The Past, Present, and Future of Colorado’s Climate

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Along with: Zach Schwalbe, Becky Bolinger, Peter Goble, Nolan Doesken
Brief history of the CCC

• Until 1973, the federal government operated a “state climatologist” program – but in 1973 this was abolished

• Later that same year, Colorado established the Colorado Climate Center at CSU with support through the Colorado Agricultural Experiment Station
Our mission

The Colorado Climate Center at CSU provides valuable climate expertise to the residents of the state through its threefold program of:

1) *Climate Monitoring* (data acquisition, analysis, and archiving)
2) *Climate Research*
3) *Climate Services* (providing data, analysis, climate expertise, education and outreach)
Annual average precipitation
Systematic weather data collection began in Colorado in the 1870s and 1880s.
Weather reports began on Pikes Peak in 1873.

Reports were sent by telegraph every few hours.

Stories abounded in the national media of the rigors of Colorado Climate.
By 1885, the initial “climatology” of Colorado was taking shape. The semiarid and highly variable nature of Colorado was identified quickly— in many ways similar to today.

Photo Credit: NOAA Photo Library
The goal back then was not to detect climate change – but to simply define and describe the climate of our region.
But "IT" was talked about even then.

Colorado being an arid state, the amount of precipitation is at all times a vital question. Liability to a marked deficiency in rainfall in any region is a matter of grave concern to those engaged in agriculture and other interests. We often hear it stated that the rainfall is changing, that the settling up of the country and the planting of trees and building of reservoirs, forming lakes and wet places throughout the country, is causing an increase in the amount of our precipitation, but long series of observations taken at different places over the world, do not bear out that claim.

YEARS OF STUDY SHOWS CLIMATE NOT CHANGING

We often hear the statement made that the climate is changing, and the popular belief that such is the case can only be explained by the generally short and defective memories of people who through exposure to a few severe storms in the past, or inconvenience, or perhaps loss from a few of them, unintentionally exaggerate the severity and frequency of their occurrence. Although large fluctuations occur in different years with some indication of periodical terms, especially in Colorado, where the range of temperature is great, there seems to be no progressive change. These fluctuations are large and often in the same direction for several successive years.

In the meteorological data for the last one hundred years, the record of some places extending still further back, there...
So, what have we learned in the ~100 years of observations and research since this time?

Let’s first look at where we get our data...
NWS Cooperative observer program – long-term measurements
The Historic Fort Collins Weather Station
National Weather Service Cooperative Station 03-3004

This is one of the longest operating weather stations in the western U.S., monitoring temperature, humidity, precipitation (rain, hail and snow), evaporation, wind, solar radiation, clouds, visibility, barometric pressure and soil temperatures. Weather observations for research, teaching and public information have been conducted on campus since the early 1870s. Continuous support for this historic weather station has been provided by the Colorado Agricultural Experiment Station since 1889.

Colorado Agricultural Experiment Station

Early data collected here aided agricultural and Early data collected here aided agricultural and irrigation research and development. Beginning in the 1930s, irrigation research and development. Beginning in the 1930s, this station provided weather support for aviation and transportation safety. Uses continue to expand today.

Data are publicly available for tracking climate trends, variations and extremes and their impacts here in northern Colorado.
National Weather Service automated stations

Map showing NWS stations (from mesowest.utah.edu)

COLORADO CLIMATE CENTER
CoAgMET

- 85 stations
- 44 stations with 5-minute data
- Interactive mapping through eRAMS
- Includes
  - Time series charts
  - Site photos

coagmet.colostate.edu
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Map showing NWS stations (from mesowest.utah.edu)

COLORADO CLIMATE CENTER
NWS stations + CoAgMET + other networks

(from mesowest.utah.edu)
SNOTEL (Snow telemetry)

Tower SNOTEL site (10,500 ft, near Steamboat) https://www.wcc.nrcs.usda.gov/siteimages/825.jpg
Remote sensing: radar and satellite

8 May 2017 hailstorm
https://twitter.com/NWSBoulder/status/993937075920625665

1 May 2018 storm in eastern Colorado
https://twitter.com/bill_line/status/991486848370466816
Mountains cause beam blockage for radars
Upper-air data

Weather balloon launch during the PECAN field campaign, June 2015

Skew T log p thermodynamic diagram
Putting them all together...

PRISM technique, prism.oregonstate.edu

NOAA multi-sensor precipitation analysis (radars + gauges)
(3 days ending 13 Sept 2013)
What Makes Our Colorado Climate

- High elevation (highest state by far)
- Mid-Latitude location (lively seasonal changes)
- Interior Continental Location far from moisture sources
- Complex Mountain topography
- Solar energy and seasonal cycles drive our climate
What have we learned from 130 years of continuous climate monitoring?
Colorado is a sunny place. People like sunshine! So does vegetation – to a point.

National Renewable Energy Laboratory: www.nrel.gov
The winds blow, but not as persistently as some places
We always experience large seasonal and diurnal temperature variations.
Complex temperature variations due to elevation and topography

Usually colder in the mountains!
We get rain and snow – but often not enough.
Seasonal precipitation in Colorado varies greatly from place to place.

Month of maximum average precipitation
Data: PRISM Climate Group, prism.oregonstate.edu
Year-to-Year Variations in Precipitation are Huge
No two years are ever the same
Water Year 2018: One to forget!

2nd driest water year on record for Colorado

3rd warmest water year on record for Colorado
### Water Year 2018: One to forget!

#### Number of 90 Degree Days

<table>
<thead>
<tr>
<th>Location</th>
<th>90° days</th>
<th>Rank</th>
<th>Normal</th>
<th>Record</th>
<th>Record Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denver</td>
<td>53</td>
<td>7th</td>
<td>37</td>
<td>67</td>
<td>2012</td>
</tr>
<tr>
<td>Fort Collins</td>
<td>37</td>
<td>10th</td>
<td>20</td>
<td>57</td>
<td>2012</td>
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<tr>
<td>Boulder</td>
<td>46</td>
<td>10th</td>
<td>26</td>
<td>60</td>
<td>1952</td>
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<tr>
<td>Colorado Springs</td>
<td>34</td>
<td>T4th</td>
<td>19</td>
<td>49</td>
<td>2012</td>
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<td>Pueblo</td>
<td>82</td>
<td>T7th</td>
<td>67</td>
<td>90</td>
<td>2000</td>
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<td>T4th</td>
<td>50</td>
<td>88</td>
<td>1954</td>
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<tr>
<td>Lamar</td>
<td>76</td>
<td>T6th</td>
<td>78</td>
<td>129</td>
<td>1934</td>
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<td>Walsh</td>
<td>77</td>
<td>9th</td>
<td>67</td>
<td>95</td>
<td>2011</td>
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<tr>
<td>Alamosa</td>
<td>5</td>
<td>T10th</td>
<td>2</td>
<td>20</td>
<td>2003</td>
</tr>
<tr>
<td>Cortez</td>
<td>60</td>
<td>2nd</td>
<td>33</td>
<td>69</td>
<td>2002</td>
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<tr>
<td>Grand Junction</td>
<td>90</td>
<td>T1st</td>
<td>59</td>
<td>90</td>
<td>2018</td>
</tr>
<tr>
<td>Montrose</td>
<td>78</td>
<td>1st</td>
<td>34</td>
<td>78</td>
<td>2018</td>
</tr>
<tr>
<td>Steamboat Springs</td>
<td>11</td>
<td>T13th</td>
<td>4</td>
<td>29</td>
<td>2002</td>
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<td>0</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Rangely</td>
<td>67</td>
<td>T5th</td>
<td>49</td>
<td>71</td>
<td>1955</td>
</tr>
<tr>
<td>Akron</td>
<td>44</td>
<td>T30th</td>
<td>40</td>
<td>73</td>
<td>2012</td>
</tr>
<tr>
<td>Trinidad</td>
<td>48</td>
<td>T7th</td>
<td>24</td>
<td>62</td>
<td>2002</td>
</tr>
</tbody>
</table>

Data gathered by Peter Goble (Colorado Climate Center)
Water Year 2018: One to forget!
Water Year 2019: Off to a better start, but still reasons for concern

**U.S. Drought Monitor**

**Colorado**

January 1, 2019  
(Released Thursday, Jan. 3, 2019)  
Valid 7 a.m. EST

### Statistics Comparison

<table>
<thead>
<tr>
<th>Week</th>
<th>None</th>
<th>D0-D4</th>
<th>D1-D4</th>
<th>D2-D4</th>
<th>D3-D4</th>
<th>D4</th>
<th>DSCI</th>
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<tbody>
<tr>
<td>2019-01-01</td>
<td>17.94</td>
<td>82.06</td>
<td>66.26</td>
<td>54.91</td>
<td>27.11</td>
<td>11.22</td>
<td>242</td>
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<tr>
<td>2018-10-02</td>
<td>14.19</td>
<td>85.81</td>
<td>72.30</td>
<td>64.41</td>
<td>48.47</td>
<td>16.21</td>
<td>287</td>
</tr>
<tr>
<td>Change</td>
<td>-3.75</td>
<td>3.75</td>
<td>6.04</td>
<td>9.50</td>
<td>21.36</td>
<td>4.99</td>
<td>45</td>
</tr>
</tbody>
</table>

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

**Author:**  
David Miskus  
NOAA/NWS/NCDC/CPC

[http://droughtmonitor.unl.edu/](http://droughtmonitor.unl.edu/)
Water Year 2019: Off to a better start, but still reasons for concern

Colorado SNOTEL Snow Water Equivalent (SWE) Update Map with Site Data

Current as of Jan 06, 2019

- Statewide: 91%
- South Platte: 109%
- North Platte: 99%
- Yampa & White: 99%
- Colorado: 101%
- Gunnison: 89%
- San Miguel, Dolores, Animas & San Juan: 68%
- Upper Rio Grande: 72%
- Arkansas: 112%

SWE Percent of Median:
- Missing or Invalid
- < 50
- 50 - 69
- 70 - 89
- 90 - 109
- 110 - 129
- 130 - 149
- >= 150
- SNOTEL

United States Department of Agriculture
Natural Resources Conservation Service
About the stations

- **Anemometer and wind vane:** Wind speed, direction and gusts
- **Pyranometer:** Solar radiation
- **Tipping bucket rain gage:**
- **Temperature/Humidity sensor in radiation shield:**
- **Solar panel:** Powers the station when the sun shines
- **Data logger:**
- **Soil temperatures:** 2 and 6 inches below ground
- **Above all else facing South:**

*Image description:*
- Station setup with various instruments labeled for meteorological measurement.
- Solar panel positioned to catch sunlight.
- Temperature/Humidity sensor in a radiation shield.
- Anemometer and wind vane for wind measurement.
- Pyranometer for solar radiation measurement.
- Tipping bucket rain gage for precipitation measurement.
- Soil temperatures at different depths below the ground.
- Data logger for recording measurements.
CoAgMET

- 85 stations
- 44 5-minute stations
- interactive mapping through eRAMS
- includes
  - time series charts
  - site photos

coagmet.colostate.edu
Growing season summaries at long-term stations: Lucerne (2017)

http://climate.colostate.edu/2017ET/et_summary_lcn_anom.html
Using the ET data, we can put each growing season into a historical perspective. Very useful for drought monitoring!
The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth’s surface and the lower atmosphere.

Solar radiation powers the climate system.

Some solar radiation is reflected by the Earth and the atmosphere.

About half the solar radiation is absorbed by the Earth’s surface and warms it.

Infrared radiation is emitted from the Earth’s surface.

(illustration to follow courtesy of Scott Denning, CSU ATS)
Fall Night in Colorado

5 PM surface temperature = 15 °C = 60 °F

4 inches = 10 cm

390 W m⁻²

Radiation emitted by soil
Fall Night in Colorado

6 AM surface temperature = -60 °C = -78 °F

390 W m⁻²

4 inches = 10 cm

radiation emitted by soil
Fall Night in Colorado

6 AM surface temperature = 5 °C = 40 °F

Radiation emitted by air: 340 W m\(^{-2}\)

Radiation emitted by soil: 390 W m\(^{-2}\)

4 inches = 10 cm
The strongest evidence for the Greenhouse Effect is that we can survive night!
What effects do gases like CO2 have?

- Doubling CO$_2$ would add 4 watts to every square meter of the surface of the Earth, 24/7
- Doing that would make the surface warmer
- This was known before light bulbs were invented!

John Tyndall, January 1863
“Scientists expect a warmer future because it’s been warming up recently”

**WRONG!**

It’s because we know that when we add heat to things, they warm up
My background is in weather modeling and forecasting: how are weather & climate models different?

- They use the same basic physics: equations describing the motion of air
- They also use similar equations to represent processes like clouds, rain, etc.
- But there are some key aspects that are really important to one type of modeling and not so much to the other...

\[
\begin{align*}
\text{Mass conservation:} & \quad \frac{\partial}{\partial t} \left( \frac{\partial p}{\partial s} \right) + \nabla \cdot \left( \mathbf{v} \frac{\partial p}{\partial s} \right) + \frac{\partial}{\partial s} \left( s \frac{\partial p}{\partial s} \right) = 0 \\
\text{Thermal energy conservation:} & \quad \frac{\partial}{\partial t} \left( \theta \frac{\partial p}{\partial s} \right) + \nabla \cdot \left( \mathbf{v} \frac{\partial p}{\partial s} \right) + \frac{\partial}{\partial s} \left( s \frac{\partial p}{\partial s} \theta \right) - \theta \frac{\partial p}{\partial s} \\
\text{Momentum conservation:} & \quad \frac{\partial \mathbf{v}}{\partial t} + (\zeta + f) \mathbf{k} \times \mathbf{v} + \left( s \frac{\partial p}{\partial s} \right) \frac{\partial \mathbf{v}}{\partial p} \\
& \quad + \nabla \left( M + \frac{v^2}{2} \right) - \Pi \nabla \theta = \mathbf{F} \\
\text{Hydrostatic Equation:} & \quad \frac{\partial M}{\partial \theta} = \Pi.
\end{align*}
\]
Initial conditions are critical for weather forecasts!

One example of a chaotic system Lorenz explains is a ski run with moguls – he suggested Cat’s Meow at Loveland

Develop a model for a ski or board pushed from the top of the slope at a specified velocity.

From Lorenz, *The Essence of Chaos*
Space the boards 10 cm apart and push down the slope at identical velocity

From Lorenz, *The Essence of Chaos*
Now space them 1 millimeter apart

It takes more time/distance, but the boards eventually diverge even in this situation

From Lorenz, *The Essence of Chaos*
But they all ended up at the bottom of the hill!

And if you pushed lots and lots of boards, you’d get a pretty good idea of where they tend to finish – this is akin to climate modeling, where you don’t care about the weather on a given day, but about the *statistics* of the weather over long time periods.

From Lorenz, *The Essence of Chaos*
And if you changed the steepness of the hill, or removed some of the moguls, you’d expect some rather different outcomes...

From Lorenz, *The Essence of Chaos*
Ensembles of models

- In both weather and climate modeling, we want to use ‘ensembles’ – multiple models with some small changes to the initial conditions, or the parameters in the model – in principle this gives a good representation of the range of possible outcomes, best and worst case scenarios, etc.
Ensembles of models

• In both weather and climate modeling, we want to use ‘ensembles’ – multiple models with some small changes to the initial conditions, or the parameters in the model – in principle this gives a good representation of the range of possible outcomes, best and worst case scenarios, etc.
Recommended reading – some of the following is based on this report

http://wwa.colorado.edu/climate/co2014report/
Statewide temperatures, 1895-2017
Average temperature increase of 2.5-5°F, for middle-of-the-road emissions scenario.
Mean: 48.3°F
Std Dev: 1.9°F
Warmest Year: 53.5°F (2012) 2017 was 2nd warmest at 52.4°F 2018: 51.2, 11th warmest
Coolest Year: 43.9°F (1912)
Lowest temperature of each year

Coldest temp (F) each year at Fort Collins, 1893-2017

Highest temperature of each year

Warmest temp (F) each year at Fort Collins, 1893-2017
Number of below-zero nights

Number of 90-degree days
Trends around the state: temperature

From “Climate Change in Colorado” report, 2014:
http://wwa.colorado.edu/climate/co2014report/
What does a 2-degree change in average temperature look like?

![Histogram of July high temperatures in Fort Collins, 1900-1958](image)

- Frequency of July high temperatures, Fort Collins, 1900-1958
- Average = 84.47°F

**Daily high temperature (F)**

**Frequency of observations**

- 0.00
- 0.01
- 0.02
- 0.03
- 0.04
- 0.05
- 0.06

*COLORADO CLIMATE CENTER*
What does a 2-degree change in average temperature look like?

![Histogram of July high temperatures, Fort Collins, 1959-2017]

- Frequency of July high temperatures, Fort Collins, 1959-2017
- Average = 86.36°F
What does a 2-degree change in average temperature look like?
**TABLE 5-1. Projected monthly temperature change for eight subregions under RCP 4.5 for 2035–2064**

<table>
<thead>
<tr>
<th>Subregion</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
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<tr>
<td>Northeastern Plains</td>
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<td></td>
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<td>Central Mountains</td>
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</tbody>
</table>

Legend:
- 3.0°F
- 3.5°F
- 4.0°F
- 4.5°F
- 5.0°F
Precipitation is a lot more complicated...
Mean: 15.1”
Std Dev: 4.0”
Wettest Year: 28.28” (1961)
Driest Year: 7.13” (1893)

Note: these averages are over the entire record, rather than the 30-year window used for official normals.
Mean: 48.1”
Std Dev: 18.3”
Record High: 114.0” (1979-80)
Record Low: 8.5” (1945-46)
Trends around the state: precipitation

From “Climate Change in Colorado” report, 2014:
http://wwa.colorado.edu/climate/co2014report/
Precipitation is a lot more complicated...

From Lukas et al. (2014), *Climate Change in Colorado*
From Lukas et al. (2014), *Climate Change in Colorado*
Climate change is water change

• Remember that even if precipitation doesn’t change (or increases slightly), higher temperatures...

• Cause more evaporation & evapotranspiration
  – Puts stress on plants requiring irrigation; can reduce reservoir levels
  – We have always had & will always have droughts in CO, but this could make them worse

• Can lead to earlier/faster spring snowmelt
  – Changes the expected time of water availability in rivers
What can be said about extreme events?


Summary (1)

• We’ve seen warming in Colorado across all seasons, with the largest trend since about 1980
• No long-term trends have been detected for statewide precipitation
• Peak snowpack (SWE) does not show a long-term trend, but the timing of the peak has shifted earlier, owing to both higher temperatures and dust-on-snow
• Long-term warming is expected to continue (with high confidence); future changes in precipitation are much less certain
• For most types of extreme/hazardous weather, it remains challenging to establish a climate-change fingerprint, aside from decreased occurrence of very cold air
  – Some, like wildland fire, likely have been influenced by climate change, but challenging to separate from other influences
Summary (2)

• By 2050, the climate of Colorado will still be recognizable as the climate of Colorado:
  – Plenty of snow in the mountains most winters
  – Summers with warm days and (relatively) cool nights
  – Highly variable precipitation from year to year
  – Regular problems with droughts, floods, fires, water availability, and severe weather

• But:
  – The snowpack is likely to melt earlier in the spring
  – More frequent occurrence of warm weather, less frequent extreme cold
  – When droughts happen, they may be worse (mainly owing to increased evaporation) – increasing threats to water supply
  – Not clear what changes there will be to other hazards like extreme rainfall, severe weather, etc.
And finally, the all-important question: “Do you have a rain gauge?” (and a snowboard!)
If you are interested in weather and the variations in precipitation, please join the Community Collaborative Rain, Hail and Snow Network

http://www.cocorahs.org

or see me today
CoCoRaHS data in Hurricane Florence, September 2018

35.05” in 7 days
Swansboro, NC
CoCoRaHS data in Hurricane Florence, September 2018

35.05” in 7 days
Swansboro, NC
Thank you!

http://climate.colostate.edu/
russ.schumacher@colostate.edu

Follow us on Facebook and Twitter! @ColoradoClimate
The annual cycle of Colorado Temperatures
But this is how daily weather, over time, defines our climate.
Seasonal Precipitation in Colorado varies greatly from place to place.

Water Year Average Precipitation for Selected Stations
E-W transect along I-70

- Grand Junction
- Vail
- Vail Pass
- Georgetown
- Denver
- Burlington

Precipitation (inches)

Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep