Colorado Dust-on-Snow Program – Water Year 2011

Update #1 - Wednesday, March 23, 2011

Greetings from the Colorado Dust-on-Snow Program (CODOS) at the Center for Snow and Avalanche Studies (CSAS), based in Silverton. CSAS wishes to thank the Colorado water management community for your continued support of CODOS and our ongoing monitoring of dust-on-snow at our Senator Beck Basin Study Area at Red Mountain Pass, and at ten additional sites throughout the Colorado mountains. CODOS affords us with an unmatched opportunity to fulfill the CSAS's mission by supporting basic dust-on-snow research, performing ongoing monitoring, and assisting in the application of both to your management of Colorado's snowmelt water resource by providing timely information.

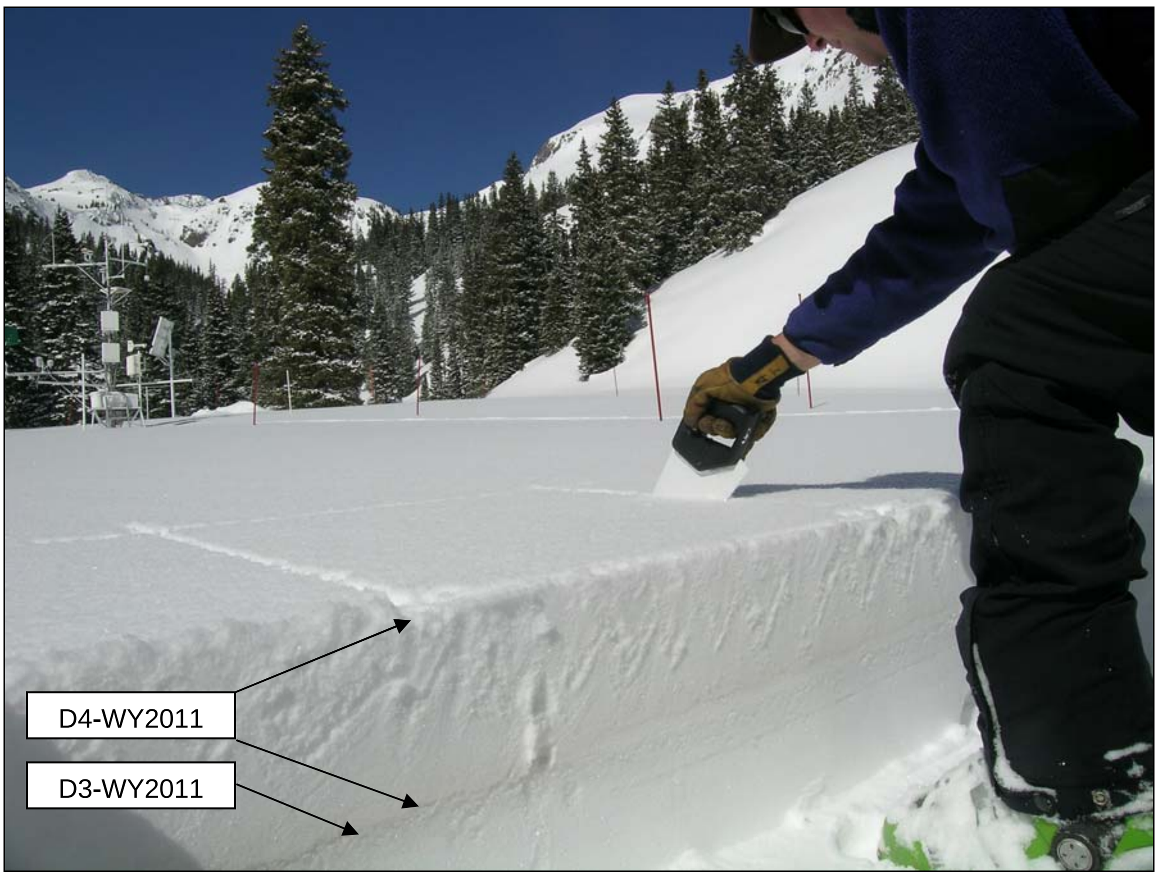

Figure 1: CSAS field assistant Andrew Temple at the Swamp Angel Study Plot at Senator Beck Basin on March 23, 2011. Andrew is preparing a 0.5 m^2 block containing dust layers D3 and the freshly deposited overlying layer containing D4, for mass load sampling.

This season's series of Water Year 2011 Updates begins by reporting that, following two barely discernible dust layers on February 17 (D1-WY2011) and March 12 (D2-WY2011), we've just experienced two additional, back-to-back events at our Senator Beck Basin Study Area at Red Mountain Pass, deposited respectively on March 17-20 (D3-WY2011), in a low-intensity but prolonged episode of apparently intermittent dry deposition (under sustained high winds), followed by a more intense and dramatic event on March 21 (D4-WY2011), deposited directly onto and merged with the D3 layer at the snowpack surface here at Senator Beck Basin (Figure 1 above). In Water Year 2009 we had already received seven dust layers by the end of March, whereas in Water Year 2010, Senator Beck Basin only received its first significant dust-on-snow event on March 30th. Table 1, below, presents a tally of dust-on-snow events since Water Year 2003.

The February 17, 2011 (D1-WY2011) event was also seen buried in the snowpack by other observers at McClure Pass and near Crested Butte, where it may have been a somewhat more substantial deposition. No other sitings of potential D2 were received but D3 dust was apparently visible in the Elk Mountains. The D4 dust storm was observed by many in the Gunnison Valley and in the San Luis Valley. The late afternoon and evening timing of D4 may have resulted in that event traversing areas in the Central and Northern mountains after nightfall, with new snow obscuring the dust by the following morning.

Dust-on-Snow Events Documented per Month, by Winter **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+ tbd*	*tbd*	*tbd*	*tbd*	*tbd*

Table 1: *Log of Dust-on-Snow Events Observed at Senator Beck Basin Study Area.*

For your further reference, the specific dates of onset of the logged dust-on-snow events at Senator Beck Basin, by winter season, were as follows (WY = Water Year):

2002/2003 (WY 2003): Feb 3, Feb 22, Apr 2

2003/2004 (WY 2004): Apr 17, Apr 28, May 11

2004/2005 (WY 2005): Mar 23, Apr 4, Apr 8, May 9

2005/2006 (WY 2006): Dec 23, Feb 15, Mar 26, Apr 5, Apr 15, Apr 17, May 22, May 27

2006/2007 (WY 2007): Dec 17, Feb 27, Mar 27, Apr 15, Apr 18, Apr 24, May 4, Jun 6

2007/2008 (WY 2008): Mar 16, Mar 26-27, Mar 30-31, Apr 15, Apr 21, Apr 30, May 12

2008/2009 (WY 2009): Oct 11, Dec 13, Feb 27, Mar 6, Mar 9, Mar 22, Mar 29, Apr 3, Apr 8, Apr 15, Apr 24, Apr 25

2009/2010 (WY 2010): Oct 27, Mar 30, Apr 3, Apr 5, Apr 12, Apr 28, May 9, May 11, May 22

2010/2011 (WY 2011): Feb 17 (1), Mar 12, Mar 17, Mar 21

(1) Amended from previously reported Feb 19, 2011 date based on reports of earlier observation of this layer by avalanche professionals in the Silverton area.

Table 2 presents current SWE data from Snotel stations adjoining or near the sites that CODOS monitors, compared to Peak SWE in 2010. Given that most of the Snotel sites are currently well above average, it appears likely that most will attain a Peak SWE value that remains above average. If so, and if the number, intensity and timing of subsequent Spring 2011 dust-on-snow events resembles the Spring of 2010, with a number of dust layers deposited in April and May high in the snowpack, and if Spring 2011 weather enables those dust layers to emerge and remain exposed at the snowpack surface for extended periods of time, very rapid melting of above-average snowpacks may ensue.

CODOS Monitoring Site	SWE at adjacent Snotel as of March 23, 2011		Peak SWE 2010	
	Inches	% Avg	Inches	Date
Swamp Angel (Red Mtn Pass)	23.2”	97%	24.2”	4/8/10
Park Cone	12.7”	125%	10.8”	4/10/10
Spring Creek Pass (Slumgullion)	13.5”	104%	14.7”	4/11/10
Wolf Creek Summit	30.3”	96%	37.1”	5/5/10
Hoosier Pass	15.7”	114%	14.7”	5/4/10
Grizzly Peak	22.8”	142%	12.8”	4/9/10
Berthoud Summit	21.8”	127%	24.5”	5/16/10
Willow Creek Pass	18.5”	164%	14.4”	5/16/10
Rabbit Ears Pass	36.5”	143%	19.2”	5/16/10
McClure Pass	21.1”	119%	20.3”	4/10/10
Grand Mesa (Mesa Lakes)	19.2”	110%	16.9”	4/9/10

Table 2: *SWE conditions as of March 23, 2011 at CODOS's dust-on-snow monitoring locations, and Peak SWE during the spring of 2010 at those sites. Where a site is not adjacent to a Snotel, the nearest Snotel site is shown in parentheses.*

As of noon today, March 23rd, the merged dust layer D3/D4 had begun to emerge at the snowpack surface on sunny (south and east) aspects in Senator Beck Basin, and around Red Mountain Pass, and shallow wet-loose avalanching in the new snow accompanying D4 had commenced, revealing a dirty “bed surface” at the D3/D4 interface. It’s reasonable to assume that, where present, the merged D3/D4 dust layer is also rapidly emerging at lower elevations on sunny and perhaps even shady aspects in our and other locales, where new snow amounts deposited after D4 were minimal.

While the snowcover in the majority of Senator Beck Basin and other alpine terrain in the San Juan Mountains still retains snow temperatures well below 0º C, the snowcover on our lowest elevation S’ly slopes in the Basin (~11,000’) and on other, even lower elevation south-facing terrain in the western San Juan Mountains had become isothermal in recent days. Solar energy absorbed by dust that emerges at the snowpack surface on lower elevation, already isothermal snowpacks will accelerate snowmelt at those locations and contribute to brief surges in streamflows, as has been seen early in the ascending phase of spring runoff hydrographs for the past several seasons.

If and as the merged D3/D4 dust approaches or emerges at the snowpack surface in the high elevation, alpine terrain of the San Juan Mountains, and in other alpine terrain throughout the State where those layers are present, thereby reducing the snow surface albedo, solar energy absorbed by the dust may produce melt water percolating into the snowpack surface. As that free water percolates as a “wetting front” deeper into the higher elevation snowpack it will encounter snow at temperatures below 0ºC and eventually lose energy and refreeze, often as a very thin layer of clear ice. This migration of radiatively (dust) forced melt energy down into the snowpack can accelerate the warming and "ripening" of the snowpack to an isothermal state, at 0° throughout.

As of this writing, the National Weather Service in Grand Junction anticipates additional winter storms and unsettled weather during the coming 5-7 day period, throughout most Colorado mountain ranges. CSAS's CODOS program staff will conduct our first 1,000 mile inspection tour of our ten CODOS sites during the next favorable period of weather in late March/early April. We will be digging full-depth snowpits at each site to document the presence or absence of the dust layers we've observed at Senator Beck Basin (or other layers), the depth of burial of dust layers found, and snowpack temperatures (to determine whether the snowpack still contains "cold content"). Favorable weather will also enable us to observe the presence/absence of dust on the mountain snowcover surface along our driving route between those sites, another important element of these field tours. To the extent that this opportunistic scheduling allows, we will inform you in advance of our itinerary and would welcome staff from participating CODOS organizations to meet us at your respective CODOS sites of interest for our field session. More soon …

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Colorado Dust-on-Snow Program – Water Year 2011

Update #2 - Monday, April 4, 2011

April greetings from the Colorado Dust-on-Snow Program. The CSAS team just returned to Silverton on Saturday afternoon, April 2nd from field visits to our ten CODOS monitoring sites. As in prior years, that five day, 1,150 mile circuit revealed considerable variation in the Colorado mountain snowscape, from the very dry to the very deep. Light brown (similar in color to iced tea) dust corresponding to the uppermost D3/D4 dust layer present at our Swamp Angel Study Plot was observed in the snowpack at all ten of those sites. Dust-in-snow was generally closest to (or at) the snowpack surface at our southern and westernmost CODOS sites. In contrast, except at Willow Creek Pass, at CODOS sites along and north of I-70 the uppermost dust layer in the snowpits was deeply buried under clean snow. One site, McClure Pass, presented an isothermal snowpack, but all other sites retained some cold content. A subsequent winter storm on Sunday, April 3rd deposited additional new snow at almost all sites but we have received no reports of new dust, to-date. Table 1 presents a summary of our snowpit observations including the depth of snow above the uppermost dust layer (in inches of snow and inches of SWE), the coinciding SWE at the nearby Snotel that day, and additional SWE added since the day of our field visit to the site.

CODOS Monitoring Site	CODOS Snowpit Data					Nearby Snotel	
	Date	Total Depth	Depth to Dust		Mean Snow Temp (°C)	Total SWE Day of Pit	Net Change SWE Since Pit
			Snow	SWE			
Swamp Angel (Red Mtn Pass)	3/29/11	85”	11.4”	1.3”	-2.7	24.2”	+0.1”
Park Cone	3/29/11	42”	8.3”	1.0”	-1.8	13.4”	+0.8”
Spring Creek Pass (Slumgullion)	3/30/11	33”	0.0”	0.0”	-2.8	13.9”	0.0”
Wolf Creek Summit	3/30/11	78”	4.3”	0.7”	-1.1	31.6”	+0.2”
Hoosier Pass	3/31/11	85”	20.9”	3.8”	-3.0	17.5”	+0.5”
Grizzly Peak	3/31/11	92”	20.1”	3.7”	-2.2	25.4”	+1.1”
Berthoud Summit	3/31/11	87”	24.0”	3.9”	-2.3	25.2”	+0.3”
Willow Creek Pass	4/1/11	49”	2.0”	0.5”	-0.8	19.6”	+1.1”
Rabbit Ears Pass	4/1/11	113”	21.3”	4.3”	-1.9	40.7”	+1.1”
McClure Pass	4/1/11	50”	2.8”	1.1”	0.0	22.2”	-0.9”
Grand Mesa (Mesa Lakes)	4/2/11	78”	4.3”	1.2”	-0.8	20.8”	+0.6”

Table 1: *recent snowpit observations at CODOS monitoring sites and data from their nearby Snotel sites. Snowpit data include the depth of burial of the observed uppermost dust layer in the snowpack, in both inches of snow and inches of SWE of that snow, and a mean snowpack temperature based on a profile of measurements made every four inches throughout the snowpack. Where a site is not adjacent to a Snotel, the nearest Snotel site is shown in parentheses.*

These CODOS site snowpit data, like Snotel data, represent “point-scale” samples of snowpack depth, temperatures, and structure, properties which are know to vary considerably with changes in elevation, slope aspect, wind exposure, and vegetation conditions. Nonetheless, given that these are “snapshots” in time, comparisons of 2010 and 2011 data from those ten sites can reveal differences of interest. Table 2 compares 2010 and 2011 data from those sites. None of the CODOS sites had received a dust-on-snow deposition prior to the March 2010 snowpits (the first dust-on-snow event in Spring 2010 was March 30th). In contrast, last week all of the CODOS site snowpacks contained dust in and/or immediately above dirty melt/freeze grains laminated within ice layers suggesting that some dust-enhanced melting occurred at the snowpack surface for a period of time before the dust layer was buried under new snow, partially reducing or ending further radiative forcing. Although the 2010 series of snowpits was conducted eight days earlier in that season, it is of interest to note that all sites but one, Wolf Creek Summit, exhibited a warmer snowpack in the recent 2011 snowpits than was observed in late March 2010. Insufficient data are available to conclude that the recently observed snow temperatures would have been significantly different (cooler) in the absence of dust, or were warmer because of dust, but they were warmer nonetheless.

CODOS Monitoring Site	2010			2011		
	Snow Pit Date	Total Depth	Mean Snow Temp (°C)	Snow Pit Date	Total Depth	Mean Snow Temp (°C)
Swamp Angel (Red Mtn Pass)	3/21/10	79”	-3.7	3/29/11	85”	-2.7
Park Cone	3/21/10	38”	-2.1	3/29/11	42”	-1.8
Spring Creek Pass (Slumgullion)	3/22/10	38”	-5.5	3/30/11	33”	-2.8
Wolf Creek Summit	3/22/10	82”	-0.9	3/30/11	78”	-1.1
Hoosier Pass	3/23/10	52”	-4.2	3/31/11	85”	-3.0
Grizzly Peak	3/23/10	37”	-4.9	3/31/11	92”	-2.2
Berthoud Summit	3/23/10	56”	-3.1	3/31/11	87”	-2.3
Willow Creek Pass	3/23/10	31”	-2.6	4/1/11	49”	-0.8
Rabbit Ears Pass	3/24/10	61”	-3.2	4/1/11	113”	-1.9
McClure Pass	3/25/10	43”	-1.6	4/1/11	50”	0.0
Grand Mesa (Mesa Lakes)	3/25/10	67”	-2.2	4/2/11	78”	-0.8

Table 2: *total snow depth and snowpack mean temperatures are compared between snowpits performed at CODOS sites on March 21-15, 2010 and on March 29 – April 2, 2011.*

With the exception of the southwest mountains and some other low elevation locations, dust was observed at the snowpack surface in only the most exposed, wind-stripped locations in the majority of high elevation terrain we observed during the circuit of the CODOS sites. However, upon our return to the San Juan Mountains, four days after leaving, significantly more dust had emerged at the snowpack surface there, and quite likely more dust had emerged at other San Juan Mountain locations where the overlying snowcover was thin during our circuit. The following are highlights of field notes made while traveling in between CODOS sites during that 1,150 mile circuit through the Colorado mountains.

On Tuesday, March 29th, only isolated pockets of dust were emerging or exposed along the Hwy 550 corridor over **Red Mountain Pass**, primarily on E aspects at the lower elevations in the Uncompahgre River gorge above Ouray. Some of the most exposed alpine terrain also had been stripped of clean snow back down to the dusty and refrozen D3/D4 melt/freeze crust surface.

In the **Gunnison Valley** dust was emerging in the shallow snowcover at high points along Hwy 50 but the valley floor was essentially snow free all the way to Almont. The lowest elevation snowcover in the Taylor River canyon had dust at the surface but the snowcover in **Taylor Park** and on the W aspects of the Sawatch Range appeared very clean (as was the Park Cone snowpack surface).

On Wednesday morning, March 30th, the **Lake Fork** valley floor was also dry to Lake City. Unfortunately, the higher terrain above Lake City was obscured by clouds but several inches of fresh snow had fallen overnight at Slumgullion Pass. Once over Slumgullion Pass, rapidly clearing, sunny skies revealed severely wind-stripped and dry (snow free) alpine terrain above **Spring Creek Pass**. Dust was emerging on E aspects at Slumgullion Pass and at highway elevations immediately south of Spring Creek Pass dust was either widely exposed or rapidly emerging on E and SE aspects where the snowpack was still present. No snow remained in the valley floor along the **Rio Grande River**. Higher terrain in the upper Rio Grande drainage also received fresh snow the previous night and the snowpack surface appeared clean from a distance.

Dust had also emerged at the lowest snow covered elevations on E and S aspects along the eastern approach to **Wolf Creek Pass** and on S aspects all the way to treeline immediately above the Pass. The San Luis Valley was snow free and strong N'ly winds were mobilizing local valley dust at the time, particularly where fields were being worked. The western flank of the **Sangre de Cristo Mountains** was notably dry and the absence of large areas of snow cover confounded our ability to detect the presence of dust at the surface of the scattered remaining patches of snow.

The same fierce N'ly winds experienced in the San Luis Valley were producing massive plumes of blowing snow in the **Collegiate Range**, generally obscuring views up the east-facing canyons. To the extent that they were visible, snowcover at the head of those canyons and on the easternmost flanks of the Collegiate peaks did not reveal exposed dust. Views of the Mosquito Range were also limited by dramatic blowing snow plumes and fast-moving clouds. The floor of South Park was essentially snow-free along Hwy 285 to Fairplay.

The next day, Thursday, ongoing blowing snow and snow squalls did limit views but brief glimpses generally revealed clean, new snow on the higher terrain north of Fairplay, at **Hoosier Pass**, and north of Hoosier Pass. Dust was only exposed in isolated, wind-stripped locations in the alpine terrain and clean new snow blanketed the terrain below treeline. **Loveland Pass** was closed for avalanche mitigation but by mid-day good views of the terrain up to and above the Grizzly Peak CODOS site and Arapahoe Basin revealed a clean snowpack surface. Similarly, the snowpack east of Loveland Pass and along the *Berthoud Pass* corridor, down to Winter Park, also appeared clean.

In **Middle Park**, dust was emerging in small pockets where wind effects had either concentrated dust or stripped overlying new snow off of a slick, dusty melt-freeze crust surface. That pattern continued up the southern approach to **Willow Creek Pass** along Hwy 125. Dust was only thinly covered in new snow at the Willow Creek Pass CODOS site but the snow surface on the alpine terrain immediately west of the Pass appeared clean. On Friday, April 1st, the extensive snowcover throughout North Park presented dust either thinly covered by new snow or emerging at the snowpack surface. The E aspects of the Zirkels and the W aspects of the Medicine Bow Mountains had solid snowcover extending to the valley floor that appeared clean, from a distance.

The lower elevations of the eastern approach to **Rabbit Ears Pass** exhibited exposed dust but no dust was observed at the snowpack surface at the Pass elevations. The **Yampa River valley at Steamboat Springs** has deep snowcover, burying fences in places. Although some patches of exposed dust were observed, as a result of wind effects, most snowcover in the valley floor appeared clean at the surface. Farther south, at the upper end of the **Yampa Valley south of Yampa**, more extensive and notably 'orange' dust was observed at the snowpack surface, at highway elevations. Another major blowing snow event partially obscured the flanks of the Flat Tops, but occasional views did not reveal a dirty snowpack surface. Views of the Gore Range from Hwy 131 also presented an apparently clean snowpack surface.

Although the upper elevations of Mount Sopris were notably wind-stripped of snow, the remaining snowcover appeared clean. Again, notably orange-tinted dust was present on the snowpack surface along the lower snow-covered elevations of the sunny aspects of the **Crystal River valley.** The Crystal River was still running clear above Redstone. **At McClure Pass,** dust was only thinly covered by wet snow at our snowpit site, located on a 6º, SSE facing slope. Based on simple visual observation of the layering in our snowpits, McClure Pass may have exhibited the most dust-in-snow among all ten of our CODOS sites (Figure 1), perhaps second only to our Swamp Angel Study Plot. Higher terrain in the Ragged Mountains appeared clean. Muddy Creek was, per its namesake, running chocolate brown under active snowmelt at lower elevations west of McClure Pass. Some ice remained on the pool in Paonia Reservoir.

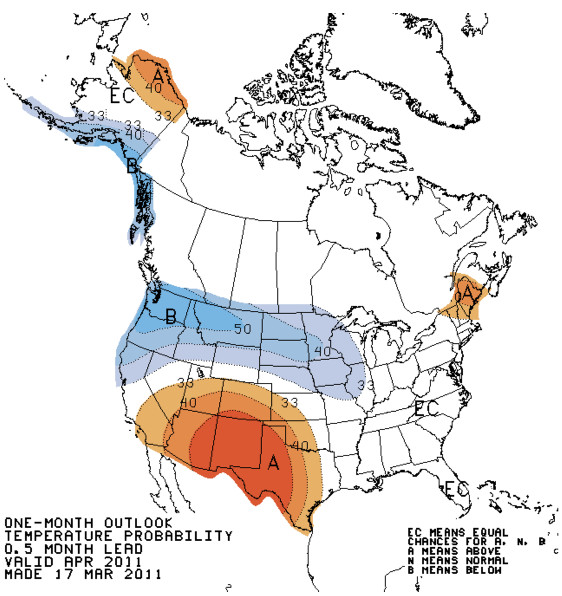
Figure 1: the near-surface dust layers at McClure Pass on Friday afternoon, April 1, 2011. The subsequent loss of SWE at this site suggests that this dust emerged on Saturday, April 2nd.

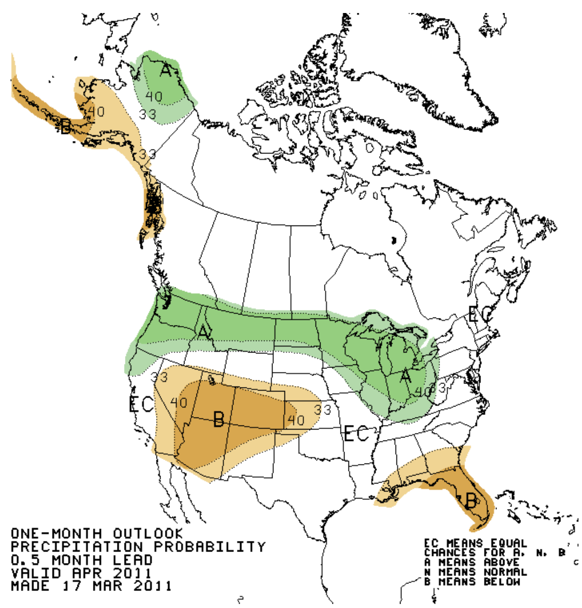
On the last leg of the circuit on Saturday, April 2nd, greening fields and blooming crabapple trees in the lower North Fork of the Gunnison River valley gave way to dirty snowcover on the southern flanks of **Grand Mesa**, similar in color to McClure Pass. On the top of the Grand Mesa, dust was thinly covered in wet snow and rapidly emerging that day.

Finally, while traveling south up the **Uncompahgre River canyon to Red Mountain Pass and back to Silverton**, substantially more dust was observed at the snowpack surface all the way to ridgelines on all but the most N'ly aspects. The snowpack surface of the N aspects of the Sneffels Range also appeared clean.

By the last two days of that circuit, very warm weather had entered western Colorado producing high temperatures in the 50's (F) by Saturday, April 2 at the Snotel stations adjacent to our ten CODOS sites, even reaching 60° at McClure Pass. Not surprisingly, hydrographs throughout the Western Slope of Colorado reflect a surge in streamflows commencing on/about April 1st. While dust was not widely observed during our circuit on the snowpack surface at/near treeline or in alpine (until our return to Red Mountain Pass), exposed dust and reduced snow albedos at the lowest snowcovered elevations may have also contributed to those surges. Our own Senator Beck Basin streamflow also surged between from the over-winter base flow of 0.1 cfs early Friday, April 1st to nearly 0.7 cfs by Sunday afternoon, April 3rd, with dust emergent at the lower elevations of Senator Beck Basin. Hydrographs available at the time of this writing indicate that a return to cooler weather and fresh snow in most locales may have ended that surge.

As of this writing, the National Weather Service in Grand Junction anticipates a series of disturbances traversing Colorado beginning Wednesday and running into next week. Each system may have associated SW'ly winds entering Colorado in advance of the storm. The first is expected to be a warm and very moist weather system, with a rain/snow mix in mountain valleys Wednesday. Thunderstorms may develop Friday. Snow will fall at higher elevations during these storms. Unsettled weather continues early next week, following a brief period of high pressure late in the weekend. The National Weather Service's National Climate Prediction Center issued the following familiar graphical forecasts for temperatures and precipitation for April 2011.





That concludes this Update #2 – Water Year 2011, prepared by Landry and reviewed by Deems.

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WESTERN WATER ASSESSMENT

CENTER FOR SNOW & AVALANCHE STUDIES

JPL

Colorado Dust-on-Snow Program – Water Year 2011

Update #3 - Tuesday, April 12, 2011

Since Update #2, a series of vigorous storm systems traversing the Colorado Plateau late last week and last weekend delivered another dust-on-snow layer at Senator Beck Basin. Based on the SWE content of overlying new snow, this new layer – D5-WY2011 – was deposited either late on Friday, April 8th under very strong and sustained SW'ly winds, during a lull between accumulating snowfalls, or early in the morning Saturday, just as snowfall resumed, still under very strong winds. That we did receive dust-on-snow on April 8th is of interest, given that large parts (but not all) of the greater Colorado Plateau source area received rain during preceding days (Figure 1).

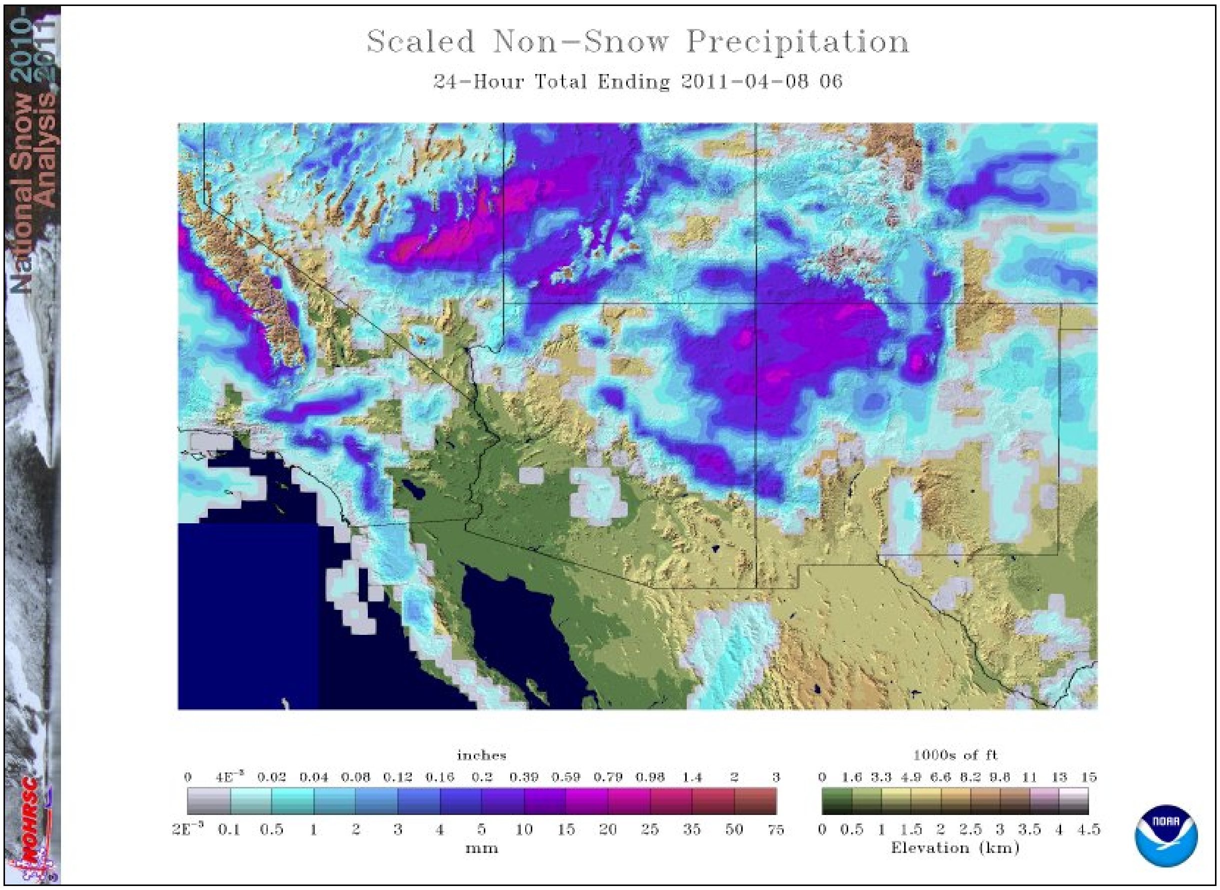

***Figure 1**: a plot by the National Weather Service – National Operational Hydrologic Remote Sensing Center showing their analysis of non-snow (rain) precipitation for the 24 hours preceding 0600 hrs Friday, April 8th. Some unshaded areas in southeast Utah, and southwest Colorado (i.e., the San Juan Mountains) that did not receive rain did receive snow. Additional rain fell in N'rn Arizona, NW'rn New Mexico, and in SW'rn Colorado on April 7th.*

During Spring 2010 the fourth dust storm of the spring was deposited on April 12th and the fifth on April 28th (Table 1 and list). While the pace of winter/spring dust events is ahead of last season, the amount of dust mass deposited to-date at Senator Beck Basin appears to be lower than in 2010.

Dust-on-Snow Events Documented per Month, by Winter 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	*1+?*	*tbd*	*tbd*	*tbd*

2002/2003 (WY 2003): Feb 3, Feb 22, Apr 2

2003/2004 (WY 2004): Apr 17, Apr 28, May 11

2004/2005 (WY 2005): Mar 23, Apr 4, Apr 8, May 9

2005/2006 (WY 2006): Dec 23, Feb 15, Mar 26, Apr 5, Apr 15, Apr 17, May 22, May 27

2006/2007 (WY 2007): Dec 17, Feb 27, Mar 27, Apr 15, Apr 18, Apr 24, May 4, Jun 6

2007/2008 (WY 2008): Mar 16, Mar 26-27, Mar 30-31, Apr 15, Apr 21, Apr 30, May 12

2008/2009 (WY 2009): Oct 11, Dec 13, Feb 27, Mar 6, Mar 9, Mar 22, Mar 29, Apr 3, Apr 8, Apr 15, Apr 24, Apr 25

2009/2010 (WY 2010): Oct 27, Mar 30, Apr 3, Apr 5, Apr 12, Apr 28, May 9, May 11, May 22

2010/2011 (WY 2011): Feb 17 (1), Mar 12, Mar 17, Mar 21, April 8

(1) Amended from previously reported Feb 19, 2011 date.

***Table 1:** Log of Dust-on-Snow Events Observed at Senator Beck Basin Study Area.*

As noted above, D5-WY2011 was deposited and subsequently buried by apparently clean new snow here at Senator Beck Basin. During our snowpack profile (#14) at the Swamp Angel Study Plot yesterday (Monday, April 11th) that (faint) layer was found covered under 12” of snow, largely distancing the dust from what we experienced ourselves as intense incoming radiation (solar loading) under “severe clear”, deep blue skies and high air temperatures (reaching 50º F). However, as is often the case, winds during the post-D5 storm had clearly stripped some of that overlying new snow on the most exposed south-facing slopes and D5 was just starting to emerge on the S-most slopes adjacent to and at the elevation of Swamp Angel Study Plot. Rapid warming in the new snow at the comparatively level Swamp Angel Study Plot was also settling the new snow layer above the D5 dust, further warmed from below by the virtually isothermal snowpack, but D5 was not yet emerging within the plot or on N’ly slopes nearby.

Despite the warming of our sub-alpine (at 11,080’) Swamp Angel Study Plot snowpack to near-isothermal from a mean of -2.7º C on March 29th, stormy and colder weather actually produced a decline in our Senator Beck basin streamflows (Figure 2) over the past week. Lower snow temperatures at our alpine Senator Beck Study Plot (at 12,200’) indicate that snowpack warming in the upper basin lags behind, as expected. Even at a peak flow of 0.7 cfs on April 3rd, spring 2011 discharge rates remain quite low in comparison to prior years. Two early surges in snowmelt had already occurred by this date in 2007, and a larger surge to over 6 cfs was underway by now in 2010. Hydrographs throughout the West Slope show a similar pattern of declining or ‘flat’ discharge rates over the past week.

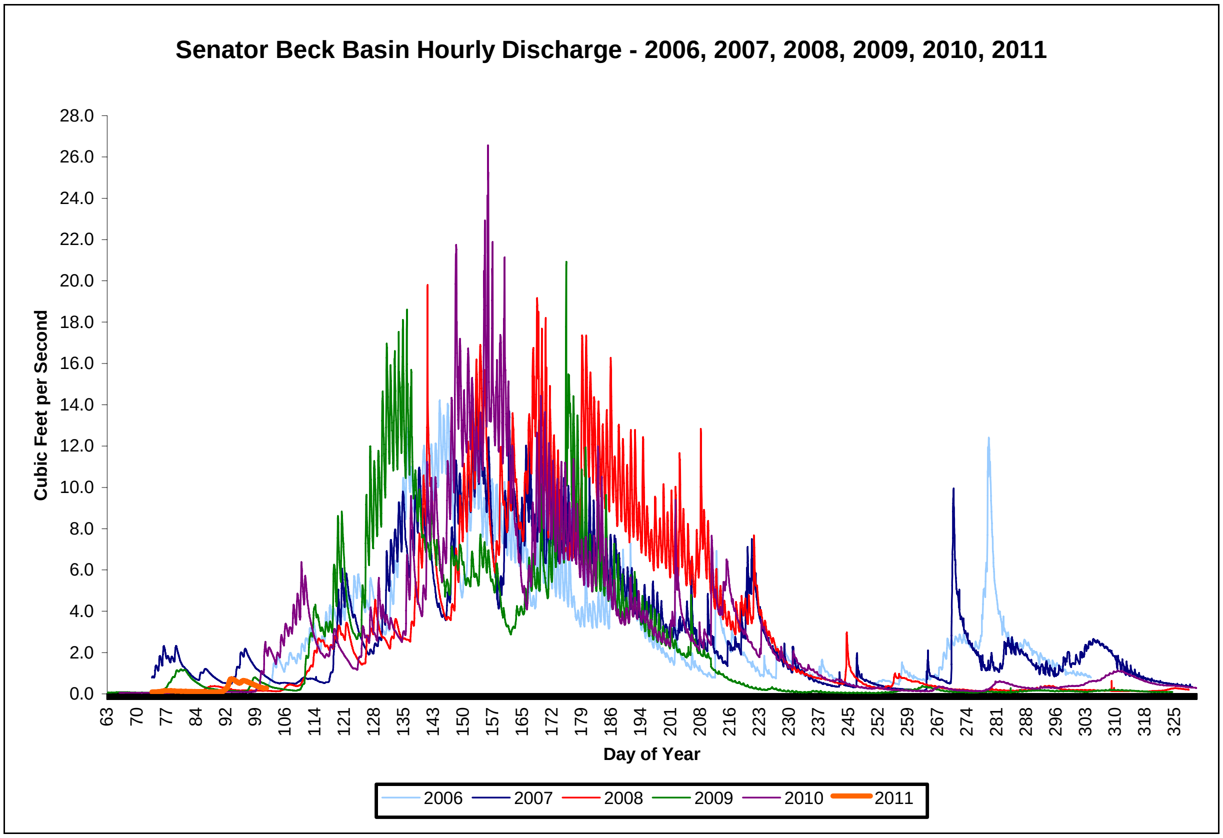

Figure 2: *Senator Beck Basin hydrographs for snowmelt seasons 2006 through 2011(shown in gold), through early today, DOY 102. Peak discharge thus far in 2011 was just 0.7 cfs on DOY 93, April 3rd.*

The spatial distribution of this D5-WY2011 event throughout the Colorado mountains is not yet known. A field visit to the Wolf Creek Pass vicinity later this week will verify the presence or absence there of this D5 layer (and possibly other layers unique to that locale), and another circuit of the other nine CODOS dust monitoring sites conducted sometime during the following week will complete the picture of D5's extent and position within the snowpack.

In the meantime, as of this writing, the National Weather Service in Grand Junction anticipates near-normal temperatures preceding an unstable airmass arriving Wednesday/Thursday, with potential for convective snow showers depositing some significant snow amounts, perhaps favoring the Northern and Central mountains. SW'ly winds may also pick up in advance of that system. Then, although the weather models exhibit uncertainty on the timing and character of embedded disturbances, NWly flow may again favor the Northern mountains with additional precipitation over the weekend. A "more amplified" system may arrive early next week, but "confidence remains low" in the models' depiction of that feature and its characteristics, at this time.

That concludes this Update #3, prepared by Landry and reviewed by Deems and Painter.

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Colorado Dust-on-Snow Program – Water Year 2011

Update #4 - Friday, April 29, 2011

The Center for Snow and Avalanche Studies' team just completed another circuit of its ten Colorado Dust-on-Snow (CODOS) program sites distributed throughout the Colorado mountains, beginning on Friday, April 22nd at Red Mountain Pass and returning to Silverton on Tuesday, April 26th. Following the previously reported D6-WY2011 dry dust deposition event on Thursday afternoon and evening, April 21st, we navigated through the stormy weather that began on Friday and affected most of the State over the Easter weekend and into early Wednesday morning. That long-duration storm added almost 3 feet of new snow and almost 4 inches of SWE to the snowpack at our Swamp Angel Study Plot at Red Mountain Pass. Nonetheless, our travel and fieldwork was unhindered and the circuit of our sites was complete until reaching our final stop at Grand Mesa, where the highway was closed just below the summit. (We performed an alternate snowpit at a somewhat lower elevation than our Grand Mesa Study Plot). For your reference, a "CODOS Field Site Atlas" was sent with this Update, as a separate PDF document, showing a Google Earth™ overview map of our typical travel route, and individual Google Earth™ images of each site.

Figure 1*: snowpit at McClure Pass, April 25, 2011, showing total depth at 101 cm (38") and the consolidated dust layer 16 cm (6") below the snow surface, with seep-stained snow and ice extending another 5-6" below. SWE content of the snow above the dust was 1.5". Among all CODOS sites visited between April 22 and 26, dust intensity at McClure Pass was arguably the most similar to the Swamp Angel Study Plot, where the greatest amount of dust was observed.*

This spring's unrelenting winter weather north of and along the I-70 corridor, recently setting a new record for snow depth at the NRCS Tower Snotel site (at 180 inches), has continued to bury the March dust layers previously observed at our CODOS sites and on higher elevation terrain in that region of the State (logged as D3 and D4 here at Senator Beck Basin). We did not find unambiguous evidence of the April 8th D5 or the April 21st D6 dust layers at Hoosier Pass, Grizzly Peak, Berthoud Summit, Willow Creek Pass, or at Rabbit Ears Pass.

At CODOS sites farther to the south and west (Park Cone, Spring Creek Pass, Wolf Creek Pass, McClure Pass, Grand Mesa) dust layers had generally consolidated into a single layer, perhaps including the April D5 and D6 events (D6 was reported as a distinct but weak event in the Aspen area by Painter and Deems). At Spring Creek Pass, on April 23rd, those merged dust layers were fully exposed at the snowpack surface, although new snow was beginning to accumulate. At all other sites, the uppermost (often merged) dust layer was found buried under some depth of clean snow, thinly at some sites and quite deeply at others (discussed below). Given the prior weather, and the ongoing storm, almost all of the snowcovered terrain that we could observe during our circuit of the CODOS sites (except the Spring Creek Pass locale) had clean new snow at the surface. All of our CODOS site snowpits presented an isothermal snowpack underneath new snow that was also already isothermal or just slightly cooler than 0º C.

As in seasons past, dust present within the lowest elevation snowcover was the first to emerge at or near the snowpack surface this spring, reducing snowpack albedo and accelerating snowmelt rates for as long as it remains exposed. Rain-on-snow, as recently occurred (and we experienced) in Middle Park, North Park, and the Yampa Valley, also accelerates snowmelt in an isothermal snowpack. The extensive, deep snowcover we observed in those Northern Mountain valleys in late March, with dust present at or near the snowpack surface, is greatly reduced. That low-elevation snowpack ablation in April, and the recently high discharge rates in the Yampa and North Platte Rivers, was enhanced by both processes, albeit at different times. Meanwhile, SWE continues to accumulate at Snotel and higher elevations in those headwaters.

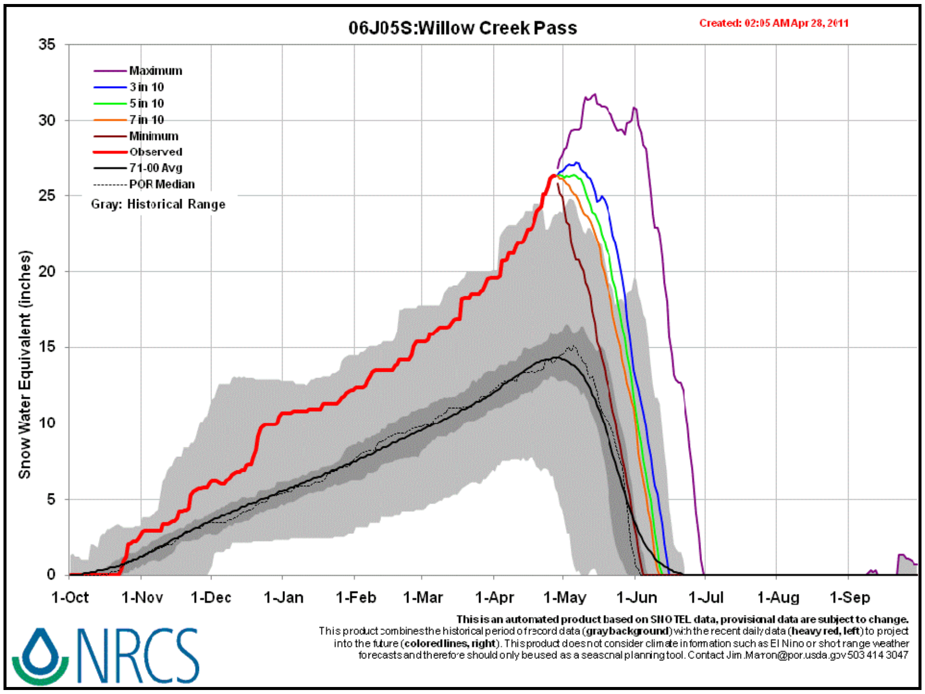
Farther to the south and west, this winter's low elevation snowcover in the Animas, San Juan, Gunnison, Rio Grande, Arkansas, and South Park locales has long-since disappeared, aided by the March dust-on-snow events (D3 and D4) where those events actually were deposited on low elevation snowcover rather than bare ground. In some of those locales, significant amounts of rain during the major December 18th-23rd storm may have resulted in disproportionately thin lower elevation snowcover, as compared to the corresponding major snowfalls during that storm at higher elevations (including Snotel network elevations). At higher elevations, SWE conditions do vary among those watersheds. However, aside from brief surges in discharge, enhanced by episodes of dust-reduced albedo, most of those river basins have exhibited near-median streamflow rates to-date and, in the wake of the recent stormy weather, are currently flowing at or below their median rates (with the Rio Grande at Del Norte falling to near 50% of median).

As and when this 'snowmelt' season begins to finally trend toward ablation, rather than accumulation, of mid- and high-elevation SWE and snowcover, already significant buried dust layers will begin to emerge. In the worst case, additional significant dust-on-snow events deposited at the top of the existing SWE column would advance the rate of ablation down to the existing buried dust and, through the process of aggregation, result in reductions in snowpack albedo and radiative forcing of snowmelt to levels perhaps comparable to those of Spring 2010, worsening the already identified risk of flooding in northwestern Colorado watersheds. However, even in the absence of additional dust-on-snow events, the dust already present in the snowpack will eventually result in non-trivial reductions in snow albedo. Table 1 presents current SWE data from Snotel stations located to our CODOS field sites and the amount of SWE currently overlying the uppermost dust layer at those sites during our recent field campaign (additional snow has since increased that overlying SWE at all sites). Although total snowpack SWE at a CODOS snowpit site is unlikely to correspond exactly with total SWE at the adjoining Snotel site, these data present a sense of the proportion of total SWE at Snotel elevations below the existing dust, and of the proportion of total SWE which will eventually be influenced by reduced snowpack albedo.

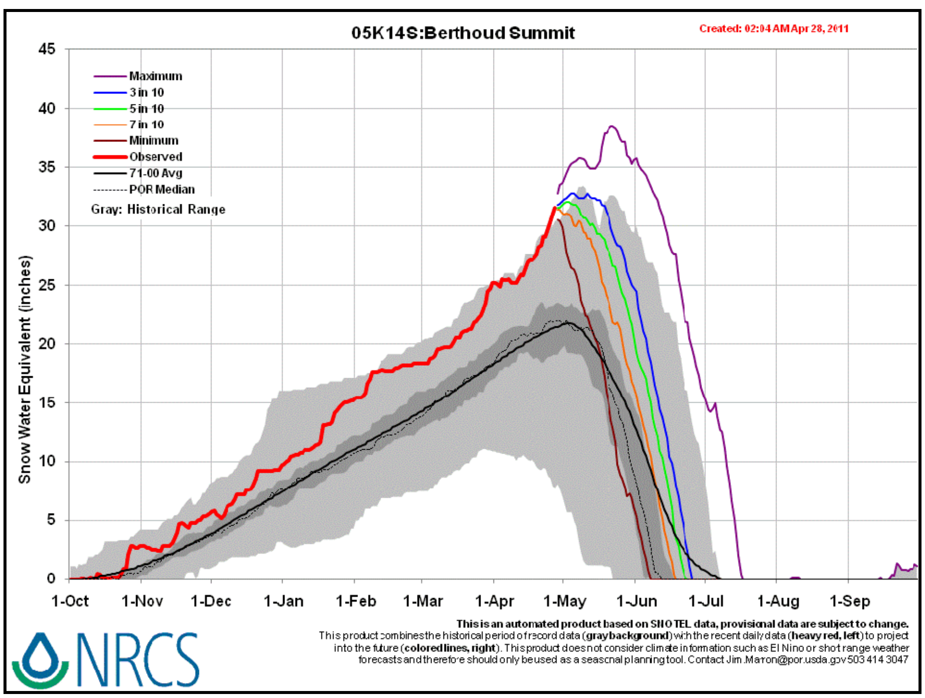
	Snotel SWE as of April 28, 2011		SWE above Uppermost Dust		
CODOS Monitoring Site	**Inches**	**% Avg**	**CODOS Pit Date**	**Pit SWE Over Dust**	**Subsequent Precip (SWE)**
Swamp Angel (Red Mtn Pass)	32.1”	118%	4/22/11	0.0”	3.8”
Park Cone	14.4”	197%	4/22/11	0.4”	1.0”
Spring Creek Pass (Slumgullion)	16.2”	111%	4/23/11	0.0”	1.5”
Wolf Creek Summit	38.5”	106%	4/23/11	0.3”	3.7”
Hoosier Pass	20.8”	126%	4/23/11	7.4”	1.3”
Grizzly Peak	31.2”	170%	4/24/11	9.0”	1.4”
Berthoud Summit	31.8”	149%	4/24/11	6.9”	1.7”
Willow Creek Pass	26.1”	183%	4/24/11	3.1”	0.9”
Rabbit Ears Pass	49.5”	164%	4/25/11	7.4”	0.1”
McClure Pass	22.2”	146%	4/25/11	1.5”	0.5”
Grand Mesa (Mesa Lakes)	26.6”	138%	4/26/11	1.9”	1.0”

Table 1: *SWE conditions as of the recent field campaign to CODOS sites, comparing the amount of SWE overlying the uppermost dust layer in a CODOS snowpit, and subsequent precipitation since the snowpit, to the current total SWE at the adjacent Snotel station.*

Snotel data from the Willow Creek Pass (Figure 2) and Berthoud Summit (Figure 3) sites illustrate the potential for dust-on-snow to facilitate problematic runoff behavior from the remaining mid- and high-elevation snowcover in the Northern Mountains, and is generally representative of our northern CODOS sites. Both sites currently exceed the historic maximum SWE value for this date (Tower is also currently at the historic maximum SWE). The dust already present in the Willow Creek Pass snowpack lies at or near the snowpack surface. At Berthoud Summit, the existing dust is still some 8-9” of SWE below the top of the SWE column, and above the approximately 23” of remaining SWE. As the existing dust approaches and then emerges at the snowpack surface, snowmelt will accelerate. A prolonged period of sunny weather in tandem with reduced snow albedo at these sites could then result in sustained high snowmelt rates, exacerbating the flooding potential of these record snowpacks in the Northern Mountains. Should unsettled, snowy weather periodically restore a higher snow albedo into June, as in spring 2008, dust effects on melt rates may be reduced.

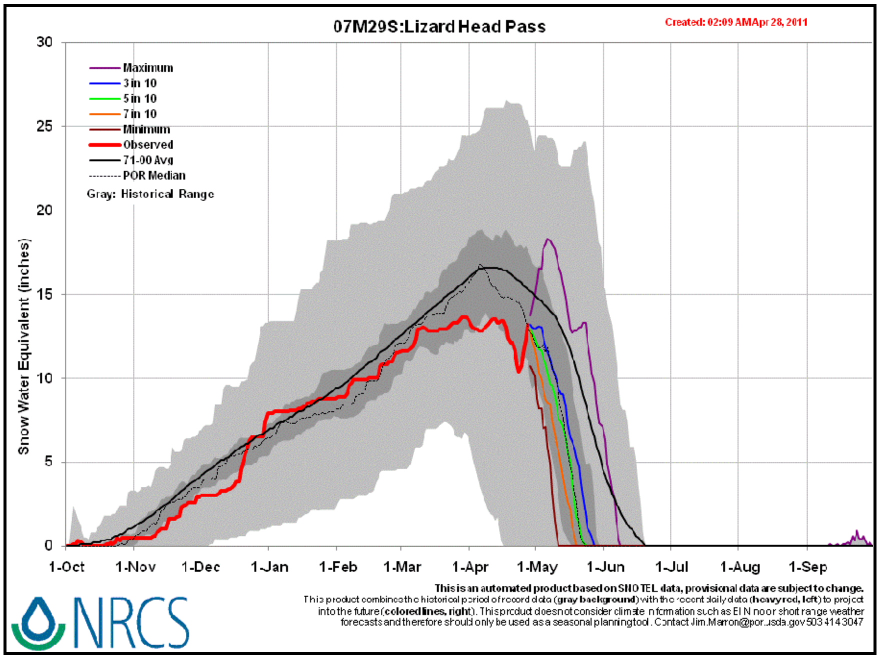


***Figures 2 (above) and 3 (below)**: current Willow Creek Pass and Berthoud Summit Snotel data exceed their respective previous highest observed values.*

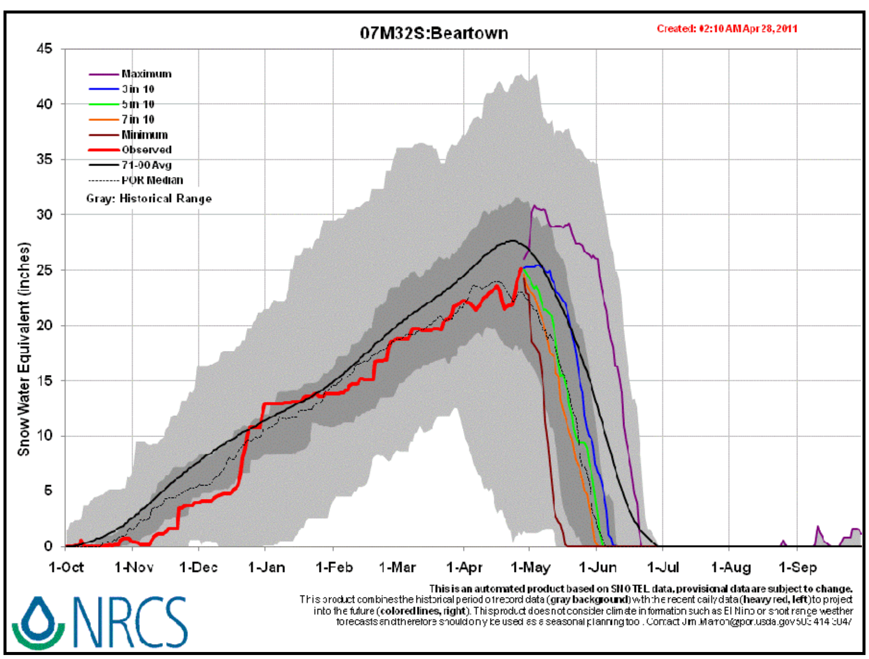


To the southwest, the current Lizard Head Pass (Figure 4) and Beartown (Figure 5) Snotel sites reflect the drier winter in the Southern Mountains, as well as the SWE impact of the recent storm.

Current SWE at both sites is below the mean, but at or above the median value, for the date. Here in the San Juan Mountains, as the currently buried dust emerges, a prolonged period of sunny weather and reduced snow albedo will result in higher if perhaps not as hazardous rates of snowmelt. However, those higher melt rates will also result in earlier “snow all gone” and a shorter duration runoff.



***Figures 4 (above) and 5 (below)**: these plots show current Lizard Head Pass and Beartown Snotel data for their respective sites at or just above the median value (dashed line).*



Snotel data from the Gunnison Basin, including Grand Mesa, show the Mesa Lakes, McClure Pass, Schofield Pass, Park Cone, Slumgullion Pass, and Red Mountain Pass Snotel sites all reporting over 100% of average snowpack, some well above 100%, despite an apparent (to this observer) absence of a corresponding and proportionate lower elevation snowcover, as discussed earlier. Nonetheless, even in the absence of dust-enhanced snowmelt occurring simultaneously at low and mid/high elevations, as occurred at times during Spring 2009 and 2010, significant dust is present in the snowpack on Grand Mesa, at McClure Pass, certainly at Red Mountain Pass and eastward to Spring Creek Pass, and at a somewhat lower intensity in the Taylor Park locale (as observed at the Park Cone CODOS site). The recent winter storm described earlier has restored a high snowpack albedo to those locales and delayed the re-emergence of that existing dust at Snotel and higher elevations, but rapid settlement in that recent new snow is underway, thinning the snow layer above the underlying D6 and merged D5/4/3 dust layers and making more radiation available to that dust. Among all Colorado regions, this portion of the State may once again be the first to see widespread, range-scale reductions in snow albedo at mid and high elevations.

All of the above discussion is predicated on the absence of additional dust-on-snow deposition in the Colorado mountains. However, over the past seven seasons, from Spring 2004 through Spring 2010, CODOS has observed a total of nine dust-on-snow events in the month of May, occurring as late as May 22 (Spring 2010). As of this writing, the National Weather Service (NWS) office in Albuquerque, NM has issued a High Wind Warning and Red Flag Alert for "very strong and potentially damaging" SW'ly winds averaging 35-45 mph and gusting to 60 mph and producing dust in northwestern New Mexico today, Friday, April 29th. The NWS in Flagstaff has also issued a Red Flag Warning and a Wind Advisory for strong SW'ly winds gusting 45-55 mph throughout northeastern Arizona for today, Friday, with areas of blowing dust. And, the NWS in Grand Junction has posted a Red Flag Warning for winds averaging 20-30 mph and gusting at over 40 mph in southwest Colorado today, Friday, April 29th. CODOS will issue a Dust Alert should these conditions produce a new dust-on-snow event.

That concludes this Update #4, prepared by Landry and reviewed by Deems and Painter.

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Colorado Dust-on-Snow Program – Water Year 2011

Update #5 - Friday, May 20, 2011

The Center for Snow and Avalanche Studies team recently completed our third circuit of our CODOS program's ten dust-on-snow field sites, beginning on Sunday, May 15th and returning to Silverton on Wednesday, May 18th. The recently reported D8 dust-on-snow event (May 9) was found as a discrete layer at the snowpack surface at five of the ten CODOS sites, and merged with preceding dust layers at the surface at four other sites. D8 was also merged with other dust at Grand Mesa, the tenth site, but being buried by new snow. New snow during the past 48 hours has temporarily restored a higher albedo at most or all CODOS sites. Some CODOS sites are approaching "snow all gone" (SAG) while many others retain a high percentage of their Peak SWE. A basin-by-basin discussion of our recent field observations follows.

San Juan, Animas, and Dolores watersheds: prior to the storm now ending, dust layer D8 was rapidly emerging from underneath the May 9th-12th storm snow throughout these headwaters (Figure 1). Accelerating melt rates contributed to surges restoring "average" (median) flow rates earlier this week. In contrast to our slightly north-sloping Swamp Angel Study Site, where several bands of cleaner snow still separate dust layers, all dust layers were observed to have merged at the snowpack surface at our Wolf Creek Pass CODOS site on Monday, May 16th.

***Figure 1**: D8 and underlying dust layers emerging at Red Mountain Pass on May 15, 2011. Dust has played a significant role in recent avalanche activity.*

Rio Grande watershed: on Monday, May 16th all dust layers were observed to have merged at the snowpack surface at both our Spring Creek Pass and Wolf Creek Pass CODOS sites. The Spring

Creek Pass site was approaching SAG as snow levels approach treeline in that locale. The Wolf Creek Pass CODOS site still had 44" of snowpack. Dust (D8) may have not yet widely emerged on the snowpack surface at the highest elevations of the upper Rio Grande headwaters, overlain by storm snow from May 9th-12th. At and below treeline, D8 was emerged on the remaining snowcover and Beartown Snotel reported a sharp decline in SWE. The new snow of the past 48 hours has restored a higher snow albedo in those headwaters and the recent surge in flows at the Del Norte gauge has reversed and fallen below average again, having just reached median flow levels on May 17th. However, a sustained return to sunny weather will produce a return to lower snow albedo values starting at the lowest elevation snowcover and quickly climbing higher.

Gunnison Basin watershed: our Park Cone and McClure Pass CODOS sites were approaching snow all gone (SAG) earlier this week, with all dust layers merged at the snowpack surface and reducing snow albedo. D8 is presumed to be contained in that substantial merged dust layer. Snowmelt rates reached 1.4" per day during the past week at Park Cone, prior to receiving new snow during the past 48 hours. Snowcover was persisting well below treeline on western and southwestern aspects in the Taylor Park locale. Again, D8 was also present at the snow surface at our Swamp Angel Study Plot at Red Mountain Pass, but not yet merged with underlying layers. New snow has slowed the most recent surge in snowmelt rates. At a peak flow, to-date, of only 3.1 cfs on May 16-17, Senator Beck Basin has yet to experience a significant surge in runoff this spring, with approximately 40" of SWE and 97" of snow remaining at the Swamp Angel Study Plot.

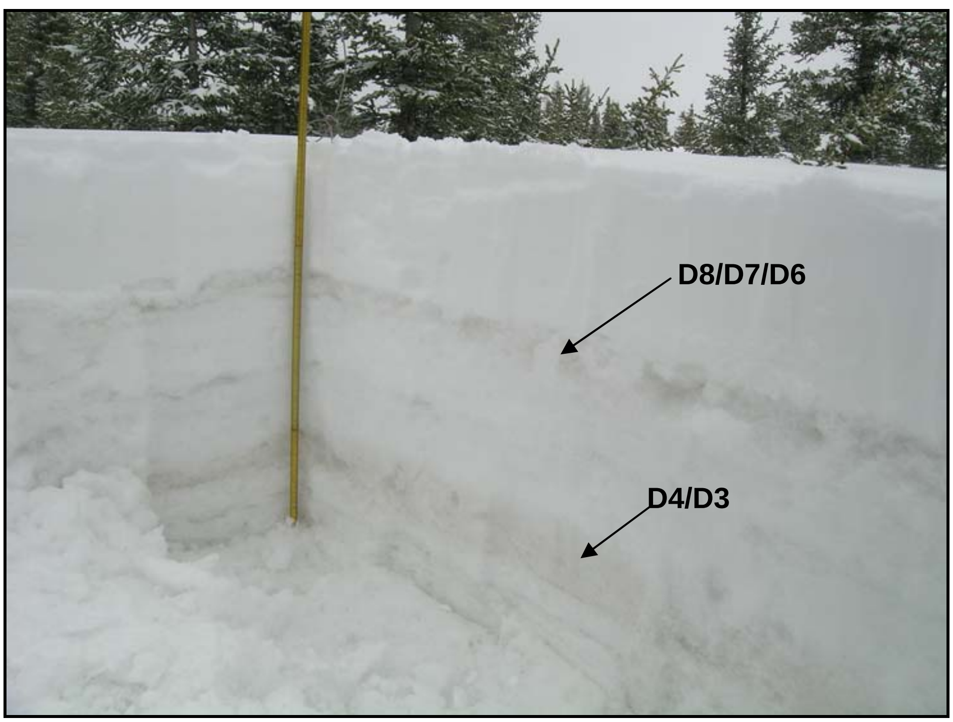

Figure 2*: snowpit at Grand Mesa, May 18, 2011, with new snow accumulating.*

Grand Mesa: a substantial dust layer, likely consisting of merged dust events D8, D7 and D6, was becoming buried on May 18th (Figure 2). That layer is separated from the underlying merged D4/D3 layer by only 2-3" of SWE. Prior to the now-ending storm, melt rates had reached 0.8" per day at the Mesa Lakes Snotel. An estimated 15”-20” of SWE lies underneath that substantial D4/D3 layer, based on the Mesa Lakes Snotel data.

Upper Colorado River watershed (and adjacent watersheds): snowmelt has also been interrupted by late season snowfalls in the northern tier of CODOS sites. Among those, the Rabbit Ears Pass CODOS site exhibits the deepest snowpack and the largest quantity of SWE (30-32”) underneath the ubiquitous merged D4/D3 layer (Figure 2). The D8 dust layer will continue to enhance melt rates at Rabbit Ears Pass, when exposed, and accelerate its merger with underlying dust layers, eventually merging with the substantial D4/D3 layer. Among our northern CODOS sites, the merging of D8 with underlying layers and eventually with the D4/D3 layer, is least advanced at Hoosier Pass, Grizzly Peak, Berthoud Summit, and Rabbit Ears Pass. However, D8 has already merged with D4/D3 at our Willow Creek Pass site, maximizing the potential dust-induced reduction in snow albedo (barring additional dust); 35” of snowpack remained at that site (Figure 4).

***Figure 3**: snowpit at Rabbit Ears Pass, on May 17, 2011. Total snowpack depth was 109 inches (277 cm). D8 was at the then-slushy snowpack surface. The merged D4/D3 dust layer (the lowest dust layer in the snowpack) is seen at 77 cm below the snow surface, and additional bands of faint dust are visible above D4/D3. In this snowpit, the D4/D3 dust layer was buried underneath 31” of snow containing 12.4” of SWE. Another 78” (199 cm) of snow containing an estimated 30” of SWE (based on nearby Snotel data) was underneath the D4/D3 layer.*

Figure 3*: snowpit at Willow Creek Pass on May 17, 2011. Total snow depth was 35". All dust layers were merged at the snowpack surface; the adjacent Snotel was reporting 25" of SWE at the time.*

At the southern CODOS sites where all dust layers have already merged, recently observed darkening of the snow surface by dust may be approaching the reductions in snow albedo observed during Spring 2010. At the Swamp Angel Study Plot, eventual merger of all eight dust layers at the snowpack surface may also result in reductions in snow albedo approaching those of late May 2010. However, so far in Spring 2011, even at sites where all dust layers have merged, observed reductions in snow albedo and snowmelt rates do not match those observed in Spring 2009 and very likely will not, barring significant additional dust deposition. Nonetheless, dust-enhanced snowmelt has already contributed to surges in runoff during which streamflows in many basins rose from below- to near- or somewhat above-average levels (Willow Creek being an exception), only to be curtailed by additional snowfalls, restoring higher snow albedo values.

In CODOS's recent basin-specific e-mails to many of you regarding snowmelt rates, and during the Joint Meeting of the Governor's Flood and Water Availability Task Forces on May 11th, CODOS reported that very substantial fractions of the record-setting snowpacks in the Northern Mountains, and also of lingering snowpacks elsewhere in the State, could be subject to the combined effects of reduced snow albedo and warm weather. Further, Colorado could receive additional dust-on-snow during the remainder of May and into June, when significant snowpacks seem likely to remain in the northern mountains. Even without additional dust, existing WY2011 dust layers will eventually merge and reduce albedo at the snowpack surface throughout the Colorado mountains, as the sun rises higher in the sky and days lengthen, maximizing the radiative absorption by dust.

The National Weather Service's Grand Junction office currently anticipates continued unsettled weather through this weekend and into next week, favoring the northern and central mountains, but perhaps some weekend drying in the south. Another storm system enters the Great Basin Tuesday and will enter Colorado, perhaps exiting on Wednesday, with drying and warming later in the week, ahead of yet another Pacific system. Given this outlook, D8 and merged dust layers may remain effectively buried until late next week, at and above treeline, minimizing their effect on snowmelt rates until they extensively re-emerge. That concludes this Update #5, prepared by Landry; Deems and Painter were on travel and unable to review this Update.

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Colorado Dust-on-Snow Program – Water Year 2011

Update #6 - Monday, June 13, 2011

***Figure 1**: a headwater tributary of Walton Creek at Rabbit Ears Pass on June 9, 2011 showing the very dark May 29th 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 29th, 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, considerable snowcover remains at and above most other CODOS site (and Snotel) elevations and current reductions in snowpack albedo will influence snowmelt rates in those snowpacks for the duration of the season.

Figure 2*: Grand Mesa Study Plot June 3, 2011. All dust layers were merged at the snowpack surface. Bands of ice and snow stained by dirty melt water are seen below the surface. Total depth was 60"; total SWE was 29.7".*

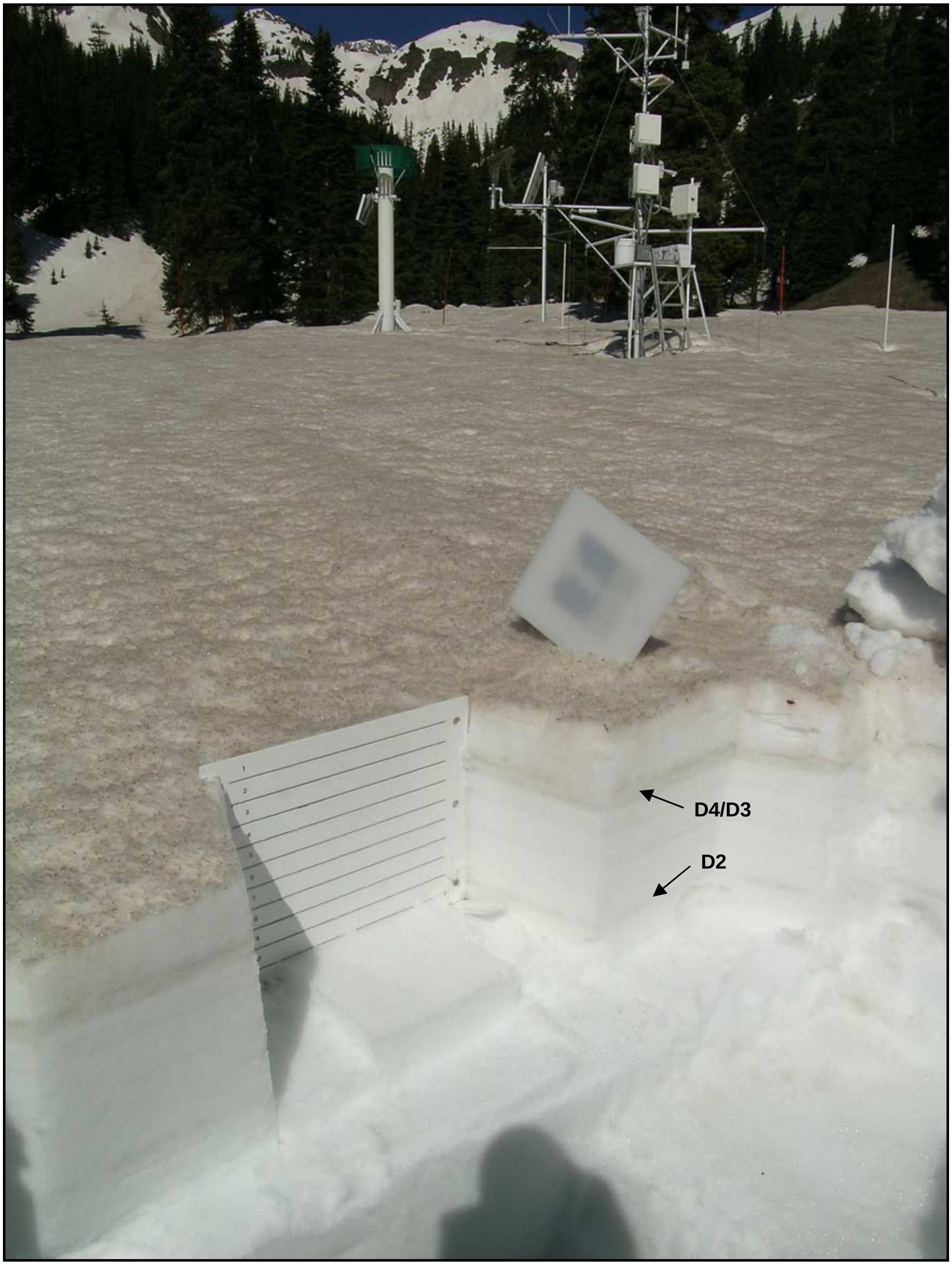

***Figure 3**: Swamp Angel Study Plot at Senator Beck Basin Study Area at Red Mountain Pass, June 8, 2011. Most dust layers (D11-5) have merged but the D4/D3 layer is seen 5" below the surface, and the very faint D2 layer is seen another 7" below D4/D3. Total depth was 55"; total SWE was 27.5".*

***Figure 4**: CODOS site adjacent to the Grizzly Peak Snotel, Loveland Pass, June 9, 2011. All dust layers have merged and are exposed at the snowpack surface; infiltrating fronts of dirty melt water are seen as bands below the surface. Total snowpack depth was 48".*

***Figure 5**: Berthoud Summit CODOS site and adjoining Snotel, June 9, 2011. All dust layers have merged; layers of ice stained by infiltration of dirty melt water are seen below the surface. Total snowpack depth was 55".*

***Figure 6**: CODOS Rabbit Ears Pass monitoring site on June 9, 2011. Most dust layers are merged at the snowpack surface, "topped" by especially black material corresponding to the D11 dust event, but layer D4/D3 lurked 8" below the surface. Total snow depth was 67".*

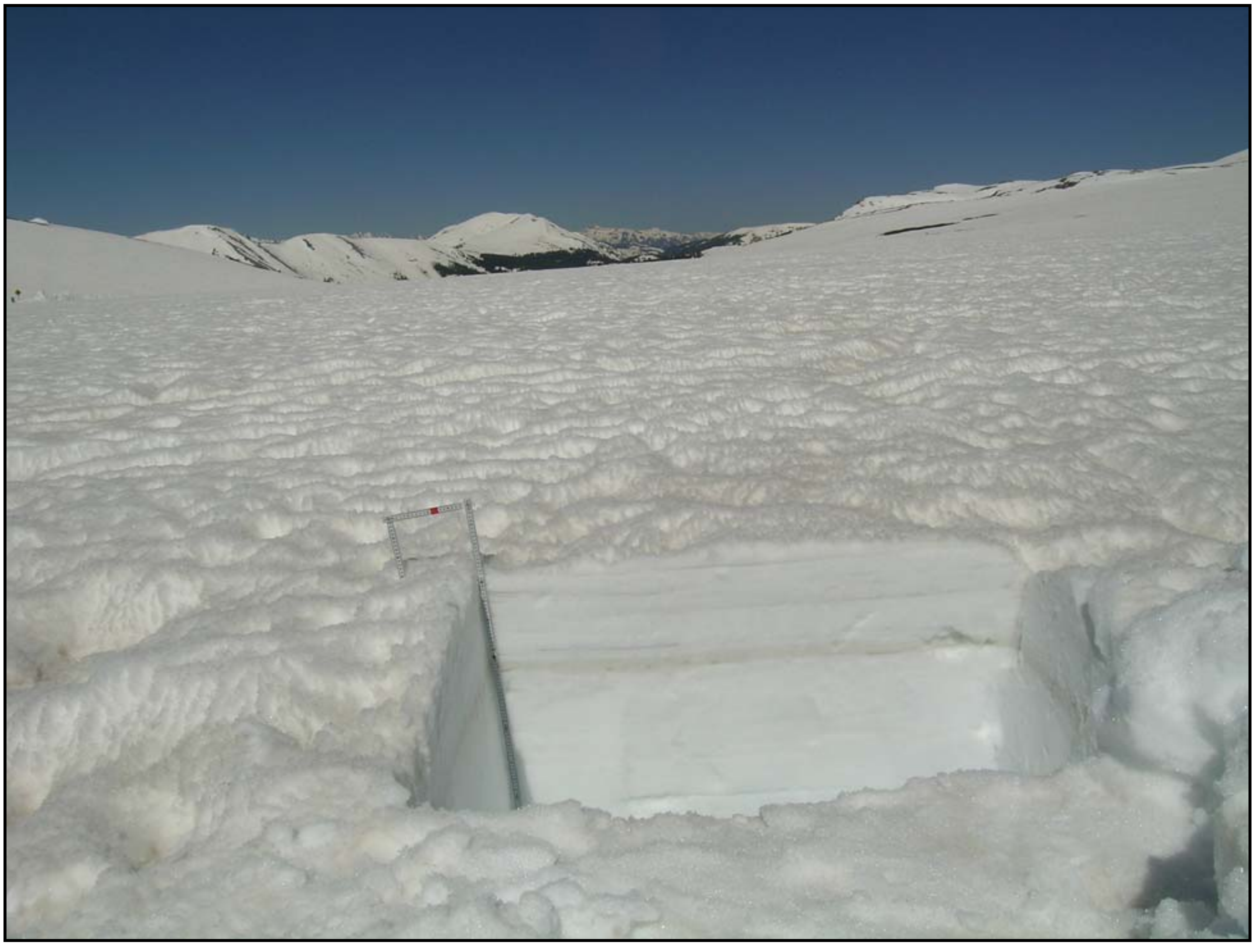

***Figure 7**: a snowpit at Independence Pass on June 10, 2011 showing most dust layers merged at the snowpack surface. Another substantial layer located 11" below the surface has yet to emerge and merge, and reduce albedo even further. The remainder of the 57" deep snowpack was "clean" (no additional visible dust layers).*

Snowmelt rates at Snotel sites adjoining CODOS sites, facilitated by a prolonged period of sunny and dry weather, likely reflects the addition of the May 29th D11 dust layer and the merging of D11 with underlying dust layers. Many of those Snotel sites are heavily shaded by adjoining trees, Berthoud Summit being a notable exception (see Figure 5). Because of this shading effect, many of these Snotel stations may understate the rates of melt in nearby open (unforested) terrain, where direct access of incoming solar radiation to dust at the snowpack surface is unimpeded on sunny days. Again, as previously reported, dust-enhanced snowmelt rates averaging 1.9" of SWE loss per day, over eight days, were documented at the Swamp Angel Study Plot in late May 2003, and rates exceeding 2" of SWE loss per day occurred in many locales during Spring 2009.

While radiative and other factors governing snowmelt energy budgets vary significantly between forested locations and adjacent open terrain, the net effects of those interactions very commonly produces "snow all gone" sooner in an open meadow than in its adjoining forest. (Beetle killed forests appear to present a unique interplay of those factors combining attributes of both (healthy) forests and open terrain, and are a special case). In any event, Snotel stations remain the best source of continuously measured snowpack ablation rates data available in near-real-time in most Colorado mountain watersheds and do provide a benchmark for snowmelt rates at their respective elevations. Recent snowmelt rates at the eleven Snotel sites adjacent to our CODOS monitoring plots are shown in Table 1. Further analysis of these Snotel SWE loss rates will be performed at the conclusion of the season and presented at a later date.

Snotel Site (respective CODOS Site)	**Daily SWE Loss Rates Since June 1**
Red Mountain Pass (Swamp Angel Study Plot)	1.0" to 1.9"
Park Cone	*SAG*
Slumgullion Pass (Willow Creek Pass Study Plot)	*SAG*
Wolf Creek Summit	0.9" to 1.5"
Hoosier Pass	0.8" to 1.1"
Grizzly Peak	0.9" to 1.6"
Berthoud Summit	0.9" to 1.6"
Willow Creek Pass	0.6" to 2.9"
Rabbit Ears Pass	1.4" to 2.0"
McClure Pass	*SAG*
Mesa Lakes (Grand Mesa Study Plot)	0.9" to 1.5"

Table 1*: showing the range of daily snowmelt rates, as loss of SWE, since June 1, 2011 at Snotel sites proximal to CODOS monitoring plot.(SAG = snow all gone).*

The state-wide reductions in snowpack albedo that have helped drive these snowmelt rates can be expected to persist for the duration of the snowmelt season, given that significant additional snowfalls capable of restoring high snow albedo are now unlikely. The National Weather Service's Grand Junction and Denver offices currently anticipate mostly sunny, dry, and mild weather to persist throughout most of the Colorado mountains this week and into next weekend. The northernmost and Front Range mountains may see some scattered showers early in the week. As a result, it appears that dust-driven radiative forcing of Colorado's snowmelt runoff will continue under near-maximum solar inputs for another week, as we approach the Summer Solstice. That concludes this Update #6, prepared by Landry and reviewed by Deems and Painter.

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Colorado Dust-on-Snow Program – Water Year 2011

Water Year 2011 Season Summary

Demonstrating, yet again, the maxim that no two Colorado winters are alike, the La Niña winter of 2010/2011 exhibited a number of notable features that, in their unique combination with substantial dust-on-snow, influenced Spring 2011 snowmelt runoff timing, rates, and volumes:

- a long-duration, warm storm, December 18-23, 2010 delivered significant rainfall amounts to snowcovered lower elevations in many watersheds, rather than snow, and tremendous amounts of snow (and SWE) at higher elevations in many locales

***Figure 1**: the final snowpit of the 2010/2011 season at the Senator Beck Study Plot near Red Mountain Pass on June 21st, the summer solstice. An isolated column of snow (center) has been horizontally scribed, at the front, in preparation for slicing into ten samples 3 cm thick (with the aid of a saw guide plate at the back of the column, not yet installed). Recent new snow (June 20th) filled and leveled what had become a very rough, "sun cupped" snow surface. The wavy horizon of dirty snow in the pit face represents all of the season's dust eleven layers merged, at the old snowpack surface. Wind duning of the new snow left bare patches of dirty snow exposed on the slope in the background.*

- a strong precipitation gradient developed across the southern ranges favoring the northern aspects of the San Juan Mountains while starving the San Juan's southern aspects and the

Sangre de Cristo Mountains.

- record-breaking snowpacks formed in the northern ranges, from Steamboat Springs (i.e., Tower SNOTEL) to the northern Front Range (i.e., Joe Wright SNOTEL)
- a very windy winter and spring in the western San Juan Mountains
- late and sometimes very late dates of Peak SWE occurred at SNOTEL sites throughout the state
- a slow starting but strong finishing dust-on-snow season, with the last (the 11^{th} and perhaps largest) event falling on May 29^{th} throughout the Colorado Mountains (Table 1)
- a very rapid transition from wet to dry weather in late May, followed by a very dry June, with a correspondingly rapid transition from generally high snow albedo values to a rapid and steady decline in snow albedo, as dust layers merged at the snowpack surface

Dust-on-Snow Events Documented per Month, by Winter **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**

Table 1*: Senator Beck Basin Dust-on-Snow Log, showing the number of observed dust-on-snow events, by month, since the winter of 2002/2003.*

Within our brief history of rigorous dust-on-snow monitoring, Spring 2011 offers another unique case study in radiative forcing of snowmelt. During the comparatively dry springs of 2006 and 2009, substantial dust loading emerged at the surface of generally normal snowpacks in early spring, advancing the full snowmelt cycle by as much as five weeks. During the comparatively big winter of 2008, ongoing snowy weather in late May and early June served to moderate the effects of dust, frequently restoring high snow albedo conditions and prolonging that runoff cycle in most locales. This spring, in a volatile combination, the relentless and prolonged extension of winter-like conditions into late May combined with major and late dust loading similar to that seen during spring 2010 resulted in a very delayed, but very high amplitude, runoff cycle. This final Update of Water Year 2011 will review these and other attributes of the just-concluding season.

Winter 2010/2011 Weather

Here in the western San Juan Mountains, Winter 2010/2011 produced the most precipitation, the most winter storms, and the most wind in our eight years of operation at the Senator Beck Basin Study Area at Red Mountain Pass. By the end of May 2011, our Swamp Angel Study Plot had logged 45.3" (1,151 mm) of precipitation for Water Year 2011, virtually all as snow, well ahead of any prior October-May period since 2003/2004 and ahead of the entire WY 2010 total of 44.37" (1,127 mm). Although WY 2011 lagged behind WY 2008 in mid-winter, the late winter and spring onslaught of storm after storm pushed WY 2011 well ahead during April and May (Figure 2).

Altogether, Winter 2010/2011 generated 34 separate winter storms (minimum 0.5” of snow water equivalent), substantially more than any prior winter.

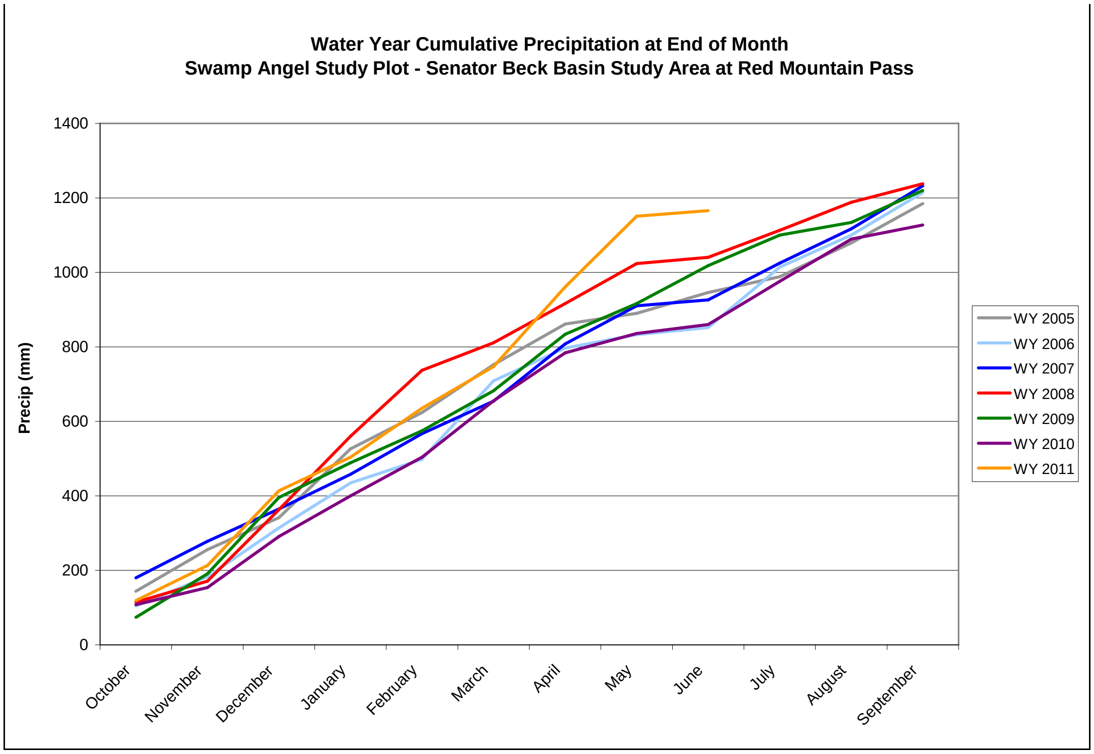

Figure 2: *cumulative Water Year precipitation at the Swamp Angel Study Plot, Senator Beck Basin Study Area, Red Mountain Pass. End-of-month total precipitation is plotted for Water Years 2005 through 2011 (to June 27, 2011), with WY 2011 in orange and WY 2008 in red.*

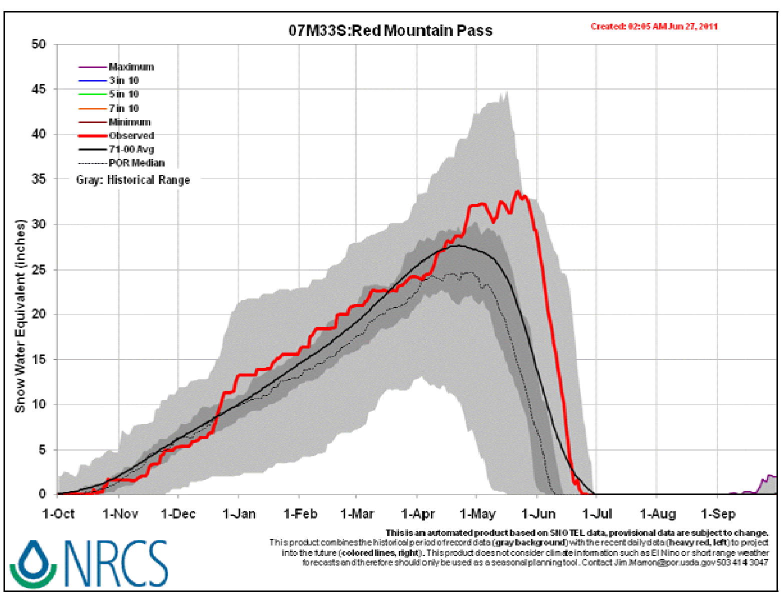

Figure 3: *Red Mountain Pass SNOTEL plot for Winter 2010/2011.*

While not a record breaking winter for the western San Juan Mountains, the nearby Red Mountain Pass SNOTEL plot located 2 km to the south of Swamp Angel Study Plot indicates that Water Year 2011 was in the upper quartile of the period of record at that site (Figure 3, above). This plot also documents the very late date of Peak SWE at that site, on May 22nd, nearly outside of the period of record. However, because of terrain shadowing, much of the Rio Grande watershed of the San Juan Mountains received substantially less snow, as exemplified at the Middle Creek SNOTEL site (Figure 4).

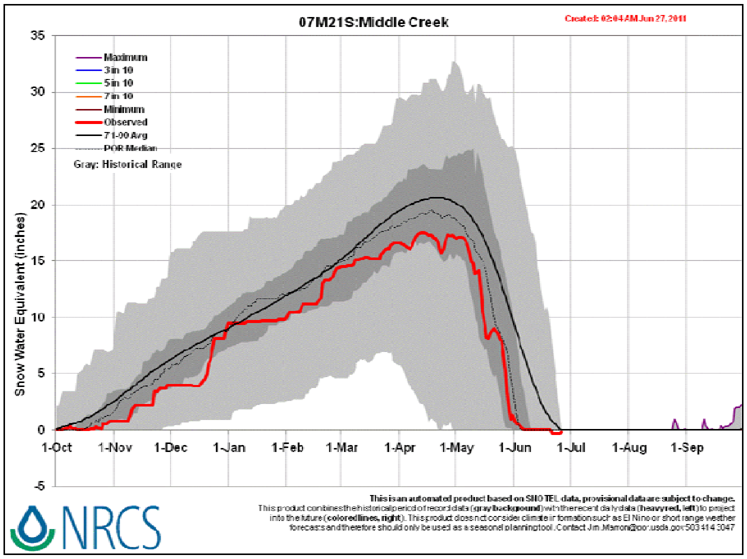

Figure 4: *Middle Creek SNOTEL plot for Winter 2010/2011.*

Snowpack records were broken at many northern mountains SNOTEL sites. Willow Creek Pass is the CODOS site farthest from our Senator Beck Basin Study Area and the SNOTEL station there recorded almost double its average Peak SWE on May 4, followed by post-peak additions of SWE.

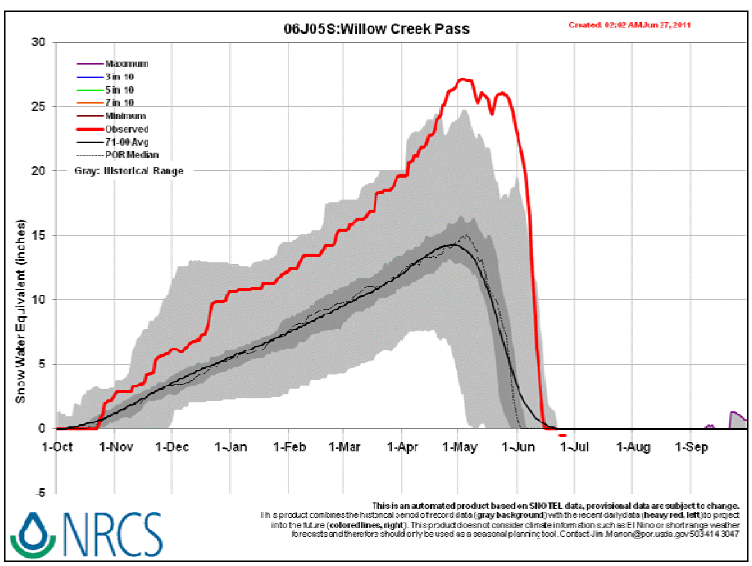

Figure 5: *Willow Creek Pass SNOTEL plot for Winter 2010/2011.*

In between those northeastern-most and southwestern-most CODOS sites, along the I-70 corridor, in the Elk and West Elk Mountains, and on Grand Mesa, most SNOTEL sites recorded Peak SWE values in the upper quartile of their period of record. Many recorded multiple near-peak SWE values in May, as seen in the Hoosier Pass SNOTEL data (Figure 6).

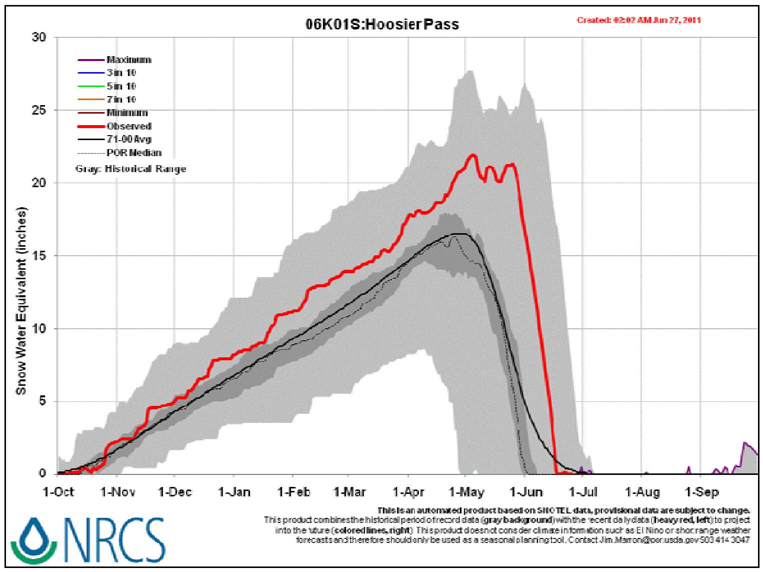

Figure 6: *Hoosier Pass SNOTEL plot for Winter 2010/2011.*

Along with a record 34 weather events labeled "storms", with at least 0.5" of snow water equivalent, Winter 2010/2011 also produced the most "miles of wind" at our Putney Study Plot since 2004/2005, a record driven largely by the highest-ever totals for April and May. April 2011 also produced more wind than *any* other month during the entire period of record (Figures 7 & 8).

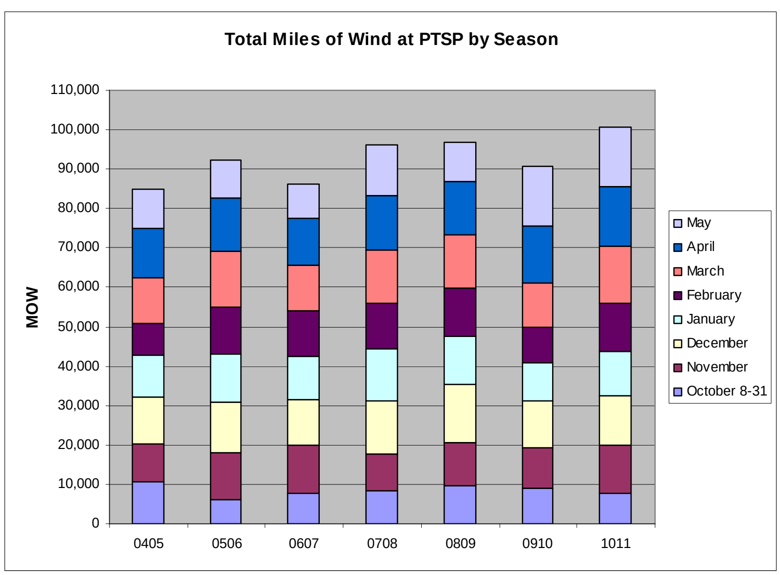

Figure 7: *October 8 through May 31 Miles of Wind (MOW) data for Putney Study Plot (PTSP), Senator Beck Basin Study Area.*

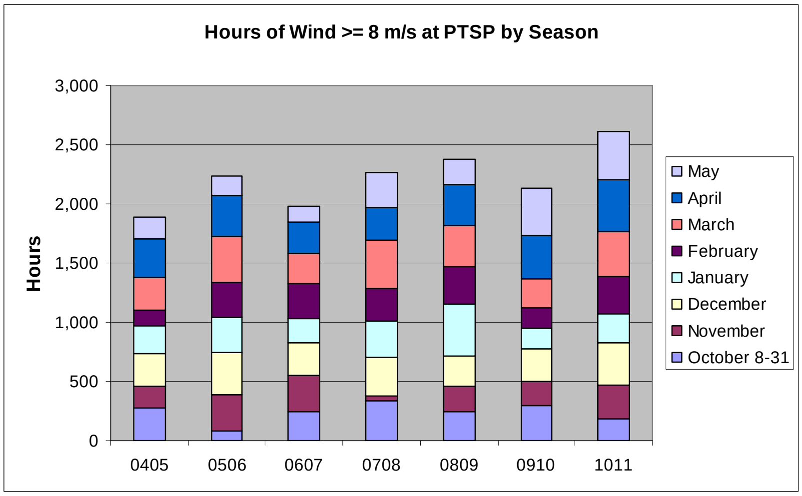

Figure 8: *total hours of wind at or exceeding 8 meters per second (18 mph), from Oct 8 through May 31. As with total miles of wind, Winter 2010/2011 also established a new period of record maximum, again driven by a very stormy April and May.*

Deposition of Colorado Plateau dust onto Colorado mountains is associated with synoptic scale weather systems generating significant S/SW/W'ly winds in advance of their fronts, often followed by a winter storm and new snow. Winter 2010/2011 provided more than ample winds (as evidenced by the alarmingly large snow cornices observed on ridgelines throughout the State this spring) to deliver eleven distinct dust-on-snow events at the Senator Beck Basin Study Area, and beyond. Evidence of many or most of those eleven events (Table 1) were found as far north and east as Willow Creek Pass, and the major dust events of the season, like D4 (March 21) and D11 (May 29) were just as substantial at some northern CODOS sites as at our Senator Beck Basin and other southern CODOS sites, testifying to the power of their wind fields.

Subsequent snowfalls often immediately buried these new dust layers, hiding them from view beneath substantial amounts of clean snow, and their presence in the snowpack was often only revealed by digging a snow pit, as shown in CODOS Updates this season. Layers D3/D4 (March 17-21) were particularly deeply buried at most CODOS sites, well into the month of May. Because of the frequency of winter storms in March/April/May, only layer D11 experienced sustained exposure at the snow surface immediately following its deposition on May 29th, as a dry dust deposition without accompanying snow precipitation. This pattern, wherein new dust layers were often deeply buried immediately after deposition, delayed their role in the snowmelt cycle until the very substantial D11 (May 29) dust event. As previously described in CODOS alerts, that D11 layer immediately accelerated snowmelt rates to 1.0"-1.5" of SWE loss per day, ablating underlying clean snow layers until reaching buried dust layers. Melt rates rose to as high as 2.0" of SWE per day at many sites in June, as dust layers successively merged at the surface and progressively reduced snowpack albedo.

Finally, last winter's very warm, long-duration storm from December 18th-23rd, or the "Solstice" storm, was of particular interest. During that 5-day storm, our Swamp Angel Study Plot (11,080') at Red Mountain Pass experienced only an hour or two of light rain, all easily absorbed by the 1-meter snowpack. Farther down the Uncompahgre River watershed, however, Ouray (7,800') residents reported periods of prolonged and heavy rain during the storm, perhaps lasting a full 24 hours, followed by snow. Shallow snowcover was present in and above Ouray prior to that rain, some of which may have been partially ablated by the rain. Silverton (9,300') did not receive more than a sprinkle of rain during the Solstice storm but other locales with low elevation snowcover in western Colorado did also receive significant rains and perhaps also had a net loss of SWE due to erosion of the pre-existing snowcover by that rainfall. Many local water managers, and the CSAS, subsequently noted scant low elevation snowcover in many West Slope watersheds as spring approached, in contrast to 'normal' higher elevation snowpacks.

The synoptic genesis and characteristics of that December 2010 "Solstice" storm are beyond the scope of this report, and may have been singular rather than symptomatic. Nonetheless, it is the general concern of regional climatologists that, as a result of regional climate warming, Colorado could experience increasingly warm early winter storms and a corresponding phase change in precipitation, from snow to rain, up to some higher elevation. If that shift were to occur, historic patterns of proportionality in snowcover SWE, from higher (i.e., SNOTEL) elevations to the lowest elevations of snowcover, would be complicated by rain erosion. It is worth noting that during the Solstice storm, which some observers characterized as a "maritime" storm, while the lowest elevations of the Gunnison River watershed were receiving rain, the Schofield Pass SNOTEL (10,700') tallied a 44" gain in snow depth containing over 9" of new SWE, perhaps offsetting lower elevation net losses of SWE. These observations of rain and snowcover effects are strictly anecdotal, and not at all systematic, but the December 2010 Solstice storm may have offered a glimpse of how warmer early winter storms could alter snowpack formation in Colorado.

Snowmelt Conditions

Spring snowmelt behaviors in the Colorado mountains are driven by interactions of weather, terrain, vegetation, elevation, slope aspect, snow albedo, and snowcover distribution, all of which exhibit significant spatial and/or temporal variation. Over the past several seasons, frequently large north/south differences in the timing of the runoff season have been the norm. Again, when compared to recent years, Spring 2011 was unusual for its nearly universal delays in Peak SWE caused by the wintry April and May weather throughout the state and for its more synchronized behavior, statewide, of May and June surging of snowmelt from mid- and high-elevation snowpacks. Both behaviors can be seen when scanning Spring 2010 SNOTEL and hydrograph data.

Variations in snowmelt rates, as directly measured at SNOTEL sites and at the CSAS's Senator Beck Basin Study Area snowpit plots, capture the first order effects of radiative forcing of snowmelt caused by dust-on-snow. These measurements include the length of time required for complete ablation of the actual snowcover, from the date of Peak SWE to the date of snow all gone (SAG), and rates of daily SWE loss during that period. These first order effects will be examined below.

Streamflow data also reflect the effects of dust-on-snow, although those data integrate all of the factors influencing watershed hydrology and stream gauge location may include elevation-driven lags and/or anthropogenic influences. The CSAS's Senator Beck Stream Gauge (SBSG) is an engineered, broad-crested weir located at 11,030' at the pour point of the 719 acre (290 ha) Senator Beck Basin Study Area. Because of its headwater location, SBSG data capture, with very short time lags and with no anthropogenic interference, the interactions governing snowmelt runoff at the catchment scale, including dust-on-snow effects.

A graph of SBSG cumulative discharge from Water Year 2006 through July 5, 2011 of Water Year 2011 (Figure 9) illustrates the essential characteristics of the past six snowmelt seasons, as previously described and discussed at length in CODOS Updates since 2007. Base flow during winter months is too low to measure without risk of freezing the instrumentation. Therefore, over-winter discharge is estimated up to resumption of instrument measurements in early March. Water Year 2011 cumulative discharge (shown in orange) shows the most delayed onset of snowmelt surging in our brief period of record, second to 2008 (shown in red), another "big winter" at Senator Beck Basin (Figure 2). More importantly, WY 2011 also presents the highest rate, sustained period of runoff, from Day 151 (May 31) to Day 182 (July 1), in our period of record.

Those sustained and high rates of Senator Beck Basin snowmelt runoff during June 2011 were enabled by a very stormy April and May, adding snow and postponing melt, followed by almost entirely dry, sunny weather throughout June. During that period snow albedo values at the Swamp Angel Study Plot fell from near 80% just prior to dust event D11, on May 29th, to 50% immediately following D11, then further to about 43% by May 15th, and perhaps even slightly lower before SAG on June 23rd. The combination of a very heavy snowpack in late May (and already containing ten dust events), with a significant dust-on-snow event at the end of May (D11) capping that snowpack, followed by an abrupt transition to dry weather just as solar inputs were being maximized at and around the Summer Solstice, all served to optimize conditions for rapid snowmelt here at Senator Beck Basin. Although northern areas experienced cloudier conditions at times during June, similar reductions in snow albedo were observed at CODOS sites throughout the state during the final June circuit (Update #6) and this general snowmelt scenario was repeated statewide.

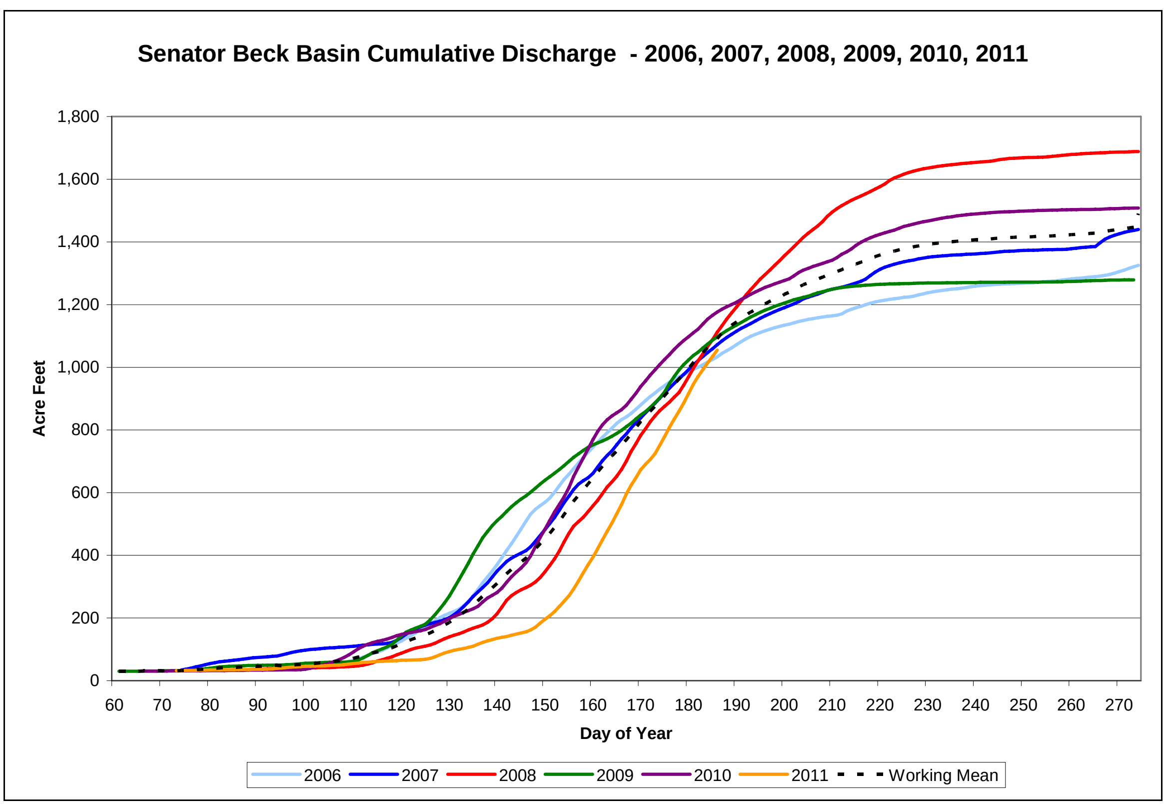

Figure 9: *cumulative discharge, in acre feet, from Senator Beck Basin from 2006 through July 5, 2011.*

Stream gauges integrate snowmelt hydrology over catchment, watershed, and entire basin scales, but snowmelt rates are measured at study plot (or point) scales, here at the Senator Beck Basin Study Area and at SNOTEL sites. The site characteristics of the Swamp Angel Study Plot (SASP) at Senator Beck Basin – a large, well-sheltered, sub-alpine, and nearly level meadow – optimize the monitoring of snow albedo and dust-enhanced snowmelt rates without complications caused by vegetation or wind effects.

During Spring 2011, CSAS's CODOS fieldwork documented the complete meltdown of the 39.3" (999 mm) of SWE measured in our May 23rd snowpack profile #20 at SASP, at or near SASP's Peak SWE, to final SAG (snow all gone) on June 23rd. That snowmelt period spanned 31 days with a mean loss rate of 1.27" (32 mm) of SWE per day, including 1.22" (31 mm) of additional SWE received after Peak SWE. Snowpack depth on May 23rd was 230 cm, or 90.5", so the average loss of snowpack depth was almost 3" per day (7.4 cm). The nearby Red Mountain Pass SNOTEL, 2 km due south, recorded its Peak SWE of 33.7" the day before, on May 22nd, and SAG came 33 days later, for a mean daily loss of SWE of 1.0" per day.

Locational differences explain those variations in snowmelt rates. Site characteristics – elevation, vegetation, and aspect – of individual SNOTEL station sites vary, but most of the SNOTEL sites that CODOS monitors are located in small forest openings, including the Red Mountain Pass SNOTEL. Primarily because of adjoining trees, radiative regimes at SNOTEL stations are generally different from those in nearby open terrain. Nonetheless, CODOS Updates and other CSAS consultations during the Spring of 2011 have referenced snowmelt rates at SNOTEL sites as a proxy for snowmelt rates in their adjoining terrain. CSAS has assembled datasets presenting Peak SWE and subsequent snowmelt rates at fifteen SNOTEL sites distributed throughout the State, eleven of which are adjacent to (or near) a CODOS monitoring site. The remaining four SNOTEL sites are in locations between CODOS sites, representing additional terrain.

Water Year 2006-2011 SNOTEL data were examined since this period spans our efforts to monitor dust-on-snow deposition and its effects on Colorado snowmelt behavior. Given that short history of just six seasons, only limited summary statistics are shown (maximum, minimum, range) for seasonal, aggregated data. Average (mean) values are calculated for annual datasets representing all fifteen sites, but those averages are intended to be merely descriptive of those years, and not predictive of past or future years. These data, and additional data not presented in this Update, are now available on-line at the CSAS website as Excel workbooks for downloading and additional analysis – see the "SNOTEL Datasets" at snowstudies.org/CODOS.

A statewide overview treating the fifteen SNOTEL sites as a group, and aggregating their behavior during each of the past six snowmelt (spring) seasons, reveals characteristics that distinguish many of those seasons from the others (Table 2 below). Spring 2006 shows the earliest date of Peak SWE, the lowest amount of post-Peak additional accumulation of additional SWE, and the earliest calendar date (May 22nd, 40 days after April 12th) of SAG (snow all gone) among all six seasons, for the group as a whole. The dry, sunny spring of 2006 enabled eight dust layers, and most notably the February 15th (D2-WY2006) layer, to emerge at the snowpack surface quickly and remain exposed for long periods, advancing the timing and rates of snowmelt.

Spring 2008 produced the slowest loss of snowpack to SAG (54 days) for the group, but from nearly the largest snowpack and with the largest amount of post-Peak-SWE additional precipitation.

Spring 2009, with the most dust-on-snow events, saw the quickest snowpack ablation to SAG and near-highest snowmelt rates. 2011 saw slightly higher Peak SWE than 2008 and almost as much post-Peak-SWE as 2008, but snowmelt rates comparable to 2009, at an adjusted daily mean loss rate of 0.75" of SWE, by a small margin the highest seasonal snowmelt rate to-date, for the group.

Aggregated CODOS and Other SNOTEL Sites - WY 2006-2011 Snowmelt Season Summary Data
15 total sites (sites are listed in Table 3)

Water Year	*Group Mean Date Peak SWE*	*Group Mean Peak SWE*	*Group Mean Days to SAG*	*Group Mean Post-Peak Added SWE*	*Group Mean Adjusted Mean Daily Loss SWE*	*Group Mean Period Mean Temp*	*Recorded SBB Dust Events*
WY 2006	4/12/06	21.4	40	1.7	0.57	3.6	8
WY 2007	4/18/07	18.8	39	3.3	0.57	3.8	8
WY 2008	4/19/08	29.3	54	4.0	0.62	3.7	7
WY 2009	4/19/09	24.2	37	2.9	0.74	4.4	12
WY 2010	4/19/10	20.1	41	3.1	0.60	3.5	9
WY 2011	5/2/11	29.4	47	3.9	0.75	5.3	11
Max	05/02/11	29.4	54	4.0	0.75	5.3	12
Min	4/12/06	18.8	37	1.7	0.57	3.5	7
Range	21	10.6	17	2.3	0.18	1.8	5

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE

***Table 2**: Snowmelt season (spring) summary data, by Water Year, aggregating fifteen SNOTEL stations located throughout the Colorado mountains. All eleven CODOS dust-on-snow monitoring sites are included plus four additional SNOTEL sites filling geographic gaps between CODOS sites. "SAG" refers to the date of "snow all gone", or total snowpack ablation, at the SNOTEL site. "Post-Peak Added SWE" shows the snow water equivalent of precipitation received after the date of Peak SWE. "Adjusted Mean Daily Loss SWE" rates include additional SWE received after date of Peak SWE. Units for precipitation and SWE are inches of water; temperatures are ° C. "SBB Dust events" refers to the total number of events observed at the CSAS's Senator Beck Basin Study Area at Red Mountain Pass (Table 1).*

However, treating these fifteen sites collectively, as a single group, obscures geographically- and weather-driven differences among the sites. Large ranges of variation in snowmelt rates, both at and between sites, are exposed when each site's behavior is considered across the period 2006-2011, rather than just the annual mean behavior of the group as a whole. Table 3 (next page) shows that variations in rates of snowpack ablation to SAG (snow all gone) and in mean daily snowmelt rates over that 2006-2011 period are quite large at most of these individual sites, and also between the sites. Again, the period of record is short, bounded by our short history of dust-on-snow monitoring, so these maximum, minimum, and range data may not capture even larger variability (and extreme values) that may have occurred in past years or be manifested in future years.

CODOS and Other Selected SNOTEL Sites Water Years 2006-2011 Snowmelt Seasons Summary Data						
SNOTEL Site	*Single Yr Max Days to SAG*	*Single Yr Min Days to SAG*	*Range Days to SAG*	*Single Yr Max Adjusted Mean Daily Loss SWE*	*Single Yr Min Adjusted Mean Daily Loss SWE*	*Range Mean Daily Loss Loss SWE*
Red Mtn Pass	66	33	33	1.06	0.51	0.55
Slumgullion Pass	50	27	23	0.61	0.38	0.22
Wolf Creek Summit	71	40	31	0.88	0.64	0.23
Beartown	52	26	26	1.11	0.58	0.52
Lizard Head	62	22	40	0.91	0.32	0.59
Park Cone	54	17	13	0.49	0.32	0.02
Schofield Pass	76	35	41	1.64	0.73	0.91
McClure Pass	62	30	32	0.89	0.38	0.37
Independence Pass	56	30	26	0.76	0.44	0.32
Hoosier Pass	61	31	30	0.57	0.41	0.16
Grizzly Peak	56	43	13	0.72	0.38	0.35
Berthoud Summit	50	23	27	1.09	0.58	0.51
Willow Creek Pass	43	21	22	0.80	0.49	0.31
Rabbit Ears Pass	62	22	40	1.09	0.69	0.40
Mesa Lakes	59	31	19	0.76	0.43	0.33
Group Max	76	43	41	1.64	0.73	0.91
Group Min	43	17	13	0.49	0.32	0.02
Group Range	33	26	28	1.15	0.41	0.88

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE
Non-CODOS SNOTEL sites shown in italics

***Table 3**: Site-by-site comparison of fifteen SNOTEL sites over the six year period 2006-2011, showing maximum and minimum rates of snowpack ablation to SAG (snow all gone) during that period and maximum and minimum single-year average daily rates of snowmelt (loss of SWE). Units for precipitation and SWE are inches of water; temperatures are ° C.*

Datasets presenting similar data for each individual Water Year snowmelt season, from 2006 to 2011, have also been prepared. Water Year 2011 data are presented in Table 4 (next page) and the remaining Water Years are presented, in order, as Appendix A-E. (The data are also available on-line as Excel files - see the "SNOTEL Datasets" at snowstudies.org/CODOS).

While the span between the earliest date of Water Year 2011 Peak SWE (March 30, at Lizard Head Pass at the headwaters of the Dolores River) and the latest date (May 26, at Schofield Pass and Berthoud Summit) was 58 days (Table 4), Spring 2011 still saw, by a wide margin, the latest average date of Peak SWE for the group as a whole in the 2006-2011 period (see also Table 2). Led by northern mountain sites, which were partially offset by Rio Grande and southern San Juan Mountain sites, Water Year 2011 also delivered the highest group average Peak SWE value during the 2006-2011 period, if only slightly higher than 2008 (Table 2), but with a very large range among sites.

CODOS and Other SNOTEL Sites - WY 2011 Snowmelt Season Summary Data						
SNOTEL Site	*Date Peak SWE*	*Peak SWE*	*Days to SAG*	*Post-Peak Added SWE*	*Adjusted Mean Daily Loss SWE*	*Period Mean Temp*
Red Mtn Pass	5/22/11	33.7	33	1.4	1.00	6.8
Slumgullion Pass	5/4/11	16.9	35	2.1	0.51	4.1
Wolf Creek Summit	5/5/11	38.9	54	4.5	0.78	7.4
Beartown	5/5/11	25.1	38	4.2	0.77	3.8
Lizard Head	3/30/11	13.6	62	6.1	0.31	2.0
Park Cone	4/7/11	14.5	54	4.1	0.33	3.0
Schofield Pass	5/26/11	56.3	35	1.0	1.55	7.9
McClure Pass	3/31/11	22.8	62	9.0	0.50	4.5
Independence Pass	5/4/11	25.0	37	2.7	0.71	4.1
Hoosier Pass	5/5/11	21.9	44	3.1	0.57	4.2
Grizzly Peak	5/5/11	31.8	52	5.7	0.71	5.3
Berthoud Summit	5/26/11	34.8	35	2.0	0.99	8.4
Willow Creek Pass	5/4/11	27.1	43	3.8	0.69	5.4
Rabbit Ears Pass	5/6/11	51.6	52	5.3	1.05	7.3
Mesa Lakes	5/4/11	27.1	41	4.0	0.72	5.78
Group Mean	5/2/11	29.4	45	3.9	0.75	5.3
Group Max	05/26/11	56.3	62	9.0	1.55	8.4
Group Min	3/30/11	13.6	33	1.0	0.31	2.0
Group Range	58	42.7	29	8.0	1.24	6.4
Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE						
Non-CODOS SNOTEL sites shown in italics						

***Table 4**: Site-by-site comparison of fifteen SNOTEL sites for snowmelt season, Water Year 2011. "SAG" refers to the date of "snow all gone", or total snowpack ablation, at the SNOTEL site. "Post-Peak Added SWE" shows the snow water equivalent of precipitation received after the date of Peak SWE. "Adjusted Mean Daily Loss SWE" rates include additional SWE received after date of Peak SWE. "Period Mean Temp" is the average of daily average air temperaures during the snowmelt period, from Peak SWE to SAG. Units for precipitation and SWE are inches of water; air temperatures are ° C.*

The range in snowmelt duration among the sites (from Peak SWE to SAG) is almost a full month. The three sites with the earliest dates of Peak SWE – Lizard Head, Park Cone, McClure Pass – also experienced the lowest "Mean Daily Loss SWE". These sites received additional SWE equivalent to 45%, 28%, and 39% of their Peak SWE, respectively, in the period after Peak SWE, stretching the snowmelt cycle to as long as 62 days (from Peak SWE to SAG). Schofield Pass, with the latest date (just prior to dust event D11) and largest amount of Peak SWE, and the lowest amount of additional 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 5th 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.

CODOS and Other SNOTEL Sites
WY 2011 Snowmelt Season Summary Data

SNOTEL Site	*Highest 5-Day Moving Average Loss SWE*	*Final Day of 5-Day Period*
Red Mtn Pass	1.74" (2x)	June 17, 19
Slumgullion Pass	1.28"	June 4
Wolf Creek Summit	1.48"	June 19
Beartown	1.74" (2x)	June 8, 9
Lizard Head	1.40"	May 31
Park Cone	1.00"	May 11
Schofield Pass	2.44"	June 29
McClure Pass	1.78"	May 30
Independence Pass	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

Non-CODOS SNOTEL sites shown in italics

***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 29th, 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 by the snow pillow monitoring SWE. That effect may not be substantially different from the absorption of radiation in the natural ground cover, by soil or rocks or vegetation, as the snowpack thins elsewhere. SNOTEL sites are generally unsuited to snow albedo monitoring due to the shading and debris fall from surrounding trees. Continuous, automated snow albedo monitoring requires both favorable site characteristics and "hands-on", human management and observation.

Conclusion

Spring 2011 has expanded CODOS's experience with dust-on-snow impacts on Colorado snowmelt behavior, now spanning six seasons. Year-to-year variations in the weather governing snowpack formation and ablation, and in the number, intensity, and timing of dust-on-snow events, have been documented and reveal a wide range of spatial variability, across the state, and temporal variation at specific sites. Our six-year dust-on-snow monitoring period of record is very short, and robust trend analyses are not supported. Nonetheless, the record displays both delayed and rapid snowmelt enhanced by late-May dust-on-snow (Springs 2010 and 2011), very early and rapid snowmelt enhanced by late winter dust-on-snow (2006), and both rapid (2009) and slow (2008) snowmelt seasons in between.

The importance of abrupt variations in snowcover albedo has become apparent in recent years, whether caused by dry dust-on-snow events (without subsequent precipitation) onto a clean snow surface (i.e., D11-WY2011), the restoration of high albedo by clean new snow over a dust layer on the surface, or by the emergence and merging of buried dust layers during snowpack ablation, progressively lowering albedo. In contrast to the dramatic, daytime dust storms of 2009 and 2010, many WY2011 dust-on-snow events eluded easy observation, either because they fell overnight and were immediately buried by new snow or because they were immediately buried by new snow during daylight hours.

As in past seasons, during Spring 2011 a time series of snowpits were required to detect the latent dust load that would ultimately emerge and reduce snow albedo statewide. CSAS's team conducted four circuits of CODOS monitoring sites located throughout the Colorado mountains, digging snowpits at each site, as well as 25 additional snowpits at the Senator Beck Basin Study Area. Rapidly changing and unusual conditions during Spring 2011 highlighted the need for frequent field monitoring (at *and below* the snowpack surface), and iterative analyses of dust-on-snow conditions and near-term weather forecasts throughout the snowmelt cycle. Forecasting dust-on-snow impacts in advance of a given snowmelt season would require forecasting the interaction of Great Basin spring weather with spring soil and vegetation conditions throughout the Colorado Plateau dust source area and is not currently feasible. However, this is one of the goals of the new NASA Interdisciplinary Science project "Integrated hydrologic response to extreme dust deposition to mountain snowcover of the Colorado River Basin" on which CSAS is a collaborator and Drs. Painter and Deems are Principal Investigator and Co-Investigator, respectively.

During Spring 2011 Dr. Painter's Snow Optics Laboratory field team also performed 4 circuits of the CODOS monitoring sites interwoven in time with the CSAS tours, collecting detailed radiation and dust loading data. The team collected full column dust loading samples at 3 cm intervals in the top 30 cm of the snowpack and then at 10 cm intervals through the remainder of the snowpack. They also measured snow spectral albedo (total reflectivity of solar radiation by wavelength) at each site using a portable Analytical Spectral Devices field spectroradiometer. These samples and spectral measurements require analysis that is more protracted than is feasible for inclusion in these CODOS reports. However, the data and those described here will be included in coming scientific publications in the next several months.

SNOTEL sites may provide a source of proxy, real-time data for changes in snowmelt rates related to albedo changes, but elevation, aspect, and vegetation driven variations in the timing of dust layer emergence during the snowmelt season complicates the interpretation of those data. Because of the long delay in Peak SWE at SNOTEL elevations in many watersheds, preceded by substantial loss of snowpack at lower elevations, WY 2011 also highlighted the potential value of knowledge of where the center of SWE mass lies in a given watershed, by elevation and aspect, during dust emergence (or dry deposition).

Finally, ongoing efforts to gain insights into the emission of dust from the Colorado Plateau were supported by CSAS and CODOS this season. Dozens of dust-on-snow samples were collected at the Senator Beck Basin Study Area and sent to the US Geologic Survey's "Effects of Climatic Variability and Land Use on American Drylands" research group, and to Dr. Painter's Snow Optics Laboratory, for their chemical, optical, and mass loading analyses.

That concludes this WY2011 Season Summary, prepared by Landry and reviewed by Painter.

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APPENDICES

A - WY 2006 Snowmelt Season Summary Data
B - WY 2007 Snowmelt Season Summary Data
C - WY 2008 Snowmelt Season Summary Data
D - WY 2009 Snowmelt Season Summary Data
E - WY 2010 Snowmelt Season Summary Data

Appendix A - WY 2006 Snowmelt Season Summary Data

CODOS and Other SNOTEL Sites - WY 2006 Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Post-Peak Added SWE	Adjusted Daily Mean Loss SWE	Period Mean Temp
Red Mtn Pass	4/8/06	24.4	50	1.2	0.51	3.1
Slumgullion Pass	4/17/06	15.9	38	0.4	0.43	2.2
Wolf Creek Summit	5/1/06	25.7	40	1.2	0.67	7.7
Beartown	4/16/06	17.9	32	0.7	0.58	2.2
Lizard Head	4/9/06	14.4	29	0.5	0.51	3.0
Park Cone	4/7/06	11.3	31	0.9	0.39	3.7
Schofield Pass	4/9/06	39.8	51	2.6	0.83	3.7
McClure Pass	4/8/06	20.5	30	1.5	0.73	6.6
Independence Pass	4/9/06	16.7	41	2.0	0.46	0.7
Hoosier Pass	4/9/06	19.3	49	2.7	0.45	3.5
Grizzly Peak	4/4/06	21.6	49	3.5	0.51	2.3
Berthoud Summit	4/21/06	24.0	41	3.8	0.68	3.5
Willow Creek Pass	4/27/06	13.4	28	0.8	0.51	3.8
Rabbit Ears Pass	4/9/06	38.0	50	2.3	0.81	4.6
Mesa Lakes	4/8/06	17.9	39	1.6	0.50	3.8
Mean	4/12/06	21.4	40	1.7	0.57	3.6
Max	05/01/06	39.8	51	3.8	0.83	7.7
Min	4/4/06	11.3	28	0.4	0.39	0.7
Range	28	28.5	23	3.4	0.44	7.0

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE
Non-CODOS SNOTEL sites shown in italics

Appendix B - WY 2007 Snowmelt Season Summary Data

CODOS and Other SNOTEL Sites - WY 2007 Snowmelt Season Summary Data						
	Date Peak SWE	Peak SWE	Days to SAG	Post-Peak Added SWE	Adjusted Daily Mean Loss SWE	Period Mean Temp
Red Mtn Pass	5/9/07	23.7	34	1.7	0.75	4.7
Slumgullion Pass	4/18/07	16.6	50	3.6	0.40	3.3
Wolf Creek Summit	4/26/07	32.3	59	5.6	0.64	6.5
Beartown	4/17/07	15.2	32	4.7	0.62	1.3
Lizard Head	4/16/07	11.2	25	2.9	0.56	2.0
Park Cone	4/18/07	7.8	17	0.5	0.49	4.5
Schofield Pass	4/17/07	29.1	44	3.1	0.73	3.1
McClure Pass	3/13/07	15.5	56	5.9	0.38	4.7
Independence Pass	4/18/07	16.3	31	2.8	0.62	2.6
Hoosier Pass	4/28/07	18.5	45	3.2	0.48	4.2
Grizzly Peak	4/20/07	20.6	43	3.0	0.55	3.0
Berthoud Summit	4/27/07	22.2	46	4.5	0.58	4.4
Willow Creek Pass	4/28/07	16.8	37	1.7	0.50	4.5
Rabbit Ears Pass	4/14/07	22.7	37	2.9	0.69	4.9
Mesa Lakes	4/14/07	13.0	31	3.1	0.52	3.32
Mean	4/18/07	18.8	39	3.3	0.57	3.8
Max	05/09/07	32.3	59	5.9	0.75	6.5
Min	3/13/07	7.8	17	0.5	0.38	1.3
Range	58	24.5	42	5.4	0.36	5.2

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE
Non-CODOS SNOTEL sites shown in italics

Appendix C - WY 2008 Snowmelt Season Summary Data

CODOS and Other SNOTEL Sites - WY 2008 Snowmelt Season Summary Data						
	Date Peak SWE	Peak SWE	Days to SAG	Post-Peak Added SWE	Adjusted Daily Mean Loss SWE	Period Mean Temp
Red Mtn Pass	4/14/08	34.4	66	4.3	0.59	2.9
Slumgullion Pass	4/20/08	19.6	49	2.3	0.45	2.9
Wolf Creek Summit	4/26/08	47.5	71	3.7	0.72	6.7
Beartown	4/19/08	31.7	52	3.9	0.68	2.2
Lizard Head	4/13/08	23.7	47	2.8	0.56	2.5
Park Cone	4/14/08	17.7	47	2.8	0.44	3.8
Schofield Pass	4/13/08	56.9	76	8.1	0.86	3.6
McClure Pass	4/16/08	29.3	40	2.3	0.79	5.5
Independence Pass	4/13/08	26.8	56	4.0	0.55	1.7
Hoosier Pass	4/15/08	20.8	61	4.2	0.41	2.5
Grizzly Peak	4/13/08	23.0	56	4.8	0.50	1.7
Berthoud Summit	5/16/08	24.4	34	1.4	0.76	5.8
Willow Creek Pass	5/16/08	21.9	30	2.0	0.80	5.8
Rabbit Ears Pass	4/15/08	38.0	62	8.5	0.75	4.1
Mesa Lakes	4/12/08	23.3	59	5.3	0.48	3.14
Mean	4/19/08	29.3	54	4.0	0.62	3.7
Max	05/16/08	56.9	76	8.5	0.86	6.7
Min	4/12/08	17.7	30	1.4	0.41	1.7
Range	35	39.2	46	7.1	0.45	5.0

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE
Non-CODOS SNOTEL sites shown in italics

Appendix D - WY 2009 Snowmelt Season Summary Data

CODOS and Other SNOTEL Sites - WY 2009 Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Post-Peak Added SWE	Adjusted Daily Mean Loss SWE	Period Mean Temp
Red Mtn Pass	4/19/09	27.5	37	1.8	0.79	4.3
Slumgullion Pass	4/21/09	16.0	27	0.4	0.61	4.5
Wolf Creek Summit	5/6/09	35.9	49	3.5	0.80	7.1
Beartown	4/19/09	27.2	26	1.6	1.11	3.5
Lizard Head	4/18/09	19.0	22	1.0	0.91	3.5
Park Cone	4/6/09	13.2	38	1.4	0.38	3.5
Schofield Pass	4/21/09	48.5	46	4.5	1.15	4.5
McClure Pass	4/8/09	24.2	30	2.4	0.89	5.5
Independence Pass	4/19/09	21.9	30	0.9	0.76	3.3
Hoosier Pass	4/20/09	17.3	47	5.3	0.48	3.8
Grizzly Peak	4/20/09	21.6	47	5.2	0.57	3.7
Berthoud Summit	4/20/09	24.7	50	5.2	0.60	4.0
Willow Creek Pass	4/20/09	14.7	37	3.4	0.49	4.8
Rabbit Ears Pass	4/21/09	32.8	40	3.8	0.92	5.7
Mesa Lakes	4/18/09	19.2	32	2.5	0.68	4.99
Mean	4/19/09	24.2	37	2.9	0.74	4.4
Max	05/06/09	48.5	50	5.3	1.15	7.1
Min	4/6/09	13.2	22	0.4	0.38	3.3
Range	31	35.3	28	4.9	0.77	3.8

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE
Non-CODOS SNOTEL sites shown in italics

Appendix E - WY 2010 Snowmelt Season Summary Data

CODOS and Other SNOTEL Sites - WY 2010 Snowmelt Season Summary Data

	Date Peak SWE	Peak SWE	Days to SAG	Post-Peak Added SWE	Adjusted Daily Mean Loss SWE	Period Mean Temp
Red Mtn Pass	4/8/10	24.2	54	3.7	0.52	1.5
Slumgullion Pass	4/11/10	14.7	45	2.6	0.38	1.1
Wolf Creek Summit	5/5/10	37.1	44	1.4	0.88	7.1
Beartown	4/8/10	22.6	43	3.2	0.60	-0.1
Lizard Head	4/5/10	16.7	41	2.8	0.48	1.3
Park Cone	4/10/10	10.8	41	2.4	0.32	3.1
Schofield Pass	4/9/10	36.1	59	7.1	0.73	2.8
McClure Pass	4/10/10	20.3	38	3.0	0.61	5.0
Independence Pass	4/9/10	16.5	49	5.0	0.44	1.5
Hoosier Pass	5/4/10	14.7	31	1.8	0.53	3.3
Grizzly Peak	4/9/10	12.8	50	6.0	0.38	1.3
Berthoud Summit	5/16/10	24.5	23	0.6	1.09	6.6
Willow Creek Pass	5/16/10	14.4	21	0.5	0.71	6.6
Rabbit Ears Pass	5/16/10	19.2	22	2.1	0.97	7.9
Mesa Lakes	4/9/10	16.9	51	5.0	0.43	2.92
Mean	4/19/10	20.1	41	3.1	0.60	3.5
Max	05/16/10	37.1	59	7.1	1.09	7.9
Min	4/5/10	10.8	21	0.5	0.32	-0.1
Range	41	26.3	38	6.6	0.77	8.0

Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE
Non-CODOS SNOTEL sites shown in italics