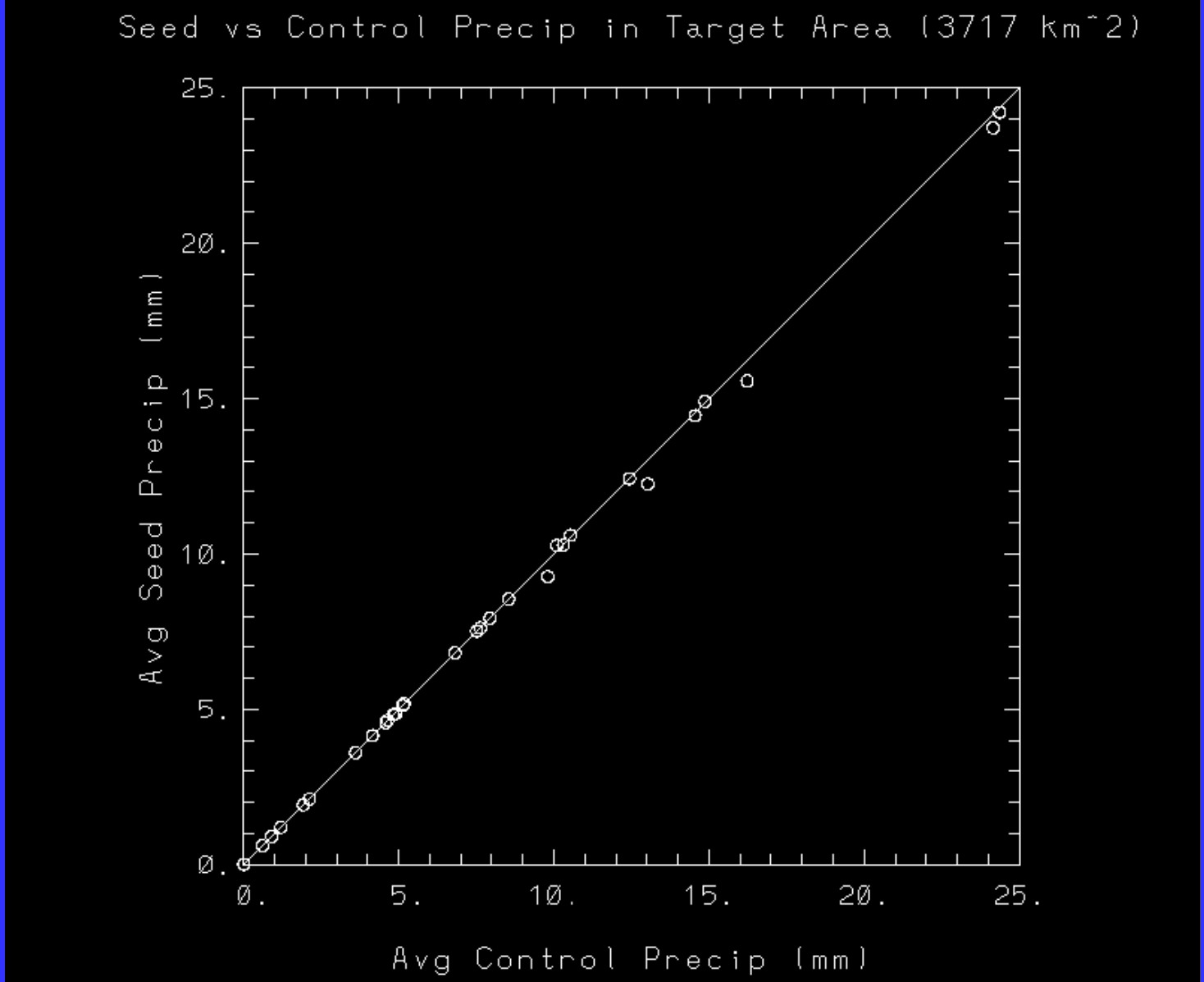
24h Seed-Control Precip, 3-4 Nov 2003

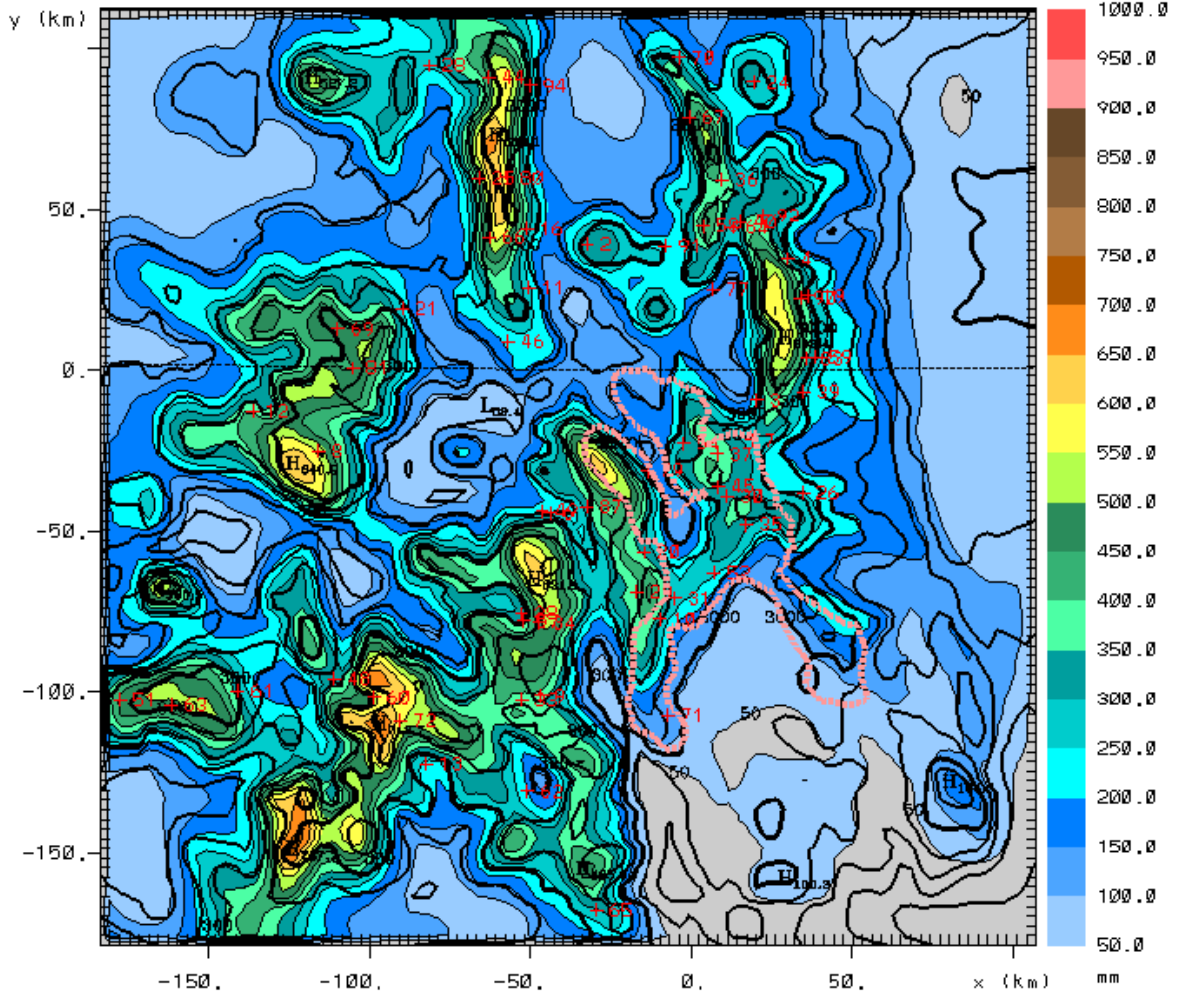


Init 11/03/03 0000 UTC seed		grid 3			
	2003-11-04-0800.00 UTC	min	max	inc	lab*
contours	seed-control precip 08- (mm)	-1.048	1.284	0.1000	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Evaluation of 30 days of seeding

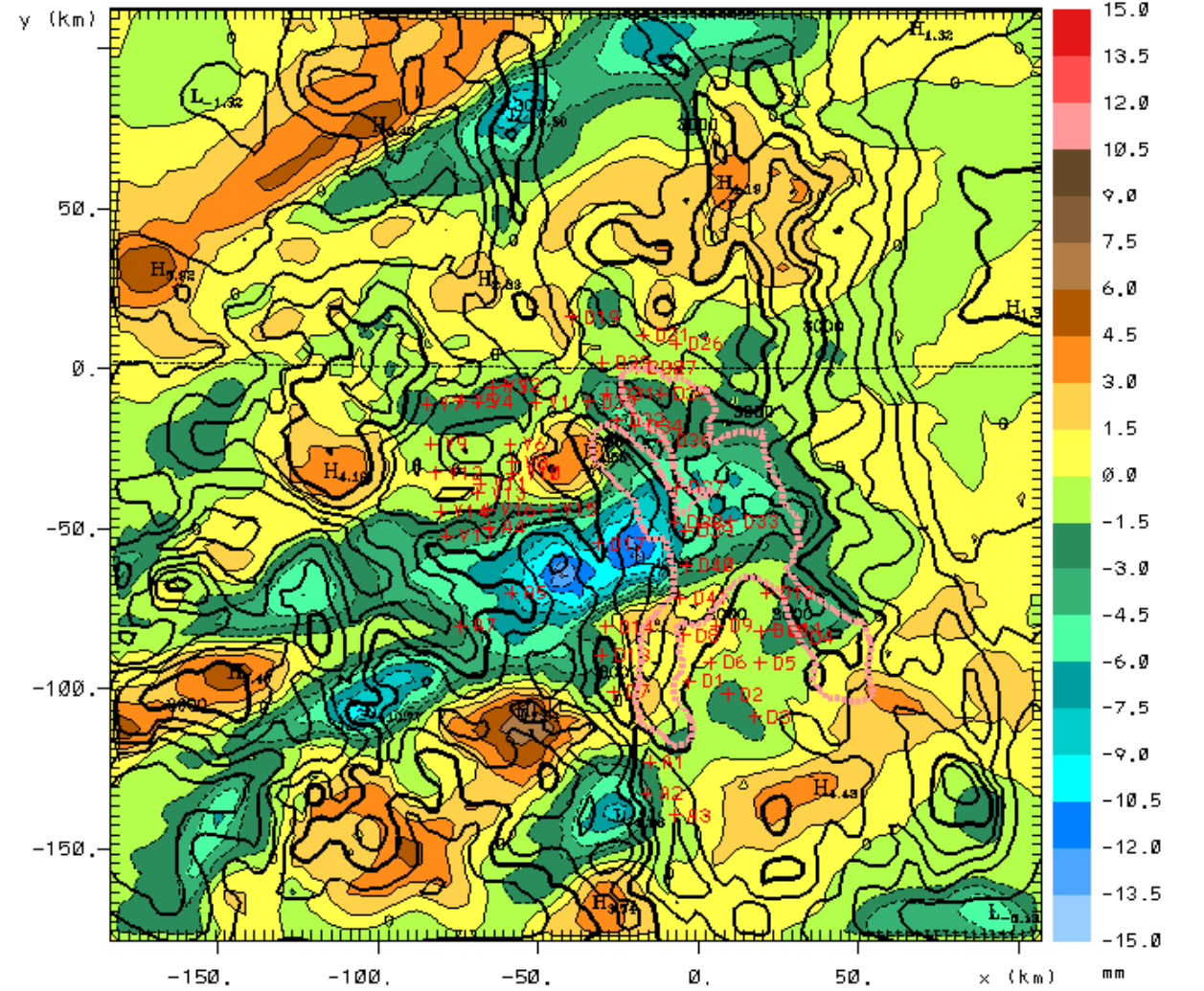
- 30 selected cases from Nov. 2003 through March 2004.


Seed vs Control Precip in Target Area (3717 km^2)
Avg Seed Precip (mm)
25.
20.
15.
10.
5.
0.
0.
5.
10.
15.
20.
25.
Avg Control Precip (mm)
(Average seeding effect in Target Area: -1.0%)



Select 30d Ctl Pc		grid 3			
	2004-03-01-0800.00 UTC	min	max	inc	lab*
contours	season precip (mm)	0.000	727.7	50.00	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Total CONTROL precipitation on Grid 3 for the 30 selected days. Snotel locations are plotted.



Select 30d S-C Pc		grid 3			
	2004-03-01-0800.00 UTC	min	max	inc	lab*
contours	season precip (mm)	-13.96	7.644	1.500	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Difference in total precip (SEED-CONTROL) for the 30 selected days. Generator sites are plotted.

Summary

- Model precipitation biases are much greater than differences between seed and no-seed amounts.
- Seed minus no-seed precipitation amounts are consistently small.
- Possible sources of model precipitation biases are:
  - Inadequate resolution of atmospheric dynamics and terrain, especially when embedded convection is prevalent.
  - Meyers formula for crystal concentrations over-predicts concentrations of natural ice crystals.

Summary (cont.)

- The small differences between seed and no-seed precipitation could be:
  - Real.
  - A result of over-prediction of natural precipitation using the Meyers formula.
  - A result of over-prediction of natural precipitation using the assumed CCN concentrations.
  - Over-prediction biases which could be a result of inadequate dynamic representation of the system due to coarse grid spacing thereby consuming supercooled water that could have been utilized by seeded clouds; a possibility with embedded cumuli.

Recommendations

- Future cloud seeding operations should include measurements of background IN, CCN, and giant CCN concentrations.
- Tests should be made of the effects of increased model resolution on precipitation prediction and/or a sub-grid model representing embedded convection.
- New statistical techniques need to be developed that include model simulated data along with observed precipitation amounts and other observable predictors.