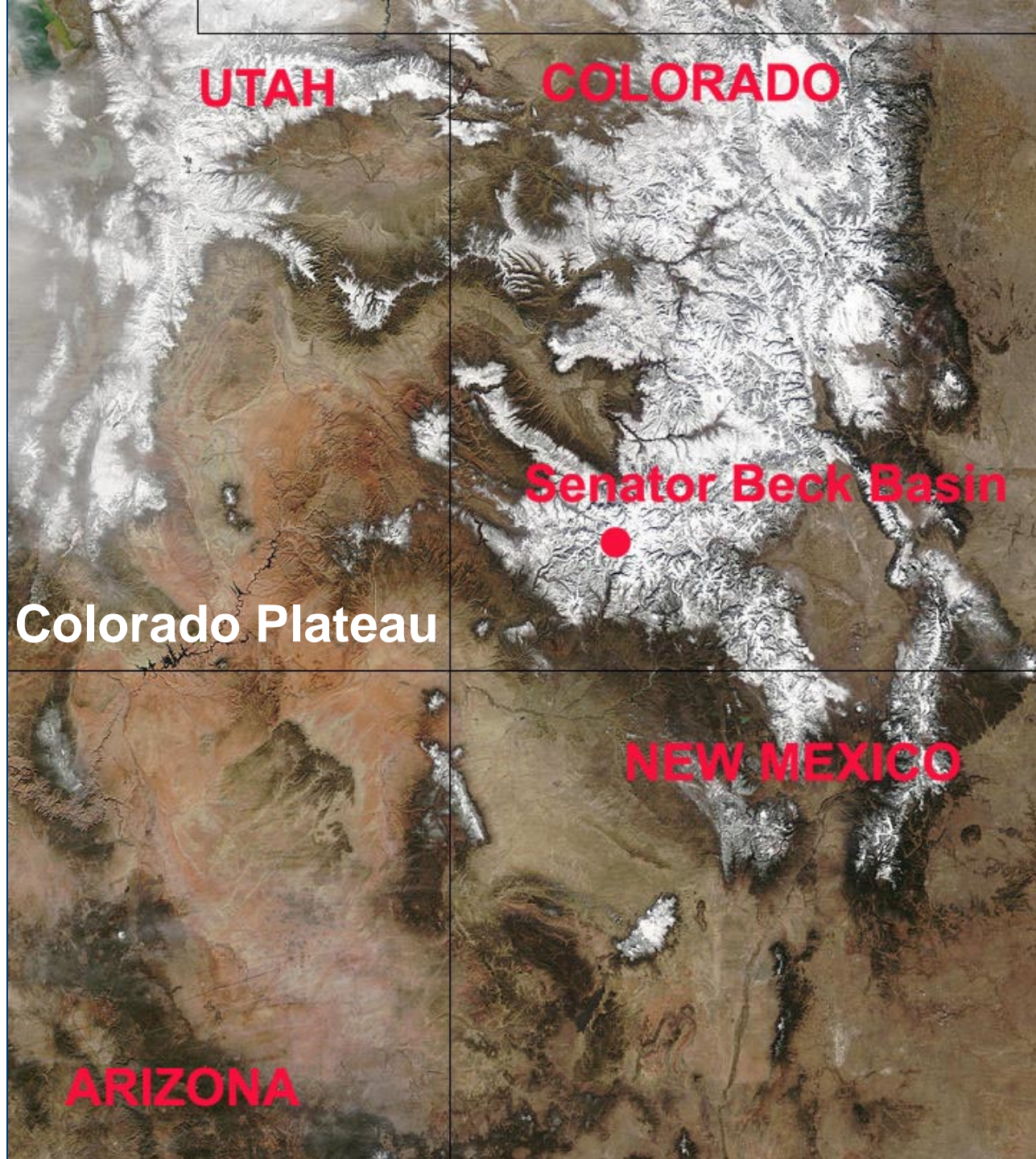


# Dust-on-Snow in Colorado and its Hydrological Effects

Chris Landry  
**CODOS**

Center for Snow and Avalanche  
Studies  
Silverton, CO



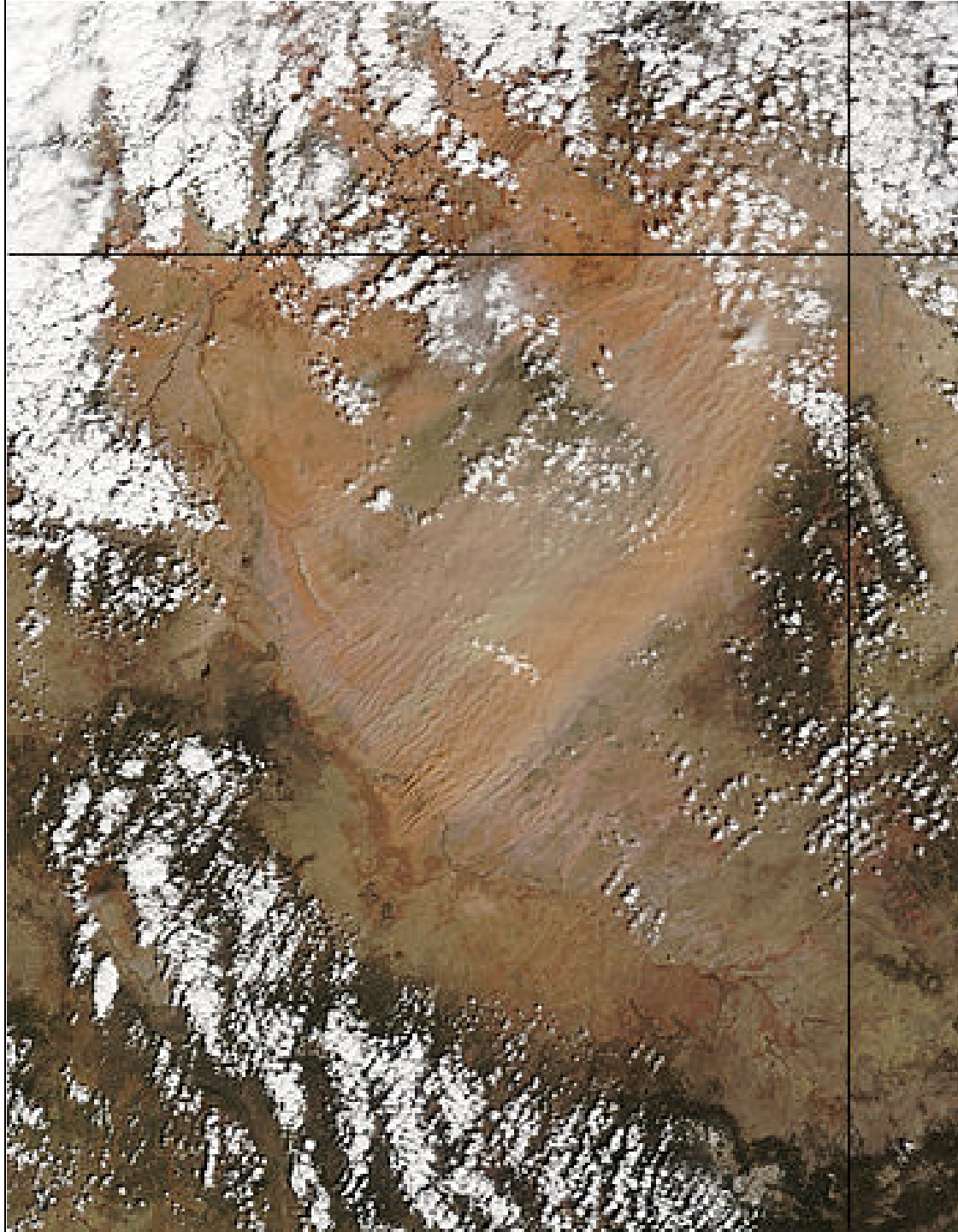


**Silverton**  
**April 3, 2009**



**Silverton**  
**April 5, 2010**





**D8 – WY2009**  
**April 3, 2009**



# D4 – WY2010

## April 5, 2010



Near USGS Research Site  
February 15, 2011



# Rigorous DOS Event Monitoring

<b>Dust-on-Snow Events Documented per Month, by Winter</b> Senator Beck Basin Study Area at Red Mountain Pass – San Juan Mountains										
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
2002/2003					2		1			3
2003/2004							2	1		3
2004/2005	0	0	0	0	0	1	2	1	0	4
2005/2006	0	0	1	0	1	1	3	2	0	8
2006/2007	0	0	1	0	1	1	3	1	1	8
2007/2008	0	0	0	0	0	3	3	1	0	7
2008/2009	1	0	1	0	1	4	5	0	0	12
2009/2010	1	0	0	0	0	1	4	3	0	9
2010/2011	0	0	0	0	1	3	3	4	0	11



# Paleo History of Dust Deposition



Neff, J.C., A.P. Ballantyne, G.L. Farmer, N.M. Mahowald, J.L. Conroy, C.C. Landry, J.T. Overpeck, T.H. Painter, C.R. Lawrence and R.L. Reynolds. 2008. Increasing eolian dust deposition in the western United States linked to human activity, *Nature Geoscience*, Vol. 1, No. 3, pp. 189-195, March 2008, doi: 10.1038/ngeo136





**May 21, 2004**

*Photo courtesy JPL - Ian McCubbin*



*Senator Beck Basin Study Area*  
*Red Mountain Pass, CO*

290 ha

Operated by  
CSAS under  
USFS Special  
Use Permit with  
Uncompahgre  
National Forest,  
Ouray Ranger  
District

**SBSP**

**SASP**

**SBSG**



0 80 160 320 480 640 800 Meters

Red Mountain Pass







**Swamp Angel Study Plot**  
**11,050' (3368 m)**

## SASP Instrumentation

6 m Mast

CR10X Dataloggers (2), Multiplexer (1)

ETI Precipitation Gauge

Wind Speed & Direction (2)

Air Temp and RH (2)

Barometric Pressure

Height of Snow

Broadband SW (2 up, 1 down, shadow array)

NIR SW (1 up, 1 down)

Pyrgeometer (1 up)

Infrared Snow Surface Temp

Snow Temperature (5)

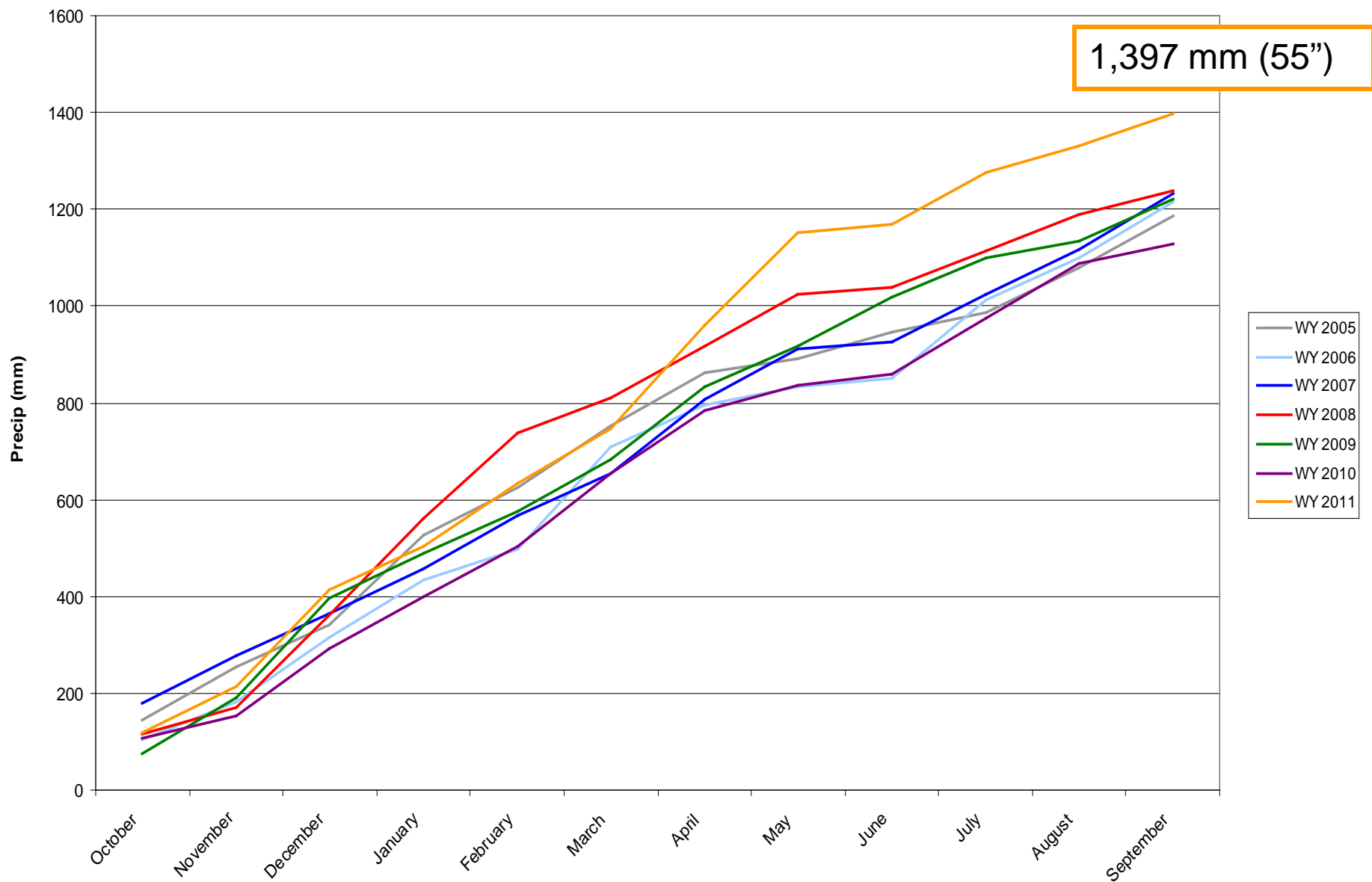
Snow Wetness Sensor

Soil Temperature (4)

Soil Volumetric Water Content

Soil Heat Flux

Water Year Cumulative Precipitation at End of Month  
Swamp Angel Study Plot - Senator Beck Basin Study Area at Red Mountain Pass





# SBSP Instrumentation

10 m Mast

Campbell CR10X Dataloggers (2),  
Multiplexer (1)

Wind Speed & Direction (2)

Air Temp and RH (2)

Height of Snow

Broadband SW (2 up, 1 down, shadow  
array)

NIR SW (1 up, 1 down)

Pyrgeometer (1 up)

Infrared Snow Surface Temp

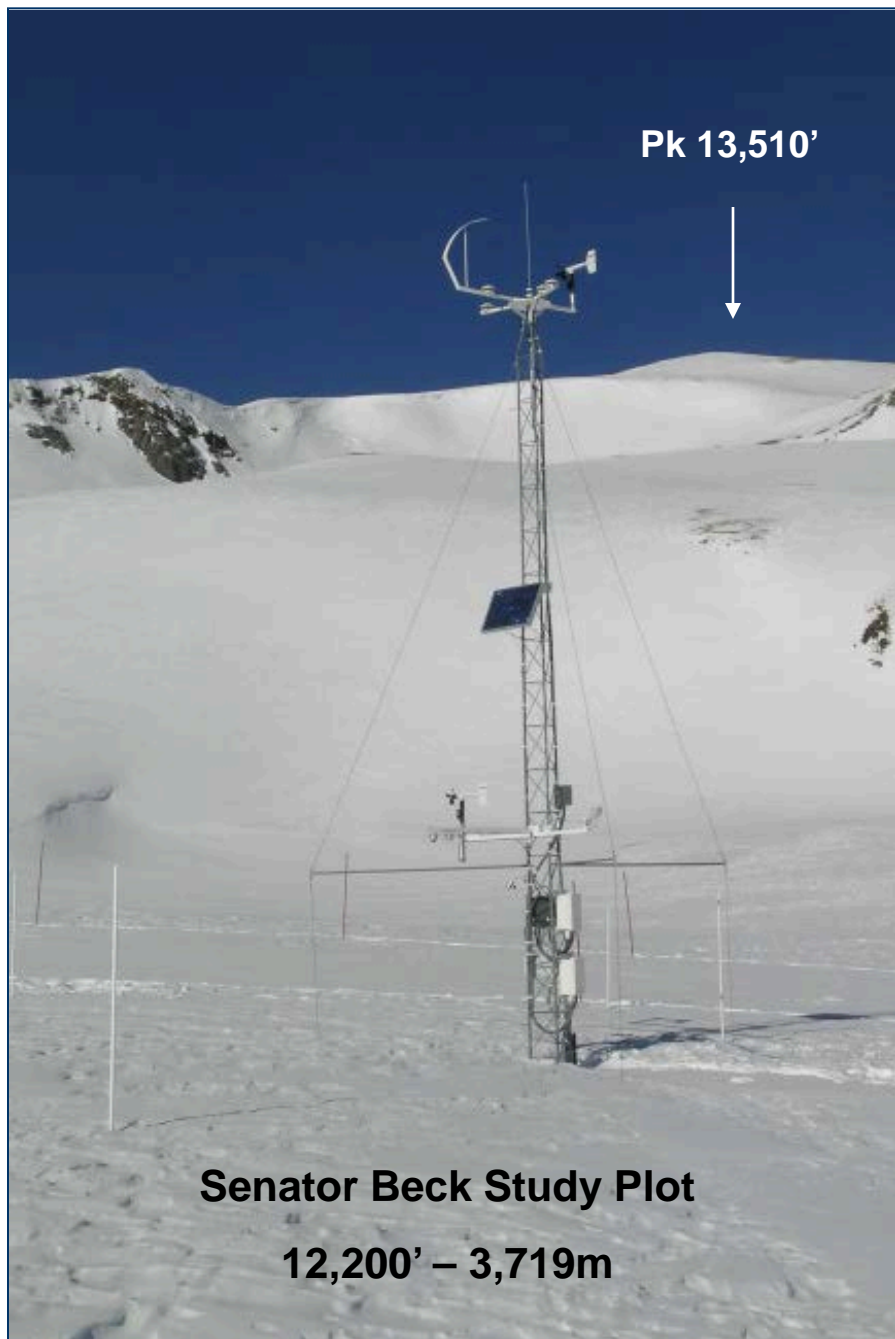
Snow Temperature (5)

Snow Wetness Sensor

Soil Temperature (4)

Soil Volumetric Water Content

Soil Heat Flux



## PTSP Instrumentation

10 m Mast  
Campbell CR10X Datalogger  
Wind Speed & Direction  
Air Temp and RH

Pk 13,510'

SBSP

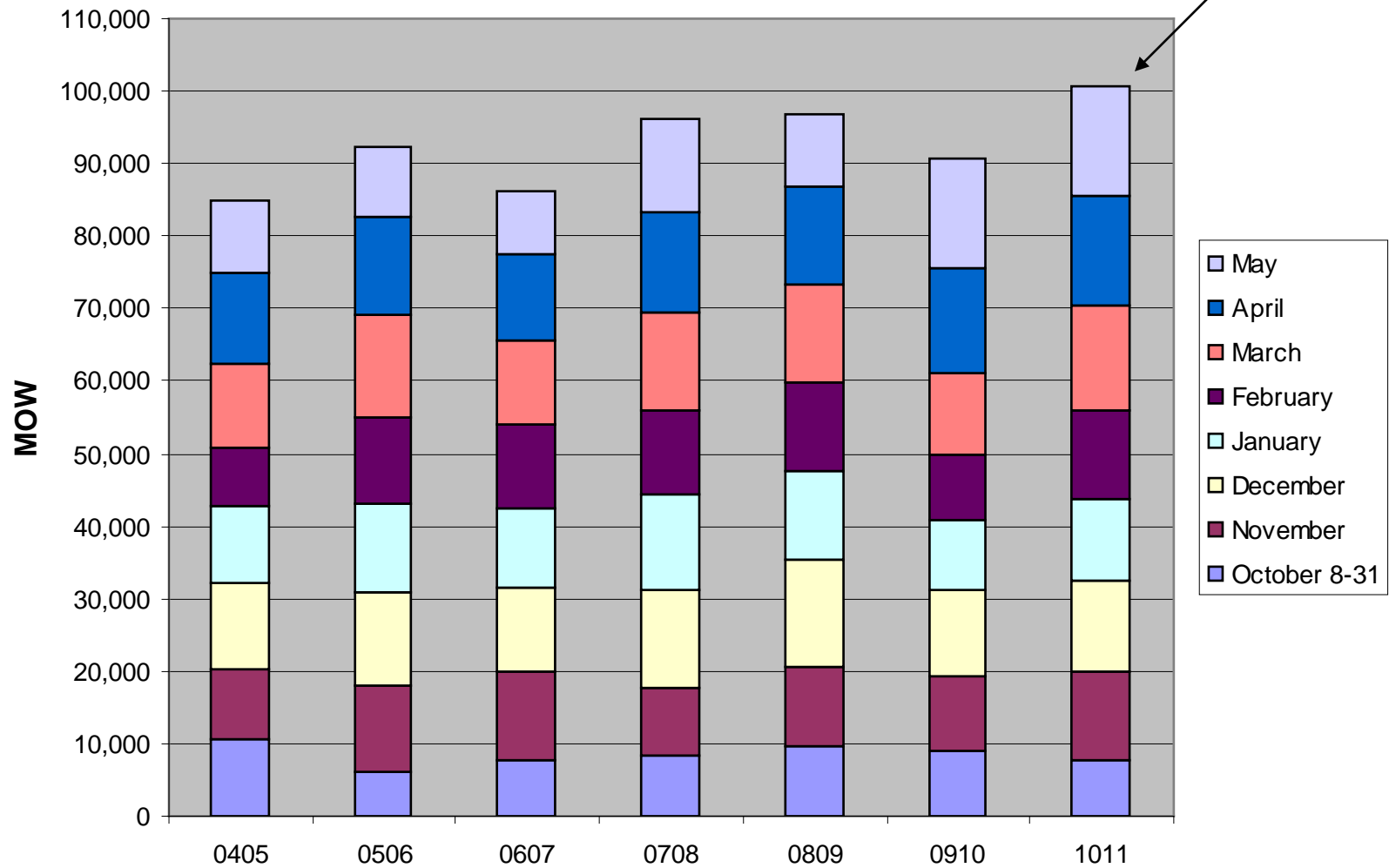
Putney Study Plot

12,325' – 3,757 m





# Total Miles of Wind at PTSP by Season



## SBSG Instrumentation

Broad-crested, notched weir

0.1 – 30 cfs capacity

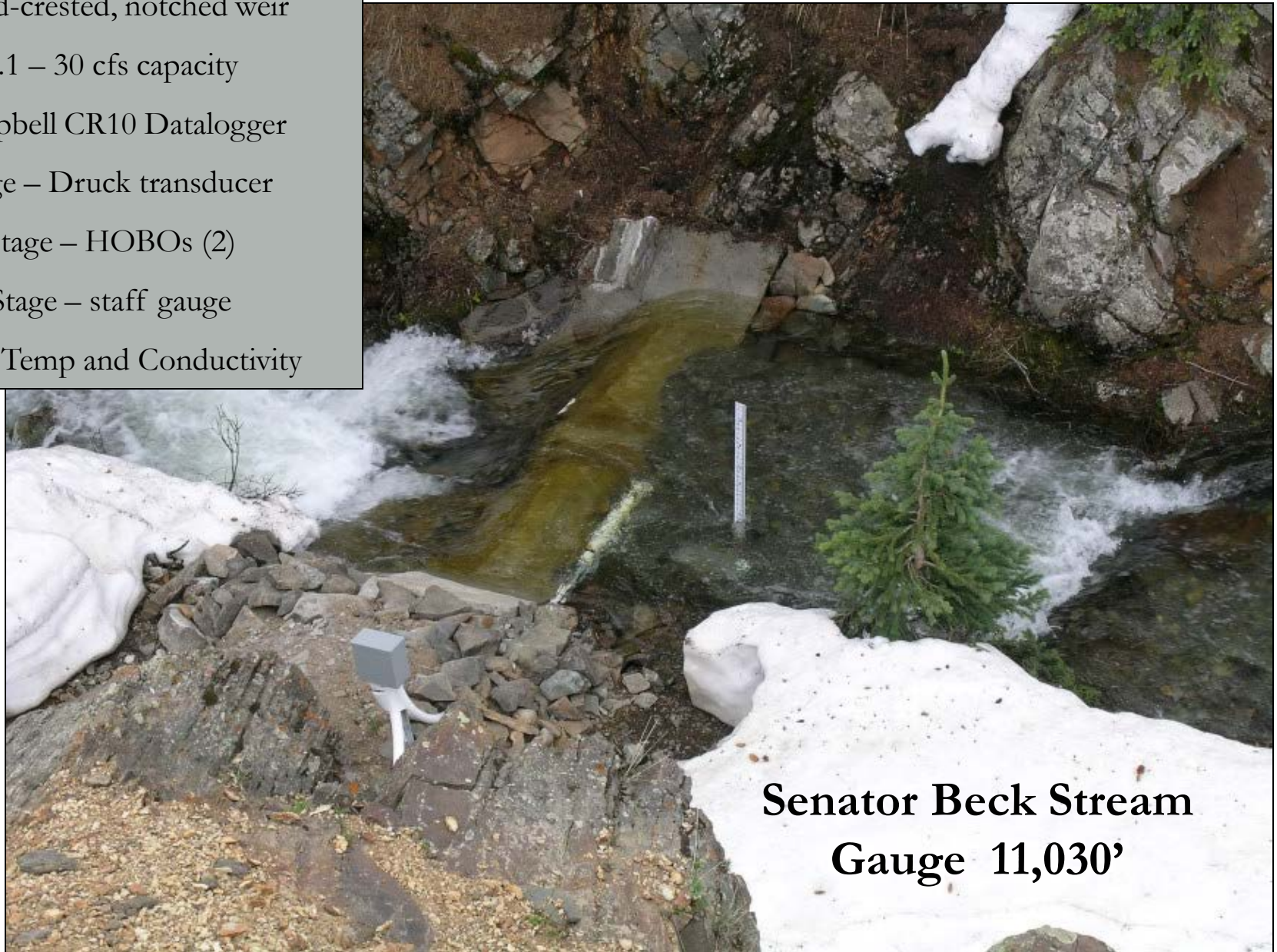
Campbell CR10 Datalogger

Stage – Druck transducer

Stage – HOBOS (2)

Stage – staff gauge

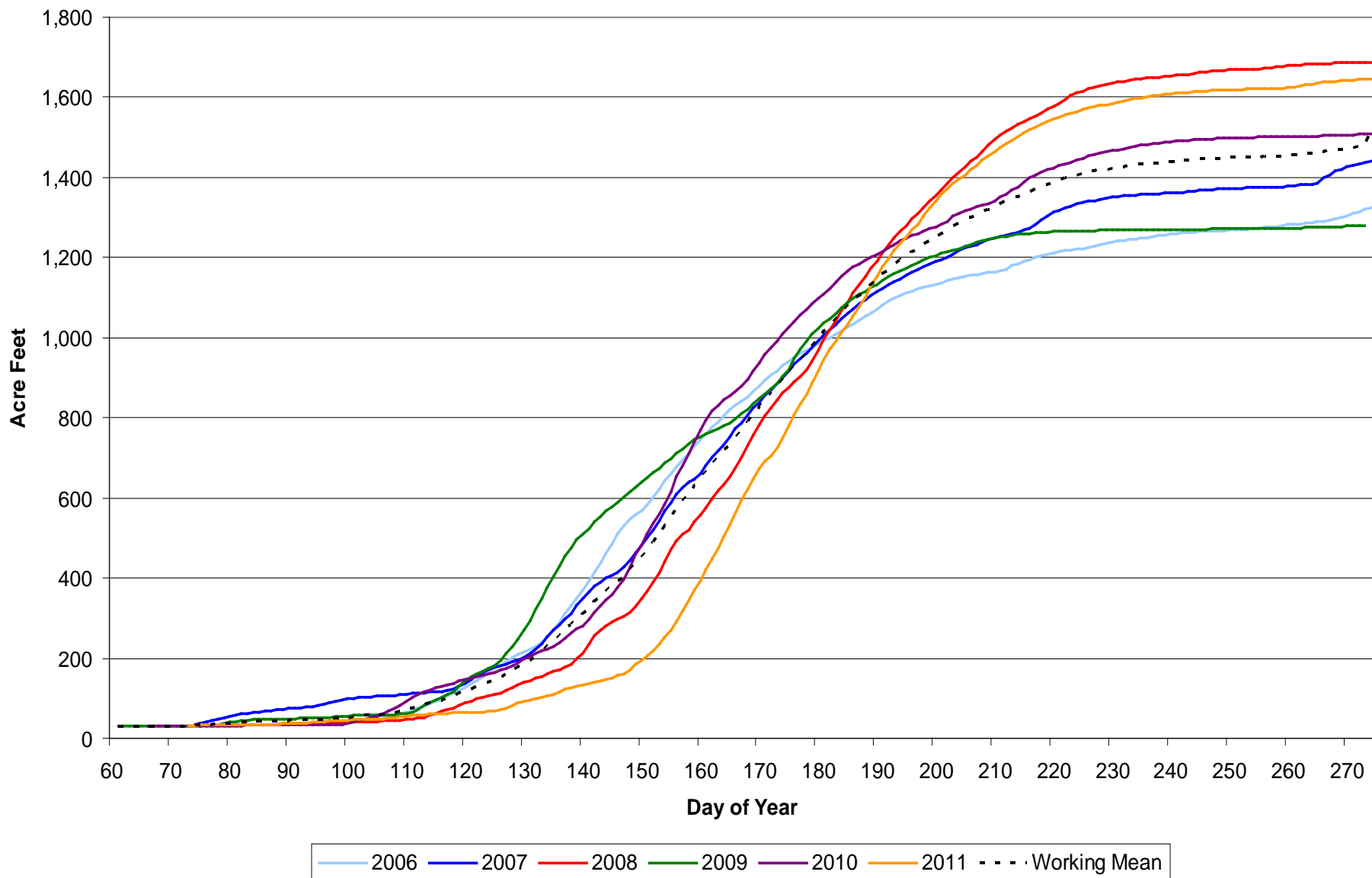
Water Temp and Conductivity



**Senator Beck Stream  
Gauge 11,030'**



# Senator Beck Basin Cumulative Discharge - 2006, 2007, 2008, 2009, 2010, 2011



# Snow Albedo Measurement

Senator Beck Study Plot 12,200'

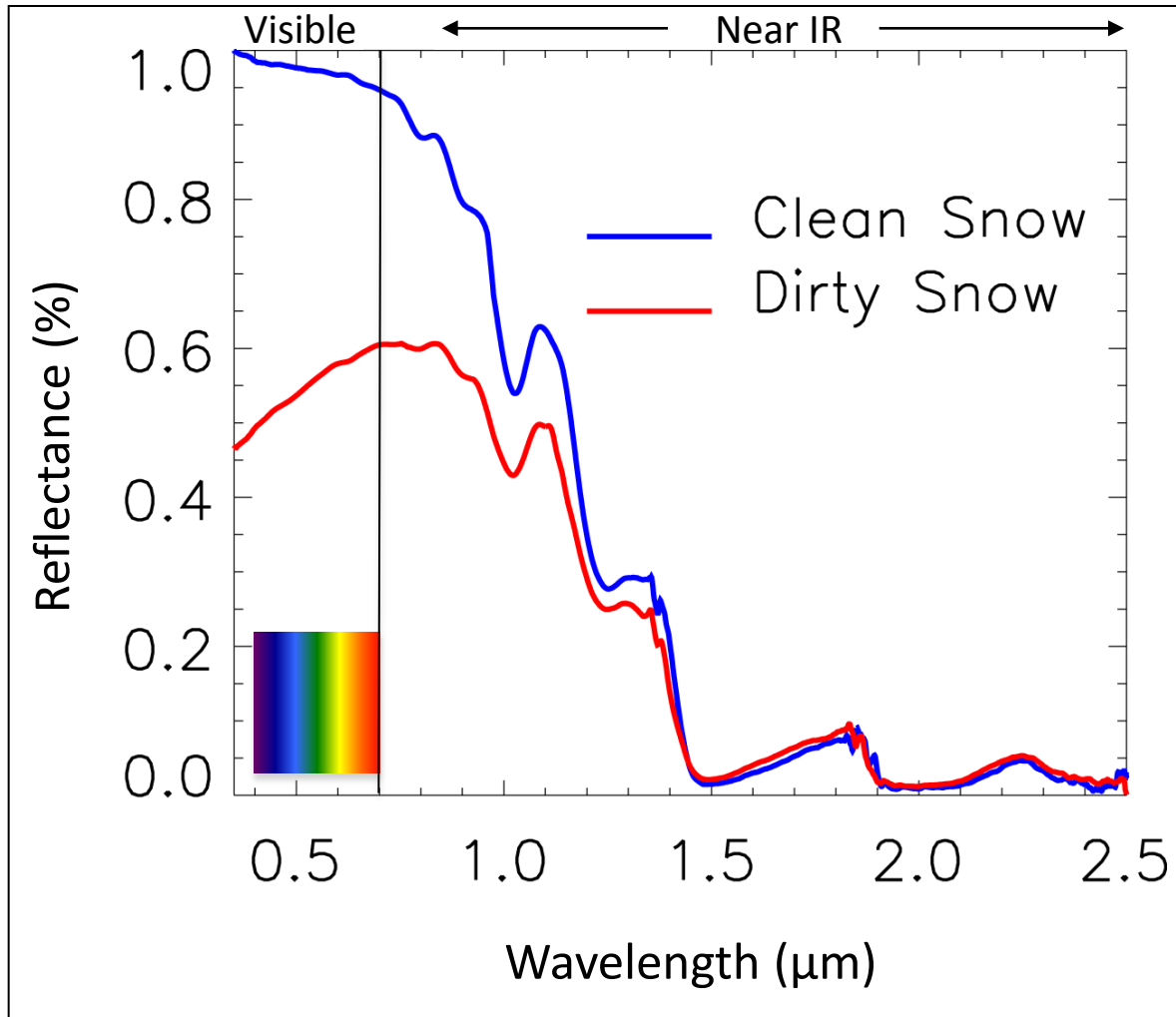






**May 12, 2009 – from Peak 13,510' at top of Senator Beck Basin Study Area**

# Dust decreases snow albedo



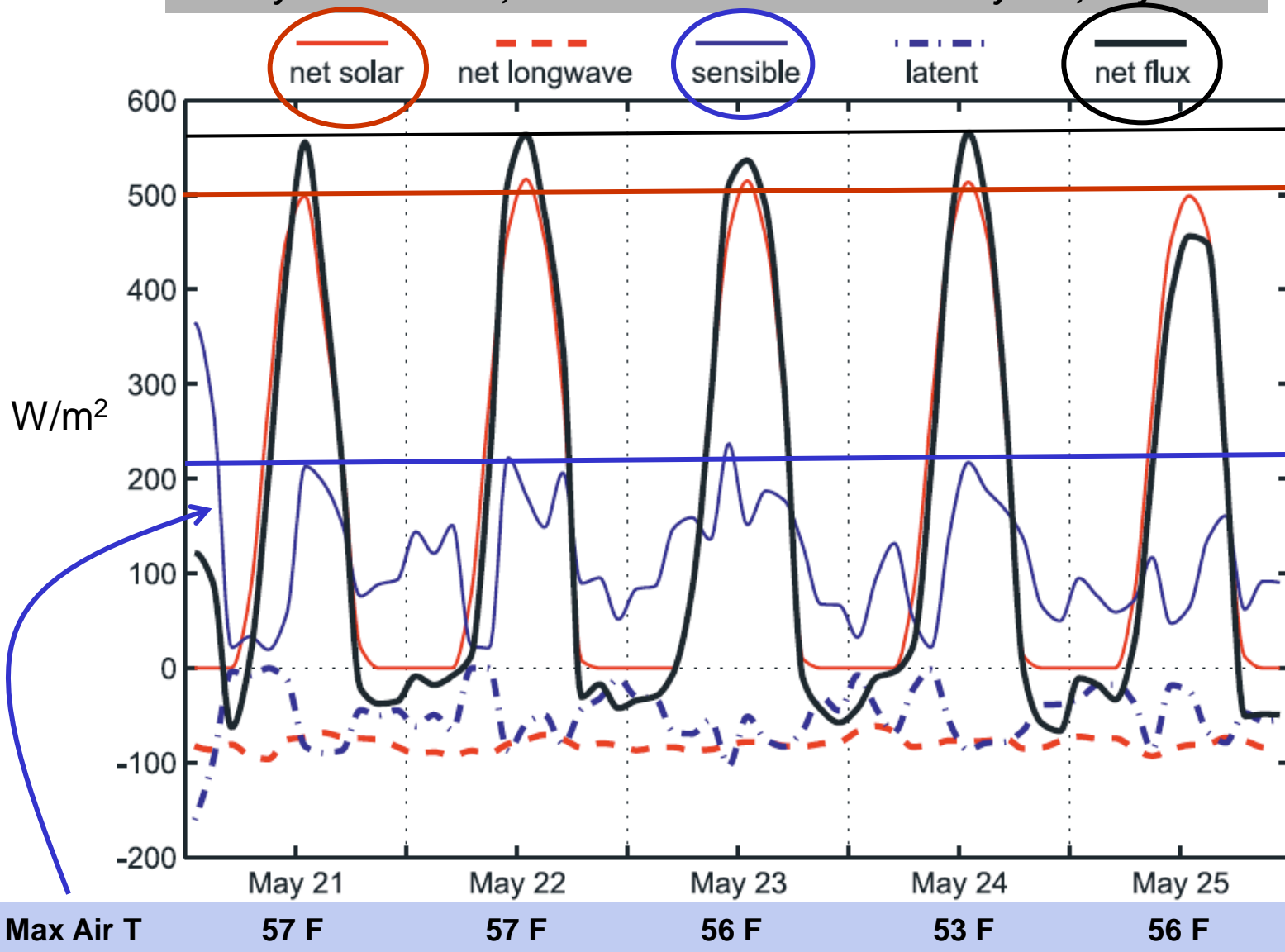
Courtesy Jeff Deems



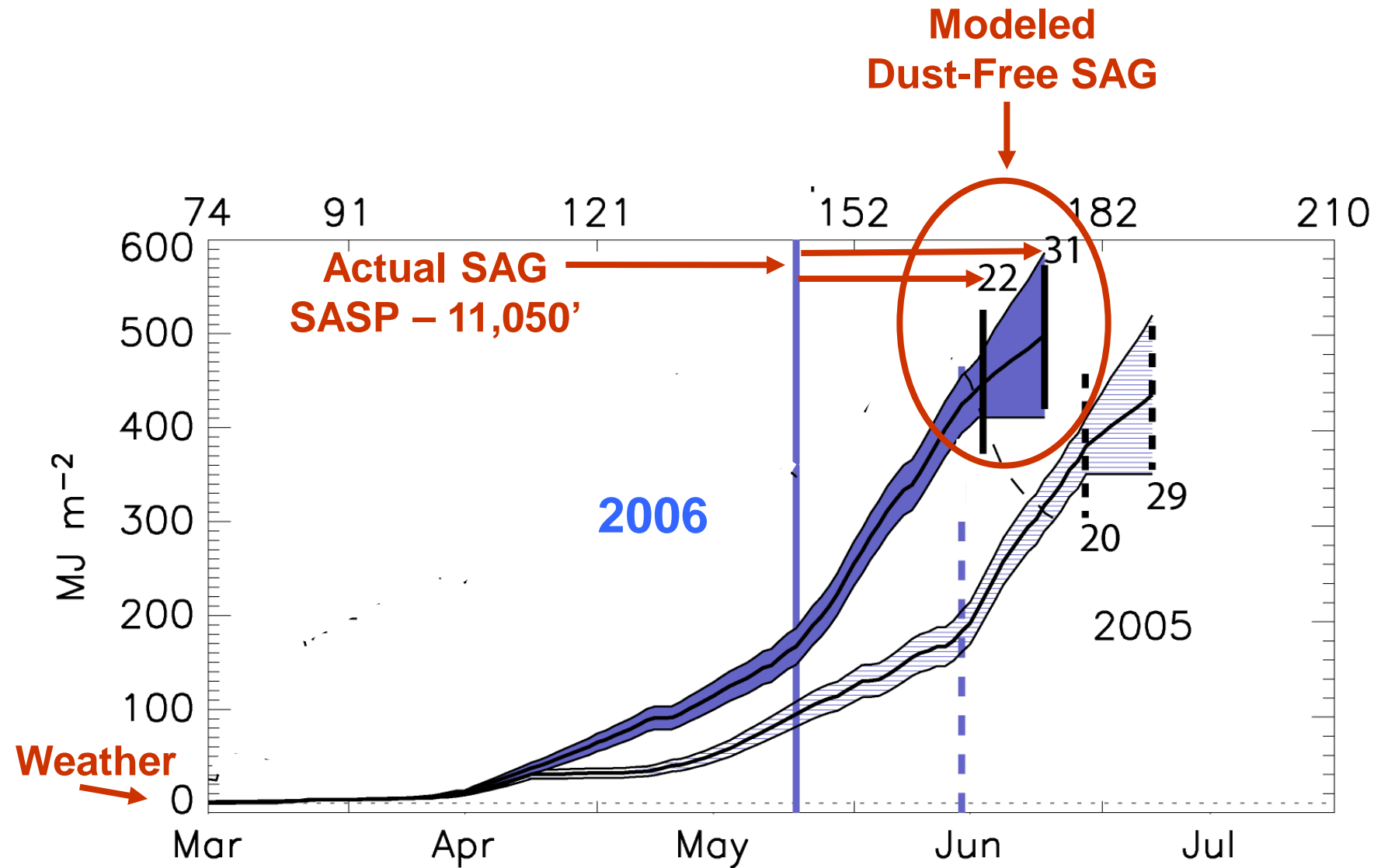


# Enhanced Snowmelt Energy Input

*Dusty Snow Surface, Clear Skies – Senator Beck Study Plot, May 2005*

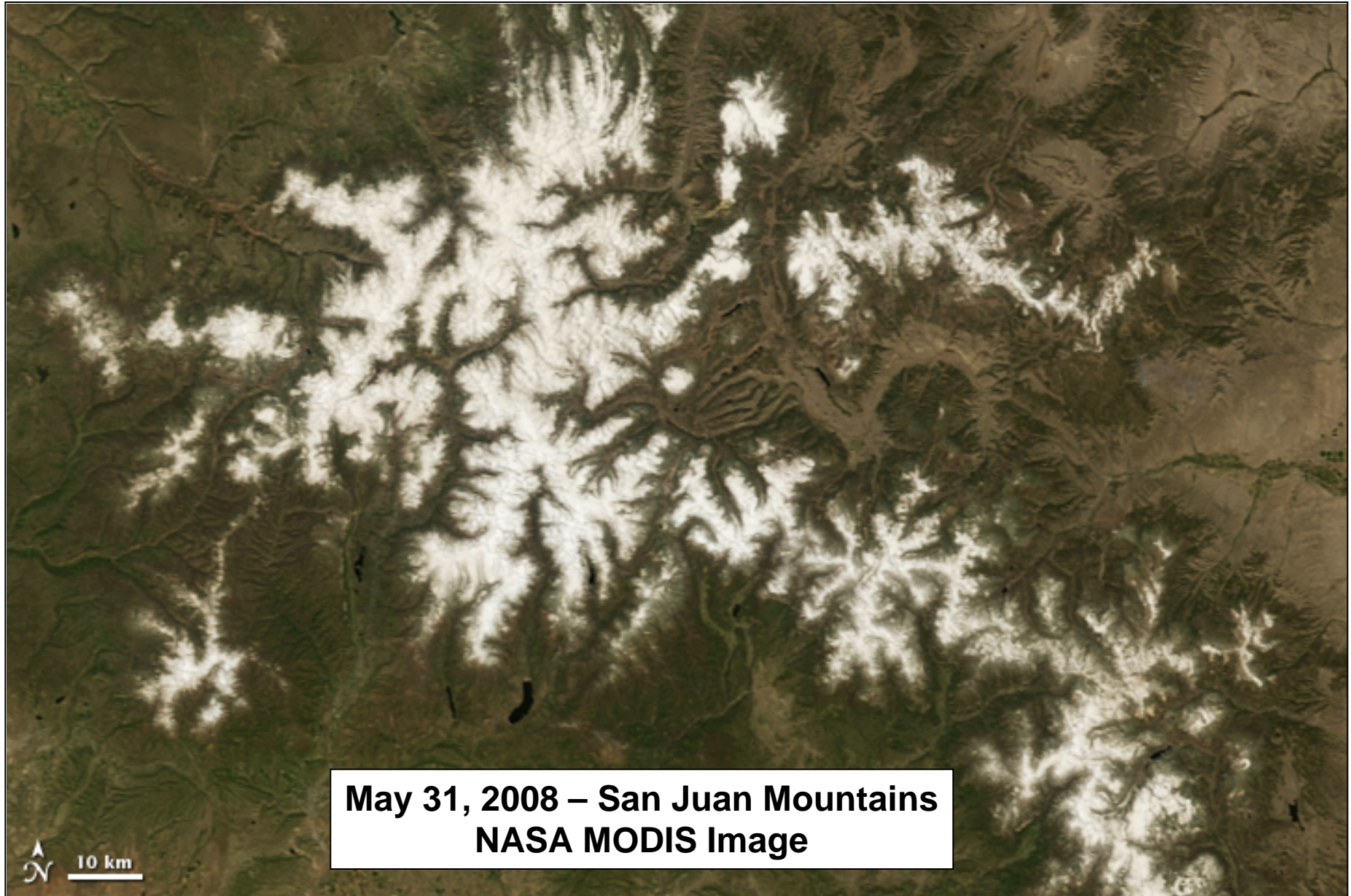


# Reduced Albedo = Snowmelt “Forcing”

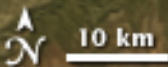




# Large-Scale Albedo Reductions

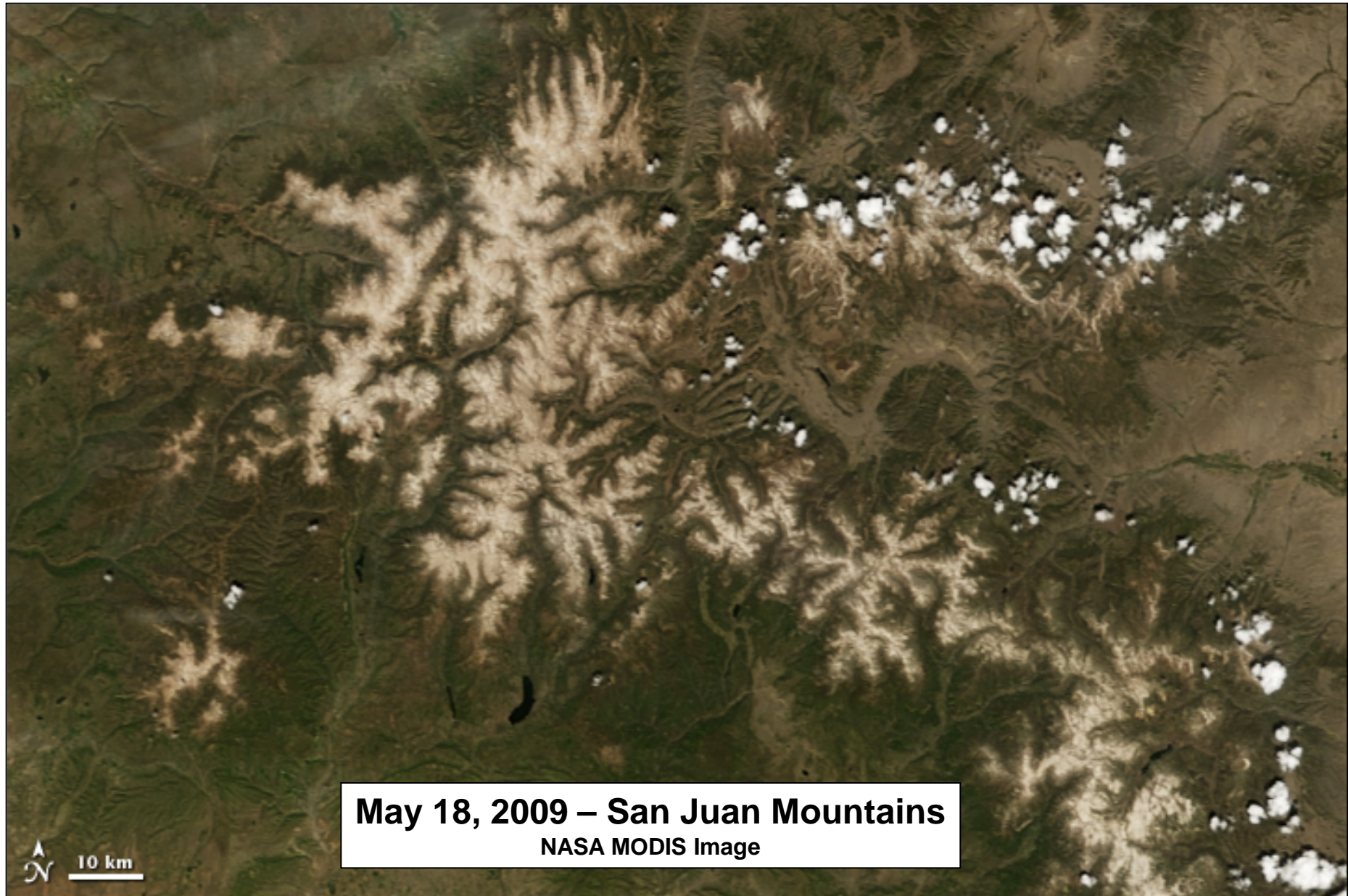


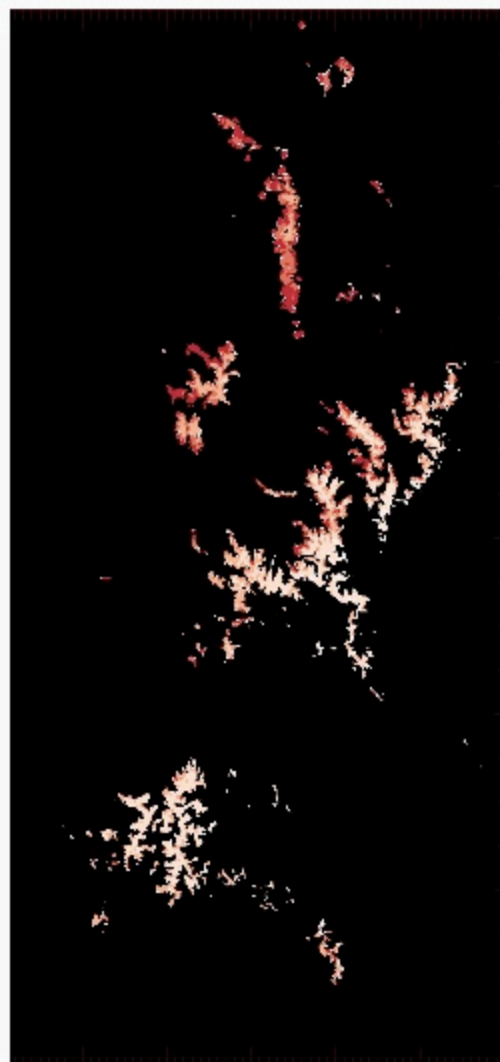
**May 31, 2008 – San Juan Mountains  
NASA MODIS Image**



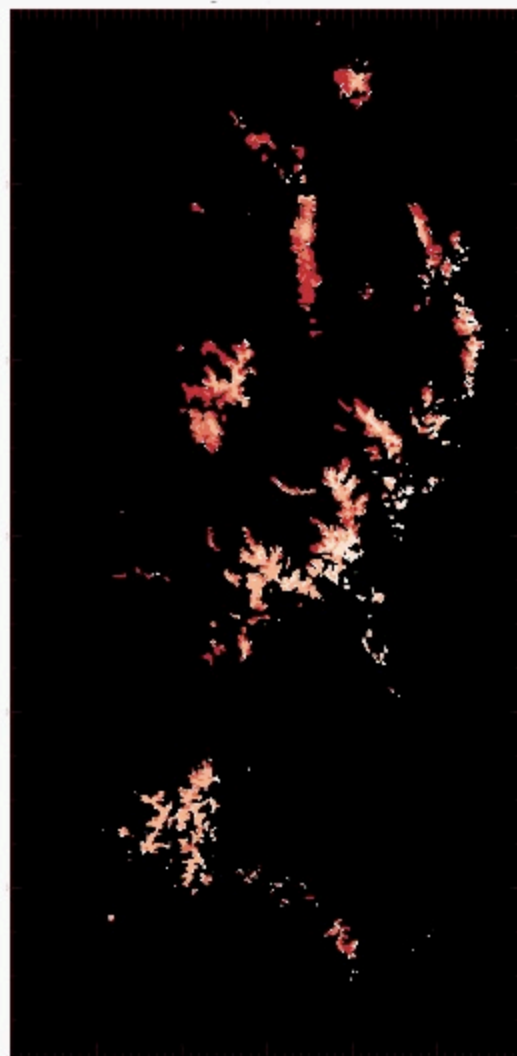


# Large-Scale Albedo Reductions

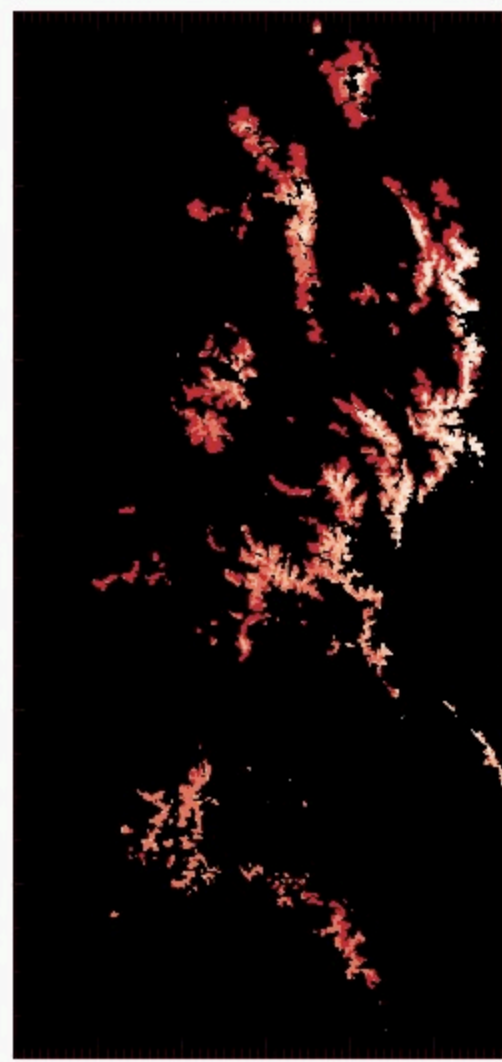




May 21, 2000



May 31, 2006



May 18, 2009

300.0

240.0

180.0

120.0

60.0

0.0



# Applied science for stakeholder agencies ....

Timely, iterative monitoring and analysis of dust effects on snowmelt timing and rates throughout the Colorado mountains ... supplemental to CBRFC forecasts.



Spring 2009 – From Senator Beck Basin Study Area

# CSAS Colorado Dust-on-Snow Program

<b>CODOS Program Funders</b>	WY 2007	WY 2008	WY 2009	WY 2010	WY 2011	<b>Proposed WY 2011</b>
Colorado River Water Conservation District	8,000	8,000	8,000	10,000	10,000	<b>10,000</b>
Southwestern Water Conservation District	5,000	5,000	4,000	5,000	5,000	<b>5,000</b>
Rio Grande Water Conservation District		3,000	4,000	5,000	5,000	<b>5,000</b>
Upper Gunnison River Water Conservancy Dist.		5,000	7,500	7,500	7,500	<b>7,500</b>
Northern Colorado Water Conservancy District			1,500	2,500	2,000	
Tri-County Water Conservancy District	1,000	1,000	1,500	2,500	2,500	<b>2,500</b>
Animas-La Plata Water Conservancy District			500	600	600	<b>750</b>
Dolores Water Conservancy District				600	600	<b>750</b>
Denver Water	2,500	2,500	2,500	5,000	5,000	<b>5,000</b>
Bureau of Reclamation – Western Colorado Area			5,000	7,500	7,500	<b>7,500</b>
Bureau of Reclamation – Lower Colorado Region				7,500	10,000	<b>10,000</b>
Bureau of Reclamation – Eastern Colorado Area					2,500	<b>2,500</b>
Bureau of Reclamation – Albuquerque Area						<b>2,500</b>
Western Water Assessment – Univ of Colorado			20,072			
Colorado Water Conservation Board				28,034	15,000	<b>25,000</b>
City of Grand Junction					2,500	<b>2,500</b>
<b>TOTAL</b>	<b>16,500</b>	<b>24,500</b>	<b>54,572</b>	<b>81,734</b>	<b>75,700</b>	<b>86,500</b>

# CODOS Products



## Colorado Dust-on-Snow Alert #8, June 1, 2008

Following the expected brief pause in snowmelt discussed in Alert #7 of May 24<sup>th</sup>, all Snotel sites that we've been monitoring this spring have shown a second steep decline in SWE during the past week. All sites showed losses in SWE of equal or greater magnitude than the drop seen earlier, in mid-May, and some sites have reached "Snow All Gone" (SAG). The substantial dust layer (composed of multiple, "merged" layers) that was temporarily covered by clean new snow over the weekend of May 24<sup>th</sup> and 25<sup>th</sup> has extensively re-emerged at the snowpack surface, first at lower elevations on all aspects, and more recently at the highest elevations on even northerly aspects. Lingering patches of the May 23/24 storm snow stand in stark, bright white contrast to the surrounding dirty snow, as seen in the May 31st photo below, looking westward at the Senator Beck Basin Study Area (far right) and nearby terrain at Red Mountain Pass, here in the San Juan Mountains.

The direct absorption of solar energy by this dust layer, in tandem with two periods of sunny weather and warm air temperatures, has produced two periods of much-greater-than-average rates of snowmelt, as compared to the 30-year average rate of decline in SWE. This is clearly evident in Snotel 2007/2008 Water Year graphs around the State. Thus, even though all the Snotel sites we monitor reported substantially greater-than-average SWE values this season, most sites are also currently on a snowmelt trajectory that will result in earlier-than-average dates of SAG (Snow All Gone), some perhaps several weeks earlier than average. Some lower elevation sites that have recently reached SAG on/about their average date have done so beginning with a much above-average season maximum SWE, under very high snowmelt rates.



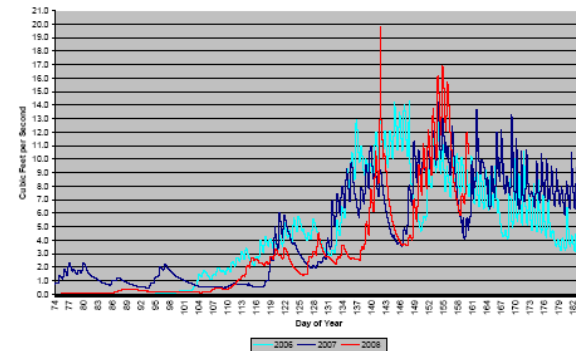
6/1/2008



## Colorado Dust-on-Snow Alert #9, June 8, 2008

As anticipated by NWS – Grand Junction, fresh snow and cool air "reset" the snowmelt clock on Wednesday and Thursday of last week; we received 16 mm of SWE in the Senator Beck Basin Study Area, as 4-8" of new snow, varying by elevation. We did not detect any fresh dust with this storm here in our study area, and have received no reports of fresh dust elsewhere. That fresh snow layer resulted in a temporary return to a high albedo that, combined with cooler temperatures, dropped our Basin discharge from near 17 cfs on June 3 to 6 cfs by June 6, as seen below, ending our second major surge of snowmelt and stretching the date of snow-all-gone (SAG) a few days further into the future. Following that low point in streamflow on June 6, however, the new clean new snow quickly succumbed to sunny skies and the absorption of direct solar radiation by the underlying dust, revealing the underlying dirty snow surface once again. Our third surge in flows this season has now begun, as of this writing, despite somewhat cooler air temperatures here in the San Juans over the past weekend.

Senator Beck Basin Hourly Discharge - 2008, 2007, 2006



Based on our first-hand observation of extensive dust layers in mid-May, it is our assumption that a similar return to high albedo (caused by new snow) occurred throughout most of the remaining Colorado mountain snowpack last Wednesday and Thursday, followed by a similar, subsequent ablation of the clean new snow and re-emergence of the underlying dirty snow surface. Some Central and Northern mountain areas may have received additional snow showers on Saturday or Sunday, but not in amounts that will cause a prolonged return to high snowcover albedo values. Therefore, given that the current NWS – Grand Jct. 7-day forecast calls for generally sunny skies through Sunday, June 15<sup>th</sup>, except for a brief disturbance on Wednesday the 11<sup>th</sup>, and temperatures at 10,000' in the 60's (except Wednesday and Thursday), another surge of dust-enhanced snowmelt is expected.

6/8/2008





*Figure 1: a headwater tributary of Walton Creek at Rabbit Ears Pass on June 9, 2011 showing the very dark May 29<sup>th</sup> D11-WY2011 dust layer merged with underlying dust layers.*

This season's largest reductions in snowcover albedo are currently contributing to Colorado's high rates of snowmelt runoff. Recent observations at most Colorado Dust-on-Snow (CODOS) monitoring sites found all of this season's desert dust layers merged and exposed at the snowpack surface, augmented in many locales by the last dust-on-snow event, D11, of May 29<sup>th</sup>, 2011. That amalgamation of all dust layers into a single, merged layer at the snowpack surface, on all aspects and at all elevations, occurred earliest in the southern mountains but is more recent (or underway) at most northern sites. The following photos illustrate the magnitude of albedo reductions at the snowpack surface at several recently visited CODOS sites, in dramatic contrast to the cleaner snow immediately below the surface. The Park Cone, McClure Pass, and Spring Creek Pass CODOS monitoring sites have lost their snowcover entirely, as has the Willow Creek Pass site. However,

Post-Peak SWE, produced the highest rate of “Mean Daily Loss SWE”. Finally, the later the date of Peak SWE, the higher the mean snowmelt period temperature, as would be expected.

Last, a comparison of WY 2011 short term snowmelt rates (Table 5 below), using a 5-day moving average beginning on the 5<sup>th</sup> day after Peak SWE and running until SAG, provides additional insight into the effects of dust-reduced snow albedo seen in the photographs in Update #6 – WY 2011.

<b>CODOS and Other SNOTEL Sites WY 2011 Snowmelt Season Summary Data</b>		
<i>SNOTEL Site</i>	<i>Highest 5-Day Moving Average Loss SWE</i>	<i>Final Day of 5-Day Period</i>
Red Mtn Pass	1.74" (2x)	June 17, 19
Slumgullion Pass	1.28"	June 4
Wolf Creek Summit	1.48"	June 19
<i>Beartown</i>	1.74" (2x)	June 8, 9
<i>Lizard Head</i>	1.40"	May 31
Park Cone	1.00"	May 11
Schofield Pass	2.44"	June 29
McClure Pass	1.78"	May 30
<i>Independence Pass</i>	1.54"	June 7
Hoosier Pass	1.20"	June 16
Grizzly Peak	1.38"	June 6
Berthoud Summit	1.46"	June 12
Willow Creek Pass	2.40"	June 11
Rabbit Ears Pass	1.94"	June 7
Mesa Lakes	1.52"	June 9
<i>Non-CODOS SNOTEL sites shown in italics</i>		

**Table 5:** showing the highest 5-day period snowmelt rates, as loss of SWE, during Spring 2011 at 11 CODOS SNOTEL sites and 4 additional SNOTEL sites. Units of snowmelt (Loss SWE) are inches of water.

Park Cone displays the slowest 5-day average rate of snowmelt; as previously discussed, Park Cone was noted as the cleanest snowpack, with the least dust, among the 11 sites monitored by CODOS during Spring 2011 (dust event D11, on May 29<sup>th</sup>, came just two days before SAG at Park Cone). Schofield Pass displays the highest 5-day average, but Willow Creek Pass is not far behind. Some of the 15 SNOTEL sites recorded their highest 5-day rate of SWE loss near the very end of snowmelt, when radiation may have penetrated through the thinning snowcover and been absorbed

**Senator Beck Basin: March 22, March 29, April 3, April 8, April 15 2009 layers**



**Below Treeline – April 22, 2009**



**Above Treeline – April 24, 2009**





**Maximum Dust at Top of Snowpack  
(all or most layers merged):**

Spring 2008 = 12 gm/m<sup>2</sup>

Spring 2009 = 55 gm/m<sup>2</sup>

Spring 2010 = ~40 gm/m<sup>2</sup>

**May 28, 2010 – Swamp Angel Study Plot**



**May 13, 2009 – Swamp Angel Study Plot**

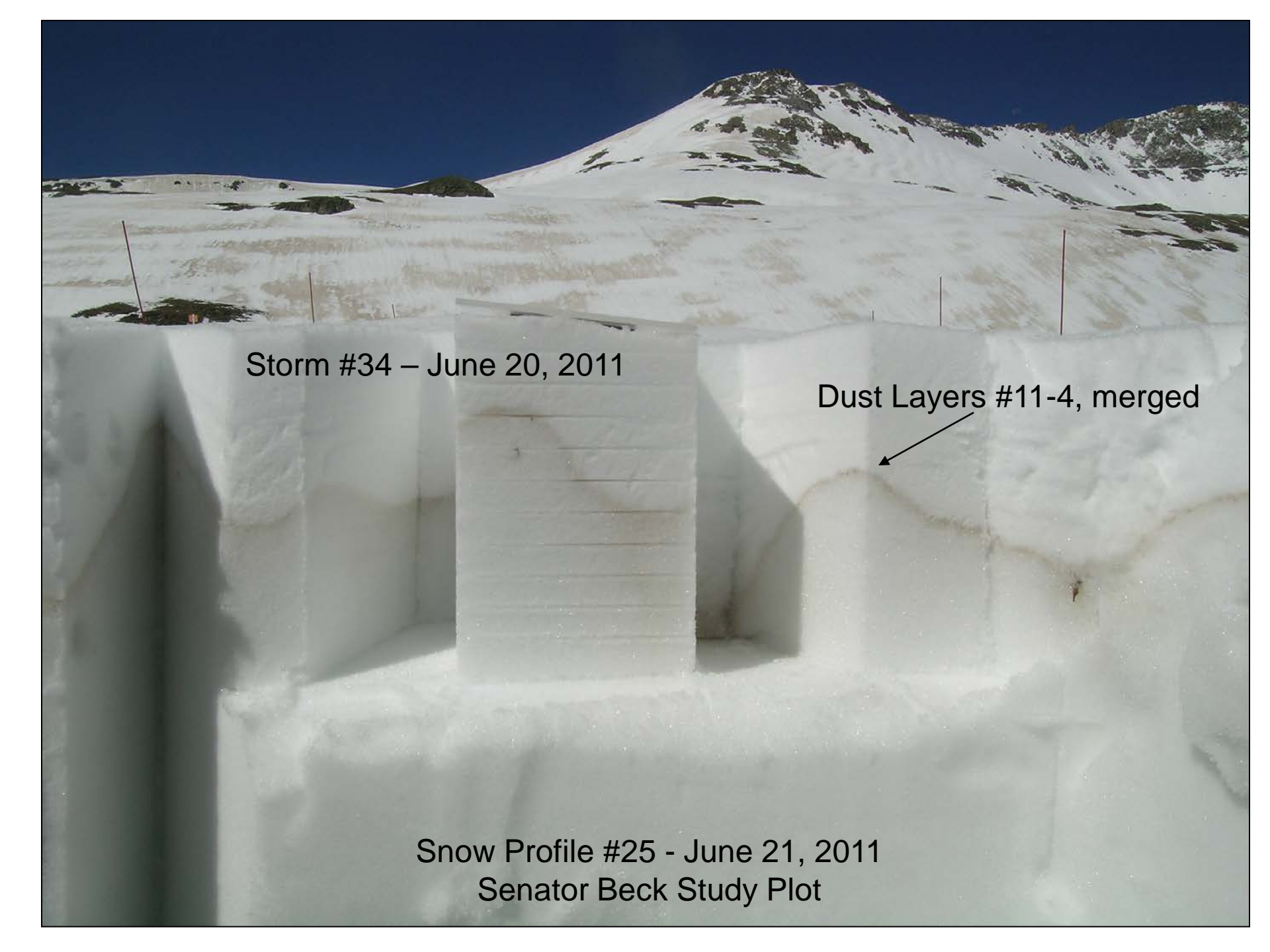






Snow Profile #24 - June 14, 2011  
Swamp Angel Study Plot



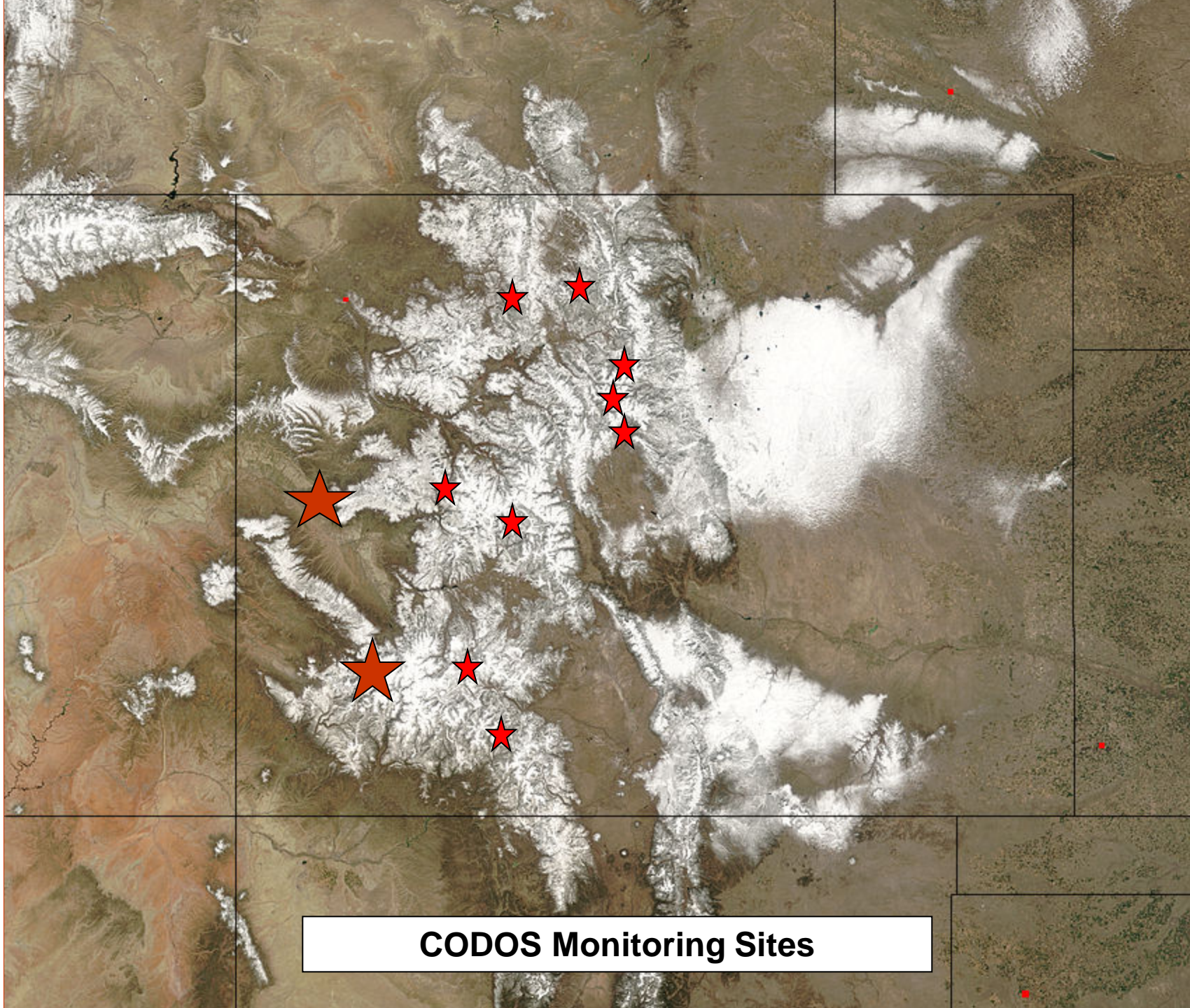


Storm #34 – June 20, 2011

Dust Layers #11-4, merged

Snow Profile #25 - June 21, 2011  
Senator Beck Study Plot





**CODOS Monitoring Sites**



**May 26, 2010 – Grizzly Peak Snotel, A-Basin**







**April 17, 2009 – Berthoud Pass**



**April 18, 2009 – Willow Creek Pass**



**May 27, 2010 – Grand Mesa**

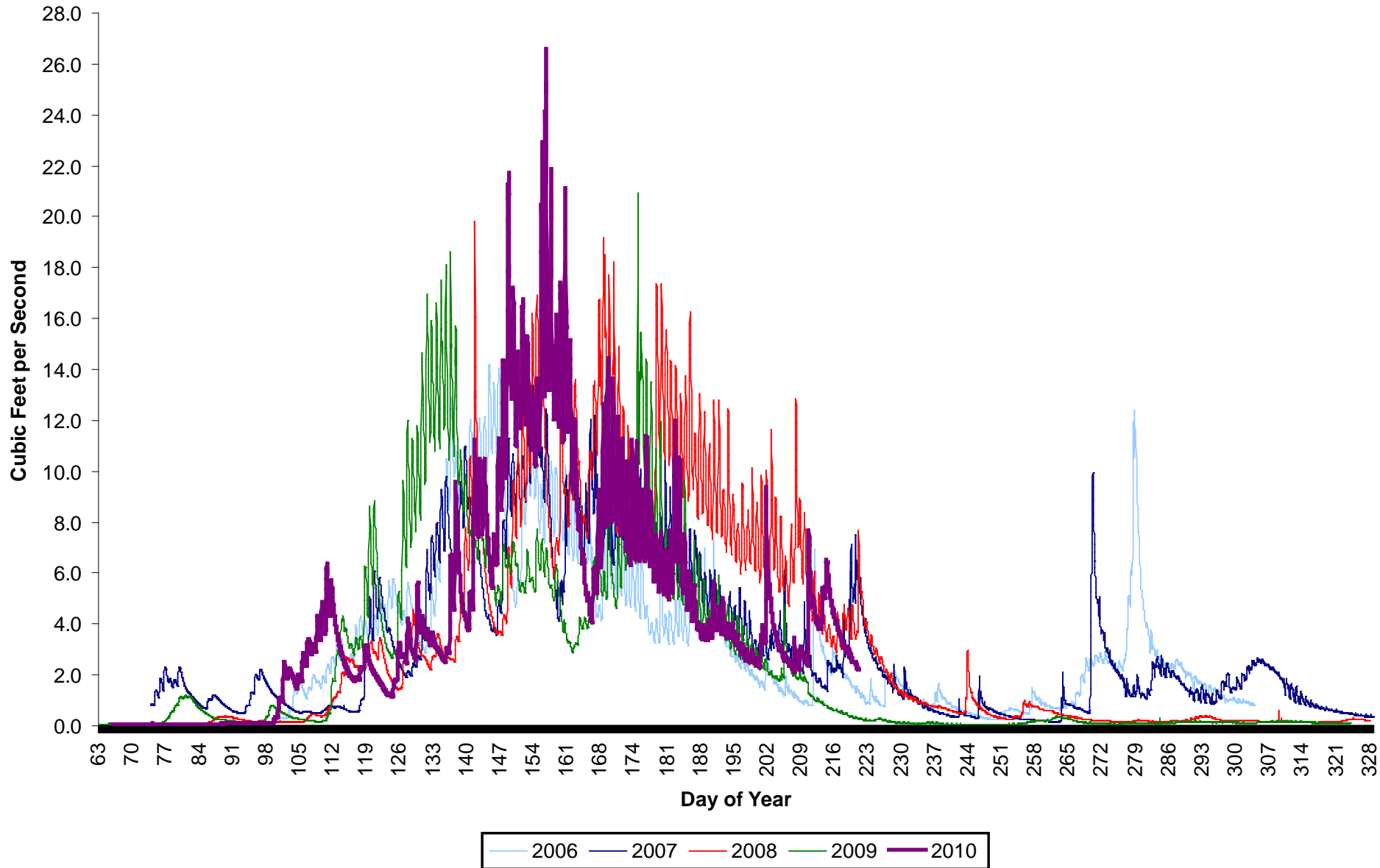




June 5, 2010 –Senator Beck Stream Gauge at 26 cfs

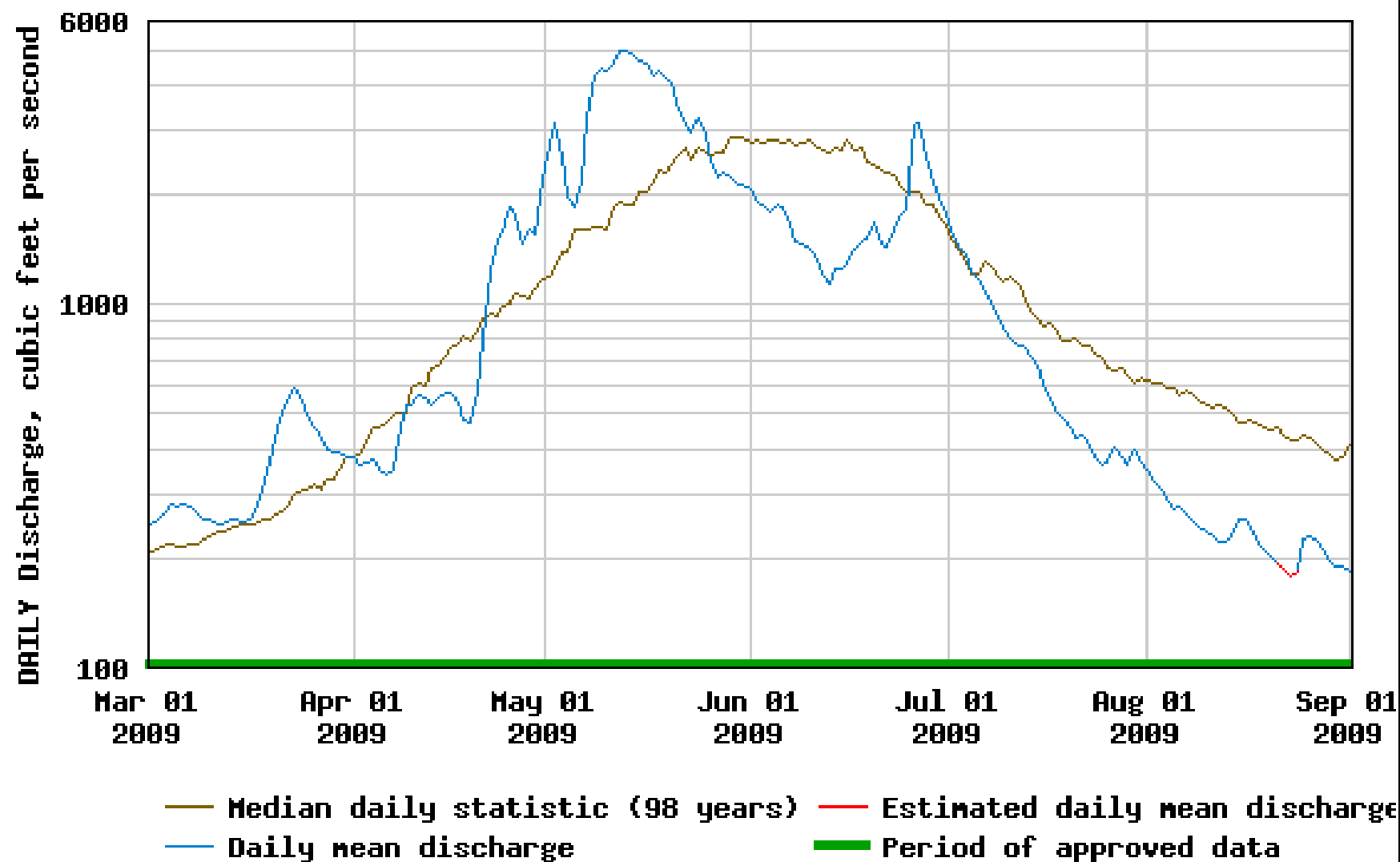


# Senator Beck Basin Discharge – WY 2006, 2007, 2008 & 2009, 2010



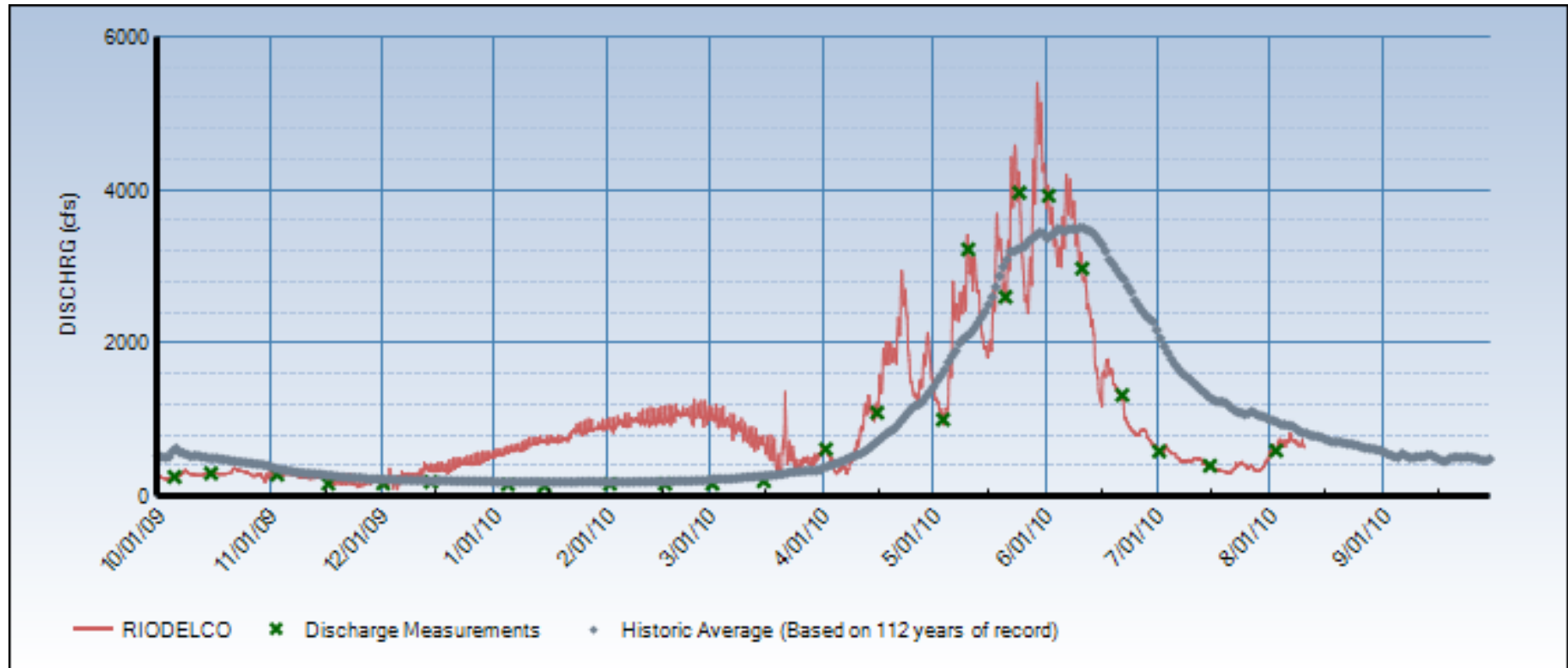


## USGS 09361500 ANIMAS RIVER AT DURANGO, CO

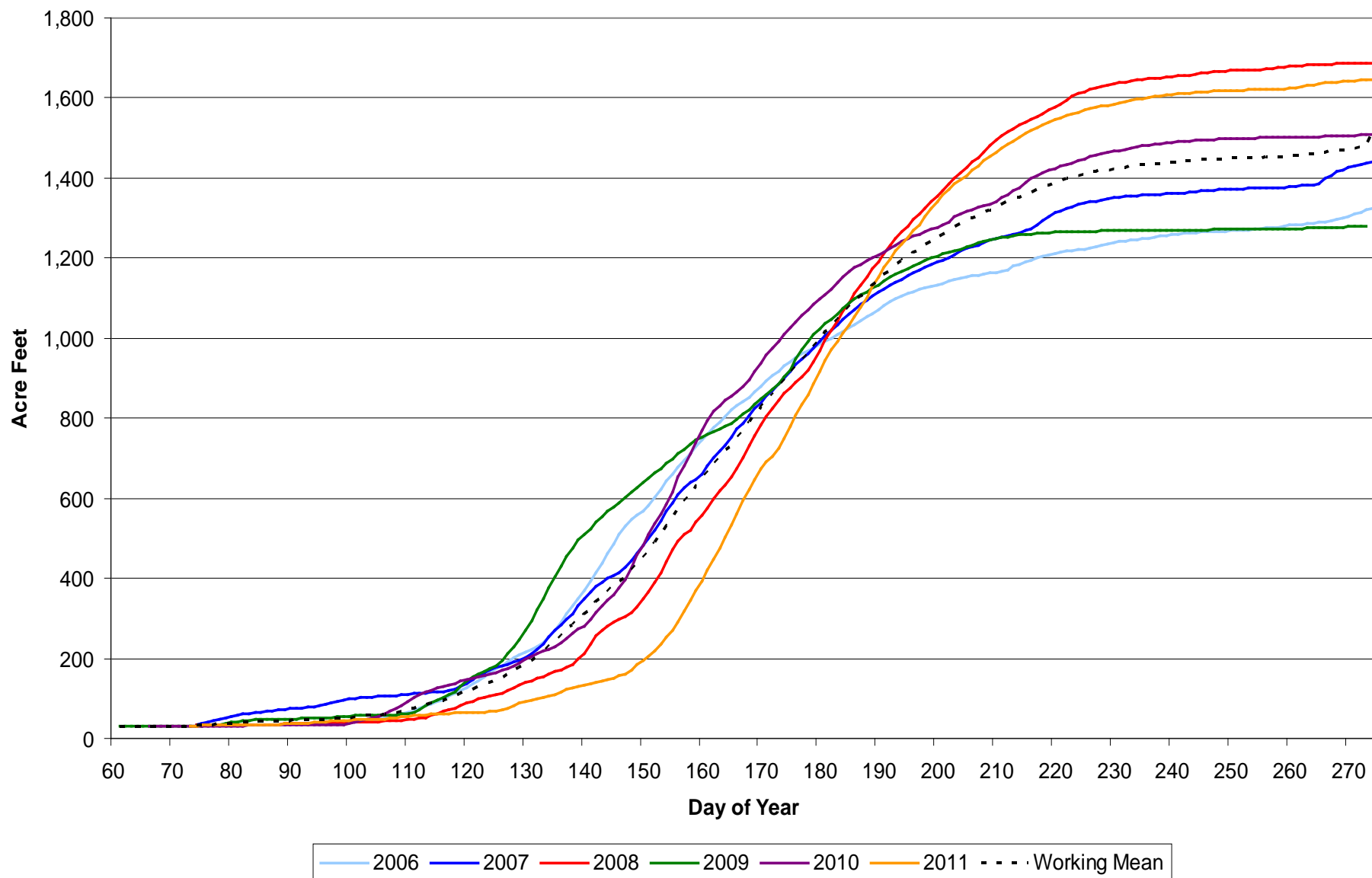




# Rio Grande at Del Norte WY 2010

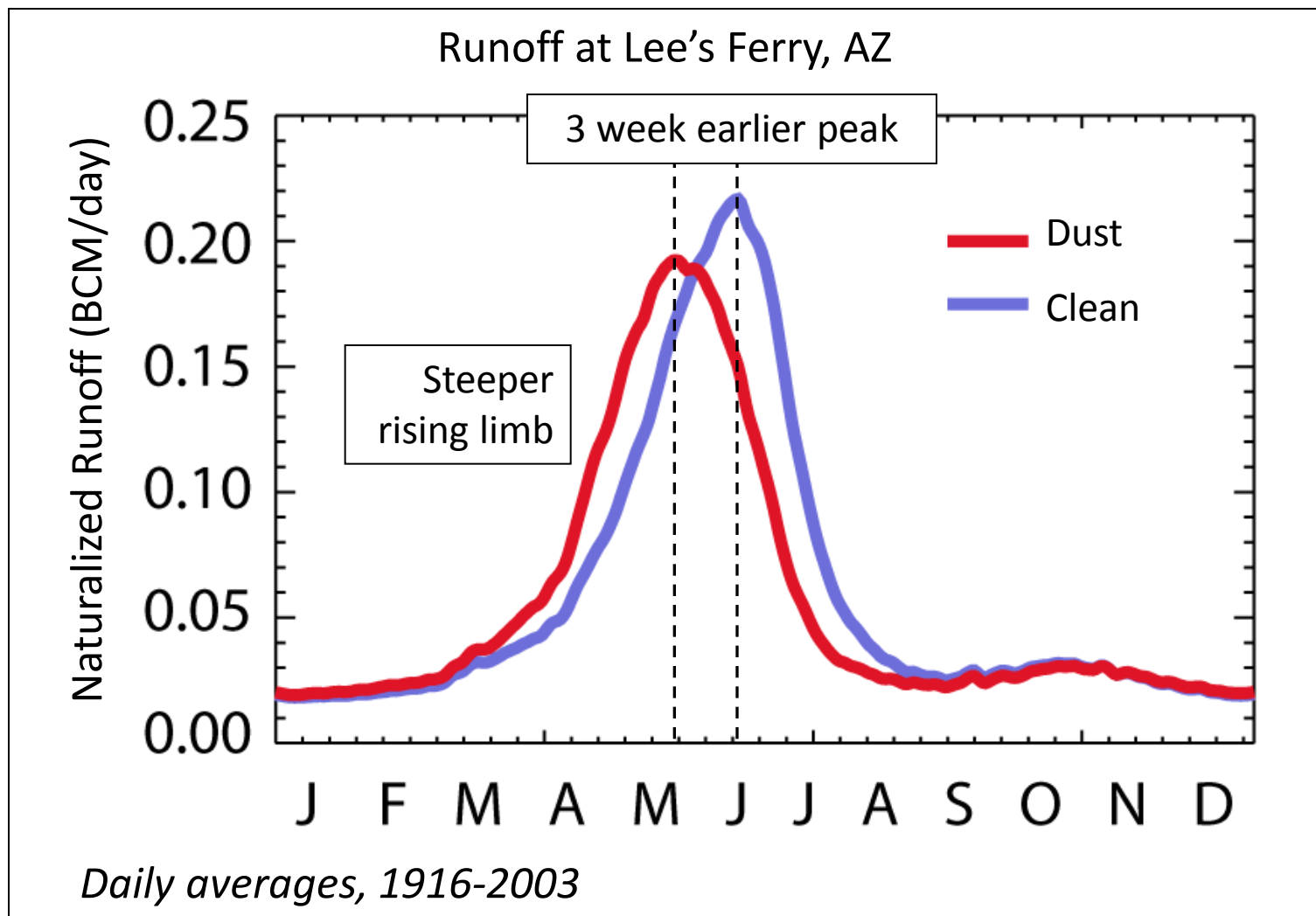


## Senator Beck Basin Cumulative Discharge - 2006, 2007, 2008, 2009, 2010, 2011



# Dust-on-Snow Shifts Upper CRB Hydrograph\*

\*not including 2009, 2010 dust deposition rates

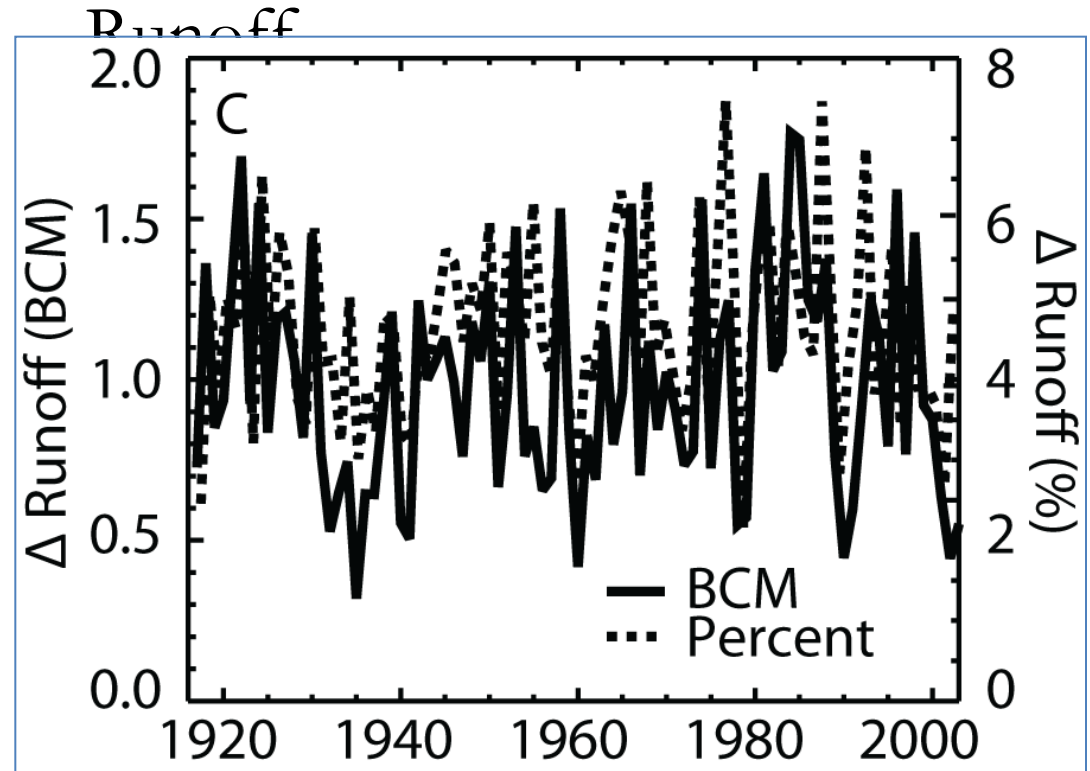




*At the scale of the Upper CRB, modeling shows:*

DOS = Earlier SAG = Increased ET = Reduced

- Mean  $\Delta$  Runoff:
  - 4.9%
  - 811,000 acre-ft
- Range:
  - 2.3 to -7.6%
  - 243k to -1,460k acre-ft



*\*based on pre-2009 dust loading*

## ***What we have learned since 2003/2004 ...***

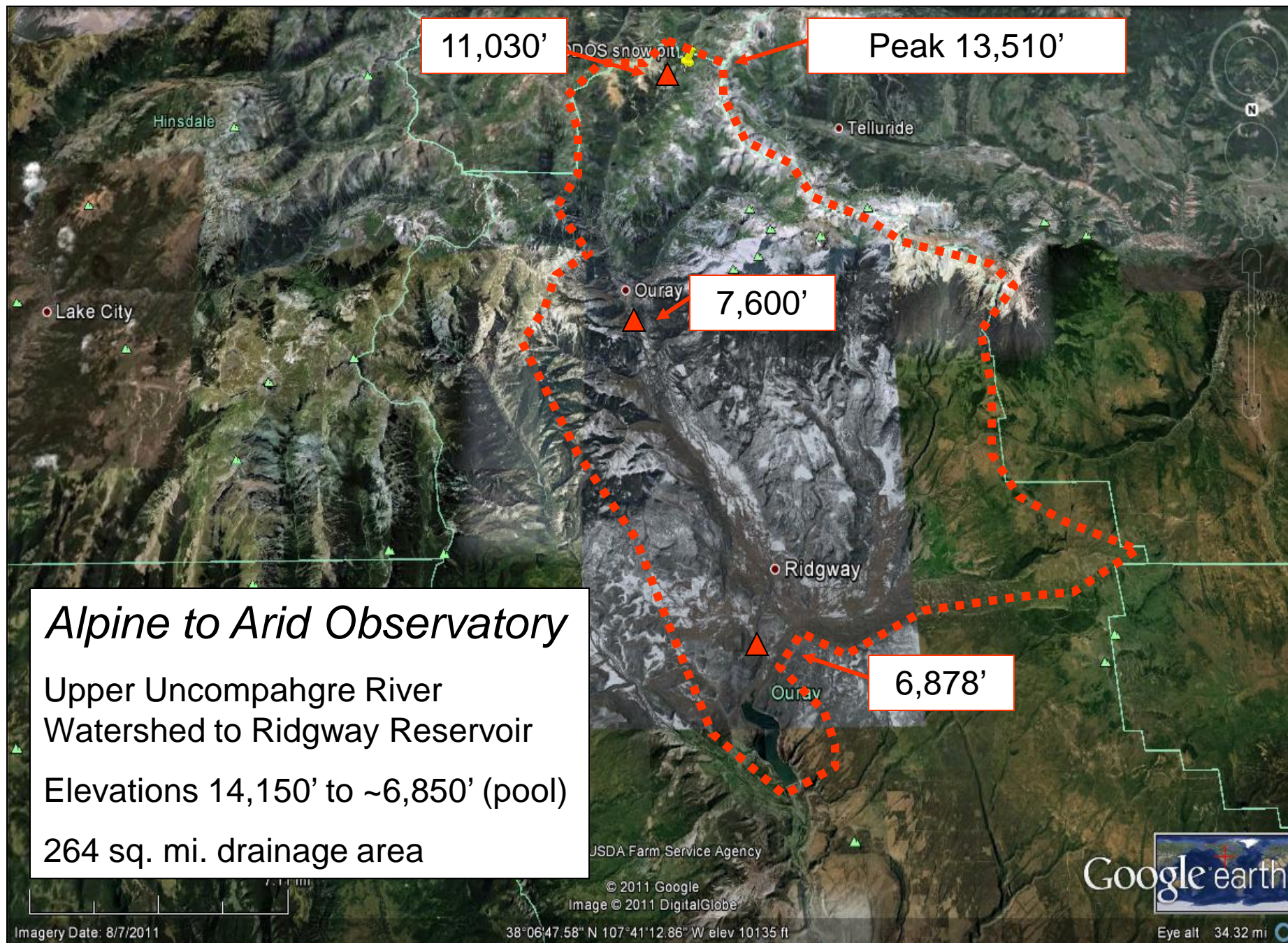
- Dust-on-snow is extensive, affecting all Colorado mountain watersheds
- Dust deposition rates are about 5X higher than pre-settlement rates
- The Colorado Plateau is the dominant source of dust on Colorado snow

## ***Dust effects vary year-to-year ...***

- Reduced albedo = 2x to 3x more melt energy available (vs. air temp only)
- Snowpack ripening and snowmelt onset are advanced (vs. air temp only)
- Melt rates accelerate, advancing SAG up to 50 days (vs. air temp only)
- Dust effects already exceed projected climate forcing effects
- Dust-on-snow has reduced Upper CRB flows at Lees Ferry by 3-7%

## ***What we do not yet know ...***

- Exactly why the winters of 2008/2009 and 2009/2010 were so dusty
- Whether 2008/2009 and 2009/2010 are a new normal
- Shares of dust attributable to the variety of agents disturbing CP soils







## **Center for Snow & Avalanche Studies**

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**Web: [www.snowstudies.org](http://www.snowstudies.org)**