“Is this global warming?”
Observed global temperature

From IPCC 2013: annual average global temperature

Approximately 1°C of global warming over the past century (U.N. target is 2°C)
“Climate Risk Management”

IPCC WGII, 2014
Ongoing California drought

Tioga Pass, January 2015

Source: Bartshé Miller
Current drought has produced many statewide records

- most severe NOAA NCDC drought indicator values
- lowest calendar-year precipitation
- lowest 12-month precipitation
- warmest calendar-year temperatures
- warmest winter temperatures
- lowest April 1st snowpack
- warmest/driest 3-year period

UC Davis (Aug 2015):

$2.7 billion damage
21,000 jobs

<table>
<thead>
<tr>
<th>Description</th>
<th>Impact</th>
<th>Base year levels</th>
<th>Percent change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface water shortage (million acre-ft)</td>
<td>8.7</td>
<td>18.0</td>
<td>-48%</td>
</tr>
<tr>
<td>Groundwater replacement (million acre-ft)</td>
<td>6.0</td>
<td>8.4</td>
<td>72%</td>
</tr>
<tr>
<td>Net water shortage (million acre-ft)</td>
<td>2.7</td>
<td>26.4</td>
<td>-10%</td>
</tr>
<tr>
<td>Drought-related idle land (acres)</td>
<td>540,000</td>
<td>1.2 million*</td>
<td>45%</td>
</tr>
<tr>
<td>Crop revenue losses ($)</td>
<td>$900 million</td>
<td>$35 billion</td>
<td>2.6%</td>
</tr>
<tr>
<td>Dairy and livestock revenue losses ($)</td>
<td>$350 million</td>
<td>$12.4 billion</td>
<td>2.6%</td>
</tr>
<tr>
<td>Costs of additional pumping ($)</td>
<td>$100 million</td>
<td>$780 million</td>
<td>75.5%</td>
</tr>
<tr>
<td>Direct costs ($)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total economic impact ($)</td>
<td>$2.7 billion</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Direct job losses (farm seasonal)</td>
<td>10,100</td>
<td>200,000$</td>
<td>5.1%</td>
</tr>
<tr>
<td>Total job losses</td>
<td>21,000</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
**Atmospheric conditions**

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**The Ridiculously Resilient Ridge**

The term was coined by Stanford graduate student Daniel Swain to describe the atmospheric pattern that's behind California's recent warm and dry winters. The graphic shows what has changed compared with how typical winter storms move across the Eastern Pacific.

**TYPICAL WINTER STORM PATTERN**

Pacific storms usually approach the West Coast from the north and west, bringing rain and high-elevation snow. The storm track wobbles north and south many times over the course of each winter, bringing periodic storminess to California. This results in rain and colder conditions along the West Coast.

**WARM AND DRY WINTERS**

The Ridiculously Resilient Ridge is a region of unusually persistent high pressure, which has pushed the Pacific storm track to the north of its typical position along the West Coast. This has prevented typical winter storms from reaching California.

Source: Daniel Swain, Stanford University

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*Swain et al., 2014*
Atmospheric conditions

• Historically ridging has caused dry conditions in California

• 2013 was lowest precipitation and most extreme Ridge on record

• 95% chance that global warming has at least tripled the probability of these atmospheric conditions

Swain et al., 2014
Anthropogenic warming has increased drought risk in California

Noah S. Diffenbaugh\textsuperscript{a,b,1}, Daniel L. Swain\textsuperscript{a}, and Danielle Touma\textsuperscript{a}

\textsuperscript{a}Department of Environmental Earth System Science and \textsuperscript{b}Woods Institute for the Environment, Stanford University, Stanford, CA 94305

Edited by Jane Lubchenco, Oregon State University, Corvallis, OR, and approved January 30, 2015 (received for review November 22, 2014)
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San Francisco Chronicle

Facing drought’s hard reality

Disturbing trends

When coupled, less precipitation and warmer temperatures mean less moisture in the ground – and less water available in California.

\textbf{Precipitation (Rain and snow)}

- More

- Less

\begin{figure}
\begin{subfigure}{0.33\textwidth}
\centering
\includegraphics[width=\textwidth]{precipitation}
\caption{Precipitation}
\end{subfigure}
\begin{subfigure}{0.33\textwidth}
\centering
\includegraphics[width=\textwidth]{temperature}
\caption{Temperature}
\end{subfigure}
\begin{subfigure}{0.33\textwidth}
\centering
\includegraphics[width=\textwidth]{soil_moisture}
\caption{Soil moisture index}
\end{subfigure}
\end{figure}

The charts above are calculated from records beginning in 1895. The lines represent anomalies from the average. The black dots represent periods of drought.

\textit{Source: Noah Diffenbaugh, Stanford University}

\textit{John Blanchard / The Chronicle}
Historically, about a quarter of years have had low precipitation and warm temperatures, and about a quarter have had low precipitation and cool temperatures.

Historically, low precipitation years have been >2x as likely to produce drought if they co-occur with warm conditions.
Observations

- Historically, about a quarter of years have had low precipitation and warm temperatures, and about a quarter have had low precipitation and cool temperatures.

= 2014

% of years that fall in quadrant

drought anomaly (s.d.)
Observations

- Historically, low precipitation years have been >2x as likely to produce drought if they co-occur with warm conditions.
Observations

- In the past two decades, 80% of years have been warm.
- Probability that:
  1. there is a drought
  2. that low precipitation years are also warm
  3. that negative precipitation years produce drought

=> have all doubled

\[= 2014\]
Global climate models

- There is very high statistical confidence that human emissions of greenhouse gases have caused:
  1. The observed long-term warming of California
  2. The observed increase in the percentage of low precipitation years that are also warm
Risk of high-impact conditions

Continued human emissions of greenhouse gases is likely to lead to:

1. Continued warming of California
2. Increased co-occurrence of dry years with extremely warm conditions
3. Increased occurrence of extremely low precipitation seasons and years
Extremely low snow years

Global Climate Model Ensemble

2°C global warming:
10-30% of years extremely low

4°C global warming:
40-80% of years extremely low

Diffenbaugh et al., 2012
Projected trend in spring snowpack

- Continued human emissions of greenhouse gases is likely to lead to:
  1. Continued warming of California
  2. Acceleration of decreasing spring snowpack
  3. Shift towards stronger influence of temperature on snowpack (regardless of uncertainty in precipitation)

Color = Trend in April 1 snow

Ashfaq et al., 2013
From Discover Magazine cover article in 1988

- Peter Gleick’s prediction of how California’s snow-dependent hydrology will respond to global warming

If atmospheric carbon dioxide levels double, the mountain snow that supplies much of California’s water will dwindle, creating winter floods and summer droughts.
Conclusions

• There is very high statistical confidence that global warming has increased the occurrence of persistent high atmospheric pressure over the northeast Pacific. (And those events demonstrate ridging, changes in the winds, and low precipitation over California…..)

• Probability that (1) there is a drought, (2) that low precipitation years are also warm, and (3) that negative precipitation years produce drought, have all doubled.

• There is very high statistical confidence that human emissions of greenhouse gases have caused: (1) the observed long-term warming of California, and (2) the observed increase in the percentage of low precipitation years that are also warm.

• Continued human emissions of greenhouse gases is likely to lead to (1) continued warming of California, (2) acceleration of decreasing spring snowpack, and (3) shift towards stronger influence of temperature on snowpack (regardless of uncertainty in precipitation).
“Is this global warming?”

Noah S. Diffenbaugh
Assoc. Professor and Senior Fellow

Source: Bartshé Miller