Colorado’s Rocky Mountains’ Winter Water Storage and ENSO Events

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The people living in the Central Rocky Mountains of North America, encapsulated in regions defined by the borders of Colorado, Wyoming, Utah, Idaho, and Montana, have faced the prospects of water supply uncertainty because of inconsistent weather patterns and incongruent artificial water applications since there have been people in these regions. Most straining to the water supply-demand ratios are the long stretches of drought which occur in this region, and which are projected to increase in length and intensity. The geographic significance of the Rockies includes sourcing and storing much of the freshwater, in the form snowpack, which supplies the American West and Plains regions. Several significant rivers are sourced in Colorado’s Rocky Mountains, including the Colorado, the most significant water supply for several metropolitan and agricultural areas in regions of Northern Mexico and seven Western U.S. states: Colorado, Wyoming, New Mexico, Utah, Arizona, Nevada, and California.

In part, because of the varied climatic events in recent years, there is an inconsistency between the projections and supply of freshwater and the demand imposed by the biological population living in these regions; the discrepancies are increasingly affected by artificial interactions along with stretches of drought. The combination of discrepancies and drought has crippling implications for the people, animals, and other biologic communities in Colorado and the rest of the Western United States.

El Niño and La Niña, collectively referred to as the El Niño-Southern Oscillation (ENSO), are patterns of warming and cooling of surface waters in the Southern Pacific Ocean. El Niño is the Spanish term for little boy, or more colloquially, The Christ Child, because it characteristically begins to occur near Christmas time, the celebration of the birth of Jesus. La Niña is a Spanish term for little girl. Presumably, the names were given to implicate the dichotomy of the two events.

During ENSO events, atmospheric conditions are affected dramatically. Large areas of warm surface water in the Pacific can drift to different locations because of shifts in low-latitude trade winds. Great, girthy columns of dry air sink toward colder regional Oceanic temperatures, variably located because of the oscillating locations of regional ocean temperatures. The event is called El Niño when the vast volume of cold surface waters and sinking, dry air are geographically adjacent to the eastern edges of Southeast Asia; when the volumes of cold surface water and sinking air are geographically adjacent to the western edges of North and Central America, the event is referred to as La Niña (Fig. 1). According to the information about the distinguishing conditions on Climate.gov, “The pattern can shift back and forth irregularly every two to seven years, and each phase triggers predictable disruptions of temperature, precipitation, and winds."

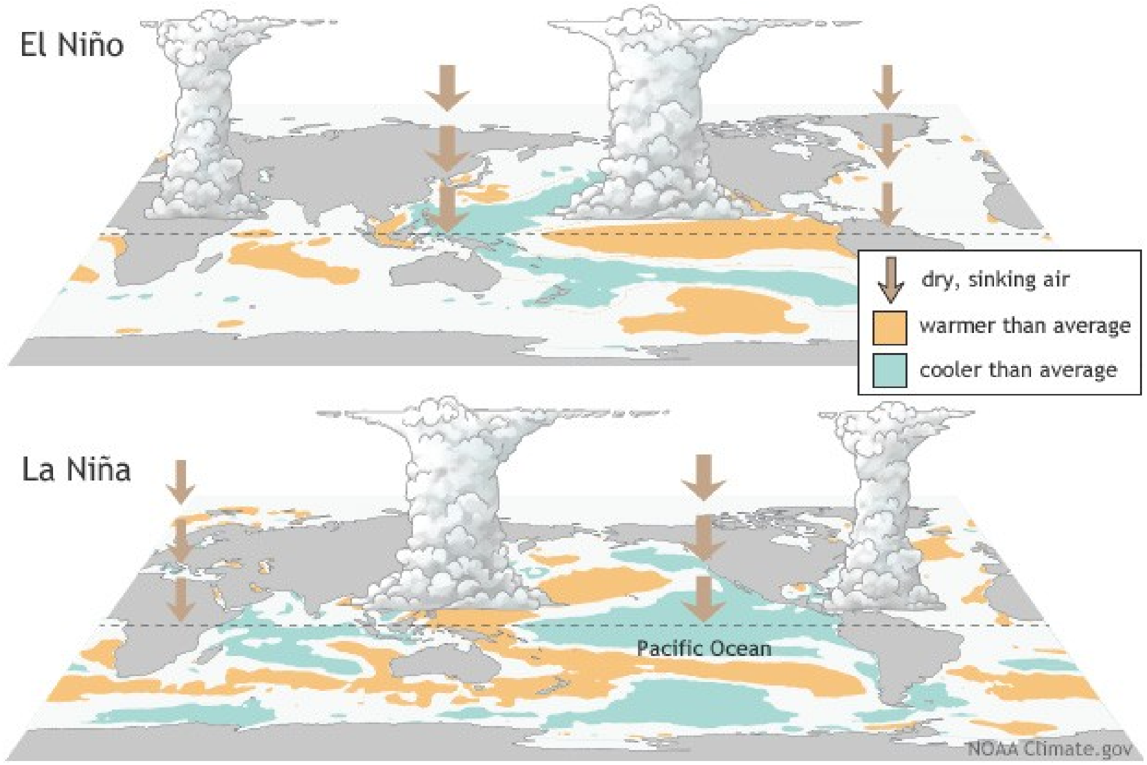

Fig. 1: Relative Oceanic temperatures and their effects on atmospheric conditions (Climate.gov). More animated graphic explanations can be viewed at ENSO by ClimateProgramOffice.

The presence of El Niño events affects the weather patterns in North America. As a result of the atmospheric conditions in the Pacific, a prevalent jet stream extends over the southern United States and Northern Mexico. High pressure barriers lie south of the jet stream, known as the Polar Jet Stream, allowing for wetter and cooler conditions in the South and Southwest United States. During La Niña events, the prevalent jet stream is pushed to the northern latitudes. Oceanic moisture columns do not travel to southern regions of the United States and leave the South and Southwest with dry conditions (Fig. 2).

It has been said and used in ethos: the El Niño and La Niña Oceanic events, but more particularly the former, have/has direct effect on the patterns of high and low precipitation in the Central Rockies. Car dealership commercials have presented images of snowbound city and highway driving, attributing the weather events to El Niño, in order to persuade potential car buyers to visit their show room to purchase the all-wheel vehicles which are advertised as impervious to such conditions. Telluride ski resort produced and published an advertisement at their scenic resort, simply by displaying snowy, blustery skiing and riding conditions along with lively, dramatic music; the advertisement is called "El Niño is Coming" (Telluride).

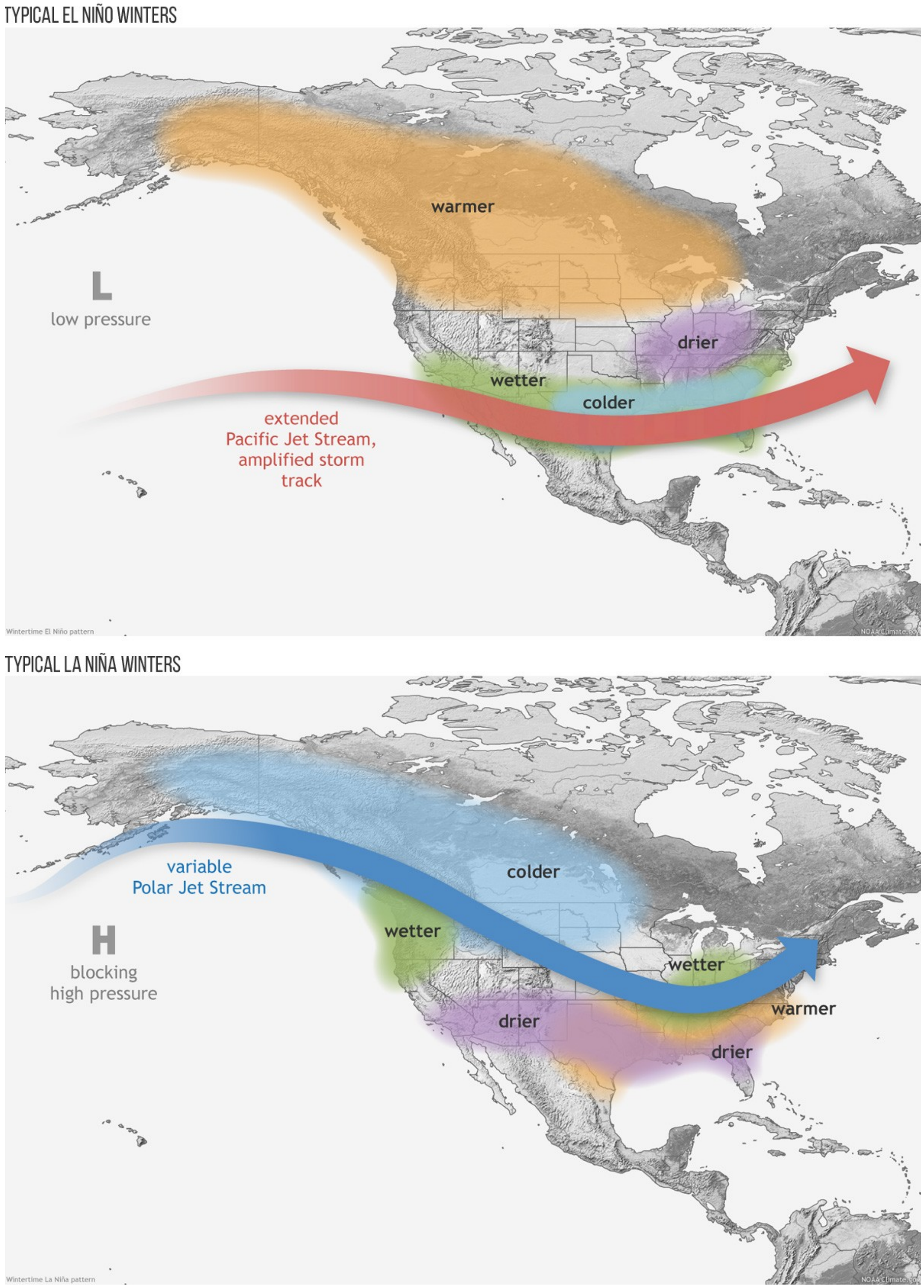

Fig. 2: Atmospheric jet stream conditions and moisture and temperature patterns typical during Niño & La Niña events

To what extent do the occurrences of El Niño and La Niña events in the Pacific Ocean affect the precipitation patterns in the Colorado Rockies during the winter months?:

- **Do the El Niño events create high snowpack totals in Colorado in the winter months? Does La Niña have the potential to do the same?**
  Hypothesis: The characteristics of El Niño events contribute to higher precipitation in the Rockies. The characteristics of La Niña events contribute to lower precipitation in the mid-continent range.

- **Is there a correlation between the events of an El Niño triggering La Niña events in the next consecutive year?**
  Hypothesis: An El Niño event will precede a La Niña event.

- **Could the intensity of a La Niña event be predicted by the presence of an El Niño event in the preceding year?**
  Hypothesis: A high intensity La Niña event, either creating higher snowpack totals or greater drought conditions, is preceded by an annual El Niño event.

- **Can the projection of ENSO events ensure water resource security for the constituents of the Rockies’ water supply?**
  Hypothesis: ENSO events deliver a volume of water which could be projected to sustain the people in the West and Plains regions, mitigate existing drought conditions, and create surplus.

Methods

This inquiry about the characteristics of El Niño and La Niña events began at Climate.gov, through which the events and their effects were initially defined.

The temporal terms *late fall, winter, and early spring* or *winter* reference the months in a 12 month period bridging across the New Year in which these seasons occur in the Northern hemisphere, generally October through May. The Water (storage) Year is defined as beginning in October and ending in September (United States Department of Agriculture).

Snowpack total refers to *Snow-Water Equivalent* as calculated by SNOTEL, an automated system operated by the Natural Resource Conservation Service, which measures snowpack. The measurements have been taken at strategic locations through mountainous areas which typically accumulate snow in the winter months.

The relative unit referred to as snowpack percentage is expressed as percent of median compared to the occurrences on the same date, a ratio of totals for the specified year compared to the median annual snowpack totals of all measured years.

Snowpack melting season typically occurs through April-June, and beyond depending on the melting and evaporation rates. Variable melting rates can affect the understanding of the ratios in any constant through time.

Because of its geographic value for snowpack and water storage in the mountains in Colorado and the nature of the region’s climate, statistics of snowpack in Colorado, provided by the United States Department of Agriculture, were investigated to reveal the correlation between and Colorado’s measured water storage by year and the ENSO events. The statistics for Colorado’s snowpack totals are organized by watershed. The snowpack total and average and median depths from the past 4 years (2016-2019) are tracked each day of the year and are current to date. There is also a historical record of snowpack percentages in ratio to the median amount listed for the past 50+ years, which is the extent of the observations (Natural Resource Conservation Services). To provide a broader range of understanding, the analysis specifically focuses on the snowpack statistics for three of Colorado’s river basin: the South Platte River, fed by the Mosquito Range and other ranges near to Denver, flowing east toward the Mississippi River; the Colorado River, fed by ranges across the Western Slope of Colorado, flowing west to the Sea of Cortez; and the Rio Grande River fed by the San Juan, La Plata, and Sangre de Cristo Ranges in the south and southwest of Colorado, flowing to the Gulf of Mexico (Fig. 3).

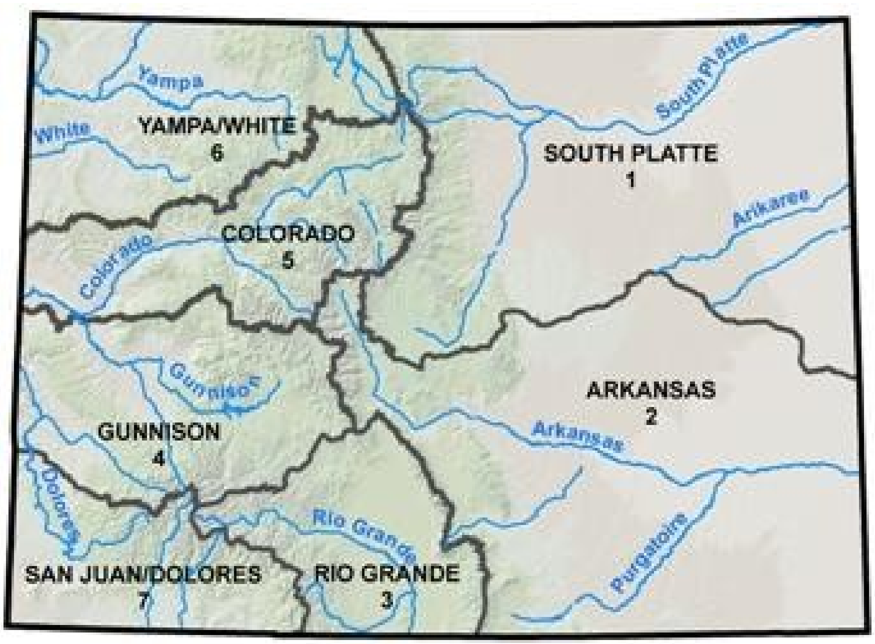

Fig. 3: The snowpack totals of three of Colorado’s river basins are examined: the South Platte (1); the Colorado (5); and the Rio Grande (3) (Colorado Water Quality…). The Yampa and White (6), Gunnison (4), and San Juan and Dolores (7) rivers are all tributaries of the Colorado

Observations

In the winter months of 2018-19, the conditions of an El Niño were identified and observed. Over the course of those months, by February of 2019, the temperature of the surface waters of the Pacific Ocean adjacent to Indonesia had risen up to 2˚ Fahrenheit above its average temperatures (Fig. 4).

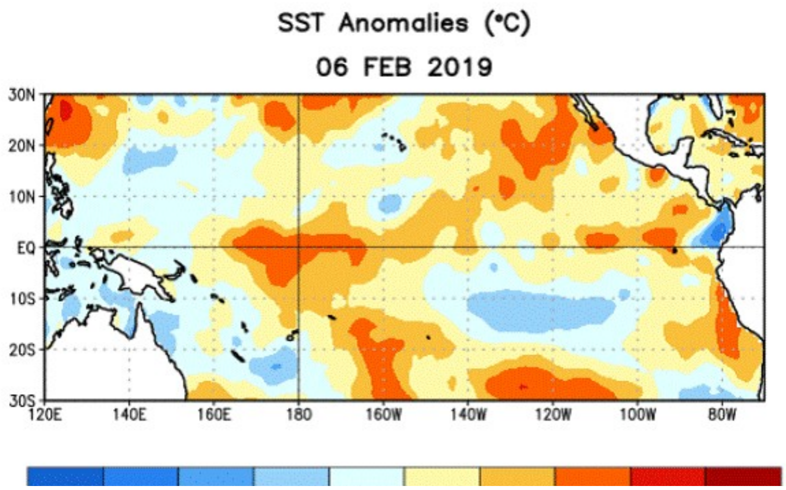

Fig 4: Average sea surface temperature (SST) anomalies (°C) for the week centered on 6 February 2019. Anomaly ratios are compared to the 1981-2010 base period weekly means for surface water temperature (NOAA)

By April of 2019, the snowpack totals for the winter revealed several locations in the south and central mountains across the Western United States, including the Sierra Nevada Range and the Rocky Mountains, had received greater than 200% of median accumulation specific to observed locations in April. Ranges in the Northwestern United States, which can lay above the observed Pacific Jet Stream consistent the El Niño events, received up to 75% of the median accumulation (United States Department of Agriculture). In May of 2019, total snowpack accumulation rose to above 120% in the South Platte River Basin, above 130% in the Colorado River Basin, and above 248% in the Rio Grande River Basin, including steep increases in all three basins in January, February, and late March-early April (National Resource Conservation Service).

Historical Context for Snowpack Totals in Colorado and the Three River Basins

For the State of Colorado and the three observed river basins within it, snowpack totals have varied with notable peaks during ENSO events in the last 50 years (Fig. 5).

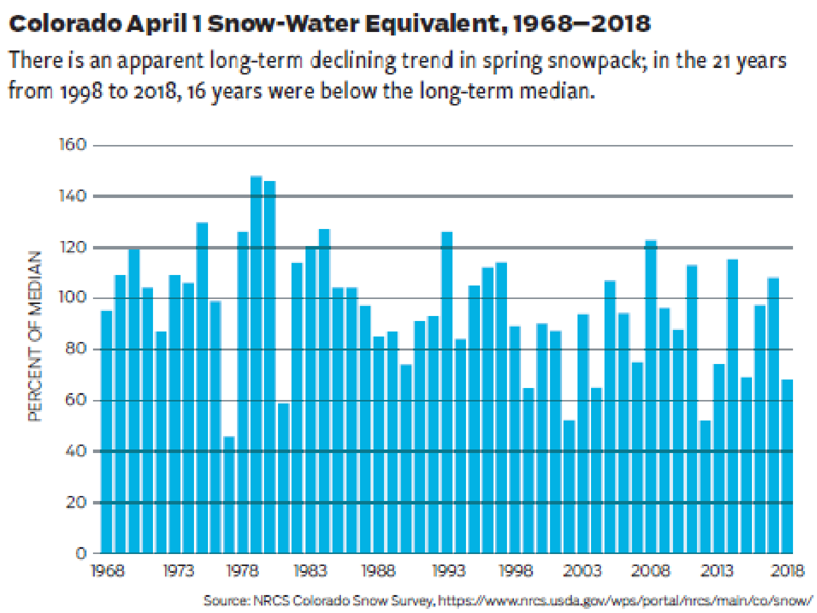

Fig. 5: Snowpack ratios in Colorado (Harvey).

Years of El Niño and La Niña events and the South Platte River Basin snowpack totals*:
(*United States Department of Agriculture)

El Niño Events Winter Months	Snowpack Ratios in April	La Niña Events Winter Months	Snowpack Ratios in April
1972-73	102%	1970-71	128%
1977-78	129%	1973-74	126%
1979-80	148%	1975-76	105%
1982-83	113%	1988-89	92%
1986-87	99%	1998-99	75%
1987-88	116%	1999-2000	106%
1991-92	102%	2007-08	118%
1994-95	84%	2010-11	137%
1997-98	94%	2011-12	61%
2002-03	125%		

2006-07	104%
2009-10	90%
2015-16	108%
2018-19	133%

Years of El Niño and La Niña events and the Colorado River Basin snowpack totals*

El Niño Events Winter Months	Snowpack Ratios in April
1972-73	94%
1977-78	140%
1979-80	140%
1982-83	119%
1986-87	86%
1987-88	106%
1991-92	94%
1994-95	109%
1997-98	94%
2002-03	111%
2006-07	88%
2009-10	81%
2015-16	107%
2018-19	133%

La Niña Events Winter Months	Snowpack Ratios in April
1970-71	134%
1973-74	119%
1975-76	95%
1988-89	83%
1998-99	78%
1999-2000	105%
2007-08	132%
2010-11	141%
2011-12	54%

Years of El Niño and La Niña events and the Rio Grande River Basin snowpack totals*:

El Niño Events Winter Months	Snowpack Ratios in April
1972-73	142%
1977-78	95%
1979-80	153%
1982-83	113%
1986-87	130%
1987-88	74%
1991-92	102%
1994-95	136%
1997-98	98%
2002-03	83%
2006-07	75%
2009-10	101%
2015-16	79%
2018-19	133%

La Niña Events Winter Months	Snowpack Ratios in April
1970-71	51%
1973-74	86%
1975-76	108%
1988-89	116%
1998-99	56%
1999-2000	66%
2007-08	132%
2010-11	82%
2011-12	54%

Five El Niño events in the past 50 years have preceded La Niña events, creating consecutive years of El Niño-La Niña events. One of those El Niño events was observed in consecutive years, in 1986-87 and 1987-88. Six El Niño events in the past 50 years have not preceded La Niña events. Of all of the events, two El Niño events which were not followed by La Niña events created above median snowpack totals for all three basins.

Snowpack ratios in April by basin for the El Niño events which were followed by a La Niña event*

Year	South Platte	Colorado	Rio Grande
1972-73	102%	94%	142%
1986-87 *	99%	86%	130%
1987-88 *	116%	106%	74%
1997-98	94%	94%	98%
2006-07	104%	88%	75%
2009-10	90%	81%	101%
2015-16	108%	107%	79%

Snowpack ratios in April by basin for the El Niño events which were NOT followed by a La Niña event*

Year	South Platte	Colorado	Rio Grande
1977-78	129%	140%	95%
1979-80	148%	140%	153%
1982-83	113%	119%	113%
1991-92	102%	94%	102%
1994-95	84%	109%	136%
2002-03	125%	111%	83%

Snowpack ratios in April by basin for the La Niña events which were preceded by an El Niño event*

Year	South Platte	Colorado	Rio Grande
1973-74	126%	119%	86%
1988-89	92%	83%	116%
1998-99	75%	78%	56%
2007-08	118%	132%	132%
2010-11	137%	141%	82%
2016-17	103%	108%	108%

Drought cycles remain prevalent in Colorado. There have been cycles of drought, at different degrees, in Colorado since measurable data has been collected and certainly prehistorically (Fig. 6 and Fig. 7).

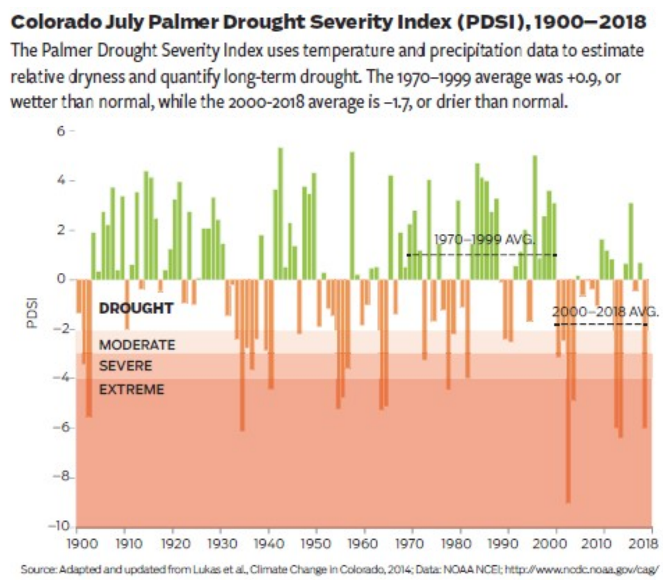

Fig. 6: The index values indicate greater severity of drought, though not increased occurrence or length, since the turn of the millennium than the nearly two decades previous (Harvey).

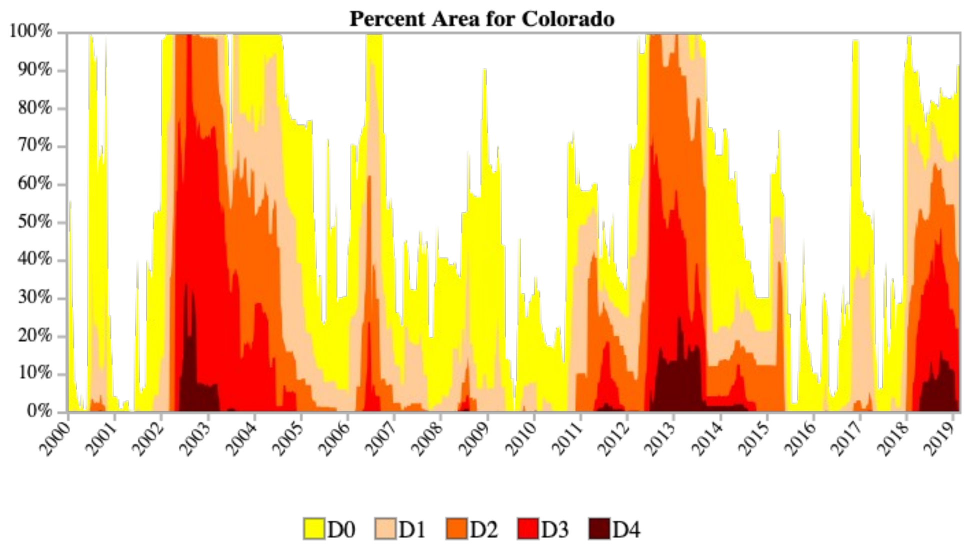

Fig. 7: The cycles of droughts are illustrated when examining The Percent Area for Colorado Affected by Different Degrees of Drought.
D0-abnormally dry; D1-moderate drought; D2-severe

Emerging Patterns and Dissonance

Few conclusive affirmative correlations can be derived from the occurrence of El Niño and La Niña and the snowpack totals relative to the median in any of the basins observed.

During El Niño events, registers for snowpack totals (percent of average) range from 84% to 148% in the South Platte River Basin, 81% to 140% in the Colorado River Basin, and 74% to 153% in the Rio Grande River Basin. Of the 14 years of the events: four (29%) of the years registered below median totals in the South Platte River Basin, 10 (71%) of the years above; five (36%) of the years registered below median totals in the Colorado River Basin, nine (64%) of the years above; and six (43%) of the years registered below median totals in the Rio Grande River Basin, eight (57%) of the years above. These ranges suggest it would not be conclusive to predict an above or below total of precipitation for the year in which the event occurs.

During the La Niña events, registers for snowpack totals (percent of average) range from 61% to 136% in the South Platte River Basin, 54% to 141% in the Colorado River Basin, and 51% to 132% in the Rio Grande River Basin. Of the 9 years of the events: three of the years (33%) registered below median totals in the South Platte River Basin, six (67%) of the years above; four (44%) of the years registered below median totals in the Colorado River Basin, five (56%) of the years above; and four of the years registered below median totals in the Rio Grande River Basin, five of the years above. These ranges suggest it would not be conclusive to predict an above average or below average total of precipitation for the year in which the event occurs.

No discernible pattern can be deduced from observing the consecutive occurrences of the events. In those years of El Niño events, the snowpack totals ranged from 74% in the Rio Grande Basin in 1987-88, to 142% in the Rio Grande Basin in 1972-73. The snowpack in the three basins in a given year exhibited ranges as low as 4% and up to 40%, which indicates be a lack of consistency of snowpack percentages within a given year of these events. It is not viable to conclude about the intensity of the precipitation in the winter months of an El Niño event based on the presence of a La Niña event on the next consecutive year. Of these, only the El Niño events of 1979-80 and 82-83 produced above median snowpack totals in all three basins.

No discernible pattern can be deduced from observing the occurrences of El Niño events which were not followed by La Niña events. In those years, the snowpack totals ranged from 83% in the Rio Grande Basin in 2002-03 to 153% in the Rio Grande Basin in 1979-80. The snowpack in all three basins, in any given year exhibited ranges as low as 6% and up to 45%, which indicates a lack of consistency of snowpack percentages in those years. It is not viable to conclude about the intensity of the precipitation in the winter months of an El Niño event in the years in which they had not been followed by La Niña events.

No discernible pattern can be deduced from observing the occurrences of La Niña events which are preceded by El Niño events. In those years, the snowpack totals ranged from 56% in the Rio Grande Basin in 1998-99, to 137% in the South Platte Basin in 2010-2011. The snowpack in all three basins in any given year exhibited ranges as low as 14% and up to 59%, which indicates a lack of consistency of snowpack percentages in those years. It is not viable to predict the intensity of the precipitation in the winter months of La Niña events in years which are preceded by an El Niño event.

The Rio Grande Basin did experience the highest ratios of snowpack of all the basins in all of the years observed in which El Niño events were followed by La Niña events: 142% in 1972-73; and in years which El Niño events were not followed by La Niña events: 153% in 1979-80. The South Platte Basin experienced the highest ratio of snowpack of all the basins in all of the years observed which La Niña events were preceded by El Niño events: 137% in 2010-11.

The years in which the PDSI (Palmer Drought Severity Index) recorded the most severe in drought conditions in the past 50 years were 1964 and 2005, which were years not characterized by ENSO events. According to Drought.gov, from the past 19 years, the highest percentages of areas of Colorado in a degree of drought occurred in 2002 and ’12. The percent of Colorado in drought conditions at any degree was at its highest in 2002, which was not a year characterized by either ENSO events.

The years in which the PDSI recorded the most favorable water security conditions were in 1983 and ’95, which were both years characterized by El Niño events. Snowpack conditions in Colorado in the past 50 years peaked between 1978 and ‘80, of which 1978 and ‘80 were prevalent El Niño years. In 2008, the seventh greatest snowpack ratio by year occurred in a La Niña year. The four highest ratios on record not including the events in ’78 and ’80 were in 1975, ’79, ’84, and ’93, all years which were preceded by an ENSO event, though not characterized by one itself. According to Drought.gov, from the past 19 years, the three years in which the lowest percentage of Colorado was in drought conditions at any degree were 2001, ’09, and ’15, all three years ones which preceded El Niño events. There seems to be no conclusive predictions for water security in the region according to the inconsistency of years with drought conditions and years in which water security is greatest according to an ENSO event.

Discussion

During the El Niño event of 2018-19, swells of moisture continued to pass over and precipitate on states in the Western U.S. through the spring, and significantly increased the amounts of snowpack throughout the Colorado’s river basins. Typically, during a time when snowpack totals decrease sharply in the melting season, the ratios in all three river basins increased in late April and early and late May. On May 27, 2019, the South Platte River basin snowpack measured 184% of median snowpack; the Colorado River basin measured 209%; and the Rio Grande River Basin increased to 286% (National Resources Conservation Service). Roads which cross the Rockies at high elevations, like Independence Pass, Mt. Evans Road, and Trail Ridge Road in Rocky Mountain National park remained closed, due to snowpack, into May and June, well past their usually scheduled opening dates. Popular ski resorts in Colorado, like Aspen Mountain and Purgatory, re-opened in late May and June because of their advantageous snowpack totals for the year. Officials in Lake City, a town in Southwestern Colorado with an elevation of 8,861 feet above sea level near the headwaters of the Cebolla Creek, a tributary of the Gunnison River, enabled a search for volunteers to help fill sand bags to mitigate flooding in May of 2019. At the same time as the rivers crested in Colorado, the storms which roll over Colorado’s Rockies continued into east-lying regions to create super cell storms and severe flooding, pummeling hail events, and frenetic tornados, ravaging Eastern Colorado, Oklahoma, and Kansas.

After the El Niño winter of 2019, the most recent severe drought cycle which began a year and a half prior, had receded. On May 24, 2019, KDVR Fox Denver declared in a headline: “It’s over: Colorado declared 99.99% drought-free after an epic winter.” Data from the U.S. Drought Monitor was cited in the article (Current Map), and the recession of the drought was emphasized: “Only 0.01% of the state -- about

8 square miles -- is experiencing abnormally dry conditions…" (It's over). Snowpack retention increased over the spring as well. By early June, the snowpack ascended to above 500% of median and over 2800% above the snowpack at the same time in 2018, indicating slower than usual snowpack melt (Natural Resources Conservation Service) (Fig. 8).

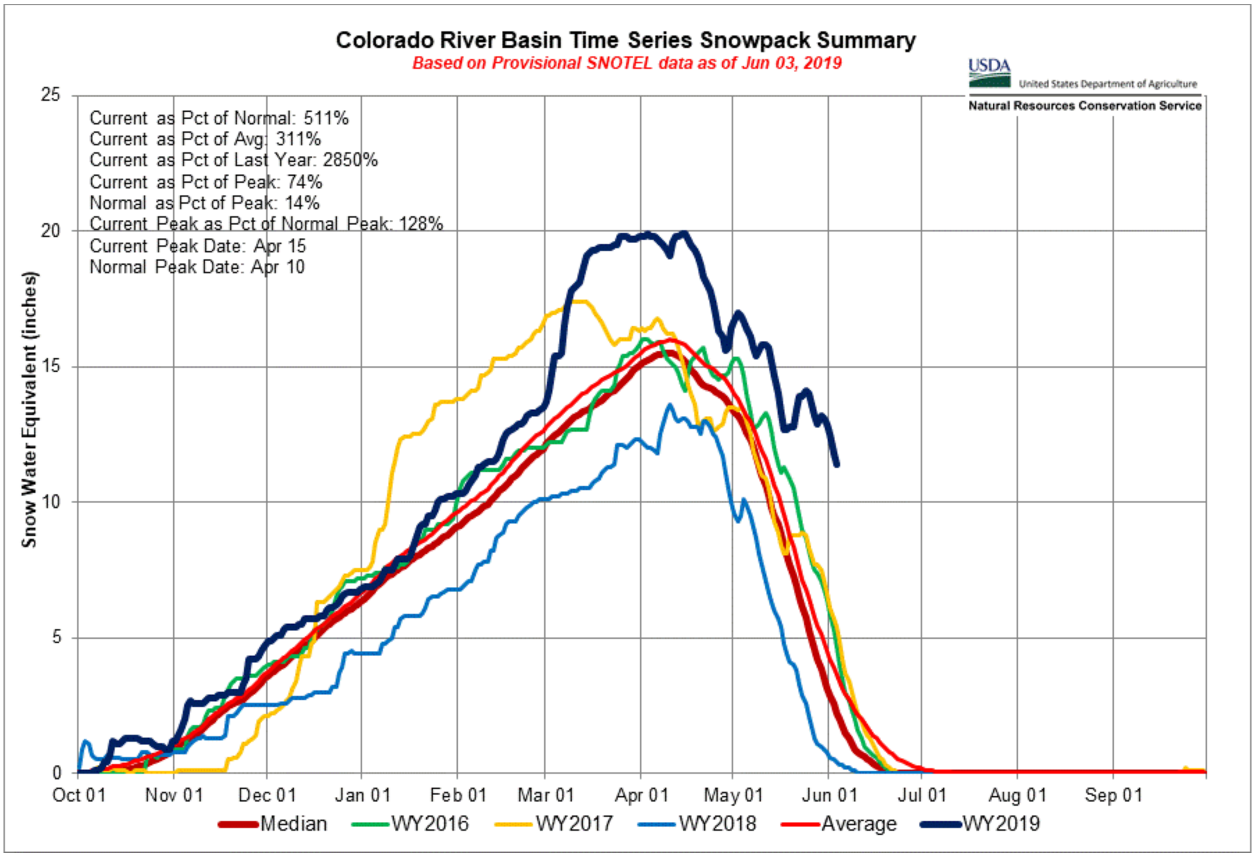

Fig. 8: The snowpack in the Colorado River basin did experience higher than normal levels, it also seemingly experienced higher than normal retention rates (Natural Resources Conservation Service).

In order to best project precipitation patterns in Colorado and the West, the next sets of data to inlay in for comparison would certainly be the incline of warming patterns according to Global Warming theories in Colorado (Fig. 9).

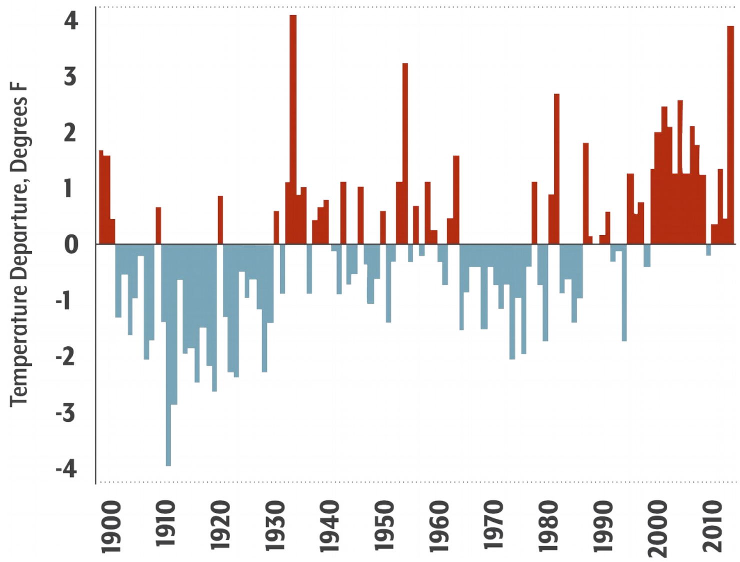

Fig. 9: In Colorado over the past 30 years, there has been a high frequency of temperature departures above normal, indicating a pattern of

On May 30th, 2019, CNN led an article about recent weather patterns in the United States: “The continental US just had its wettest 12 months in 124 years on record,” referring to the water year from May 1, 2018 to April 30th 2019. The precipitation trends are attributed to “the broad trend of climate change pushing up precipitation in the US,” characterized by hurricanes, bomb cyclones, and El Niño events of that water year (Murphy). **How are precipitation results affected by global warming patterns? How effective can we be projecting precipitation/snowpack totals by analyzing data and trends?**

Certainly cloud seeding, the practice of vaporizing and elevating silver iodide into storm-bearing clouds to accelerate precipitation, has played a part in the variation of precipitation which occurs over the Rockies. Cloud seeding programs have occurred in Colorado the 1950s and the 1980s, and now have been practiced more since the droughts of the early 2000s. **How effective are cloud seeding programs at escalating precipitation totals?**

When late season percentages are calculated, there is a contingency on the rates of snowmelt for the time period. **What are the variances of snowmelt rates in April for the years of El Niño and La Niña events? How have they affected ratios? What is the effect of their reporting on the sentiment of general water security for the population in the West?**

Conclusion

The ENSO events in the Pacific Ocean have an evident effect on the weather patterns in the Rocky Mountain region and across North America. It is unclear if there are definitive correlations from the events to the winter precipitation patterns in the Colorado Rockies; in anticipation of ENSO events, it is not feasible to forecast any degree of water security for the regions to which the snowpack waters supply. Too much variation of snowpack totals has been recorded in the past 23 events to determine any certainty for predictions. Furthermore, any assurance which could be derived will be diluted by a number of other variables, including global warming patterns, existing drought cycles, cloud seeding programs, and erratic melting rates.

Resources

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