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# Dirty Snow: Documenting the 2009 Dust Storm Events in Colorado's San Juan and Elk Mountains with Repeat Photography and Historical Snow Pack Data

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## ABSTRACT

In early spring 2009, a succession of five storm systems moved out of the Pacific Northwest and into the desert Southwest region of the United States. In particular, the 4 April 2009 storm system brought strong dynamics at all atmospheric levels including a 97mph wind speed maximum at 500mb, and maximum surface wind gusts up to 84mph. The 4 April storm system was the first storm of the series to entrain desert dust and deposit it onto the deep April snowpack of the San Juan and Elk Mountain ranges of western and southwestern Colorado. SNOTEL (SNOw TELemetry) data from 32 sites across those mountain ranges were examined to assess the rate of snowmelt at least one month earlier than 30-year historical records indicate in association with the storm-deposited dust.

In this article we present meteorological data, snow pack data, streamflow data, and repeat photography of high mountain basins during the summer months to demonstrate that the events of 2009 exhibited an accelerated rate of snowmelt and a much earlier melting of snow cover from year-to-year changes in large-scale weather patterns. This includes radiative forcing by desert dust deposits as a snow-melt contributing factor over prior years of the past decade, particularly 2005 and 1999.

## 1. Introduction

On a recent climb to the highest peak in the San Juan Mountains of Colorado in June of 2009, one obvious part of the climb could not be ignored. Snow fields of the upper Nellie Creek basin on the east slopes of Uncompaghre Peak (14,309'/4361m) were tinted brown and remaining snow was covered in brownish-red dirt, dust, and soil particles. The simple explanation is that abnormally windy spring storm systems deposit desert dust across Colorado's high mountains. The phenomenon has happened naturally through time, becoming more prominent in recent decades due in part to large scale grazing and agriculture in the southwest, as

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well as expansion of recreational use on the Colorado Plateau, which erodes desert soils (Belnap and Gillette, 1997; Reynolds et al., 2001; Neff et al., 2005, 2008; Tanaka and Chiba, 2006; Wells et al., 2007). Some of the dust may originate from across the Pacific from the Gobi and Taklimakan deserts in China, and it has been suggested that the intensity of those dust storms has increased since 1990 (Liu and Diamond, 2005; Wells et al., 2007).

The primary effect of dust on snowpack is increased melting from heat absorption. Snow has the highest albedo of any naturally occurring surface on Earth (Conway et al., 1996; Painter et al., 2007; Gabler et al., 2009). Dust causes the snow to exhibit a decreased albedo (especially from visible wavelengths) and thus absorbs more solar radiation than pure white snow, causing a rapid meltdown of the snowpack (Warren and Wiscombe, 1980; Conway et al., 1996). Dust has a negative effect not only on the snowpack but on the entire watershed. In heavy snow years like the winter of 2008-2009, dust-covered snow may cause flooding problems especially in locations accustomed to seeing peak meltwater flows in rivers during the June instead of May. In fact, recent trends and investigation of radiative forcing by desert dust deposits on mountain snow in the San Juan Mountains reveal shortened snow cover duration by one month in years 2003-2006 (Painter et al., 2007; Steltzer et al., 2009). In combination with warm spring temperatures, low snow years, and especially year-to-year changes in large-scale weather patterns, dust can help contribute to premature and accelerated meltdown leading to drier than normal soil conditions during the later part of July and August (Neff et al., 2008). Furthermore, according to anecdotal evidence, historical research, and recent observations related to the timing of phenological events (Steltzer et al., 2009), the San Juan Mountains receive multiple dust deposition events annually in February through May, arriving before and during the snowmelt period (Painter et al., 2007). Therefore, it is logical that dust is affecting the spatial and temporal pattern of snowmelt.

Increased dust deposition means concerns for popular recreational activities such as spring skiing, whitewater rafting/kayaking, and hiking. The rapid melting of snow could have a significant impact on the local rafting and fly-fishing companies who rely on historical river flows to keep their businesses running for the entire summer. Dust can accelerate the melt of a deep spring snow pack while also phenologically impacting summer wildflower populations if meltwater dries up early. Some flowers may bloom earlier in the summer or not be seen at all.

In April and May of 2009 desert dust was deposited onto the San Juan and Elk Mountain range's snowpack, causing an increased level of heating from solar radiation to occur on the surface of the snow and a reduced albedo, thus apparently accelerating the snowmelt. This caused the peak of the spring runoff to take place in early May instead of early June. This 'month earlier' trend is consistent with predictions made prior by experts in the field (Jones, 1913; de Quervain, 1947; Painter et al., 2007), as well as by advocates who suggest that climate change has induced more accelerated and earlier snowmelt runoff (Mote, 2003; Stewart et al., 2005).

The impact of dust on snowpack has to be considered relative to differences in the main contributing factors of temperature and snowfall (maximum total snowpack equivalent for the winter), which fluctuate from year to year. All years are not created equal, and low snowpack combined with higher spring temperatures are likely the most dominant factors in an early snowmelt year. Furthermore, consideration should be given to global weather patterns such as ENSO, MJO, and PDO. Jet stream locations can generally be forecast-based on these kinds of global patterns. Knowing the dominant pattern(s) several months before a dust event and/or season can, in theory, serve as a guideline in determining what effects might be expected, including the likelihood of dust deposition on Colorado's snowpack. Temperatures, snowpack, global weather patterns, jet stream positions, strength and extent of Mexican monsoons, and quantity of dust deposition are all contributing factors. The extent of their contribution will vary with conditions and specific mountain locations for any given year. Alternatively, not all effects of dust directly lead to less snowpack. Due to additional melting induced by dirty snow in a particular snowpack, subsequent wind events and snowfalls after a dust event may indeed exhibit less blowing snow than they would have if the original dust had not been present. Melting increases the density of a given snowpack, and snowpack of increased density is less susceptible to blowing away at a later time.

In this article, we present meteorological data, snow pack data, and repeat photography of high mountain basins in the San Juan and Elk Mountains of Colorado to demonstrate that the events of 2009 were much different than years of the past decade, particularly 2005 and 1999, and continue to mirror the trends predicted by climate and snowpack experts in this region. Therefore, the findings we present act as a guideline useful to current and future stakeholders and researchers to attempt to isolate dust as a factor that impacts snow-melt.

## 2. Analysis of Dust Storms and Meteorological Timeline of Events

The first and most pertinent 2009 dust-depositing storm occurred on 4 April 2009 across the San Juan and Elk Mountain ranges of Colorado (Fig. 1). Both mountain ranges have peaks exceeding 14,000' (4267m) and receive significant snowfall of over 350 inches (890cm) annually at elevations above 8,000' (2438m). This storm system was followed by a succession of four other dynamic storm systems during April (Table 1a). Using AERONET (AERosol RObotic NETwork), reverse aerosol wind trajectories were analyzed (NASA, 2010) and identified desert dust source regions from as far away as Baja California (Fig. 2a). The four additional storm systems following the 4 April 2009 storm moved through the southwest United States also entraining exotic dust and depositing soil particles onto the San Juan and West Elk Mountain snowpack. Each storm system showed similar meteorological characteristics to the 4 April 2009 storm: wind speed maxima close to 100mph aloft and at the surface (Tables 1a-b). This paper describes the meteorological events of 2009 only, but it is important to recognize that similar storm systems have been occurring with increasing regularity and intensification since 2005 (Table 1c), and particularly in 2006 (Painter et al., 2007) whereas 1999 was a very low dust-storm intensity year (CDPHE, 1999; HPRCC, 2009; NSIDC, 2009).

### *a. 4 April 2009 storm system: an example of a dust-deposit-inducing event*

On 2 April 2009 a 1004mb low pressure and attendant cold front at the surface travelled south from the Pacific Northwest supplanting a 1012mb high pressure (Fig. 2b, NOAA, 2009a). By 3 April 2009 the low pressure had strengthened to 992mb completely dislodging the 1012mb high pressure and pushing it toward the Gulf Coast (Fig. 2c, NOAA, 2009b). The 500mb analysis on 3 April 2009 shows a large trough, diffluence over Colorado, and a 69mph wind speed maximum passing through the deserts of California, Northern Arizona, and Utah pushing into western Colorado. By 4 April 2009 there were strong winds at the surface (84 mph at 03UTC at CAEGE) and the 500mb map series confirm strong winds aloft as well up to 97mph (Fig. 2d, NOAA, 2009c; Tables 1(a-b), CAIC, 2010). This suggests momentum transfer between 500mb and the surface station CAEGE and the plausibility of desert dust deposition.

It is important to recognize that the origin of the dust is not from deserts alone. Low-altitude, semi-arid portions of Oregon, Idaho, Nevada, California, Arizona, Utah, New Mexico are also responsible for contributing to these dust storm events. These semi-arid steppe regions consist of sand, dry soils, and light weight soil particles. These blowing soils, (later deposited as loess) extend much higher into the atmosphere than sand, and can be transported further.

## 3. Discussion of Mountain Ranges, Associated Snow Pack Data, and Basin Photography

In 2009, all Colorado mountain ranges showed earlier than normal "melt-out" dates as well as an accelerated rate of melting for the overall snowpack. Early melt-out dates were widespread in the San Juan Mountains, but none as abnormally early as the West Elk Mountains.

In this analysis, seasonal snowpack melt-out rates from both mountain ranges will be examined in detail in relationship to the meteorological events.

### *a. San Juan Mountains and Uncompaghre Peak*

Uncompaghre Peak, the monarch of the San Juan Mountains, is located in the northern part of the range, and rises to 14,309'/(4361m). In late June of 1999, 2005, and 2009, the snowpack was visibly decreased each year leading up to the present (Figs. 3(a-c), Figs. 4(a-b)). The 2009 snowpack numbers indicate that the San Juan Mountains were impacted by the desert dust, increased spring temperatures, and decreased snowpack levels at the SNOTEL sites. SNOTEL data from 17 sites averaged together (Table 2, NRCS, 2009a-b) specify the snow throughout the San Juan Mountain range melted-out 30 days earlier in 2009 (Table 3, Figs. 5(a-b), NRCS, 2009c) than the 30-year running average (June 22 versus July 22). One noteworthy limitation is that both temperature and snow pack data presented in this analysis were collected and averaged from sites located at much lower valley elevations than where basin photos were taken. Temperatures were higher in lower valley locations, whereas average snowpack may be higher at higher elevations where photos were shot as opposed to data collected at the SNOTEL sites.

The early and rapid "melt-out" is further evidenced by earlier incidence of maximum peak stream flows in the Lake Fork of the Gunnison River as reported by the USGS at Gateview (Table 4). Peak stream flows in Cubic Feet per Second (CFS) have been recorded each year since 1938. 26 June 1999 was the latest peak run-off flow since 11 July 1983, and the 4th latest peak since 1938. 25 May 2005 and 19 May 2009, respectively, were among two of the earliest peak flow years for Gateview, as well as the 27 May 2006 reading (USGS, 2009a). In fact, 19 May 2009 matched 1970 and 1963 for the earliest peak flow in the records since 1938. This indicates that the dust deposited on the snow may have been a catalyst for more rapid snowmelt earlier in

2009 and 2006. Photos from 1999, 2005, and 2009 of both Nellie Creek basin (Figs. 3(a-c) and Figs. 4(a-b)) and Matterhorn Creek basin near the summit of Uncompaghre Peak looking west (Figs. 6(a-e)) depict these descriptions in detail and correlate with the peak stream flow information presented for the USGS gage at Gateview. The Lake Fork of the Gunnison River flows north from Lake City and is the main drainage for all snow contained within the Nellie Creek basin east of Uncompaghre Peak, and the Matterhorn Creek basin southeast of Wetterhorn Peak (14,017'/4272m).

Furthermore, data indicated above normal temperatures for April to June 2009 across the San Juan Mountains (Table 5, HPRCC, 2009). Even though the temperatures were above normal in 2009, 2005 and 1999, the solar insolation from decreased albedo on the surface of the snow from deposited dust also played a role in an earlier and faster rate of snowmelt in 2009 over 2005 and much earlier than 1999. Rate of snowmelt for 2009 and 2005 is demonstrated in Figs. 5(a-b) (1999 minor dust year data unavailable). The steeper the curves from NRCS, the more rapid the melt-off, which is more likely in a dust year. The melt-rate curve for 2009 is steeper and of shorter duration (late April to late June) compared to 2005 (early April to early July). An important aspect of seasonal temperature departures from the normal is spatial context. For example, 2009 and 2005 were warmer at high elevation (10,200' at Lizard Head Pass) compared to 2008 (MesoWest 2010). Also, the amount of seasonal snowfall was less in 2009 than 2008 (Figs. 5(a-b)). Early snowmelt is certainly expected in light water years. Therefore, the impact of dust has to be considered relative to differences in temperature and snowfall, which are the main factors contributing to the rate of snowmelt.

### *b. Elk Mountains and Pierre Lakes Basin*

The Elk Mountain range contains a majority of Colorado's most isolated and rugged Fourteeners (Kedrowski, 2006, 2009). These mountains are characterized by steep granite spires, loose sedimentary cliff bands, and rugged glacial-cut basins that hold snow nearly all year. For example, the remote glacial basins surrounding Capitol Peak and Snowmass Mountain show noteworthy contrasts in the amount of remaining snowpack by late August, especially since 2005 (Figs. 7(a-g)). SNOTEL sites in the Elk Mountain range that represent the 30 year melt-out dates in closest proximity to the Pierre Lakes basin and the upper west Snowmass Creek basin near Capitol Peak and Snowmass Mountain are listed in Table 3. SNOTEL data suggests that the 'Elks' were hit harder by the 2009 dust than the San Juans (see photos Figs. 7(a-g)). The 2009 snowpack data from 17 different SNOTEL sites closest to Pierre Lakes basin (Tables 3-4) averaged together indicated the snow throughout the Elk Mountain range melted-out 40 days earlier and melted much faster in the spring than the 30-year running average (June 5 versus July 15, NRCS, 2009b). The Gunnison River basin high/low snowpack summary for 2009 and 2005 is presented in Figs. 8(a-b), showing that the melt-out date for the basin and the Elk range was much earlier in 2009 than 2005 (1999 data not available). The melt-rate curve for 2009 is steeper and of shorter duration (mid-April to 1 June) compared to 2005 (early April to early July). Recent trends generally indicate rapid melting of snow and melt-outs earlier in the summer in past years, especially since the drought years of 2000-2002 (Painter et al., 2007; NRCS, 2009b; d).

Furthermore, data indicated below normal temperatures for April to June 2009 across the Elk Mountain range (HPRCC, 2009), compared to warmer than normal temperatures in 2006, 2005 and 1999 (Table 5). This indicates that the temperatures were less of a factor than the solar insolation from decreased albedo on the surface of the snow from deposited dust which may have contributed to earlier snowmelt in 2009 over 2005 and 1999. This is especially evident in the Pierre Lakes basin in late August for both 2009 and 2005 (Figs. 7(a-g)).

Stream-flow data to support these trends is not as clear because of the distance and orientation of where the USGS has located the stream-flow gauges for run-off coming directly from the Pierre Lakes and West Snowmass creek drainages in the Elk Range. The basins below Snowmass Mountain and Capitol Peak feed into creeks that eventually flow into the Roaring Fork River northwest of Aspen. Therefore, a reasonable site to assess is the Roaring Fork River in Glenwood Springs, a river carrying the majority of the Elk Range's snowmelt. The early "melt-out" happened again in the Elk Mountains by incidence of maximum peak in stream flows in the Roaring Fork River as reported by the USGS at Glenwood Springs (Table 6). Peak stream flows in CFS have been recorded for each year since 1906. By sheer coincidence to the Lake Fork of the Gunnison River in the San Juan Range, 26 June 1999 was also the latest peak run-off flow for the Roaring Fork River since 13 July 1985. 24 June 2005 was also a later than normal year for a peak flow similar to that of the 1999 year. In quite a contrast, a same date to the San Juan site of 19 May 2009, the Roaring Fork River peak flow was among the earliest peak flow years for the Glenwood Springs location (USGS, 2009b). In fact, 19 May 2009 was the earliest peak flow in the records since 8 May 1966. 2006 was a very similar peak stream-flow year to 2009, as peak flow was recorded on May 23, much earlier than 1999 and 2005. This suggests that the dust deposited on the snow may have factored into a more rapid melt earlier in 2009 and 2006 for the Elk Mountains. Photos from 2009, 2005, and 1999 of the Pierre Lakes basin (Figs. 7(a-g)) depict these descriptions in detail and correspond with the peak stream flow data presented for the USGS gauge at Glenwood Springs. CFS for the four years (2009, 2006, 2005, and 1999) were very similar, even though peak stream flows occurred at a different time of year (Table 6).

## 4. Conclusions

The repeat photography demonstrates clear and striking differences in snowpack within the San Juan and Elk Mountain ranges from 2009, 2005, and 1999 from the same locations during the same week of each year for the mountain basins. The meteorological data shows that a succession of five significant April 2009 storm systems, eight 2006 events, and four 2005 storms entrained desert dust from the southwestern U.S. depositing it onto the high, rugged, and remote areas of both mountain ranges. The data averaged from SNOTEL sites across mountain ranges for 2009 and 2005 reveal three primary findings: 1) the San Juan Mountain snowpack melted-out one month earlier and at a much faster rate overall than the 30-year average melt-out date; 2) the Elk Mountain range melted-out at least 40 days earlier and at a much faster rate overall than the 30-year average melt-out date; and, 3) repeat photos available from three separate years within the past decade (2009, 2005, and 1999) from specified mountain basins visually indicate the earlier melt-out and more accelerated rate of snow-melt for the years closest to the present.

Why? Dusty snow absorbs more incoming shortwave radiation than clean snow and melts faster. The duration of snow pack in the mountains of Colorado critically controls the timing and magnitude of water supplies, power generation, agricultural activities, and forest fire regimes (Westerling et al., 2006). The net impacts are earlier melt-out dates, accelerated melting rates overall, and less summer snowpack in the San Juan and Elk Mountains. When less water runs down river basins during late summer and fall, it can impact farming and ranching communities, and river rafting companies, as well as wildflower populations, and the overall soil moisture of surrounding watersheds.

While this dust-storm phenomenon is not the only factor for increased melt, higher than average seasonal temperatures and lack of snowfall in particular basins are contributing factors that will also require more investigation. The rate of decrease is a better indicator than the date of melt-off. If the snowpack builds to a sub-normal level, it is susceptible to early melt-off whether there is dust or not. Potential for avalanches and blowing snow on slopes that have been layered by dust particles also needs further research (CAIC, 2010). The recent trends may continue for the San Juan and Elk Mountains if drier soil conditions in the southwestern United States remain for future decades. Therefore, continual monitoring by repeat photography in addition to tracking snowfall totals and seasonal temperatures would need to be done for these basins for every season in future years to document potential trends.

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# TABLES AND FIGURES

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**Table 1a.** 2005 and 2009 dust storm events in Southwestern Colorado. (In 2006 there were eight events, but dates of those events and photos are not available and thus omitted here. In 2005, there were four major dust storm events, three of which occurred in early April and one in early May (Painter et al., 2007; Steltzer et al., 2009), whereas 1999 demonstrated a lack of significant dust storm events compared to recent years).

| **2009** | April 4* | April 9 | April 12 | April 17 | April 26 |
|---|---|---|---|---|---|
| 500mb Wind Speed: | 97mph | 92mph | 69mph | 81mph | 69mph |
| Surface Wind Speed: | 84mph | 38mph | 72mph | 46mph | No Data |
| **2005** | April 1* | April 4 | April 8 | May 9 | |

*Indicates primary weather event in each year.
Surface Wind Speed data courtesy of the Colorado Avalanche Information Center (CAIC, 2010).

**Table 1b.** Surface Winds associated with the primary weather event in 2009. Data courtesy of the CAIC reporting station CAEGE (Eagle Station, CAIC, 2010) in the San Juan Mountains.

| **2009 Surface Wind Speed Maxima** |
|---|
| 2 April – 64mph at 03UTC |
| 3 April – 72mph at 18UTC |
| 4 April – 84mph at 03UTC |
| 5 April – 43mph at 00UTC |

**Table 1c.** A look back: qualitative summary of dust storm intensity by year.

| | |
|---|---|
| **2009** | **Above Average** |
| **2006** | **Above Average** |
| **2005** | **Average** |
| **1999** | **Below Average** |

**Table 2.** NRCS SNOTEL sites from 17 sites across the San Juan Mountains and 15 sites from the Elk Range for the years of interest in the photos presented. (Although some of the Elk Range sites may not be geographically located within the mountain range, the total number of sites were used by NRCS to determine snowpack and 30 year melt-out averages for the complete drainages for the mountain ranges and any adjacent mountain ranges).

| **San Juan Mountains**<br>**Site Name (Site #)** | **Elk Mountains**<br>**Site Name (Site #)** |
|---|---|
| 1. Idarado (538) | 1.North Lost Trail (669) |
| 2. Red Mountain Pass (713) | 2. McClure Pass (618) |
| 3. Mineral Creek (629) | 3. Schofield Pass (737) |
| 4. Molas Lake (632) | 4. Butte (380) |
| 5. Cascade (386) | 5. Upper Taylor (1141) |
| 6. Cascade #2 (387) | 6. Cochetopa Pass (1059) |
| 7. Beartown (327) | 7. Columbine Pass (409) |
| 8. Lizard Head Pass (586) | 8. Idarado (538) |
| 9. El Diente Peak (465) | 9. Mesa Lakes (622) |
| 10. Scotch Creek (769) | 10. Overland Reservoir (675) |
| 11. Columbus Basin (904) | 11. Park Cone (680) |
| 12. Lone Cone (589) | 12. Porphyry Creek (701) |
| 13. Mancos (905) | 13. Red Mountain Pass (713) |
| 14. Sharkstooth (1060) | 14. Sargents Mesa (1128) |
| 15. Vallecito (843) | 15. Slumgullion Pass (762) |
| 16. Stump Lakes (797) | |
| 17. Wolf Creek Pass (843) | |

Map of sites available at: http://www.wcc.nrcs.usda.gov/snotel/Colorado/colorado.html

**Table 3.** Snowpack melt-out dates for each mountain range study area (NRCS, 2009a-b). Although we do not have photos of the basins from 2006, the melt-out date was earlier than that of 2009 which was also earlier than 2005.

| | **30-Year Melt-Out Date** | **2009** | **2006** | **2005** | **1999** |
|---|---|---|---|---|---|
| **San Juan Range:** | July 22 | June 22 | June 8 | July 5 | June 28 |
| **Elk Range:** | July 15 | June 5 | June 2 | July 3 | June 16 |

For the Elk Range, two recent years were quite similar, 2006 and 2009, with earlier melt-out dates of June 2 and June 5, respectively. In 2005, by contrast, the year was closer to the average melt-out of July 15 with snow completely disappearing by July 3. In 1999, melt-out was a month earlier as well, as temps were slightly higher than normal, but the Elk Range snowpack overall was only 85% of the average normal snowpack for the preceding winter which may have contributed to earlier melt-out by June 16 (NRCS, 2009b; NRCS, 2009d).

**Table 4.** Peak stream flow of daily mean discharge statistics from stream flow gauges on the Lake Fork of the Gunnison River monitored by the U.S. Geological Survey at Gateview, CO (USGS 2009a). Years of interest (2009, 2006, 2005, & 1999) are in **bold**. Notable years listed. Runoff for the three years of interest were also very similar, even though peak stream flows may have occurred at different times of the year.

| Water Year | Date of Peak Flow | Gage Height (Feet) | Stream Flow (CFS) |
|---|---|---|---|
| **2009** | **May 19** | **4.25** | **1690** |
| 2008 | June 4 | 4.32 | 1780 |
| 2007 | June 6 | 3.98 | 1450 |
| **2006** | **May 27** | **3.75** | **1370** |
| **2005** | **May 25** | **4.18** | **1720** |
| 2004 | June 8 | 3.65 | 1320 |
| 2003 | May 30 | 4.04 | 1700 |
| 2002 | May 21 | 2.34 | 406 |
| 2001 | May 28 | 3.71 | 1370 |
| 2000 | May 30 | 4.08 | 1730 |
| **1999** | **June 26** | **4.26** | **1720** |
| 1998 | June 3 | 3.64 | 1240 |
| 1997 | June 5 | 4.61 | 2080 |
| 1996 | May 20 | 4.05 | 1500 |
| 1970 | May 19 | 3.37 | 1780 |
| 1963 | May 19 | 2.62 | 975 |

**Table 5.** Temperature variations (°F) from normal in southwestern Colorado (HPRCC, 2009; MesoWest 2010).

| | **April-June 2009** | **April-June 2006** | **April-June 2005** | **April-June 1999** |
|---|---|---|---|---|
| **San Juan Range:** | 0 to (+3) | 0 to (+4) | 0 to (+1) | 0 to (+2) |
| **Elk Range:** | 0 to (-4) | 0 to (+3) | 0 to (+1) | 0 to (+1) |

**Table 6.** Peak stream flow of daily mean discharge statistics from stream flow gauges on the Roaring Fork River (Elk Range drainage) monitored by the U.S. Geological Survey at Glenwood Springs, CO (USGS 2009b). Years of interest (2009, 2005, & 1999) are in **bold**. Notable years are also listed.

| Water Year | Date of Peak Flow | Gage Height (Feet) | Stream Flow (CFS) |
|---|---|---|---|
| **2009** | **May 19** | **6.41** | **6100** |
| 2008 | June 20 | 6.72 | 7850 |
| 2007 | June 18 | 5.27 | 4490 |
| **2006** | **May 23** | **6.08** | **6350** |
| **2005** | **June 24** | **6.09** | **6370** |
| 2004 | June 8 | 5.13 | 4080 |
| 2003 | May 31 | 6.43 | 7650 |
| 2002 | June 1 | 4.39 | 2480 |
| 2001 | June 2 | 5.10 | 3880 |
| 2000 | May 30 | 5.99 | 6240 |
| **1999** | **June 26** | **6.10** | **6240** |
| 1998 | June 2 | 5.74 | 5530 |
| 1997 | June 8 | 6.72 | 8170 |
| 1996 | June 22 | 6.25 | 6630 |
| 1995 | July 13 | 8.31 | 13000 |
| 1994 | June 2 | 5.19 | 4550 |

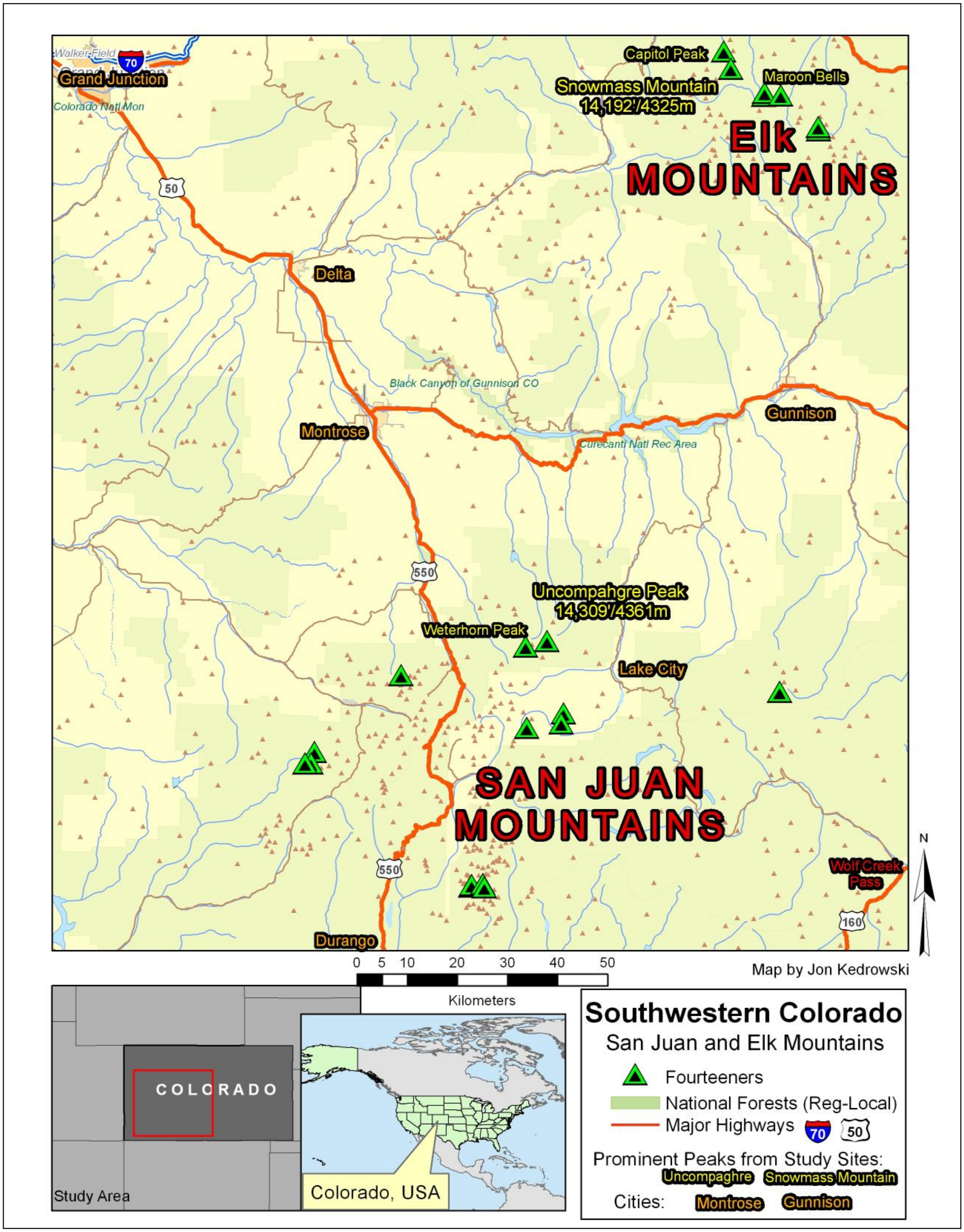

**Figure 1.** Study Area: San Juan and Elk Mountains of Southwestern Colorado.

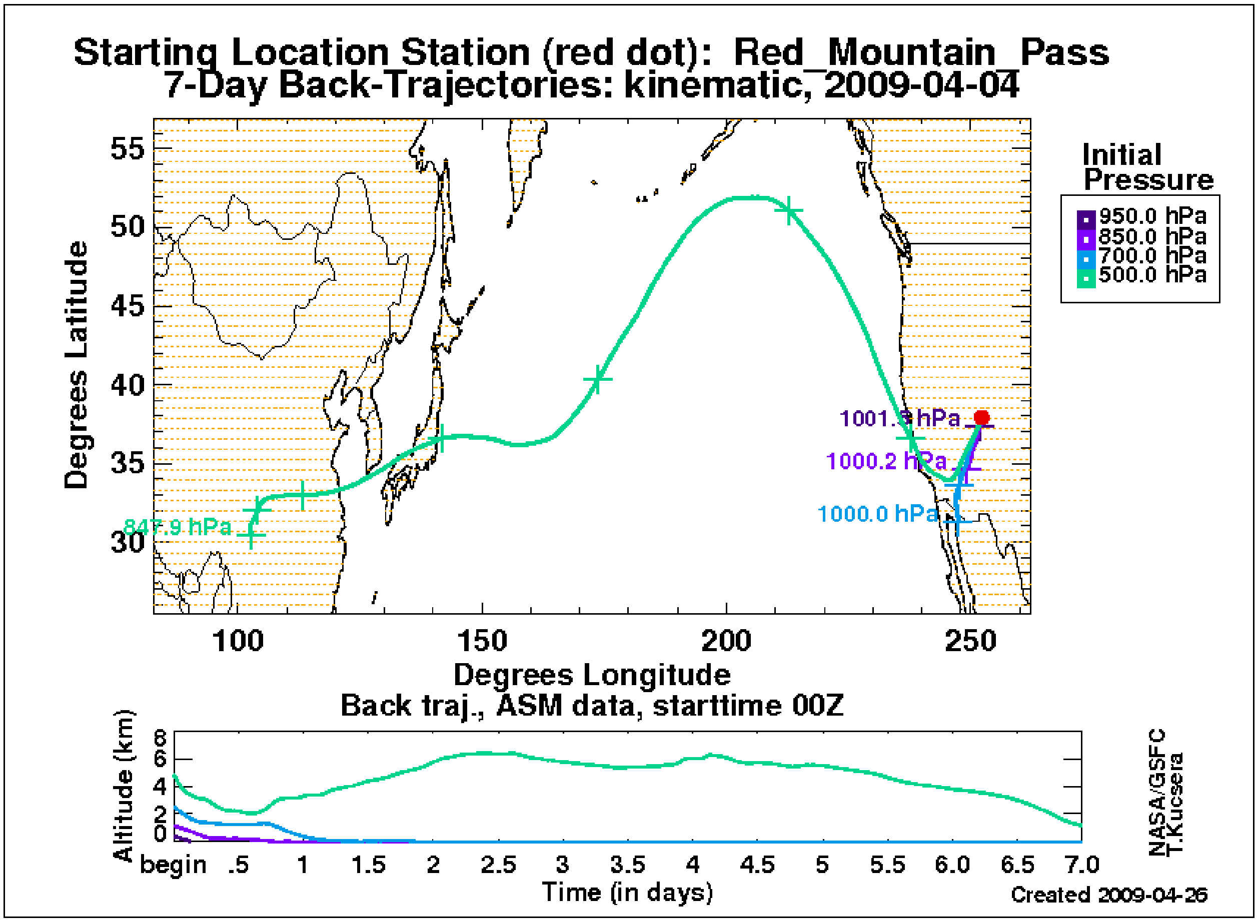

**Figure 2a.** AERONET (AERosol RObotic NETwork). Reverse aerosol trajectory for 4 April 2009. Note the reverse trajectory from Baja California (NASA, 2010). Red dot indicates location of Red Mountain Pass, Colorado.

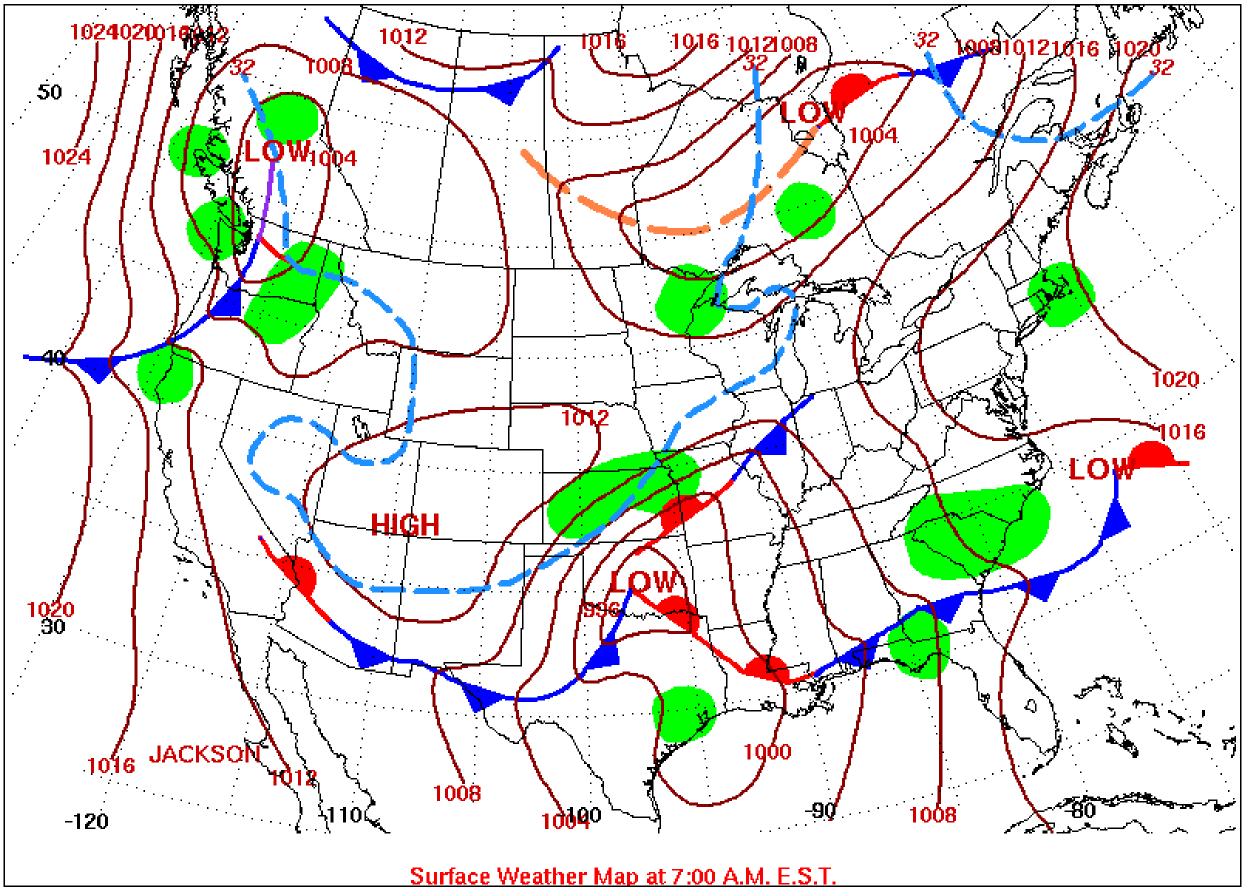

**Figure 2b.** The location of storm and frontal systems on 2 April 2009 which generated the primary dust storm events for 4 April 2009 impacting southwestern Colorado (NOAA, 2009a).

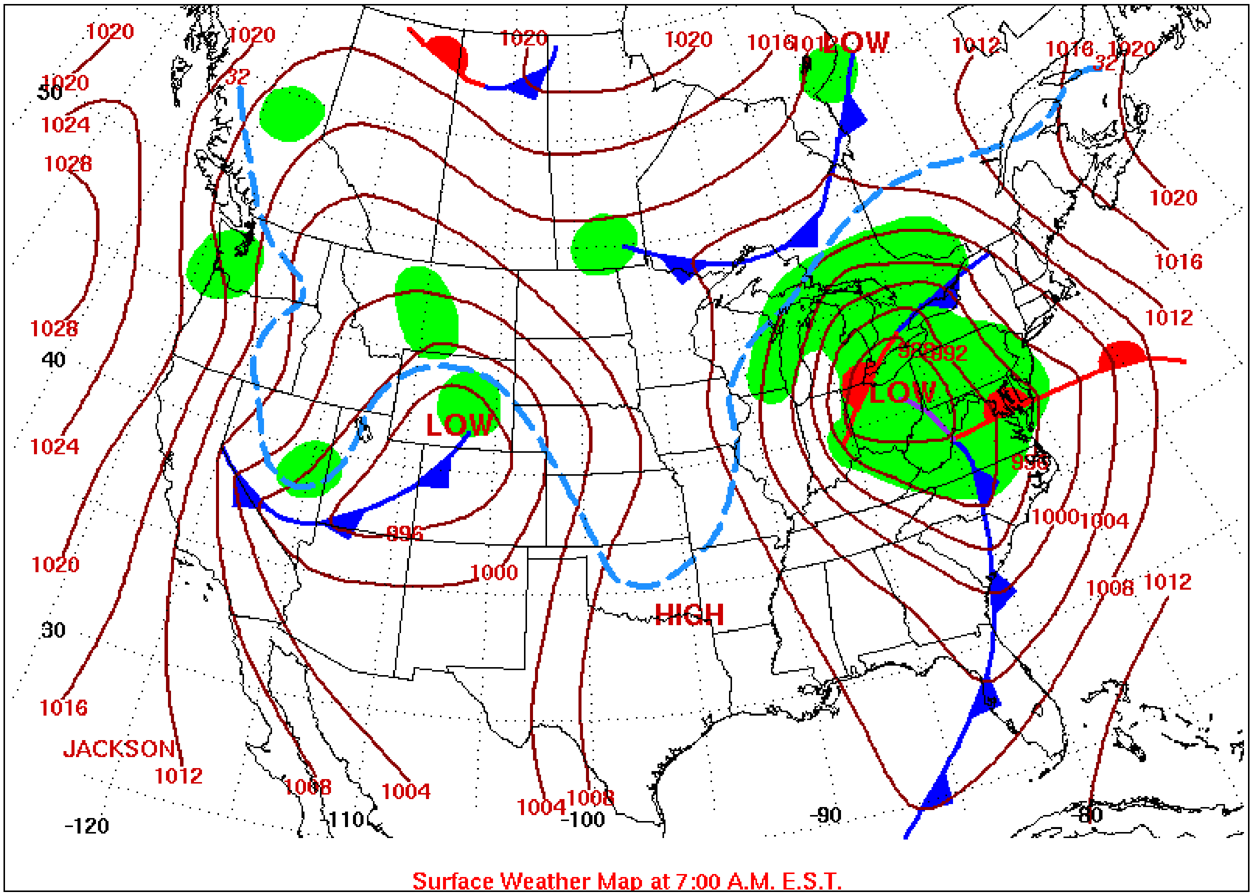

**Figure 2c.** The location of storm and frontal systems on 3 April 2009 which generated the primary dust storm events for 4 April 2009 impacting southwestern Colorado. Notice the tight packing of the isobars at the surface over Nevada, Utah, Eastern California and Northern Arizona (NOAA, 2009b).

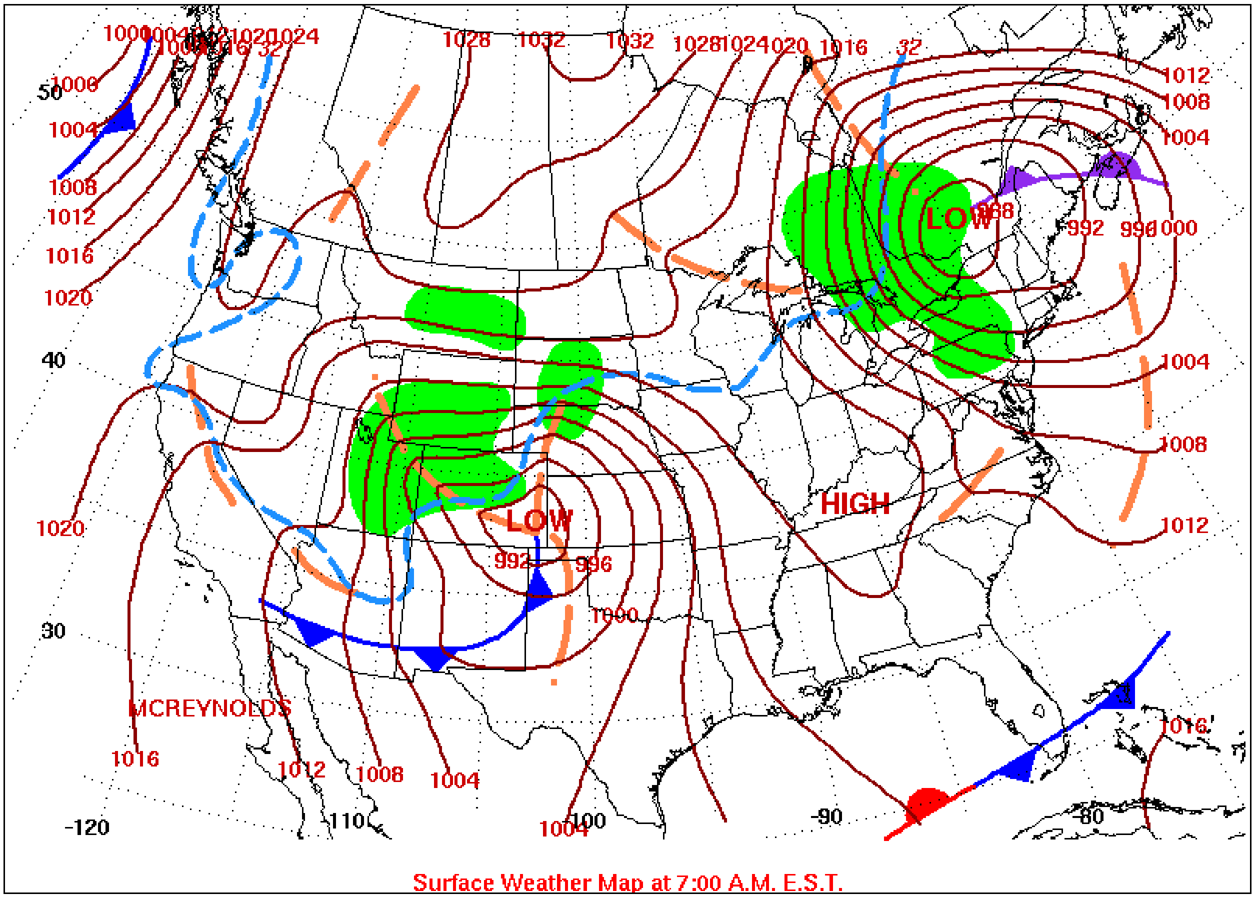

**Figure 2d.** The location of storm and frontal systems on 4 April 2009 which generated the primary dust storm events impacting southwestern Colorado. Notice that, by 4 April 2009, the packing of the isobars was even tighter across same areas including western Colorado (NOAA, 2009c).

**Figure 3a.** 21 June 1999 Nellie Creek Basin just east of Uncompaghre Peak (4361m).

**Figure 3b.** 23 June 2005 (Above). **Figure 3c.** 26 June 2009 (Below).

**Figure 4a.** Nellie Creek Basin 21 June 1999 (Above).

**Figure 4b.** 23 June 2005 (Below).

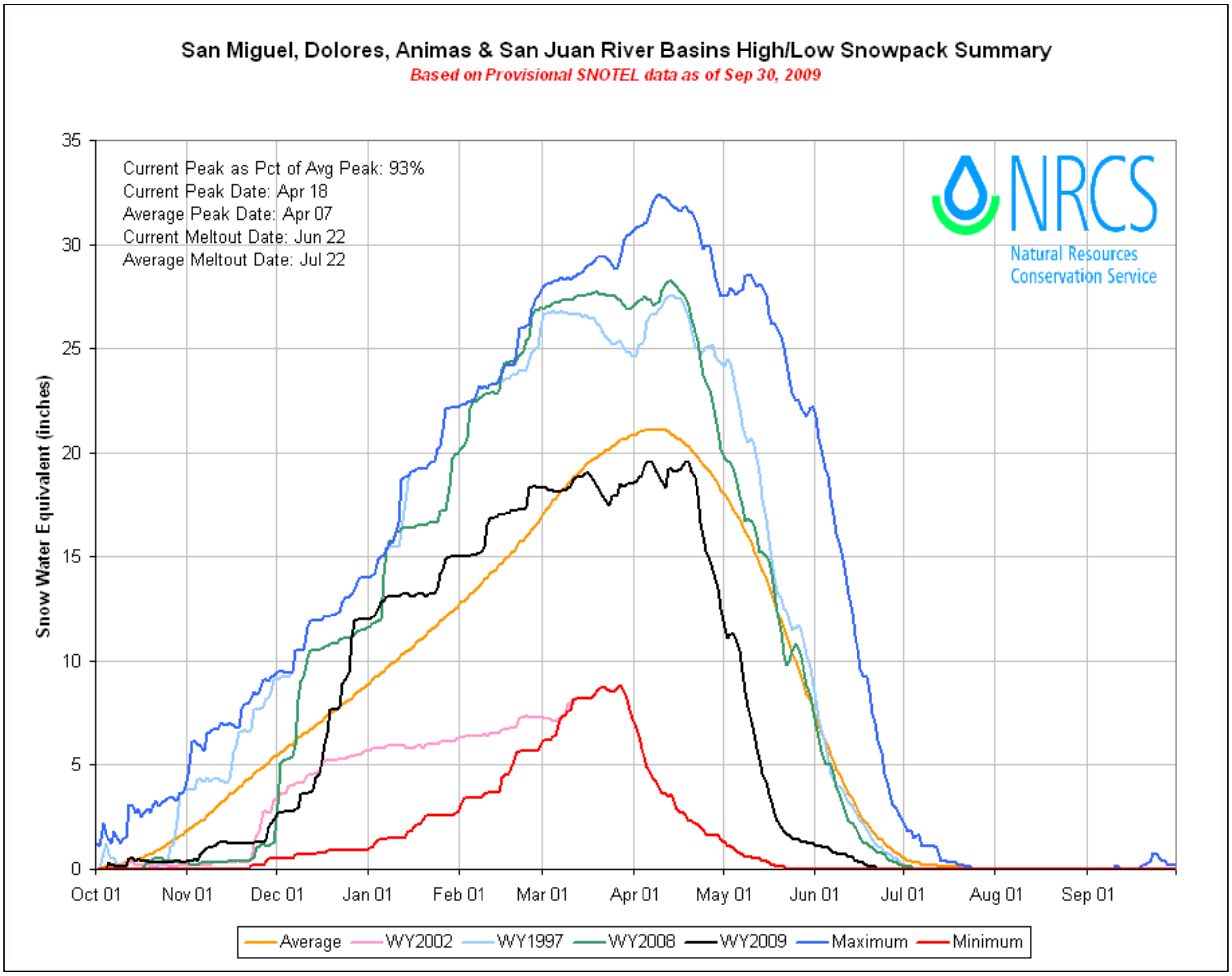

**Figure 5a.** Colorado NRCS line graph snow summary: 30 year averages, maximum and minimum including the 2009 line. The river basins listed have their sources in the San Juan Mountains (NRCS, 2009c).

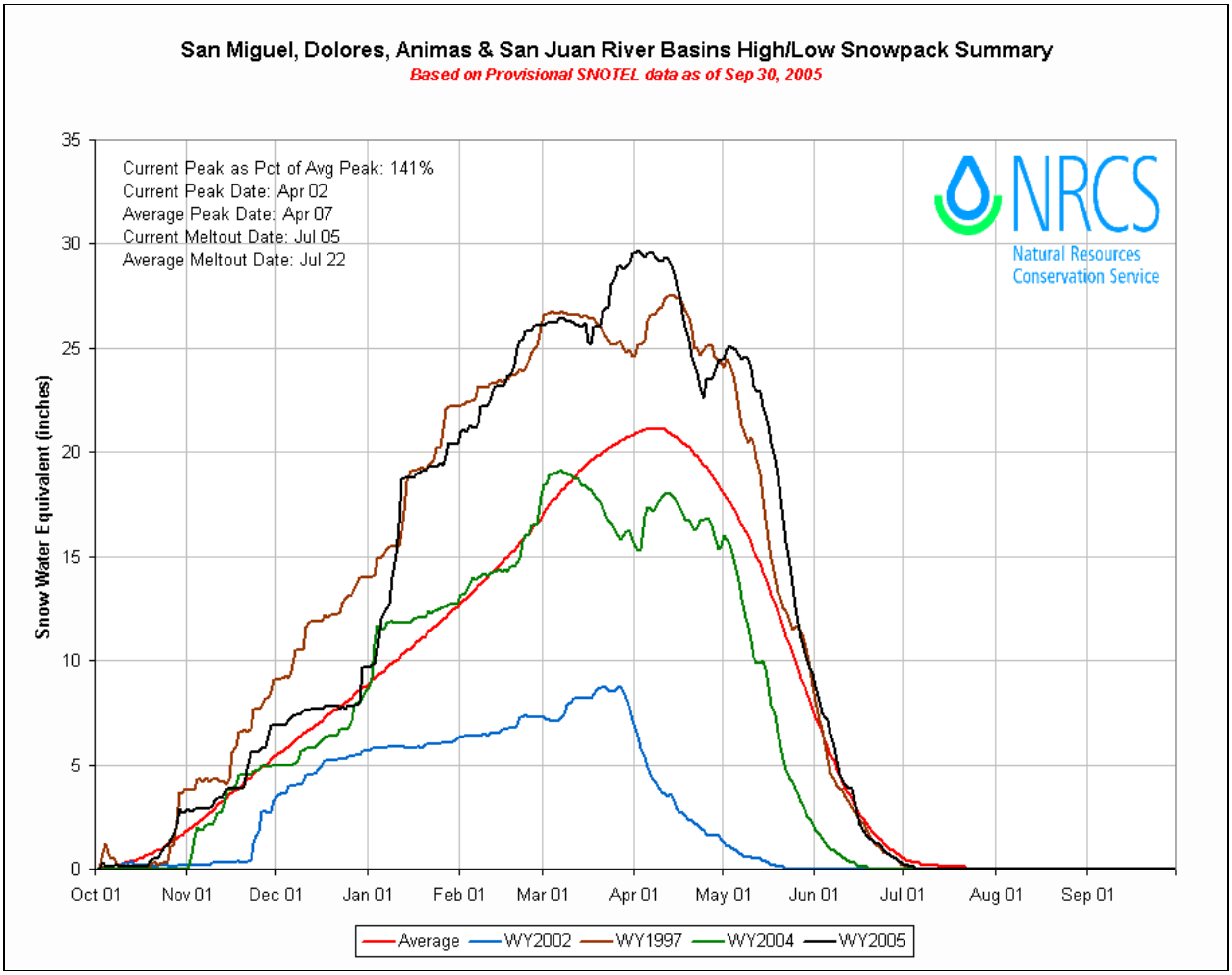

**Figure 5b.** Colorado NRCS line graph snow summary: 30 year averages, maximum and minimum including the 2005 line. The river basins listed have their sources in the San Juan Mountains (NRCS, 2009c).

**Figure 6a.** Wetterhorn Peak, upper Matterhorn Creek basin (left of peak) and extreme upper East Fork Cimarron River Basin (right of peak) on 23 June 2005.

**Figure 6b.** 26 June 2009 (Below).

**Figure 6c.** 26 June 2009.

**Figure 6d.** 23 June 2005.

**Figure 6e.** 26 June 2009.

**Figure 7a.** Pierre Lakes Basin and Snowmass Mountain (14,092’/4325m) 14 August 1999.

**Figure 7b.** 18 August 2005. Pierre Lakes Basin and Snowmass Mountain. Note the presence of ice in the lower lake at bottom of photo.

**Figure 7c.** 22 August 2009. Pierre Lakes Basin and Snowmass Mountain. Note the lack of ice in the lake closest to bottom of photo as compared to 2005, as well as the dusty tint of the snow in 2009.

**Figures 7(d-e).** 18 August 2005 (Above). Pierre Lakes Basin and Snowmass Mountain looking south from the summit of Capitol Peak. 22 August 2009 (Below).

**Figure 7f.** 18 August 2005. Pierre Lakes Basin and Snowmass Mountain from Capitol's Summit.

**Figure 7g.** 22 August 2009. Pierre Lakes Basin and Snowmass Mountain from Capitol's Summit

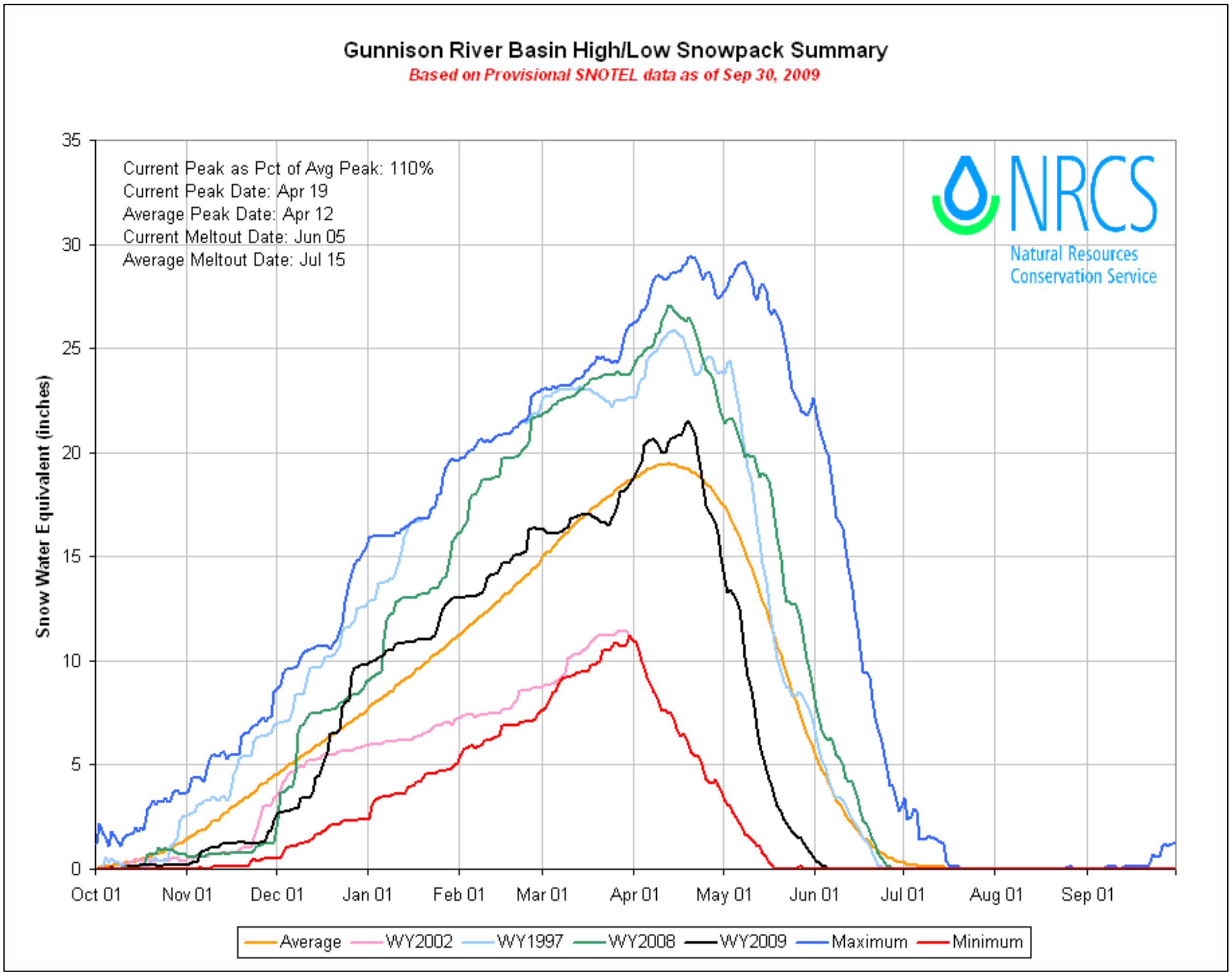

**Figure 8a.** Colorado NRCS line graph snow summary: 30 year averages, maximum and minimum, including the 2009 line. The Gunnison river basin source is in the Elk Mountains to the north and San Juan Mountains to the south (NRCS, 2009d).

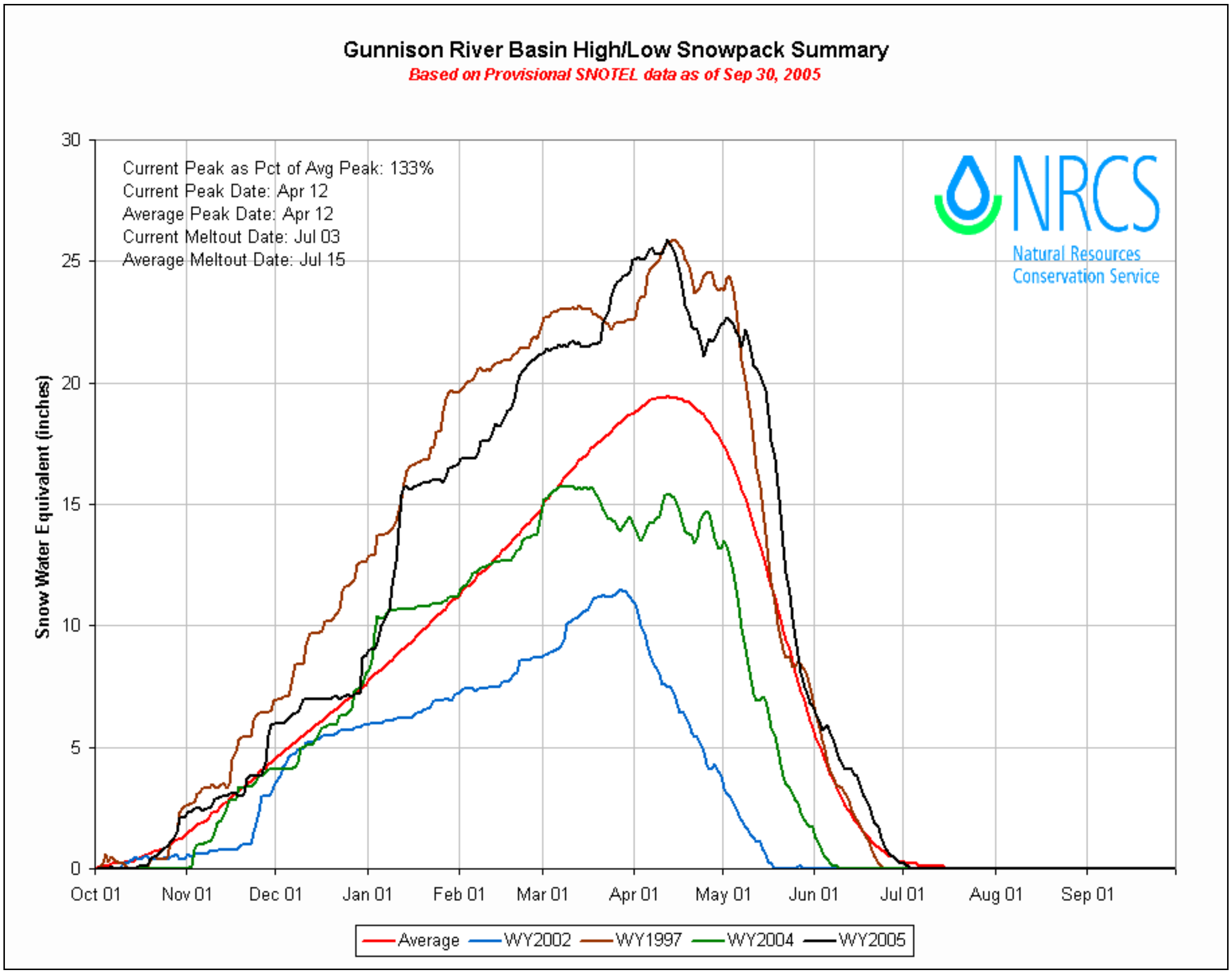

**Figure 8b.** Colorado NRCS line graph snow summary: 30 year averages, maximum and minimum, including the 2005 line. The Gunnison river basin source is in the Elk Mountains to the north and San Juan Mountains to the south (NRCS, 2009d).