CENTER FOR SNOW & AVALANCHE STUDIES

CSAS

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COLORADO DUST-ON-SNOW PR0JECT

Final Report

For

Colorado Water Conservation Board

WSRF Grant End Date 07/31/19

Contract # CTGG1 2017-1239

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PROJECT DESCRIPTION

The Center for Snow & Avalanche Studies (CSAS) is an independent, not-for-profit 501(c)(3) organization that operates the Colorado dust-on-snow (CODOS) Project. Dust events on the snowpack can advance snowmelt timing, enhance runoff intensity, and decrease snowmelt yields. CODOS is the only organization monitoring dust-on-snow in Colorado in a comprehensive, applied manner on behalf of the water management community, providing forecasts of dust-on-snow impacts on snowmelt runoff behavior throughout the State in the form of timely and actionable updates and alerts. These iterative products describe current dust-in-snow conditions, by major watershed, and predict the likely influence of dust-on-snow on near-term snowmelt timing and rates. Analyses includes association of dust-on-snow, snowpack, and weather conditions to hydrograph patterns observed since 2006 at 19 headwater stream gauges monitored in most major watersheds. As the season unfolds, plausible and probable patterns in spring dust-enhanced snowmelt behaviors are identified.

CSAS's Senator Beck Basin is home to the CODOS "sentry site" for dust-on-snow deposition for the Colorado Mountains. Ten additional sites are monitored throughout the winter season including:

- Park Cone
- Spring Creek Pass
- Wolf Creek Pass
- Hoosier Pass
- Grizzly Peak
- Berthoud Summit
- Willow Creek Pass
- Rabbit Ears (west)
- McClure Pass
- Grand Mesa

CSAS performs field work at all eleven sites and documents dust-in-snow layers along with other snowpack variables, ongoing monitoring of Snow Telemetry (SNOTEL) sites and evaluation of regional hydrologic data. These data along with consultations with local observers forms the analyses that are then published in CODOS Updates.

The CODOS Project also:

- Contributes information to support the Colorado Basin River Forecast Center and other River Forecast Centers effort to quantify dust effects on snowmelt in their streamflow forecast products
- Continues to collect field samples from Senator Beck Study Basin (SBB) and the other ten CODOS monitoring sites for Dr. Harland Goldstein at the U.S. Geological Survey in Denver in support of his team's research program in the Colorado Plateau titled "Effects of Climatic Variability and Land Use on American Drylands"

- Through our Senator Beck Study Basin, continue to provide field support and sampling services to NASA-funded and Cold Regions Research and Engineering Laboratory research teams in an effort to improve snowpack monitoring and modeling.

PROJECT OBJECTIVES

The Center for Snow and Avalanche Studies enables the interdisciplinary investigation of the mountain and alpine snow system's behavior and role in human/environment relationships. The best way to understand dust-on-snow severity and extent is by direct field observations. The WSRF grant funded field activities and assisted in the development of interpretative tools deployed on the CODOS website and mobile apps. The CODOS Project objectives were to continue to collect (continuing an essential dataset) and disseminate dust-on-snow information while expanding and improving operational efficiencies. Specifically, the CODOS Program objectives were to:

• Conduct Statewide dust-on-snow field campaigns to track the severity and extent of dust events throughout the snow accumulation and ablation period for WY2017, WY2018, and WY2019.

• Provide timely and applicable updates and alerts to forecasters and the water community.

• Operate long-term snow and meteorological study sites in Colorado’s San Juan Mountains.

• Manage dust-on-snow and meteorological data collection, management, validation, and reporting. Ensure correct operation of instruments. Maintain data, metadata, and sensor status files.

• Maintain project webpages with data files, graphics, and relevant information.

• Initiate website upgrades to improve access, and support data, graphics, and interpretation platforms.

• Develop visualization and interpretative tools on project webpages for easy dissemination of information.

• Provide educational outreach for K-12 schools in Southwest Colorado.

TASKS

Project objectives took the form of four main tasks: **Task 1** - *Monitor Statewide Dust-on-Snow Conditions,* **Task 2** – *Frequent and Timely Dust-on-Snow Updates and Reports,* **Task 3** - *Data Management, Quality Control, and Reporting*, **Task 4** – *Near-Real Time Data Availability, Graphics, and Interpretation tools.*

TASK 1 – Monitor Statewide Dust-on-Snow Conditions

Description of Task: Collect dust-on-snow information at SBB and at least 10 other locations throughout Colorado during the winter and spring, including: Park Cone, Spring Creek Pass, Wolf Creek Pass, Hoosier Pass, Grizzly Peak, Berthoud Summit, Willow Creek Pass, Rabbit Ears Pass, McClure Pass, and Grand Mesa.

Method/Procedure: Timely statewide visits, via motorized vehicle, to CODOS sites to collect snowpack information. These profiles of the snowpack allow the documentation of the severity and spatial extent of dust events. A field assistant will accompany Director on trip, and, when appropriate will visit some sites solo to optimize human resources. Field trips will occur at least 3 times a year.

Deliverable: Field data documentation including snow profile forms, pictures of dust-on-snow profiles and surrounding landscapes. Collection of snow samples and delivered to USGS project partners for mass loading and chemical analysis.

TASK 2 – Frequent and Timely Dust-on-Snow Updates and Reporting

Description of Task: Collation of field observations and timely creation of dust-on-snow updates and alerts to water community. Season summary and funder progress reports.

Method/Procedure: Field data formatted and summarized, data includes the collection of USGS streamflow data, NRCS SNOTEL data, and NWS weather forecasts. Creation of dust-on-snow analysis documents.

Deliverable: These timely, actionable, iterative updates and alerts describe current dust-in-snow conditions, by major watershed, and predict the likely influence of dust-on-snow on near term snowmelt timing and rates. Analyses includes association of dust-on-snow, snowpack, and weather conditions to hydrograph patterns observed since 2006 at 19 headwater stream gauges monitored in most major watersheds. Project reports to CWCB and other funders. Consultations and presentations to supporters, funders, general public, university and K-12 students.

TASK 3 – Data Management, Quality Control, and Reporting

Description of Task: Dust-on-snow and meteorological measurements, data collection, management, validation, and reporting. Maintenance and calibration of instrumentation.

Method/Procedure: Maintain instrumentation, communication, data collection server, storage and archive servers. Data QA/QC. Maintain dust-on-snow data files.

Deliverable: Access, via the CSAS and CODOS webpages, to serially complete near-real time and archived meteorological and dust-on-snow data files.

TASK 4 – Near-Real Time Data Availability, Graphics, and Interpretation Tools

Description of Task: Website upgrades to improve data access, visualization, interaction, interpretation, and dissemination of dust-on-snow and related information.

Method/Procedure: Web Administrator, or appropriate third party, creates platforms, tools and webpage content.

Deliverable: Ability to download near-real time data files to be used in forecasting and hydrologic modeling, the creation of near-real time dust-on-snow and meteorological data graphics, and the construction of an interactive webpage that allows the water community to post, share, and view dust-on-snow conditions throughout the Colorado Mountains.

PROJECT PERFORMANCE

Monitor Statewide Dust-on-Snow Conditions

All water year (WY2017 thru WY2019) tasks and objectives were completed throughout the winter seasons successfully. The CODOS team visited sample locations around Colorado at least three (March, April, May) occasions, with a fourth trip usually performed to collect end of season dust-on-snow samples for USGS analyses. Sites visited were Park Cone (near Taylor Reservoir), Spring Creek Pass, Wolf Creek Pass, Hoosier Pass, Loveland Pass, Berthoud Pass, Willow Creek Pass, Rabbit Ears Pass, and McClure Pass to inspect the snowpack for the presence/absence of dust layers, the proximity of dust to the snowpack surface, and collecting snow samples. We also sampled at Senator Beck Research site continuously, documenting snowpack and dust-on-snow conditions.

We performed continuous field monitoring at the Senator Beck Basin Study Area at Red Mountain Pass for dust-on-snow events during the grant period, documenting 19 desert dust deposition events. Performed an estimated 70 formal profiles during winter with 15 sets of gravimetric samples collected which capturing dust concentrations in the top 30 cm of the snowpack of the final snowpits of the season. All gravimetric snow samples were melted, bottled, and shipped to USGS.

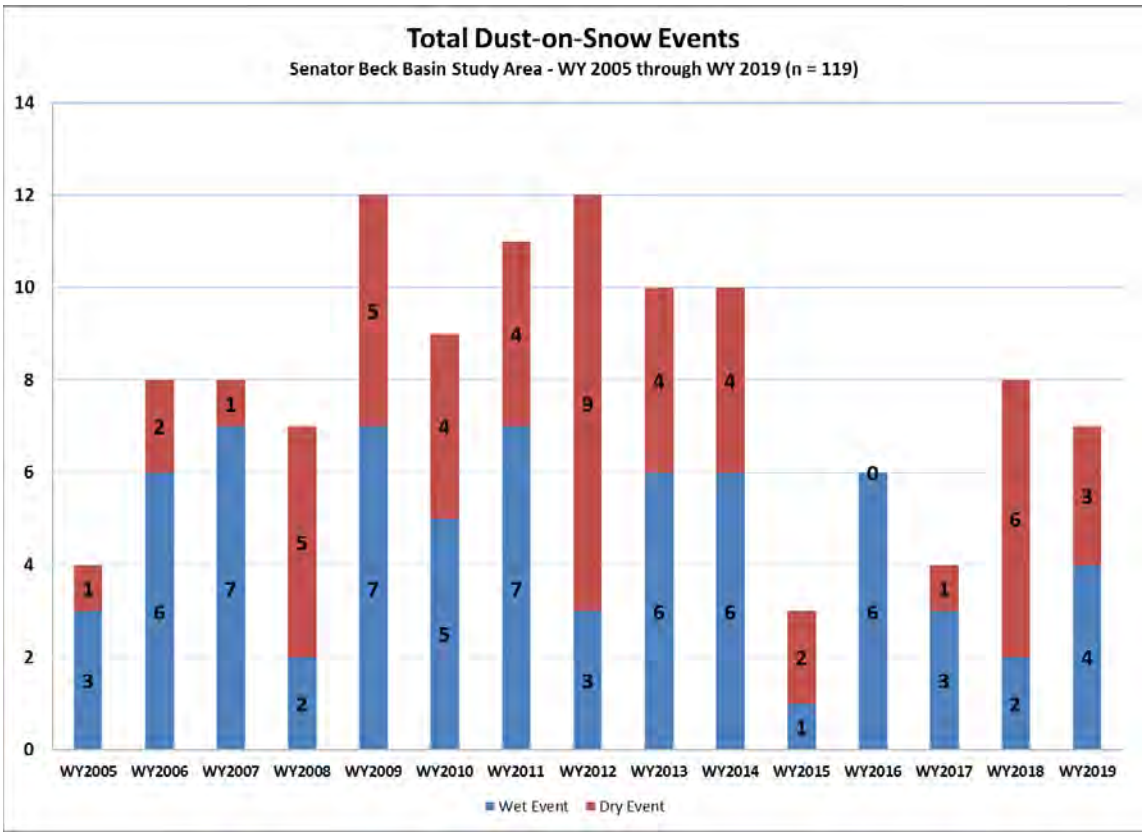


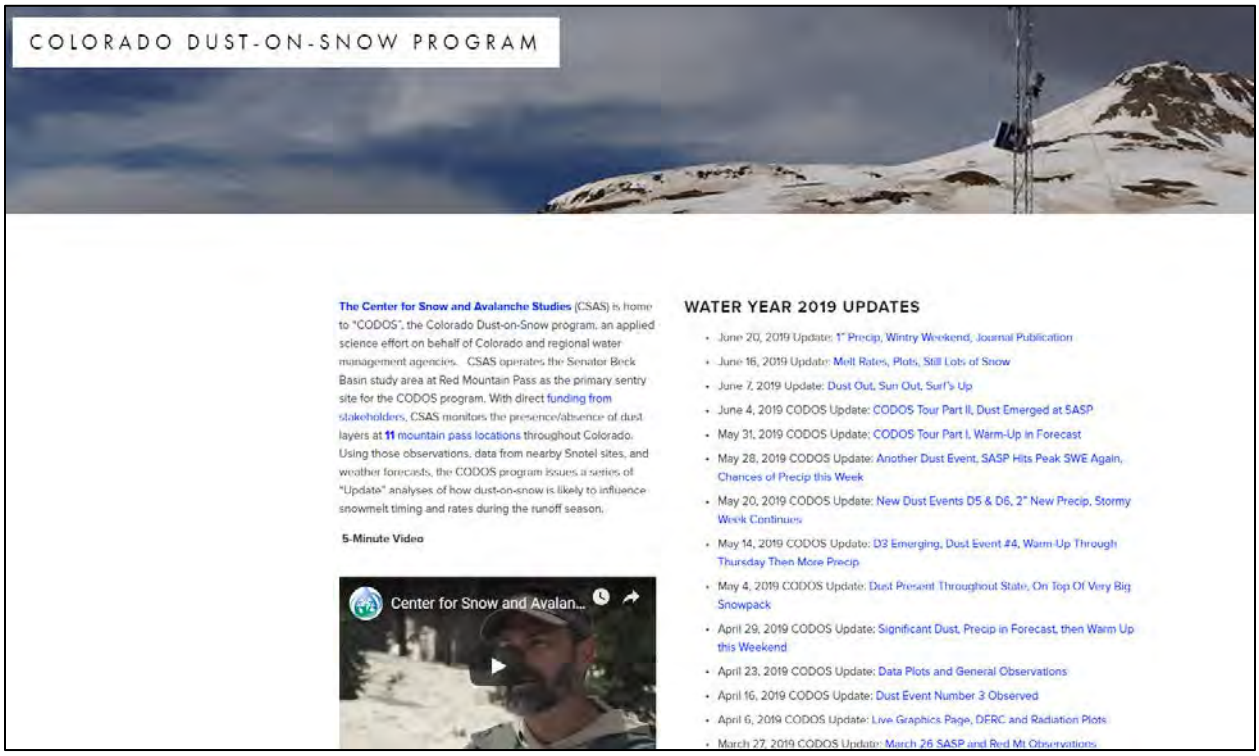
Figure 1. Bar graph of dust events by year. Blue indicates number of wet dust deposition events and red indicates the number of dry deposition events.

Jeff Derry and his Center for Snow and Avalanche Studies field assistants maintained and operated the CSAS's climate, snowpack, radiation, and soils monitoring instrumentation and stream gauging station at the Senator Beck Basin Study Area throughout grant period, as well as the sun photometer located at the SBB Swamp Angel Study Plot (the NASA AERONET "Red Mountain Pass" site).

WY2019 was notably a very big snow year. We had many challenges. Red Mountain Pass was closed for over three weeks preventing access to our research basin, but our weather stations continued to work flawlessly, providing valuable information to road crews, emergency managers and snow/avalanche professionals. Also, the snow was deep! We did a lot of digging to gather needed information. This took a toll on our backs and threatened our Program's budget as well, as tasks took longer to accomplish. But, all the data was collected and objectives met on schedule and within budget.

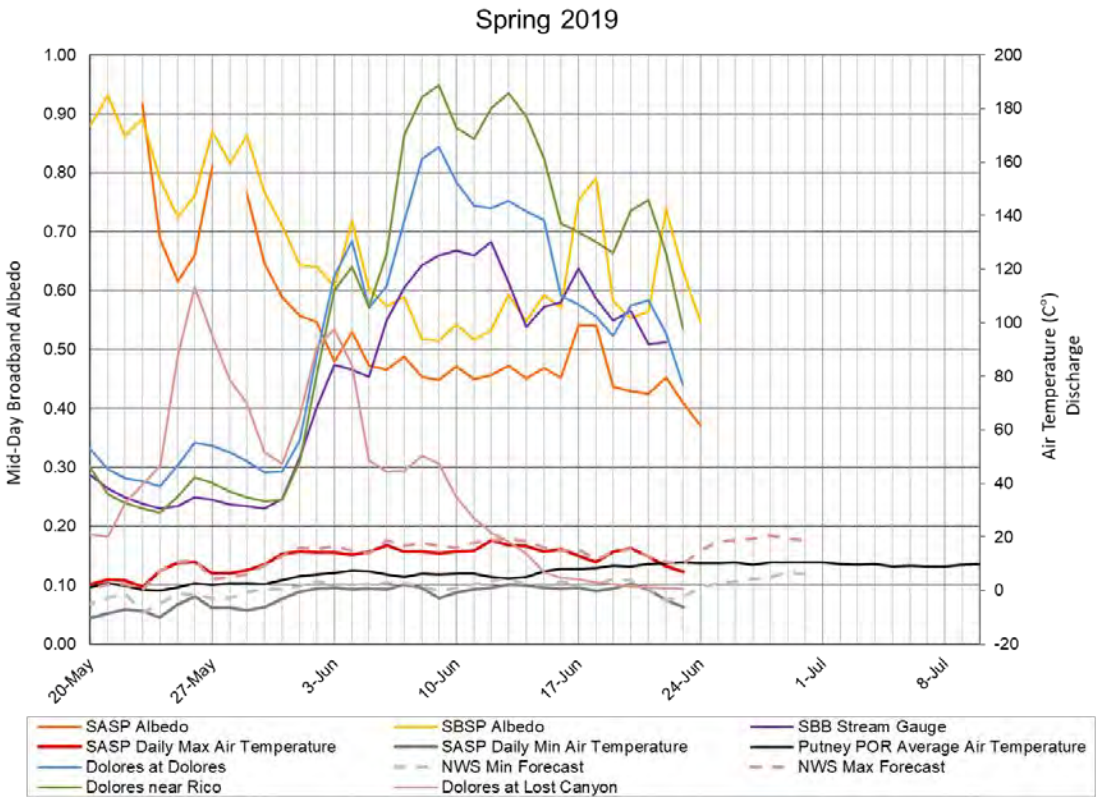
Frequent and Timely Dust-on-Snow Updates and Reporting

Throughout the winter and spring WY2017-WY2019 at least twenty-one timely dust-on-snow alerts and updates were issued, plus an end of season summary report published for WY2017 and WY2018. The snowpack in WY2019 lasted well into July delaying the publication of the WY2019 end of season report. This report will be published on the codos.org website in August 2019. There were no issues that hindered or prevented all objectives to be met in a timely fashion. These updates can be viewed at: http://www.codos.org/#codos

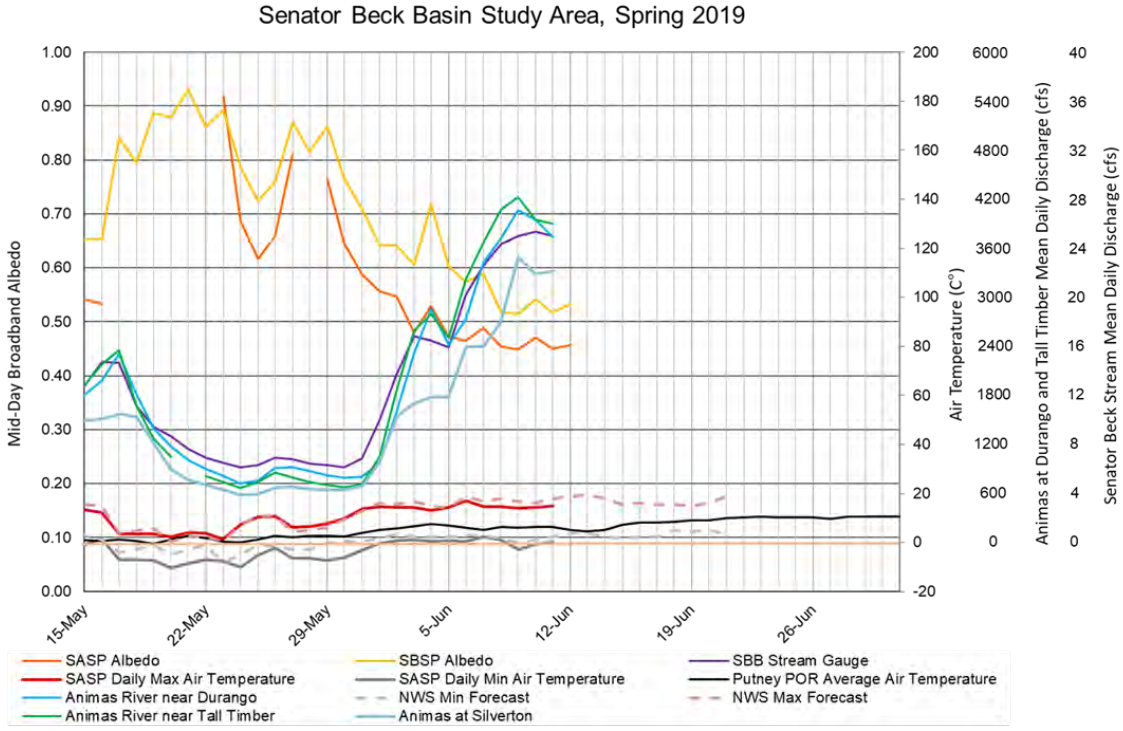


CODOS Project issued at least 21 alerts and updates throughout the winter/spring of WY2017-WY2019 seasons, at least 63 alerts and updates total for grant period.

Bureau of Reclamation and reservoir operators rely on our observations and data in making decisions - particularly for operations in Southwest Colorado because our high elevation Senator Beck Study Basin is located near the headwaters of four major watersheds (San Miguel, Animas, Uncompahgre, and Rio Grande). The Bureau of Reclamation Western Colorado Office incorporates our data and analyses in their decision making with Navajo, McPhee, Vallecito and Lemon reservoir operations. This involves the time consuming task of providing daily e-mailed updates of data, observations and graphics starting in April and continuing until full snow ablation. In a year such as WY2019 it proved very beneficial in managing high streamflows safely and to full efficiency.



Example of graphics provided to Bureau of Reclamation on a daily basis throughout snowmelt period.



Example of graphics provided to Bureau of Reclamation on a daily basis throughout snowmelt period.

Data Management, Quality Control, and Reporting

The CODOS Program collects data in three main ways; from our three metrological stations and one stream gauge station in Senator Beck, from our snow profiles that include dust-on-snow observations, and from dust-on-snow sample collections for USGS analyses. All of this data needs to be collected, organized, QA/QC'd, analyzed and published. Grant funding was very essential in providing the resources to make these tasks a reality.

Station data is posted on our website free of charge. Our data is highly sought after by hydrologists and modelers to better understand snow processes understanding and investigating systematic errors and methods to improve snow accumulation/ablation models. As an example a paper was recently published on that very subject.

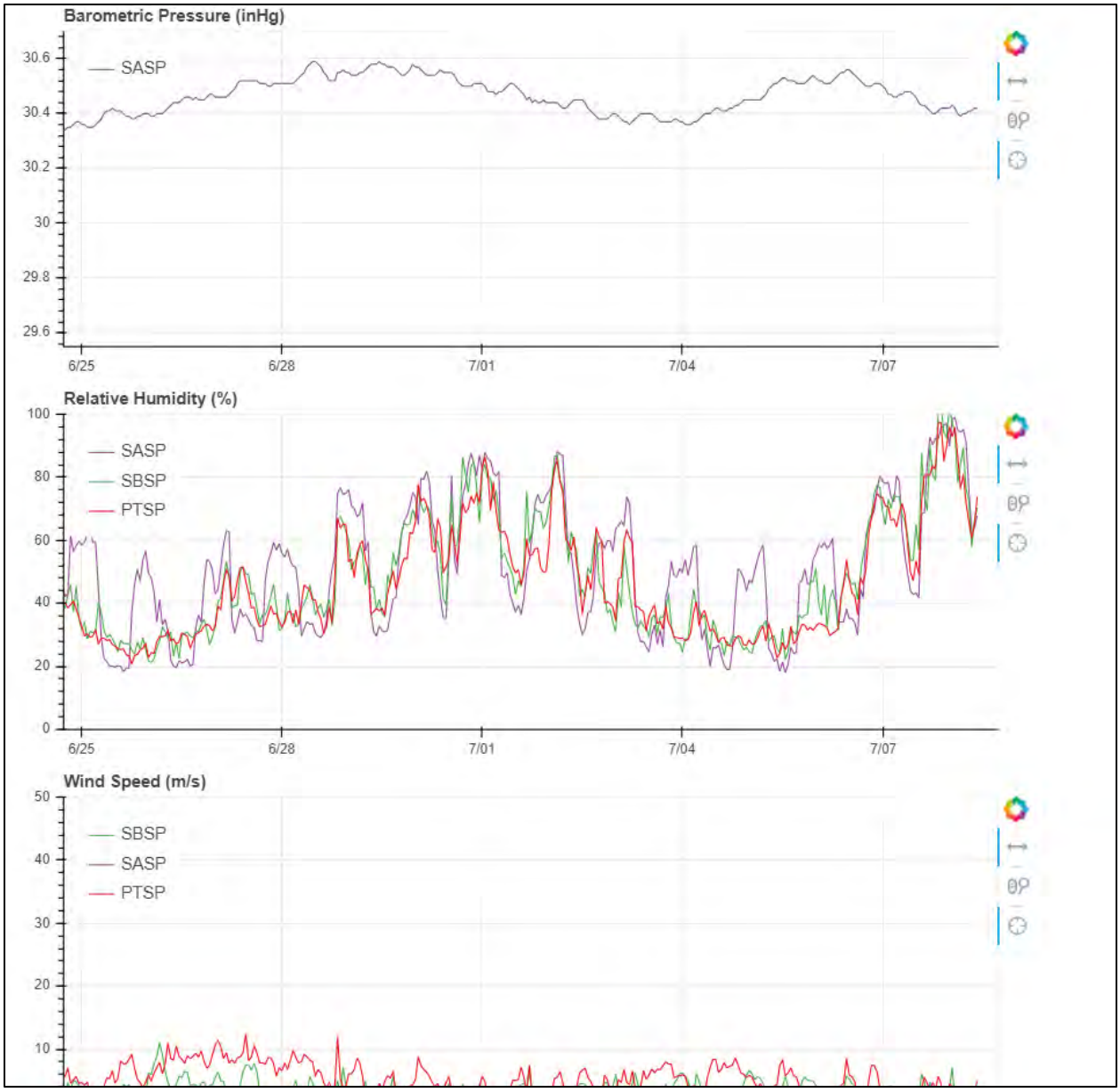
In addition to dust presence and location in the snowpack, snow profile data includes depth, SWE, temperature, grain type/size, wetness, and hardness. This data is important to water professionals and researchers in understanding the current state of the snowpack for runoff forecasting and instrumentation calibration. These data are also maintained and located on the snowstudies.org website.

Dust samples are submitted to USGS for processing and the data values are returned to the CODOS Program for record keeping and ongoing analysis of number of dust events, source analyses, and dust composition and effects on albedo and streamflow analyses.

Near-Real Time Data Availability, Graphics, and Interpretation Tools

Over the duration of the term of the WSRA grant large improvements were made in how we make our data available to stakeholders. For one, we updated our snowstudies.org website to Wordpress, a much for versatile and user friendly web interface. Second, the creation of a near-real time data graphics webpage was created along with the entire supporting database system. These data graphics offer flexible viewing options over user defined timescales. This new tool allows users to visually see hourly data from our SBB stations immediately upon collection as well as trends over time and historical data.

The near-real time data graphics page can be viewed at: https://snowstudies.org/live-plot/



Example of the new near-real time data graphics on the snowstudies.org website.

The third accomplishment under this task is the foundation for a mobile phone app has been created that will allow users to take and upload pictures of dust-on-snow conditions to an interactive map along with comments, facilitating a platform where the community can share observations and talk about the implications on a forum, as well as providing much needed field observations to the CODOS Program. The app has passed through review and required alterations of Apple in order for it to be used on an i-phone, a time consuming process. The next phase involves dialing in the functions and graphics to be tested by a small group of people before full release of the tool to the community.

The fourth significant accomplishment for data availability is the continued operation and improvement of the near-real time data tables under the "Current Conditions" page. These data are provided for researchers who wish to collect recent data for insertion into a spreadsheet and for folks who prefer to see an exact number of data collected as opposed to seeing data on the graphic page. Available data has been increased and easier to download.

CONCLUSIONS

The Colorado Dust-on-Snow Project operated by Center for Snow and Avalanche Studies is an ongoing applied science effort on the behalf of the Colorado water community. The dust-on-snow, snowpack, and meteorological information we collect is unique to our organization. *No one else, no other entity, is collecting this kind of information let alone making it available to Colorado water stakeholders*. WSRA funds provided over the last three years was crucial in enabling the Colorado Dust-on-Snow Project to have the means to continue operations and implement much needed communication, website, and technical upgrades, as well as continue the essential work of collecting and managing the data, analyzing and publishing the information in a timely manner in order to be used for ongoing operations, planning, and forecasting. The productive and successful grant period totaled three water years, WY2017, WY2018, and WY2019 with all grant objectives and tasks completed thoroughly and on schedule.

APPENDIX A:

WATER YEAR 2017 SEASON SUMMARY

COLORADO DUST-ON-SNOW PROGRAM: WY 2017 SEASON SUMMARY AND FINAL REPORT

Also available at: http://www.codos.org/codosupdates/2017seasonsummary

SUMMARY

After a worrisome October and November when Colorado received very little precipitation and experienced very warm temperatures, winter finally kicked into action and Colorado started receiving abundant snowfall, building the snowpack rapidly during the months of December, January, and into February. One of the big stories this winter season is the *atmospheric rivers* that fueled these productive storms, which were record breaking in some locations. On the other end of the spectrum, one of the other big stories this winter is the observed warmest March on record. The effects of this hot month (preceded by a very warm February) was a rapid warming of the snowpack and snowmelt at lower elevations and valleys, resulting in most stream gauges observed a 2-3 week bump in stream flow in mid-March thru the first part of April. However, Colorado recovered from the hot/dry spell with a long stretch of regular precipitation beginning around March 23 – April 4. A dry spell was again repeated April 5-19. And, starting the latter part of April regular precipitation (however sparse) was observed steadily but intermittently until June 1.

At the Center for Snow and Avalanche Studies' (CSAS) Senator Beck Basin Study Area (SBB) at Red Mountain Pass, the primary Colorado Dust-on-Snow Program (CODOS) monitoring site, WY2017 produced a total of four separate dust-on-snow events, on the light side of a typical dust loading season based on observations going back to WY2005. Dust season began relatively late in the season. With the abundant moisture in the dust source area, the Southern Colorado Plateau, dust mobilization was kept in check until March when soils started drying out. Dust-on-snow events March 5, 23, 31 and on April 9 were documented. Surprisingly no dust events were observed the rest of April and May, although a couple haze events were noted. On June 12 a big dust storm in the desert southwest was observed with the USGS dust cameras, additional dust on any remaining snow in the Colorado Mountains was not observed at lower elevations, but it is possible some higher elevation snow cover could have received additional dust from this event. Of the four documented dust events, two of these events were pretty heavy in their severity. The end result, even though total mass loading of dust was light, with the location of the dust in the snowpack (i.e. upper portion) and its consequential role in snowmelt, we classified dust severity as "Average", albeit the lighter side of average at SBB. Northern and some Central CODOS sample sites in Colorado were classified as "Minimum" dust severity. The transition from "Average" to "Minimum" severity took place in Central Colorado, thus some Central and all Southern CODOS sites were classified as "Average".

This Season Summary will often reference or link to snowpack, streamflow, weather, and climate products generated by the NRCS SNOTEL program, USGS National Water Information System, and NOAA National Weather Service and Climate Prediction Center respectively, as presented and archived on CODOS monitoring site webpages.

MONTHLY WEATHER CONDITIONS

October:

October was a very dry month, with no winter storms and only 0.8" of precipitation. This is about one fifth of average precipitation for the month. Only 0.4" of precipitation came in as snow and warm temperatures characterized the majority of the month. October's precipitation did not contribute to our season snowpack in SBB. For our period of record, 9 winter seasons out of 13 we have seen winter snow accumulation begin in October at Swamp Angel Study Plot (SASP).

November:

November started warm and dry, but about halfway through the month we began to build our season's snowpack in the San Juan Mountains. This was the latest that snow accumulation began at SBB for our period of record (the last 13 years). Our first winter storm of the season was on November 17 and although it was a relatively minor event, this storm laid down our basal layer for the season. The second half of November was cold, with two additional winter storms and notable snow accumulation. Total precipitation for the month was 4.5", all as snow, this is above average precipitation for the month. Latter November signaled the beginning of a very snowy early to mid-winter to follow.

December:

December was a generally cold and snowy month. Temperatures were consistently below average in the San Juan Mountains and precipitation all came in as snow. Precipitation was average at 5.3", but December is historically our biggest month for winter precipitation. During the period snowpack in the SBB grew rapidly, with snow height at SASP at over a 3' (1 meter) by the end of the calendar year. Because the month was relatively cold, there was less snowpack settlement, so the snowpack gained significant height for the amount of precipitation received. This set us up well for the exciting month to come.

January:

January was a month of historic snowfall and major increases in snowpack in SBB and state-wide. As a whole, temperatures were average throughout the month, although there were several swings between exceptionally warm and cold periods. With an incredible 8" of water over the course of 5 storms, precipitation for the month was 173% of average. This is the most precipitation recorded for any January in SBB since CSAS started monitoring 13 years ago, and it is also the fourth snowiest month overall during that same period. Snow height at SASP increased by about 3' (1 meter) over the course of January, bringing our snowpack into the 7 foot (2 meter) range by the end of the month. Adding to the excitement, a large majority of this January snowfall can be attributed to atmospheric river events. Common to the Sierra, Cascades and other Maritime ranges in North America, atmospheric rivers are narrow bands of moisture which carry the majority of precipitable water in a given storm system. This warm

water vapor, originating near the tropics, are essentially a firehose for precipitation, and in the San Juan Mountains we were right on track to get pummeled by several of these events. This is unusual. Atmospheric river features rarely make it this far inland and this year we received around five events in January and February! Please see links below related to atmospheric rivers in the "Looking Ahead" section.

February:

February saw significant declines in precipitation for the basin and well above average temperatures. Although February matched January for number of winter storms, the precipitation for the month was about half of the prior month with only 4", which is slightly below average. Statewide temperatures were well above average, with many days setting significant record highs which made national news. These very warm temperatures, especially toward the beginning and end of the month kept snow height relatively level, with almost no net gains throughout the month. Height of our snowpack normally continues to build through February and March in the San Juans, but this year we saw a leveling off in snow height following an early February atmospheric river event, the last of the season. At this point, low to moderate snowfall and warmer temperatures played a game of accumulation versus settlement, and it essentially ended in a tie. SASP maintained about a 7-foot (2-meter) snowpack for the month. However, remember that even without gains in snow height, we still had input in SWE during the month and our snowpack remained above average from a total water standpoint.

March:

One of the big stories this winter season was that Colorado had it's warmest March on record. Despite the warm March snowfall remained about average thanks to an active period in the latter part of the month. With 4.6" of precipitation in SBB over 5 storms snowfall only made moderate contributions to the snowpack. Additionally, March was the beginning of our dust season, with three of our four dust events of the season occurring during the month. Dust event #1 (D1) and D2 were minor events and difficult to discern in the snowpack, although they still, when concentrated at the surface, contributed to the overall impact on snow surface albedo. Our third event (D3) was a significant wet event which drastically lowered snow albedo when exposed. In addition to dust increasing the absorption of solar radiation, very warm temperatures contributed to significant snowpack warming. SASP reached isothermal snowpack conditions on March 22, which is by far the earliest date for this condition on CSAS record. This warming of the snowpack resulted in the first spike in streamflow out of SBB for the season. Just as with February, March began and ended with about a 7-foot (2-meter) snowpack.

April:

April was yet another warm month, and precipitation was well below average. Only 3.3" of precipitation was recorded at SASP, which is about 68% of the CSAS 13-year average. SBB saw an additional dust event (D4) on April 9, the last recorded event for the season. This dry event

was patchy in its accumulation, favoring lee slopes and north through east aspects, but was highly visible across the landscape. Peak SWE at SASP was observed on April 26, with 30" of water. During April there were also several periods of increased runoff, which were associated with warming events and the emergence of dust layers. See the section on the CSAS Dust Enhanced Runoff Classification (DERC) approach below for more information on these spikes associated with dust emergence.

May:

May, overall, was cooler than normal and, largely in mountain regions and Eastern Colorado, was wetter than normal. More specifically at SBB, a sunny and warm beginning and end to May was divided by a notably cold and stormy period. Precipitation was exactly average with 3" recorded at SASP. There were only two winter storms during the month, which is near average, and one was a significant event, delivering over a foot of snow to SBB. This buried our dust layers, all of which were merged on the surface at the time. Although this "albedo reset" was welcome, it was relatively short lived. Following this storm the temperatures soared and the dust was back on the surface in only a few days. Dust remained at or near the surface the remainder of the season thereafter. Many long-range forecasts suggested above average precipitation for May, and while there was notable precipitation this ended up falling a bit flat in some areas compared to the very optimistic precipitation outlooks. However, the month of May we observed precipitation 14 out of 31 days, and these minor precipitation events brought temporary cloud cover and reduced air temperatures, and dustings of new snow, which tapped the brakes on the rate of snowmelt. Although these periods were generally brief, they certainly had notable influence on delaying snowmelt at the end of what was an otherwise warm spring. Towards the end of May dusty conditions and decreasing albedo began to gradually dominate as streamflows climbed back to average and progressed towards their peak snowmelt discharge of the year. This general trend has occurred the past few winters where the San Juan Mountains (and Colorado in general) have seen cooler than average temperatures and at least average snowfall in May, consistently burying and re-burying exposed dust layers.

June:

We observed 1 winter storm in June and it just barely broke the threshold. The San Juan Mountains were warm, sunny and dry. Temperatures held around average to above average for the majority of the month, and the weather was characteristic of summertime. Only 0.63" of precipitation were recorded at SBB, with 0.47" of that coming in on June 1 and no precipitation after June 7 meaning that although June is historically a dry month for the area, this year we saw a significant dry spell of 23 days. Average June precipitation is around 1.2", so barely half of the average precipitation came to the San Juan Mountains. All of this dry, clear weather took it's toll on the snowpack. Although low June precipitation meant very little rain-on-snow, which can rapidly diminish the snowpack, it also meant consistent sunny weather. With the sun's arc passing as high as it does all year, all aspects of slopes consistently received their annual maximum sunlight. This means that dust on the snow surface had ample opportunity to absorb

radiation, in turn warming the snow surface and accelerating snowmelt. Snow all gone was recorded at SASP on June 13, and while snow lingered at higher elevations (and continues to in isolated areas) melt occurred rapidly at all elevations during June.

SENATOR BECK STUDY BASIN DATA

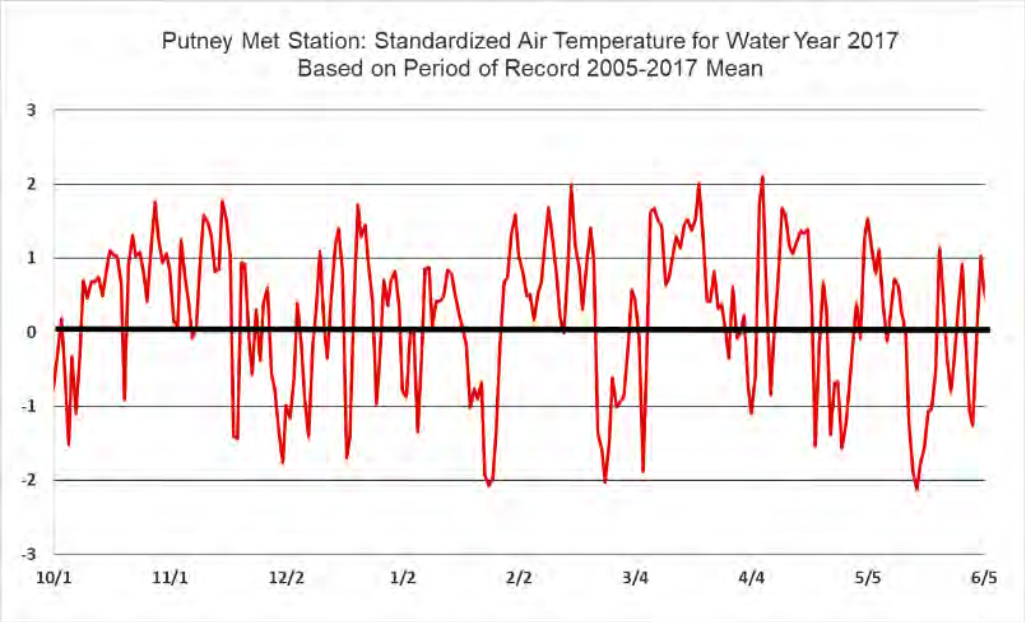
This section describes conditions and data collected by the Center for Snow and Avalanche Studies at our Senator Beck Basin Study Area (SBB) at Red Mountain Pass under our Mountain System Monitoring program, which includes the CODOS program. At SBB, snowpack, weather, soils, and radiation conditions are monitored and measured at the well-sheltered subalpine Swamp Angel Study Plot (SASP, 11,060') and at the more exposed, alpine Senator Beck Study Plot (SBSP, 12,180'). Nearby, wind speed, wind direction, air temperature, and humidity data are collected at the Putney Study Plot (PTSP, 12,323'), located to minimize the influence of local terrain on those measurements. Finally, SBB streamflow discharge is continuously measured at the SBB pour point at the Senator Beck Stream Gauge (SBSG, 11,030'), in a broad-crested, notched weir.

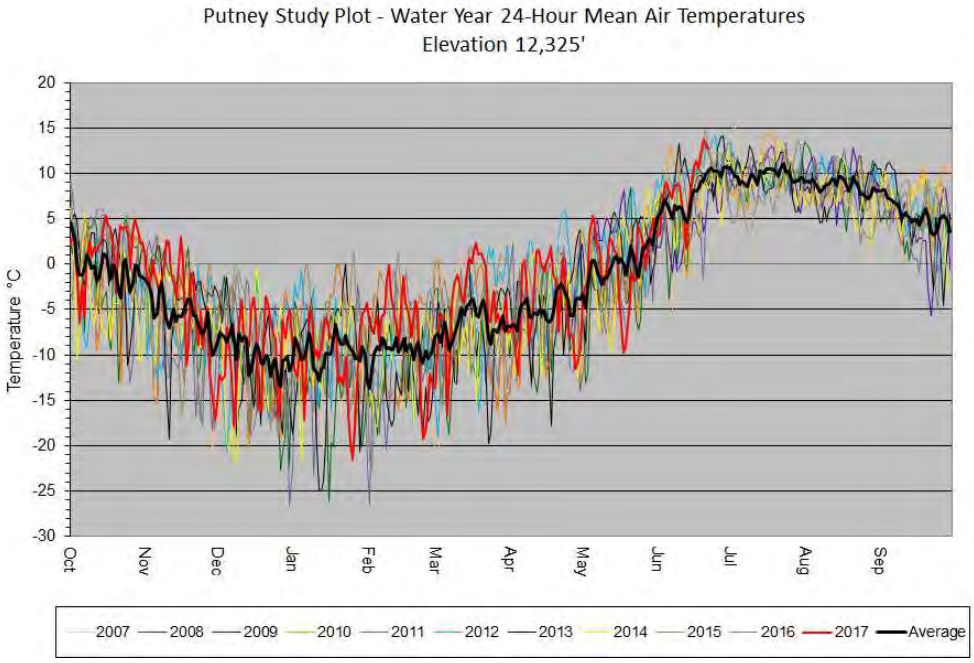
In many ways observations at SBB mirrored general Colorado conditions over the winter but in other respects the data show some uniqueness. The warm/dry October and November is very apparent in the SBB data, as is the warm February and March. What is notable about air temperatures this season was the extended periods of warmer than average temperatures, while colder than average temperatures tended to be more short lived (please see standardized air temperature graph below).

In terms of snowpack, snow profiles (where we collect SWE, grain type/size, density, layers, and dust information) are conducted every 7-10 days at SASP and as often as possible at SBSP. In addition, both SASP and SBSP stations are equipped with an automated SR50 snow depth sensor. SWE observations started out well above normal during the Jan/Feb timeframe at SASP. During the month of February the SnowEx field campaign collected SWE measurements throughout SBB (see Update http://www.codos.org/codosupdates/mar12017), with average SWE observations generally comparing well with Red Mountain SNOTEL at certain elevations. Starting around the end of February the rapid snow accumulation tapered off with peak SWE at SASP reaching near average at 30" (average and median peak SWE at SASP is 29"). While at nearby Red Mt. Pass SNOTEL, peak SWE was 27.4" (median peak SWE of 24.6"), 2.8" greater than median. At higher elevations, SBSP fell right in the middle of the mix as well, with SWE amounts tending above the average for our period of record (WY2004-WY2017) the first part of winter, but with peak SWE ending near the median.

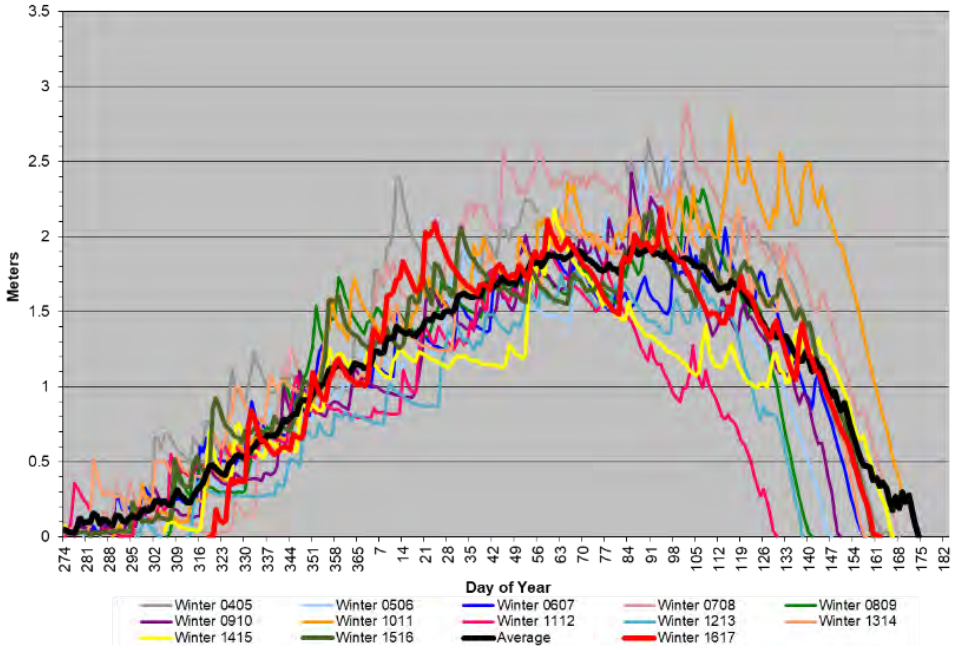
Cumulative precipitation at SASP stayed very near the period of record average. Once the winter season actually started during the latter part of November, the month of December played a little bit of catch up with a pretty steep accumulation rate, and then another sharp increase is noted in January. Red Mountain SNOTEL shows a similar trend although starting in January cumulative precipitation stayed above the median for the majority of the rest of the

season. Data compare well considering spatial variability and gauge undercatch are common realities when trying to measure precipitation in mountain environments.

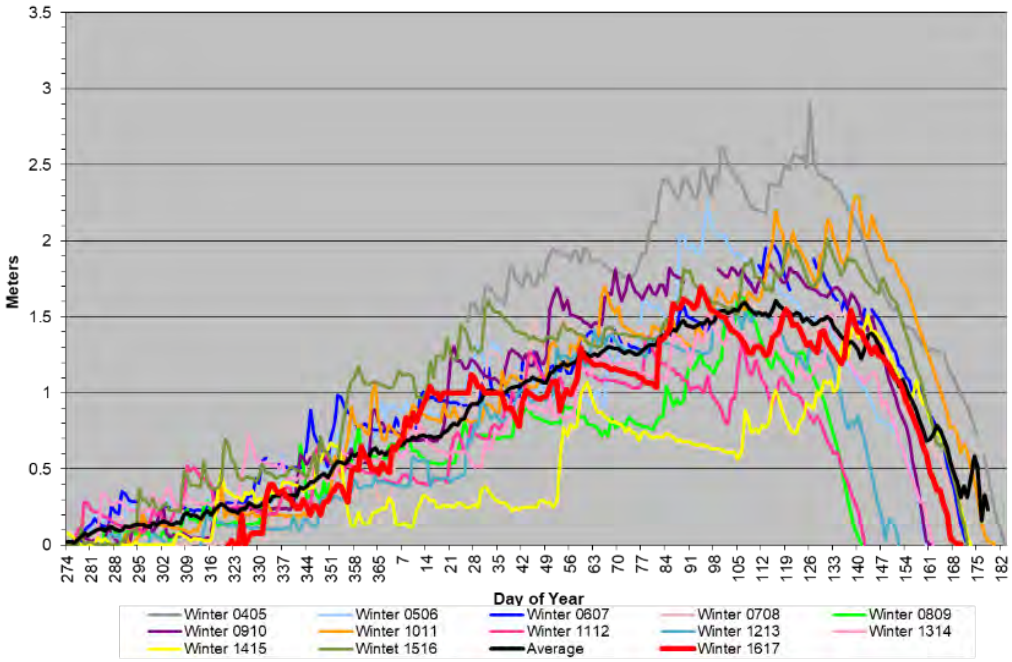


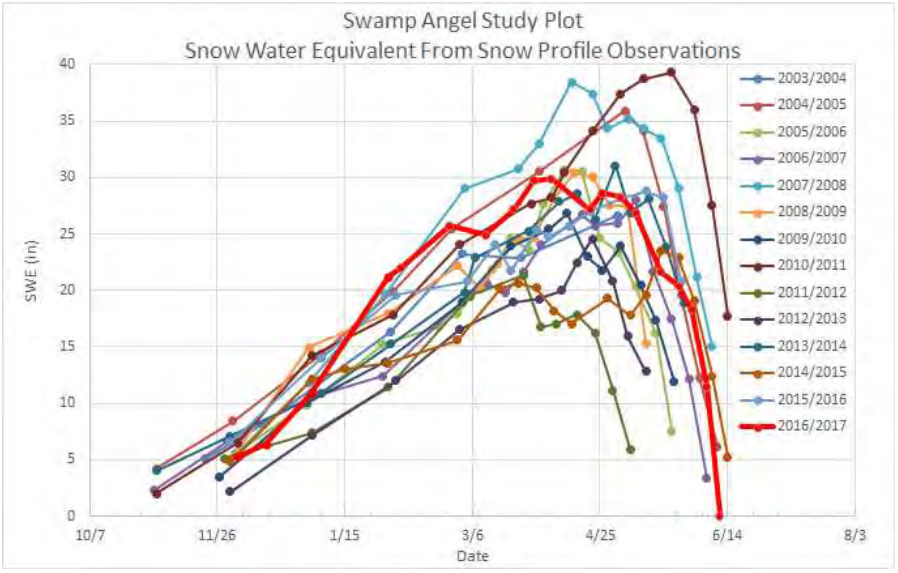


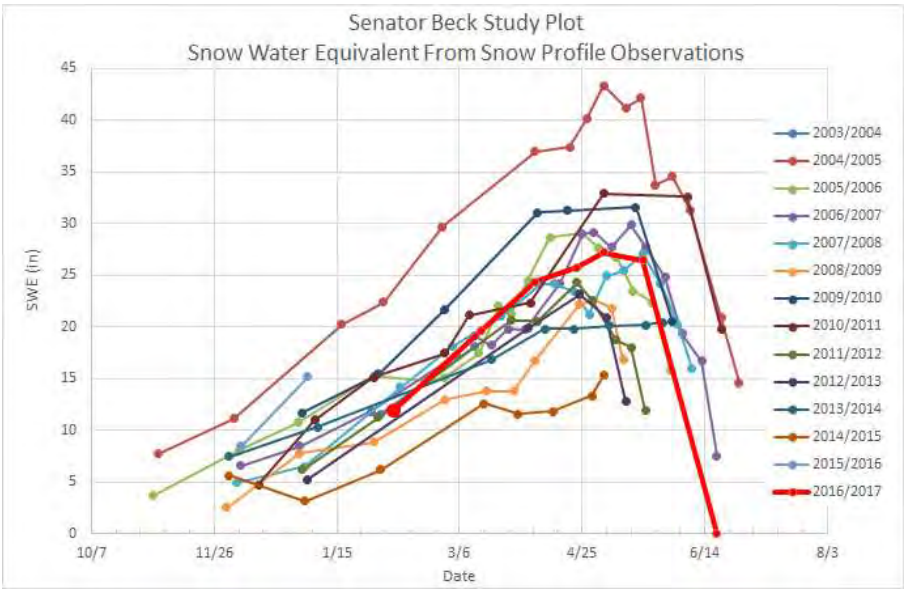
Height of Snow - Swamp Angel Study Plot
as of 2400 hours

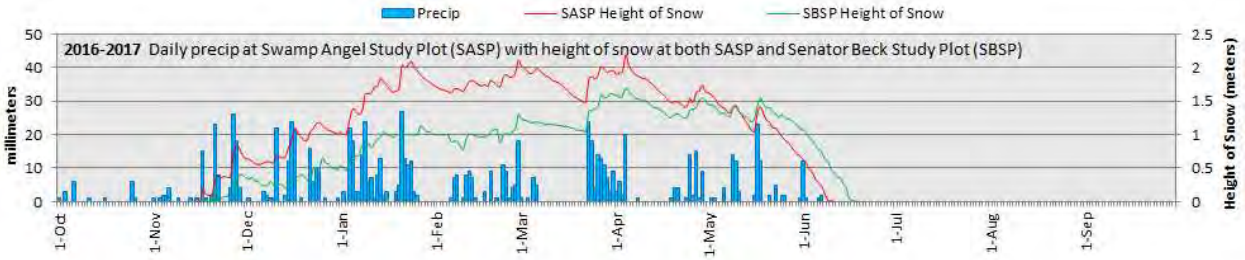


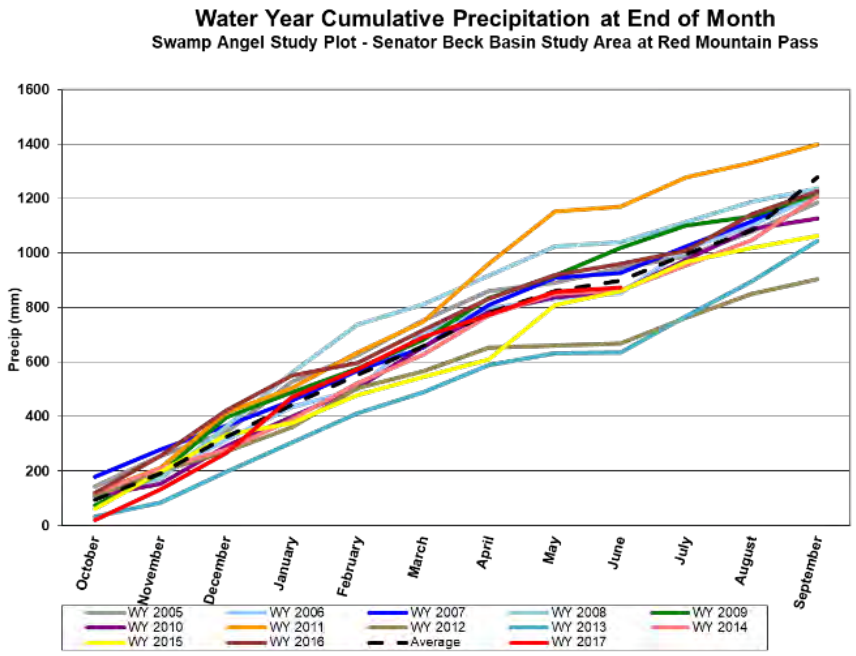
Height of Snow - Senator Beck Study Plot
as of 2400 hours

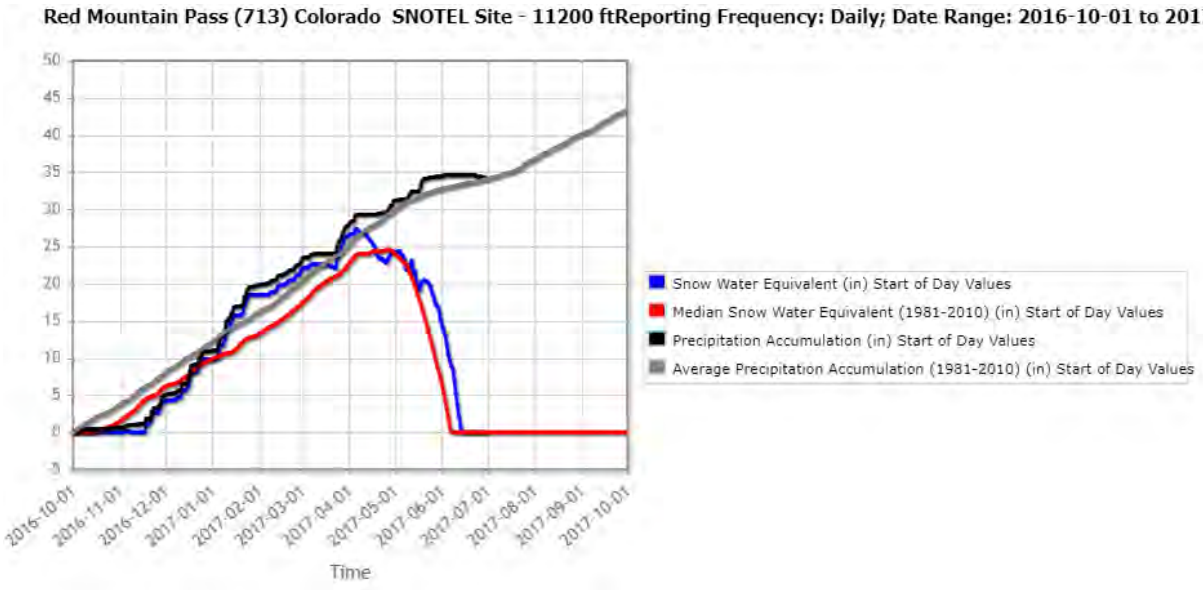



Swamp Angel Study Plot
Snow Water Equivalent From Snow Profile Observations
SWE (in)
Date
0
5
10
15
20
25
30
35
40
10/7
11/26
1/15
3/6
4/25
6/14
8/3
2003/2004
2004/2005
2005/2006
2006/2007
2007/2008
2008/2009
2009/2010
2010/2011
2011/2012
2012/2013
2013/2014
2014/2015
2015/2016
2016/2017


Senator Beck Study Plot
Snow Water Equivalent From Snow Profile Observations
SWE (in)
Date
0
5
10
15
20
25
30
35
40
45
10/7
11/26
1/15
3/6
4/25
6/14
8/3
2003/2004
2004/2005
2005/2006
2006/2007
2007/2008
2008/2009
2009/2010
2010/2011
2011/2012
2012/2013
2013/2014
2014/2015
2015/2016
2016/2017


Precip
SASP Height of Snow
SBSP Height of Snow
2016-2017 Daily precip at Swamp Angel Study Plot (SASP) with height of snow at both SASP and Senator Beck Study Plot (SBSP)
millimeters
Height of Snow (meters)
0
10
20
30
40
50
0
0.5
1
1.5
2
2.5
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep

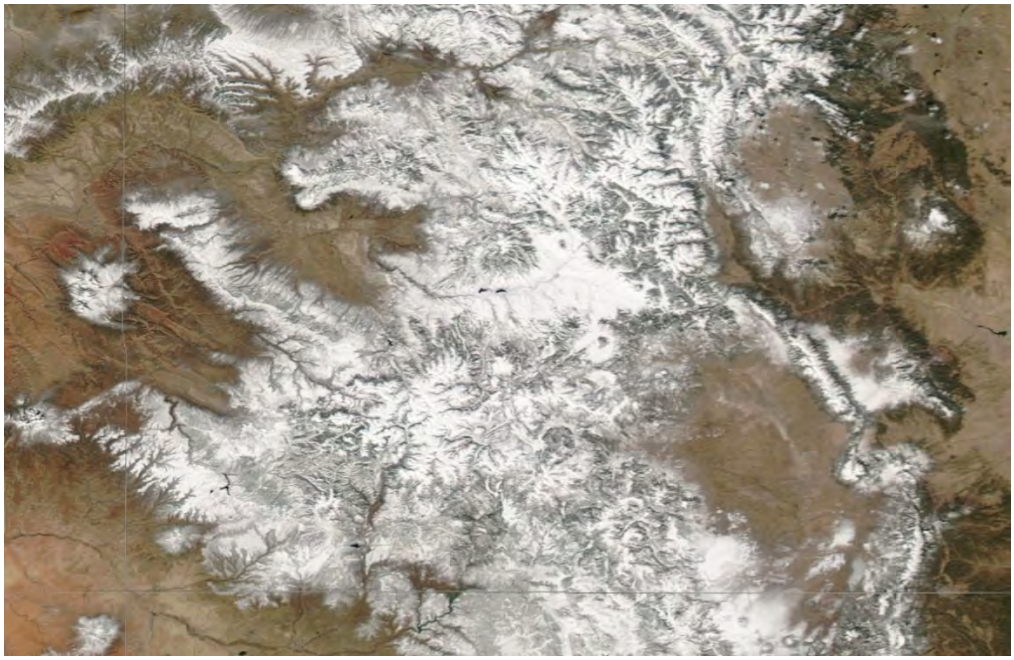




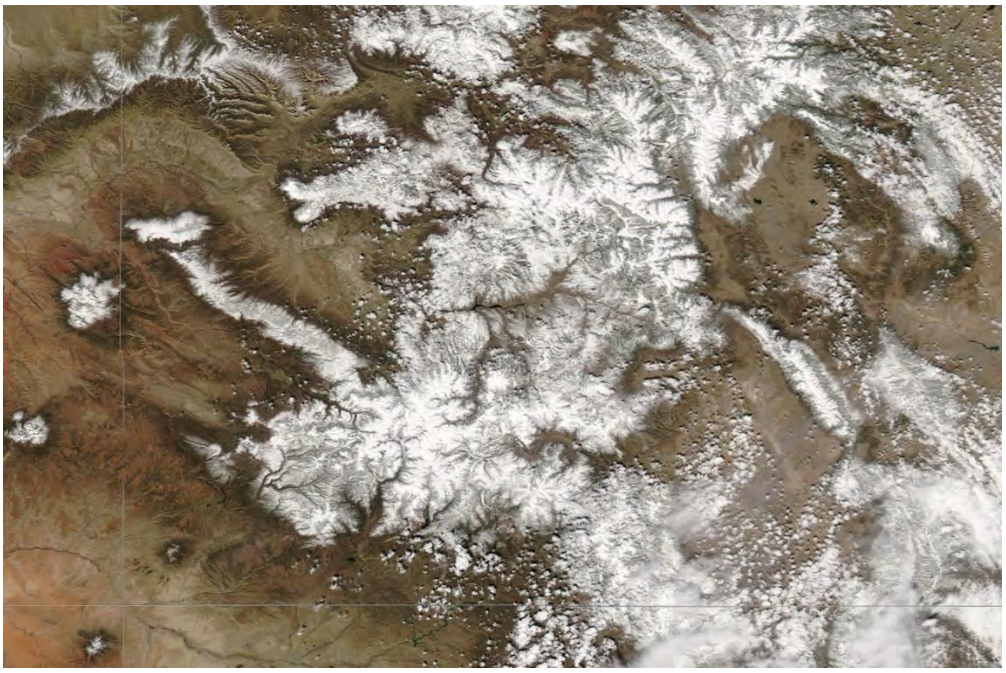
SNOWPACK CONDITIONS

After the wonderfully plentiful snow accumulation we saw the first part of the winter season the snowpack started seeing occasional setbacks from temporary periods of heat and drought. Looking back, around the first week of March most SNOTEL SWE data was showing a peak, following the mid-March drought and beginning the latter part of March snowfall resumed, with another secondary peak occurring around the first week of April at most sites. The first part of April turned dry again, but the latter portion saw a series of storms which gave our snowpack – as seen in the SWE data - a third hump.

As a result of the warm but mostly normal mountain precipitation in February followed by the warmest March on record, the snowpack warmed rapidly and reached isothermal conditions by March 22 at SASP. With this rapid warming and melt at lower elevations – as seen in the hydrographs in the March – it was a concern just how earlier than normal snowmelt might occur. But, with the stormy periods mentioned above, and another cooler/wetter May (the last four years the mountains have seen a cooler/wetter May), that provided additional snow accumulation and temporary albedo resets, cooler temperatures, and overcast conditions that attenuated the amount of solar radiation available going towards warming the snowpack, all of which served to slow snowmelt. In addition, at many locations, there was simply more snow to warm and melt than usual; just considering the SNOTEL stations that CODOS tracks, on average peak SWE was 122% of normal (see table below). Please see MODIS images below showing snowcover depletion between March 2 and March 29.



Snow cover in Colorado on March 2, 2017. Snow cover is widespread following a productive Dec/Jan/Feb.



Snow cover in Colorado on March 29, 2017. Following a dry/hot mid-March, lower elevations and valleys experienced a fair bit of snow ablation.

Summary data for WY2017 at the 15 SNOTEL stations that CODOS monitors. The table shows peak SWE, and calculated from the day of peak SWE, melt rates, days to snow-all-gone, and mean temperature.

CODOS and Other SNOTEL Sites - WY 2017 Snowmelt Season Summary Data								Maximum	
								Maximum	
							Adjusted	5-Day Moving	SBBSA
			%		Post-Peak	Period	Daily	Average of	DOS
	Date	Peak	Median	Days	Added	Mean	Mean Loss	Daily Loss	Post
	Peak SWE	SWE	Peak SWE	to SAG	SWE	Temp C	of SWE	of SWE	Peak SWE
Red Mtn Pass	4/5/2017	27.4	111%	67	5.3	0.2	0.5	1.2	1
Slumgullion Pass	4/7/2017	16.0	109%	47	3.5	1.6	0.4	1.1	1
Upper San Juan	4/9/2017	39.8	123%	57	4.5	4.5	0.8	1.6	0
Wolf Creek Summit	4/6/2017	42.0	119%	72	3.3	5.8	0.6	1.7	1
Beartown	4/9/2017	27.1	114%	54	2.9	1.8	0.6	1.8	0
Lizard Head	3/16/2017	21.8	133%	69	6.6	2.6	0.4	1.2	3
Park Cone	4/8/2017	17.5	173%	43	1.6	3.6	0.4	1.2	1
Schofield Pass	4/8/2017	49.8	148%	71	4.9	4.2	0.8	1.7	1
McClure Pass	3/12/2017	18.1	111%	51	3.1	4.7	0.4	1.1	3
Independence Pass	4/5/2017	16.0	97%	54	4.9	1.8	0.4	1.0	1
Hoosier Pass	5/4/2017	17.2	108%	42	4.8	5.3	0.5	1.2	0
Grizzly Peak	4/7/2017	22.1	129%	64	6.5	3.1	0.4	1.3	1
Berthoud Summit	4/7/2017	18.6	85%	67	7.8	2.6	0.4	1.2	1
Willow Creek Pass	5/4/2017	19.3	133%	37	3.4	6.0	0.6	1.2	0
Rabbit Ears Pass	4/19/2017	38.6	148%	46	9.2	4.2	1.04	1.9	0
Mesa Lakes	4/12/2017	18.9	103%	51	5.5	3.8	0.5	1.0	0
Mean	04/08/17	25.6	122%	56	4.9	3.5	0.5	1.3	0.9
Max	05/04/17	49.8	173%	72	9.2	6.0	1.0	1.9	
Min	03/12/17	16.0	85%	37	1.6	0.2	0.4	1.0	
Range	79	33.8	88%	35	7.6	5.8	0.7	0.9	
Adjusted Daily Mean Loss SWE rates include additional SWE received after date of Peak SWE									
Non-CODOS SNOTEL sites shown in italics									

A summary of WY 2006-2017 snowmelt rates and associated conditions at the 15 SNOTEL stations that CODOS routinely monitors, statewide. Days to SAG refers to the time between peak SWE and "snow all gone" at the SNOTEL sites. Adjusted Daily Mean Loss calculates the rate of snowmelt following peak SWE, including all precipitation received after peak SWE (assumed to be snow). Melt rate tables are presented for each of the 11 CODOS monitoring sites on their webpages.

Aggregated CODOS and Other SNOTEL Sites - Snowmelt Season Summary Data WY 2006 through WY 2017

15 total sites

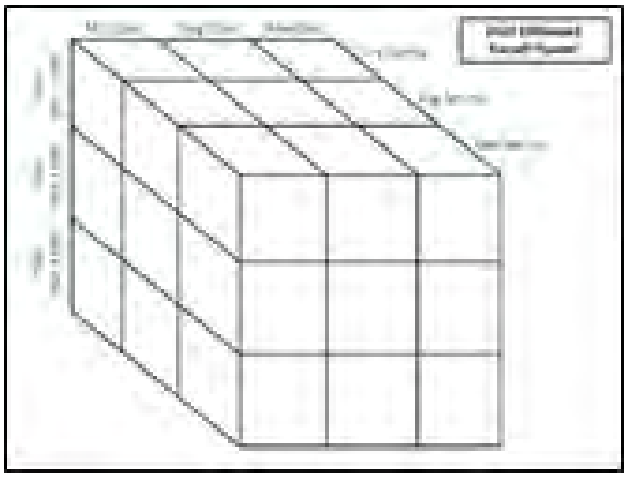
	Group Mean Date Peak SWE	Group Mean Peak SWE	Group Mean Days to SAG	Group Mean Post-Peak Added SWE	Group Mean Adjusted Daily Mean Loss SWE	Group Mean of Max 5-Day Moving Average Daily Loss SWE	Group Mean Period Mean Temp C	Recorded SBB Dust Events
WY 2006	4/11/06	21.0	40	1.8	0.56	1.2	3.4	8
WY 2007	4/18/07	18.0	38	3.2	0.57	1.2	3.7	8
WY 2008	4/18/08	29.3	53	4.0	0.63	1.4	3.4	7
WY 2009	4/17/09	23.7	36	2.7	0.75	1.4	4.4	12
WY 2010	4/16/10	19.6	43	3.3	0.58	1.3	3.1	9
WY 2011	5/3/11	29.0	43	3.7	0.79	1.7	5.3	11
WY 2012	3/21/12	13.6	46	2.3	0.35	0.9	2.8	12
WY 2013	4/23/13	18.0	32	0.9	0.60	0.6	4.4	10
WY 2014	4/14/14	22.9	49	4.6	0.58	1.4	3.4	9
WY 2015	4/12/15	16.1	52	6.5	0.51	1.1	3.6	3
WY 2016	4/20/16	20.7	44	3.8	0.58	1.4	4.1	6
WY 2017	4/8/17	25.6	56	4.9	0.55	1.3	3.5	4
Max	05/03/11	29.3	55.8	6.5	0.8	1.7	5.3	12.0
Min	03/21/12	13.6	32.3	0.9	0.3	0.6	2.8	3.0
Range	43	15.7	23.5	5.6	0.4	1.1	2.5	9.0

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

DUST-ON-SNOW CONDITIONS

DUST ENHANCED RUNOFF CLASSIFICATION:

In Water Year 2015 CODOS introduced a Dust Enhanced Runoff Classification (DERC) approach to linking dust-on-snow, snowpack, and spring weather conditions to patterns in statewide hydrographs within a 3x3x3 Dust Enhanced Runoff Space. The below table presents the final DERC classification of WY2017 parameters at each of the 20 stream gauges monitored by CODOS. Water Years 2006-2017 classifications are contained in Excel workbook Runoff_Space_by_Region_and_WY.xlsx. Another workbook, Runoff_Space_by_Watershed.xlsx, contains individual DERC analyses for WY 2006-2017 for each of the 20 stream gauges.



A conceptual Dust Enhanced Snowmelt Runoff Space integrating the interactions of March 1 SWE, dust intensity, and spring precipitation.

Based on the discussions describing the DERC approach in characterizing the watersheds that CODOS monitors, WY2017 snowmelt season conditions are summarized in the tables below. In broad terms, with local variations, Colorado WY2017 snowmelt runoff behaviors fell into general patterns of “Average Dust” or “Min Dust”, mostly “High" March 1 SWE, and mostly “Dry” spring.

WY2017 DERC matrix classification of factors influencing snowmelt runoff behavior at 20 stream gauges located in watersheds monitored by CODOS.

Distribution of instances within DERC matrix for the Water Year (n = 20 stream gauges)

		Dry Spring	Avg Spring	Wet Spring
LOW March 1 SWE	Min Dust			
	Avg Dust			
	Max Dust			
AVG March 1 SWE	Min Dust		Ya	
	Avg Dust			
	Max Dust			
HIGH March 1 SWE	Min Dust		Fr+Sn+Co	Bl+Ta
	Avg Dust	An+Cr+Do+Ea+Tf+Mu+No +Pl+Ri+Sa+Sm+Su+Un	La	
	Max Dust			

Dry Spring	Avg Spring	Wet Spring
13	5	2
65%	25%	10%

Low Swe	Avg Swe	High SWE
0	1	19
0%	5%	95%

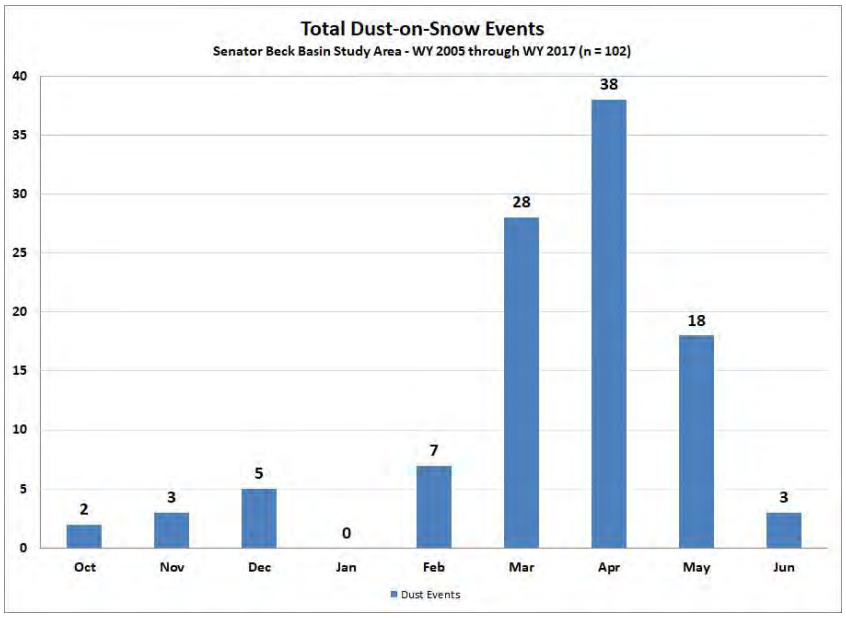
Min Dust	Avg Dust	Max Dust
5	15	0
25%	75%	0%

Key: An = Animas, Un = Uncompahgre, Do = Dolores, Tf = Taylor Fork, Ea = East River, La = Lake Fork, Ri = Rio Grande, Sa = San Juan, Sm = San Miguel
Key: Bl = Blue River, Ta = Tarryall Creek, Sn = Snake River, Fr = Fraser River, Co = Upper Colorado River
Key: Ya = Yampa River, Cr = Crystal River, Mu = Muddy Creek, No = North Fork Gunnison, Su = Surface Creek, Pl = Plateau Creek

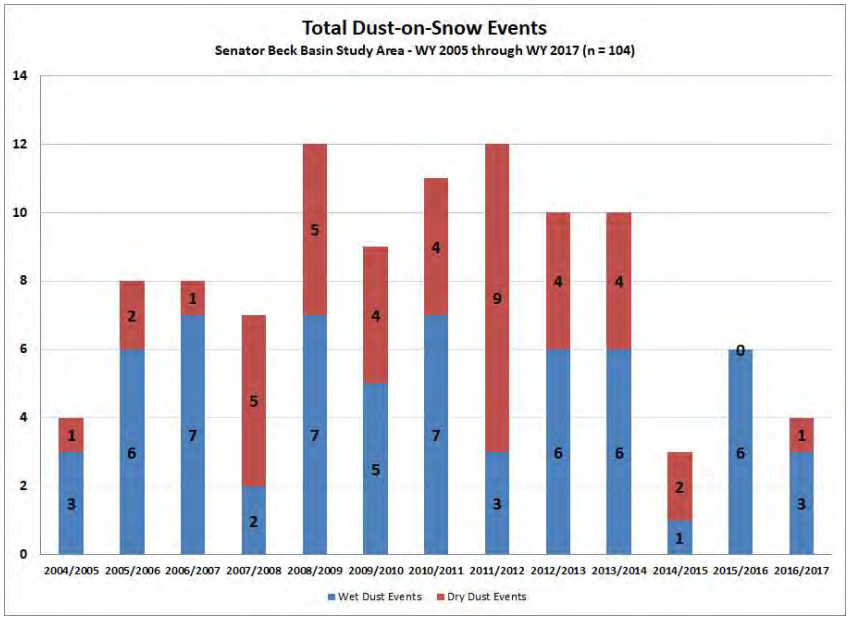
Table below indicates placement of individual CODOS sites for WY2017 within the DERC framework and suggests years with comparable local hydrographs, where applicable.

CODOS Monitoring Site	Dust Event(s) # Observed	Total Dust Severity, to Date	March 1st DERC Classification	DERC Spring Conditions	Water Years with Comparable Hydrographs
Swamp Angel	1-4	Average	High	Dry	’08/’16
Senator Beck	1-4	Average	High	Dry	‘08/’16
Park Cone	1-4	Average	High	Dry	‘14
Spring Creek	1-4	Average	High	Average	---
Wolf Creek	1-4	Average	High	Dry	‘08
Hoosier	1-3	Min	High	Wet	‘15
Loveland	1-3	Min	High	Average	‘07
Berthoud	1-3	Min	High	Average	---
Willow Creek	1-3	Min	High	Average	---
Rabbit Ears	1-3	Min	Average	Average	‘15
McClure	1-4	Average	High	Dry	‘08/’14
Grand Mesa	1-4	Average	High	Dry	---

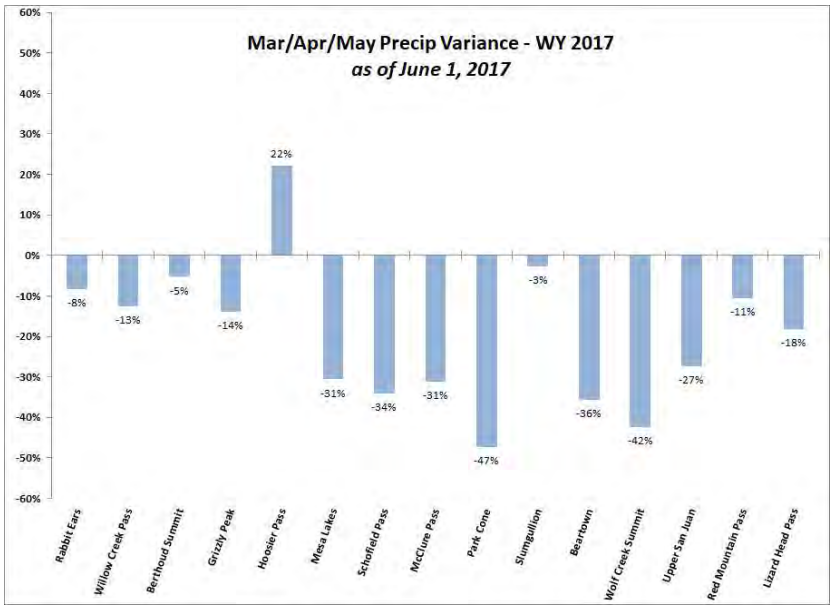
Although SBB only received four dust events, the impacts of the dust on snow albedo and melt rates was more characteristic of an "Average" dust year. Normally, with only four events we would qualify this amount of annual dust as "Minimum." However, with two notable and very visible events (D3 and D4), and measurable decrease in albedo along with significant spikes in streamflow observed when dust emerged on the surface in many areas, we believe that this qualifies as an "Average" year at many locations within the DERC framework, albeit perhaps on the lower side of Average. Areas in the Northern and Eastern mountains saw less dust this year and are classified as having "Minimum" dust severity in WY2017. Rivers such as the Yampa, Fraser, Upper Colorado, Snake, Blue and Tarryall have all seen less significant spikes in streamflow during the melt season, and the surges in melt that have been observed can be closely tied to rapid warming events. While the rest of the state’s rivers have seen increases in discharge during or following significant warming periods, surface dust has driven an acceleration of the melt rates and the presence of dust on the surface is evident in many hydrographs. Below is a hydrograph from the Uncompahgre River near Ridgeway from March 1 through mid-June, indicating occasions when dust was observed at the surface of the snowpack in the Senator Beck Basin. Also, please see the albedo and streamflow plot in “Runoff Behavior” section.



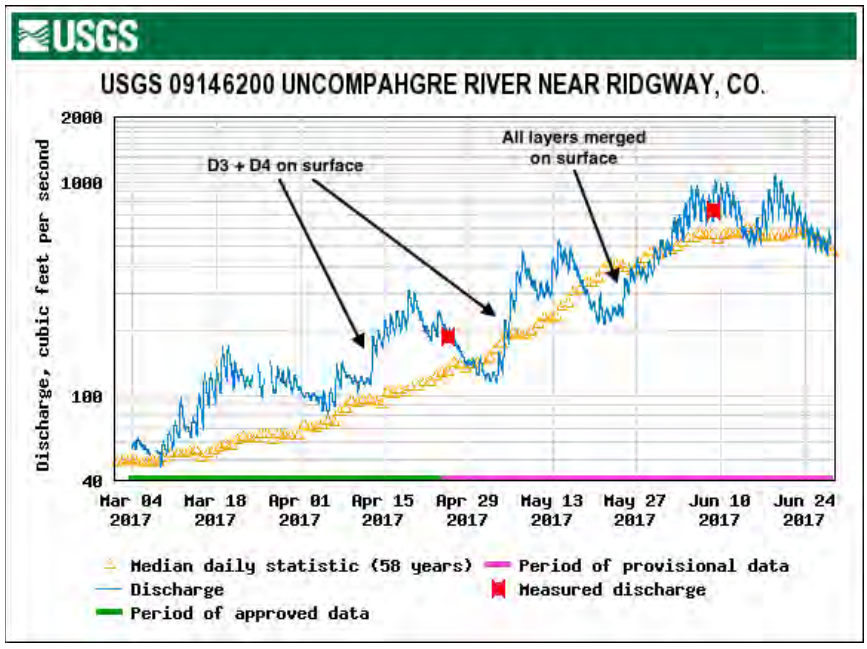
Total dust-on-snow events by month. March begins the more intensive part of dust-on-snow season. In WY2017 all four dust events occurred after March 1st, placing those dust layers within the upper portion of the snowpack.



Total dust-on-snow events by year. Three dust events in 2016/2017 were "wet" events, accompanied with precipitation. One event was "dry", occurring just prior to precipitation.



Variance of combined March, April, and May precipitation as of June 1, 2017, for the fifteen SNOTEL stations adjacent to or near CODOS monitoring sites.



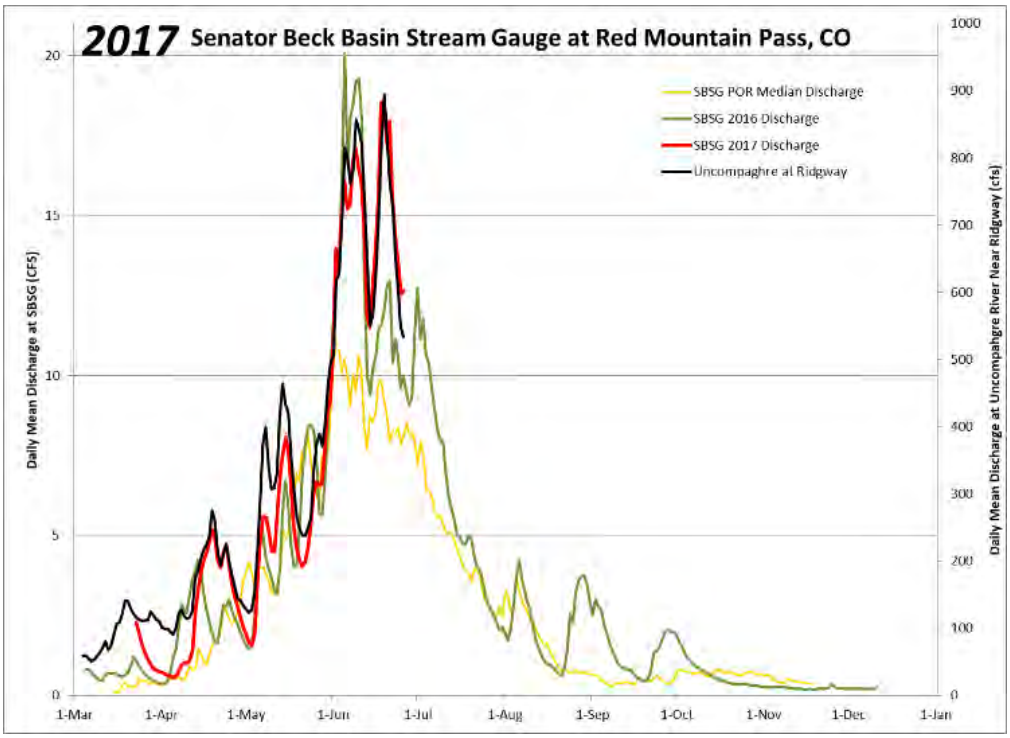
Hydrograph from the Uncompahgre River near Ridgeway from March 1 through mid-June, WY2017. Periods when dust was exposed on the surface and associated surges in discharge are indicated. Dust exposure was determined by visual observation and albedo measurements from SASP and SBSP.

Most of the mountainous parts of the state experienced a dry spring, with many areas receiving less than 70% of their median March-May precipitation. Areas experiencing average years were all below median values as well. The only exception was Hoosier Pass, which received 122% of

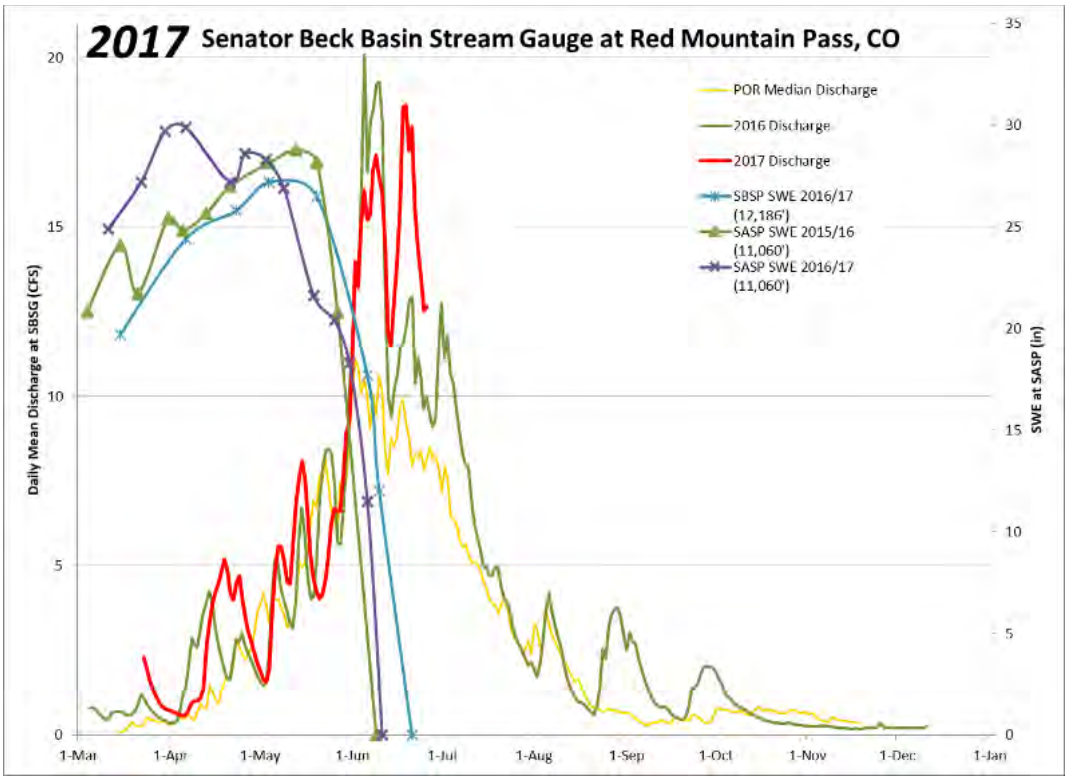
median springtime precipitation. Additionally, almost every site monitored by CODOS met our "high" March 1 SWE requirement of 110% of median March 1 SWE or above. Only Rabbit Ears Pass fell into our "Average" category, with 109% of median March 1 SWE. The take home here is that while Colorado went into the spring with a healthy snowpack, a mostly dry spring combined with, in many places, significant dust driven snowmelt occurred periodically when clear/sunny conditions existed, resulting in periodic rapid snowpack loss seen at a number of stream gauges throughout the state. Peak discharge and snow all gone dates occurred mostly near median timeframes, but earlier than our March 1 snowpack would have suggested in and of itself.

RUNOFF BEHAVIOR

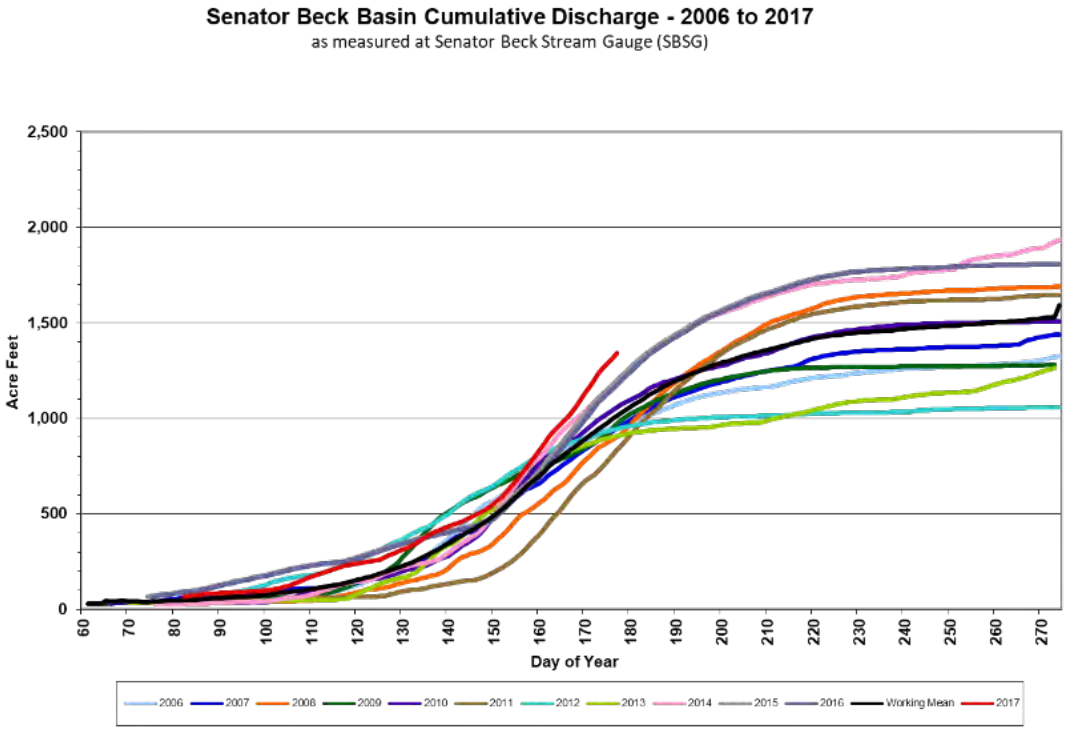
At SBB the beginning of peak discharge began squarely within the median timeframe, towards the end of May, a month that saw cooler/wetter periods. Streamflow appeared to have also peaked nearly within the median timeframe and very similarly to WY2016 as well. However, unlike WY2016 and the typical median scenario, it was the second surge in streamflow that resulted in the snowmelt peak discharge for WY2017. This is likely due to the remaining mid-elevation snow and the abundance of higher elevation snowpack noted in a June 6 CODOS update. While station data at SBSP indicated near average snow height during this period, the landscape as a whole appeared to have a plentiful amount of snow, especially at higher elevations.



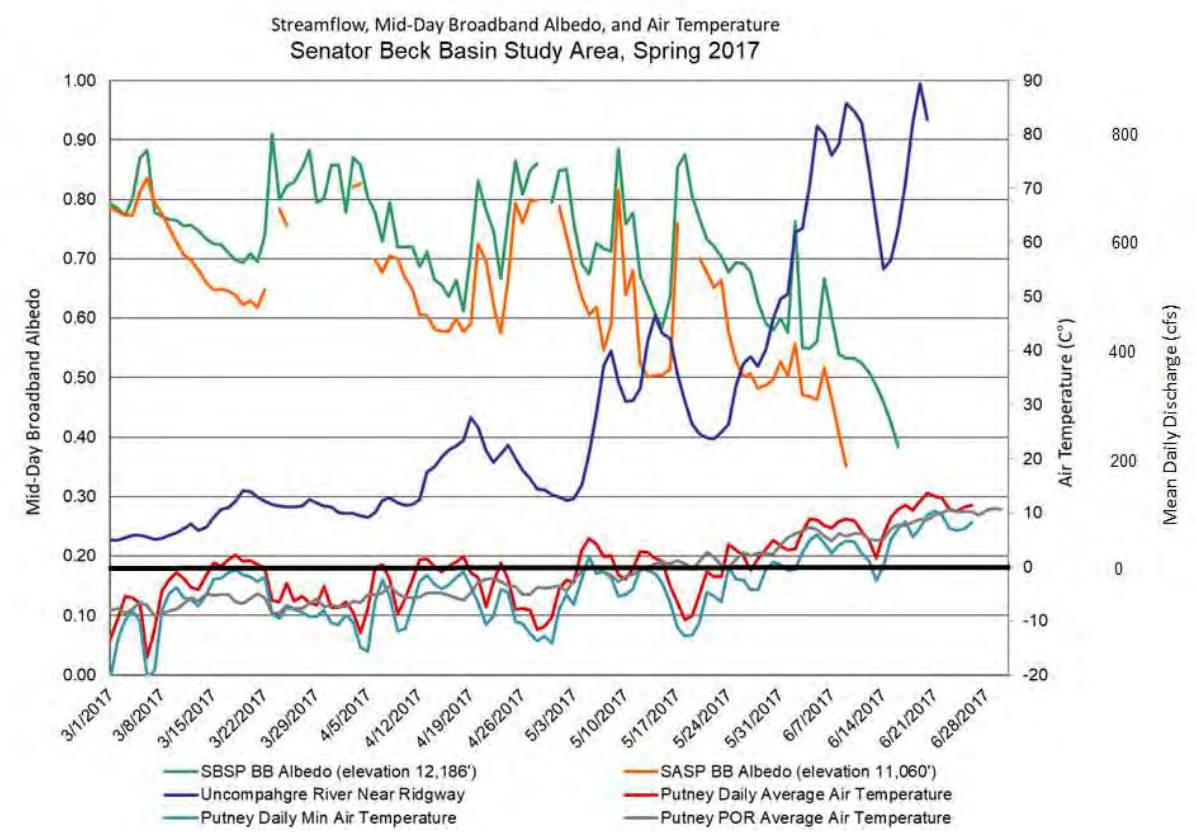
With SBB stream gauge being in the headwaters of the Uncompaghre watershed, it is common for the two stream gauges to track each other closely. Note the bump in streamflow in March due to the hot conditions.



This year at SBB we observed a peak discharge of 18.59 cfs on June 19, this is second to the record peak discharge of 20.07 cfs on June 5, 2016. Peak SWE in WY2017 was 1" greater than in WY2016.



As of early summer cumulative streamflows are greater than previous years.



SBB stream discharge as it relates to albedo (or reflectance) of the snowpack. Much like last year, a series of albedo "resets" occurred throughout May due to precipitation (snow) temporarily covering dust layers, decreasing absorption of solar radiation and slowing snowmelt. These storms bringing precipitation also bring cloud cover and cooler temperatures, slowing energy going towards snow warming and melt. With all dust layers at the surface of the snowpack, along with a stretch of very warm/sunny days, snowmelt kicked into full gear and streamflow rapidly spiked.

LOOKING AHEAD

Much snow is now gone in the San Juan Mountains, and although rivers are still showing some signs of a diurnal snowmelt cycle (running higher in the evenings after a day of melt and lower in the morning after the cooler night) the big spring peak in runoff has come and gone. Currently, essentially all major stream gauges are in the normal range. The mountains are experiencing summertime conditions, with temperatures consistently well above freezing day and night, even at the highest elevations statewide. Streamflow will continue to slowly taper off, with additional spikes during and after big rain events, especially during monsoon season which usually impacts the Southwestern US between mid-August and late September.

There was the usual hype about El Niño Southern Oscilation (ENSO) this past winter and what it would mean for the snowpack. In the end, our ENSO conditions returned to neutral by the height of winter, so impacts were little to none on the seasonal scale. These ENSO neutral conditions are forecasted to remain into the fall, after which the onset of El Niño conditions are expected. While it appears that any El Niño will be weak, we will be closely following these conditions as a strong El Niño often means more precipitation for Colorado. It does appear that we benefited from the lesser-understood and –discussed Pacific Decadal Oscillation (PDO) which is in a positive phase and is thought to have contributed to the significant number of atmospheric river events this year. PDO is a longer term condition, and looking forward there is some hope for a repeat of this winters' isolated drought-busting storms, although in continental (farther inland) areas like CO it is harder to predict these impacts. Despite these conditions, current long-term outlooks are suggesting a warm winter with average precipitation. Forecasting for a winter during the summer before is tricky business, so while we can make some entertaining guesses, in the end we will just have to wait and so how things pan out.

APPENDIX B:

WATER YEAR 2018 SEASON SUMMARY

WATER YEAR 2018 SEASON SUMMARY

Going into Water Year 2018 there was some serious portents due to moderate La Nina conditions combined with, or because of, a strong low pressure in the east and a strong ridge near the West Coast creating a high amplitude "blocking pattern", which usually result in extended periods of dry/warm or cold/wet conditions. For Colorado, it mostly meant dry/warm and storm tracks routed north of Colorado. The result was the season starting out slow, or close to non-existent, with no winter storms observed at Red Mountain Pass by the end of December. By the end of January we saw 3 storms when normally we receive a cumulative total of 12 storms by this timeframe. February was closer to an average month in terms of average precipitation statewide and at Red Mt we documented 5 storms (average for the month is 3.4). March was dismal for most of Colorado except for possibly the Yampa/White which was 85% of normal. April continued the trend in the southern half of the state but very close to average in the Colorado Mainstem, Yampa, and Gunnison. After a productive storm May 1-2, we observed no precipitation for 16 days, then it was only 0.3" over a couple days. Immediately following the May 1-2 storm conditions were ripe for an early and fast snowmelt season; a shallow snowpack, above to above-average dust conditions, and warm/sunny conditions all led to the snow ablation ~5 weeks earlier than normal. With only the one storm the month of May, by the end of the month snow covered area was only ~7%, essentially full ablation. By the end of June we documented 15 winter storms compared to a period of record average of 25.

At CSAS'Senator Beck Basin Study Area (SBB) at Red Mountain Pass, the primary Colorado Dust-on-Snow Program (CODOS) monitoring site, WY2018 produced a total of seven separate dust-on-snow events, about a slightly above average dust loading season based on observations going back to WY2005. The dust season began relatively late in the season since the lack of storm opportunities also meant reduced chances to receive dust-on-snow (DOS) events. But with the Southwest gradually digging its way into an exceptional drought, it was only a matter of time before eventual storms would track through the source region and bring dust to the Colorado snowpack.

Dust-on-snow events occurred on December 21, February 18-19, March 25, April 1-3, April 12, April 17, April 19, and May 12. The first event (D1) was inconsequential since it was deposited on the basal layer of the snowpack. D2, occurring on February 18-19 was about 30" above the ground by springtime and was on of moderate intensity. D3 was light and deposited March 25 as a dry event, without precipitation, on the surface of the snow. D4 was another dry event deposited directly onto D3 from April 1-3. It was slightly stronger than D3, and the two layers combined were very evident on/in the snowpack at SASP. D5 was a major dry event, arriving with high winds on April 12 and followed by ~9" of snow accumulation at SASP. D5 fell on top of D3/D4 which were mostly on the surface of the snow, combining these three dust layers. Both D6 and D7 were of light intensity but since they immediately merged once D7 occurred it made for a heavy-moderate layer. Events D3 thru D7 occurred near peak snow accumulation

and played a consequential role in snowmelt for essentially the entire melt season, which occurred ~ 1 month early and played out quickly especially in Southern Colorado. By late April D3-D7 were fully merged at the surface of the snow and by early May D2 had also merged with these surface layers.

We classified dust severity as "High End of Average" in SBB. All layers made for a very dirty dust-on-snow season but not quite enough to be a "Maximum" dust loading year. Northern and Central CODOS sample sites in Colorado were classified as "Average" dust severity. Besides Grand Mesa which was also considered "High End of Average", dust loading in Central/Northern Colorado were classified as "Average".

This Season Summary will often reference or link to snowpack, streamflow, weather, and climate products generated by the NRCS SNOTEL program, USGS National Water Information System, and NOAA National Weather Service and Climate Prediction Center respectively, as presented and archived on CODOS monitoring site webpages, http://www.codos.org/#codos and https://snowstudies.org/.

MONTHLY WEATHER CONDITIONS

October-December Weather Summary

The fall saw minimal snowpack building with more rain than snow at the Swamp Angel Study Plot. November and December were both the driest on our record overall with 0.7" (17 mm) and 0.83" (21 mm) of precipitation respectively. October was the first October on our record with no snow (we received 1.7" (44 mm) of precipitation total, all as rain). On average the Senator Beck Basin receives 8 winter storm events during this three month period, while this year we received none, making this year our latest-to start winter on record as well. The small amount of snow which did fall during these months was subject to heavy metamorphism, becoming large facets before being buried fully in January. On December 21 we received a minor dust event, noticeable only after weeks of metamorphosing with the basal snow layer. But since this dust was located at the base of the snowpack it was inconsequential influencing spring snowmelt.

January Weather Summary

In January the San Juan Mountains finally started to build the winter snowpack. There were three winter storms during the month, the first of the season to meet CSAS criteria to be classified as winter storms. The heavily metamorphosed early season snow, which had been sitting exposed to primarily clear and dry weather, was buried, creating a layer of basal facets which persisted through the rest of the winter. Total precipitation was 3.9" (99 mm), well below the monthly average of 4.6" (118 mm), which brought the year-to-date precipitation to 7.1" (181 mm) (the water year begins October 1). This year-to-date total was a miserable 41% of average for that date (17.4" (442 mm) is the CSAS average for WY2004 – 2017). Once again, the San Juan's remained dust free for the month of January, continuing the perfect record of never having a January dust storm in our period of record.

February Weather Summary

For the first month of the winter season, February saw above average precipitation with 4.9" (125 mm) of water making it 113% of the CSAS average. We received 5 winter storms by CSAS criteria. None of these were major drought busting events, but the consistent snowfall made February our most significant snowpack-building month of the year. We ended February with 12" (306 mm) of year-to-date precipitation, which is 57% of average for that date. While this number is still distressingly low, it was a welcome uptick from the end of January a month prior. On February 18th the San Juans also received the first notable dust event of the season. D2 was a wet event which was very diffuse within new snow. The layer became far more visible as the snow settled during the spring.

March Weather Summary

March saw only three more storms in the San Juans with just 2.6" (65 mm) of precipitation at Swamp Angel, 63% of the CSAS March average. March was also warm, with long stretches of warm sunny weather between storms, especially during the first half of the months when we received almost no precipitation. Snowpack continued to increase, although only moderately. The San Juans saw the third dust event of the season on March 25-26, which was the most significant dust loading event up to this point. March ended with 14.6" (371 mm) of cumulative water year precipitation, which is only 58% of average for the date, maintaining the low cumulative snowpack that characterized the entire season.

April Weather Summary

After February, April was our second biggest month for precipitation of the winter. With 4.4" (112 mm) of precipitation we received 93% of average precipitation for the month. April was yet another warm month, resulting in more than an average amount of precipitation falling as rain (estimated 16mm). We only received 3 winter storms during the month, as well as other scattered smaller amounts of precipitation, which we saw on 15 of the 30 days of the month in at the Swamp Angel Study Plot. We also had our biggest dust month of the year. Four events, with two of them bringing a significant dust load, were recorded in the Senator Beck Basin. Several events were dry and remained on the surface, accelerating snowmelt. Additionally, snowpack at Swamp Angel was Isothermal early in the month and was ripe for melting when temperatures were warm and dust was on the surface. All of this came together to see notable snowpack losses throughout the month, despite having the second most precipitation of any month this year. April ended with 483mm of cumulative water year precipitation, which is just 64% of average for the date, and continuing the low snow year we have been experiencing all season.

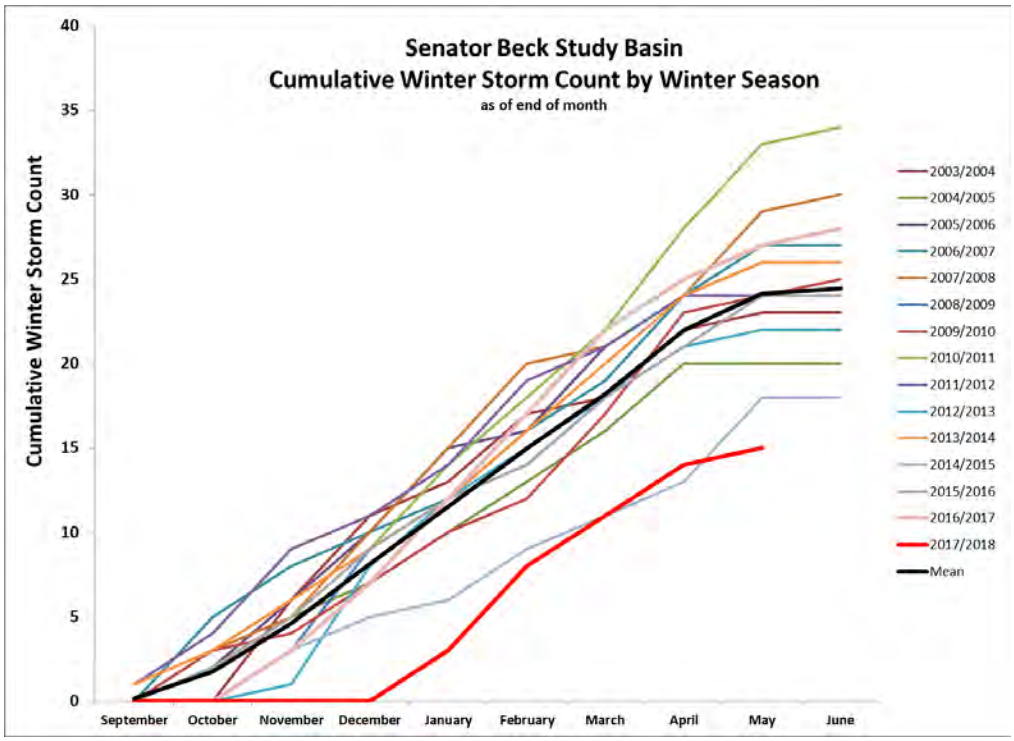
May:

After a productive storm May 1-2, we observed no precipitation for 16 days, then it was only 0.3" over a couple days. Immediately following the May 1-2 storm conditions were ripe for an early and fast snowmelt season; a shallow snowpack, above to above-average dust conditions, and warm/sunny conditions all led to the snow ablation ~5 weeks earlier than normal. With only the one storm the month of May, by the end of the month snow covered area was only ~7%, essentially full ablation.

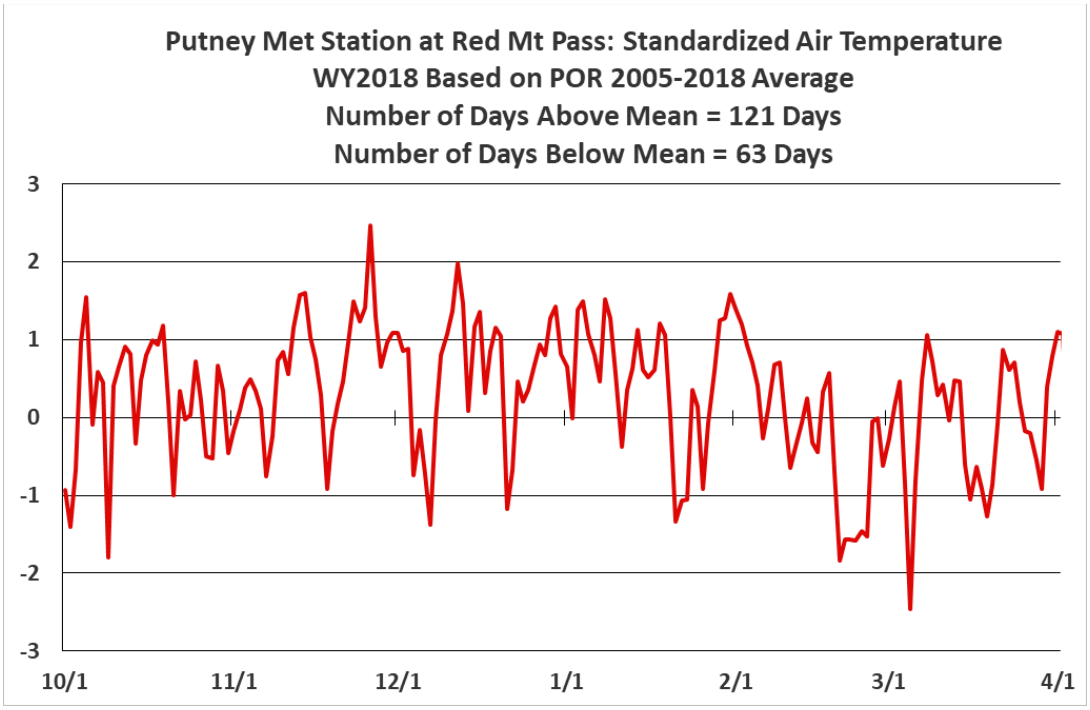
SENATOR BECK STUDY BASIN DATA

This section describes conditions and data collected by the Center for Snow and Avalanche Studies at our Senator Beck Basin Study Area (SBB) at Red Mountain Pass under our Mountain System Monitoring program, which includes the CODOS program. At SBB, snowpack, weather, soils, and radiation conditions are monitored and measured at the well-sheltered subalpine Swamp Angel Study Plot (SASP, 11,060') and at the more exposed, alpine Senator Beck Study Plot (SBSP, 12,180'). Nearby, wind speed, wind direction, air temperature, and humidity data are collected at the Putney Study Plot (PTSP, 12,323'), located to minimize the influence of local terrain on those measurements. Finally, SBB streamflow discharge is continuously measured at the SBB pour point at the Senator Beck Stream Gauge (SBSG, 11,030'), in a broad-crested, notched weir. In terms of snowpack, snow profiles (where we collect SWE, grain type/size, density, layers, and dust information) are conducted every 7-10 days at SASP and as often as possible at SBSP. In addition, both SASP and SBSP stations are equipped with an automated SR50 snow depth sensor.

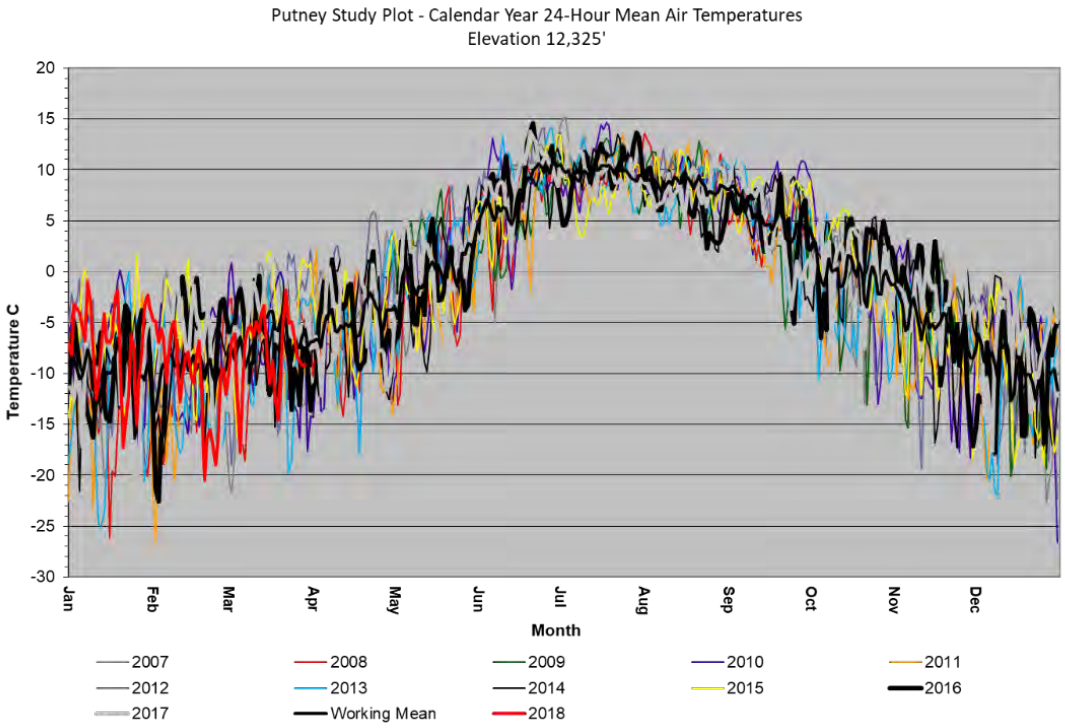
What is notable about air temperatures this season was the extended periods of warmer than average temperatures, while colder than average temperatures tended to be more short lived (please see standardized air temperature graph below). The winter did not really start until well into January, that is when we recorded our first winter storm of the season. By the end of January we had received 3 winter storms, the average is 12.



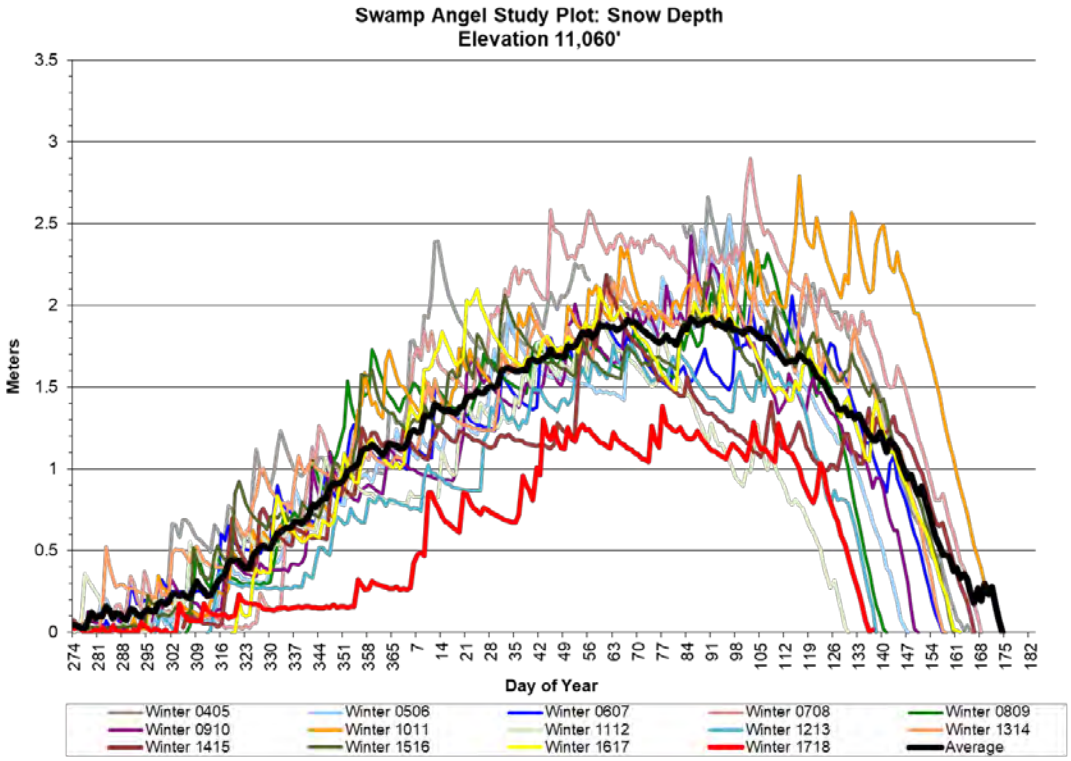
We received no winter storms until January. By the end of January we recorded 3 winter storms, the average is 12. Total, we received 15 storms this season. The average for our period record is 25.



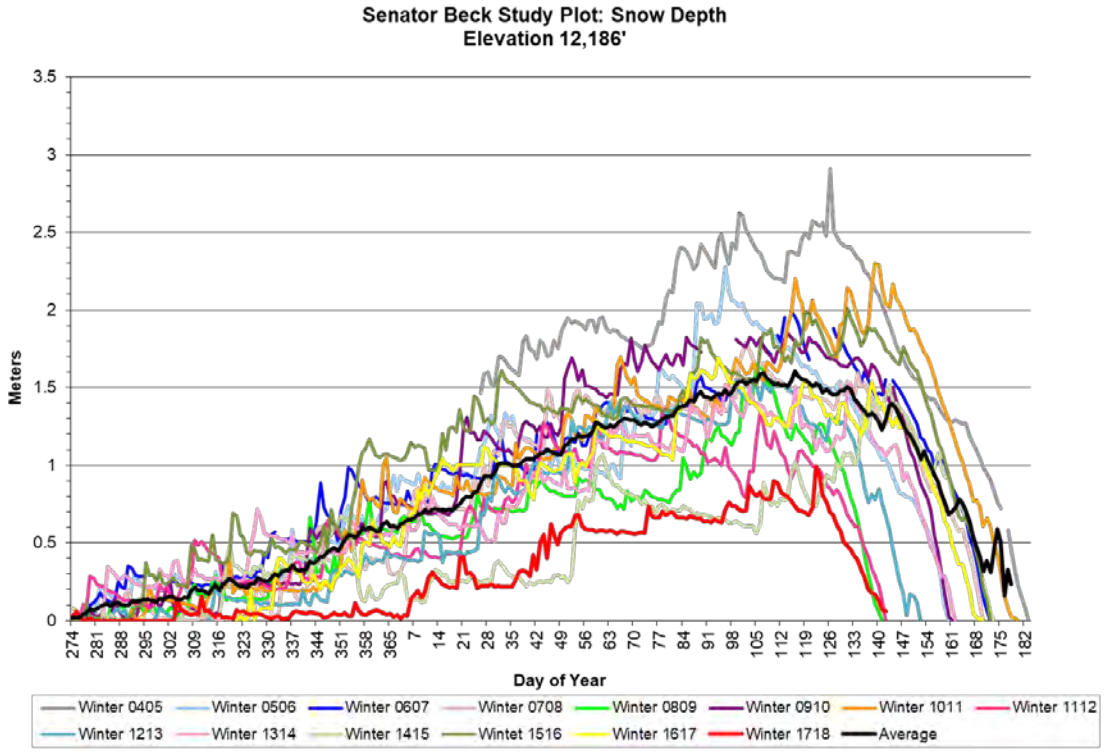
Air temperatures were consistently higher than average this winter. Cold periods were short lived downward spikes.



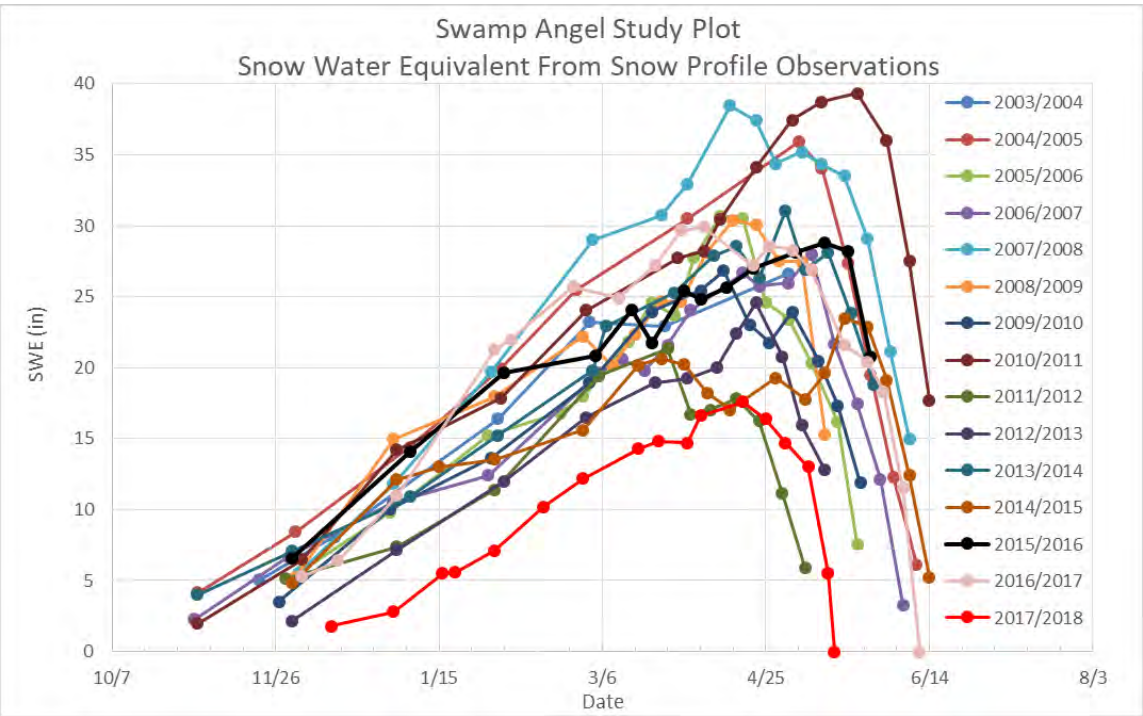
Air temperature plot comparing WY2018 with years in period of record.



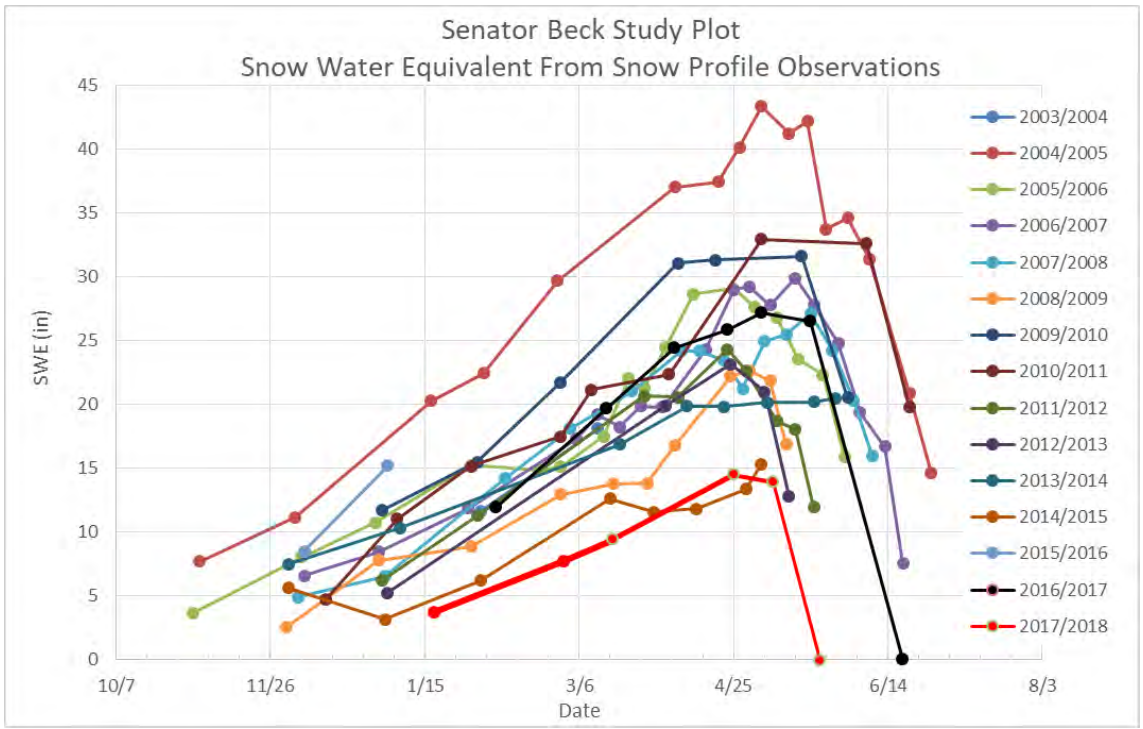
WY2018 was shallowest snowpack in our period of record.



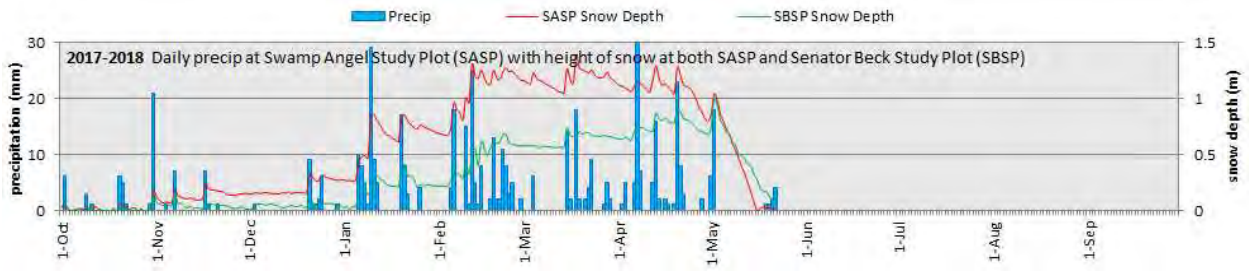
Higher elevations also received little snow accumulation in WY2018.



In terms of SWE, WY2018 is on par with WY2002.



Snow ablated over a month early at Senator Beck.

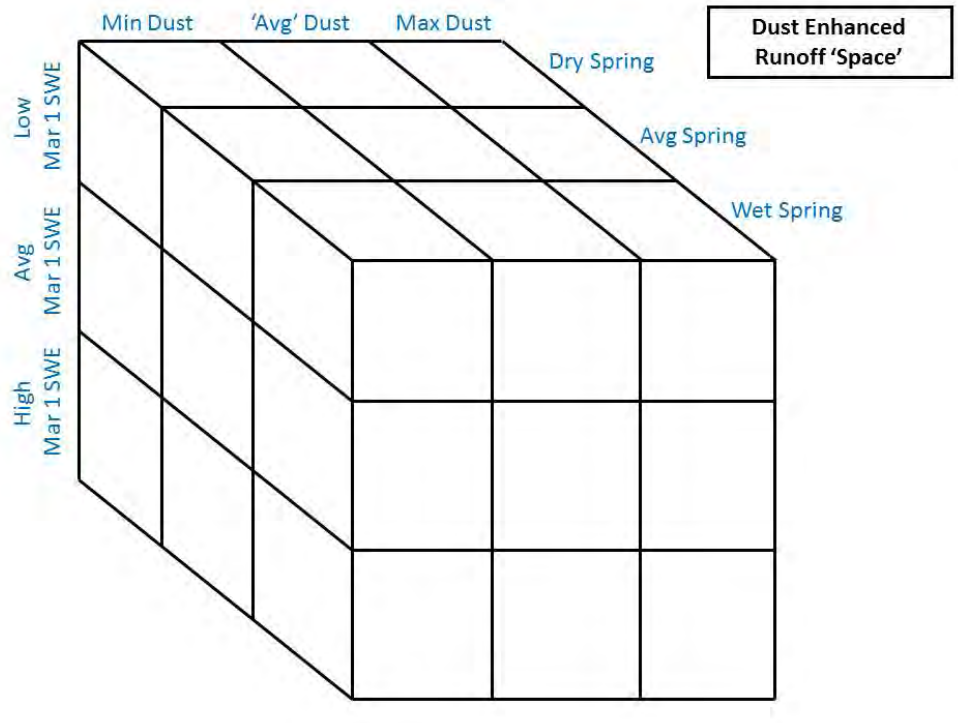


Only the month of February and April were near average precipitation.

DUST-ON-SNOW CONDITIONS

DUST ENHANCED RUNOFF CLASSIFICATION:

In Water Year 2015 CODOS introduced a Dust Enhanced Runoff Classification (DERC) approach to linking dust-on-snow, snowpack, and spring weather conditions to patterns in statewide hydrographs within a 3x3x3 Dust Enhanced Runoff Space. The below table presents the final DERC classification of WY2018 parameters at each of the 20 stream gauges monitored by CODOS. Water Years 2006-2018 classifications are contained in Excel workbook Runoff_Space_by_Region_and_WY.xlsx. Another workbook, Runoff_Space_by_Watershed.xlsx, contains individual DERC analyses for WY 2006-2018 for each of the 20 stream gauges.

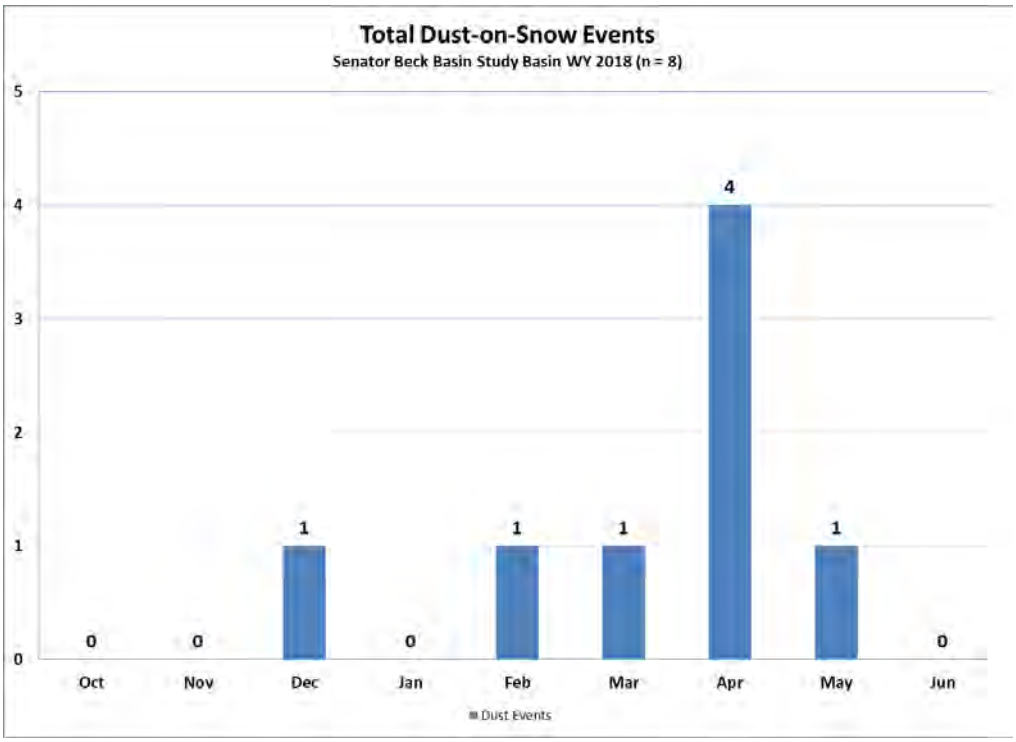


A conceptual Dust Enhanced Snowmelt Runoff Space integrating the interactions of March 1 SWE, dust intensity, and spring precipitation.

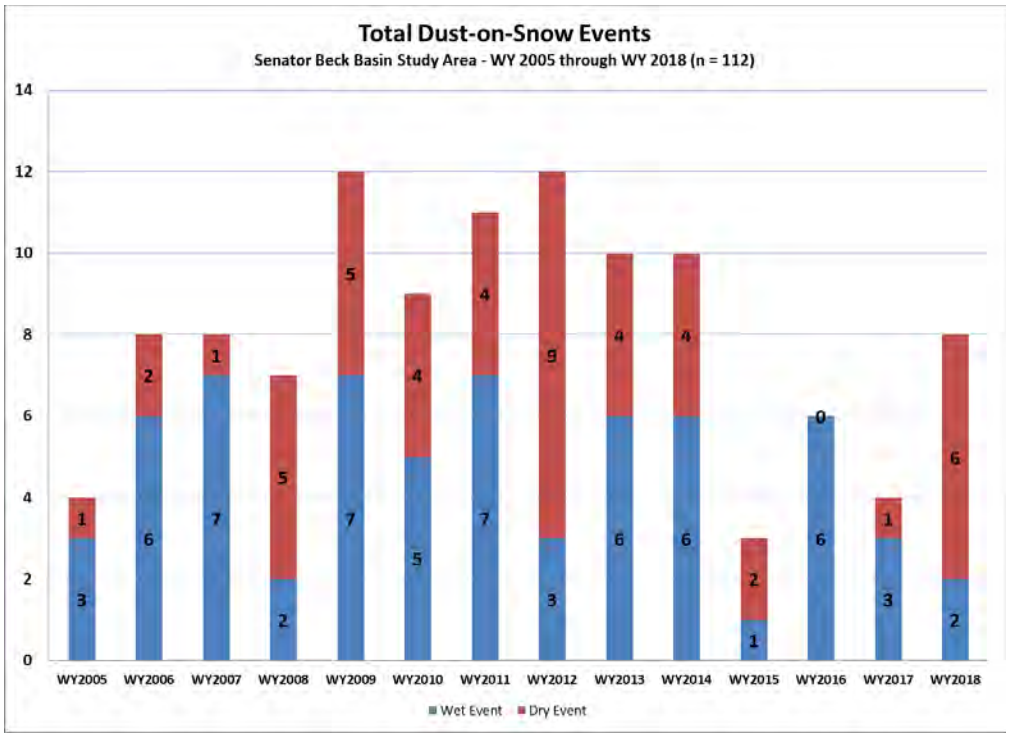
Based on the discussions describing the DERC approach in characterizing the watersheds that CODOS monitors, WY2018 snowmelt season conditions are summarized in the tables below. In broad terms, with local variations, Colorado WY2018 snowmelt runoff behaviors fell into general patterns of “Average Dust” or “High-End of Average Dust”, mostly “Low" March 1 SWE, and mostly “Dry” spring.

Table below indicates placement of individual CODOS sites for WY2018 within the DERC framework and suggests years with comparable local hydrographs, where applicable.

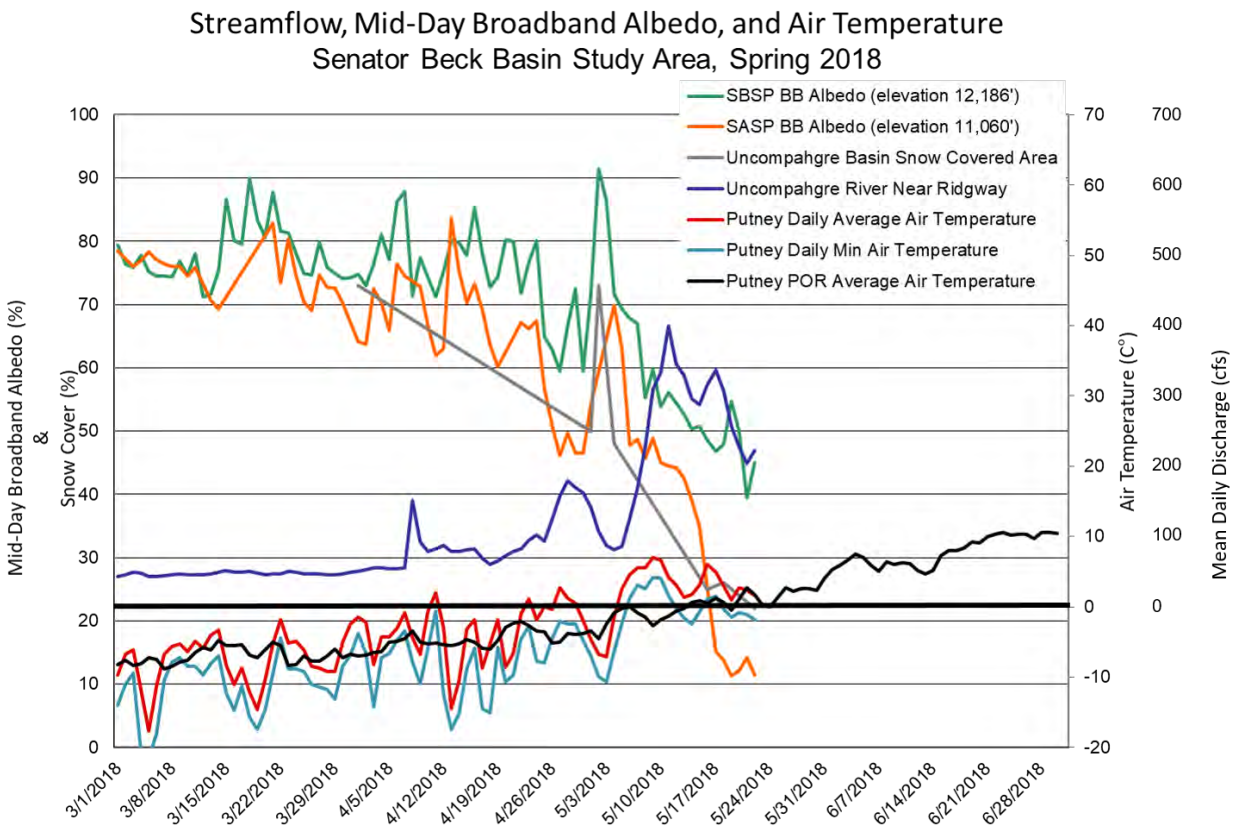
CODOS Monitoring Site	**Dust Event(s) Observed**	**Total Dust Severity, to Date**	**March 1st DERC Classification**	**Current DERC Spring Conditions**	**Water Years with Comparable Hydrographs**	**Total SWE (in)**	**Average Snowpack T° (C°)**
Swamp Angel	1-7	Average	Low	Dry	*’12 (’13)*		0
Senator Beck	1-7	Average	Low	Dry	*’12 (’13)*	--	0
Park Cone	1-5 (6/7?)	Average	Low	Dry	*’12* ***(‘07/’13)***	8.2	0
Spring Creek	1-5 (6/7?)	Average	Low	Dry	***‘13***	4.5	0
Wolf Creek	1-5 (6/7?)	Average	Low	Dry	***‘13***	11	0
Hoosier	1- 3, 5 (6/7?)	Average	Average	Average	***‘10/'12***	15.5	-0.7
Grizzly	1-3, 5 (6/7?)	Average	Average	Average	*‘15/’16*	18.8	-0.3
Berthoud	1-3, 5,(6/7?)	Average	Low	Wet	*‘12*	19.4	-0.3
Willow Creek	5 (6/7?)	Average	High	Wet	*‘11/’14* ***(08'/'16)***	8.7	0
Rabbit Ears	1-5 (6/7?)	Average	Low	Wet	***‘10/'13***	32.4	0
McClure	1-5 (6/7?)	Average	Low	Dry	*‘12*	0	NA
Grand Mesa	1-5 (6/7?)	Average	Low	Dry	*’12* ***(07/’13)***	12	0



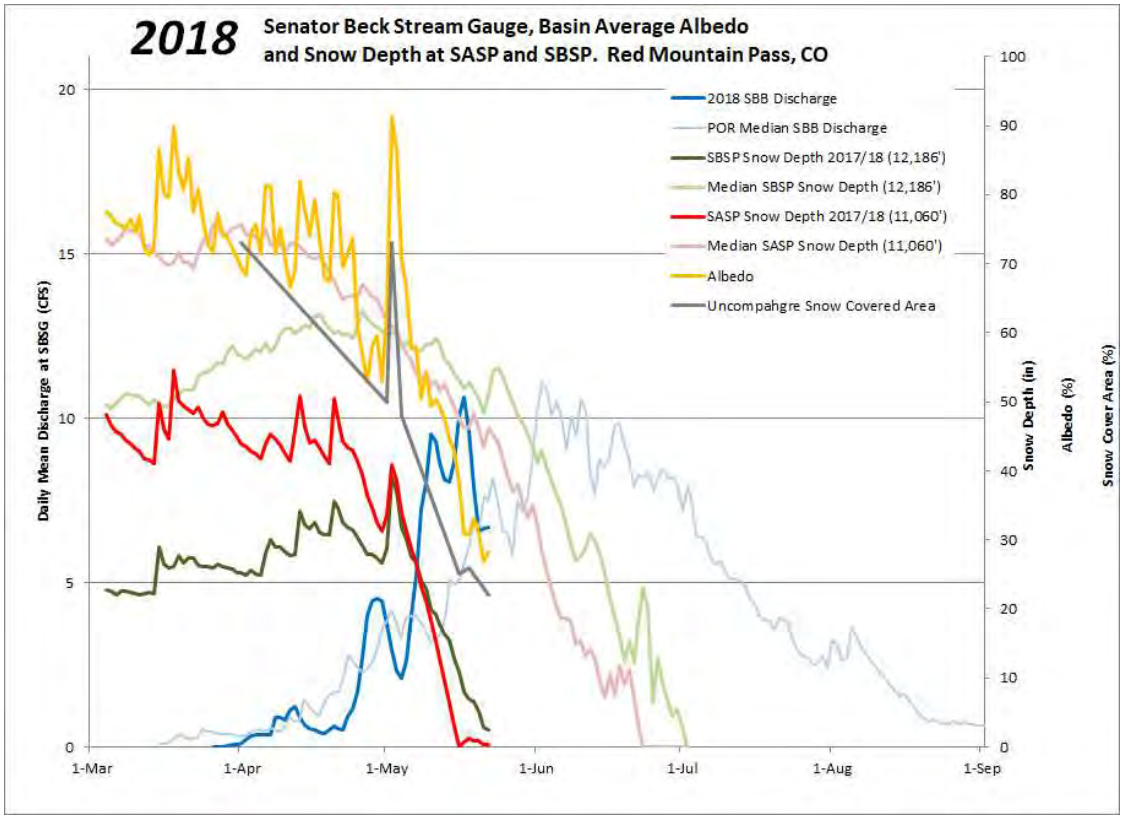
Total dust-on-snow events by month. March begins the more intensive part of dust-on-snow season. In WY2018 dust layers were located within the upper portion of the snowpack.



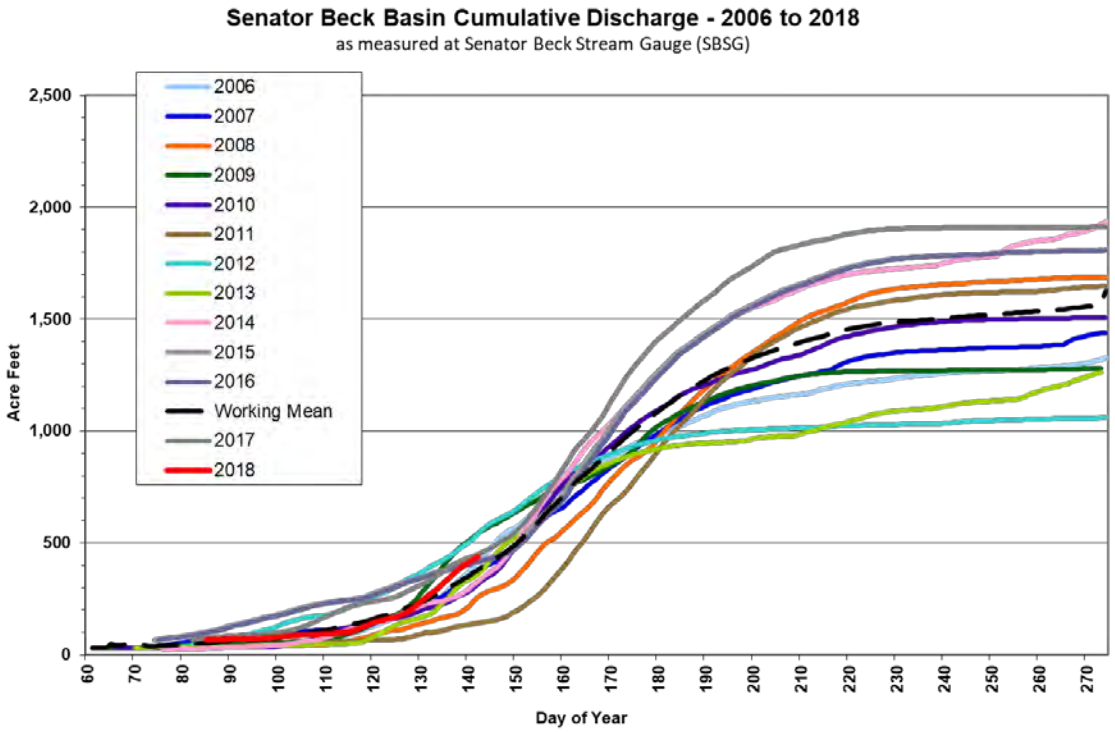
Total dust-on-snow events by year. Two dust events in WY2018 were “wet” events, accompanied with precipitation. Six events were “dry”, occurring just prior to precipitation.



Plot shows albedo at Senator Beck with streamflow and air temperatures. SBB stream discharge as it relates to albedo (or reflectance) of the snowpack. A series of albedo "resets" occurred throughout May due to precipitation (snow) temporarily covering dust layers, decreasing absorption of solar radiation and slowing snowmelt. These storms bringing precipitation also bring cloud cover and cooler temperatures, slowing energy going towards snow warming and melt. With all dust layers at the surface of the snowpack, along with a stretch of very warm/sunny days, snowmelt kicked into full gear and streamflow rapidly spiked.



This year at SBB we observed a peak discharge of 10.64 cfs.



As of early summer cumulative streamflows are greater than previous years.