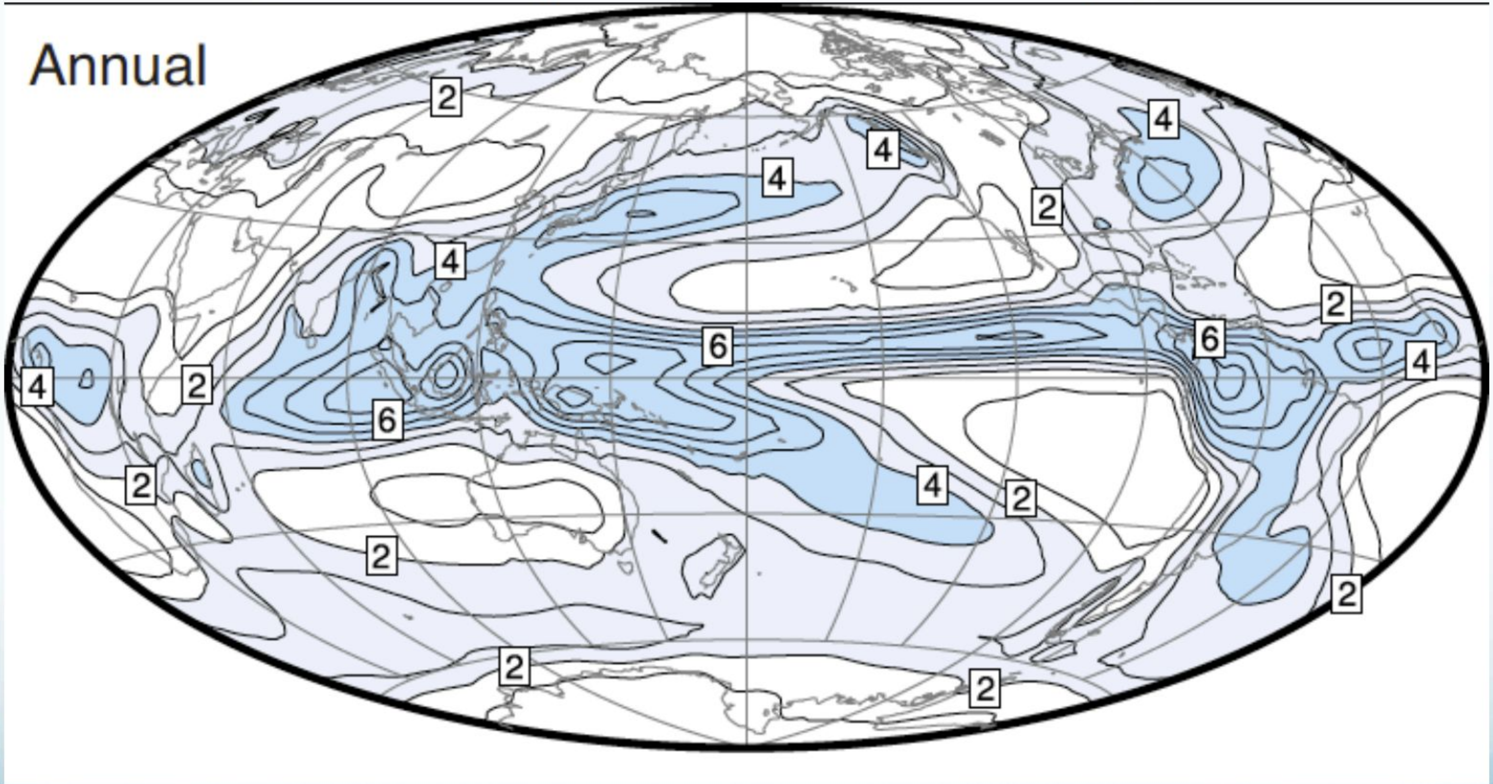
Precipitation in a changing climate

Resources:

- Global warming science: chapter 12
- Global physical climatology: chapter 5

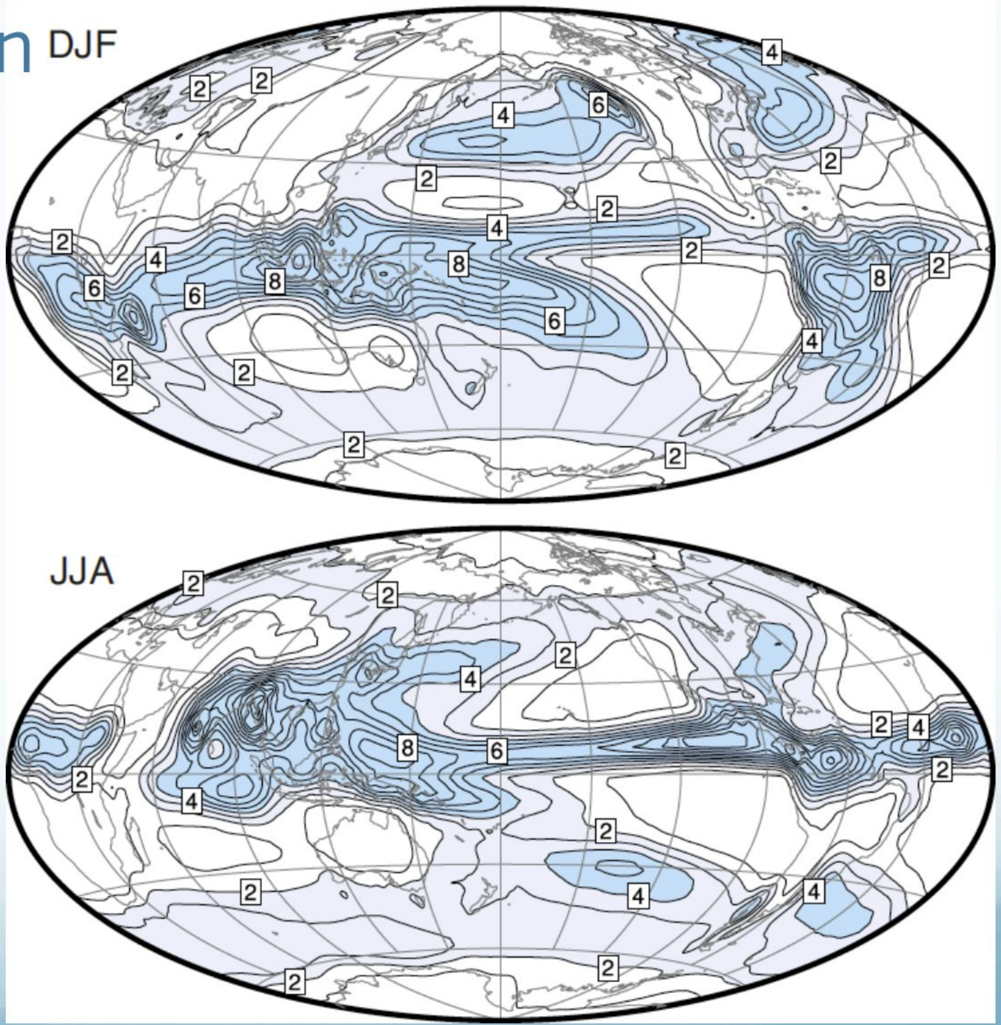
Precipitation Maps

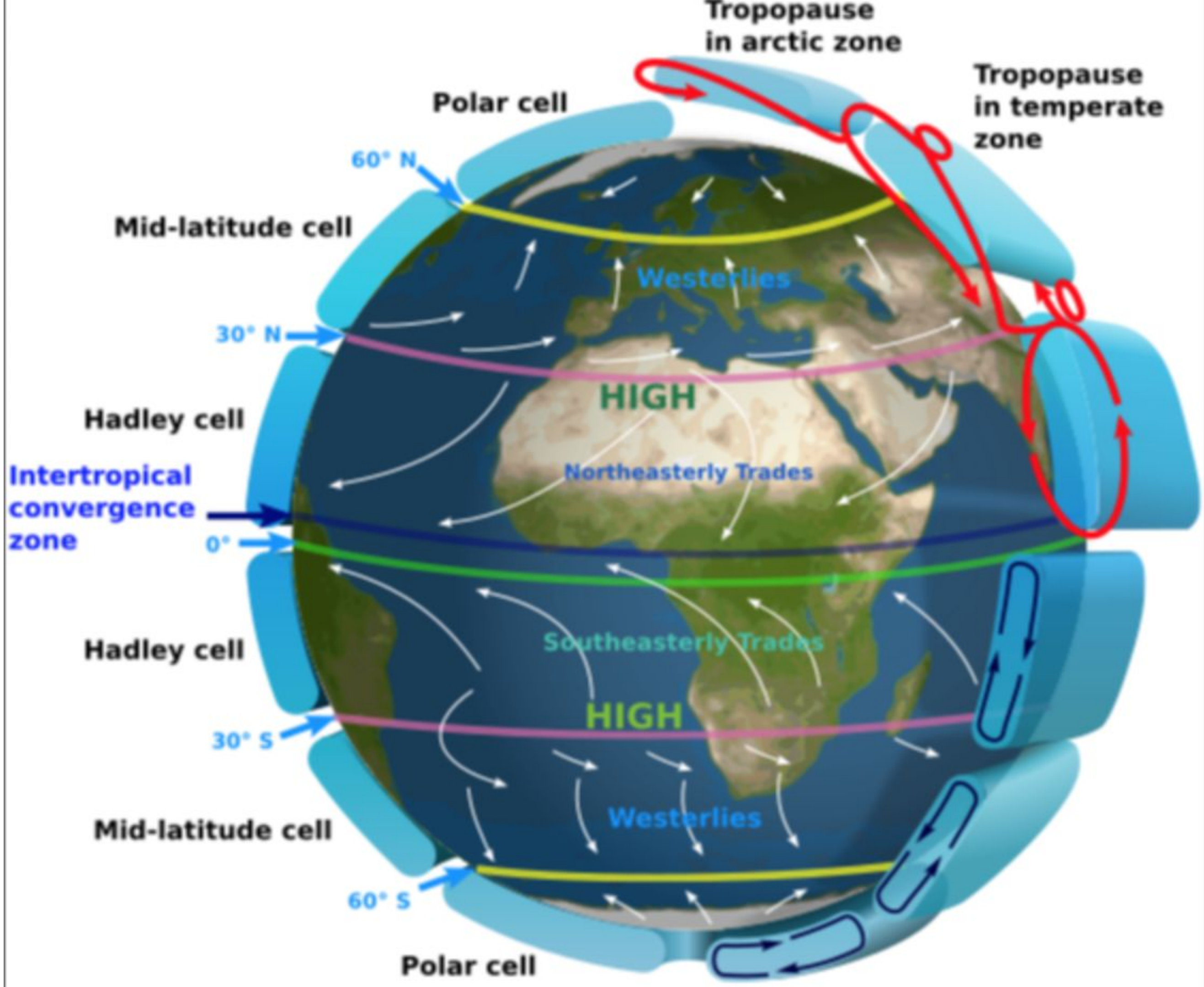


- Global from gauges and satellites

Precipitation Maps: Seasonal

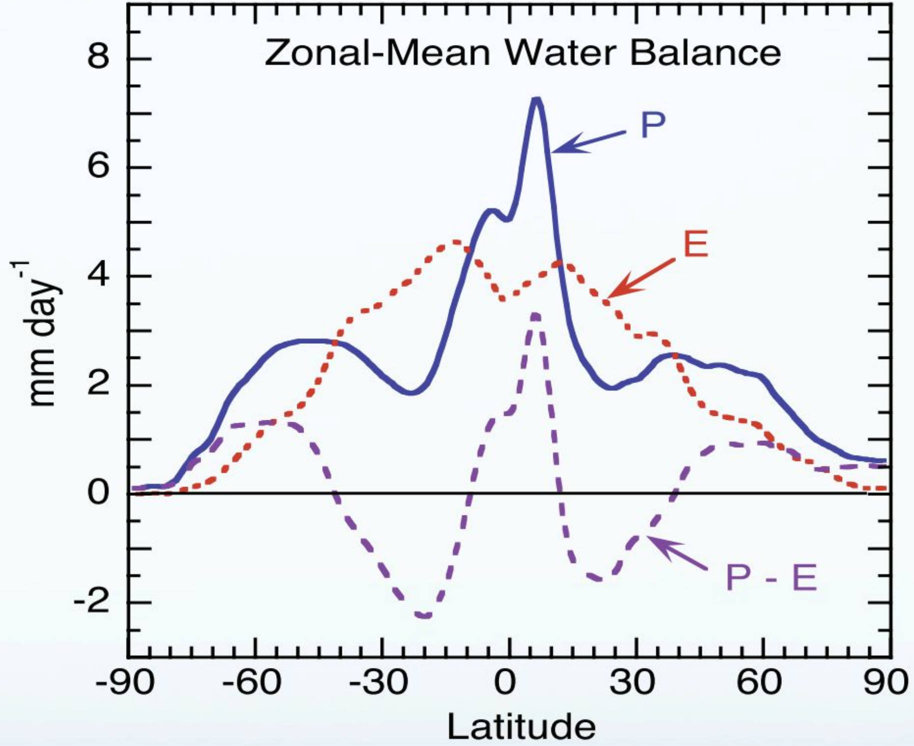
- Global from gauges and satellites





Tropopause
in arctic zone
Tropopause
in temperate
zone
Polar cell
60° N
Mid-latitude cell
Westerlies
30° N
HIGH
Hadley cell
Intertropical
convergence
zone
Northeasterly Trades
0°
Southeasterly Trades
Hadley cell
HIGH
30° S
Westerlies
Mid-latitude cell
60° S
Polar cell

Water Balance: Zonal-Annual Means



- P, E and runoff as functions of latitude
- Equator and midlatitudes wet, subtropics dry.

Wet and dry regions

Tropics

- Wet regions found where mean wind ascent (convection)

- Dry regions found where mean wind descent (subsidence)

Extra-Tropics

- Seasonal variability

- Extra-tropical weather that carries relatively warm and moist air from the oceans to land

Precipitation response to climate change

- Mean precipitation response
- Extreme events: droughts and floods

Sahel Droughts

https://sahelconsortium.com/2016/10/31/france-and-the-united-states-in-western-sahel-cooperation-and-competition-in-an-interlocking-conflict-conference-presentation/

Sahel, rainy season

https://www.vaticannews.va/en/church/news/2018-02/jpii-foundation-for-sahel-set-to-finance-development-projects.html

https://www.cirad.fr/en/our-research/research-results/2014/sipsa-an-information-system-for-monitoring-pastoral-dynamics-in-the-sahel

Sahel forest near Kayes Mali

Rangeland, rainy season, near Mbeuleké, Senegal (© I. Touré/CIRAD)

Sahel, drought

https://alchetron.com/Sahel-drought

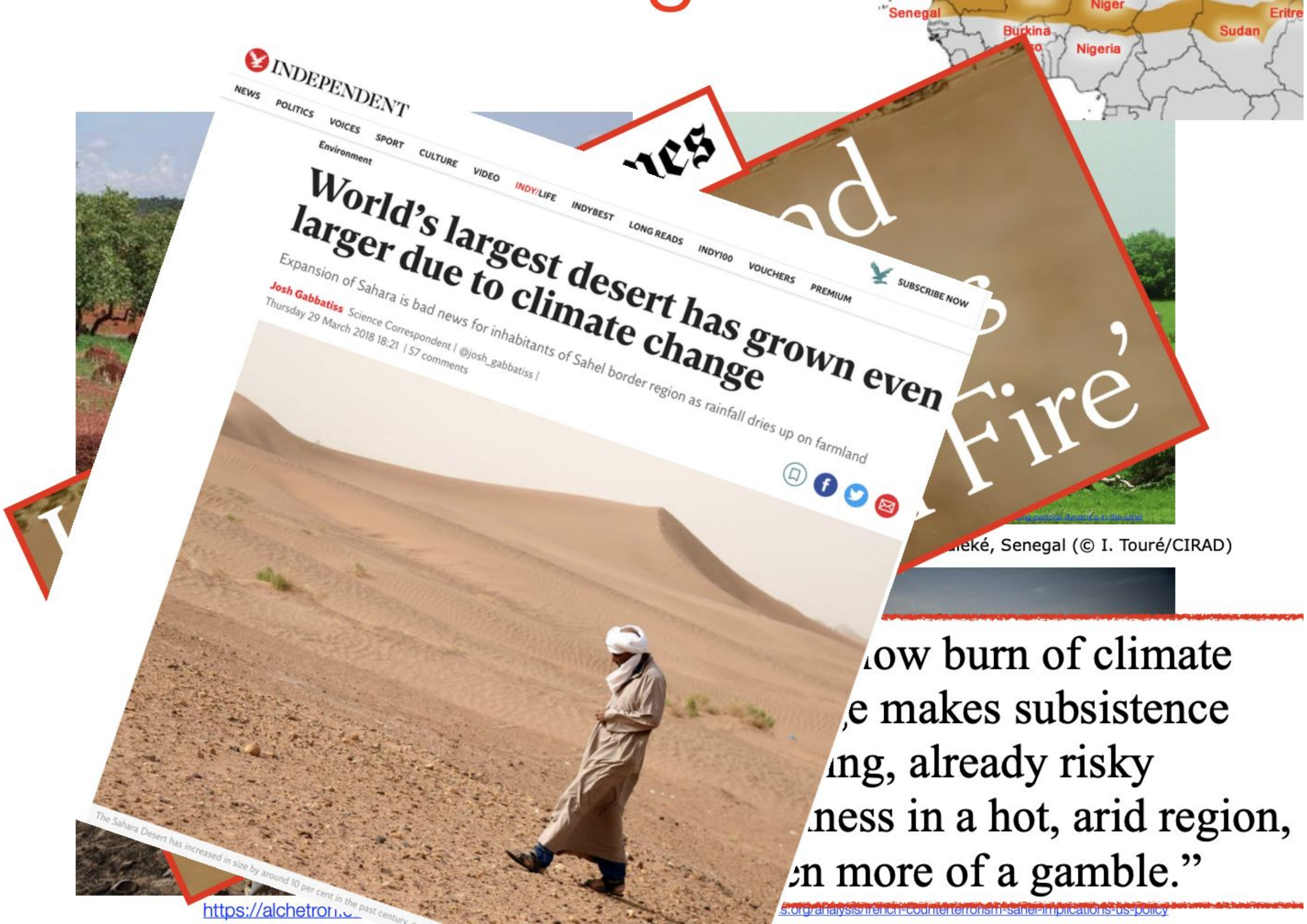
https://www.csis.org/analysis/french-counterterrorism-sahel-implications-us-policy

Sahel Droughts

"The slow burn of climate change makes subsistence farming, already risky business in a hot, arid region, even more of a gamble."

https://alchetron.com/Sahel-drought

https://www.csis.org/analysis/french-counterterrorism-sahel-implications-us-policy


Senegal
Niger
Eritre
Burkina
Nigeria
Sudan
INDEPENDENT
NEWS
POLITICS
VOICES
SPORT
CULTURE
VIDEO
INDY/LIFE
INDYBEST
LONG READS
INDY100
VOUCHERS
PREMIUM
SUBSCRIBE NOW
Environment
World's largest desert has grown even larger due to climate change
Expansion of Sahara is bad news for inhabitants of Sahel border region as rainfall dries up on farmland
Josh Gabbatiss Science Correspondent | @josh_gabbatiss |
Thursday 29 March 2018 18:21 | 57 comments
The Sahara Desert has increased in size by around 10 per cent in the past century
Fire'
Senegal (© I. Touré/CIRAD)
ow burn of climate
e makes subsistence
ing, already risky
ness in a hot, arid region,
n more of a gamble."
https://alchetron.c
s.org/analysis/french-counterterrorism-sahel-implications-us-policy

California Droughts

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

The New York Times

California Braces for Unending Drought

Gov. Jerry Brown of California last month in New ... d an executive order on Monday making permanent the water conser... ing the state's five-year drought.
Mary Altaffer/Associated Pr...

DEC 24, 2012

On Our Radar: A Parched Southwest

BY THE NEW YORK TIMES

The cracked bed of O.C. Fisher Lake in San Angelo, Tex., in August 2011. Things could get far worse in decades to come, a new study projects. Associated Press

New projections by researchers indicate that dry spells will get progressively worse in coming decades in California, Nevada, the Colorado River headwaters region and Texas,

Italy droughts

Italy's Southern Islands Drought Made 50% More Likely By Climate Change, Study Finds

BY MARTINA IGINI | EUROPE | SEP 4TH 2024 | 4 MINS

EARTH.ORG IS POWERED BY OVER 150 CONTRIBUTING WRITERS

Sardinia and Sicily have been experiencing "exceptional" drought conditions intensified by climate change, leading to water shortages and severely compromising agriculture, which both islands heavily rely on.

Home > Drought > Climate change key driver of extreme drought in water scarce Sicily and Sardinia

Climate change key driver of extreme drought in water scarce Sicily and Sardinia

04 September, 2024

Drought

Europe, Mediterranean

Sicily and Sardinia, the two largest Italian islands, important centres of agriculture and tourism have suffered from exceptionally low rainfall and very high temperatures over the last 12 months, culminating in extreme drought conditions from May 2024 onwards

Extreme weather: Droughts

https://www.youtube.com/watch?v=vhO0LgEvxW0

Droughts=disasters…

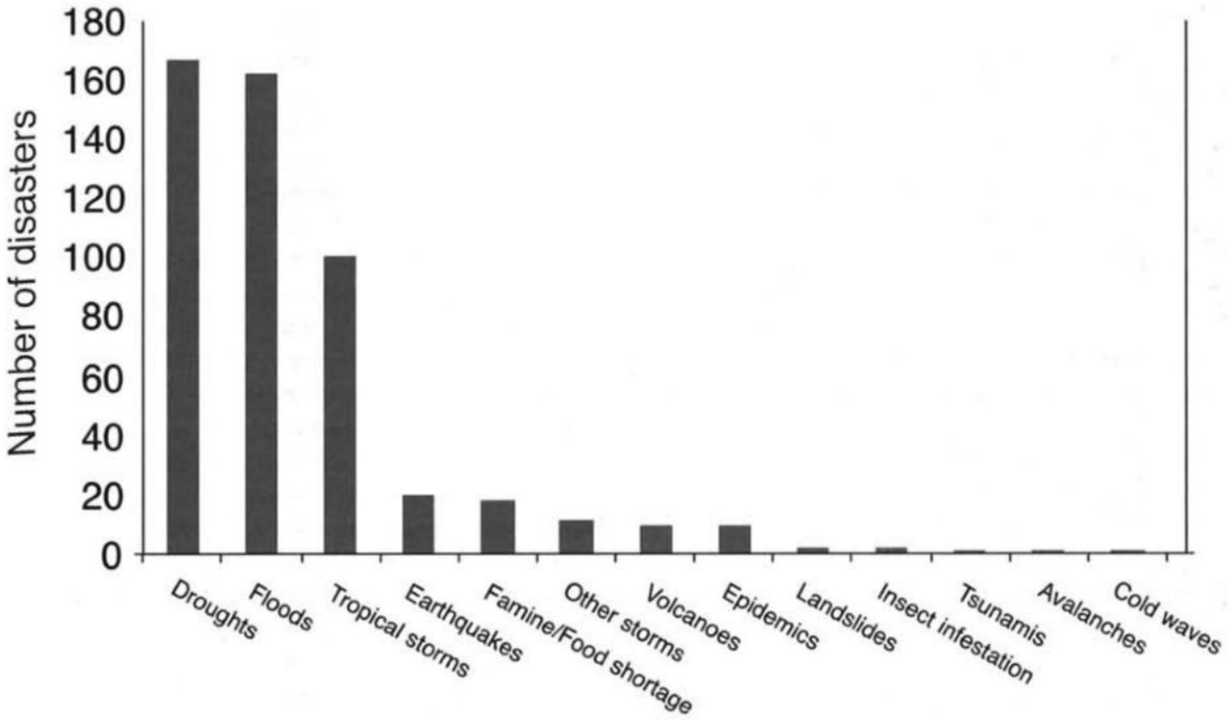


Figure 1.2. Disasters, by type, affecting 1% or more of total population, 1963–92.

[WILHITE, "DROUGHT AS A NATURAL HAZARD," 2000]

Definitions

Drought: *A period of* ***abnormally dry weather, relative to mean conditions****, long enough to cause a serious hydrological imbalance.*

meteorological drought: abnormal precipitation deficit

hydrological drought: reduced runoff and surface water, streams, lakes, etc (depends on precipitation and evaporation over recent past)

agricultural drought: shortage of precipitation during the growing season impinges on crop production or ecosystem function

socioeconomic drought: affecting human society

evapotranspiration: evaporation plus water transport from ground to atmosphere via plants.

potential evaporation: evaporation that would have occurred given current conditions, assuming no lack of surface water.

megadrought: a long & pervasive drought, usually a decade or more.

Relevant processes

Soil moisture: Amount of water stored in soil (bucket model for soil)

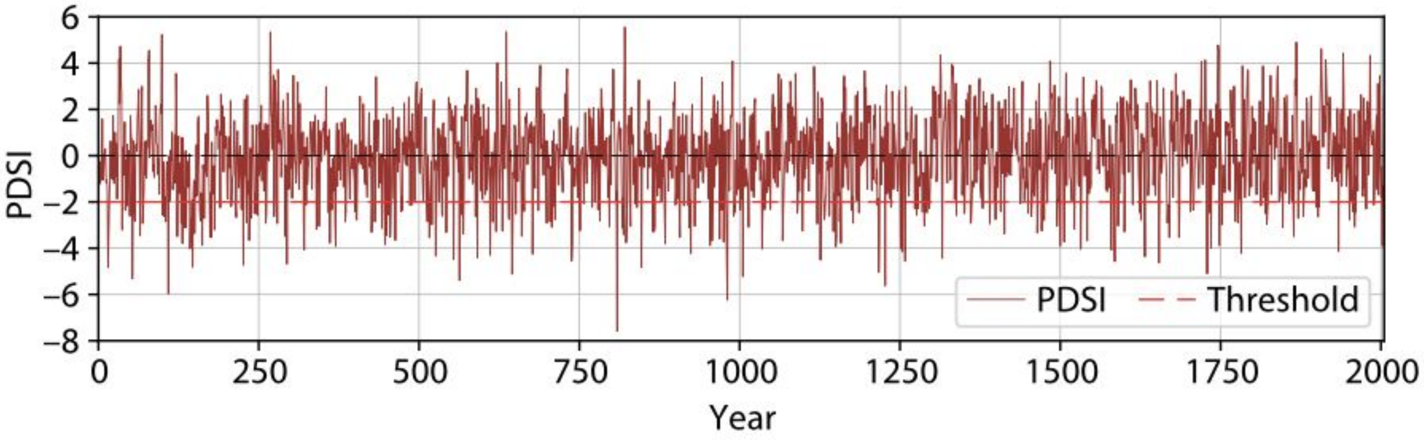
Evapotranspiration: The sum of evaporation from the soil plus evaporation from stomata in leaves that is bed by transpiration (i.e., movement of water within plants from roots to leaves)

Potential evapotranspiration (PET): The amount of evapotranspiration that would have occurred given the meteorological conditions (wind, air temperature, humidity, insolation) if the surface water source was not a limiting factor (*i.e., "demand" for evaporation determined by meteorological conditions*)

Palmer Drought Severity Index (PSDI): Ranges from -10 (dry) to +10 (wet) with values < -3 representing severe droughts.

Relevant processes

Palmer Drought Severity Index (PSDI): Ranges from -10 (dry) to +10 (wet) with values < -3 representing severe droughts.



From tree rings in USA

Figure 12.1: **A long-term drought record.**
A PDSI time series reconstructed for the Southwest United States from tree-ring data (section 12.4).

PSDI formula

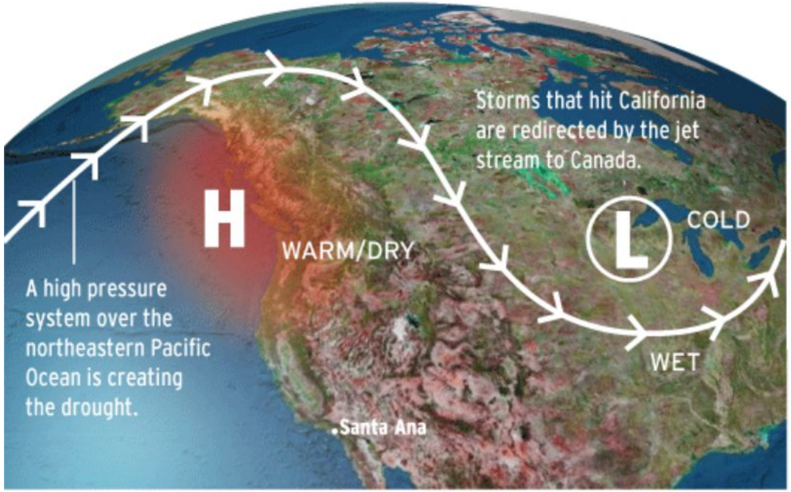
Palmer Drought Severity Index Formula

The formula for the PDSI is a complex, multi-step calculation that involves the following components:

1. **Moisture Supply (P - E):**
   - **P**: Precipitation (usually monthly or seasonal rainfall).
   - **E**: Potential evapotranspiration (PET), which represents the amount of water that could be evaporated and transpired by plants if water were available.
2. **Soil Moisture Anomaly (SM):**
   - **SM** is the deviation of the actual soil moisture from the normal, adjusted for climate.
   - This considers both moisture loss from the soil due to evaporation and moisture gain due to precipitation.
3. **Moisture Departure (MD):**
   - The **moisture departure** is a calculated departure from the normal moisture content in the soil, which is influenced by the balance of precipitation, evapotranspiration, and the current state of soil moisture.

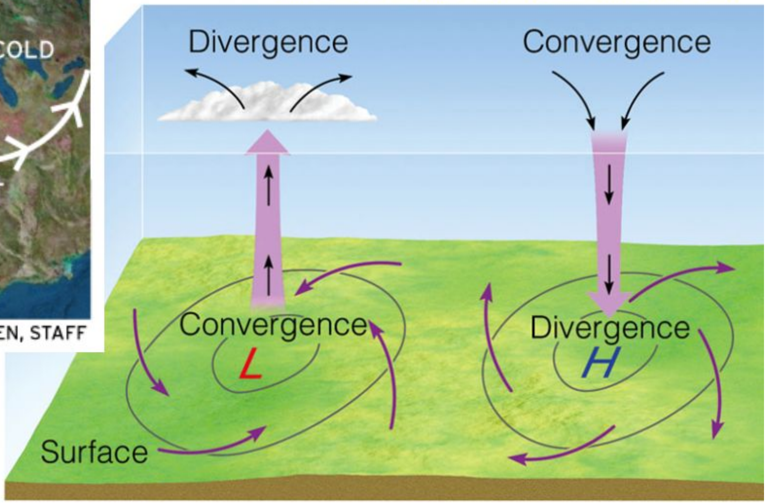
Why do droughts happen, and what can make them change in the future:

High sea level pressure: (1) diverts rain storms
(2) causes subsidence and therefore drying



Source: Stanford Woods Institute JEFF GOERTZEN, STAFF

https://blog.weatherops.com/how-does-subsidence-affect-weather



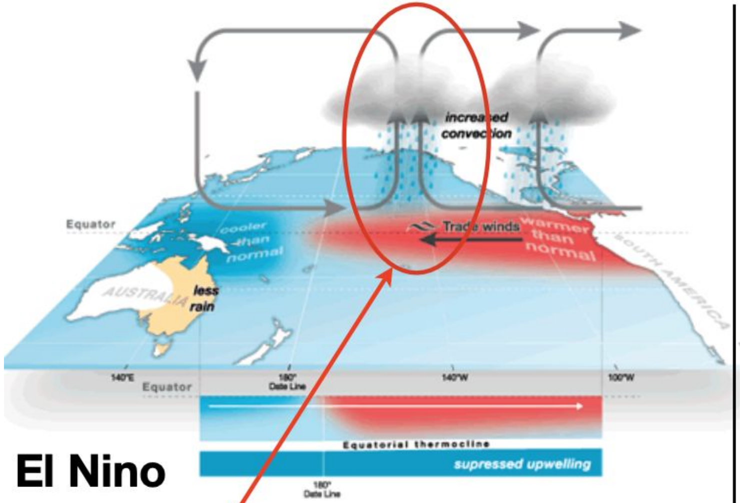
Cause of high pressure? Sea surface temperature anomalies

Why do droughts/floods happen: sea surface temperature & atmospheric teleconnections

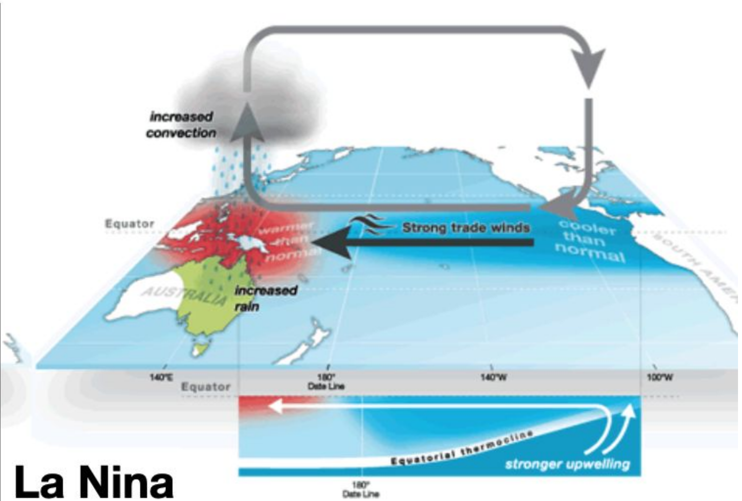
Three examples of processes that lead to sea surface temperature anomalies, leading to drought-causing high pressure signals:

1. El Nino
2. Indian Ocean dipole
3. Atlantic multi-decadal oscillation

El Nino - Southern Oscillation (ENSO)

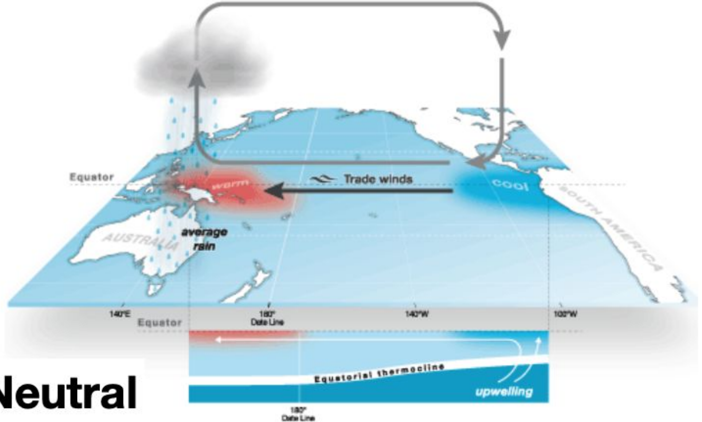


El Nino



La Nina

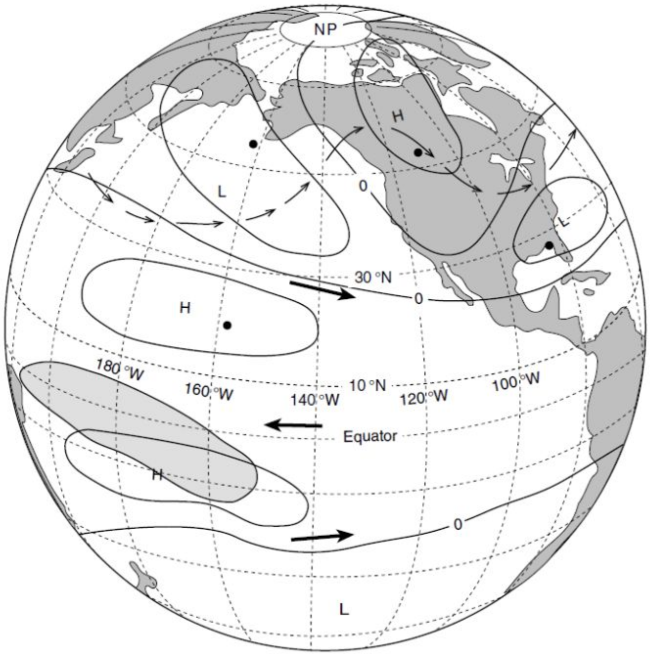
precipitation and
atmospheric heating which
forces atmospheric waves



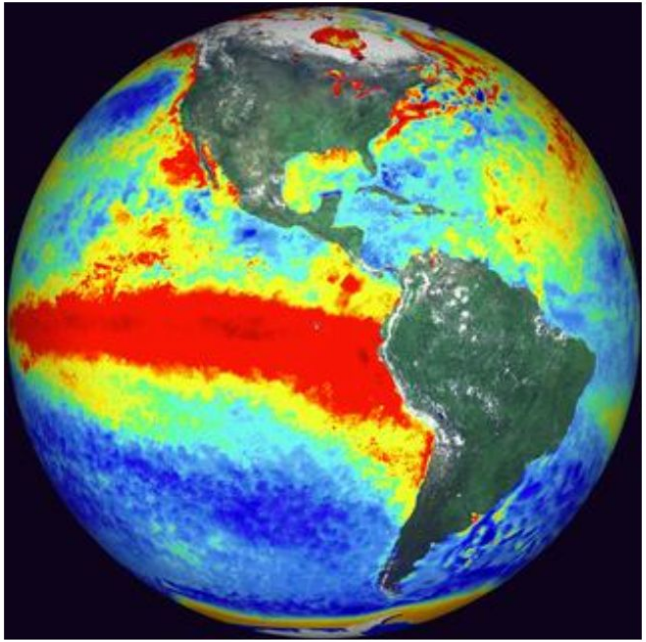
Neutral

http://www.bom.gov.au/climate/enso/history/ln-2010-12/three-phases-of-ENSO.shtml

Atmospheric teleconnections: **Rossby wave** train forced by ENSO

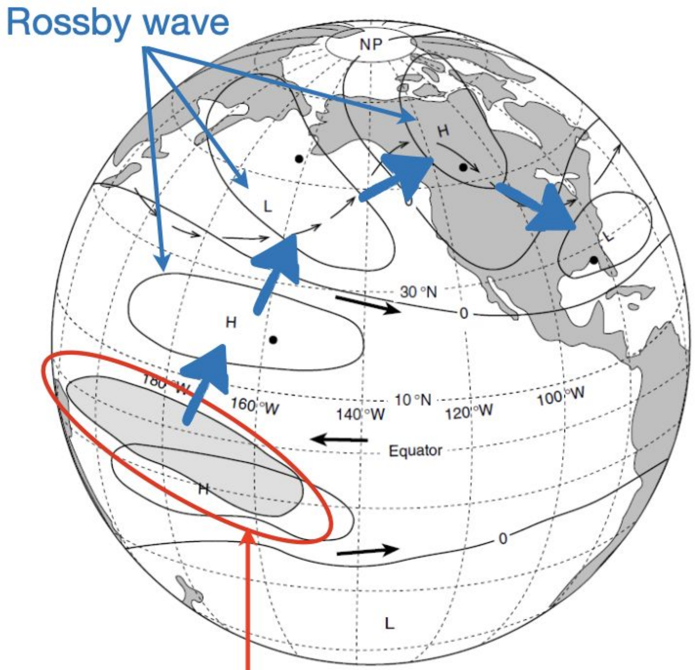


solid contours: schematic upper atmosphere geopotential height anomaly; shaded area at equator: enhanced cloudiness and rain. Light arrows: mid-tropospheric stream line distorted by wave pattern. (Horel & Wallace 1981)

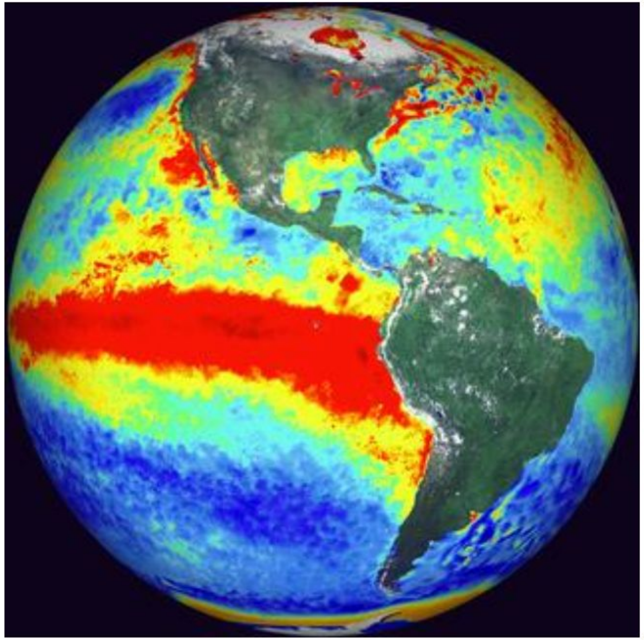


sea surface temperature anomaly during an El Nino event (https://snowbrains.com/noaa-el-nino-update-today/)

Atmospheric teleconnections: **Rossby wave** train forced by ENSO



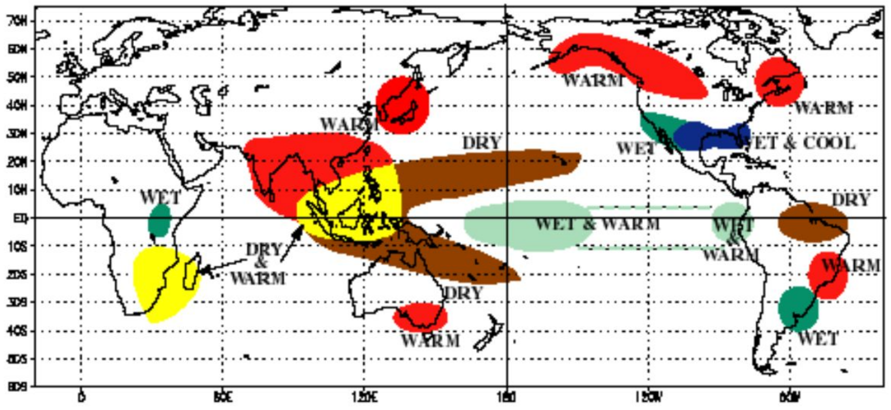
solid conto... atmospher... anomaly; s... enhanced ... arrows: mi... distorted by wave pattern. (Horel & Wallace 1981)



sea surface temperature anomaly during an El Nino event (https://snowbrains.com/noaa-el-nino-update-today/)

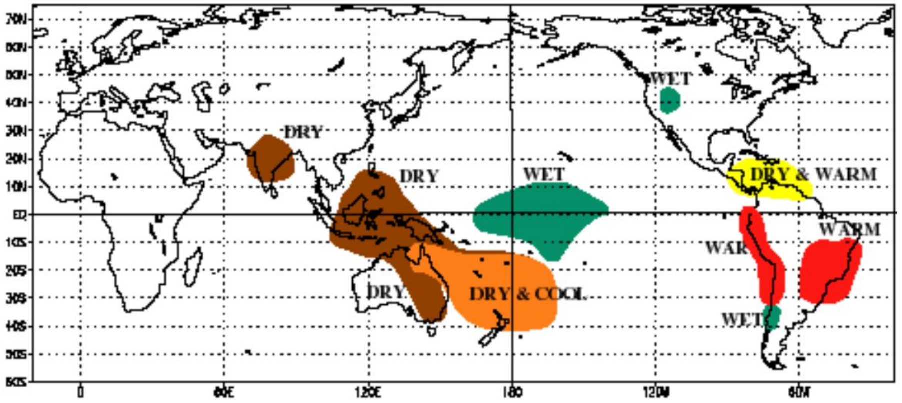
El Nino - Southern Oscillation (ENSO) teleconnections: **El Nino**

WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY

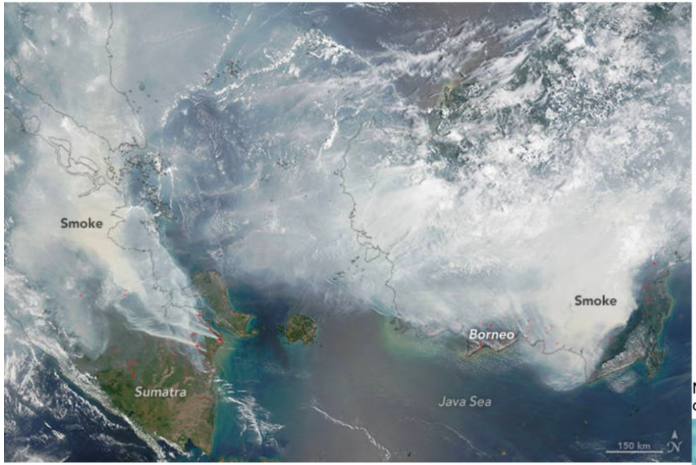


Regional impacts of warm ENSO episodes (El Niño)

WARM EPISODE RELATIONSHIPS JUNE - AUGUST

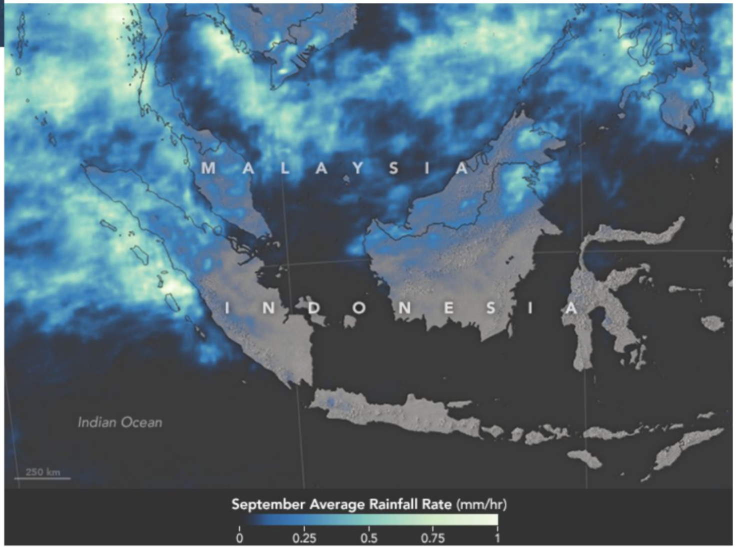


“El Niño Brought Drought and Fire to Indonesia”



NASA image by Jeff Schmaltz, LANCE/EOSDIS Rapid Response. Caption by Adam Voiland.

NASA Earth Observatory map (top) by Joshua Stevens and Jesse Allen, using IMERG data provided courtesy of the Global Precipitation Mission (GPM) Science Team’s Precipitation Processing System (PPS).

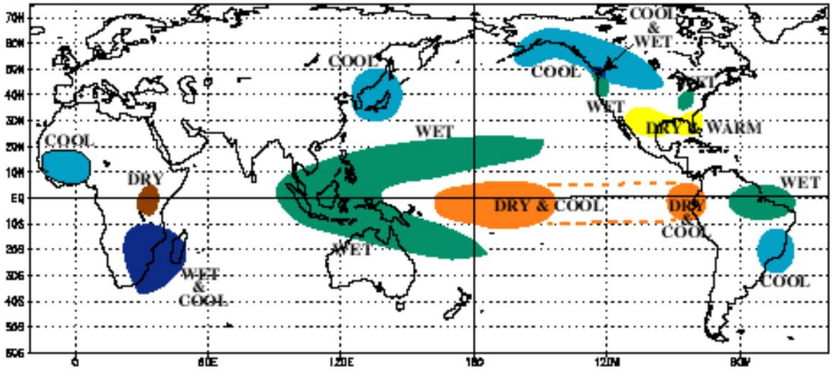


“One of the most predictable consequences of a strong El Niño is a change in rainfall patterns over Indonesia. During El Niño years, rain that is normally centered over Indonesia and the far western Pacific shifts eastward into the central Pacific; as a result, parts of Indonesia experience drought. That is what happened in 2015.”

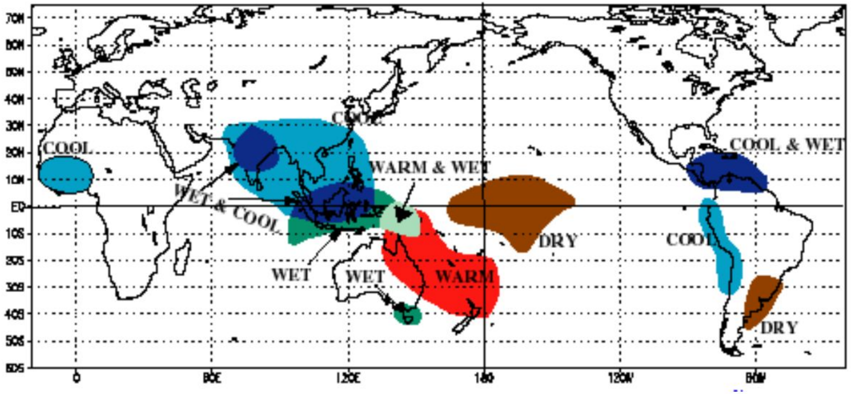
https://www.nasa.gov/feature/goddard/2016/el-nino-brought-drought-and-fire-to-indonesia

El Nino - Southern Oscillation (ENSO) teleconnections: **La Nina**

COLD EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



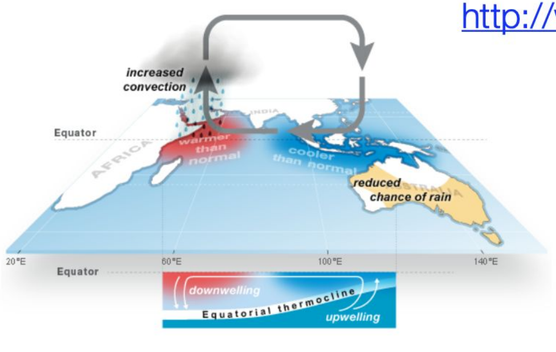
COLD EPISODE RELATIONSHIPS JUNE - AUGUST



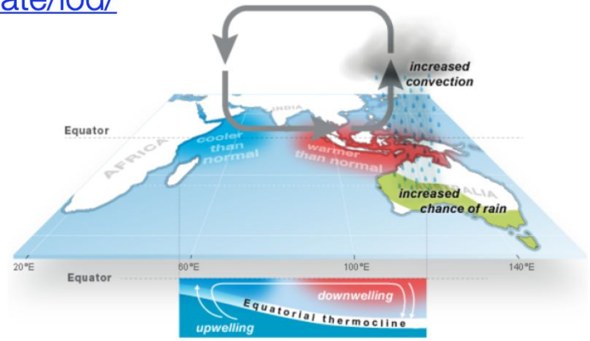
https://commons.wikimedia.org/wiki/File:La_Nina_regional_impacts.gif

Indian Ocean Dipole

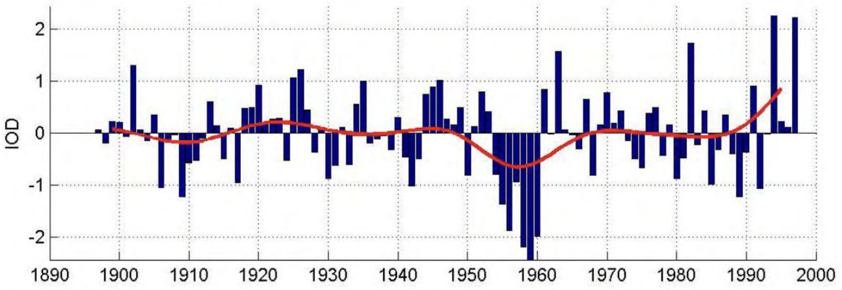
http://www.bom.gov.au/climate/iod/



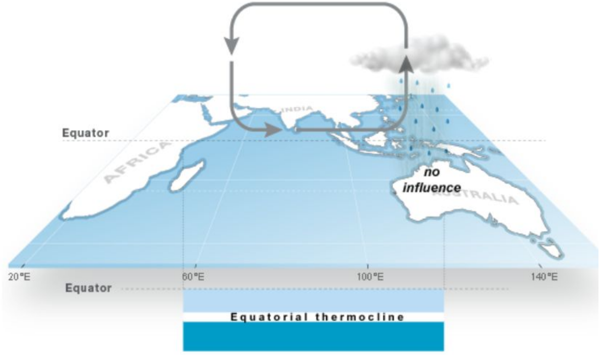
Indian Ocean Dipole (IOD): **Positive phase**



Indian Ocean Dipole (IOD): **Negative phase**



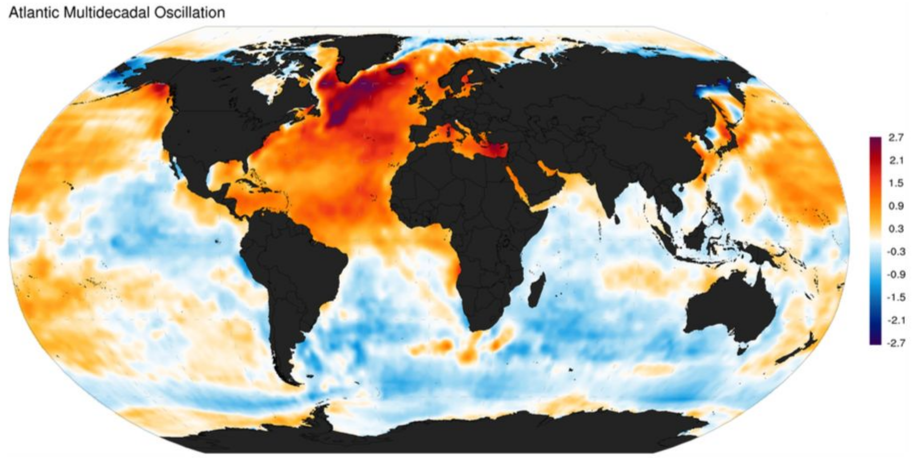
IOD time series, Berthot et al, 2017

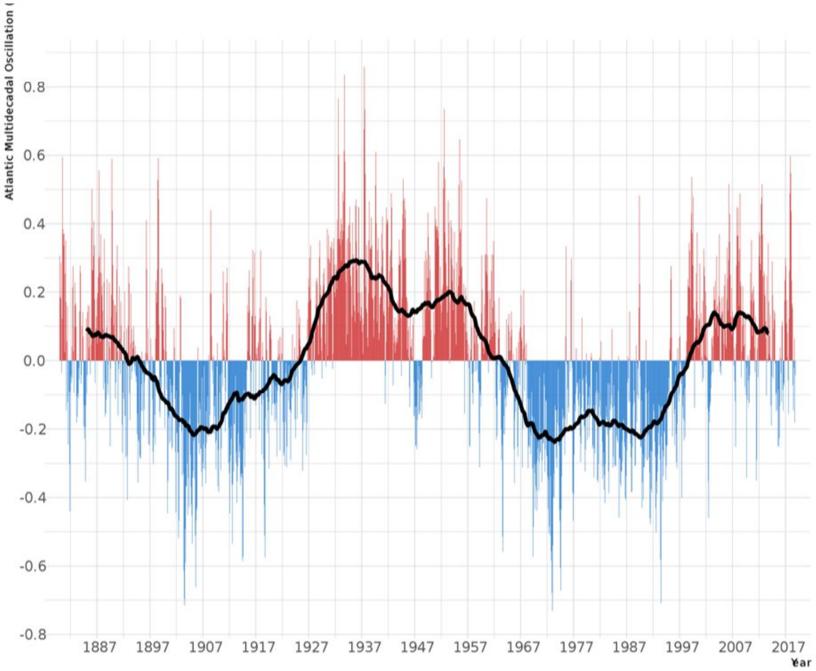


Indian Ocean Dipole (IOD): **Neutral phase**

A surface temperature gradient (“dipole”) between the east & west **Indian Ocean**, triggers a vertical east-west circulation & therefore droughts/ precipitation

Atlantic Multi-decadal Oscillation





The **Atlantic Multi-decadal Oscillation index** (right) is the averaged SST over the North Atlantic (0-70N). Shows an oscillation with a time scale of about 50 years.

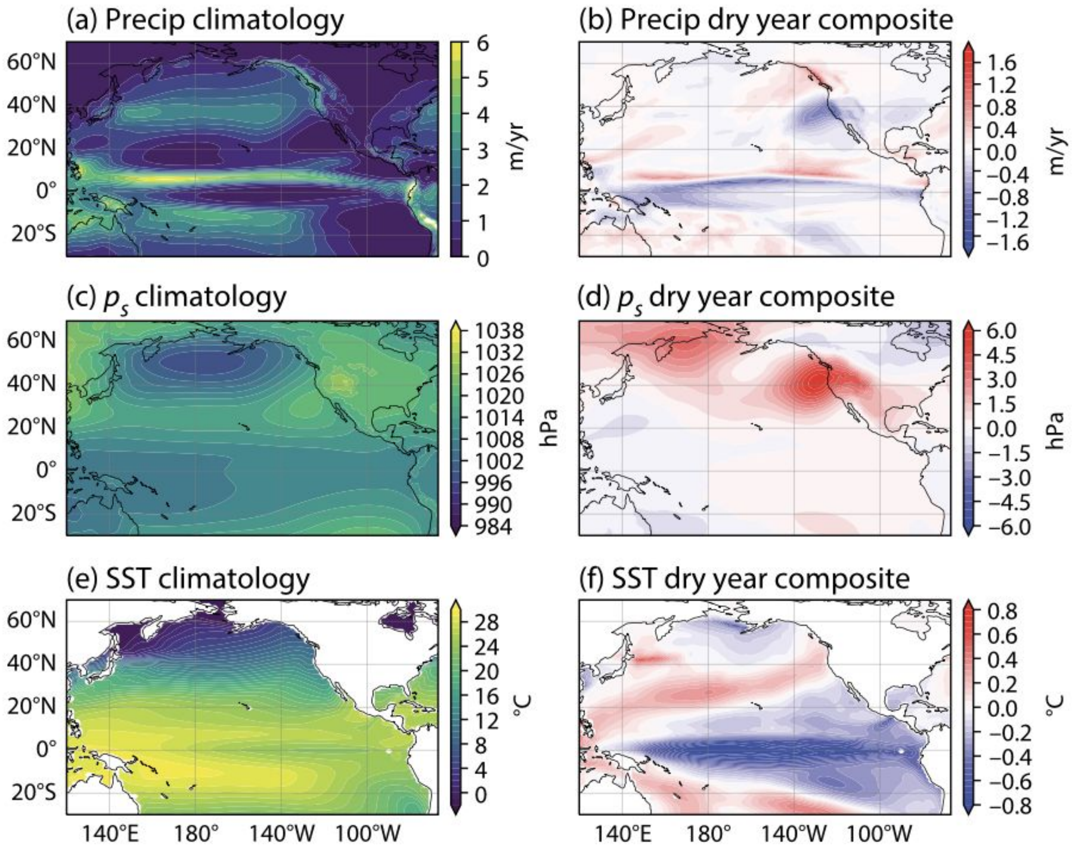


Figure 12.2: **Analysis of California droughts in a climate model**.
The coupled ocean-atmosphere model is run at a preindustrial CO_2 concentration: climatological January averages (*left*) and the deviations from these climatologies averaged over dry California Januaries (*right*) for precipitation (*top*), sea level pressure (*middle*), and SST (*bottom*).

So, what can make *regional* droughts change in the future?

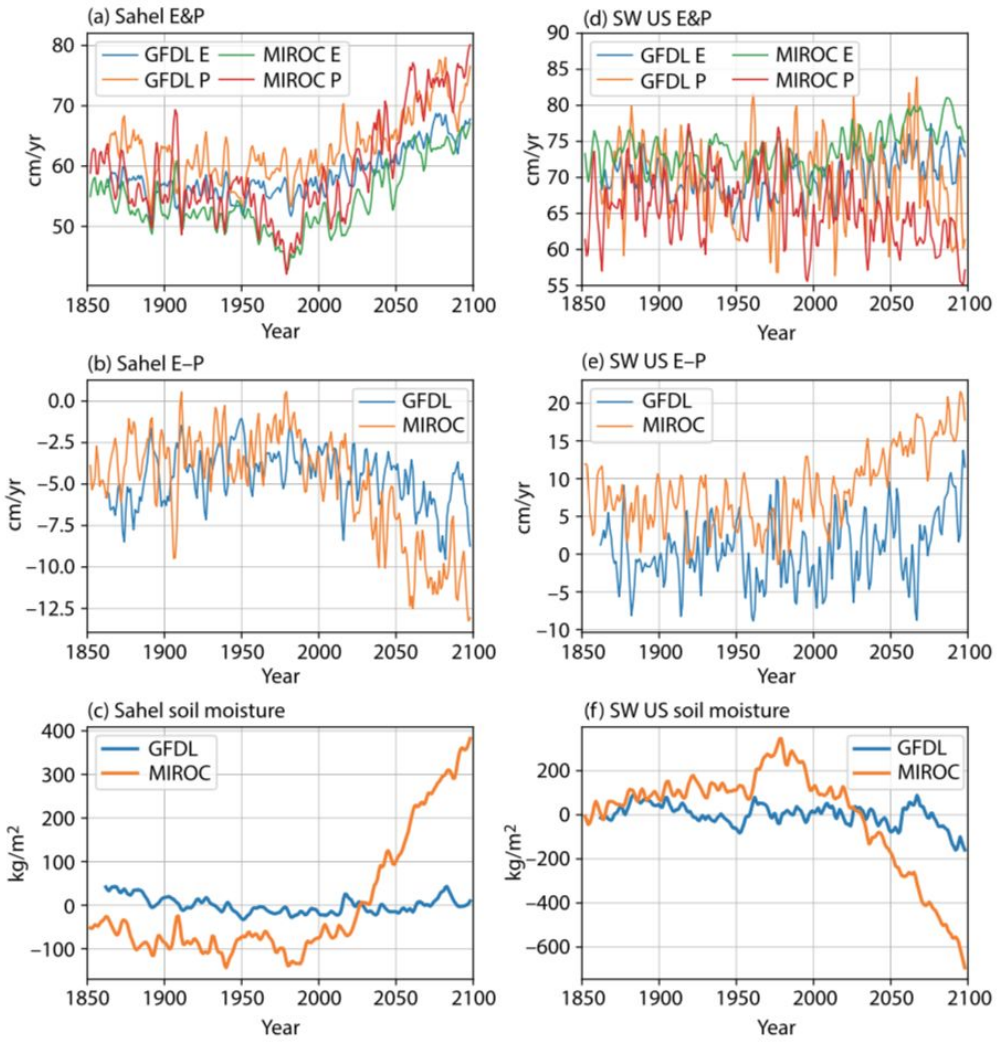
Droughts can change due to changes to natural variability modes (El Nino, AMOC, Indian dipole), or other **changes to *gradients* in sea surface temperature** (both due to mean state and variability) that lead to changes in the location/ occurrence of high pressure centers

Observations and future projections of droughts

Test cases:

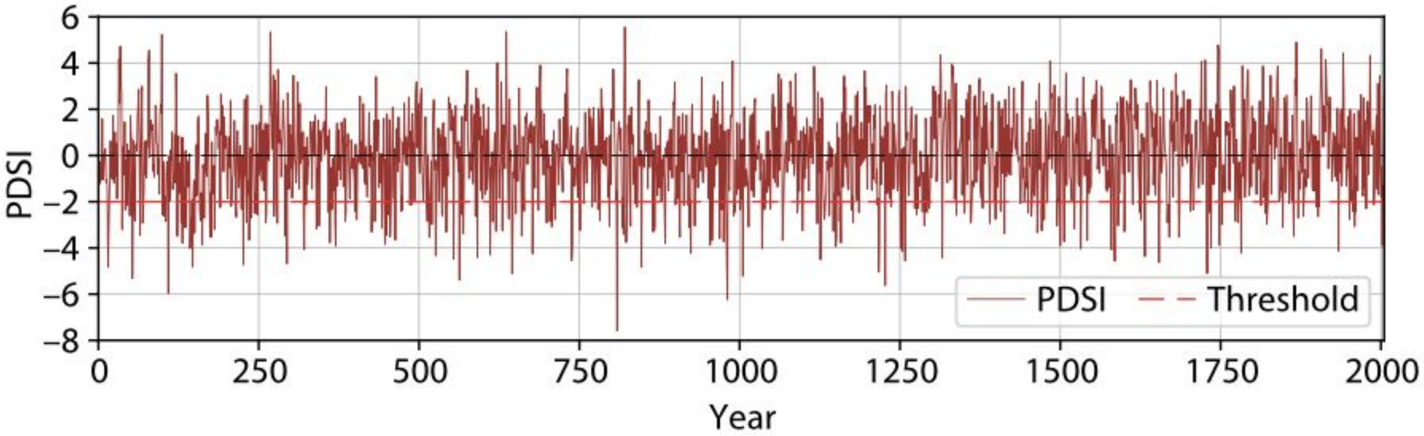
- California
- Sahel
- **Global perspective**

Droughts regional predictions are uncertain



Detection of climate change in droughts (and other extreme events)

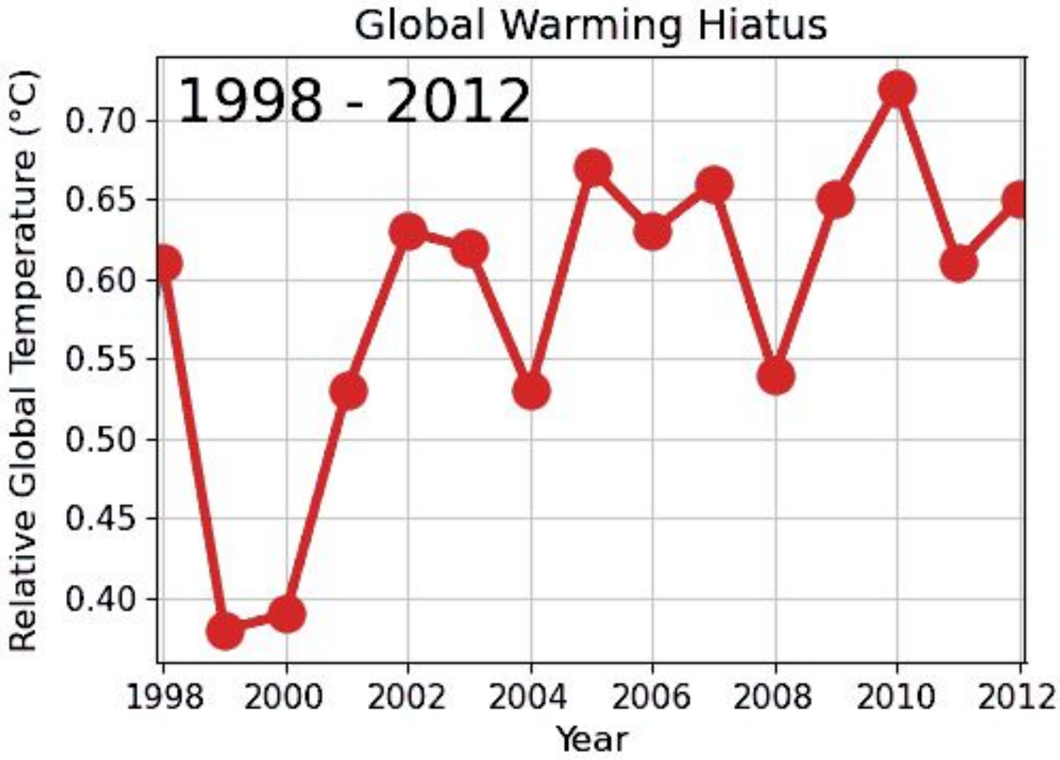
Palmer Drought Severity Index (PSDI): Ranges from -10 (dry) to +10 (wet) with values < -3 representing severe droughts.



From tree rings in USA

Figure 12.1: **A long-term drought record.**
A PDSI time series reconstructed for the Southwest United States from tree-ring data (section 12.4).

When is a trend significant?



Statistical significance of a linear trend

Step 1: Perform Linear Regression

In a linear regression, we model the relationship between the dependent variable Y and the independent variable X as:

$$Y = \beta_0 + \beta_1 X + \epsilon$$

- Y is the dependent variable (e.g., outcome).
- X is the independent variable (e.g., time or another predictor).
- β_0 is the intercept (the value of Y when $X = 0$).
- β_1 is the slope (the rate of change of Y with respect to X).
- ϵ represents the residuals (random errors).

The goal is to test whether the slope β_1 is significantly different from zero, which would indicate a trend.

Step 2: Estimate the Slope (β_1) and Standard Error

When you run a linear regression, you will get the following estimates:

- **Estimated slope ($\hat{\beta}_1$)**: The value that best fits the data.
- **Standard error of the slope**: This is a measure of the variability in the slope estimate.

The **standard error** (SE) is a measure of the variability or uncertainty in an estimate of a population parameter, such as the slope in linear regression. For linear regression, we typically compute the **standard error of the slope** $\hat{\beta}_1$, which is used to assess the precision of the slope estimate.

Step 3: Hypothesis Testing

To test whether the slope is significantly different from zero, we set up the following hypotheses:

- **Null Hypothesis (H_0)**: $\beta_1 = 0$ (there is no trend).
- **Alternative Hypothesis (H_A)**: $\beta_1 \neq 0$ (there is a significant trend).

We then perform a **t-test** to determine if the estimated slope $\hat{\beta}_1$ is significantly different from zero.

The test statistic is calculated as:

$$t = \frac{\hat{\beta}_1}{\mathrm{SE}(\hat{\beta}_1)}$$

Where:

- $\hat{\beta}_1$ is the estimated slope.
- $\mathrm{SE}(\hat{\beta}_1)$ is the standard error of the slope.

The **standard error** (SE) is a measure of the variability or uncertainty in an estimate of a population parameter, such as the slope in linear regression. For linear regression, we typically compute the **standard error of the slope** $\hat{\beta}_1$, which is used to assess the precision of the slope estimate.

Formula for the Standard Error of the Slope $\hat{\beta}_1$

In simple linear regression, the formula for the standard error of the slope $\hat{\beta}_1$ is:

$$\text{SE}(\hat{\beta}_1) = \sqrt{\frac{\text{Residual Sum of Squares}(RSS)}{(n-2)} \cdot \frac{1}{\sum(X_i - \bar{X})^2}}$$

Where:

- n is the number of data points.
- X_i represents the individual values of the independent variable X.
- $\bar{X}$ is the mean of the X values.
- RSS is the residual sum of squares (also called the error sum of squares).

Breaking Down the Components

1. **Residual Sum of Squares (RSS):** This is the sum of the squared differences between the observed Y-values and the predicted Y-values (i.e., the residuals). It reflects the total error in the regression model.

   $$\text{RSS} = \sum (Y_i - \hat{Y}_i)^2$$

   Where Y_i is the observed value and $\hat{Y}_i$ is the predicted value from the regression model.

2. **Sum of Squared Deviations of X (denoted $\sum (X_i - \bar{X})^2$):** This is the sum of the squared differences between each individual X-value and the mean $\bar{X}$ of all the X-values. It is a measure of the variation in the independent variable X.

3. **Degrees of Freedom (df):** The degrees of freedom for the error term in simple linear regression is $n - 2$, where n is the number of data points. We subtract 2 because we are estimating two parameters (the slope and the intercept) from the data.

Step 4: Calculate the p-value

Once you have the t-statistic, you can use the **t-distribution** to find the **p-value** associated with the test statistic. The p-value indicates the probability of observing a slope at least as extreme as $\hat{\beta}_1$, assuming the null hypothesis is true.

- A **low p-value** (typically less than 0.05) suggests that the slope is significantly different from zero, implying a significant linear trend.
- A **high p-value** (typically greater than 0.05) suggests that the slope is not significantly different from zero, implying no significant trend.

To find the **p-value** from a **t-statistic**, you need to compare the t-statistic to the **t-distribution** with the appropriate degrees of freedom (df). The p-value tells you the probability of observing a t-statistic as extreme (or more extreme) than the one you calculated, assuming the null hypothesis is true.

Steps to Find the p-value from the t-statistic

1. Calculate the t-statistic

The t-statistic is computed as:

$$t = \frac{\hat{\beta}_1}{\mathrm{SE}(\hat{\beta}_1)}$$

Where:

- $\hat{\beta}_1$ is the estimated slope from the regression.
- $\mathrm{SE}(\hat{\beta}_1)$ is the standard error of the slope.

2. Determine the Degrees of Freedom (df)

For a **simple linear regression**, the degrees of freedom for the error term is:

$$df = n - 2$$

Where:

- n is the number of data points (observations).

This is because you estimate two parameters in the regression (the slope and the intercept), and the degrees of freedom account for the number of observations minus the number of parameters estimated.

3. Look Up the p-value Using the t-distribution

The p-value is the probability that the t-statistic would be as extreme as observed (or more extreme) under the null hypothesis. This is calculated based on the **t-distribution** with $n - 2$ degrees of freedom.

- **One-tailed test**: If your hypothesis is directional (e.g., $H_0 : \beta_1 = 0$ vs. $H_A : \beta_1 > 0$ or $H_A : \beta_1 < 0$), you only care about one side of the distribution.
- **Two-tailed test**: If you're testing for any non-zero effect (e.g., $H_0 : \beta_1 = 0$ vs. $H_A : \beta_1 \neq 0$), you need to account for both tails of the distribution.

4. Find the p-value from the t-statistic

- The **p-value** is the area under the t-distribution curve that is more extreme than the observed t-statistic. You can find the p-value by using a **t-distribution table** or a **statistical software** like Python, R, or Excel.

The p-value corresponds to the probability that the t-statistic would fall in the tail(s) of the t-distribution.

- **For a two-tailed test**, the p-value is twice the area in one tail of the distribution:

$$p\text{-value} = 2 \cdot P(T \geq |t|) \quad \text{(for two-tailed test)}$$

  where T follows the t-distribution with df degrees of freedom.

- **For a one-tailed test**, the p-value is the area in one tail beyond the observed t-statistic:

$$p\text{-value} = P(T \geq t) \quad \text{(for one-tailed test)}$$

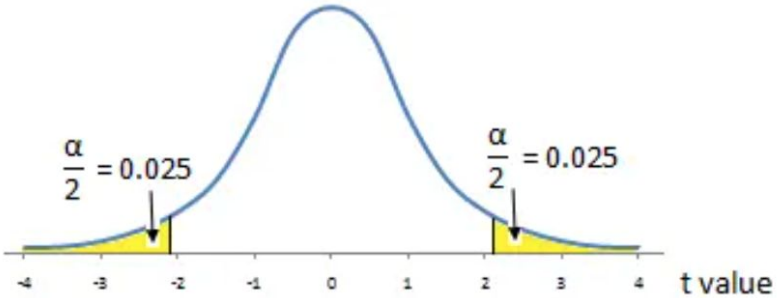
5. **Use a t-distribution table or software**

Using a t-distribution table:

- **Find the critical value** for your calculated t-statistic based on the degrees of freedom and the significance level (usually $\alpha = 0.05$).
- **Compare the calculated t-statistic** with the table values to find the p-value.

Student's t Distribution Table

For example, the t value for 18 degrees of freedom is 2.101 for 95% confidence interval (**2**-Tail $\alpha = 0.05$).



	90%	95%	97.5%	99%	99.5%	99.95%	**1**-Tail Confidence Level
	80%	90%	95%	98%	99%	99.9%	**2**-Tail Confidence Level
	0.100	0.050	0.025	0.010	0.005	0.0005	**1**-Tail Alpha
df	0.20	0.10	0.05	0.02	0.01	0.001	**2**-Tail Alpha
1	3.0777	6.3138	12.7062	31.8205	63.6567	636.6192	
2	1.8856	2.9200	4.3027	6.9646	9.9248	31.5991	
3	1.6377	2.3534	3.1824	4.5407	5.8409	12.9240	
4	1.5332	2.1318	2.7764	3.7469	4.6041	8.6103	
5	1.4759	2.0150	2.5706	3.3649	4.0321	6.8688	
6	1.4398	1.9432	2.4469	3.1427	3.7074	5.9588	

Step 5: Conclusion

- **If p-value < 0.05**: Reject the null hypothesis, and conclude that there is a statistically significant linear trend in the data.
- **If p-value ≥ 0.05**: Fail to reject the null hypothesis, and conclude that there is no statistically significant linear trend.

Parametric test for statistical significance of a linear trend

- Perform linear regression $Y = \beta_0 + \beta_1 X + \epsilon$

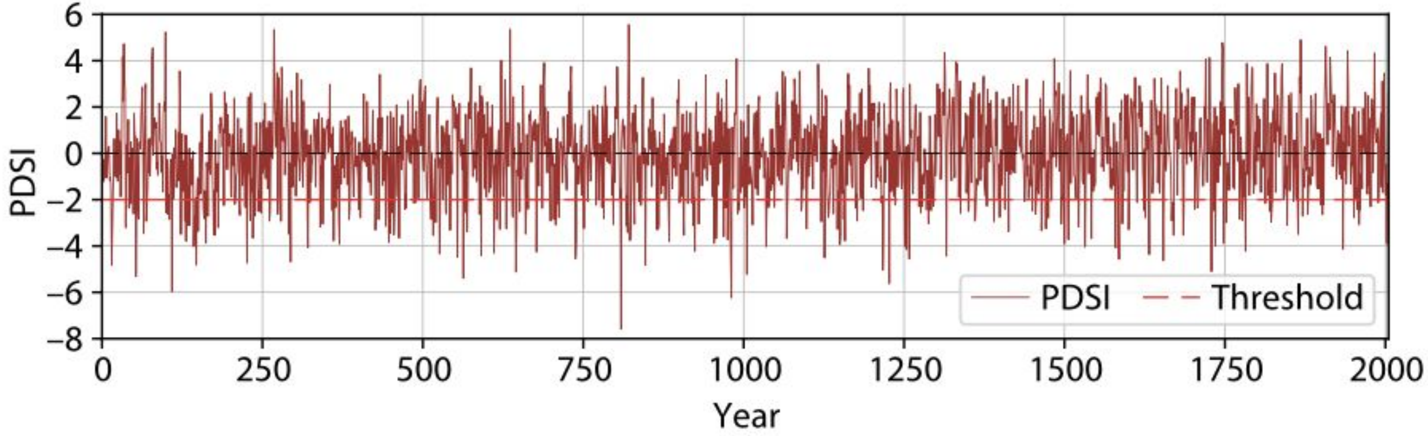
- Determine the degrees of freedom

- Look up the p-value using the Student's t distribution

- Accept or reject the null hypothesis

Non parametric statistical analysis of a trend

There are three drought years (PSDI < -2) in the last three decades of the record, which only extends to year 2000. **How unusual is such a period?**



Non-parametric testing

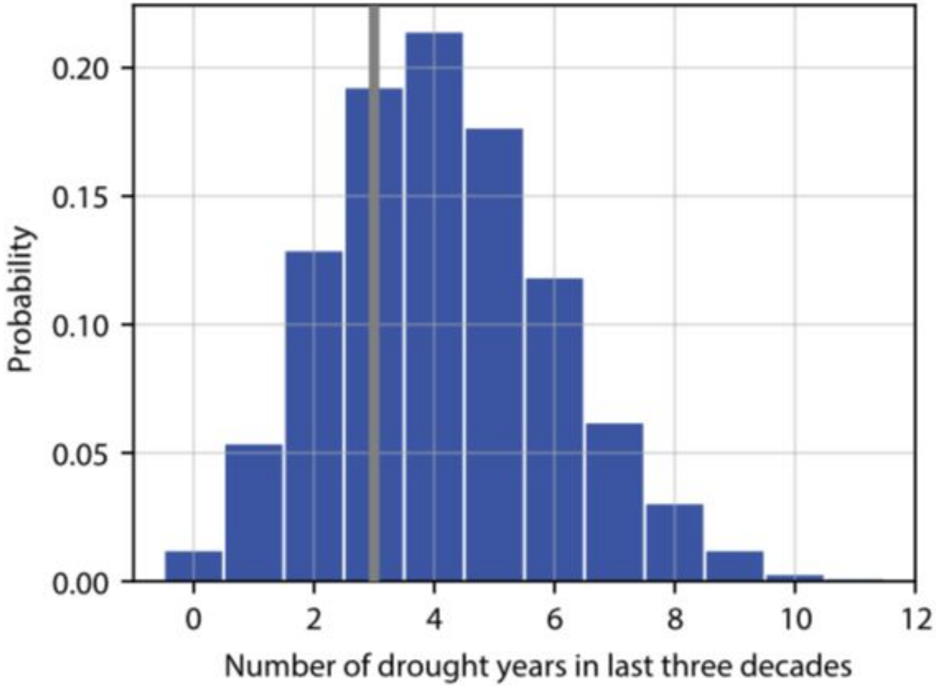


Figure 12.3: Detection of climate change.
A probability distribution function of the number of drought years within the last three decades, obtained by repeatedly randomly shuffling the PDSI record in Figure 12.1.

1. Shuffle the data points in the time series
2. Calculate the number of droughts in the last decades in the shuffled time series
3. Repeat a high number of times (e.g., 10k realizations)
4. Calculated the Probability Distribution Function of the number of drought years

Conclusions: droughts

- Definition: ***abnormally dry weather, relative to mean condition****s, long enough to cause a serious hydrological imbalance. these are NOT weather events, need to last a few months.*
- Types: meteorological, hydrological, agricultural, socioeconomic
- causes: often remotely forced by a persistent sea surface temperature anomaly via atmospheric Rossby Waves that lead to a persistent high pressure over the drought region. Examples of such SST anomalies due to climate variability modes: El Niño/La Niña, Indian Ocean Dipole, etc.
- Projections: changes are guaranteed, but regional details are not clear. In this case, change is not good, given human/agriculture adaptation to current climate patterns.
- Uncertainty: we don't know well enough what El Nino/Indian Ocean Dipole, etc, will do in a warm future climate.

Floods, Pakistan 2022

Floodwaters in Sohbatpur, a city of roughly 200,000 in southern Pakistan. Zahid Hussain/Associated Press

Asif Hassan/Agence France-Presse — Getty Images

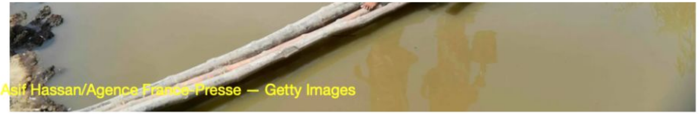
https://www.redcross.org/about-us/news-and-events/news/2022/red-cross-and-red-crescent-respond-to-flooding-in-pakistan.html

Hussain Ali/Anadolu Agency via Getty Images

Floods, Pakistan 2022

NYTimes: *“In a First Study of Pakistan’s Floods, Scientists See Climate Change at Work*

A growing field called attribution science is helping researchers rapidly assess the links between global warming and weather disasters.”



***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”

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."***

Floods

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

https://www.youtube.com/watch?v=fbyK1z1_W4s&t=135s

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.

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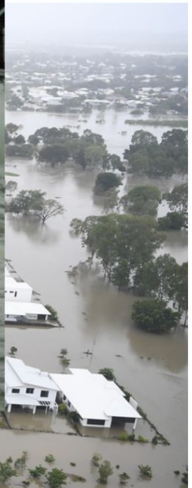
B. Flash floods/surface water floods: start within a few hours of a rain event. When the soil cannot absorb abrupt & intense rain. In cities due to large paved areas/deserts with loess soil (dust) that seals due to initial moisture.

Three types of floods

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

B. Flash floods/surface water floods: start within a few hours of a rain event. When the soil cannot absorb abrupt & intense rain. In cities due to large paved areas/deserts with loess soil (dust) that seals due to initial moisture.

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



Extreme precipitation and floods

(NYTimes, a thoughtful article this time :-)

"How Is Climate Change Affecting Floods?"
"***While extreme precipitation events are increasing due to climate warming, there is less evidence for an increase in floods."***

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.

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

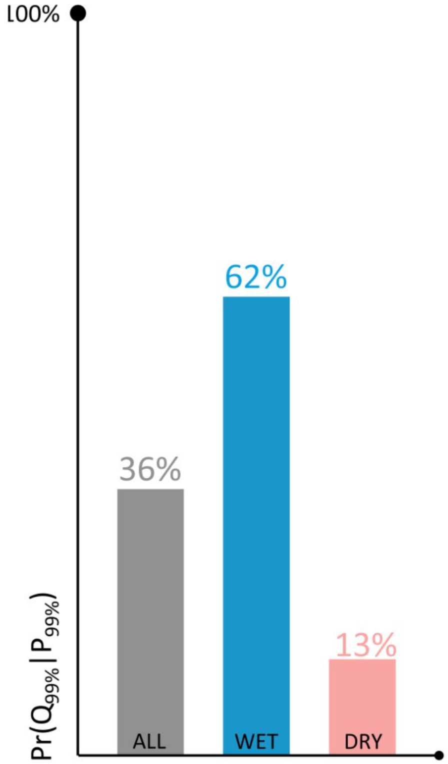
https://www.nytimes.com/article/flooding-climate-change.html

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).



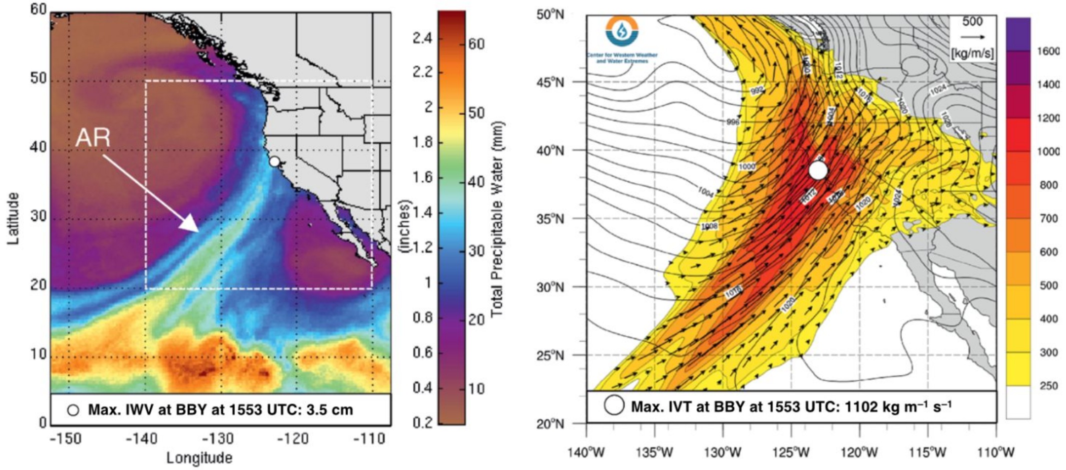
This suggests that overall larger precipitation, leading to moister soil, increases the probability of floods

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



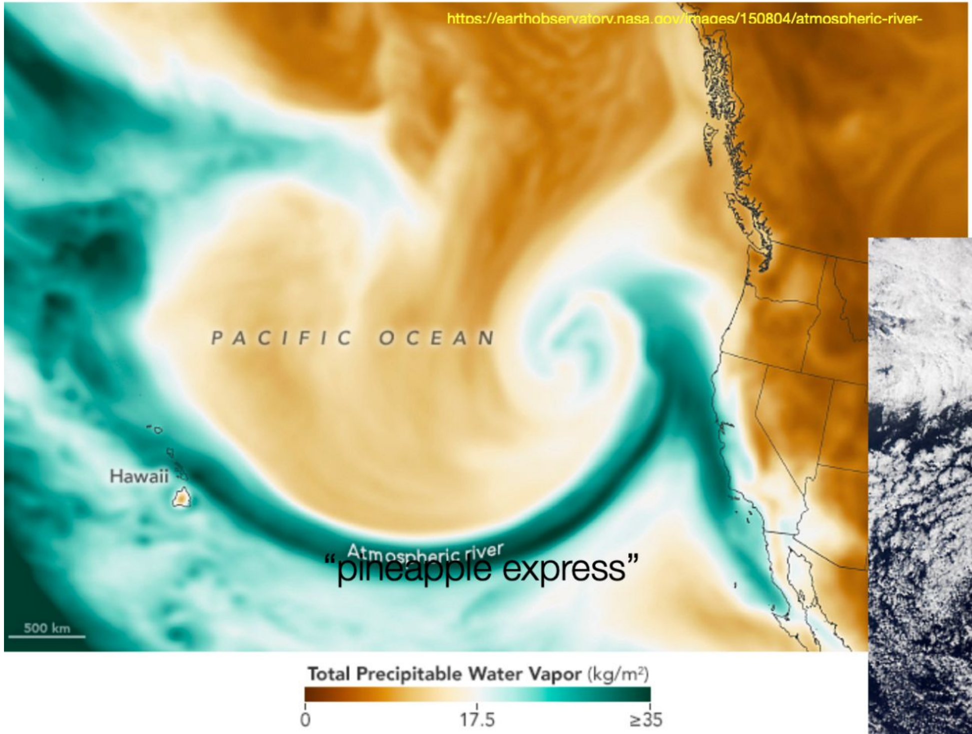
Ralph et al 2019

Defining/ quantifying ARs:

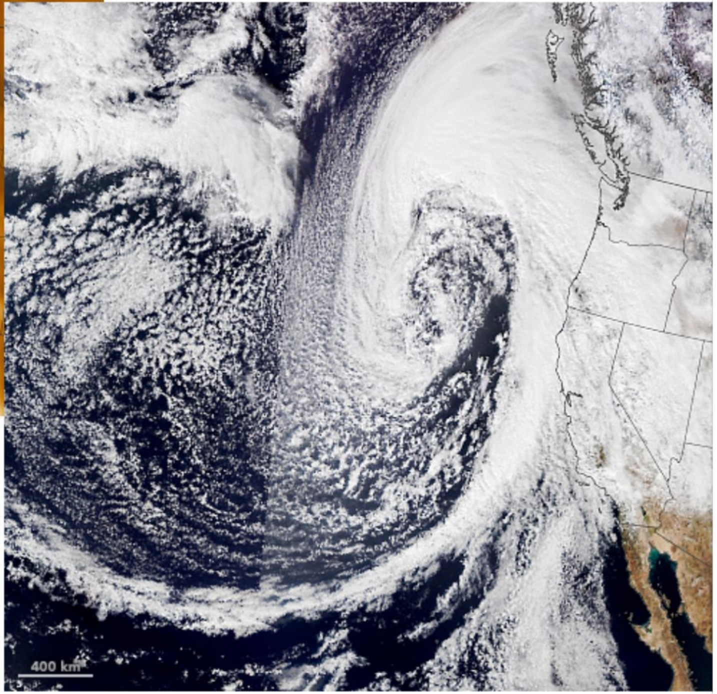
- IVT: vertically integrated water vapor transport $IVT = \int \mathbf{u}q\,\rho dz = -\int \mathbf{u}q\,dp/g$
- IWV: vertically integrated water vapor (precipitable water, the depth of water in a column of the atmosphere, if all water were precipitated as rain) $IWV = \rho_w^{-1}\int \rho_a q\,dz$

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

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



Jan 4, 2023



visible infrared imaging radiometer

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.

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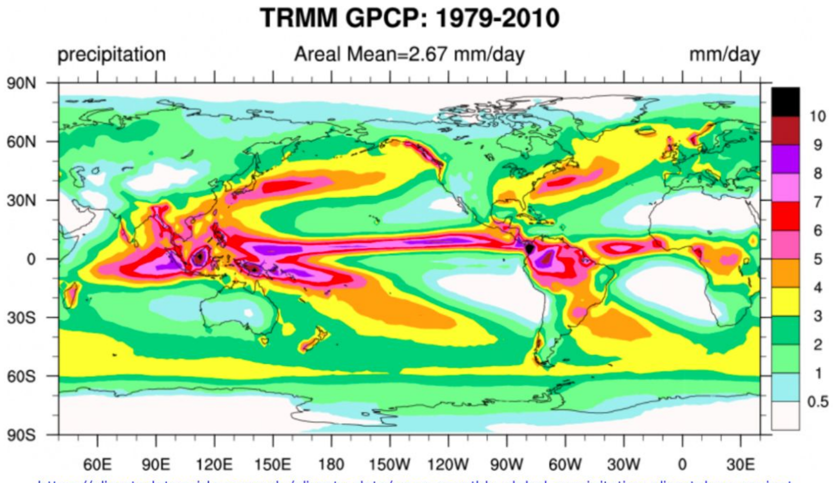
C. ➡ Understanding the expected increase in ***extreme precipitation events*** in a warmer climate.

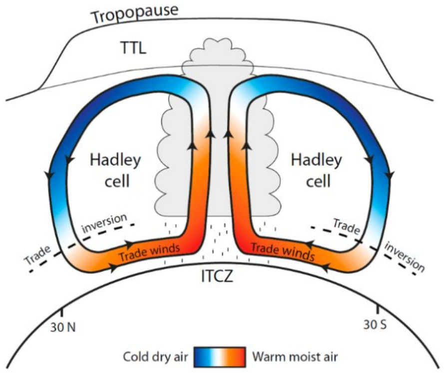
Mean precipitation patterns & the Hadley circulation



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

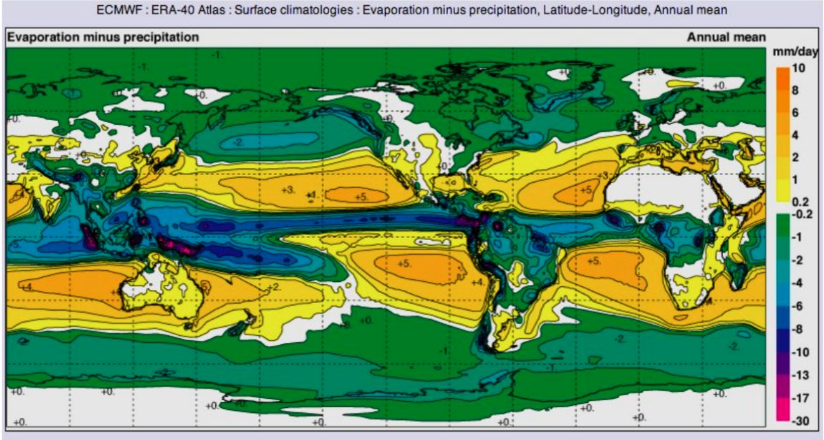
Climatological annual mean precipitation (mm/day) for 1979-2010.
Global mean = 2.67 mm/day. (Climate Data Guide; D. Shea)

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



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

Weakening and poleward expansion of the Hadley circulation

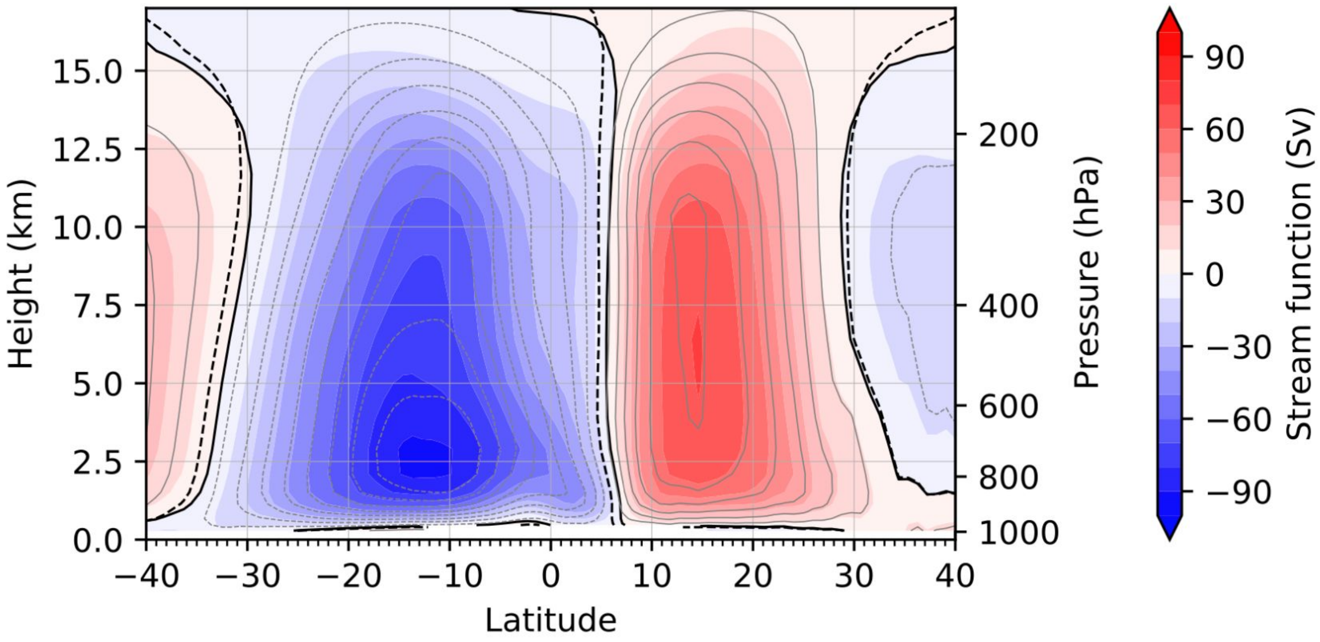


Figure 12.6: Projected Hadley cell expansion under global warming. Color shadings: the zonally-averaged atmospheric meridional overturning circulation evaluated by a climate model for 1920–1940. Contour shading levels: transport in Sverdrups (Sv, here 10^9 kg/s). Gray lines: same quantity for RCP8.5,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

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.

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.

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.

Wet get wetter, dry get drier

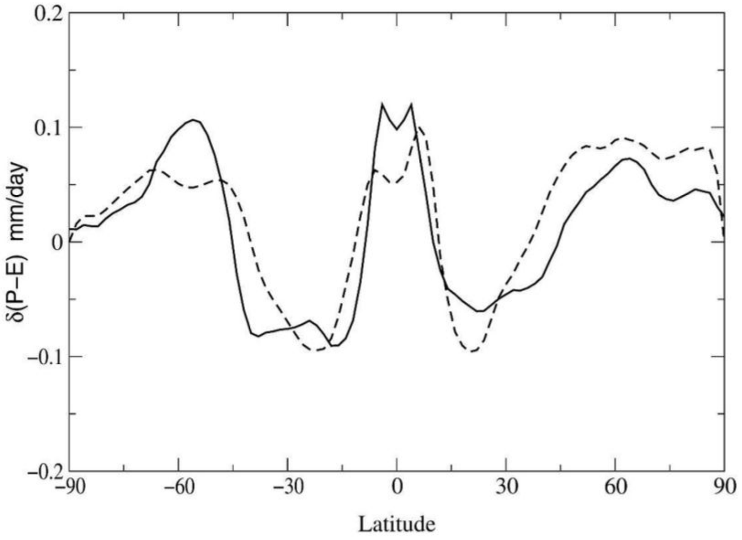
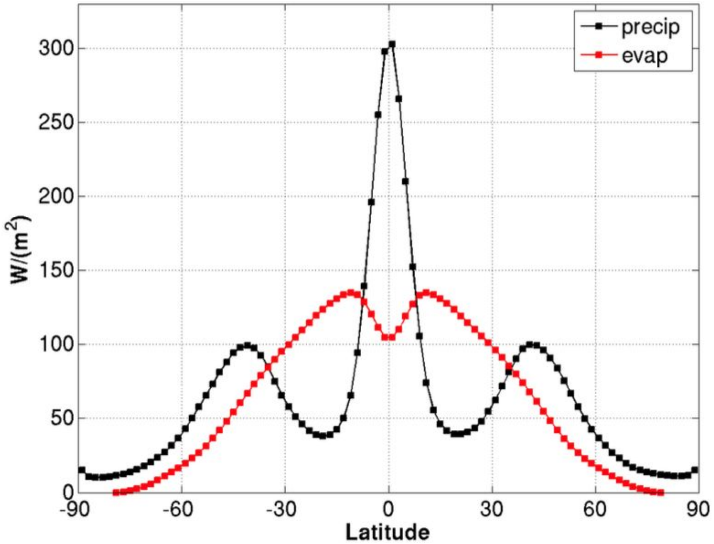
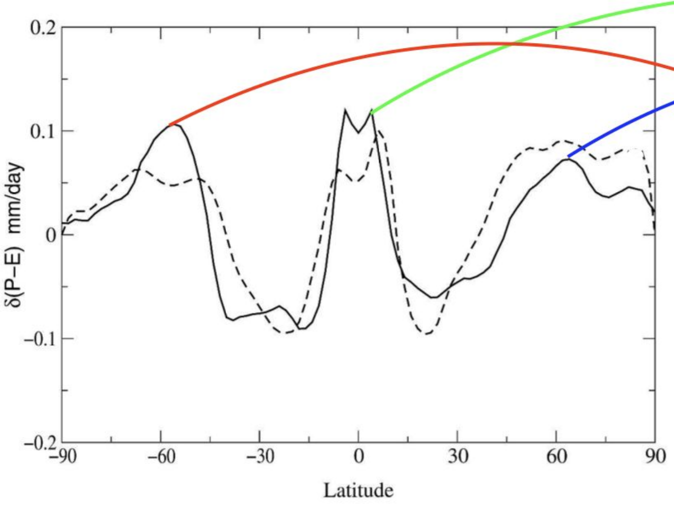


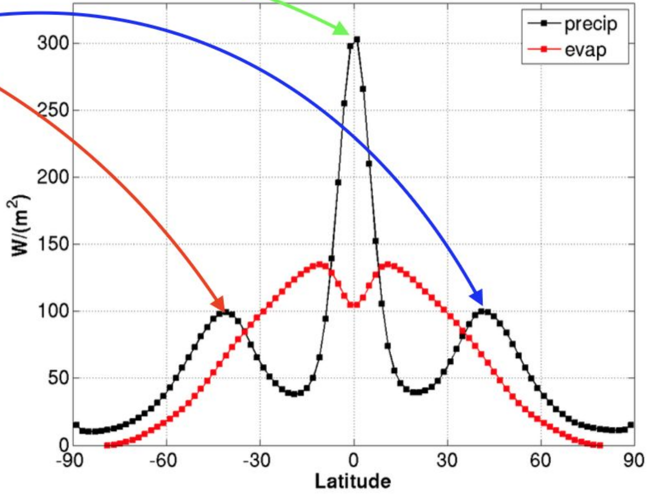
FIG. 6. Projected zonal mean change $\Delta(P - E)$ from AR4 models (solid) and the thermodynamic component (dashed) predicted from (6). From simulations using the SRES A1B. Held & Soden 2006



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/





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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/

➡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

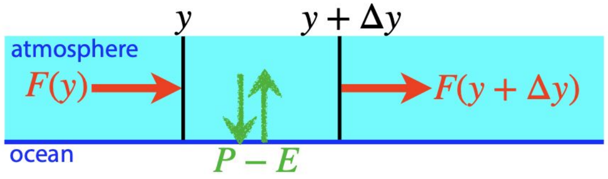
Global projections: Wet getting wetter, dry getting drier

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

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

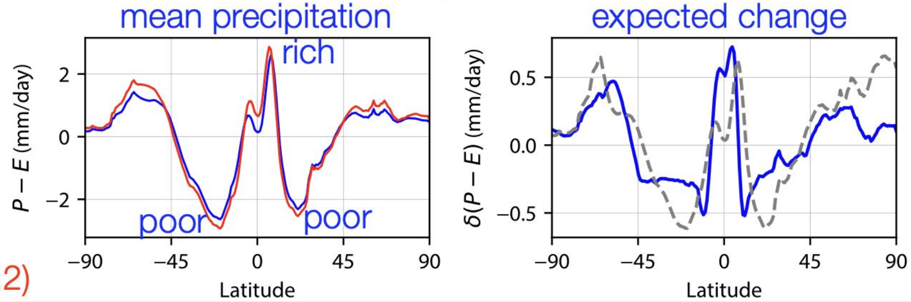
are related via: $(P-E)=-\dfrac{dF}{dy}$. This is derived from the moisture budget of a slice of air:



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

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

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



(Following Held and Soden, 2000)

Textbook section 12.6.2 (notes 12.3.2)

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

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

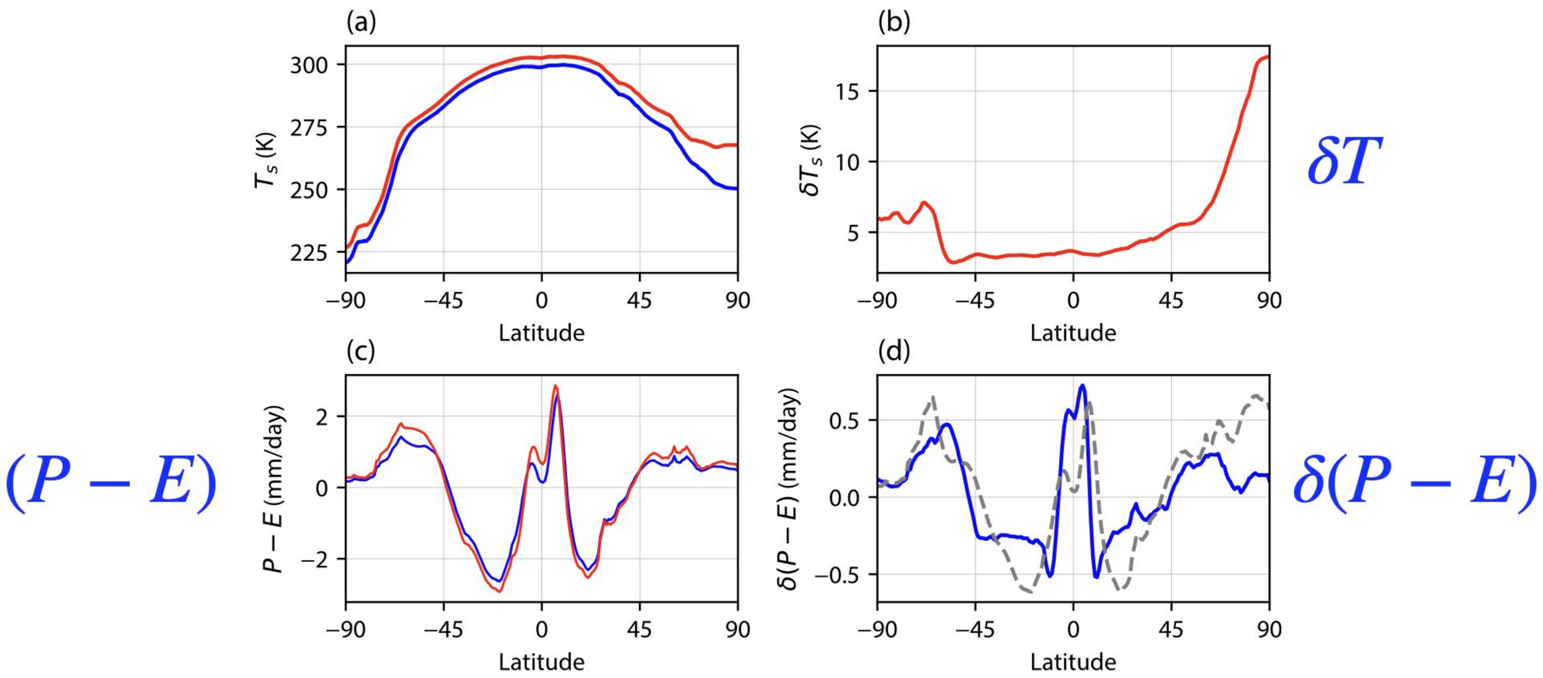


Figure 12.7: Attempting to explain the global response of precipitation minus evaporation to a warming scenario. (a) Zonally-averaged surface temperature as a function of latitude during 1920–1940 (blue) and 2080-2100 (red) in the RCP8.5 scenario. (b) The net warming as a function of latitude. (c) Zonally 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).**

Outline

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Conclusions: Floods

1. Types and causes:
   - A. Flash floods/River floods/coastal flooding.
   - B. Many occur due to extreme precipitation events.
   - C. Floods (rain-driven) depend on many factors: precipitation magnitude, duration & area, soil saturation, infrastructure failure, and urbanization.
2. Mean precipitation patterns are expected to change:
   - D. Hadley cell expansion would shift rain/dryness latitude belts
   - E. Rich getting richer: a result of Clausius-Clapeyron, ~7%/degree C, does not hold well over land, where patterns are complex.
3. Precipitation extremes are expected to get stronger:
   - A. Due to Clausius-Clapeyron again.
   - B. Difficult to see in individual weather stations, but detectable when analyzing larger regions.
   - C. The short record makes the attribution of individual events difficult.
   - D. Current trends in floods are uncertain, no clear trend.
   - E. Future projections of stronger precipitation extremes are still robust.