Floods

Global Warming Science, EPS101

Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

Floods, Pakistan 2022

Asif Hassan/Agence France-Presse — Getty Images

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https://www.redcross.org/about-us/news-and-events/news/2022/red-cross-and-red-crescent-respond-to-flooding-in-pakistan.html

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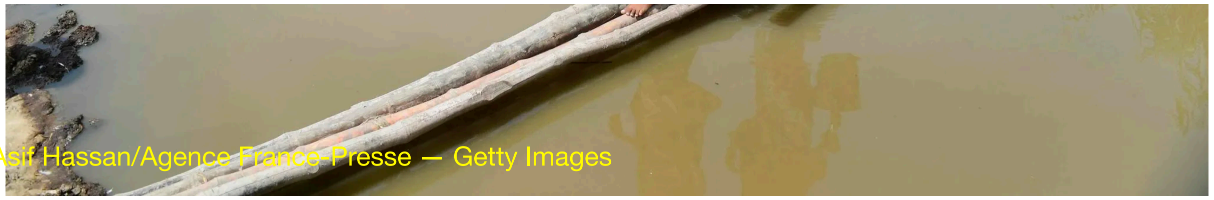

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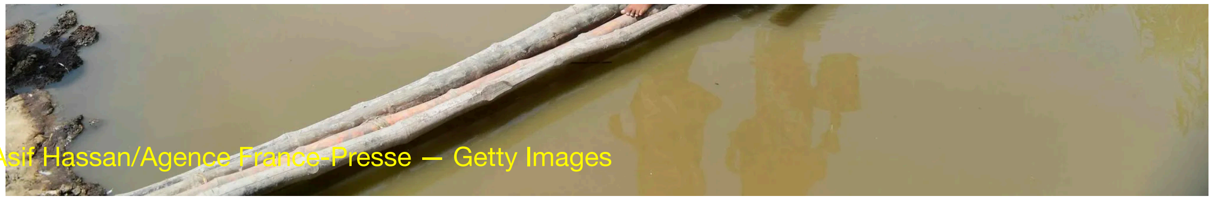

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***Scientific American** is much more careful…:* “One-third of the country is underwater … Pakistan has received almost three times its average annual rainfall. Researchers say the catastrophe started with phenomenal heatwaves. … temperatures above 40 °C for prolonged periods … Warmer air can hold more moisture … Scientists say several factors have contributed to the extreme event”

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Floods, Germany 2021. ***NYTimes:*** ***"It Is All Connected: Extreme Weather in the Age of Climate Change. The storm that brought flooding and devastation to parts of Europe is the latest example of an extreme weather event. More are expected."***

Flash flood damage in Bad Neuenahr-Ahrweiler, Germany. Friedemann Vogel/EPA, Shutterstock

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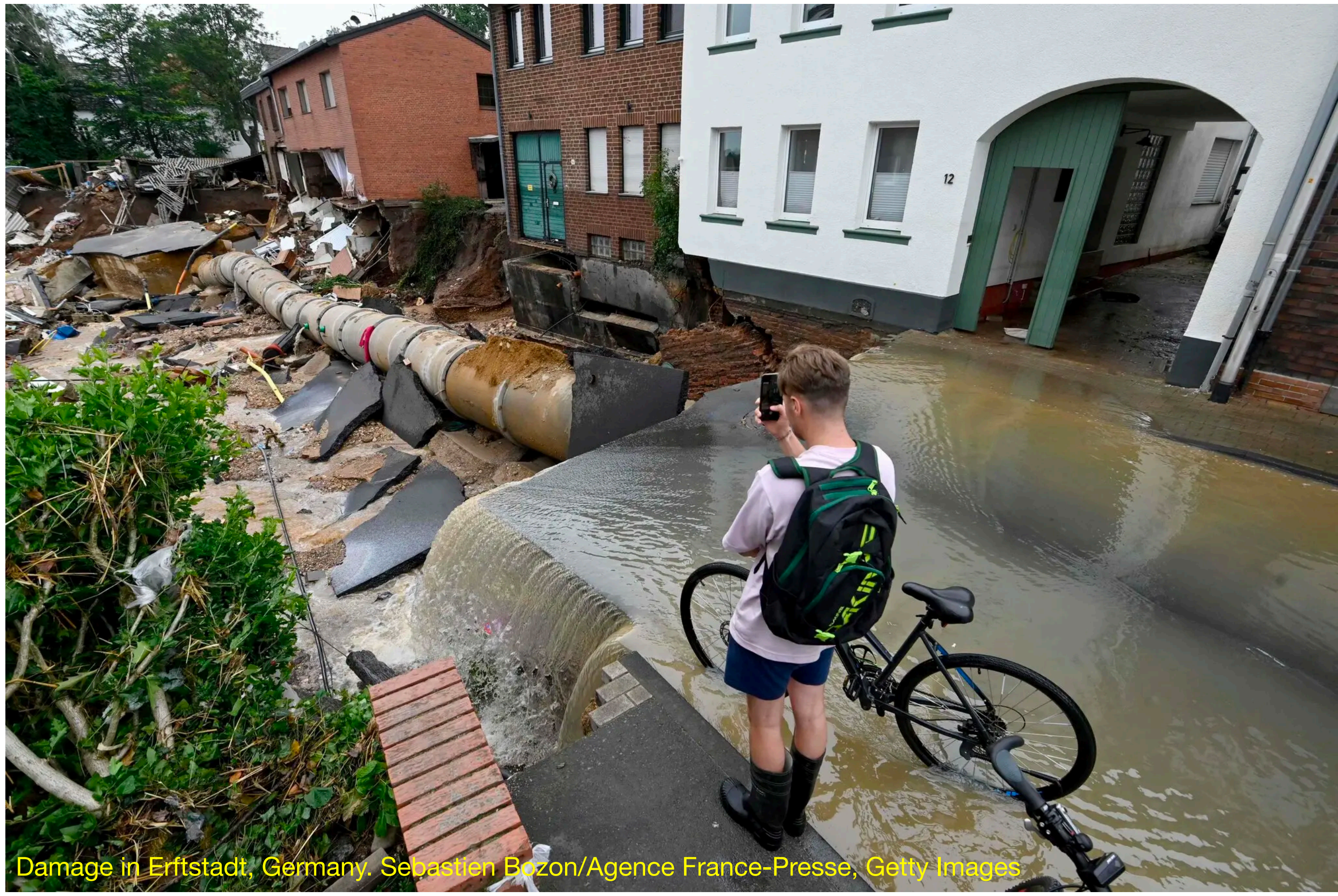

Damage in Erftstadt, Germany. Sebastien Bozon/Agence France-Presse, Getty Images

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Erftstadt, Germany, heavy rainfall broke banks of Erft river. Michael Probst/AP

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Floods, Libya 2023, failed dams, Wadi Derna, ~20,000 dead

https://www.nytimes.com/2023/09/12/world/middleeast/libya-floods-dams-collapse.html

Heavy rainfall (up to 414 mm/day!) by storm Daniel led two dams in Libya to collapse, killing thousands of people and creating a massive humanitarian disaster.

Reuters: **“Climate change made 2023 Libya flooding 50 times more likely”**

Human error is another major element that led to the severity of the event

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https://eos.org/thelandslideblog/further-information-about-the-wadi-derna-dams

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(Our focus here is on floods due to extreme precipitation rather than due to sea level rise)

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Outline

A. Flood basics: types, causes, atmospheric rivers

B. ➨ A global perspective on changes to the ***mean precipitation patterns*** in a warmer climate:

  1. Hadley cell weakening and expansion
  2. Wet getting wetter, dry getting drier

C. ➨ Understanding the expected increase in ***extreme precipitation events*** in a warmer climate.

Three types of floods

A. River floods: river overwhelmed by intense rain/snow or ice melting upstream, water level goes up, floods nearby areas.

https://en.wikipedia.org/wiki/2011_Missouri_River_Flood

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C. Coastal flooding: due to storm surges, possibly amplified by high tide.

https://en.wikipedia.

https://www.preventionweb.net/news/developing-nations-face-devastating-cost-future-coastal-flooding-new-study-says

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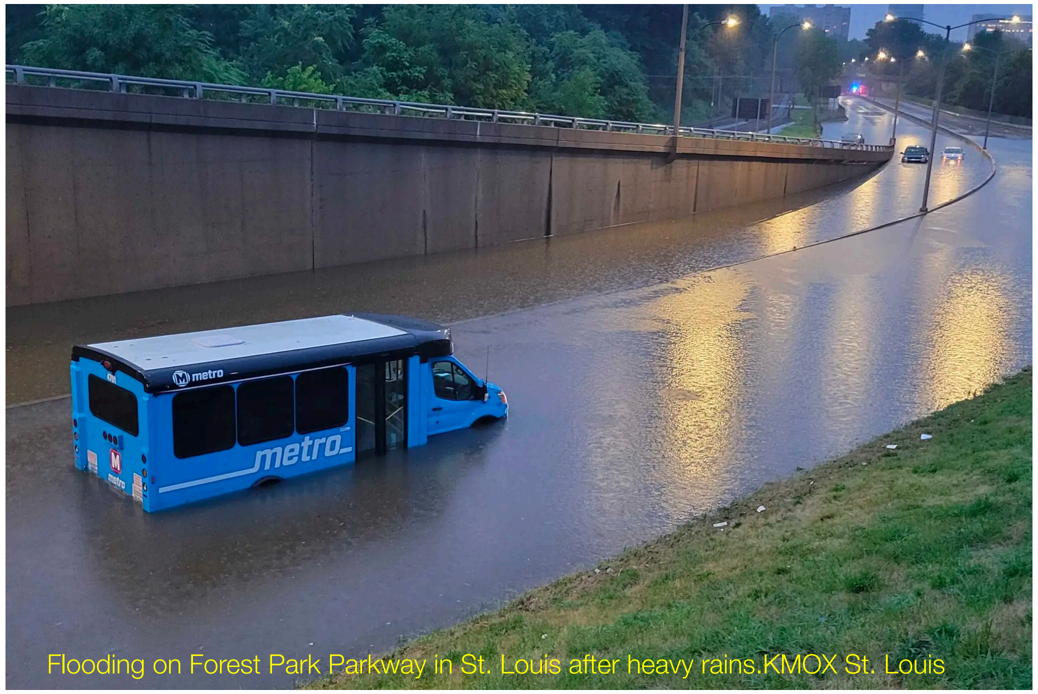
Extreme precipitation and floods



Flooding on Forest Park Parkway in St. Louis after heavy rains.KMOX St. Louis

(NYTimes, a thoughtful article this time :-)

"How Is Climate Change Affecting Floods?"

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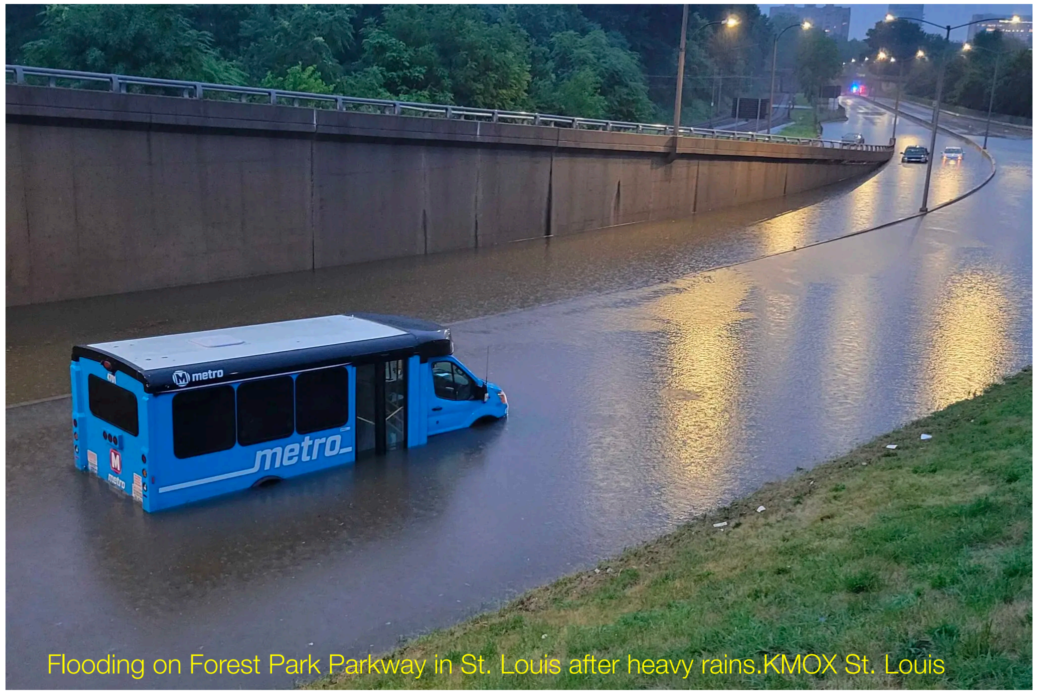

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Ingredients contributing to flood development:

A. Precipitation (especially intense, persistent, and large-area),
B. Snowmelt,
C. Topography (collecting precipitation from large areas and slopes leading to rapid flow),
D. Soil wetness/saturation in the catchment area,
E. Land-use changes, including urbanization/paved roads.
F. Infrastructure failing, e.g., levee/dam breaking.

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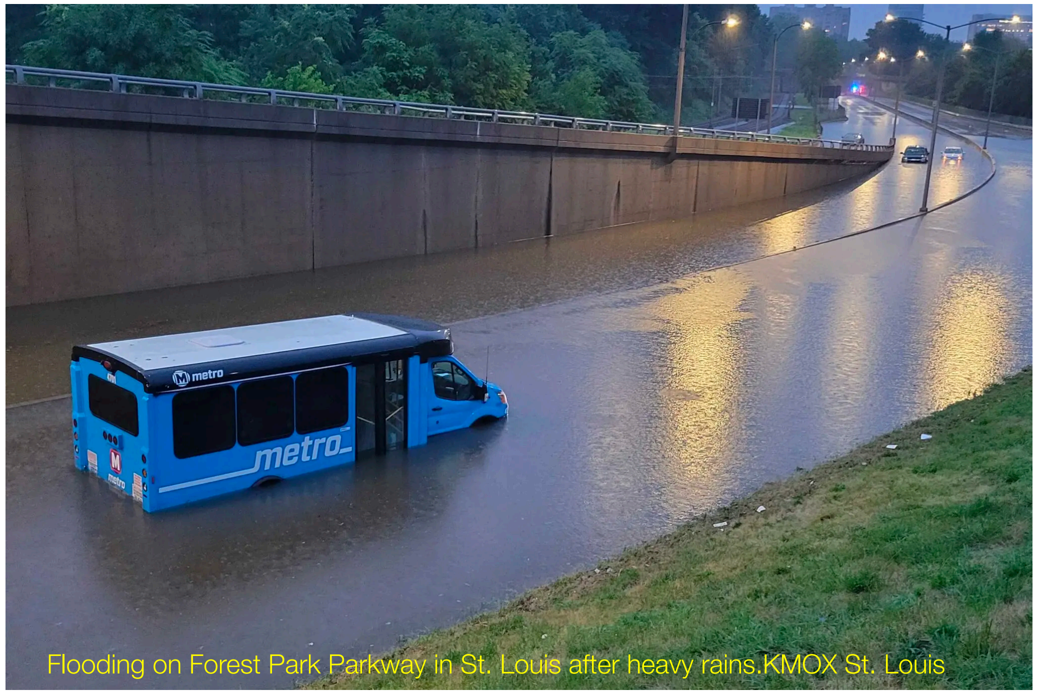
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How floods are measured

- Stage height (the height of the water in a river relative to a specific point)
- Flow rate (how much water passes by a specific location over a particular period).
- Statistical characterization of the severity of a flood: "a 100-year flood," a flood that has a 1 percent chance of striking in any given year

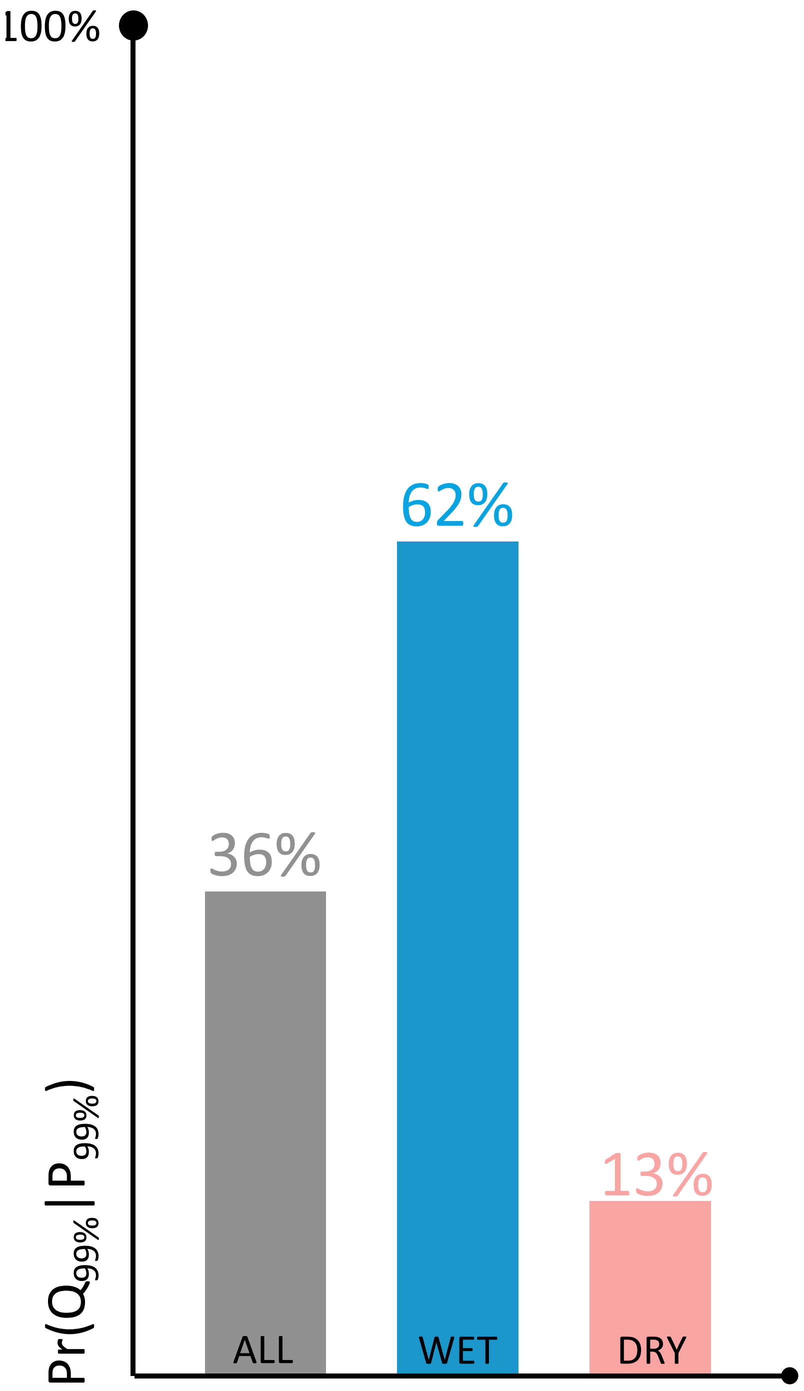
https://www.nytimes.com/article/flooding-climate-change.html

Extreme precipitation and floods

The role of soil moisture in catchment area:

“The probability of an upper 99th percentile discharge event ($Q_{99\%}$) being associated with an upper 99th percentile precipitation event ($P_{99\%}$) across the contiguous United States.

Wet (antecedence) is defined as a soil moisture wetness above the median, and dry (antecedence) is defined as below the median.” (Sharma et al 2018, Ivancic and Shaw 2015).



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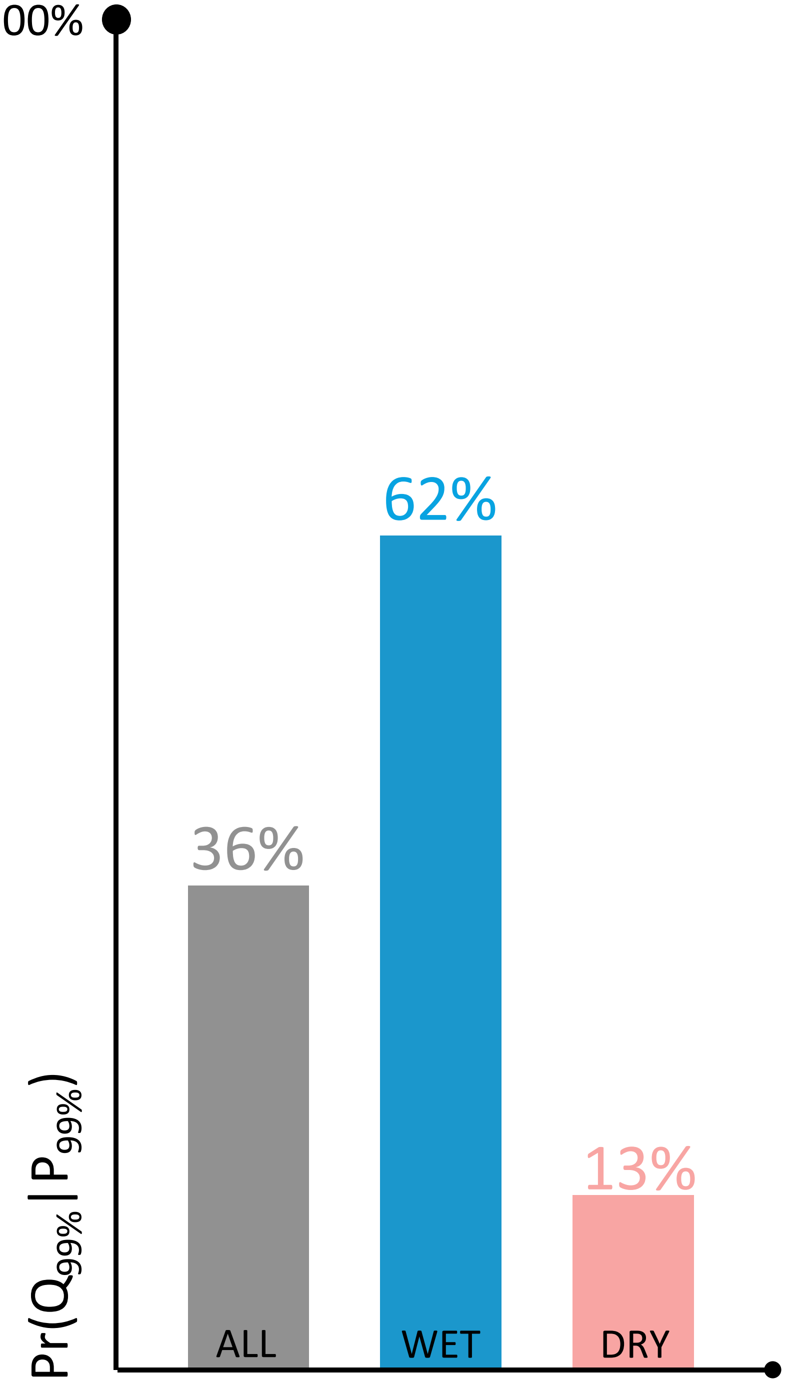

This suggests that overall larger precipitation, leading to moister soil, increases the probability of floods

Workshop

4. Global pattern of projected precipitation change in an RCP8.5 projection

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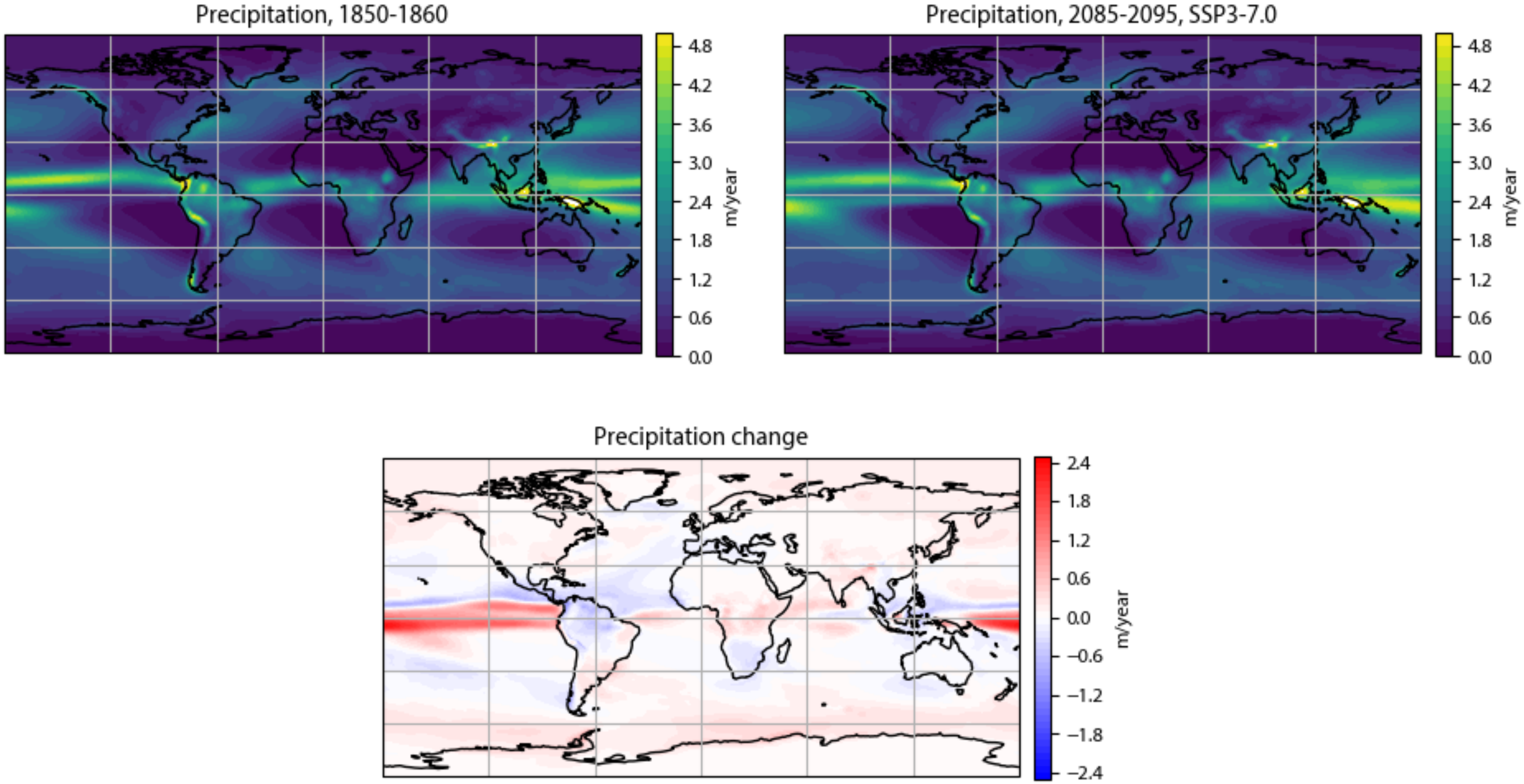

California’s future: Droughts or Floods?

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CBS news https://www.youtube.com/watch?v=yILP76p4rH0

The Fingerprints on Chile’s Fires and California Floods: El Niño and Warming. *Feb. 5, 2024.*

Behind these risks are two powerful forces: Climate change, which can intensify both rain and drought, and … El Niño, which can also supersize extreme weather. In California, meteorologists had been warning for days that an unusually strong … atmospheric river was gathering force because of extraordinarily high Pacific Ocean temperatures.

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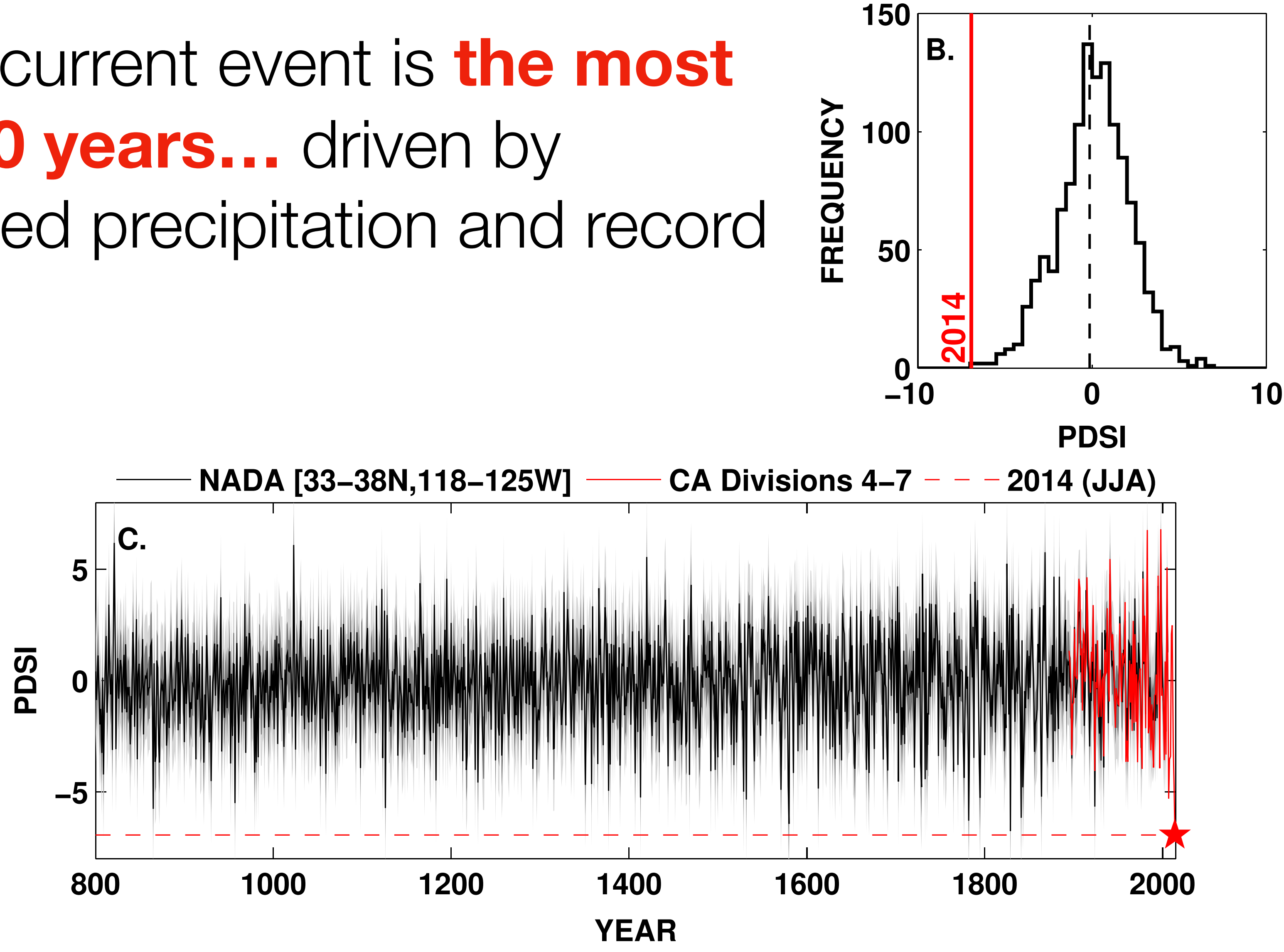

Figure 1. NADA: North American Drought Atlas for Central/ Southern California (33°N–38°N & 118°W–125°W [Vose et al., 2014]. Red line & star: 2014 value. **(B)** Distribution of the composite NADA-NOAA JJA PDSI values for the period 800–2014. **(C)** Long-term (800–2014) composite NADA-NOAA (black) and instrumental (red) PDSI.

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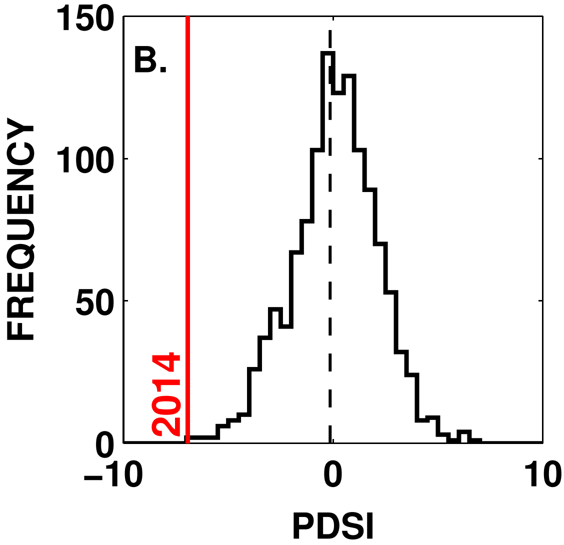
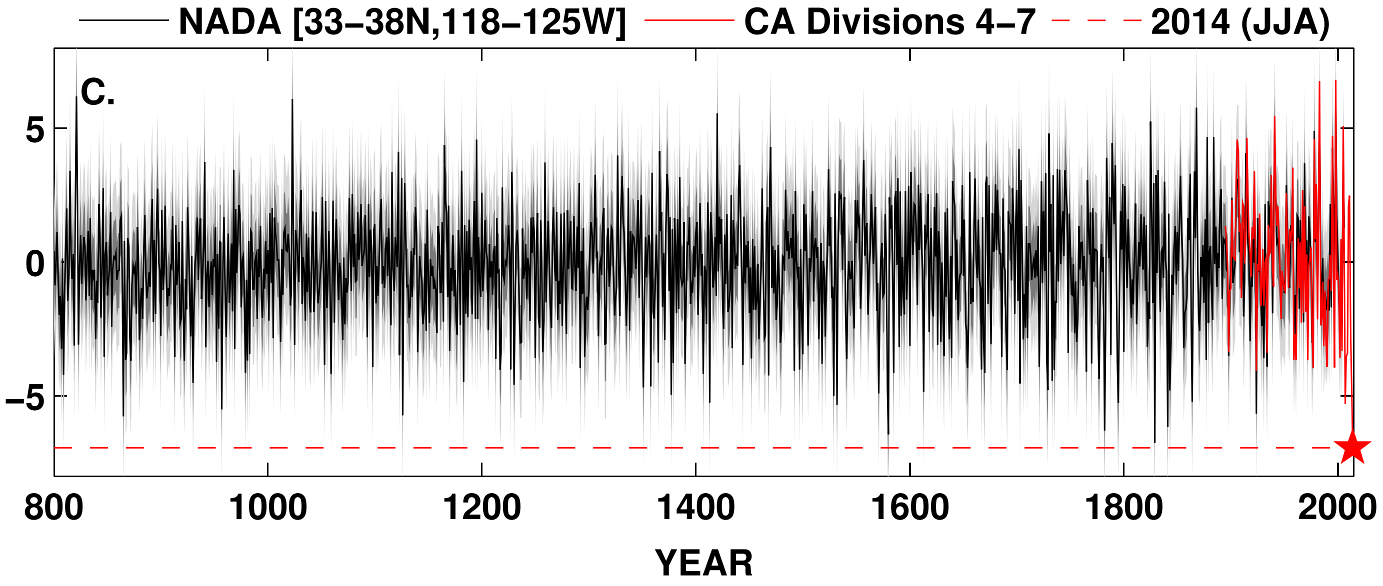


The New York Times

California Drought Is Made Worse by Global Warming, Scientists Say

Visitors along the recessed shores of Beal's Point in California's Folsom Lake State Recreation Area. A new study has found that inevitable droughts in California were made worse by global warming.

Damon Winter/The New York Times



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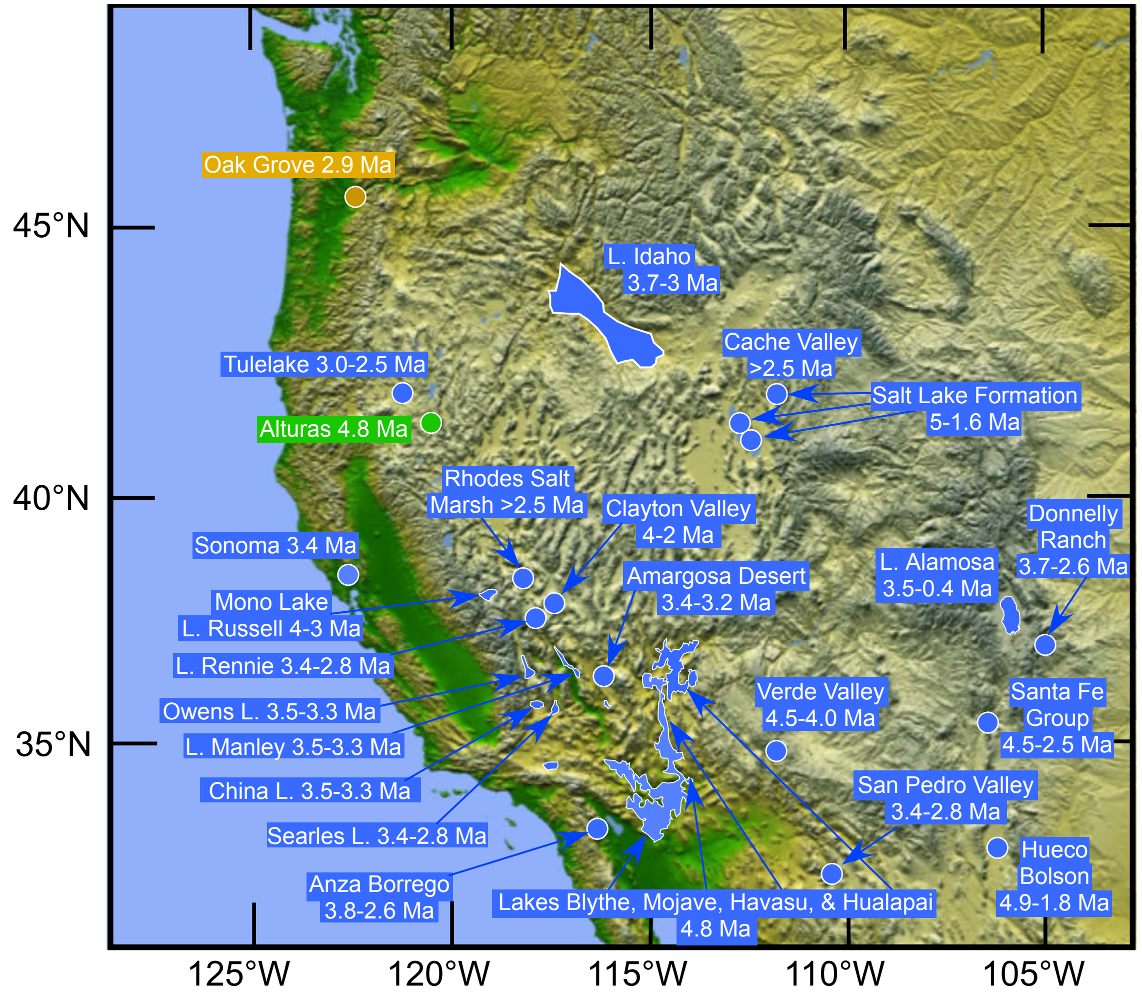
Wet California during the Pliocene (2–5 Myr, 400 ppm CO_2)



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- lacustrine sediments,
- fish fossils,
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- fossils of animals,
- pollen,
- diatoms,
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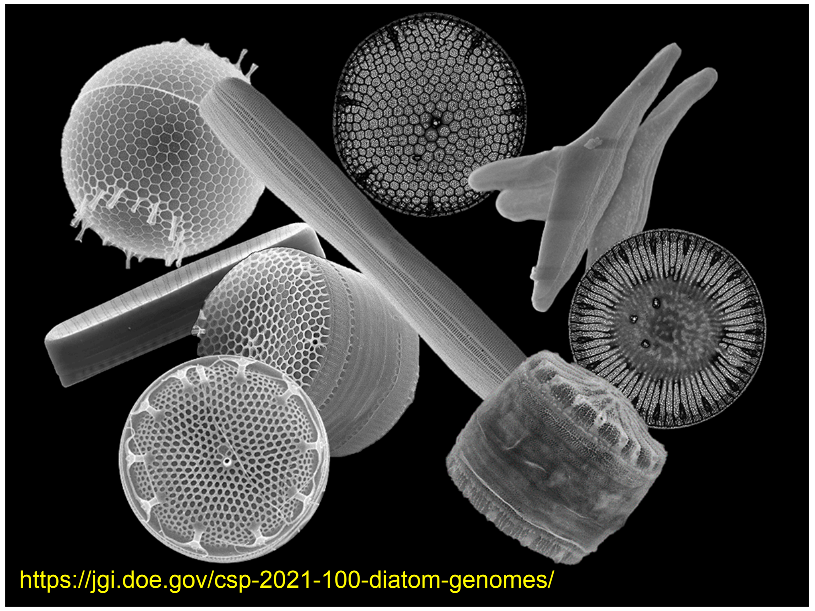
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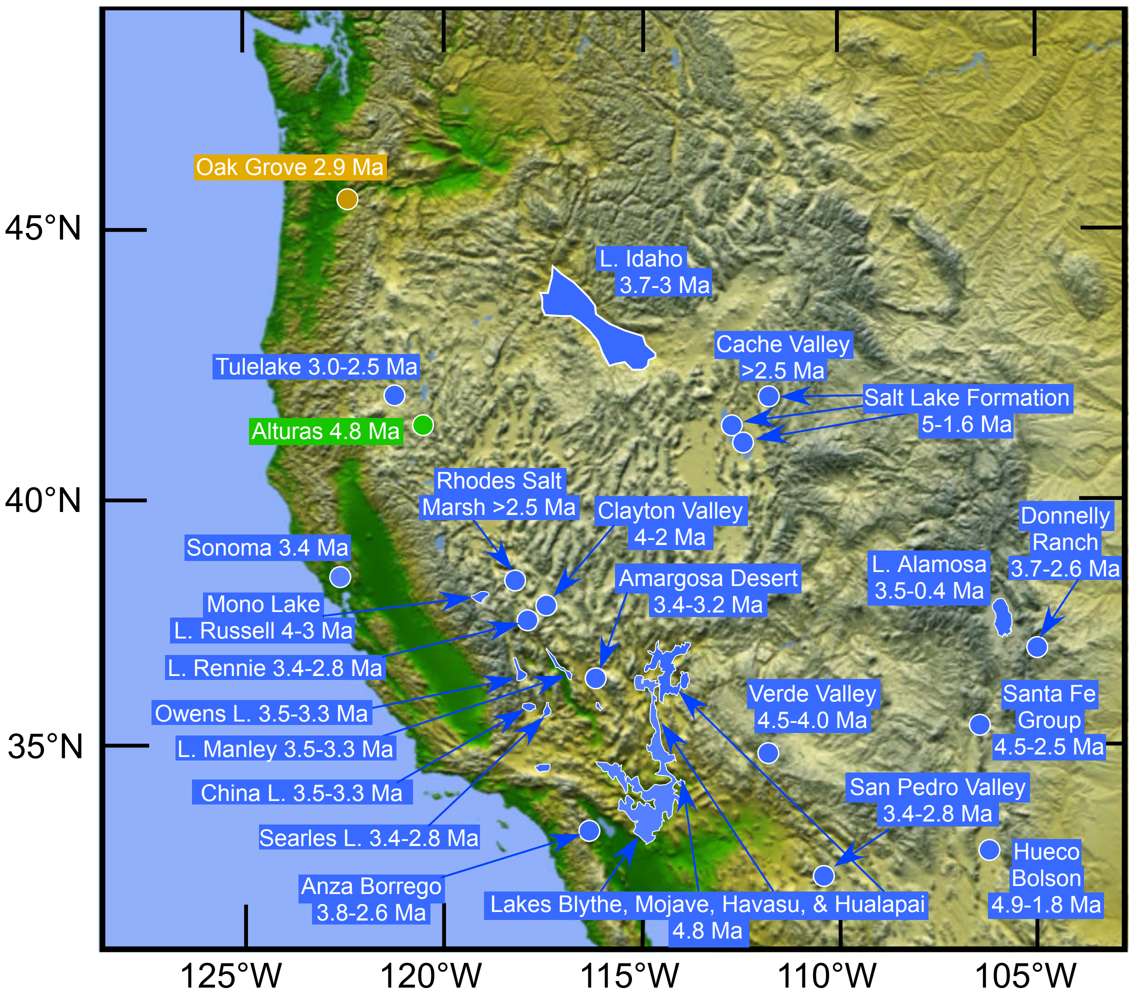


https://landscape.soilweb.ca/lacustrine-environment/


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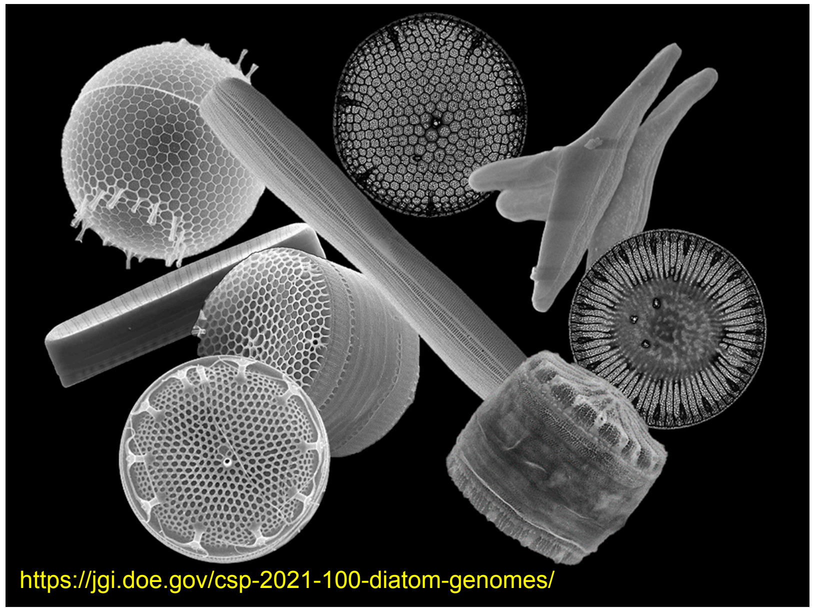
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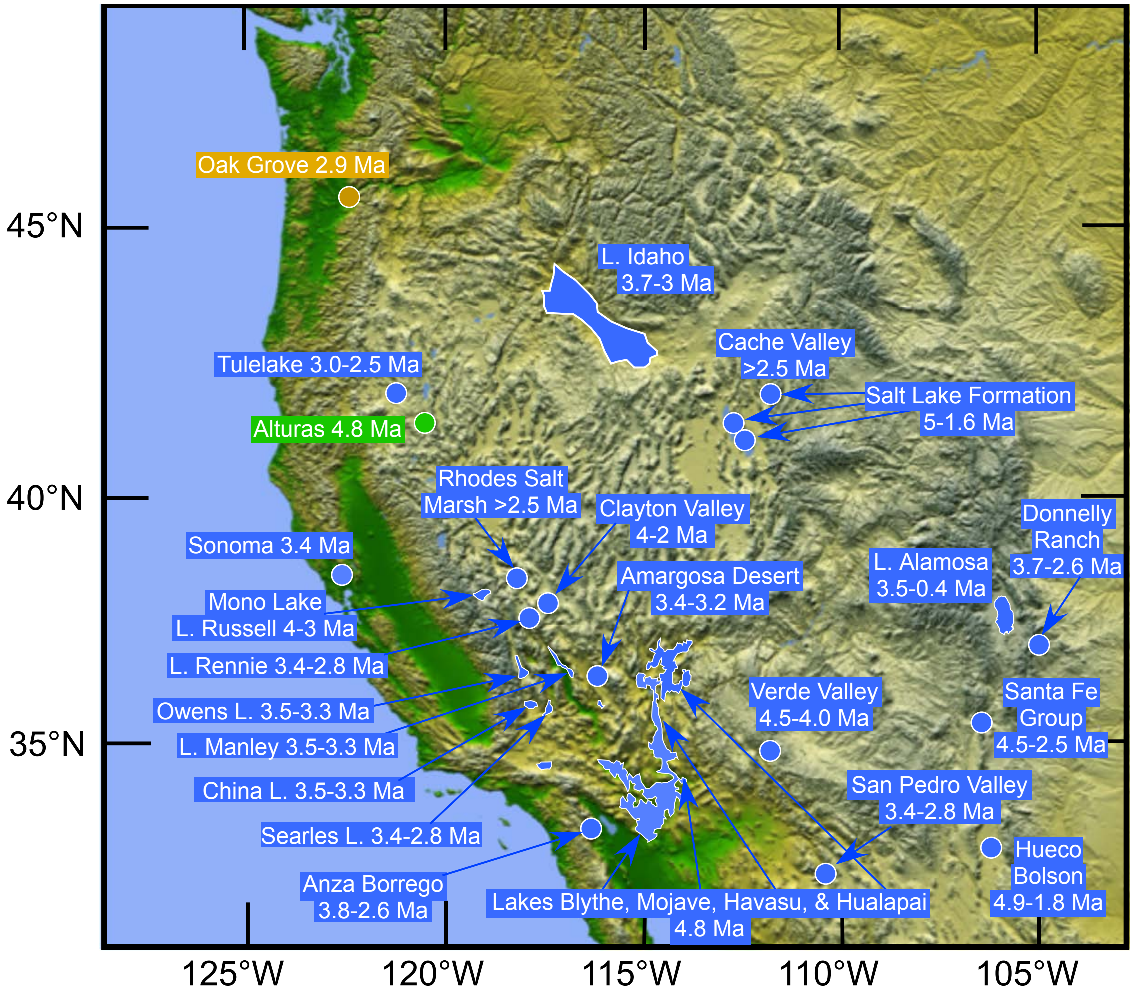


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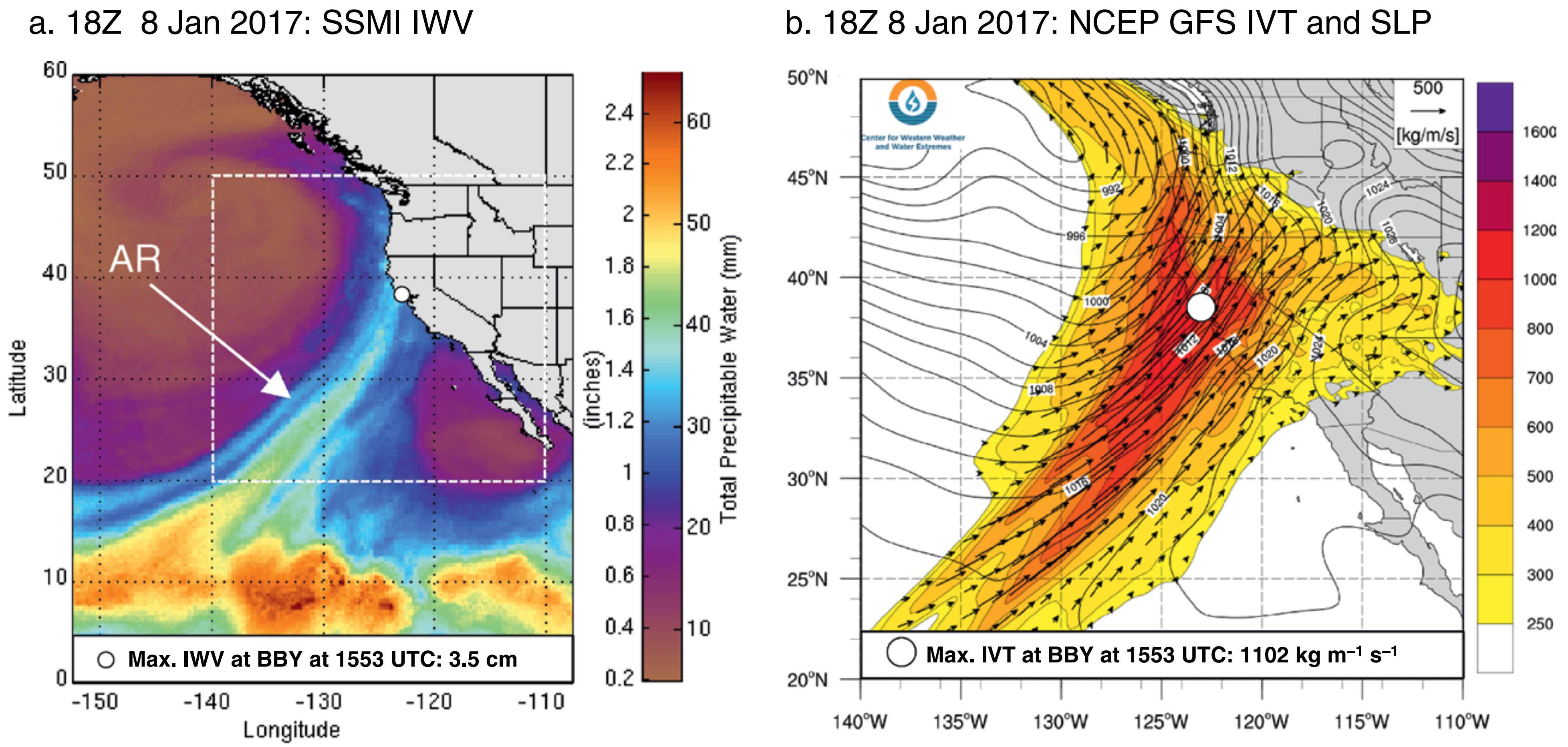
Topographic map of the western US showing Pliocene lakes and other sites where lacustrine deposits or fossil finds indicate wetter environments than today. Pollen and megaflora fossils call for a drier environment than today at Oak Grove, but wetter at Cache Valley and Sonoma. Abundant lacustrine sediment with fish fossils and pollen suggestive of moist environments attest to **a large lake, Lake Idaho, that had formed before 3.7 Ma and lingered until ~3 Ma**. Diatoms, pollen, and ostracods attest to a wetter environment in Tulelake than today, but ostracods and other organisms in lacustrine sediment dated to 4.8 at Alturas suggest little difference from today. Pliocene lacustrine sediment, in some cases with pollen, mega-plant fossils, and fossils of animals, suggestive of **environments wetter than those today, have been reported from numerous inland sites:** the Salt Lake Formation in Lake Bonneville cores and Cache Valley; Rhodes Salt Lake, Clayton Valley, and Lakes Russell and Rennie; Verde Valley; Donnelly Ranch, Santa Fe Group in the Rio Grande Rift, and Hueco Bolson. The chemistry of caliche and related deposits were used to infer marshland and ponds in the Amargosa Desert, and for the San Pedro Valley. A large lake occupied the Alamosa Basin throughout much of Pliocene and Quaternary time. **Shorelines of a number of Pliocene Lakes in the Death Valley**-Owens Valley region: Lake Russell, the predecessor to Mono Lake, Lake Manley, Owens, China, Searles Lakes, and other small lakes. Widespread lacustrine sediment that seemed to occupy a series of early Pliocene lakes (Blythe, Mojave, Havaus, and Hulapai) along the modern Colorado River valley in California-Arizona. Petrified wood from the Anza Borrego Desert suggests a wetter climate there.

Floods and Atmospheric Rivers (e.g., California 2023)

Wikipedia: “Atmospheric rivers are narrow corridors or filaments of concentrated moisture in the atmosphere. Typically thousands of km long and only a few hundred km wide. A single one can carry a greater water flux than the Earth’s largest river, the Amazon. There are typically 3–5 of these present within a hemisphere at any given time.” (https://en.wikipedia.org/wiki/Atmospheric_river)



a. 18Z 8 Jan 2017: SSMI IWV

b. 18Z 8 Jan 2017: NCEP GFS IVT and SLP

Ralph et al 2019

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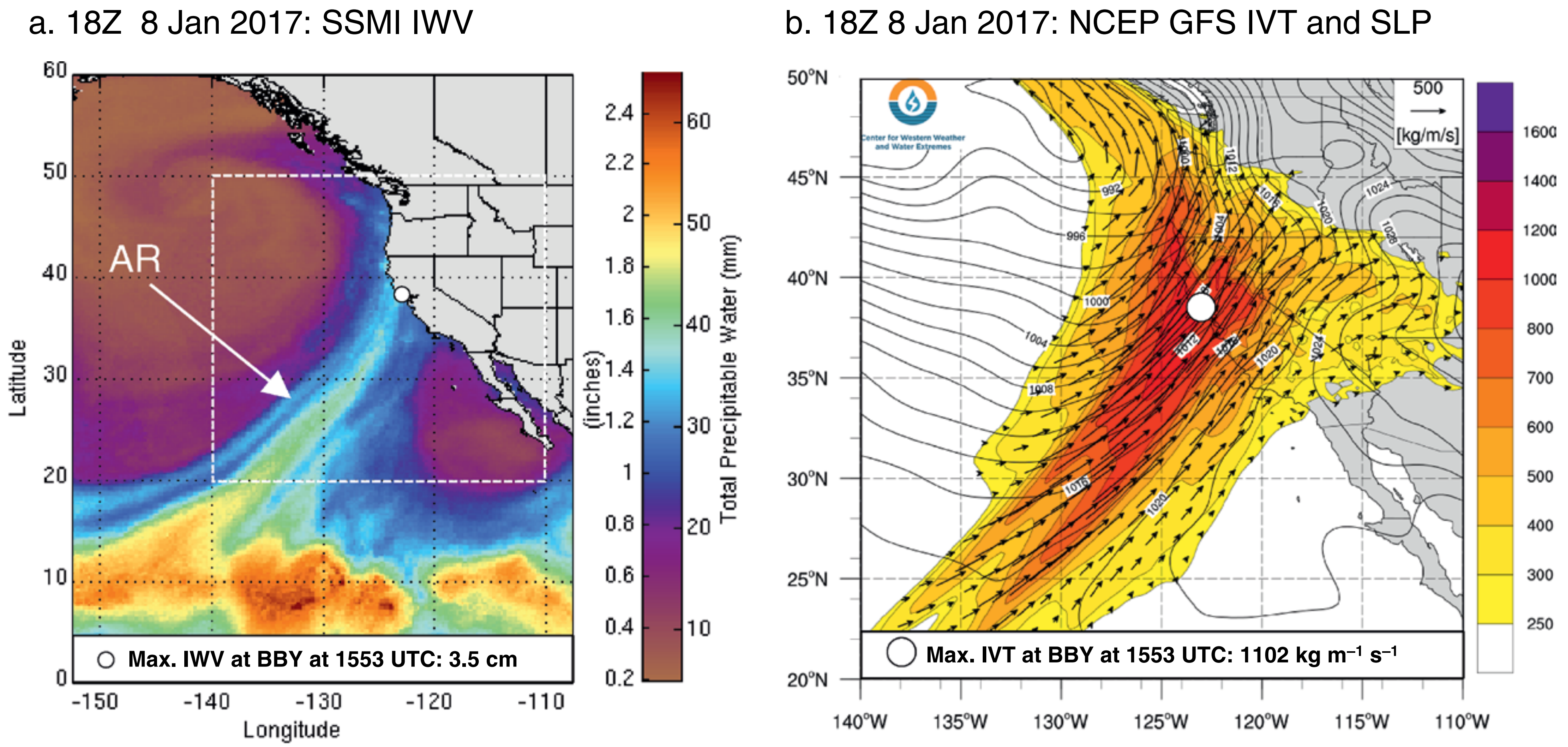


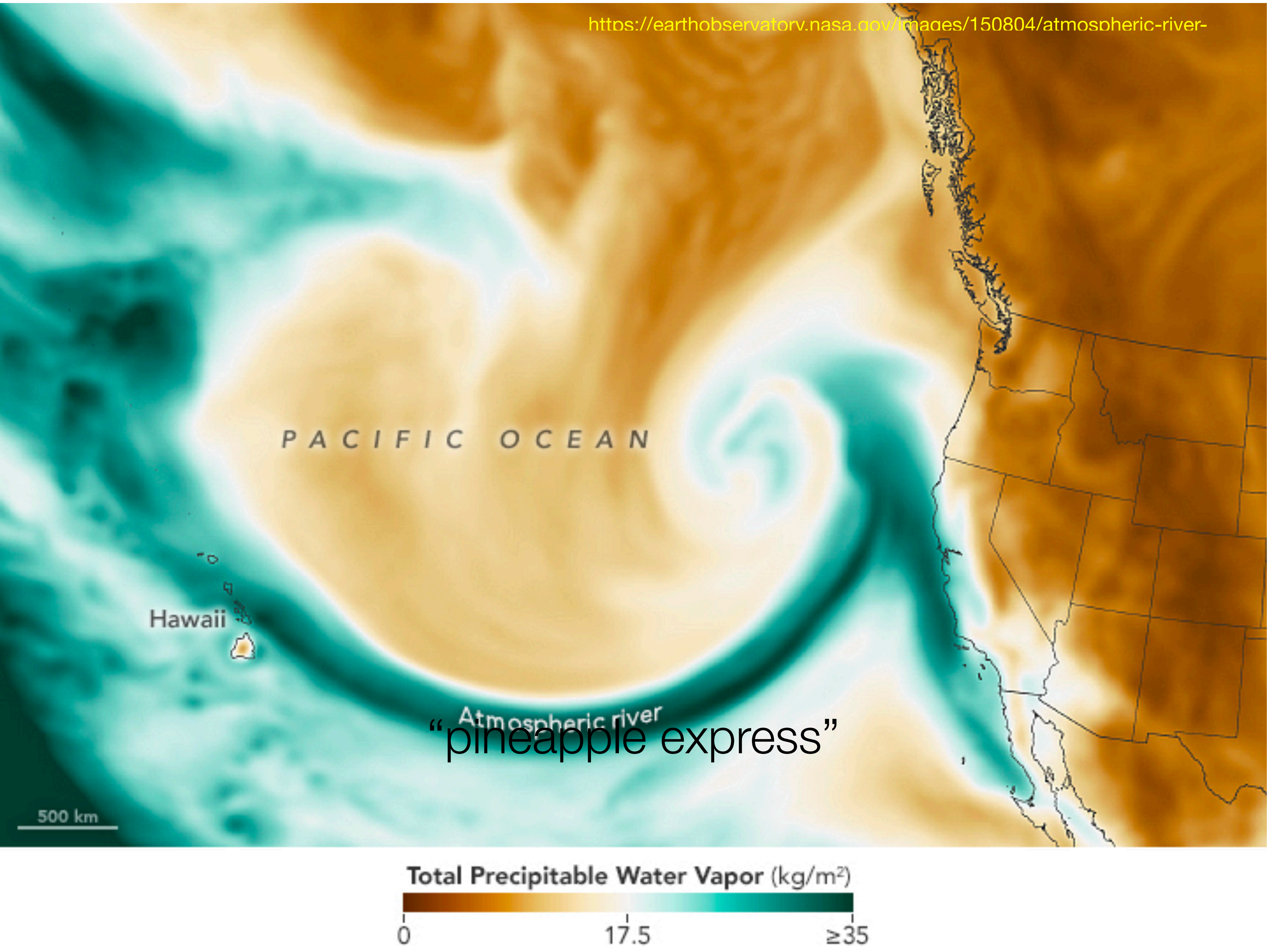
Ralph et al 2019

Defining/ quantifying ARs:

- IVT: vertically integrated water vapor transport $IVT = \int \mathbf{u} q \, \rho dz = - \int \mathbf{u} q \, dp/g$
- IWV: vertically integrated water vapor (precipitable water, the depth of water in a column of the atmosphere, if all water were precipitated as rain) $IWV = \rho_w^{-1} \int \rho_a q \, dz$

An atmospheric river is, by definition, IVT ≥ 250 $\text{kg m}^{-1}\text{s}^{-1}$ and IWV ≥ 2.0 cm.

Floods and Atmospheric Rivers (e.g., California 2023)



https://earthobservatory.nasa.gov/images/150804/atmospheric-river-

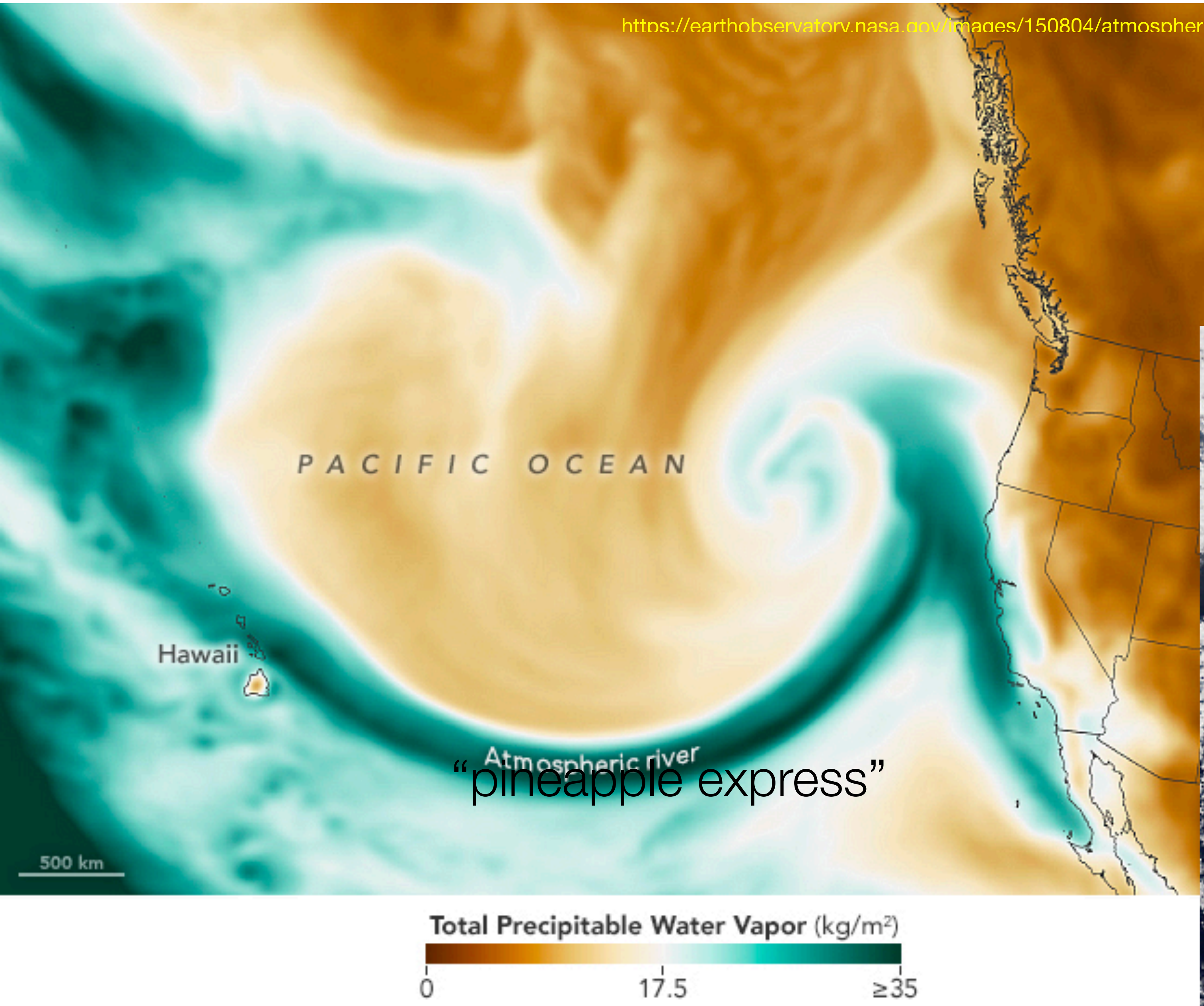
“pineapple express”

Jan 4, 2023

Atmospheric rivers occur regularly in wintertime, and they account for up to 50 percent of all rain and snow that falls in the western United States. 12 of them hit California in March 2023, causing floods and drought relief.

https://earthobservatory.nasa.gov/images/150804/atmospheric-river-lashes-california

Floods and Atmospheric Rivers (e.g., California 2023)



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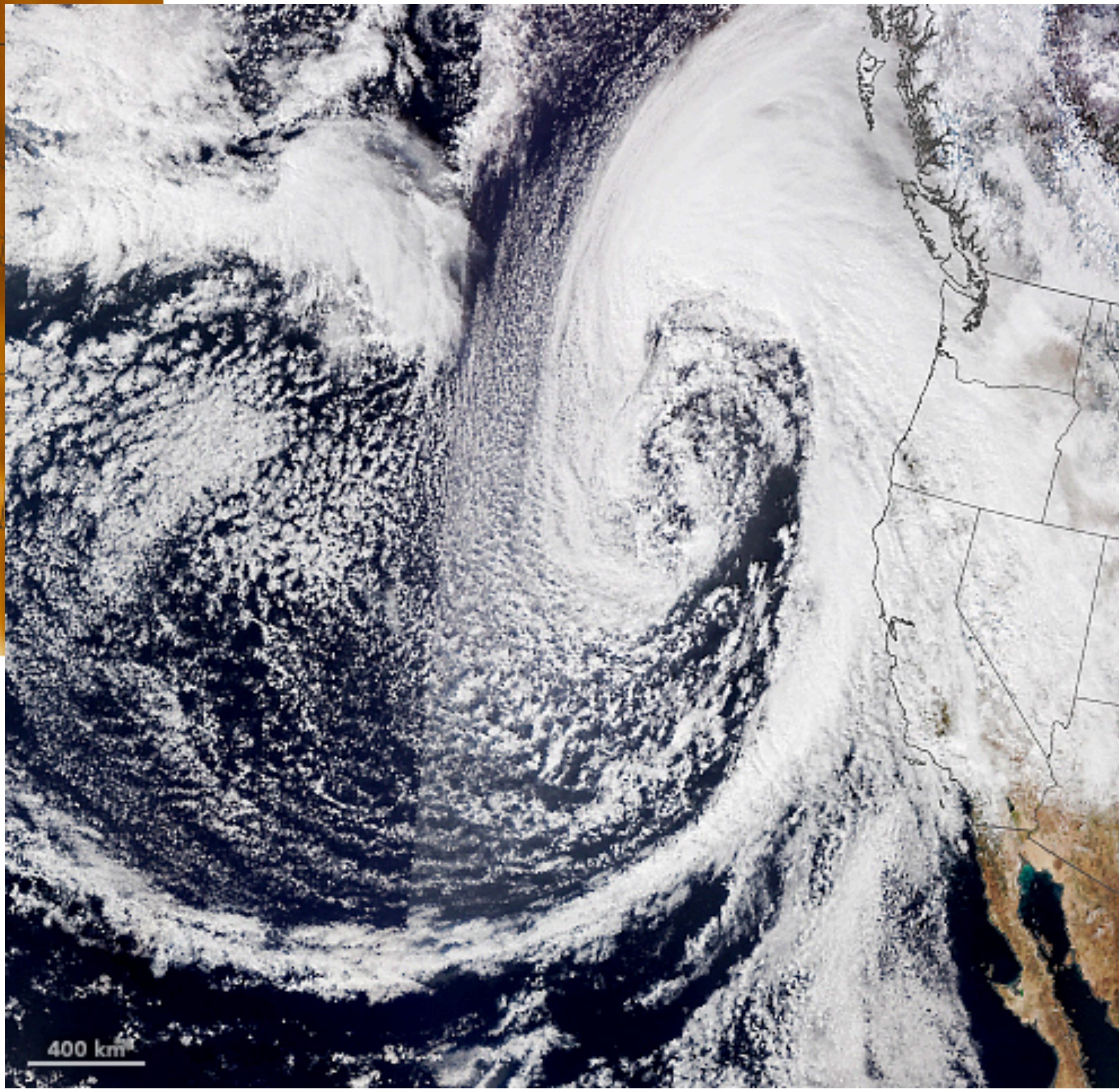

visible infrared imaging radiometer

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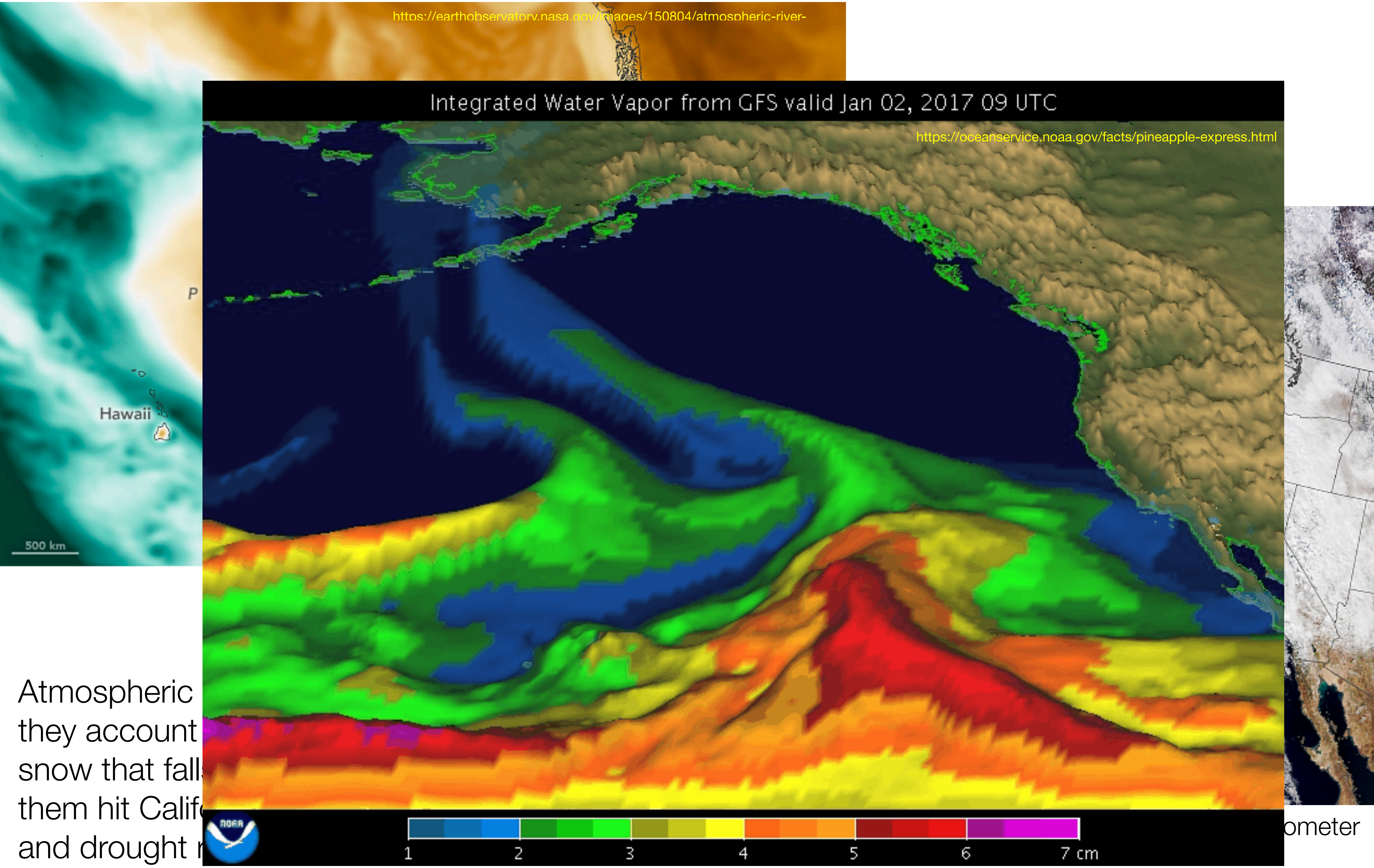

Atmospheric
they account
snow that fall
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and drought r

ometer

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Outline

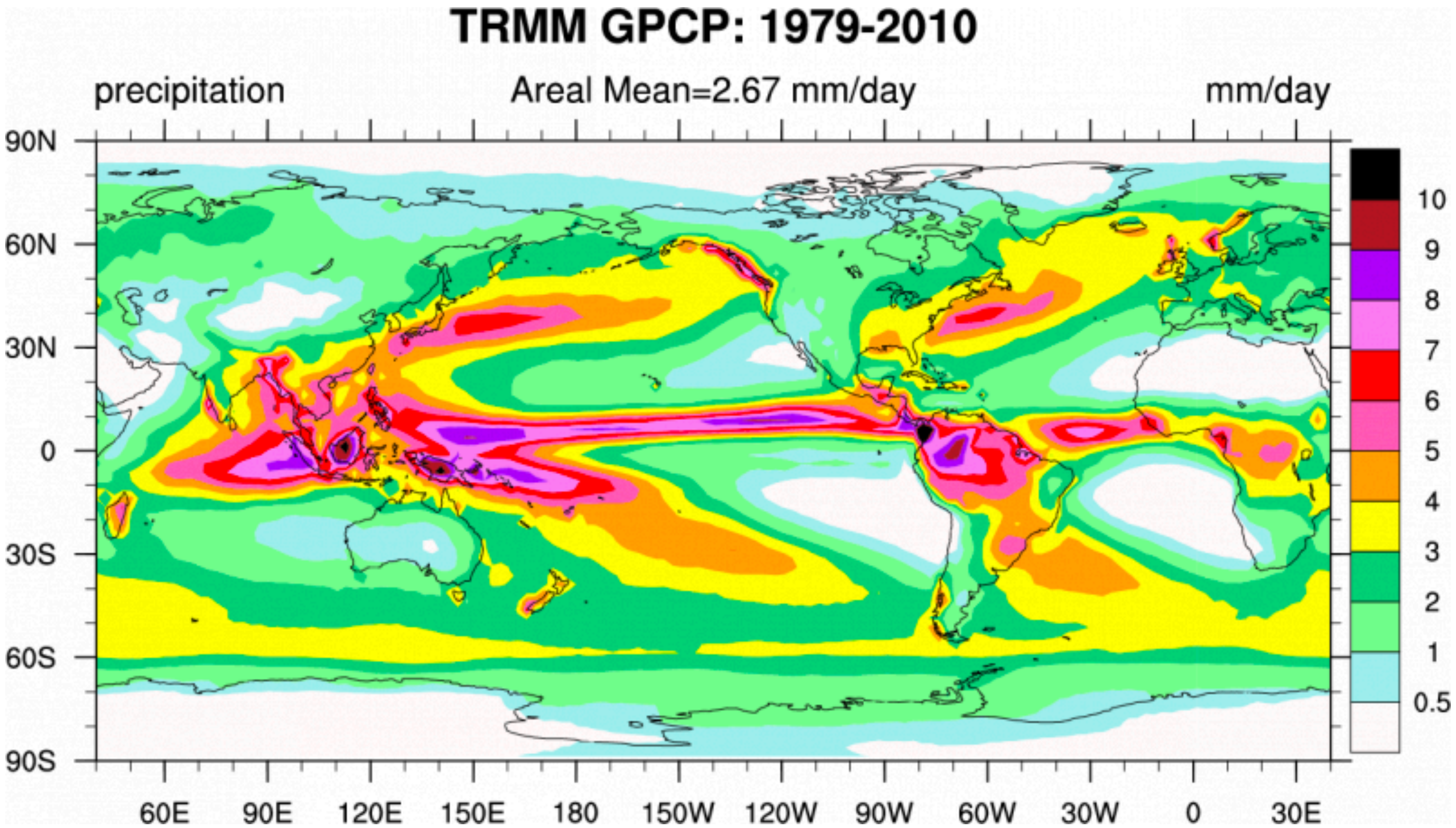
A. Flood basics: types, causes, atmospheric rivers

B. ➨ A global perspective on changes to the ***mean precipitation patterns*** in a warmer climate:

   1. Hadley cell weakening and expansion
   2. Wet getting wetter, dry getting drier

C. ➨ Understanding the expected increase in ***extreme precipitation events*** in a warmer climate.

Mean precipitation patterns & the Hadley circulation

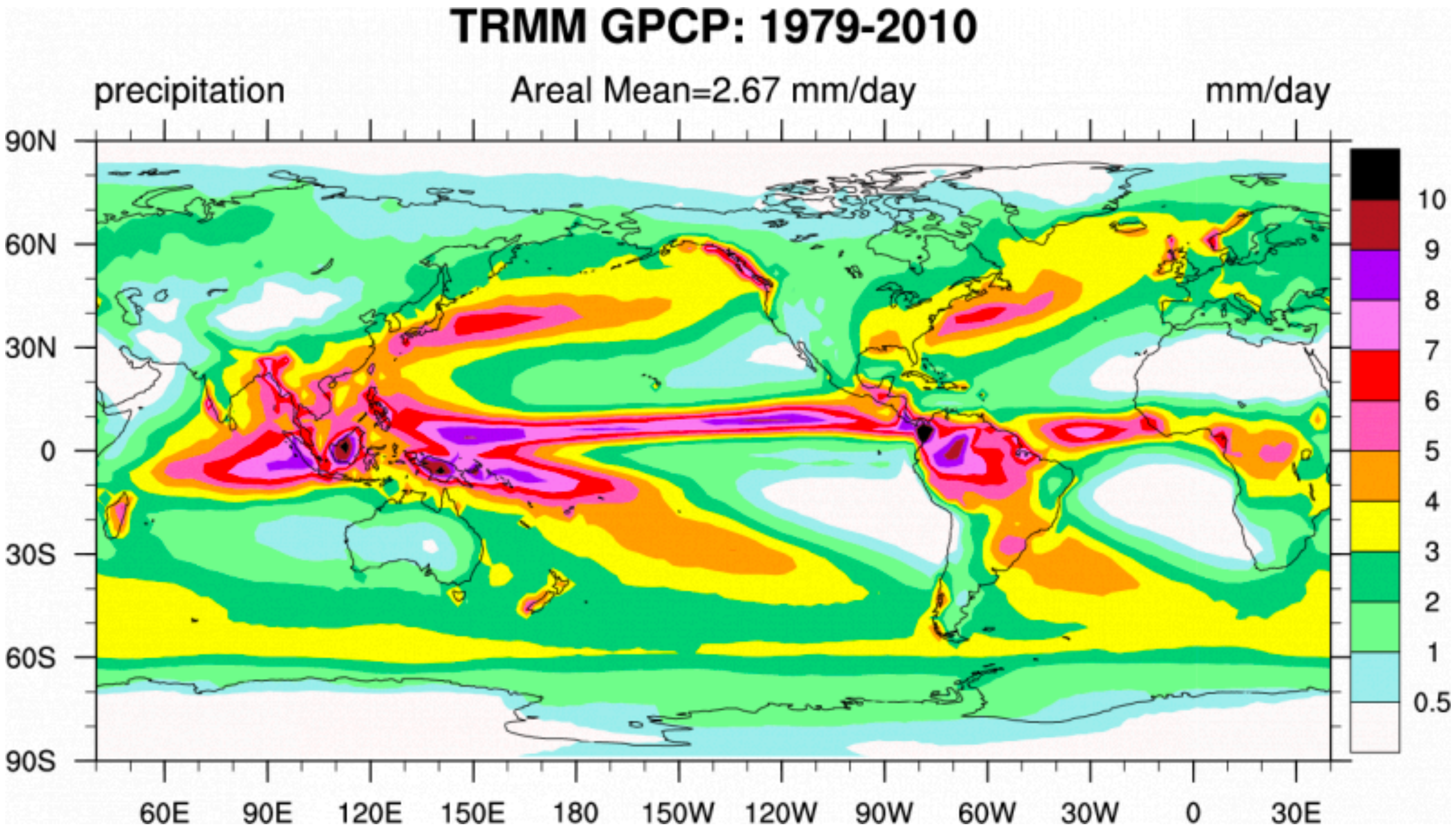


https://climatedataguide.ucar.edu/climate-data/gpcp-monthly-global-precipitation-climatology-project

Climatological annual mean precipitation (mm/day) for 1979-2010.

Global mean = 2.67 mm/day. (Climate Data Guide; D. Shea)

Mean precipitation patterns & the Hadley circulation



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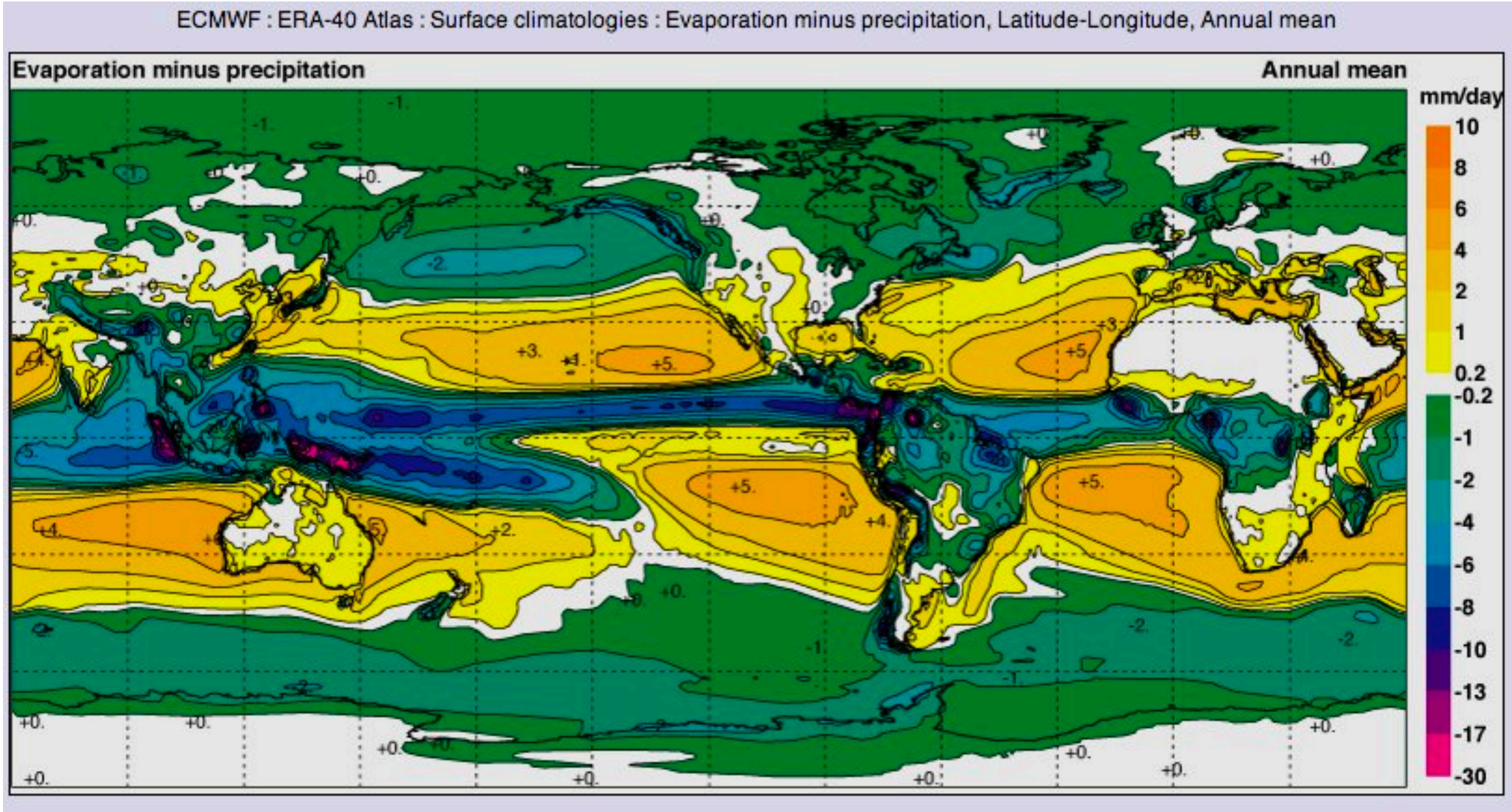
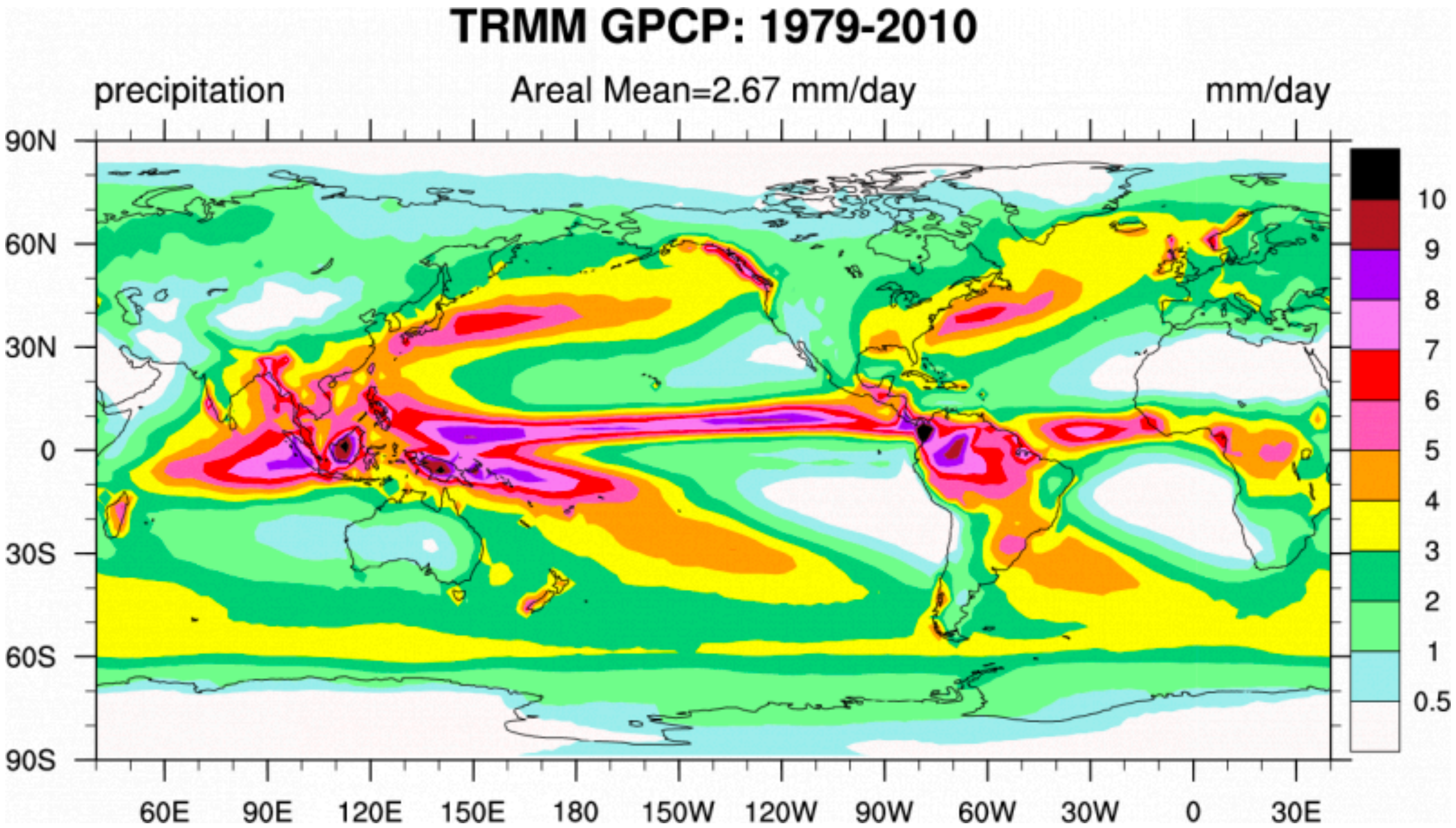


https://commons.wikimedia.org/wiki/File:Latitude_Longitude_Evaporation_minus_precipitation.jpg

Global map of Annual mean Evaporation minus precipitation
ERA-40 Atlas; NASA & ECMWF

Mean precipitation patterns & the Hadley circulation



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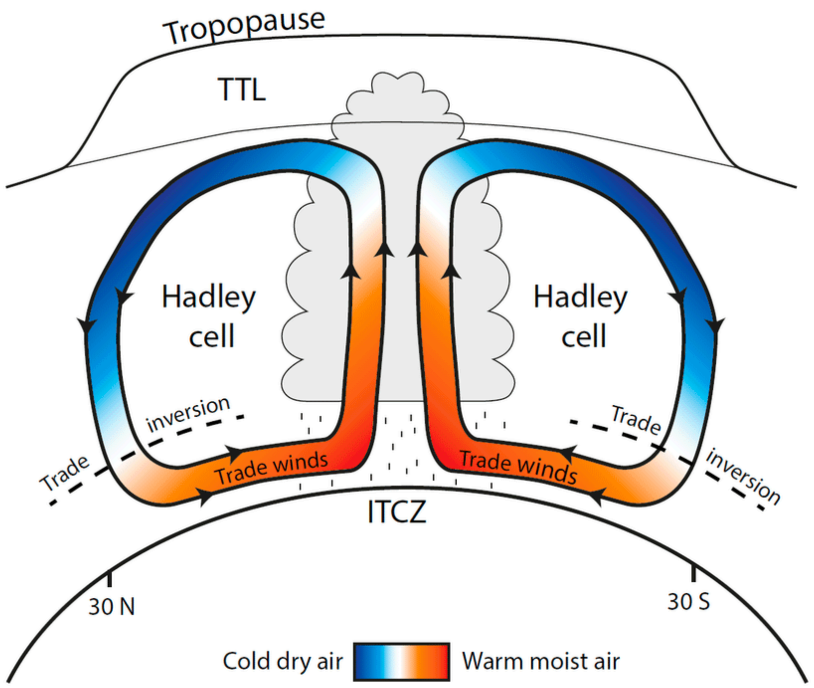
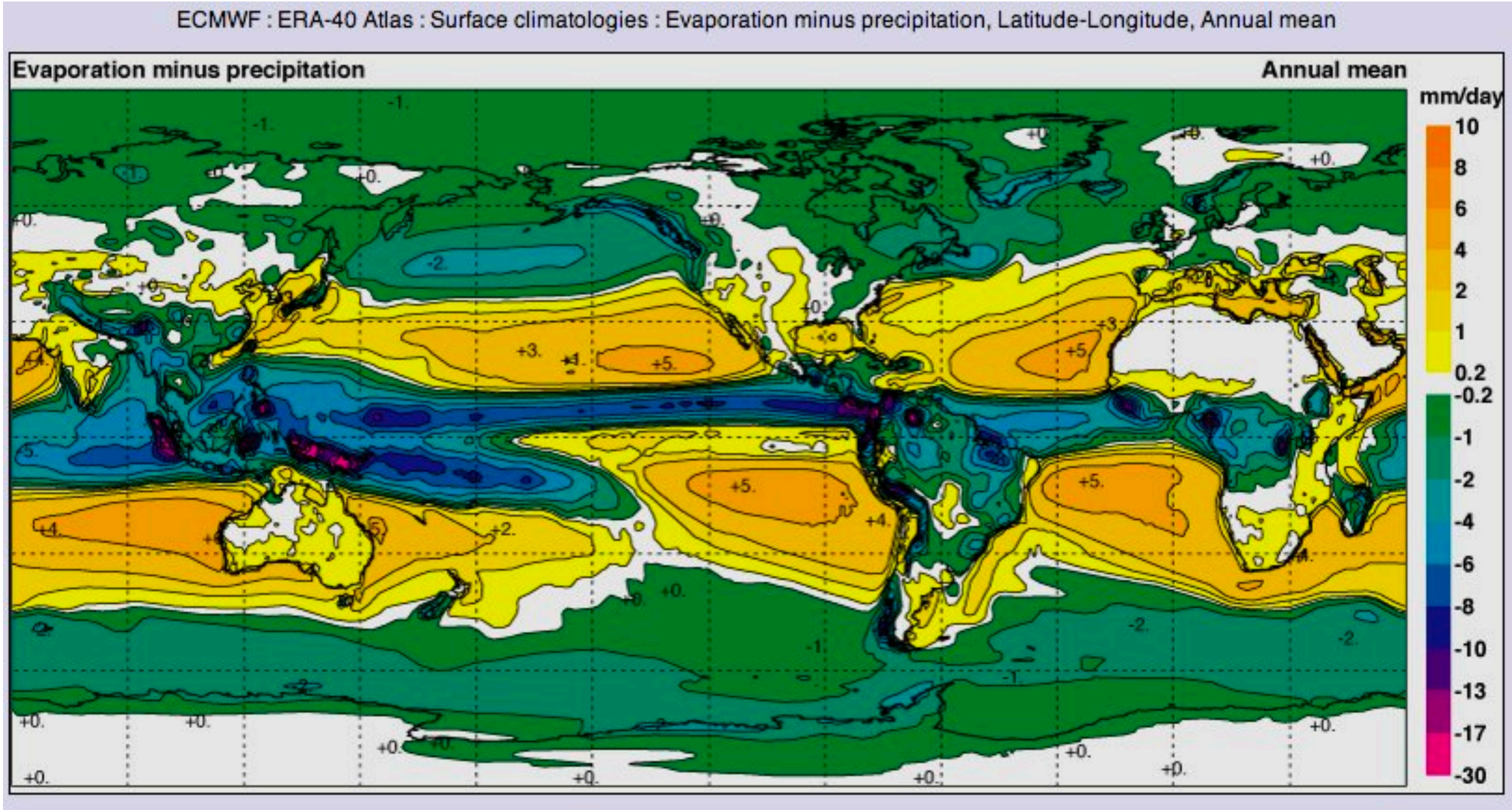
The Hadley Cell/Circulation



https://www.researchgate.net/figure/Schematic-of-the-Hadley-circulation-Abbreviations-TTL-Tropical-tropopause-layer_fig1_322886947

The downward branch is associated with dry areas



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Global map of Annual mean Evaporation minus precipitation

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Weakening and poleward expansion of the Hadley circulation
Textbook section 12.6.1 (notes 12.3.1)

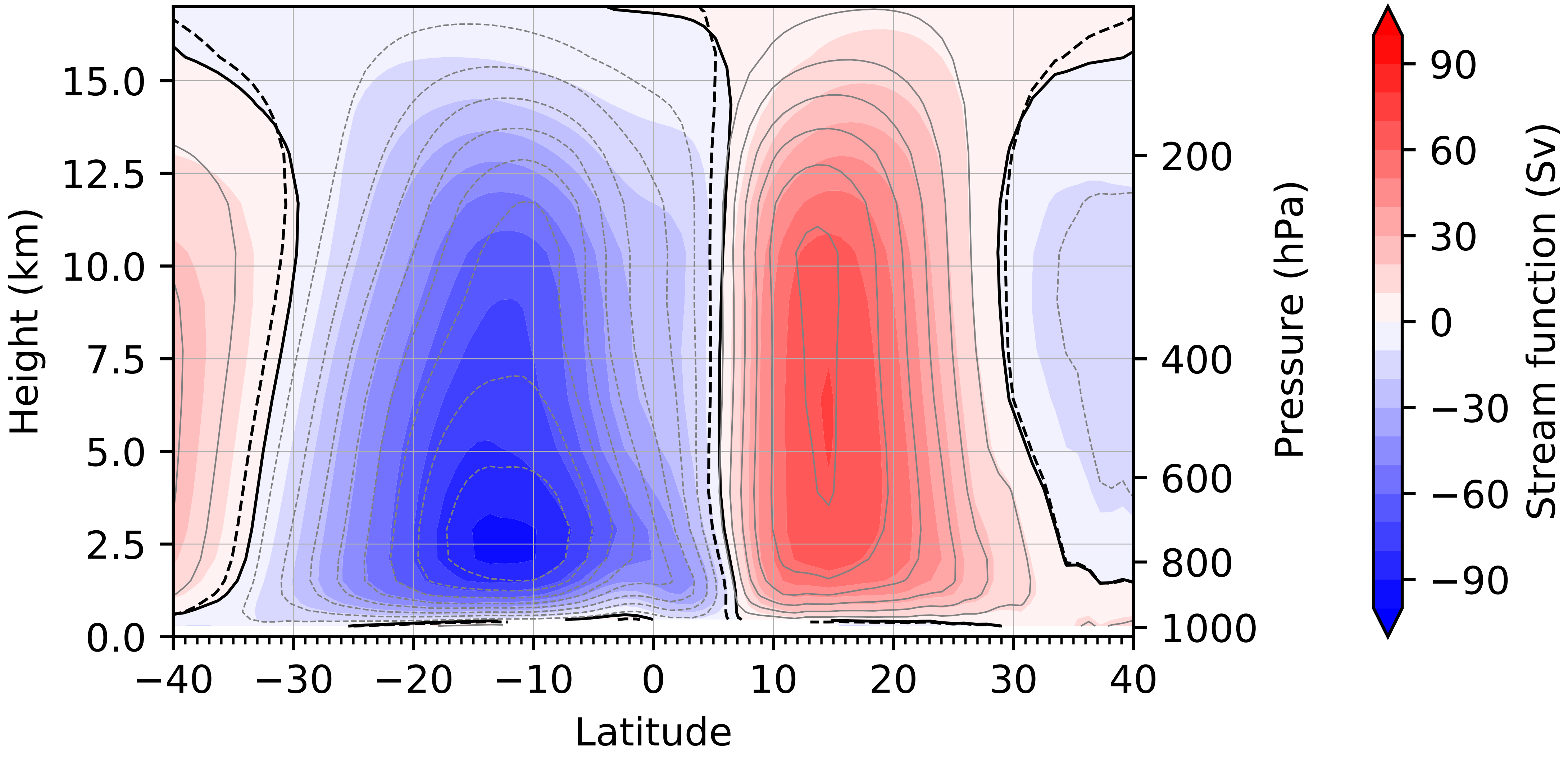

Figure 12.6: Projected Hadley cell expansion under global warming. Color shadings: the zonally-averaged atmospheric meridional overturning circulation evaluated by a climate model for 1920–1940. Contour shading levels: transport in Sverdrups (Sv, here 10^9 kg/s). Gray lines: same quantity for RCP8.5, averaged over 2080–2100. Solid black contour: zero contour of the 1920–1940 stream-function, & dashed black contour is that for 2080–2100.

Weakening and poleward expansion of the Hadley circulation
Textbook: “Hadley cell expansion and weakening”

Hadley weakening

Weakening and poleward expansion of the Hadley circulation
Textbook: “Hadley cell expansion and weakening”

Hadley weakening

The tropical near-surface atmospheric humidity increases by 6% per 1 °C of surface warming, assuming the relative humidity does not change, or by about 20% for a 3 °C warming. ➨ a moister boundary layer air ➨ the present-day upward tropical air mass transport would carry 20% more moisture out of the boundary layer. The surface evaporation rate is less sensitive to warming ➨ The boundary layer would dry out unless the Hadley cell transport weakens.

Weakening and poleward expansion of the Hadley circulation Textbook: “Hadley cell expansion and weakening”

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The poleward expansion of the Hadley cells

An air parcel rising in the present climate at the equator and traveling poleward at an altitude of a few km is shifted by the Coriolis force to the right in the Northern Hemisphere, creating the subtropical upper-level westerly (eastward) tropospheric jet. The jet becomes stronger the further the air moves poleward, eventually becomes unstable, and breaks into weather-scale motions, not allowing the jets to strengthen further and setting the poleward edge of the Hadley cell. The tropical lapse rate weakening in a warmer climate allows the Hadley cell to further expand poleward before becoming unstable.

Weakening and poleward expansion of the Hadley circulation
Textbook: “Hadley cell expansion and weakening”

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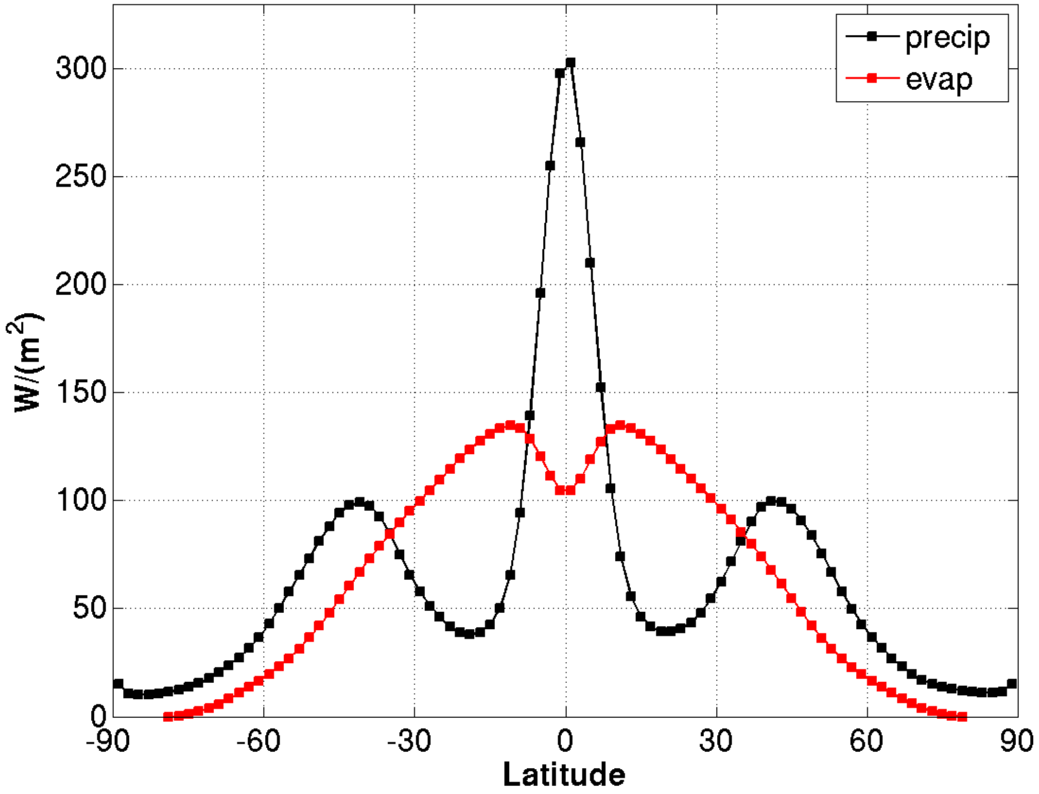
Caveat:

These mechanisms for both the weakening and expansion of the Hadley cell in warmer climates are partial and oversimplified. Additional factors in play in the Hadley cell weakening and expansion include changes to the atmospheric lapse rate, tropopause height, and more.

Mean precipitation trends: Wet getting wetter, dry getting drier

Textbook section 12.6.2 (notes 12.3.2)



Mean precipitation P and evaporation E as a function of latitude.

https://www.gfdl.noaa.gov/blog_held/13-the-strength-of-the-hydrological-cycle/

Mean precipitation trends: Wet getting wetter, dry getting drier

Textbook section 12.6.2 (notes 12.3.2)

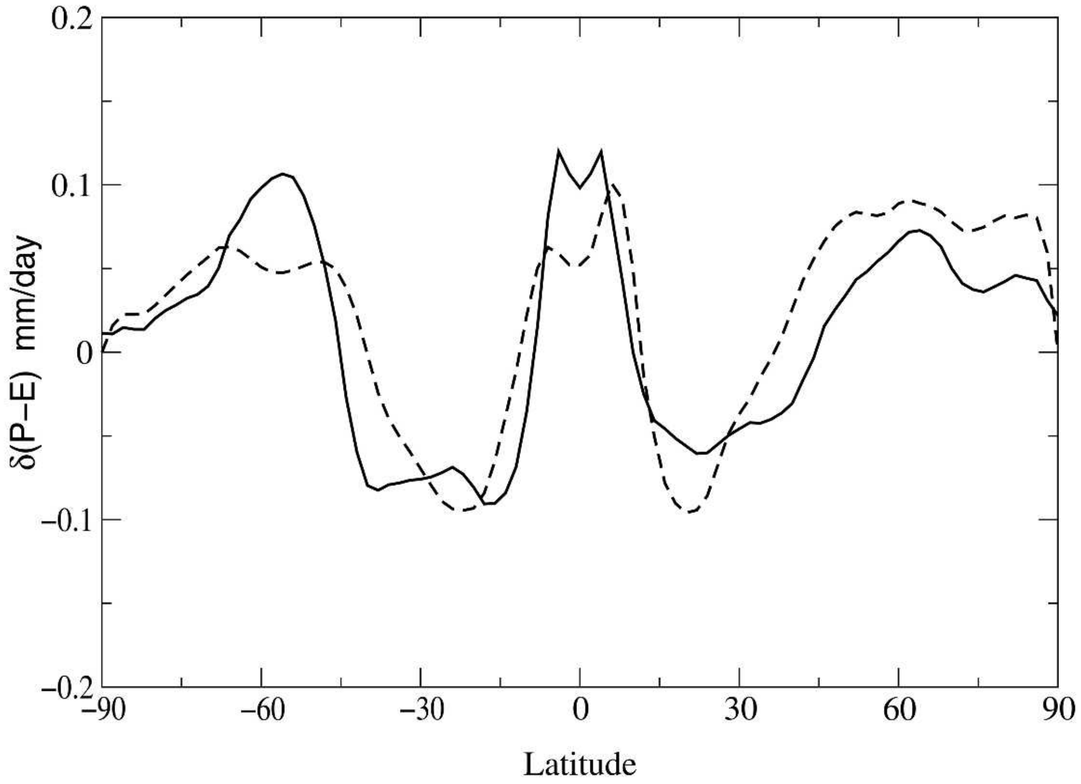
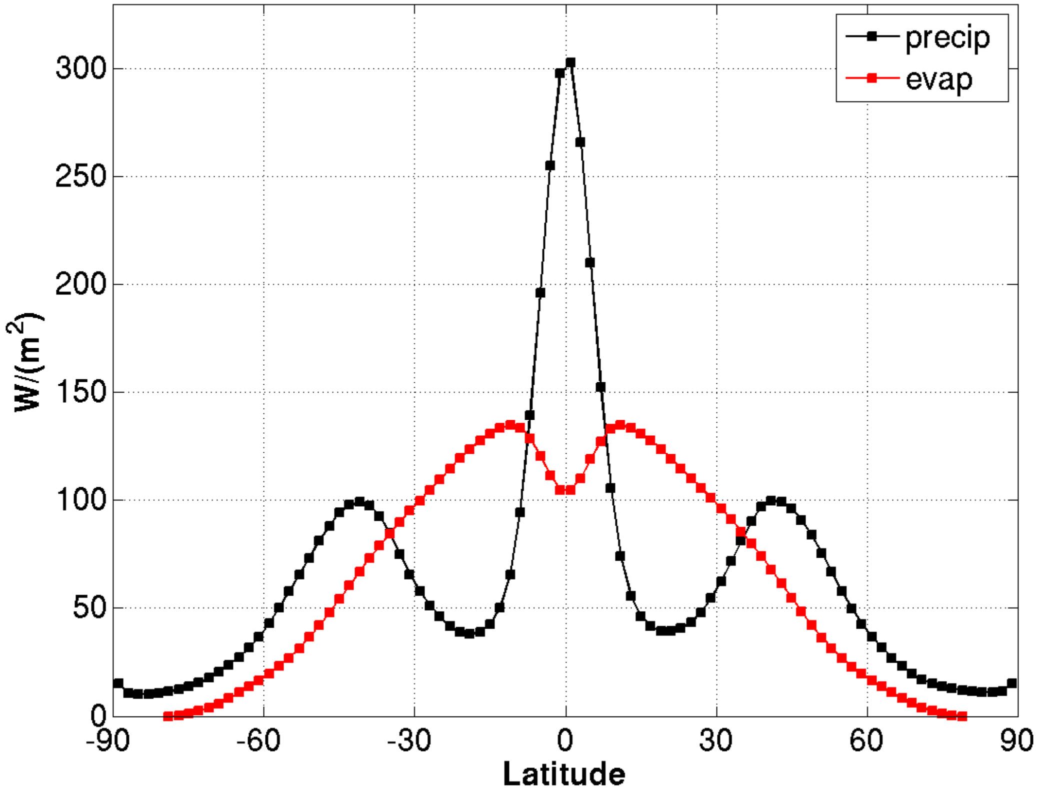


FIG. 6. Projected zonal mean change $\Delta(P-E)$ from AR4 models (solid) and the thermodynamic component (dashed) predicted from (6). From simulations using the SRES A1B. Held & Soden 2006



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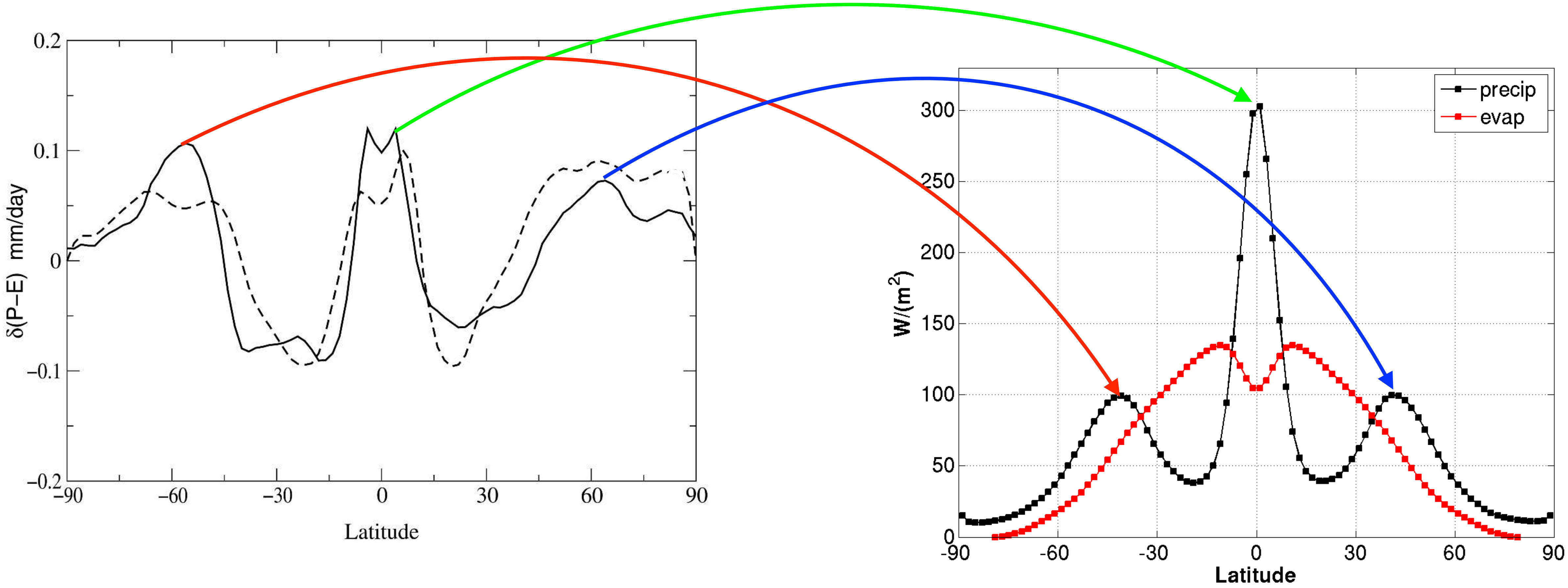
Textbook section 12.6.2 (notes 12.3.2)



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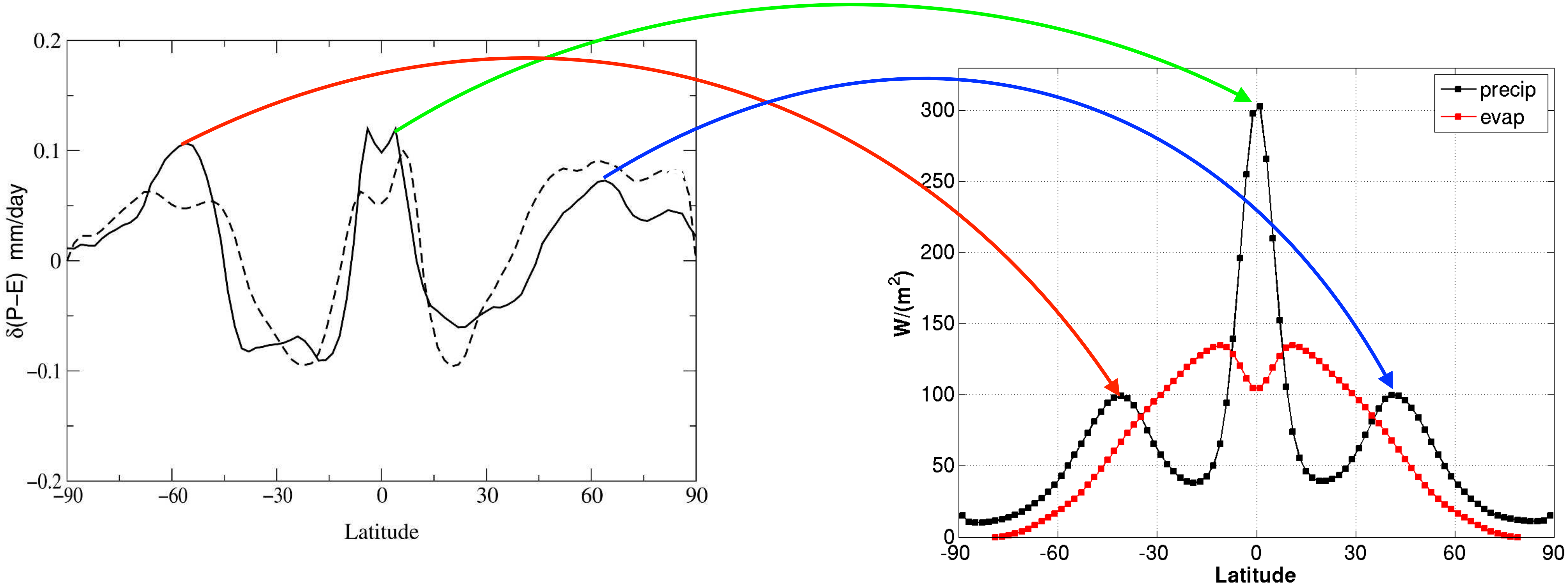
Mean precipitation trends: Wet getting wetter, dry getting drier

Textbook section 12.6.2 (notes 12.3.2)



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Mean precipitation P and evaporation E as a function of latitude.

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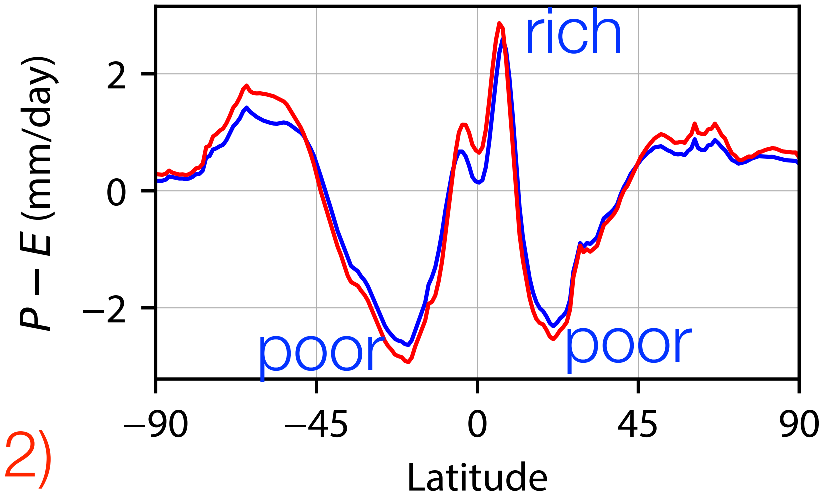
➡Rich get richer, poor get poorer

IPCC AR5: The ‘wet-get-wetter’ and ‘dry-get-drier’ response that is evident at large scales over oceans can be understood as a simple consequence of a change in the water vapor content carried by circulations, which otherwise are little changed. Wet regions are wet because they import moisture from dry regions, increasingly so with warmer temperatures. section 7.6.2

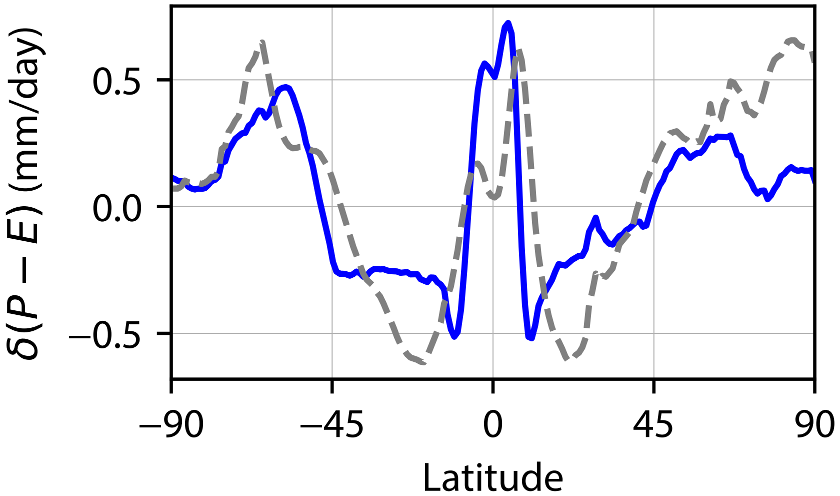
Global projections: Wet getting wetter, dry getting drier

Why is the change to precipitation-evaporation in a warming scenario proportional to its mean value: $\delta(P-E)=\alpha_{cc}\delta T\times(P-E)$?

mean precipitation



expected change



(Following Held and Soden, 2000)

Textbook section 12.6.2 (notes 12.3.2)

Global projections: Wet getting wetter, dry getting drier

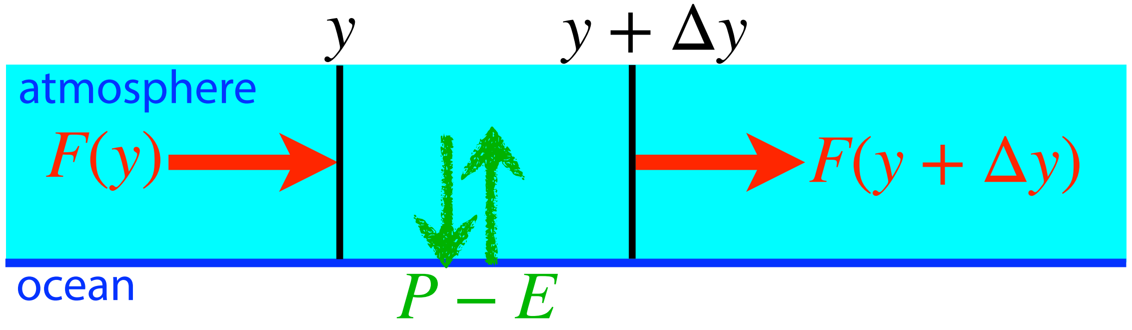
Why is the change to precipitation-evaporation in a warming scenario proportional to its mean value: $\delta(P-E)=\alpha_{cc}\delta T\times(P-E)$?

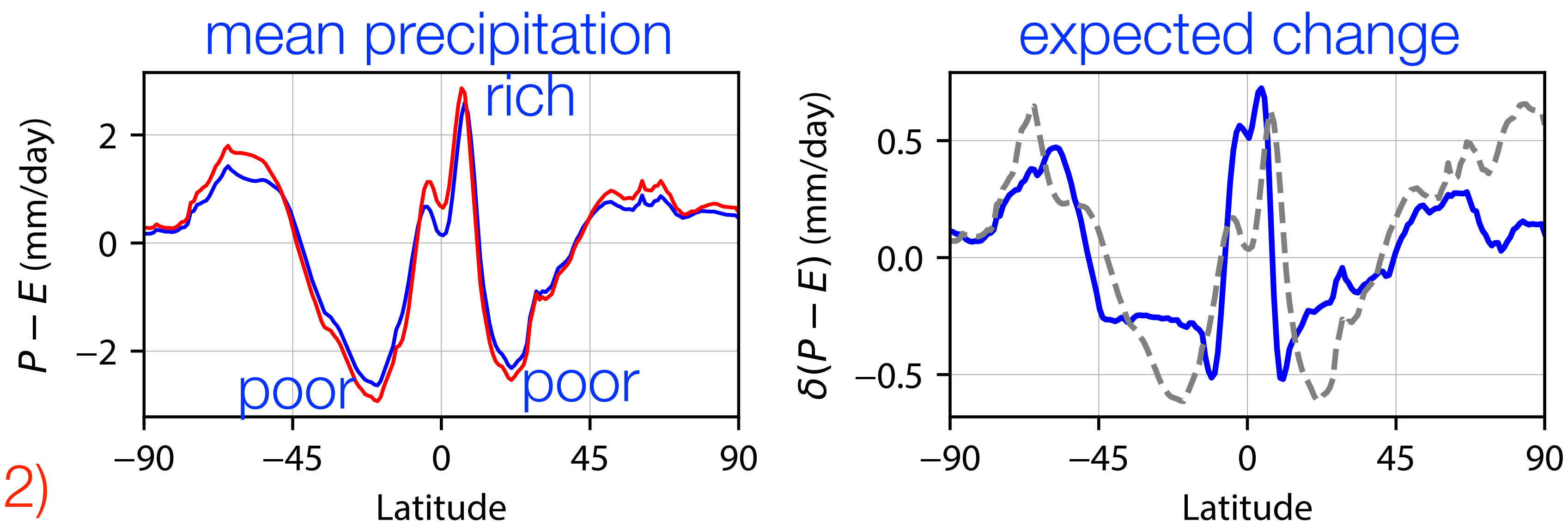
The two factors:

- $F(y)$ Northward moisture flux: the poleward air velocity times the atmospheric moisture times air density, integrated over height, in kg moisture per second per (east-west) meter.
- $P-E$ precipitation minus evaporation, in kg moisture per second per m^2

are related via: $(P-E)=-\dfrac{dF}{dy}$. This is derived from the moisture budget of a slice of air:

$$F(y)-F(y+\Delta y)-(P-E)\Delta y=0.$$





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Textbook section 12.6.2 (notes 12.3.2)

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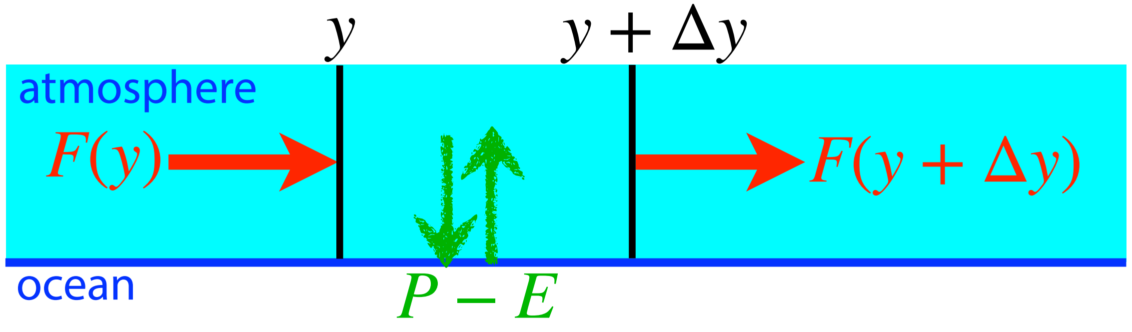
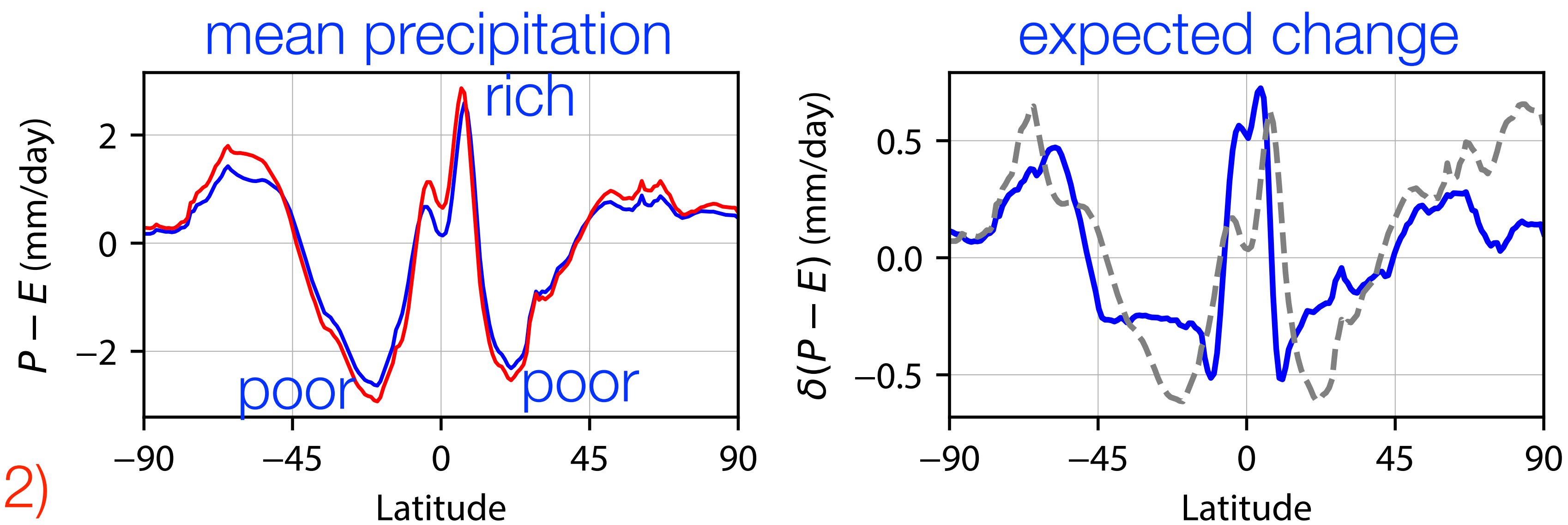


$$F(y)-F(y+\Delta y)-(P-E)\Delta y=0.$$

Also, assume $\delta F/F=\delta q^*/q^*=\alpha_{CC}\delta T$ so that $\delta F=\alpha_{CC}\delta T\times F$. Then,



mean precipitation

expected change

(Following Held and Soden, 2000)

Textbook section 12.6.2 (notes 12.3.2)

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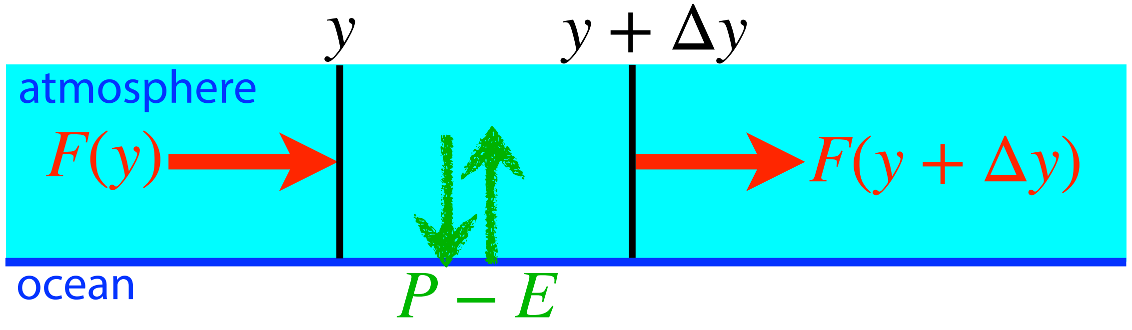

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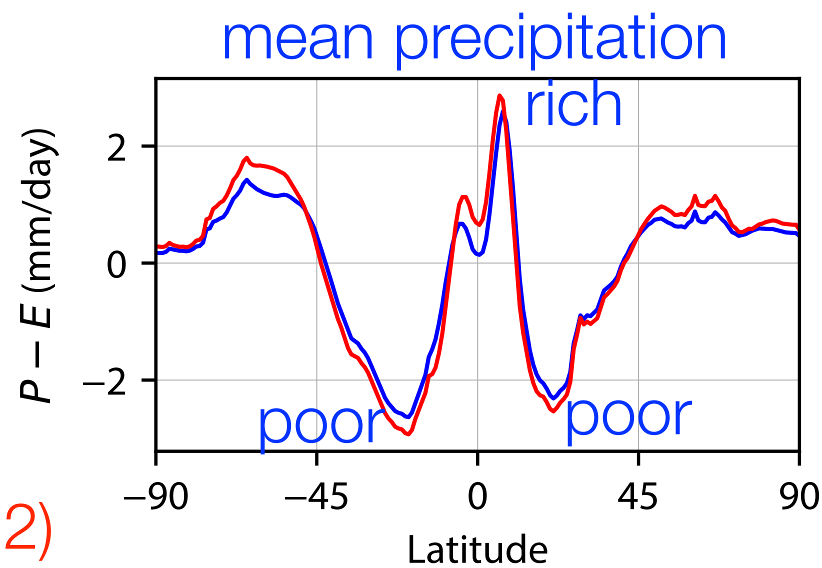
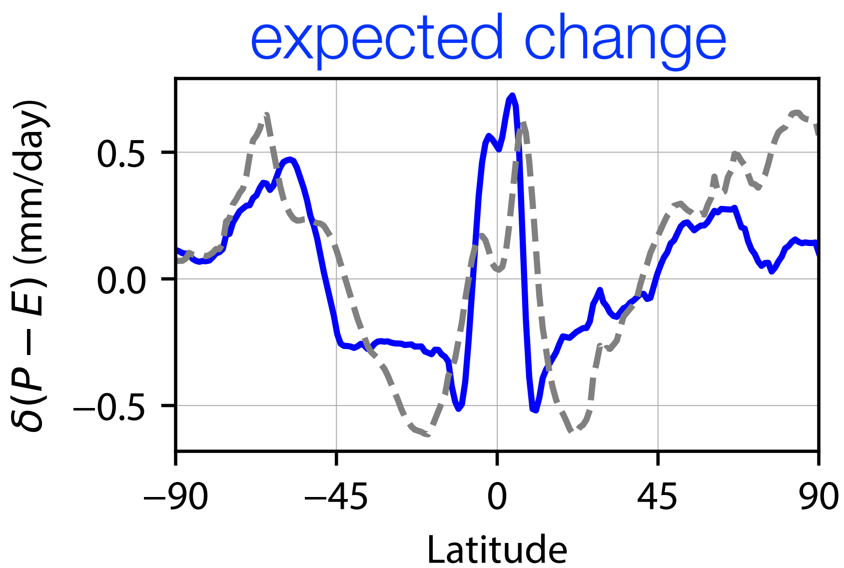
$$\delta(P-E)=-\frac{d}{dy}(\delta F)=-\frac{d}{dy}(\alpha_{cc}\delta T\times F)\approx-\alpha_{cc}\delta T\times\frac{d}{dy}(F)=\alpha_{cc}\delta T\times(P-E),$$





(Following Held and Soden, 2000)

Textbook section 12.6.2 (notes 12.3.2)

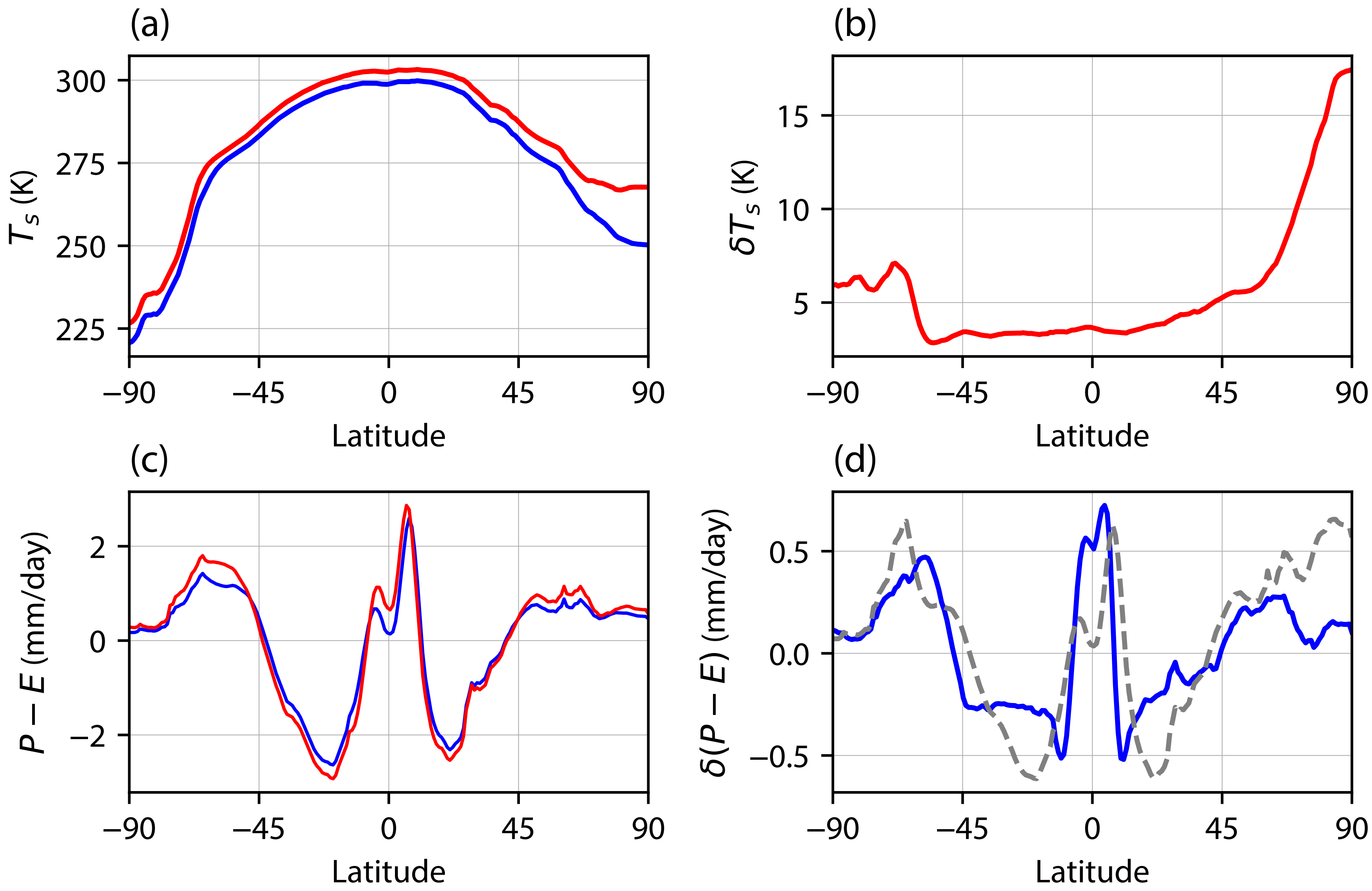
Mean precipitation trends: Wet getting wetter, dry getting drier

Textbook section 12.6.2

The change to precipitation-evaporation in a warming scenario proportional to its mean value:

$$\delta(P-E)=\alpha_{cc}\delta T\times(P-E)$$

δT



$(P-E)$

$\delta(P-E)$

Figure 12.7: Attempting to explain the global response of precipitation minus evaporation to a warming scenario. (a) Zonally-averaged surface temperature as a function of latitude during 1920–1940 (blue) and 2080-2100 (red) in the RCP8.5 scenario. (b) The net warming as a function of latitude. (c) Zonally averaged P – E for the same year ranges. **(d) The change in *P – E* (solid) vs its predicted structure based on equation 12.2 (dash).**

Workshop

5. “Wet getting wetter, dry getting drier” projections:

Workshop

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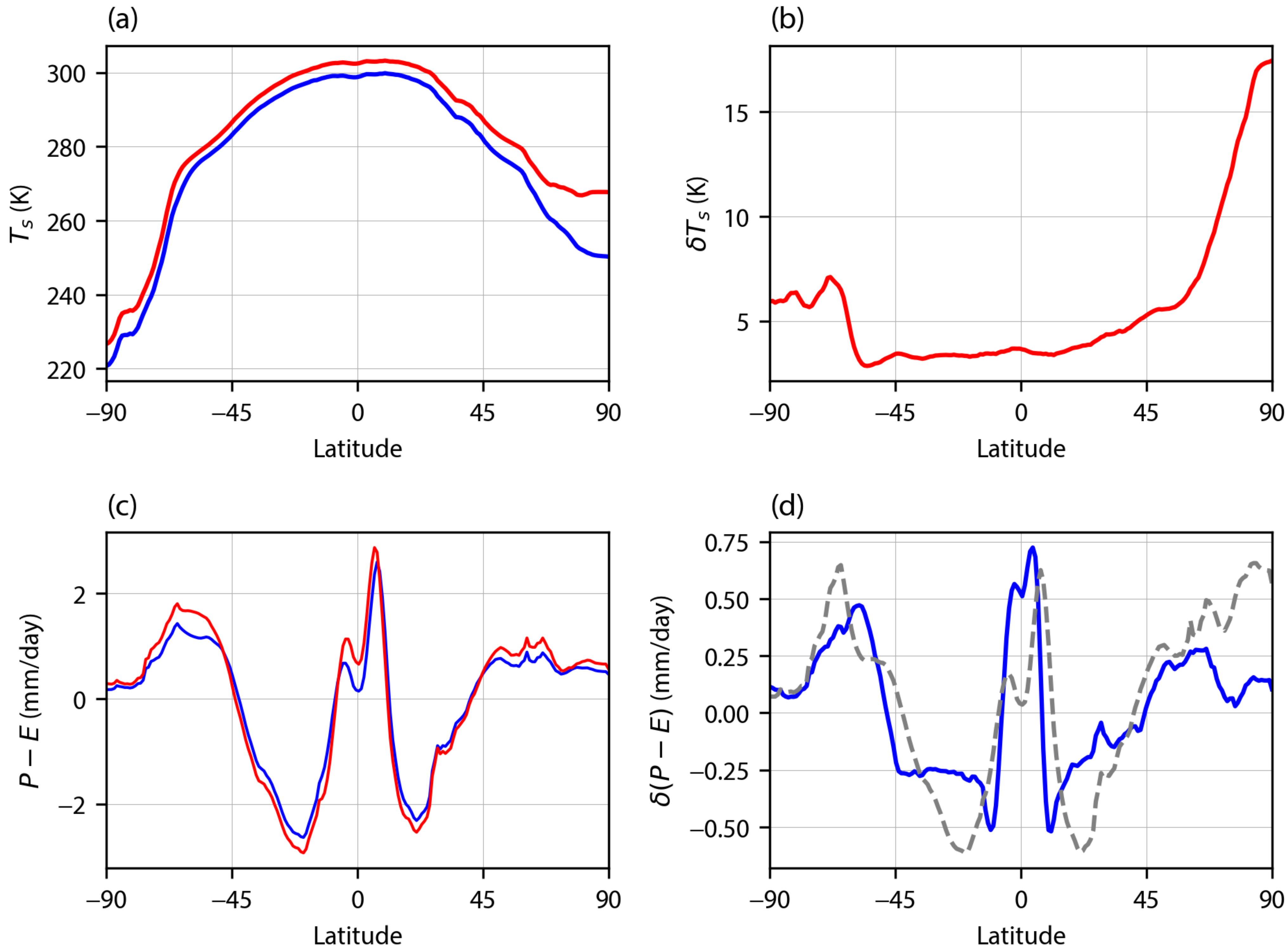

Outline

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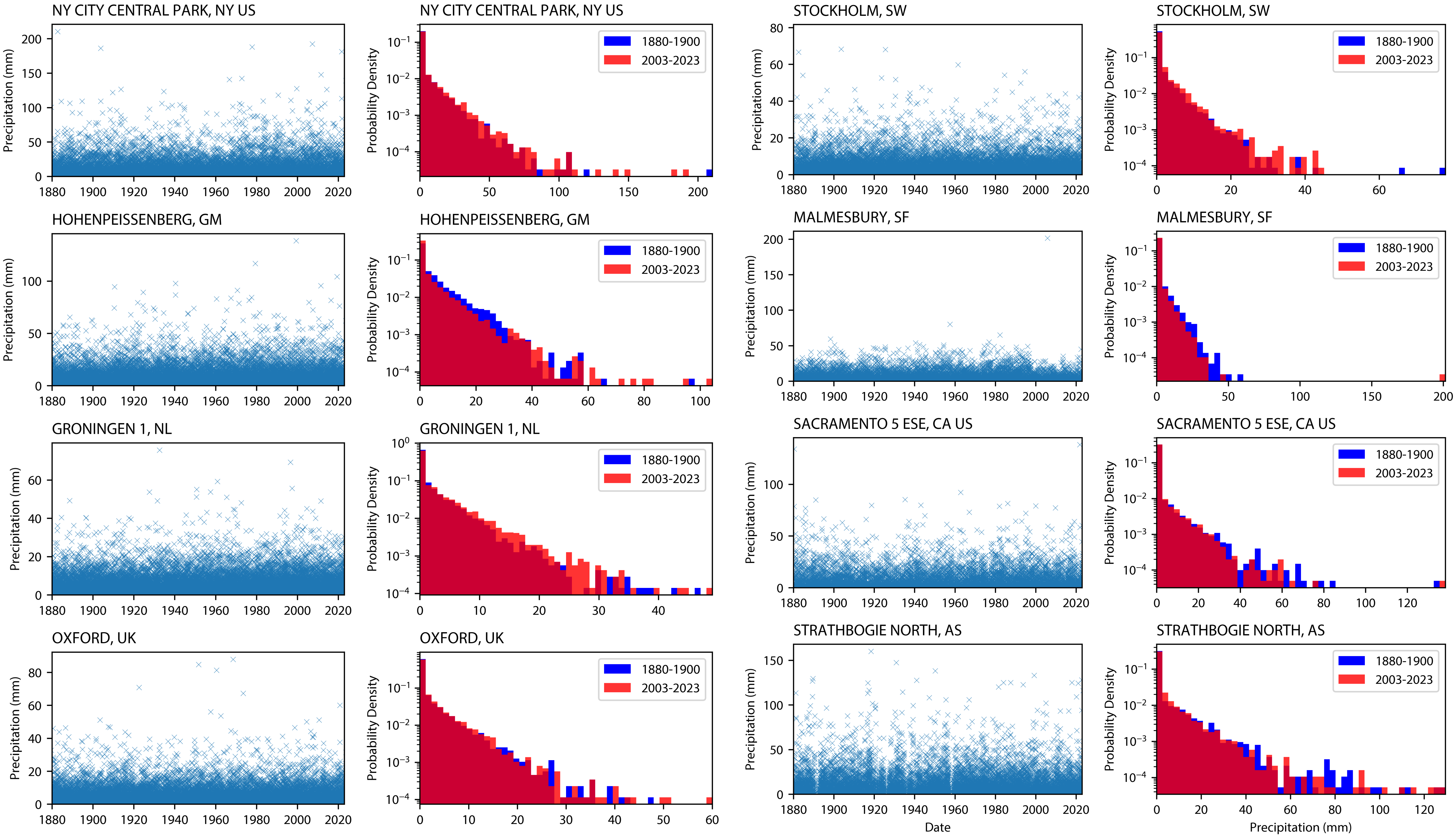
Workshop

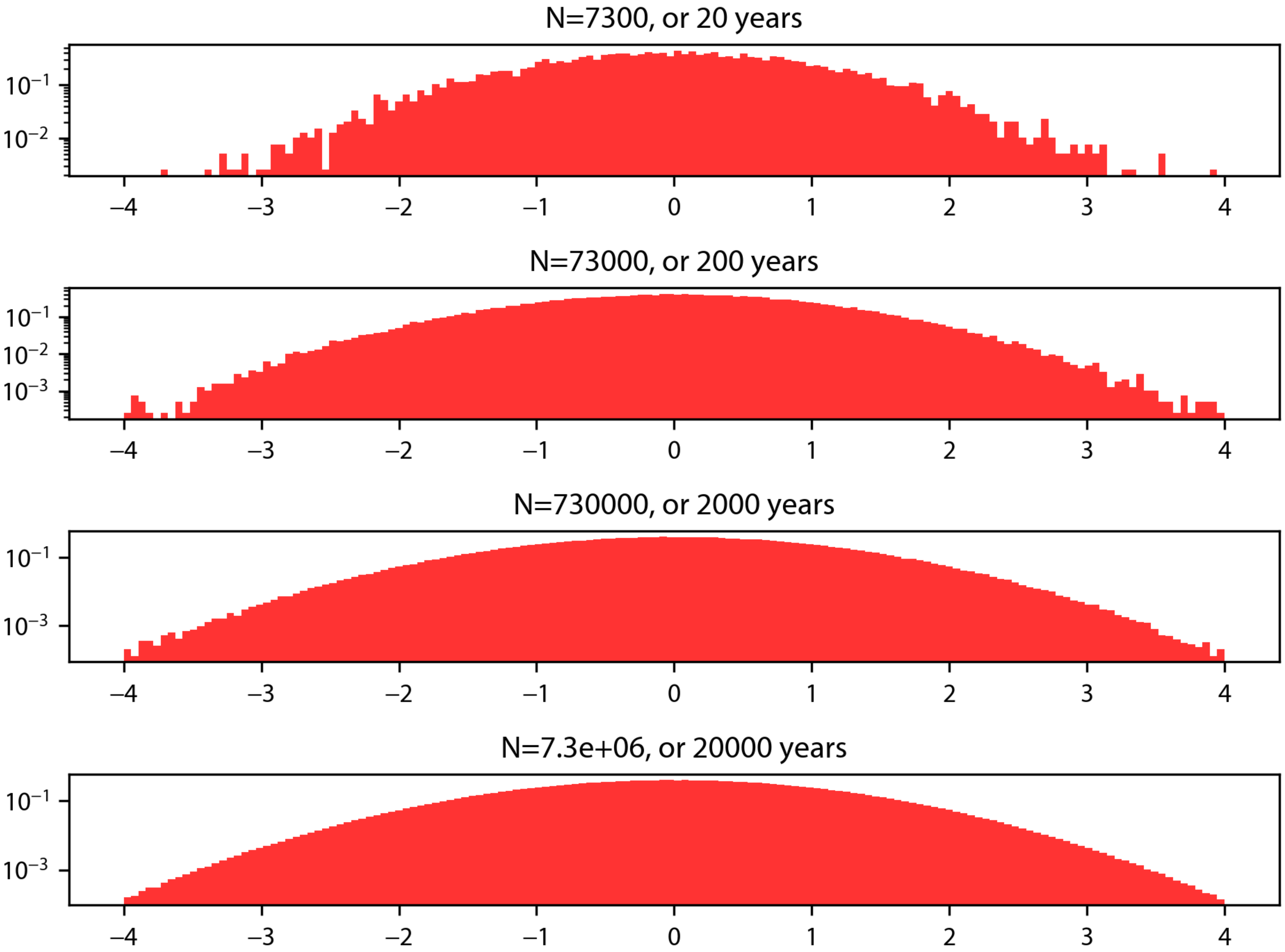
6. Analyzing extreme precipitation in weather station data

Workshop

6. (a) Analyzing extreme precipitation in weather station data



6 (b) Extreme precipitation in weather station data



Discuss attribution consequences of workshop results

Increase in extreme precipitation events in warmer climate

Textbook section 12.6.3 (notes 12.3.3)

Estimate the increased precipitation rate in extreme events, P_e: (O'Gorman & Schneider, 2009)

Increase in extreme precipitation events in warmer climate

Textbook section 12.6.3 (notes 12.3.3)

Estimate the increased precipitation rate in extreme events, P_e: (O'Gorman & Schneider, 2009)

- As an air parcel rises beyond the lift condensation level (LCL) a further decrease in the saturation specific humidity leads to condensation whose rate is equal to the rate of decrease in the saturation specific humidity of the parcel, $-dq^*/dt$.

Increase in extreme precipitation events in warmer climate

Textbook section 12.6.3 (notes 12.3.3)

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- The contribution to surface precipitation rate is $-\epsilon_p dq^*/dt$, where ϵ_p is the "precipitation efficiency," the fraction of the condensed water that precipitates to the ground, vs re-evaporated or horizontally transported away.

Increase in extreme precipitation events in warmer climate

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- Next, $dq^*/dt = (dq^*/dp) \times (dp/dt)$. Denote $\omega = dp/dt$ (negative for a rising air). Remember that as the moisture in the parcel condenses, latent heat is released and moist static energy is conserved, so we need to take the derivative dq^*/dp at a constant MSE.

Increase in extreme precipitation events in warmer climate

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Increase in extreme precipitation events in warmer climate

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Increase in extreme precipitation events in warmer climate

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➡Three possible factors can lead to a change in extreme precipitation in a warmer climate.

First, the precipitation efficiency may change due to cloud microphysical effects.

Increase in extreme precipitation events in warmer climate

Textbook section 12.6.3 (notes 12.3.3)

(Following O'Gorman and Schneider, 2009) The total extreme precipitation rate at the surface is then the vertical integral over the precipitation efficiency times the condensation rate,

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First, the precipitation efficiency may change due to cloud microphysical effects.

Second is the vertical velocity during extreme precipitation events (dynamical component). It may be due to wind over a mountain, to vertical velocities in mid-lat weather systems, or to updrafts in convection with a small horizontal length scale of a few hundred meters to a few kilometers.

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Third is the thermodynamic component, which may be written somewhat less cryptically as

$$\left. \frac{dq^*(T,p)}{dp} \right|_{\mathrm{MSE}} = \frac{\partial q^*(T,p)}{\partial p} + \left. \frac{\partial q^*(T,p)}{\partial T} \frac{\partial T}{\partial p} \right|_{\mathrm{MSE}} .$$

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The final factor here is related to the moist adiabatic lapse rate $\partial T/\partial z$ taken at a constant MSE,

$$\left.\frac{\partial T}{\partial p}\right|_{\mathrm{MSE}} = \left.\frac{\partial T}{\partial z}\right|_{\mathrm{MSE}} \frac{\partial z}{\partial p},$$

where $\partial z/\partial p$ can be calculated from the exponential dependence of the pressure on height.

Increase in extreme precipitation events in warmer climate

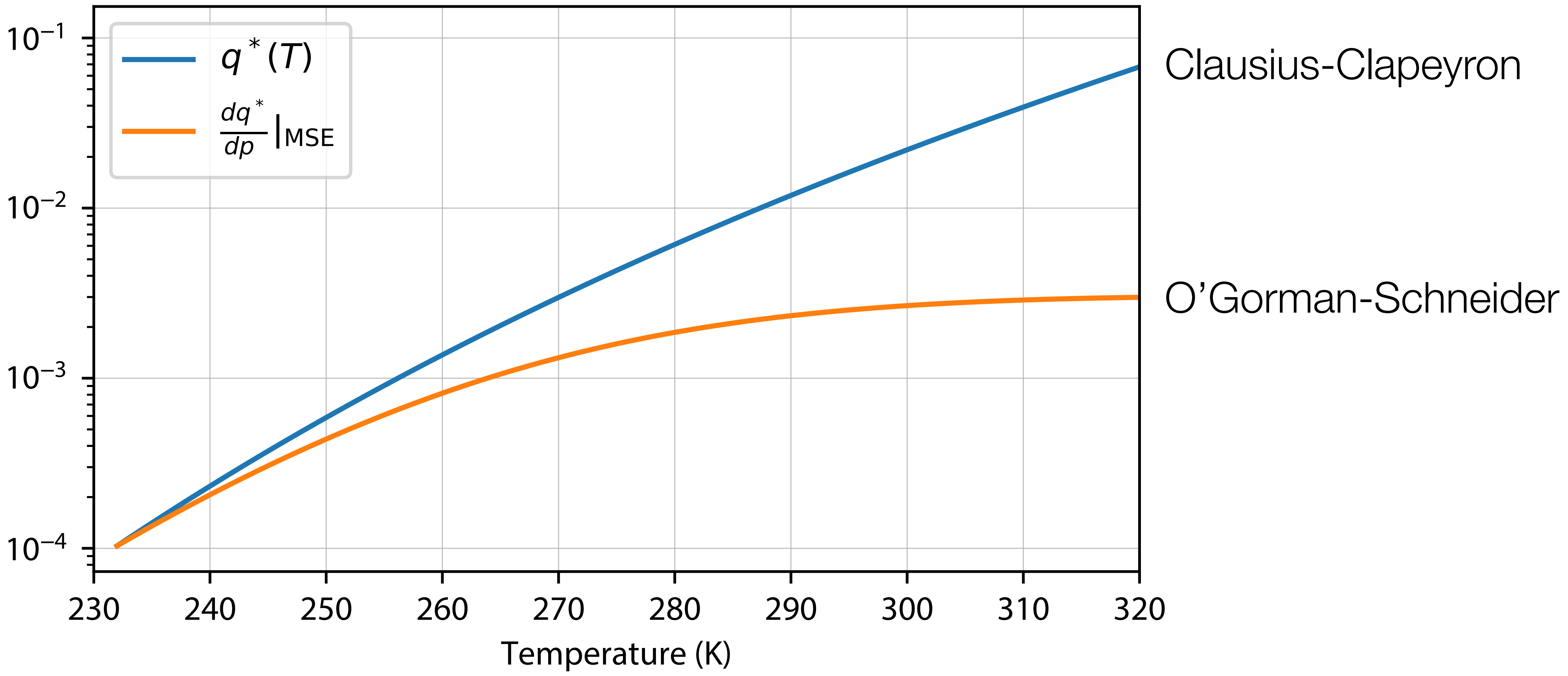

Figure 12.10: Two estimates for the dependence of extreme precipitation rates on temperature. One is based on the saturation specific humidity (Clausius-Clapeyron scaling, blue) and the other on the thermodynamic component of the estimate from equation (12.3). The orange curve is scaled by a constant factor to have the same value as the blue one at the lowest temperature plotted.

Increase in extreme precipitation events in warmer climate

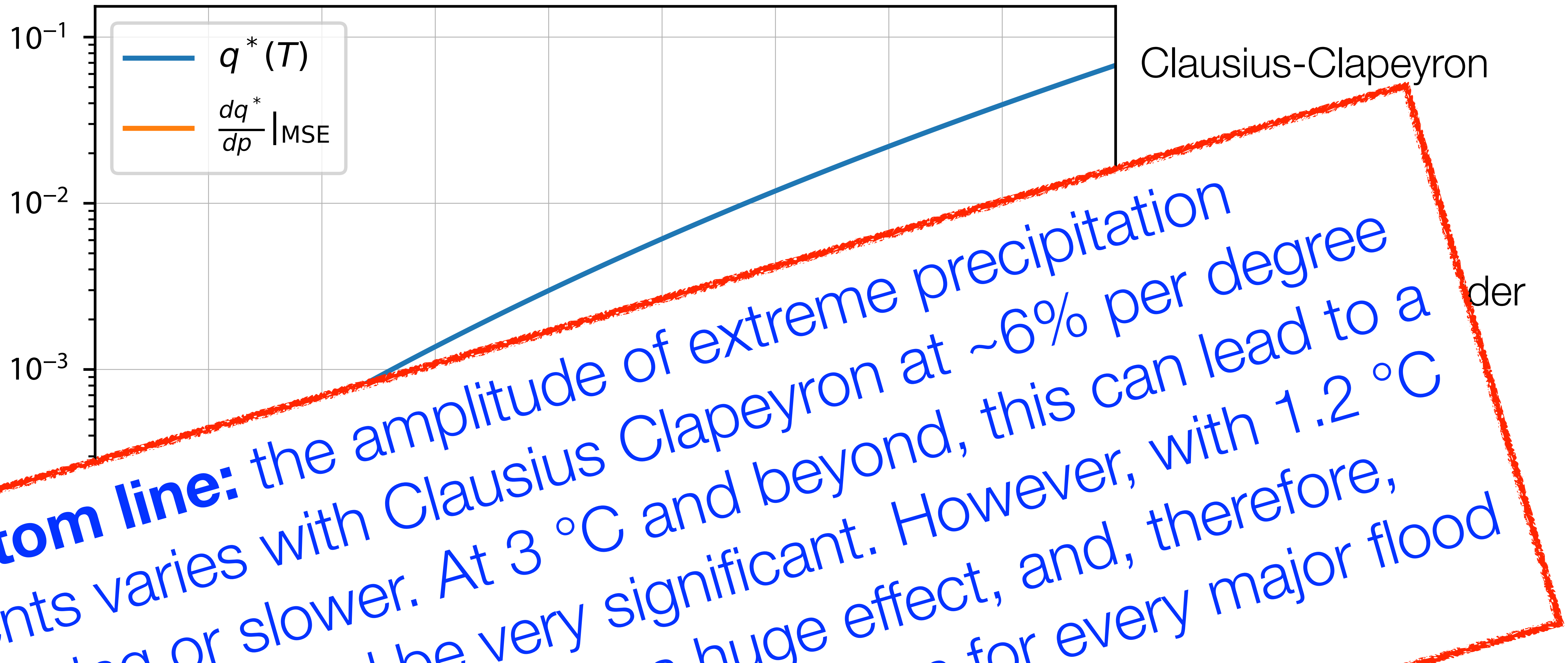

Fig **es on temperature.**
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Bottom line: the amplitude of extreme precipitation events varies with Clausius Clapeyron at ~6% per degree warming or slower. At 3 °C and beyond, this can lead to a >20% effect and be very significant. However, with 1.2 °C warming so far, this is not a huge effect, and, therefore, cannot be expected to be the reason for every major flood that is being observed.

Floods in IPCC AR6, 2022

[Chapter 11.5.2, page 1568}

The SREX (Seneviratne et al., 2012) assessed low confidence for observed changes in the magnitude or frequency of floods at the global scale. This assessment was confirmed by AR5 (Hartmann et al., 2013). The SR1.5 (Hoegh-Guldberg et al., 2018) found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. While the number of studies on flood trends has increased since AR5, and there were also new analyses after the release of SR1.5 (Berghuijs et al., 2017; Blöschl et al., 2019; Gudmundsson et al., 2019), hydrological literature on observed flood changes is heterogeneous, focusing at regional and subregional basin scales, making it difficult to synthesize at the global and sometimes regional scales. The vast majority of studies focus on river floods using streamflow as a proxy, with limited attention to urban floods. Streamflow measurements are not evenly distributed over space, with gaps in spatial coverage, and their coverage in many regions of Africa, South America, and parts of Asia is poor (e.g., Do et al., 2017), leading to difficulties in detecting long-term changes in floods (Slater and Villarini, 2017).

Peak flow trends are characterized by high regional variability and lack overall statistical significance of a decrease or an increase over the globe as a whole. Of more than 3500 streamflow stations in the USA, central and Northern Europe, Africa, Brazil, and Australia, 7.1% stations showed a significant increase, and 11.9% stations showed a significant decrease in annual maximum peak flow during 1961–2005 (Do et al., 2017). This is in direct contrast to the global and continental scale intensification of short-duration extreme precipitation (Section 11.4.2).

Workshop

7. Projected extreme precipitation events

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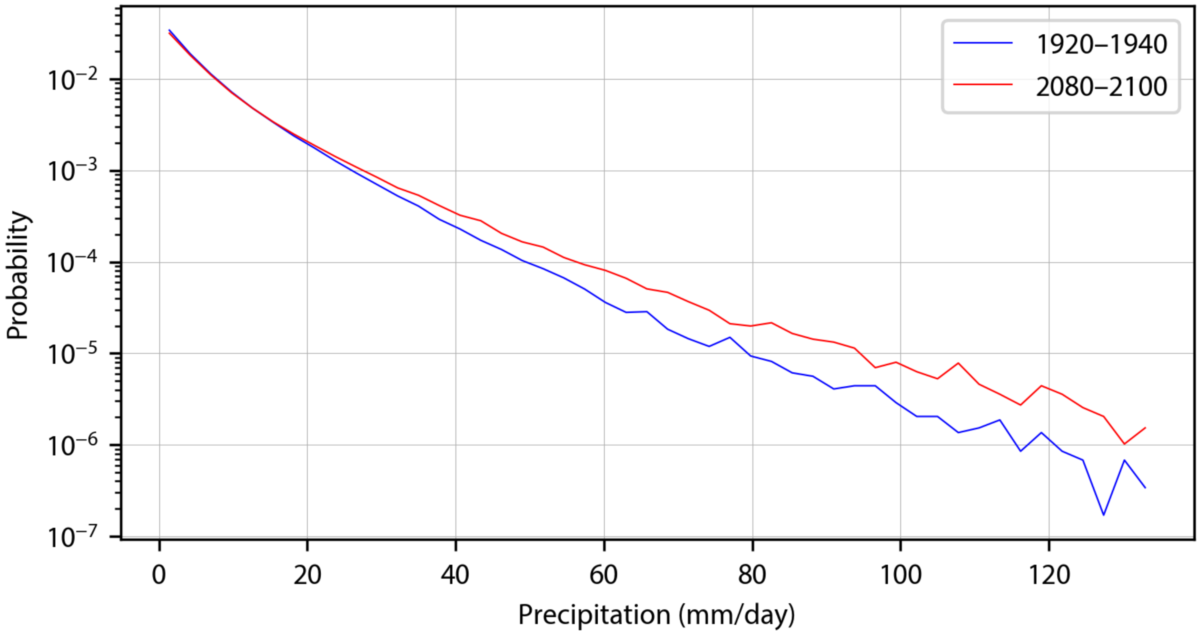

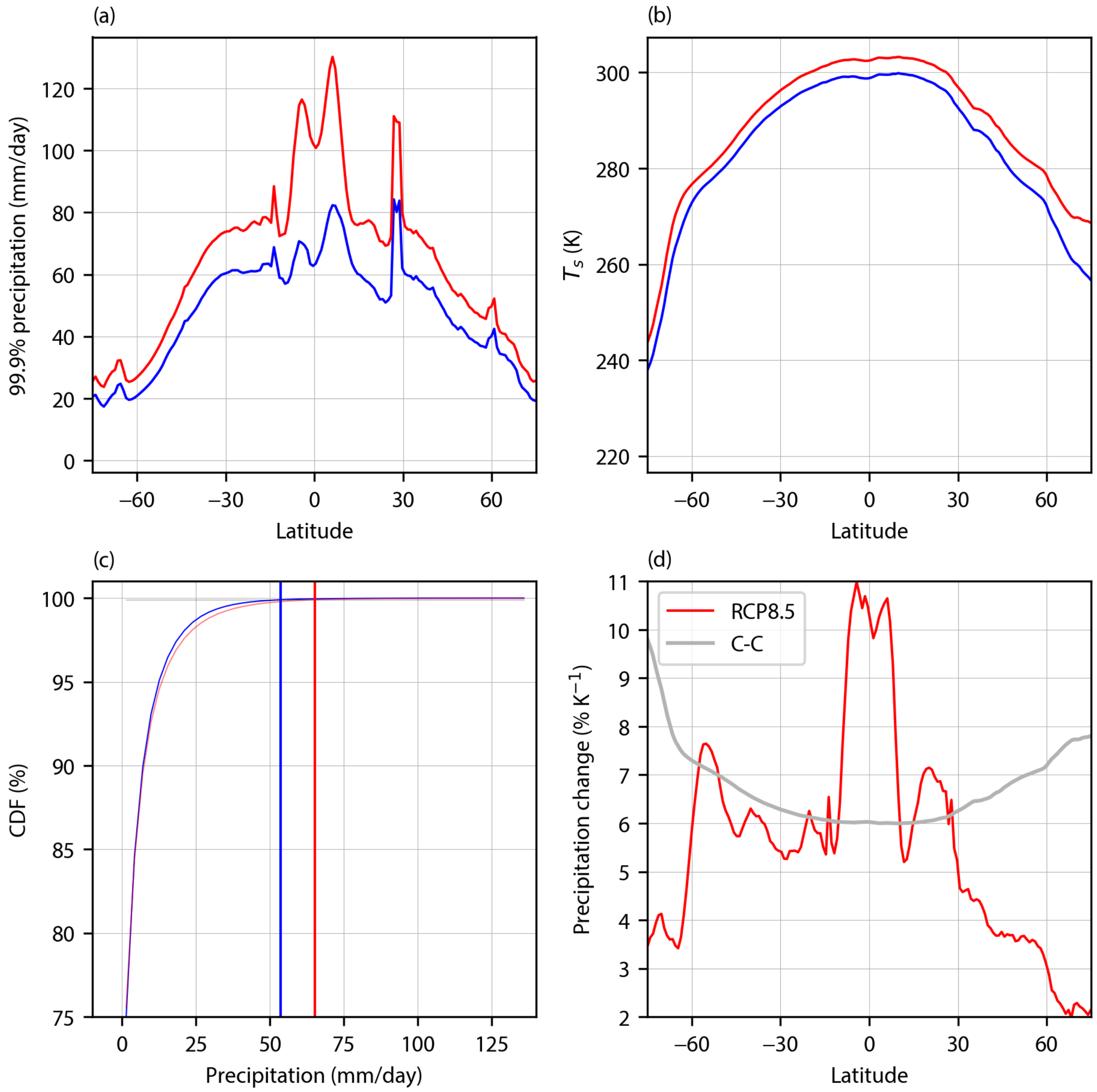

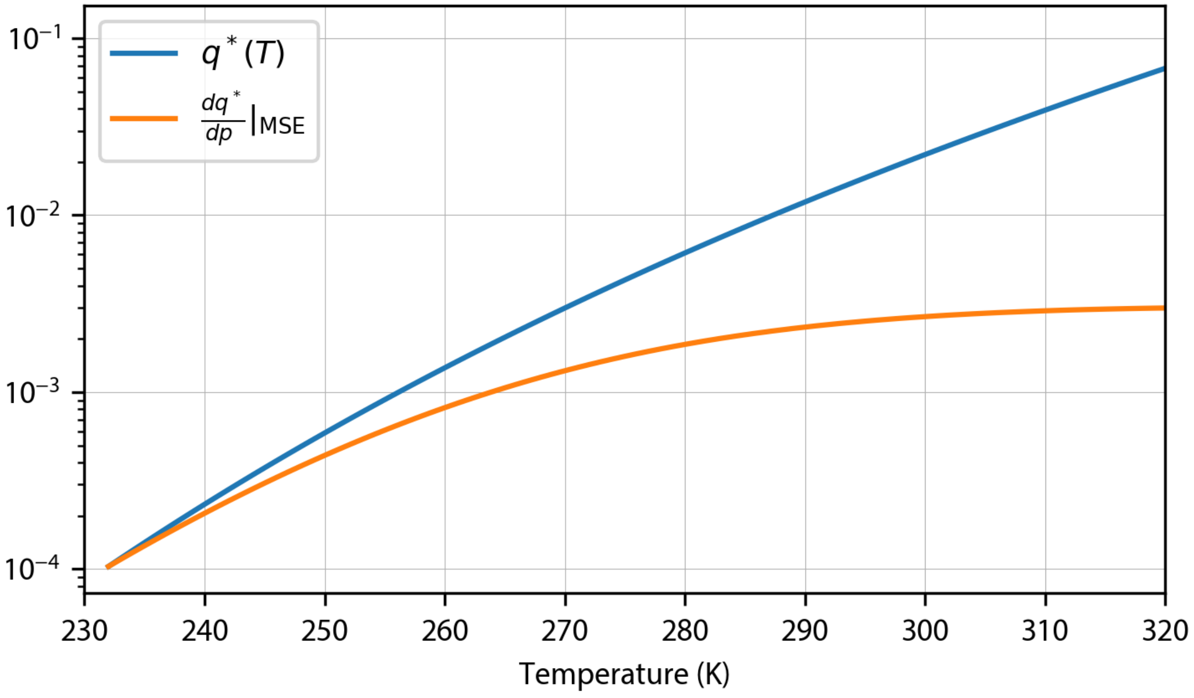

Conclusions: Floods

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   E. Future projections of stronger precipitation extremes are still robust.

The End