How California's Climate Shapes Water Resources

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Rationalizing the Allocation of California Water Workshop
Caltech
April 19, 2016

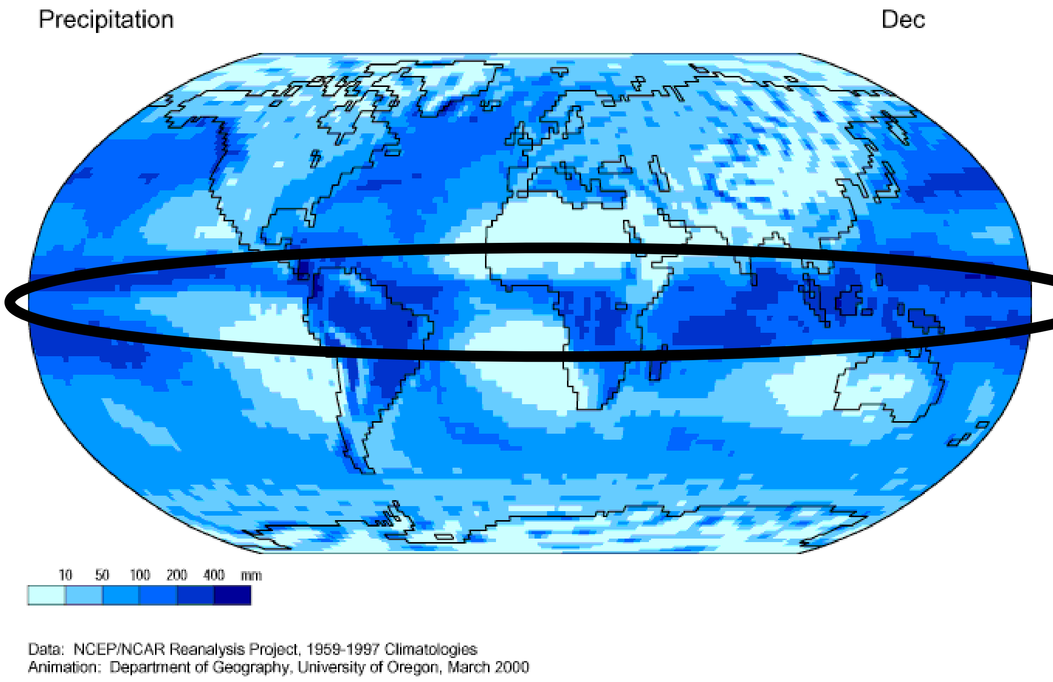
Today's Talk

1. A Mediterranean Climate
2. California's Precipitation Distribution in the Current Climate
3. Hydrologic Cycle Intensification
4. Changes in Extremes

1. A Mediterranean Climate

The global distribution of precipitation

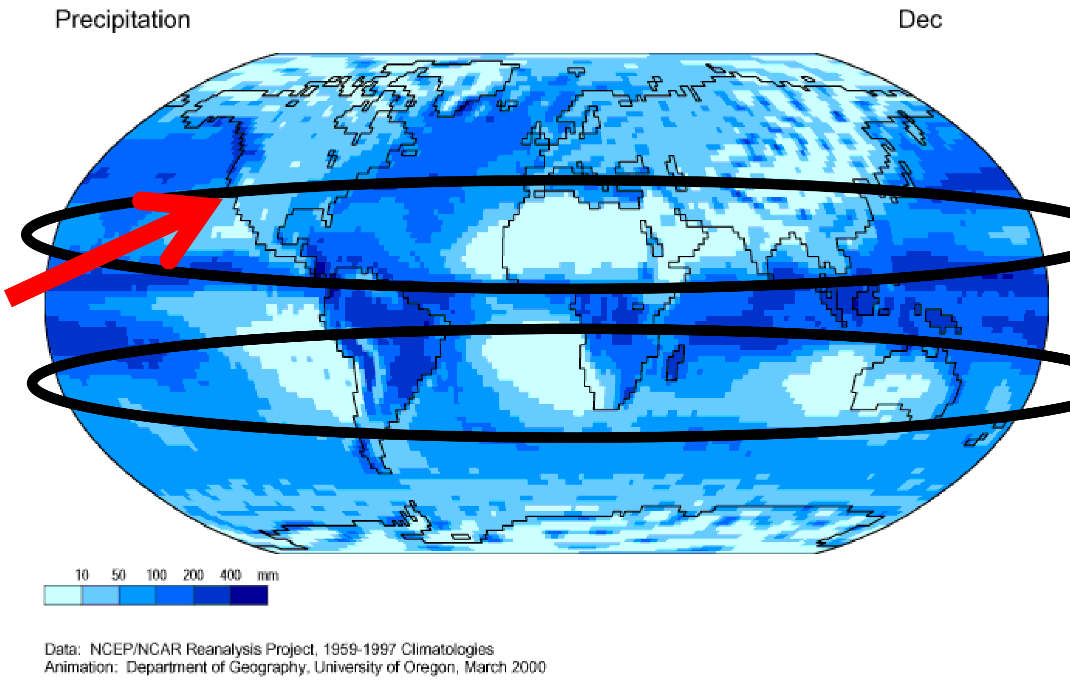
- Rising and sinking of air drives the distribution of precipitation across the globe.
- A key overturning cell, the Hadley cell, operates in the tropics and subtropics.
- Near the equator, air is heated by solar radiation. Heated air:
  - contains water vapor evaporated from the land or ocean surface
  - rises in the atmosphere
- As the air rises, it cools.



- Cooled air can hold less water vapor. The excess falls as precipitation.
- As a result, the deep tropics receive the most precipitation, globally.

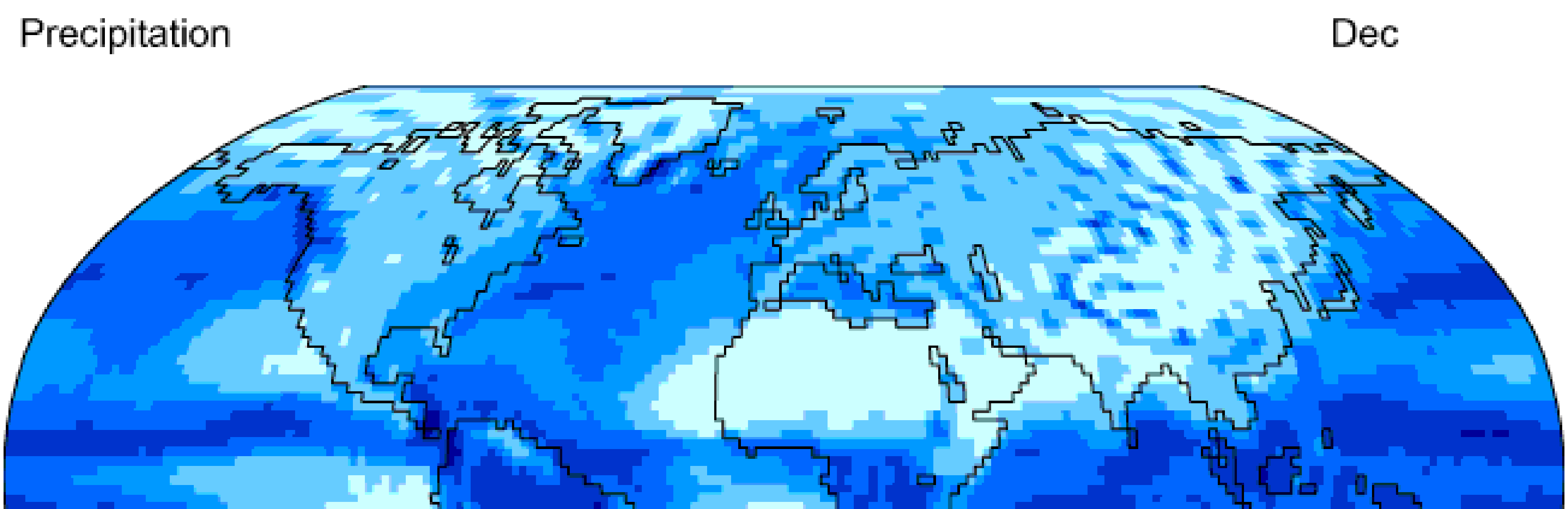
The global distribution of precipitation

- After rising, the air moves poleward to the subtropics. Then it sinks, and warms.
- This air is now very dry, since nearly all the water vapor precipitated in the rising branch of the cell.
- This creates the world's major deserts in the subtropics.
- California is located at the northern edge of a great subtropical dry zone.
- The North American / North Pacific zone of sinking and dryness has its greatest geographical extent in northern hemisphere summer.



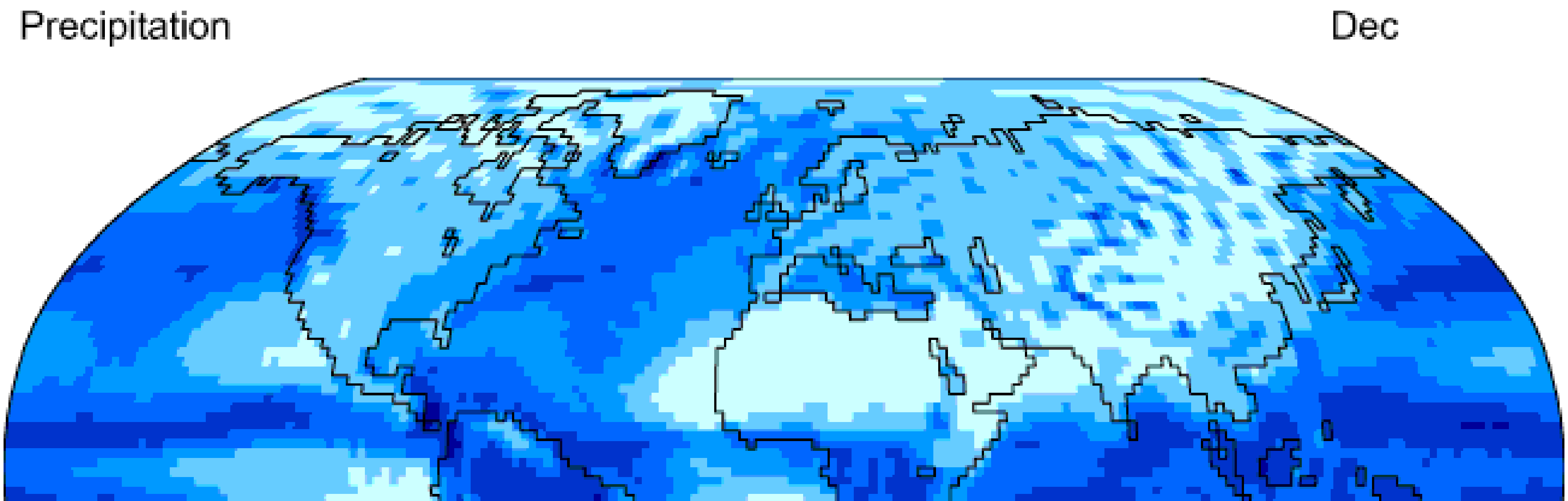
Precipitation distribution at mid- and high-latitudes

- There is a secondary precipitation maximum in the mid- to high latitudes of both hemispheres.
- It is greatest in winter.
- The seasonal variation is especially noticeable in the northern hemisphere, where there are clear North Pacific and North Atlantic "storm tracks."
- These storm tracks are associated with a strong eastward **mid-latitude jet stream** in both hemispheres about 45–55 degrees.
- This jet stream is highly turbulent, and there is turbulence, rising motion, cloud, and precipitation embedded within it.



Precipitation distribution at mid- and high-latitudes

- In the winter, California lies at the southern fringe of the northern hemisphere mid-latitude jet stream.
- This is why the State receives some precipitation in the winter, saving much of it from being a true desert.
- Instead, most of California has a "mediterranean" climate.



About mediterranean climates

- Mediterranean climates occur on the western edges of continents between 30° and 45° latitudes.
- They are ambiguous hybrids of the subtropical desert climates, and the wetter mid-latitude climates. They are characterized by:
  - Long, dry, warm-to-hot summers
  - Short, wet, mild-to-cool winters

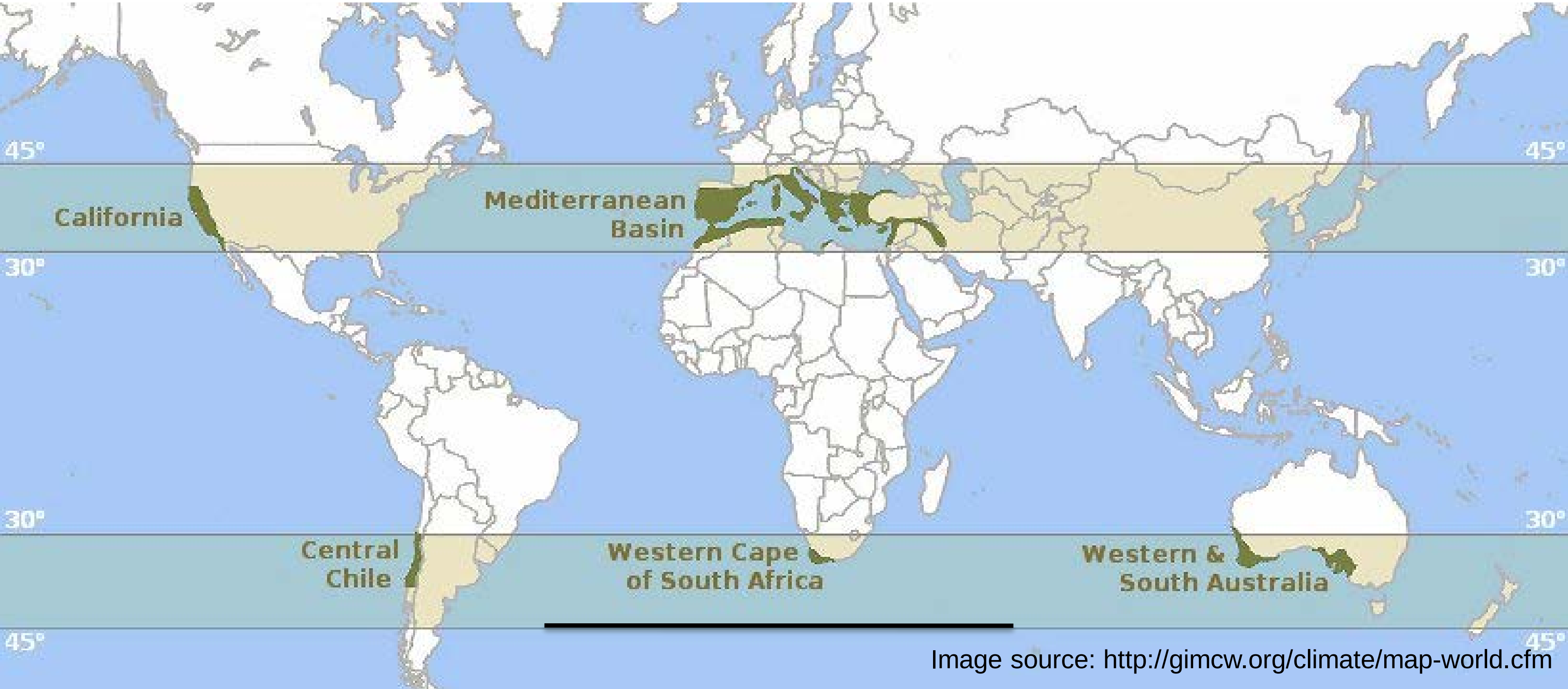
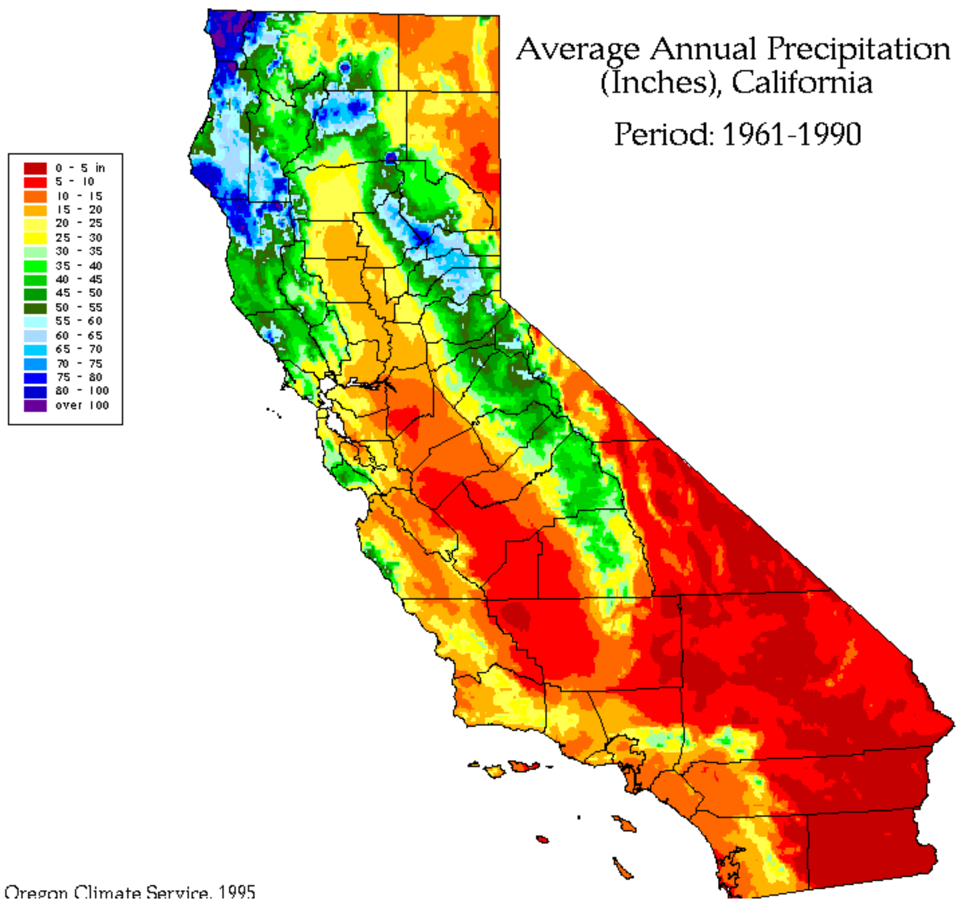


Image source: http://gimcw.org/climate/map-world.cfm

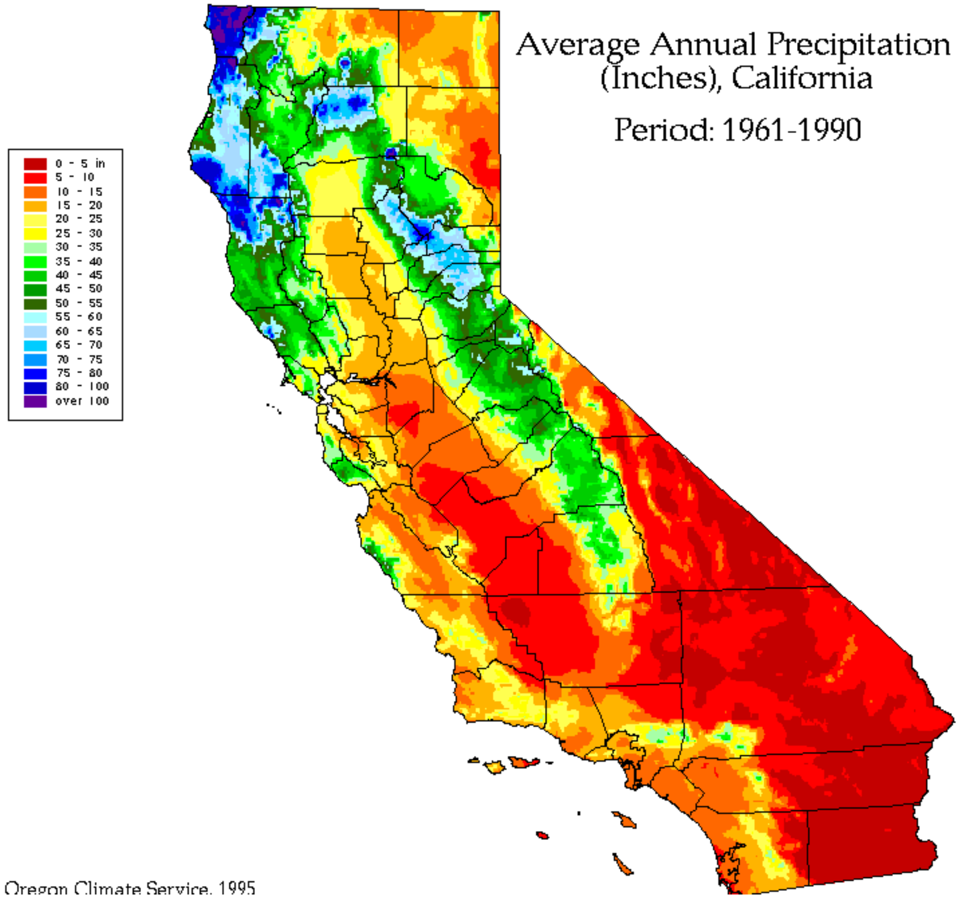
2. California's Precipitation Distribution in the Current Climate

High vs Low, Northern vs. Southern



- Most precipitation in California is **orographic**, meaning it occurs when moist air masses embedded within the mid-latitude jet stream are forced upward over mountains.
- As the moist air rises, it cools, and water precipitates.
- This mechanism is evident in the distribution of mean precipitation over the state: The most precipitation occurs at the highest elevations.
- It is also clear that more precipitation falls in the north.
- Northern California is more like the mid-latitude climate regions north of the state, since mid-latitude disturbances visit it more frequently.

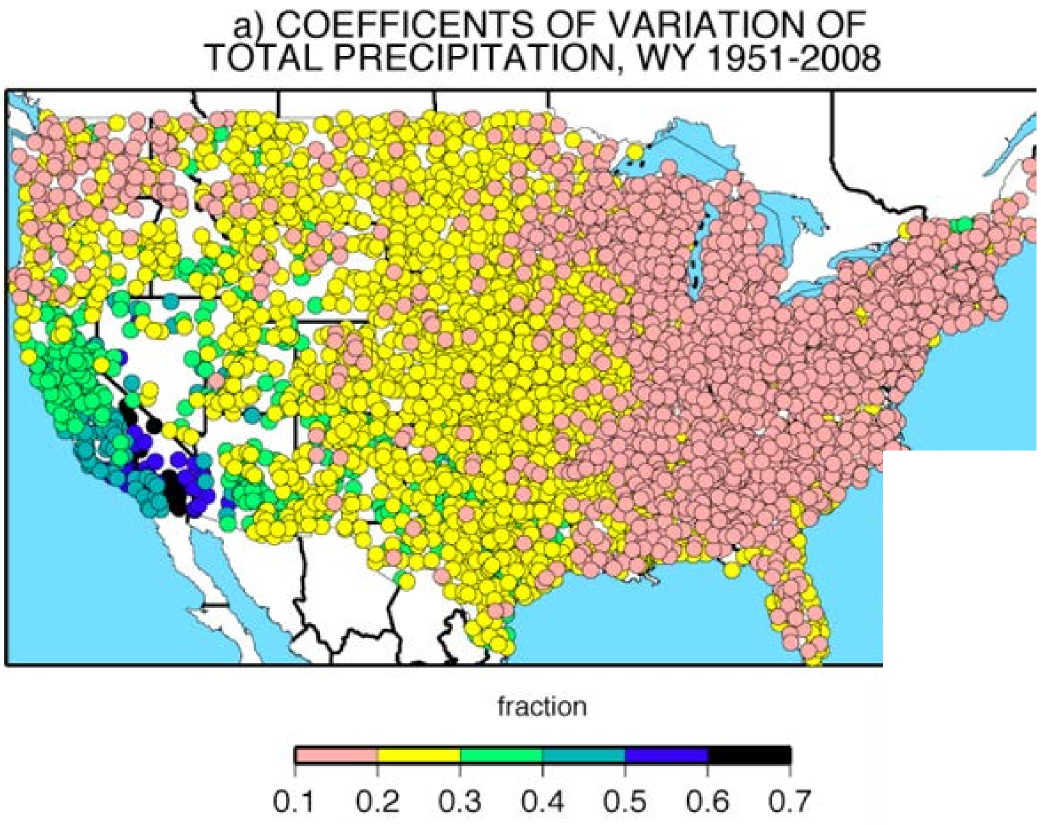
High vs Low, Northern vs. Southern



- By contrast, Southern California is more like the desert regions to the south.
- At higher elevations, temperatures are generally cold enough that precipitation falls as snow during the wet (winter) season.
- Mountain snowpack is a key water resource, providing 60% of California's freshwater.
- Snowpack acts as a natural reservoir, storing water in frozen form until it gradually melts and runs off in the spring and summer.

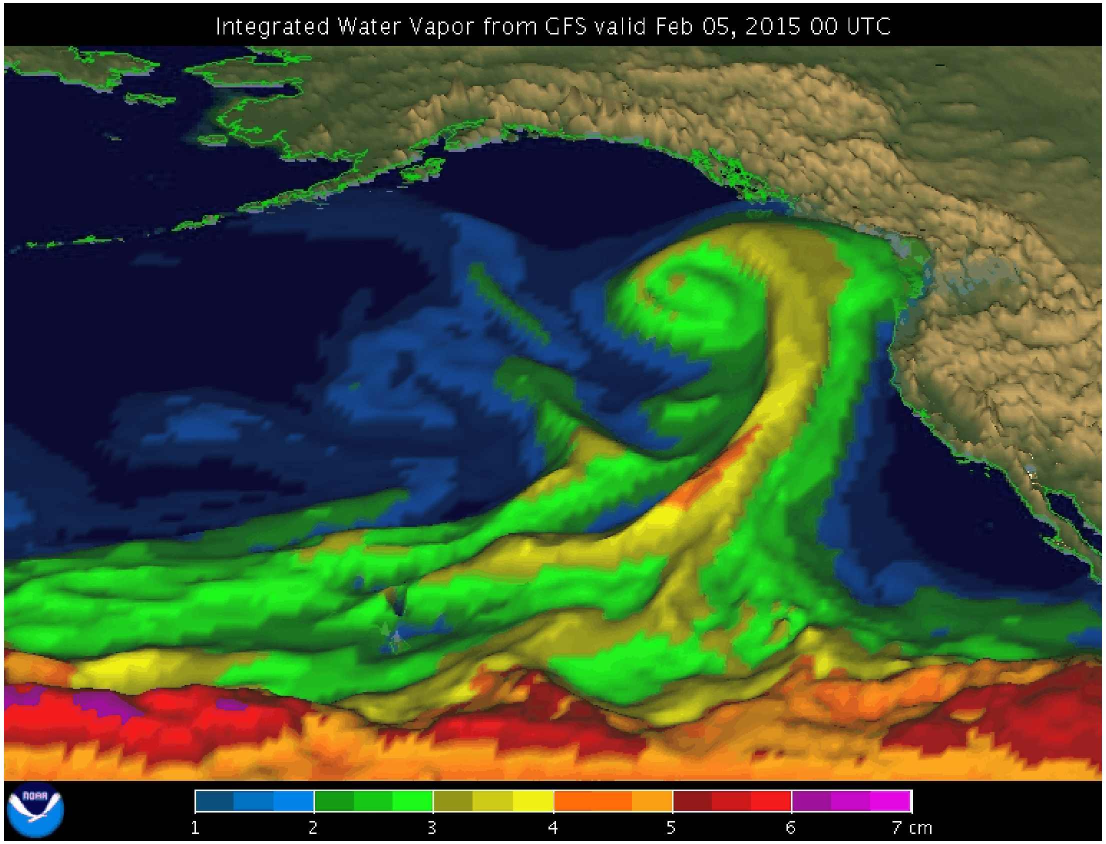
California hydroclimate is unusually variable.

- This figure shows the "coefficient of variation" for annual total precipitation between 1951 and 2008 across the U.S.
- This metric is the ratio of the standard deviation to the mean, and is a measure of interannual variability in precipitation.
- In most places in the U.S., the amount of total precipitation from year to year is relatively stable.
- Not so in California, where the coefficient of variation is much higher, meaning precipitation varies greatly from year to year.



Dettinger et al. (2011)

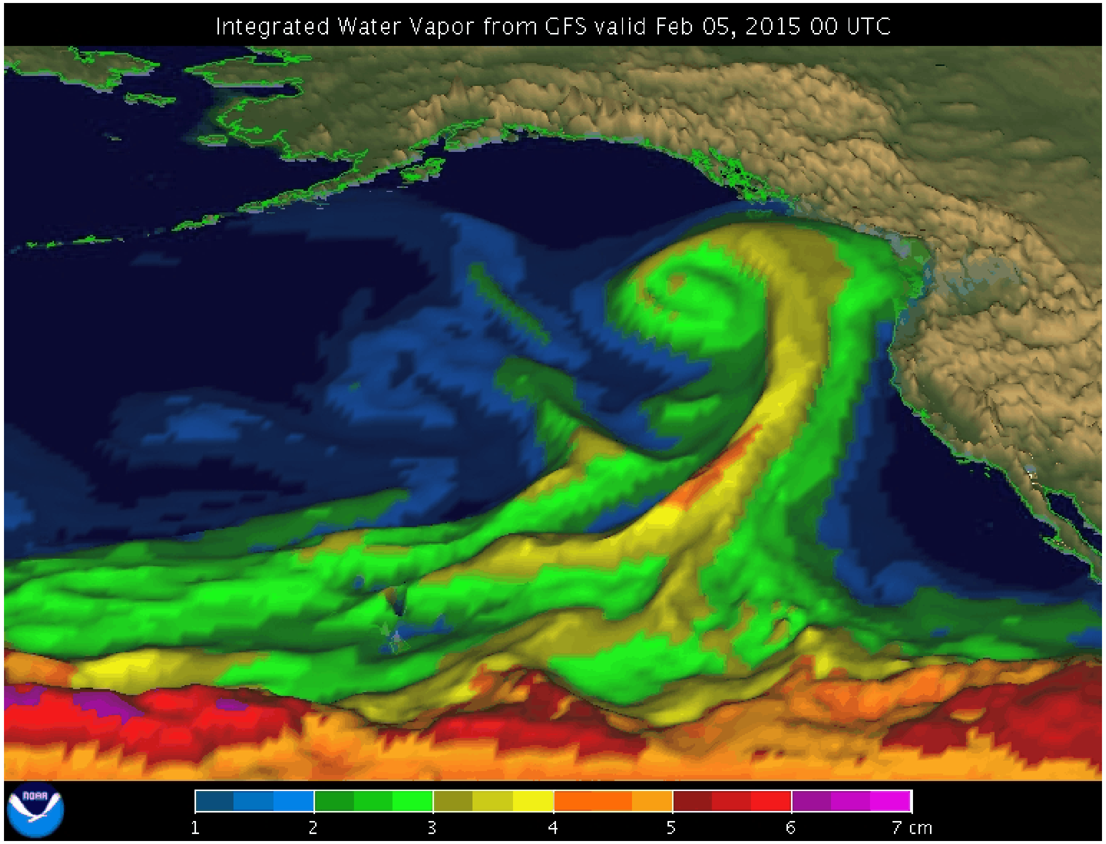
Atmospheric rivers



- Atmospheric rivers are narrow bands of atmospheric moisture that cause heavy precipitation when they make landfall, especially as they pass over mountains.
- In California, atmospheric rivers are commonly known as the “Pineapple Express.” They almost always coincide with heavy precipitation, and are responsible for 20% to 50% of California’s precipitation and streamflow.

Source: NOAA ESRL PSD Climate Data Repository

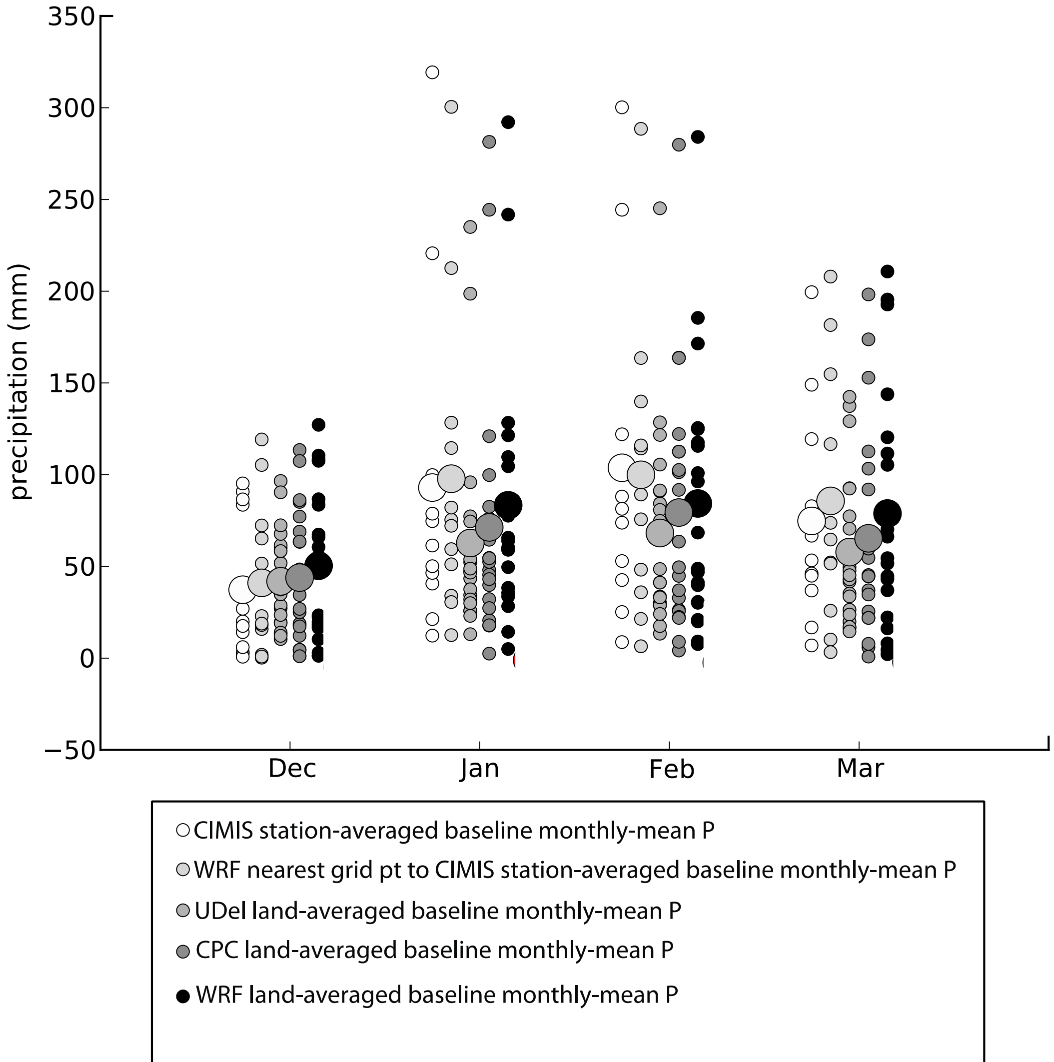
Atmospheric rivers



- Most of California's precipitation accumulates on just 5–15 days of the year, when atmospheric rivers hit the coast.
- In other words, each atmospheric river event makes an important contribution to the State's total precipitation. A few atmospheric river events can make the difference between a wet year and a dry year.

Source: NOAA ESRL PSD Climate Data Repository

Land-averaged precipitation during the wet season: variability



- This is precipitation averaged over the LA region for 1981-2000, broken down by four months of the wet season, according to five data products.
- Interannual variability is huge.
- The very wet months correspond to frequent occurrence of atmospheric rivers.

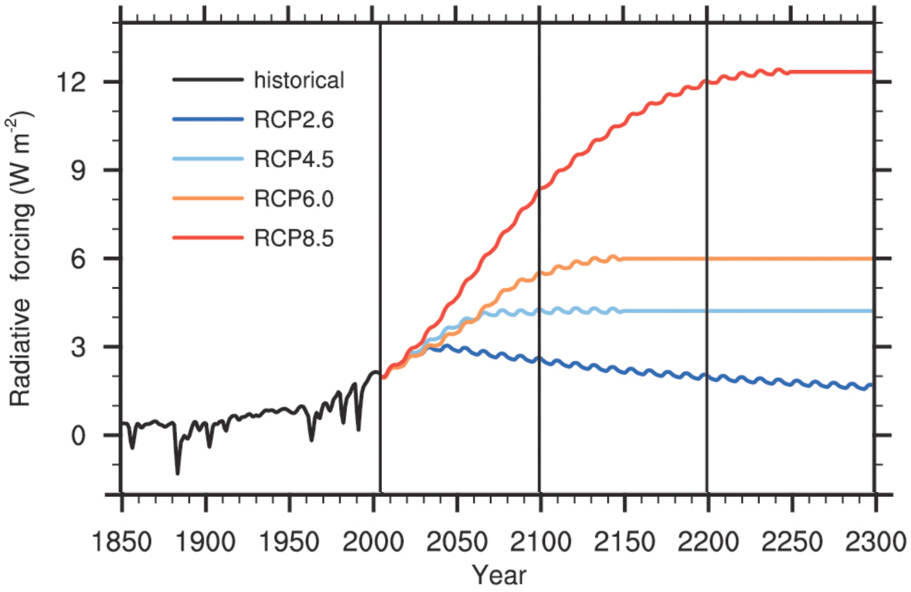
Berg et al. (2015a)

3. Hydrologic Cycle Intensification

Coordinated climate change experiments

- There are roughly 3 dozen global climate modeling centers around the world, each of which has developed a global climate model (GCM), with typical resolutions of 100-200 km.
- To prepare for the 2013 IPCC report, the various global climate modeling centers around the world organized a common set of climate change experiments, to be undertaken at every modeling center.
- The name of this coordination effort is **Coupled Model Intercomparison Project Phase 5**, or CMIP5.

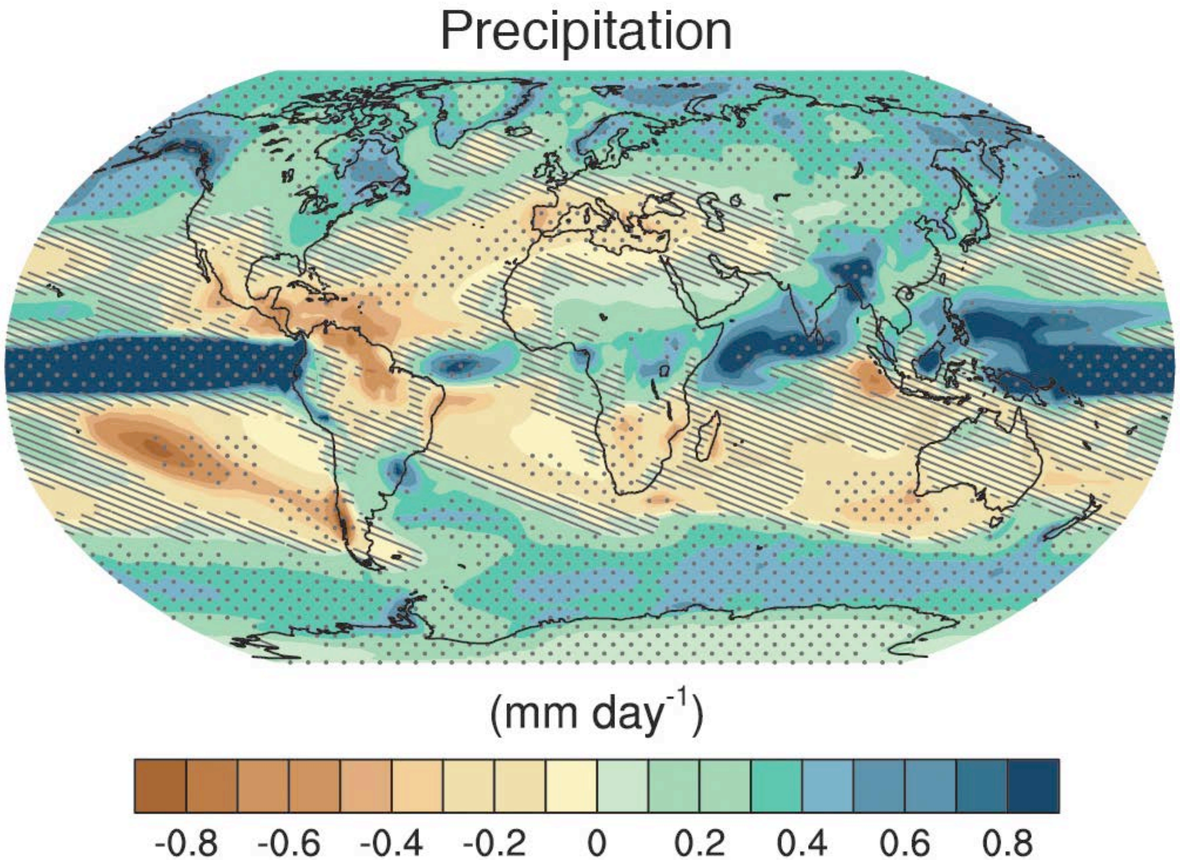
Radiative forcing scenarios



- The CMIP5 organizers created four future radiative forcing scenarios to be imposed on the GCMs.
- The most aggressive scenario (RCP8.5) is one where greenhouse gas emissions continue increasing, and has the nickname “business as usual.”
- A “mitigation” or greenhouse-gas-reduction scenario similar to that envisioned by the 2015 Paris climate agreement might be the one labeled RCP4.5.

Source: IPCC 5th Assessment Report (2013)

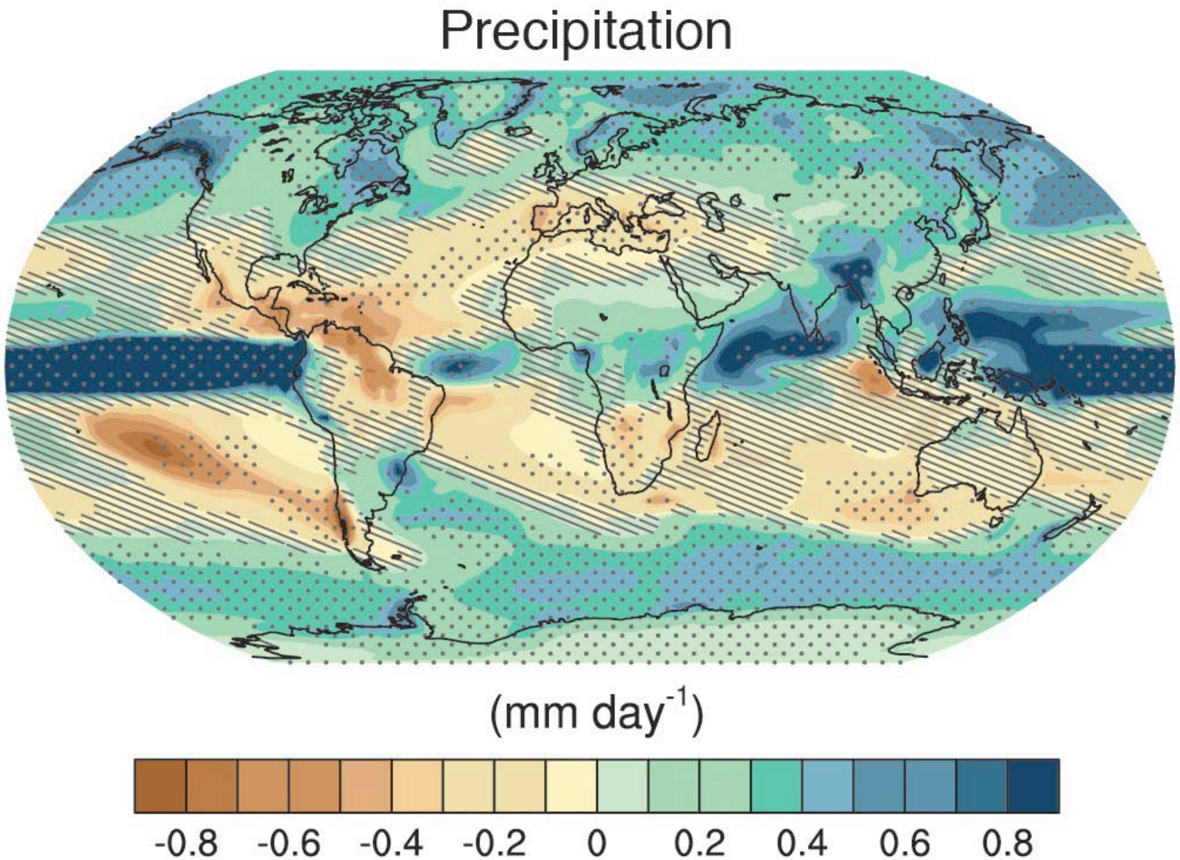
Hydrologic cycle intensification in GCMs



- This plot shows GCM-projected precipitation changes by 2081–2100, compared with 1986–2005.
- These are the ensemble-mean (average across the GCMs) changes associated with the RCP8.5 forcing.
- The other forcing scenarios have similar spatial patterns, though they are dialed down compared to this one, consistent with less overall warming.

Source: IPCC 5th Assessment Report (2013)

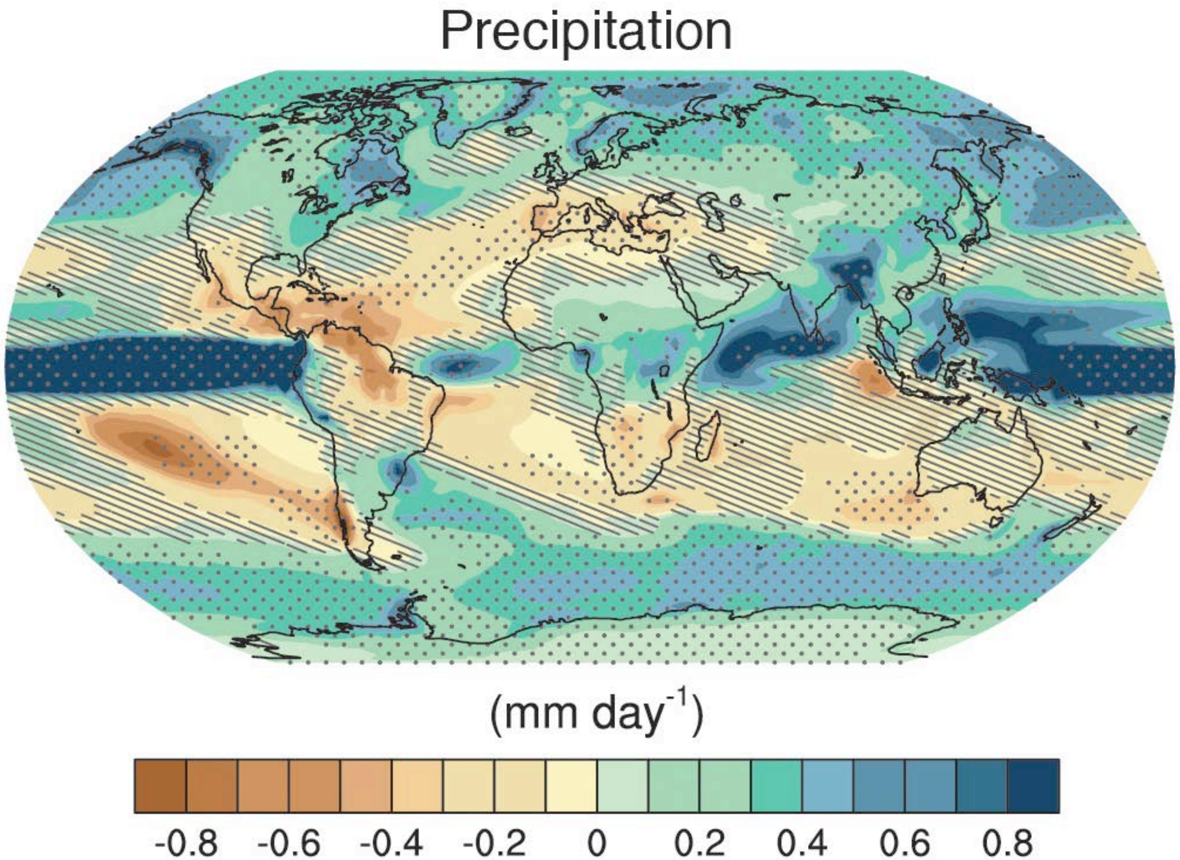
Hydrologic cycle intensification in GCMs



- Changes in precipitation are not uniform across the globe.
- There are significant increases in the deep tropics, but little precipitation increase is seen in the subtropics.
- In the mid-latitude rain belts, a significant precipitation increase is also seen.

Source: IPCC 5th Assessment Report (2013)

Hydrologic cycle intensification in GCMs

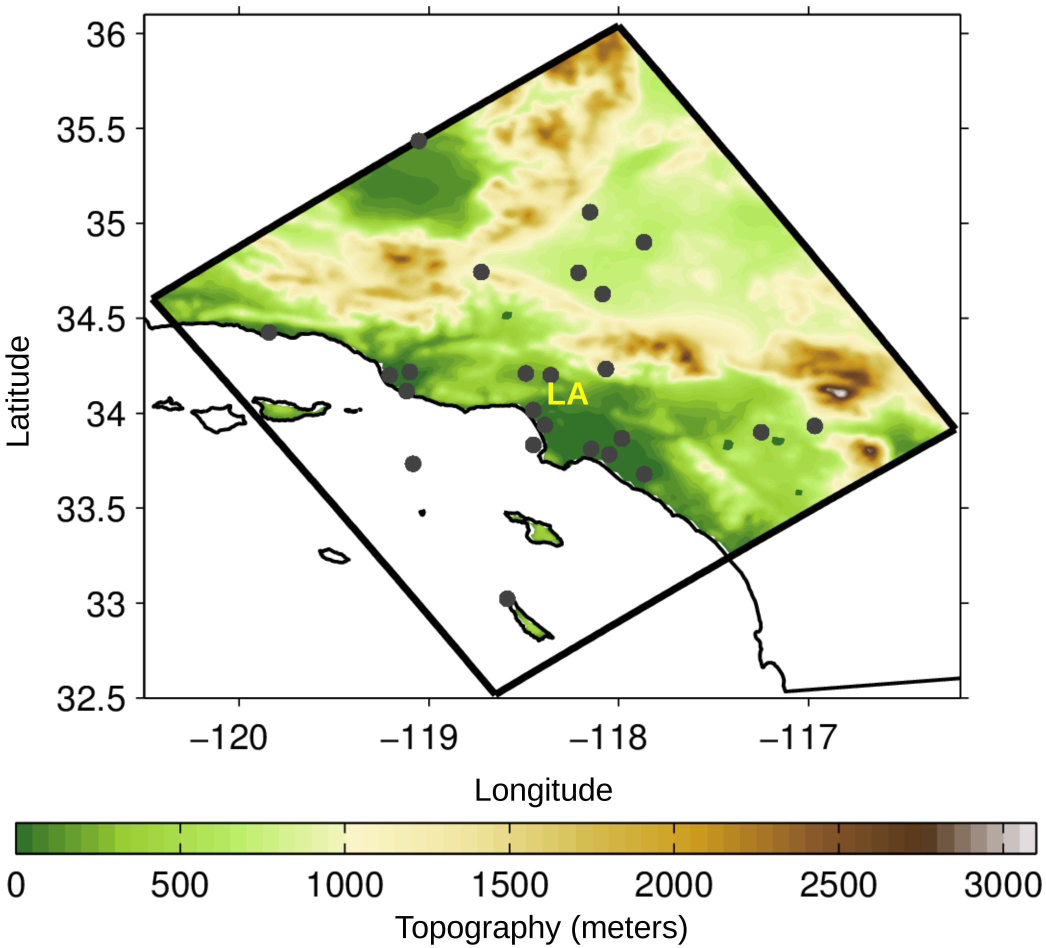


- Looking at these changes together, we see that with climate change:
  - Areas that are currently wet get wetter
  - Areas that are currently dry get drier

- As we've seen, the mediterranean climates are at the boundary between wet and dry zones. As a result, the GCMs tend to predict only weak changes in precipitation in these areas.

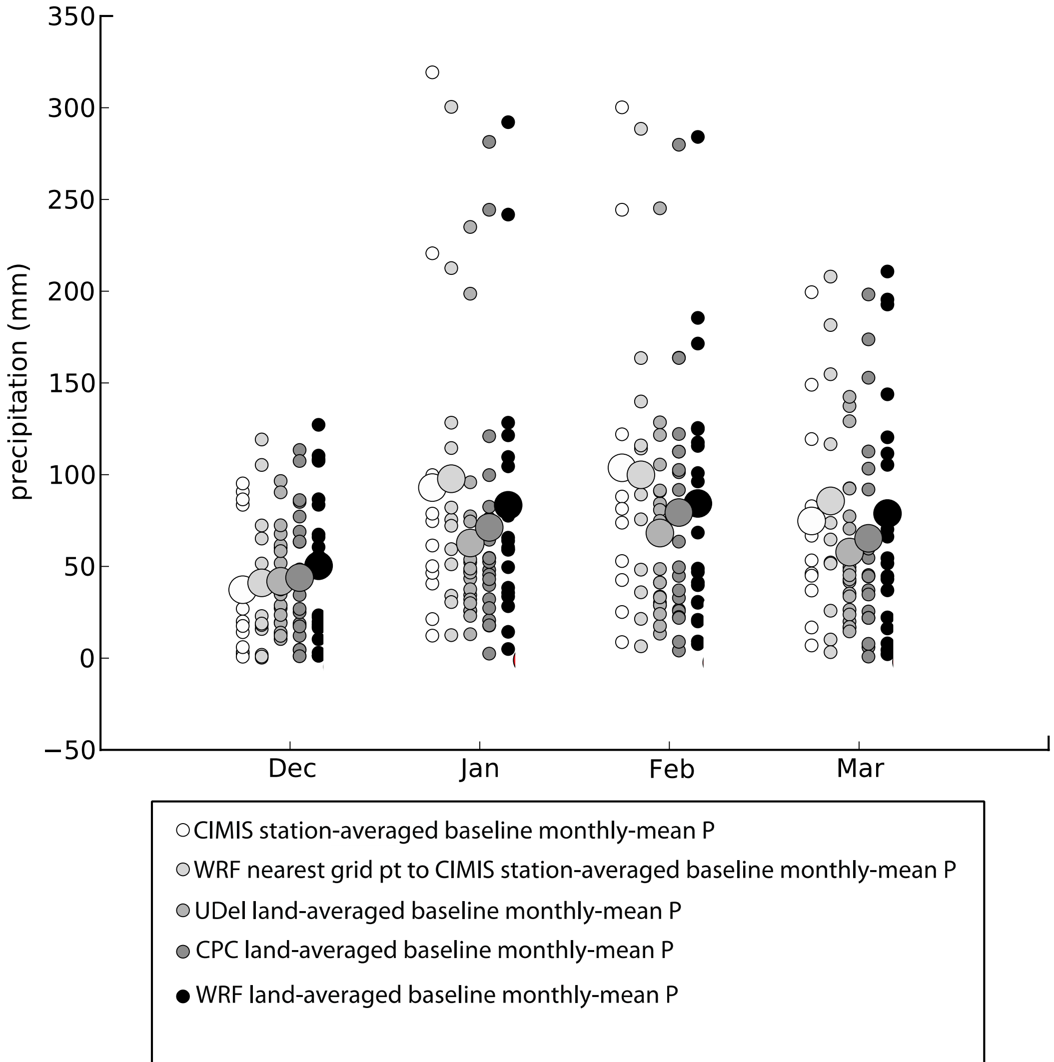
Source: IPCC 5th Assessment Report (2013)

The “Climate Change in the Los Angeles Region” Project



- At UCLA, we recently completed a high-resolution regional climate modeling project over LA.
- We developed a “hybrid” method to **downscale** GCM information to 2-km resolution, using:
  - Dynamical downscaling with the Weather Research and Forecasting (WRF) model
  - A statistical model mimicking the dynamical model
- We downscaled 30+ GCMs over the greater Los Angeles region.
- We looked at several aspects of climate. Here we focus on precipitation.

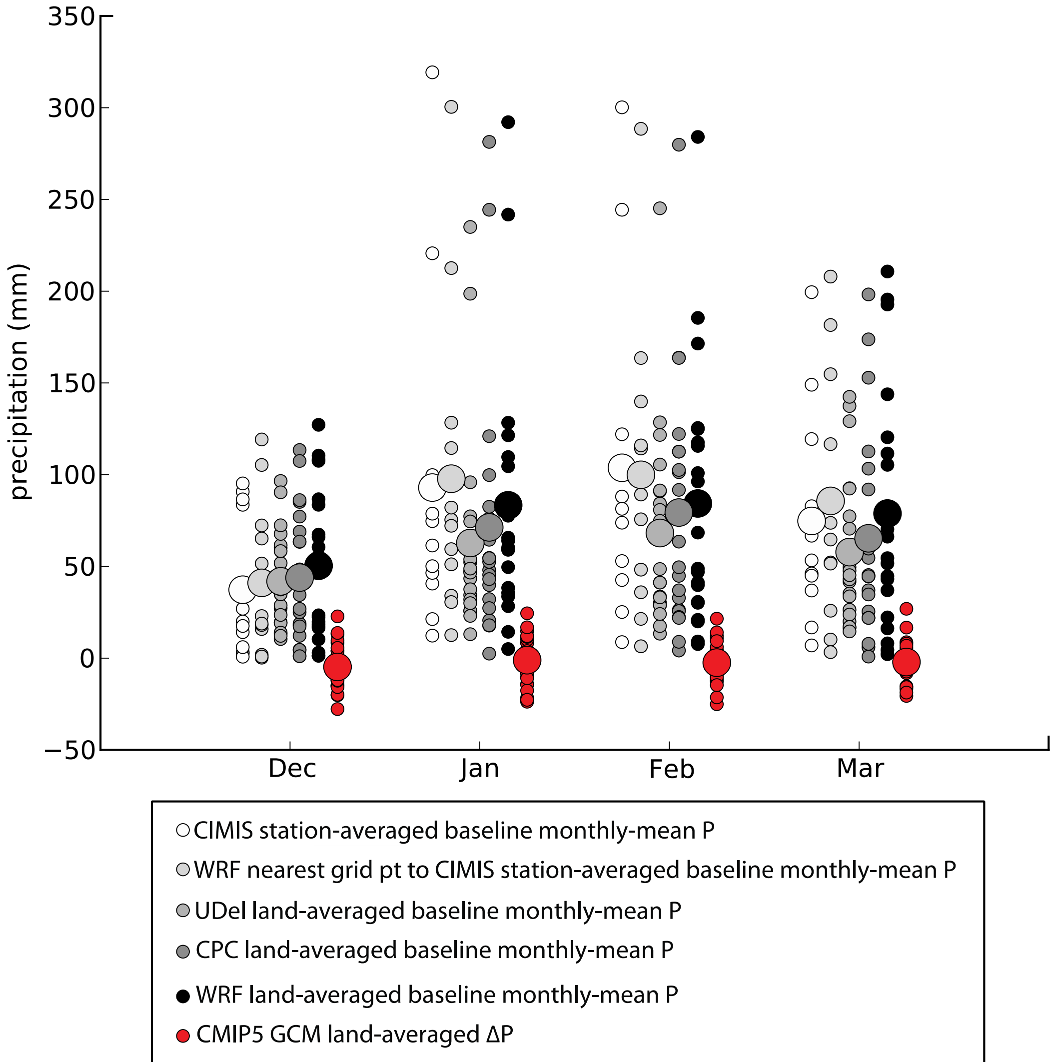
Land-averaged precipitation during the wet season: variability and change



- Recall the precipitation averaged over the LA region, broken down by four months of the wet season, according to five data products.
- One data product (black dots) is our downscaled simulation of historical climate (1981–2000) at 2-km resolution, using the WRF regional climate model.

Berg et al. (2015a)

Land-averaged precipitation during the wet season: variability and change

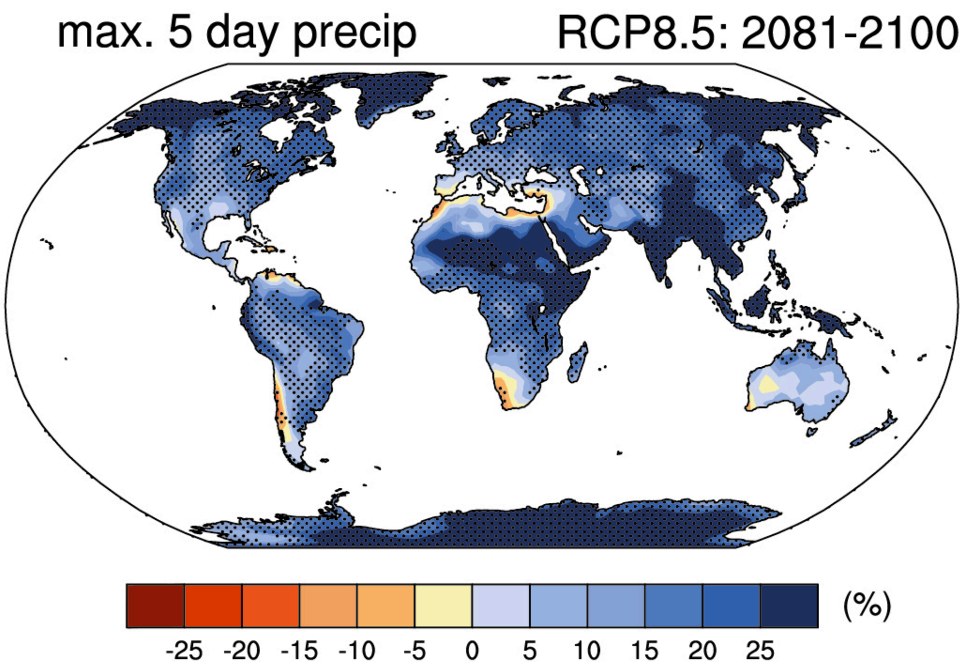


- The large red dot is the ensemble-mean precipitation change (RCP 8.5, 2041–2060), produced with the hybrid downscaling technique.
- The small red dots show the change in individual models, also produced with hybrid downscaling.
- The interannual variability dwarfs the model spread associated with climate change.

Berg et al. (2015a)

4. Changes in Extremes

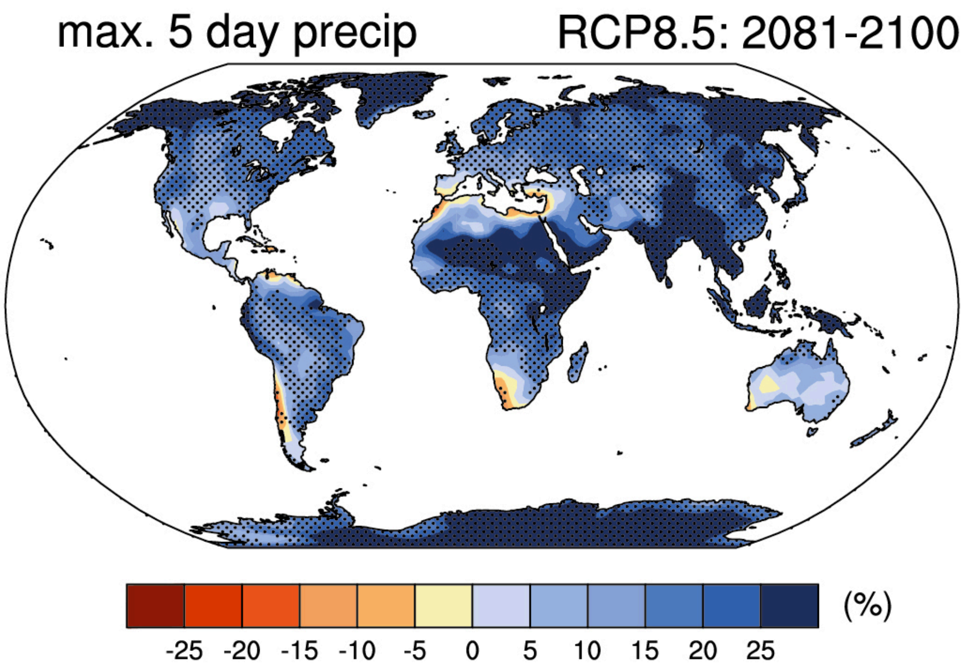
More rain on the rainiest days with climate change



- The 2013 IPCC WG1 report provides information about changes in precipitation extremes at the global scale.
- The report quantified the ensemble-mean change in the precipitation accumulation over any five-day period within a given year.
- Here is how that change is distributed over land areas under the RCP 8.5 greenhouse gas forcing scenario.

Source: IPCC 5th Assessment Report (2013)

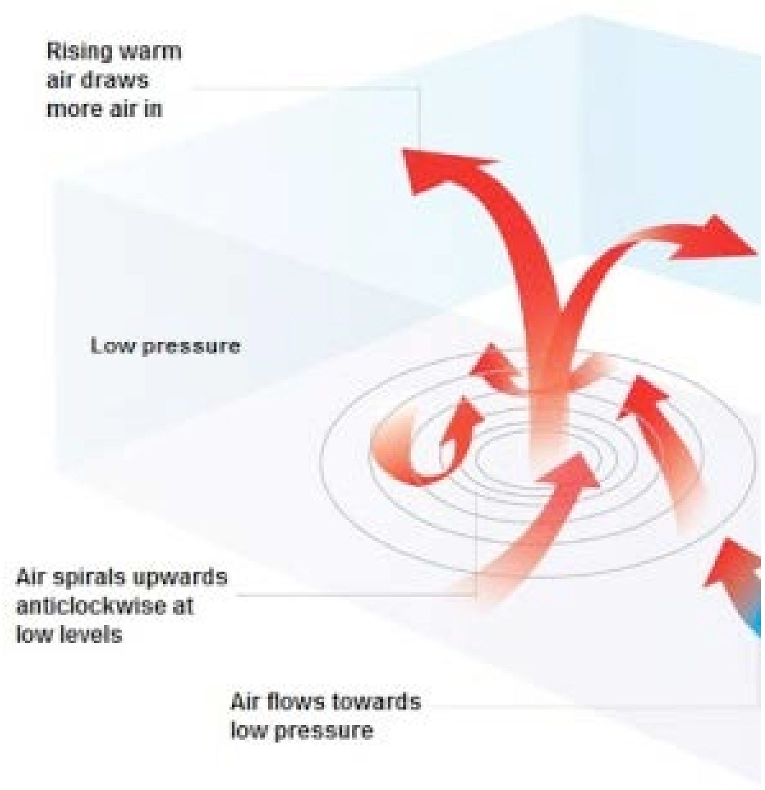
More rain on the rainiest days with climate change



- Increases are generally about 20%, meaning that the rainiest consecutive few days will be about 20% rainier.
- The change is very robust, being found nearly everywhere in all GCMs.

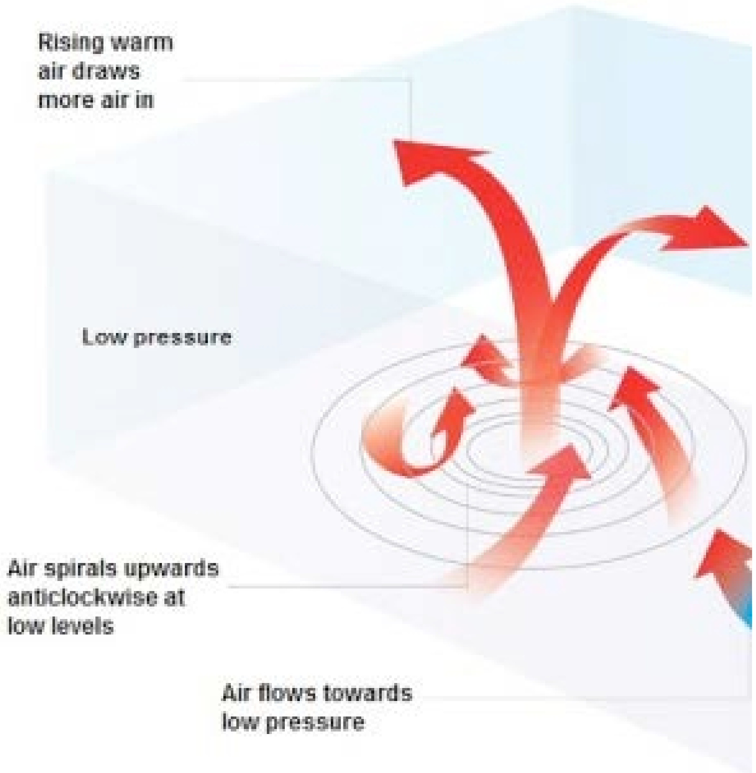
Source: IPCC 5th Assessment Report (2013)

Why do heavy precipitation events increase?



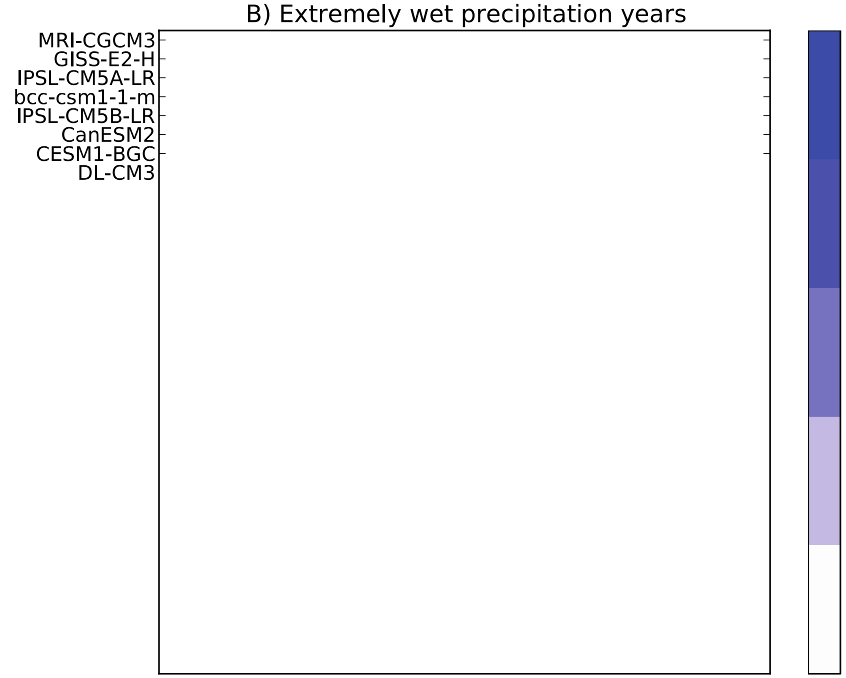
- As we've seen, precipitation generally occurs when air masses containing large amounts of water vapor are forced by the atmospheric flow to converge, and then rise. This process produces condensation, clouds and precipitation.
- The increase in heavy precipitation events is driven by a general increase in atmospheric water vapor as climate warms.
- The increase in water vapor is a simple consequence of the fact that warmer air can "hold" more water vapor.

Why do heavy precipitation events increase?



- If water vapor generally increases in a warmer climate, then these converging air masses will also contain more water vapor, and will therefore produce more precipitation.
- In spite of the GCM results, and the robustness of the general physical arguments underpinning them, it is still difficult to be quantitative about changes in precipitation extremes at the regional scale.

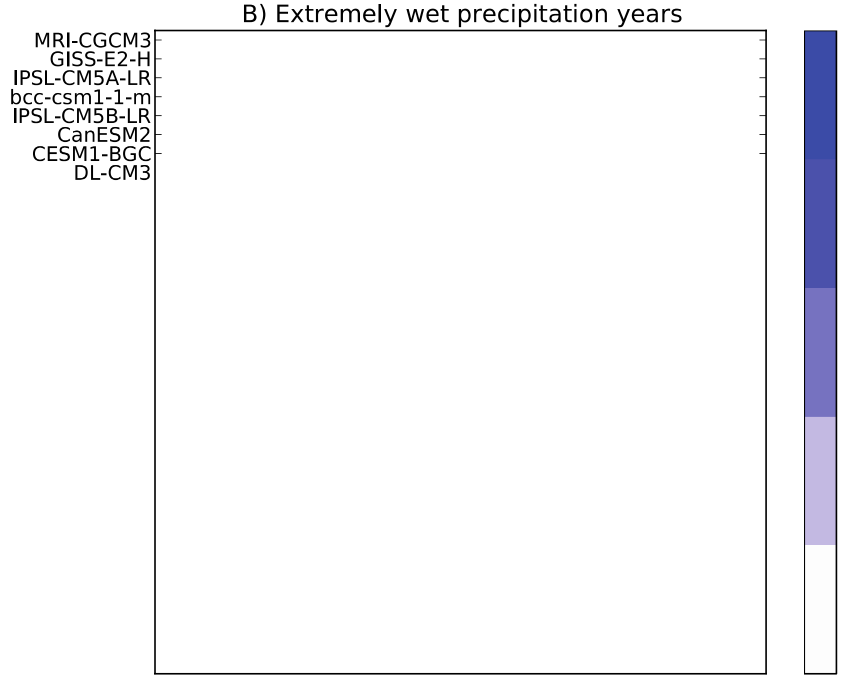
Extreme precipitation changes in the 21st century



- We can start to regionalize GCM information by focusing only on GCM data over California.
- In this plot, every column is a 20-year period of the 21st century.
- Every row is a GCM.
- The colors represent the number of extremely wet years, and an extremely wet year is defined so that one is expected every 20 years, based on the historical period (1900–2005).

Berg et al. (2015b)

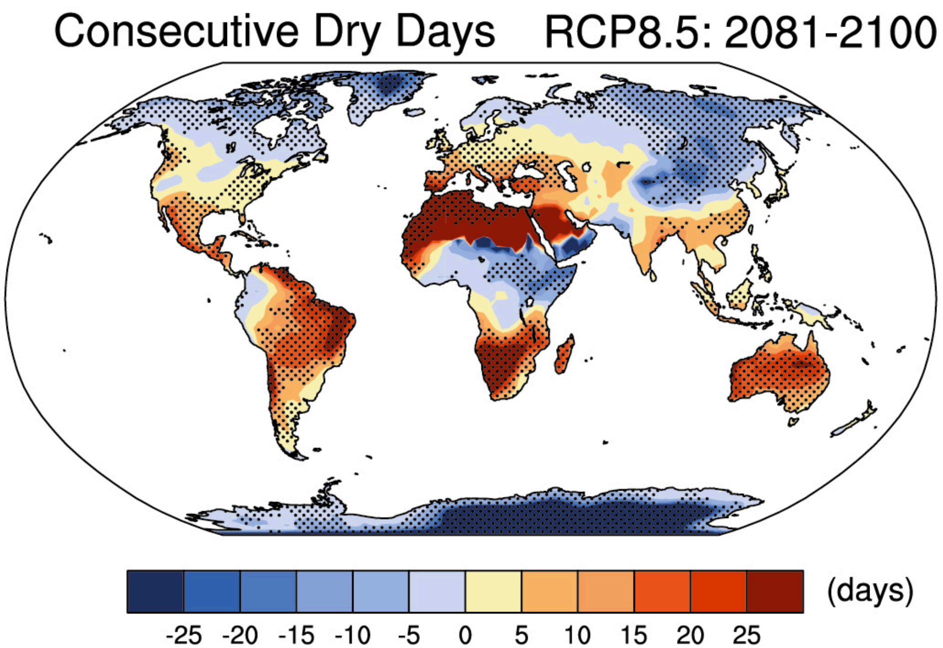
Extreme precipitation changes in the 21st century



- If the box is white, that GCM is projecting numbers of extremely wet years that roughly match those in a historical period of 1900–2005.
- The bluer the boxes, the more the numbers of extremely wet years exceed the expectation set by the historical period.
- In many GCMs, by the end of the century, there are 3–5 extremely wet years per 20 year period, instead of just one.

Berg et al. (2015b)

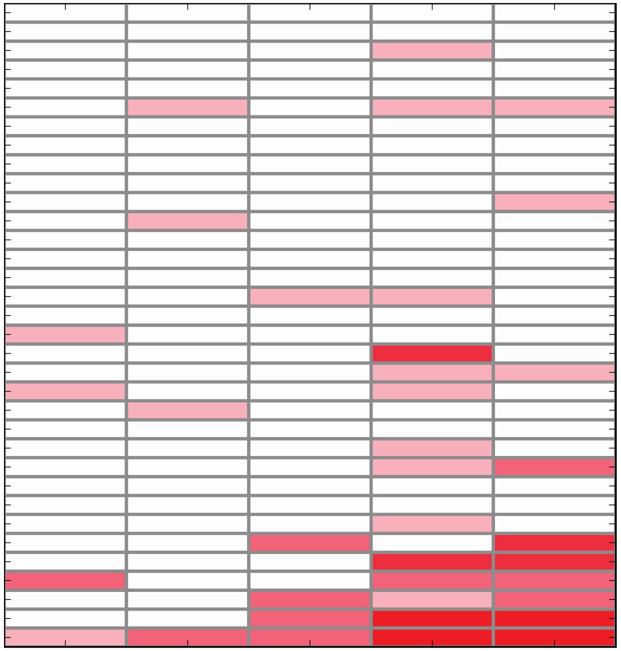
Longer dry spells with climate change



- The 2013 IPCC WG1 report also provides information about changes in the length of time between precipitation.
- This is a very rough measure of increase in drought driven by a precipitation deficit.
- Many areas show an increase in consecutive dry days.

Source: IPCC 5th Assessment Report (2013)

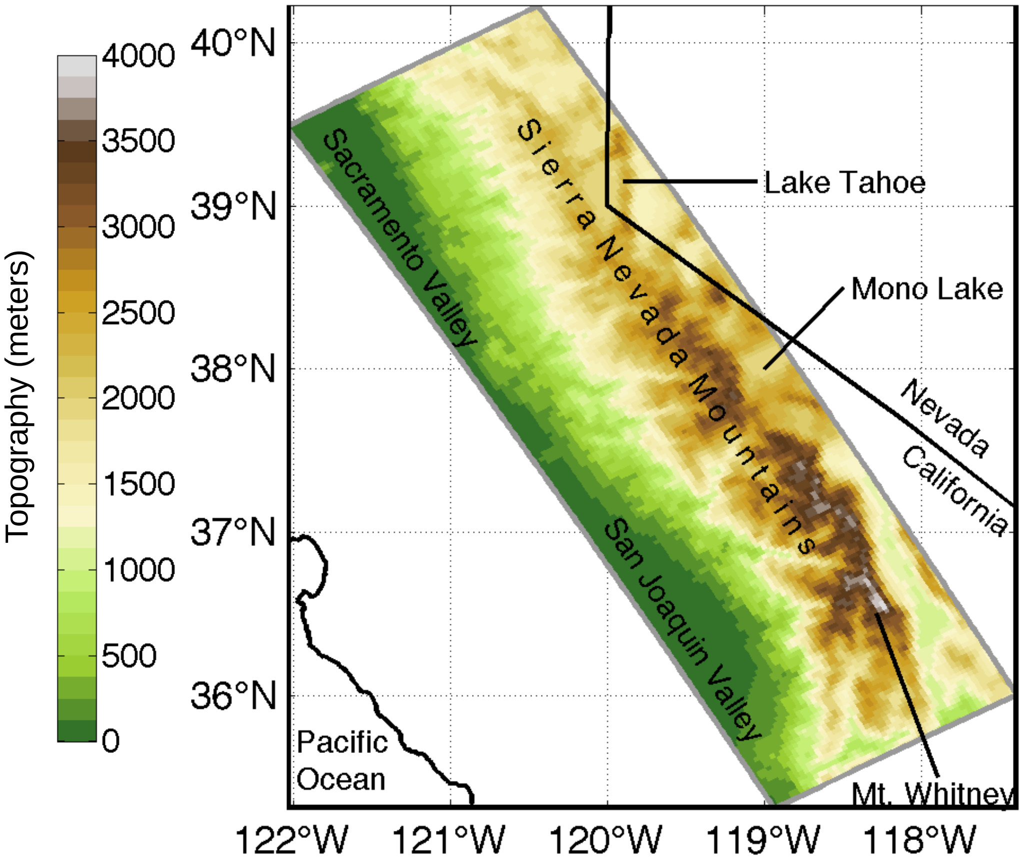
Extreme precipitation changes in the 21st century



- For California, we can play the same game for the extremely dry years as we did for precipitation.
- These also tend to increase, but the numbers generally don't exceed natural variability levels until the end of the century.
- However, water availability during a drought is driven by more factors than just a deficit of precipitation.
- Warming also plays a significant role in reducing snowpack and enhancing evaporation.

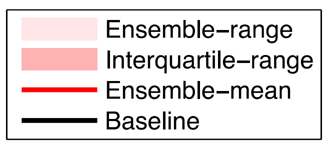
Berg et al. (2015b)

The "Climate Change in the Sierra Nevada" Project



- At UCLA we are now completing a high-resolution regional climate modeling project over the Sierra Nevada.
- Using the same "hybrid" methodology as in the LA region study, we downscaled 30+ GCMs to 3-km resolution.
- As in the LA study, we looked at several aspects of climate. Here we focus on snow and soil moisture.

Snow loss

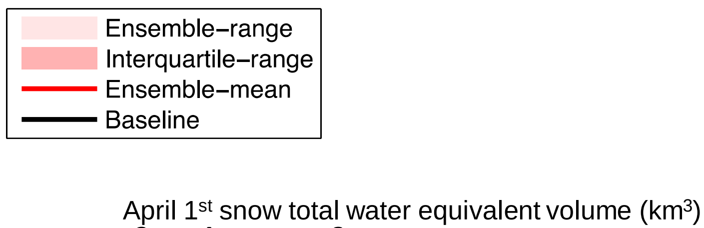


April 1st snow total water equivalent volume (km^3)

- Here is the total snow water equivalent volume for 2091–2100 for the RCP8.5 forcing scenario. The values for the 1991-2000 baseline period are also shown.
- Total water equivalent volume is a measure of the total water resource stored in the snowpack. The losses are on average about 50%.
- Snowpack decreases significantly in the RCP4.5 "mitigation" scenario as well.

Sun et al. (2016)

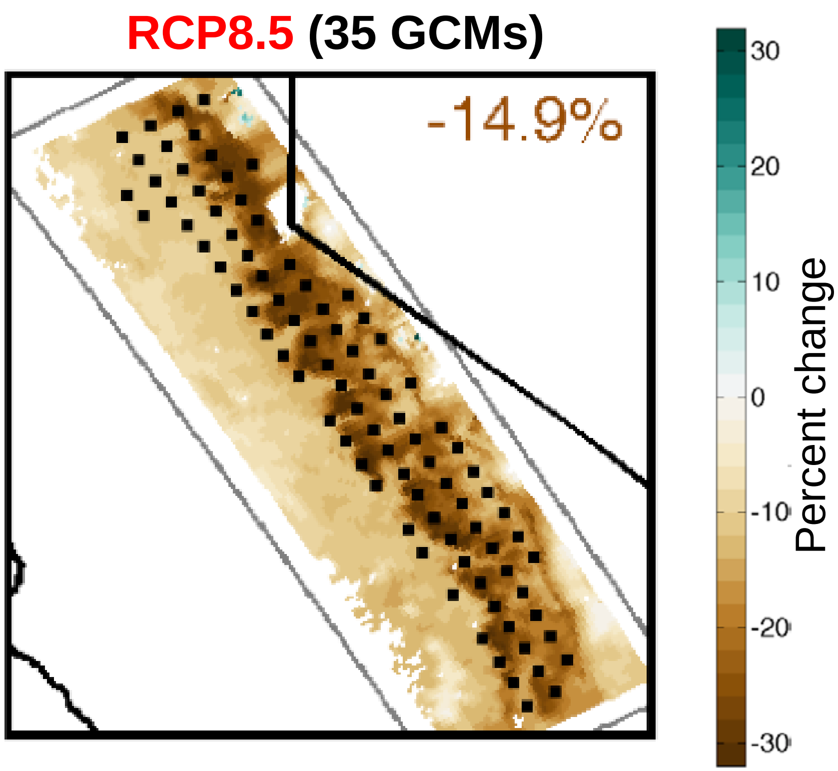
Snow loss



- There are several reasons for loss of snow:
  - Warmer temperatures cause a greater share of precipitation to fall as rain instead of snow.
  - Snow melts and runs off earlier in the spring.
- A process called **snow albedo feedback** accelerates snow loss. As snow retreats, it uncovers land that absorbs more solar radiation than snow would have.

Sun et al. (2016)

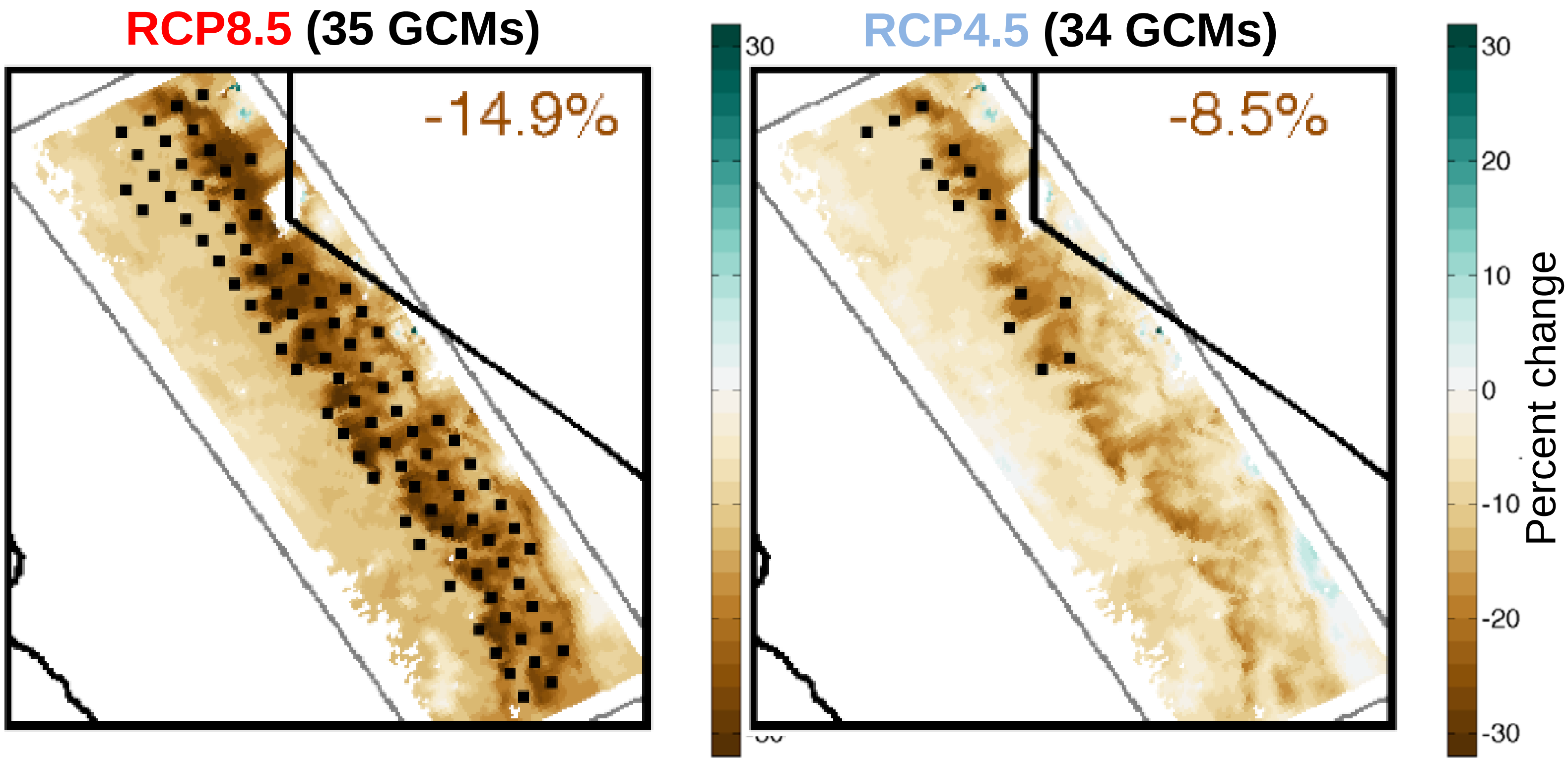
Soil moisture declines



- This figure shows the ensemble-mean change in 0–10cm soil moisture by 2091–2100, compared with 1991–2000, for the RCP8.5 forcing scenario.
- The percentage in the upper right corner is the moisture loss averaged over the entire domain.
- These values are averaged over the dry season, and factor in precipitation increases in many GCMs during the Dec-Mar wet season.

Schwartz et al. (2016)

Soil moisture declines



- In other words, increased evaporation and snow loss due to warming outpace any increases in incoming moisture, leading to overall drying.
- Overall drying occurs even in RCP 4.5, the "mitigation" scenario.
- This result points to the likelihood of more severe future droughts and fire seasons, similar to conditions California has experienced over the past few years.

Schwartz et al. (2016)

Summary

- California has a mediterranean climate with highly variable precipitation.
- Most precipitation occurs at higher elevations, and mountain snowpack is an important natural reservoir for the state.
- In future climate projections, mean precipitation doesn't change dramatically.
- But very wet years are expected to occur more frequently.
- Very dry years are expected to occur somewhat more frequently as well.
- Loss of snow and enhanced evaporation due to warming are expected to exacerbate drought conditions in low-precipitation years.

References

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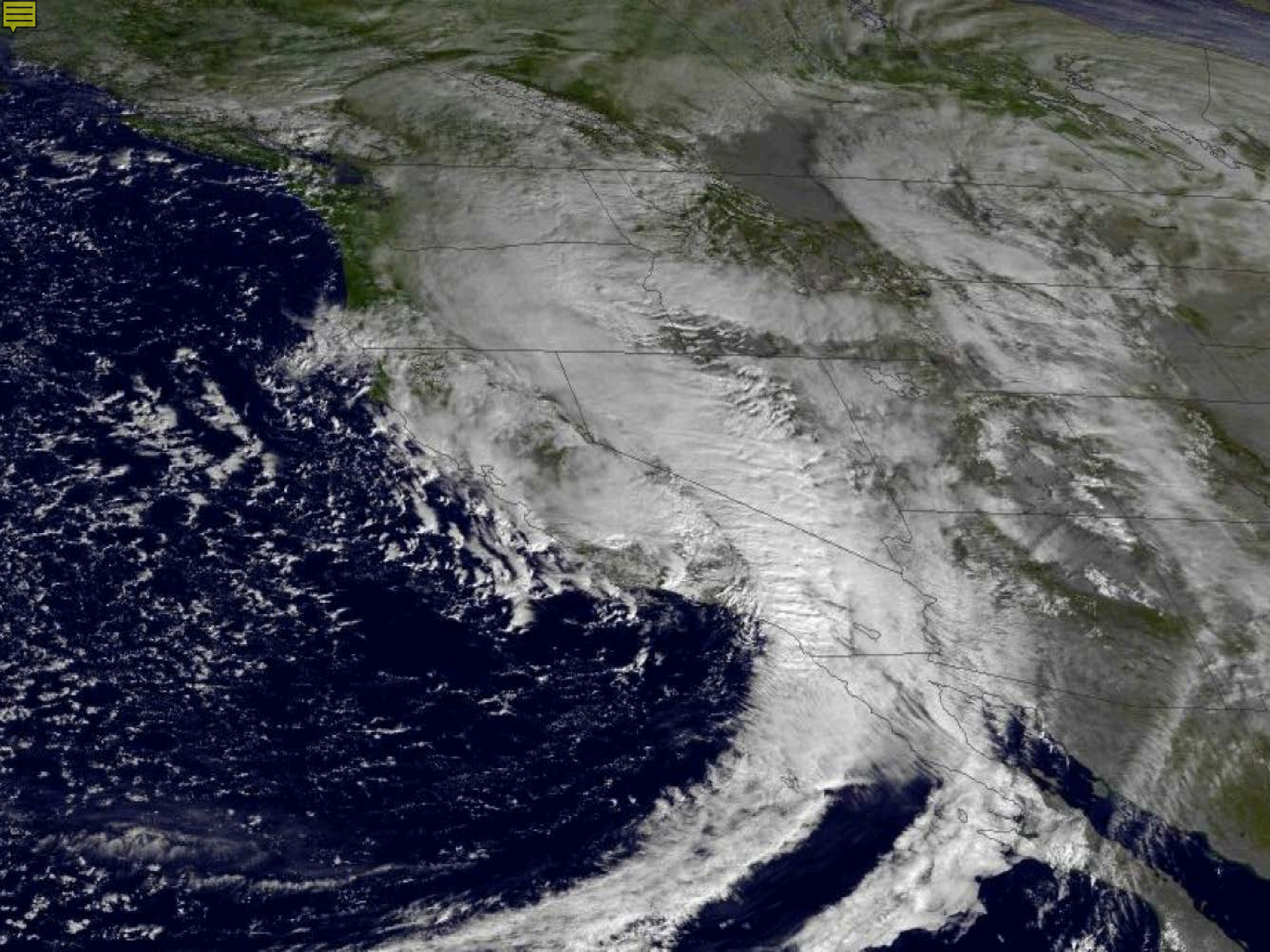
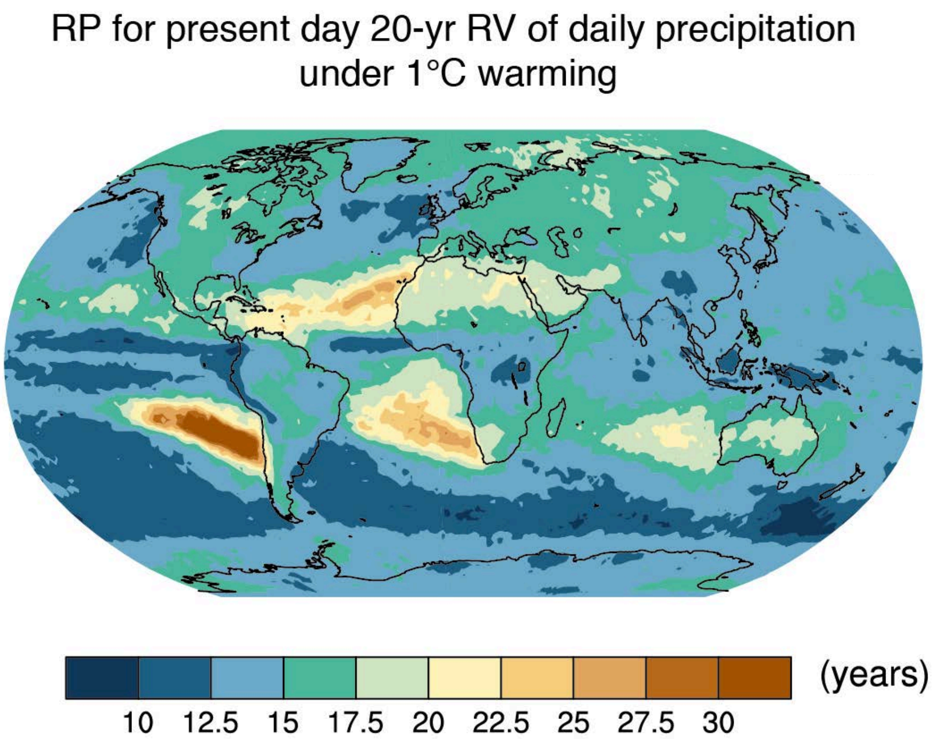


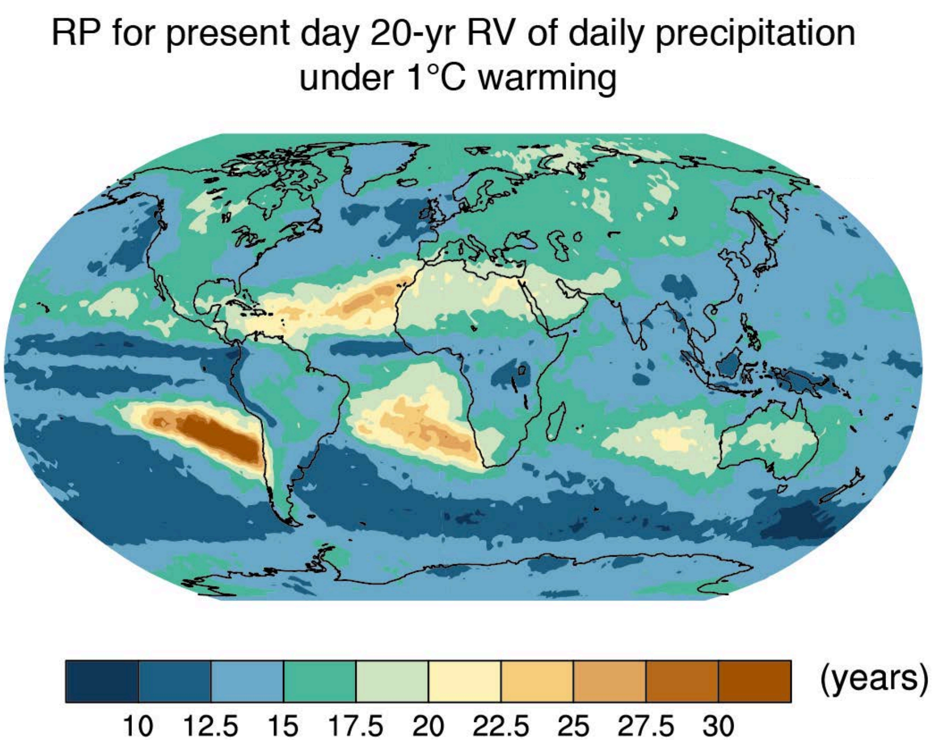
The most extreme precipitation happens more frequently



- Another measure of precipitation extremes is the “return period” of some extreme daily precipitation total.
- At every location on the planet, you can define a day that is so wet that it only occurs every 20 years in the current climate.
- Then you ask, how often will this day return in the future?
- Here is a map of the return period of that extremely wet day after only 1 deg C of warming.

Source: IPCC 5th Assessment Report (2013)

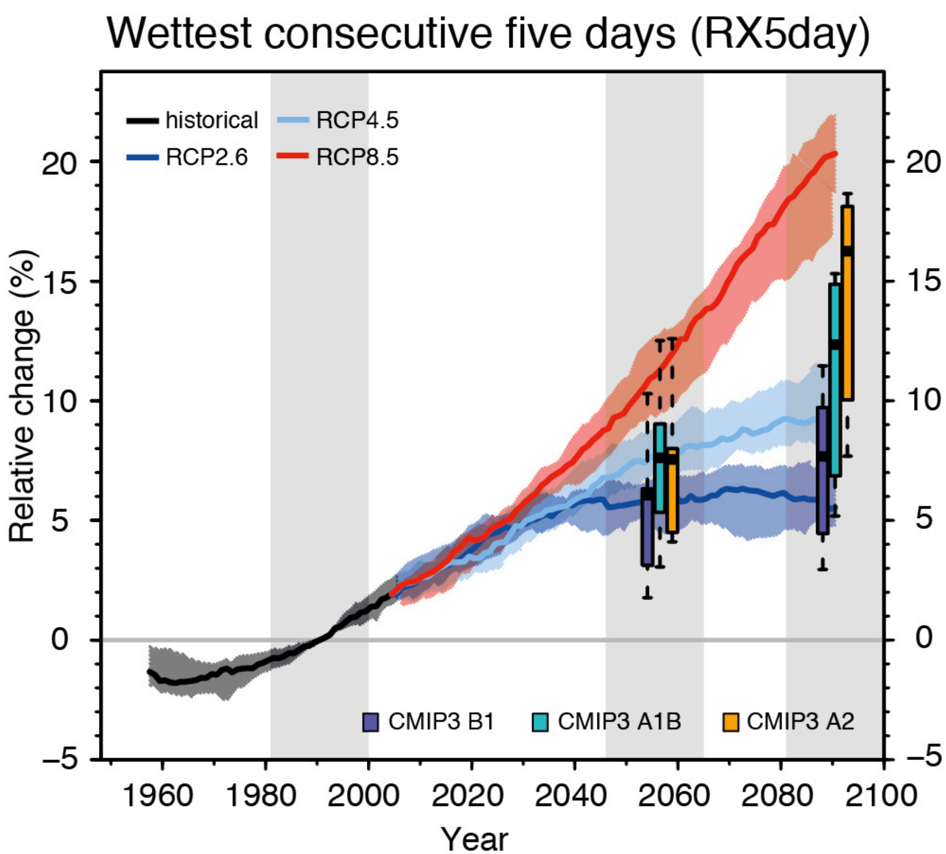
The most extreme precipitation happens more frequently



- It typically occurs every 10–17 years instead of every 20 years.
- Note that warming under "business as usual" is ~4 deg C by the end of the century, so the projected declines in return period are much greater than these values by the end of the century.

Source: IPCC 5th Assessment Report (2013)

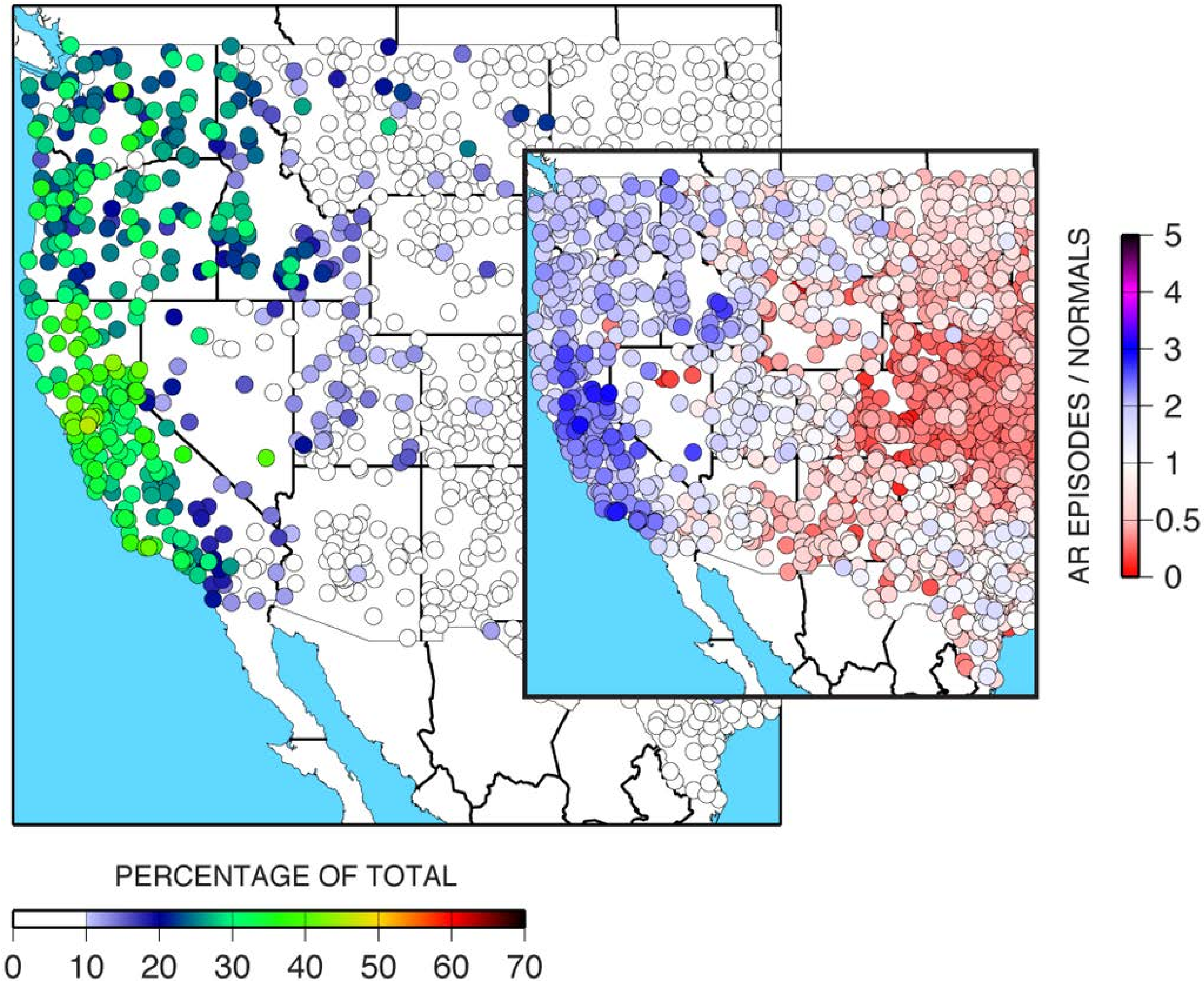
More rain on the rainiest days



- If you average this metric over the globe, you can see how it changes over time.
- The red curve shows the rain increase during extremely rainy consecutive days over the course of the 21st century under "business as usual" (ensemble-mean).
- The light blue curve shows the corresponding change for the "mitigation" scenario.
- Even under "mitigation," there is still a substantial rain increase during consecutive rainy days.

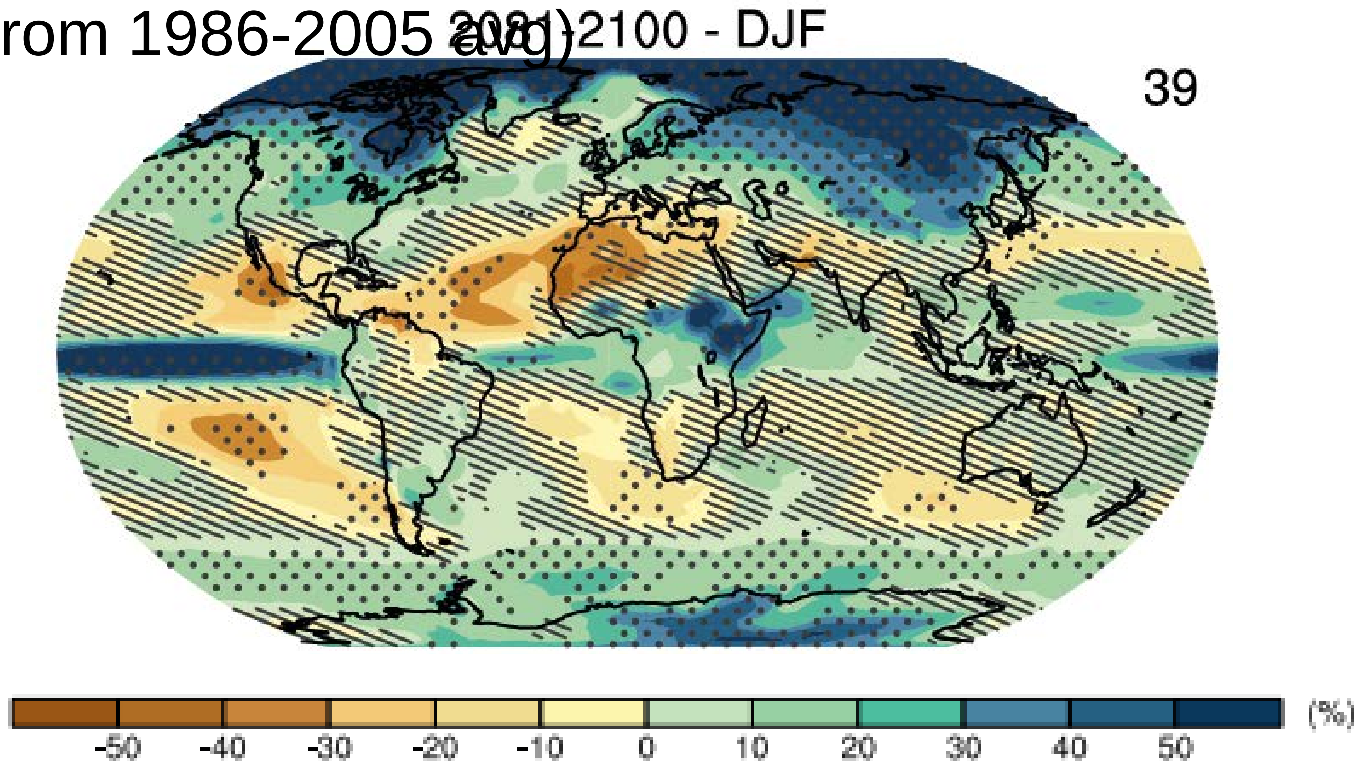
Source: IPCC 5th Assessment Report (2013)

CONTRIBUTIONS OF ALL AR EPISODES (days 0 to +1) TO TOTAL PRECIPITATION, WY 1998-2008



The global context

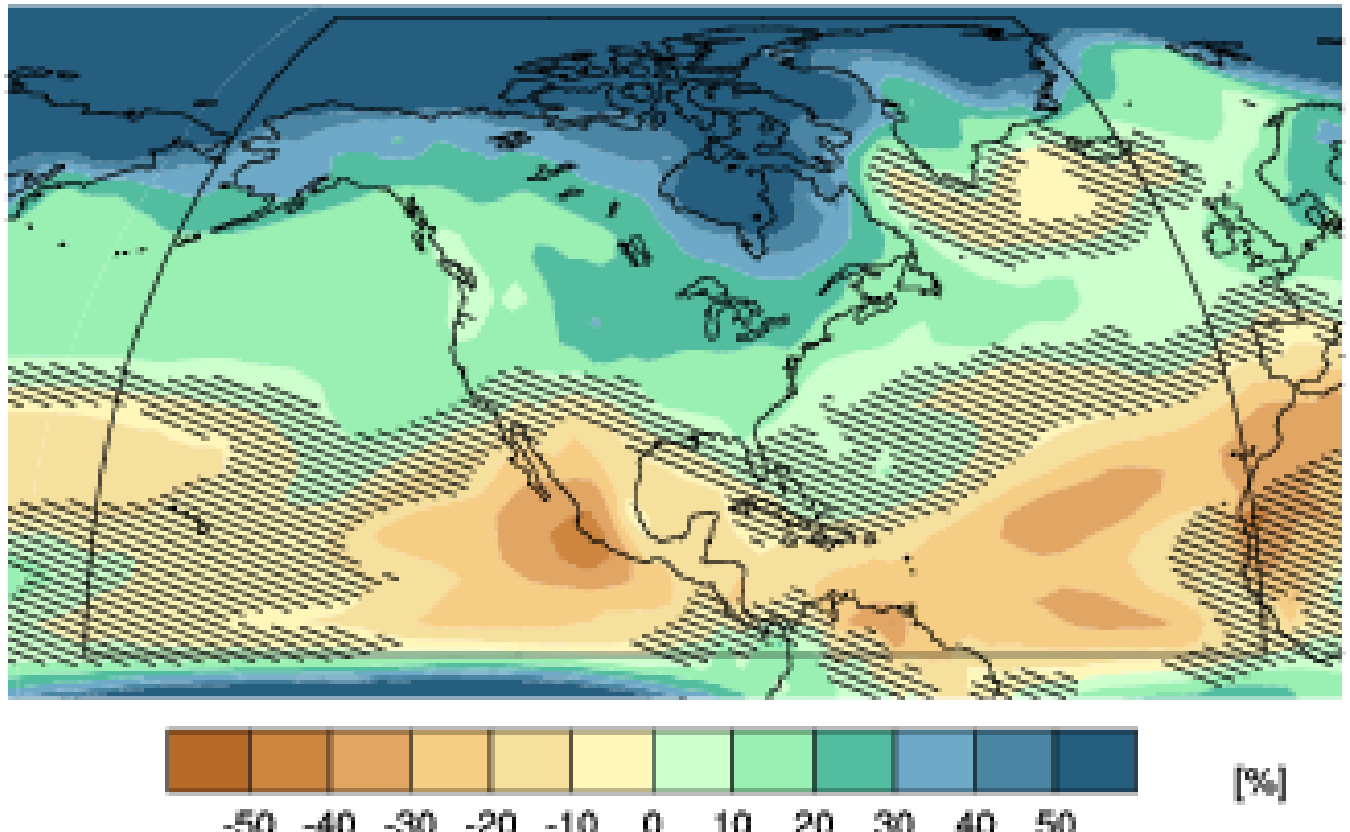
RCP8.5 DJF precipitation changes (% difference from 1986-2005 avg)



Hatching: multi-model mean change is < 1 standard deviation of internal variability

Stippling: multi-model mean change is > 2 standard deviations of internal variability AND where at least 90% of models agree on the *sign* of the change

The global context



- This figure from the IPCC 5th Assessment Report data shows precipitation changes (% difference between 2081–2100 average and 1986–2005 average) under RCP 8.5.
- Hatching shows where GCM ensemble-mean change is less than 1 standard deviation of internal variability.
- The LA region lies in this area, on a node between slight wetting and slight drying.

Source: IPCC 5th Assessment Report (2013)
Annex data via KNMI Climate Change Atlas