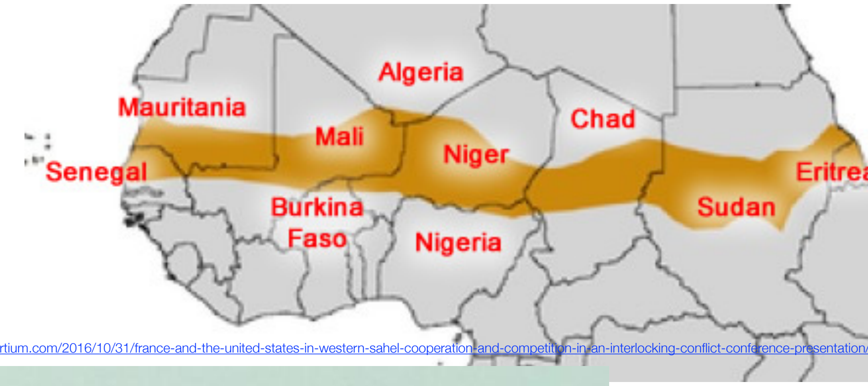
Droughts

Global Warming Science, EPS101

Eli Tziperman

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

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

Sahel forest near Kayes Mali

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

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

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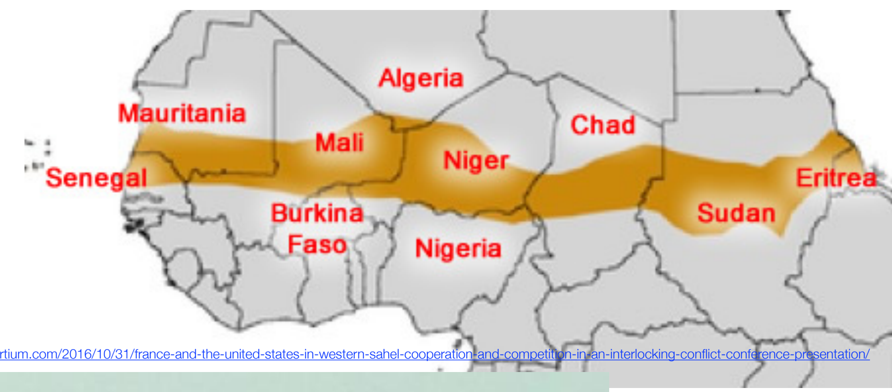

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Sahel, drought

https://alchetron.com/Sahel-drought

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

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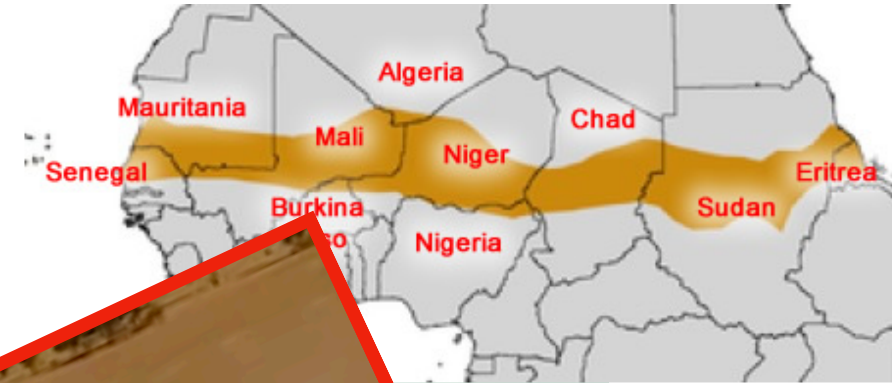

"The slow burn of climate change makes subsistence farming, already risky business in a hot, arid region, even more of a gamble."

https://alchetron.com/Sahel-drought

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Sahel Droughts

California Droughts

California Drought Is Made Worse by Global Warming, Scientists Say

The New York Times

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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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

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California Braces for Unending Drought

Gov. Jerry Brown of California last month in No… making permanent the water conser… d an executive order on Monday …ing the state's five-year drought.
Mary Altaffer/Associated Pr…

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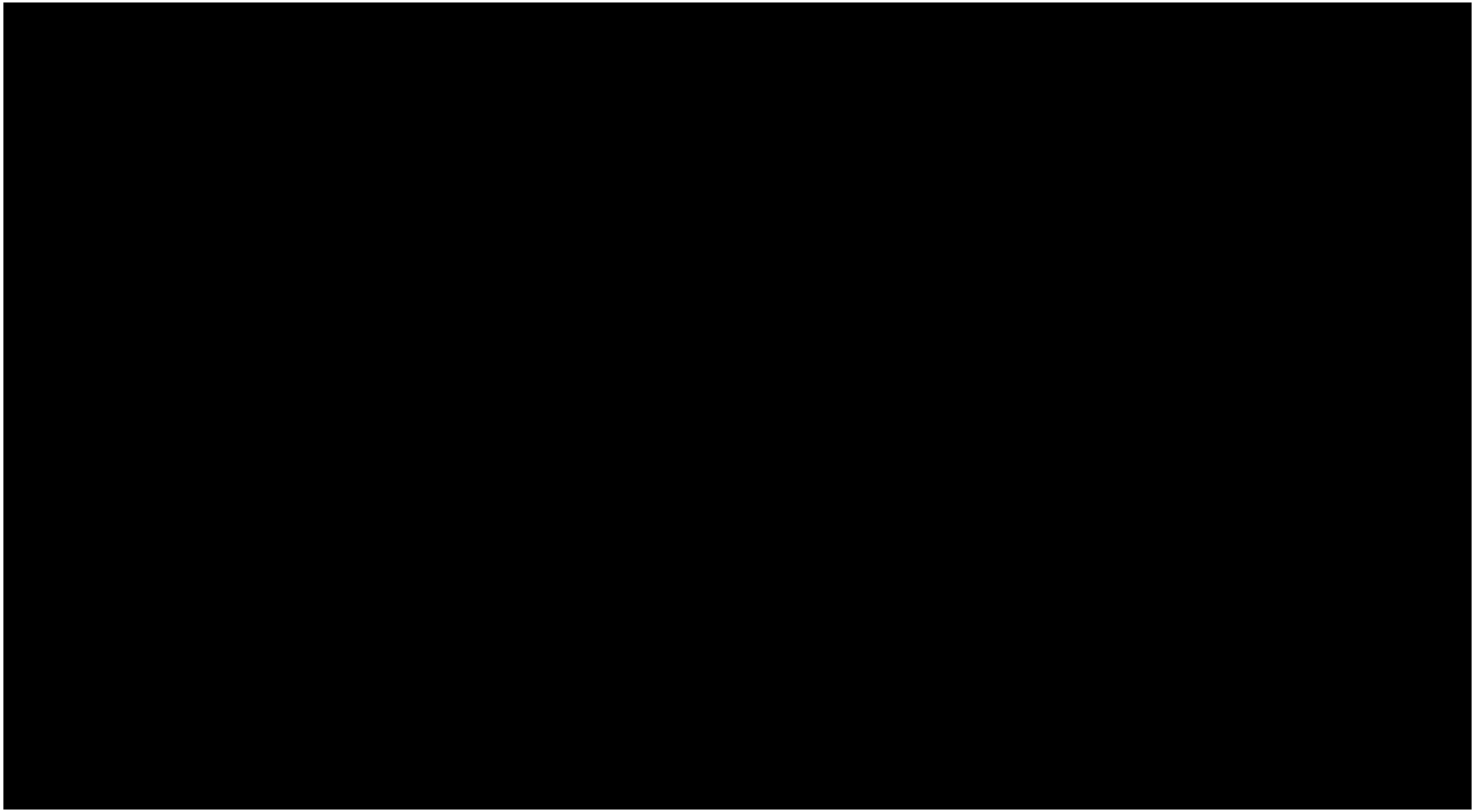
Extreme Weather 101: Drought
www.Climatecentral.org



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

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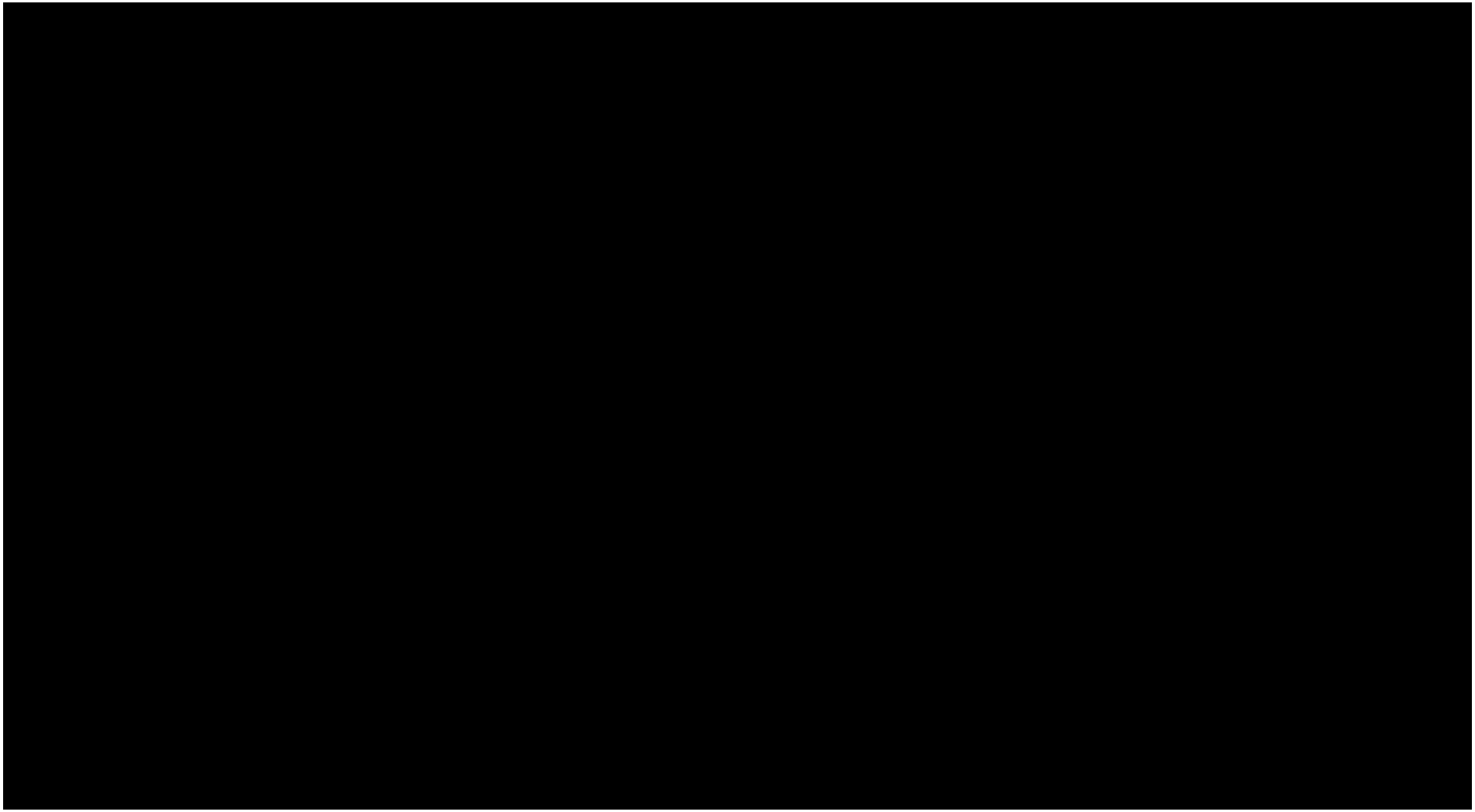

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Droughts 101, National Geographic

https://video.nationalgeographic.com/video/00000144-0a2c-d3cb-a96c-7b2d6b200000

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Droughts=disasters…

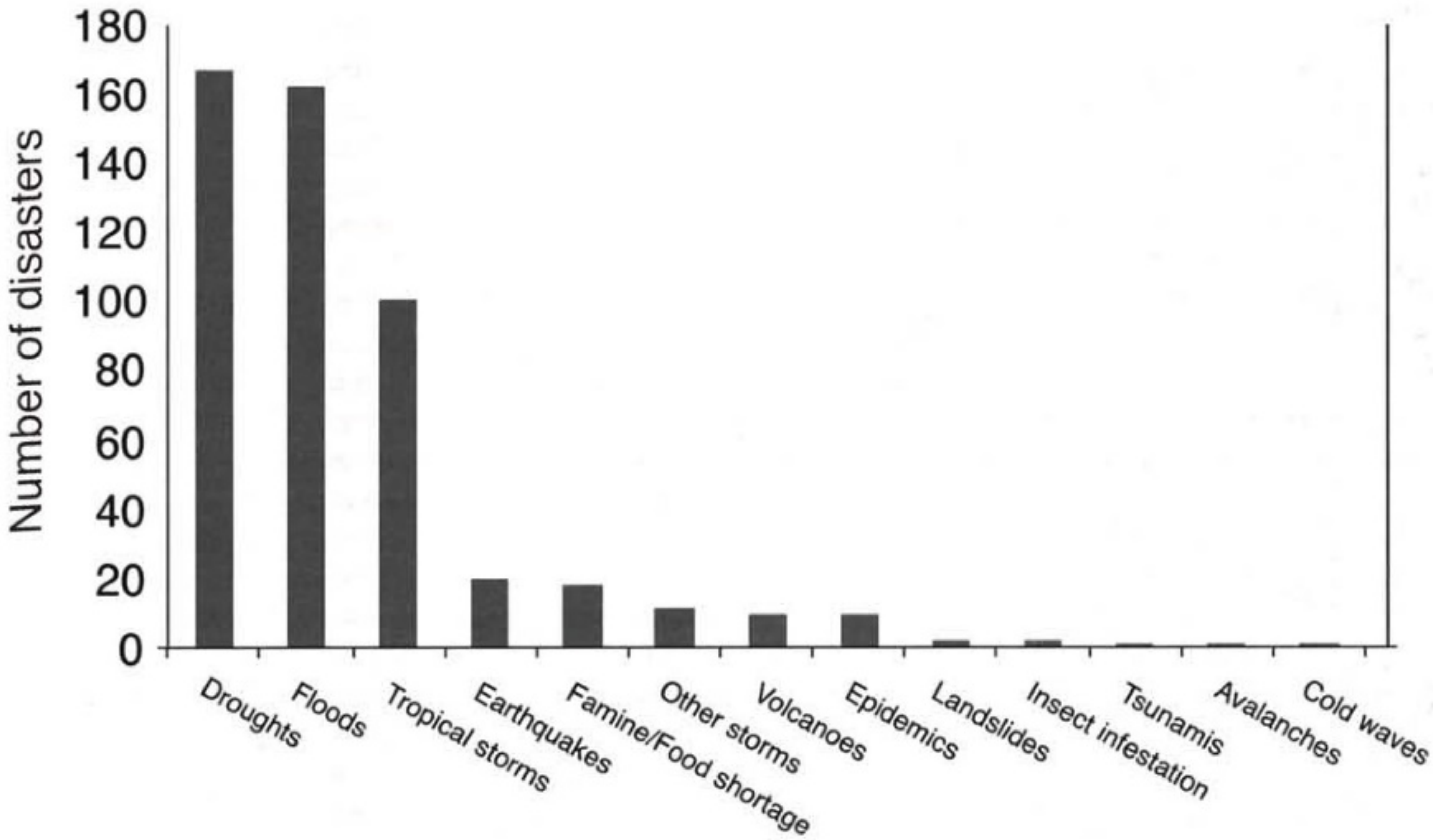

Figure 1.2. Disasters, by type, affecting 1% or more of total population, 1963–92.

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

Definitions

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

workshop #1:
past and future of Sahel & South-West US droughts

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

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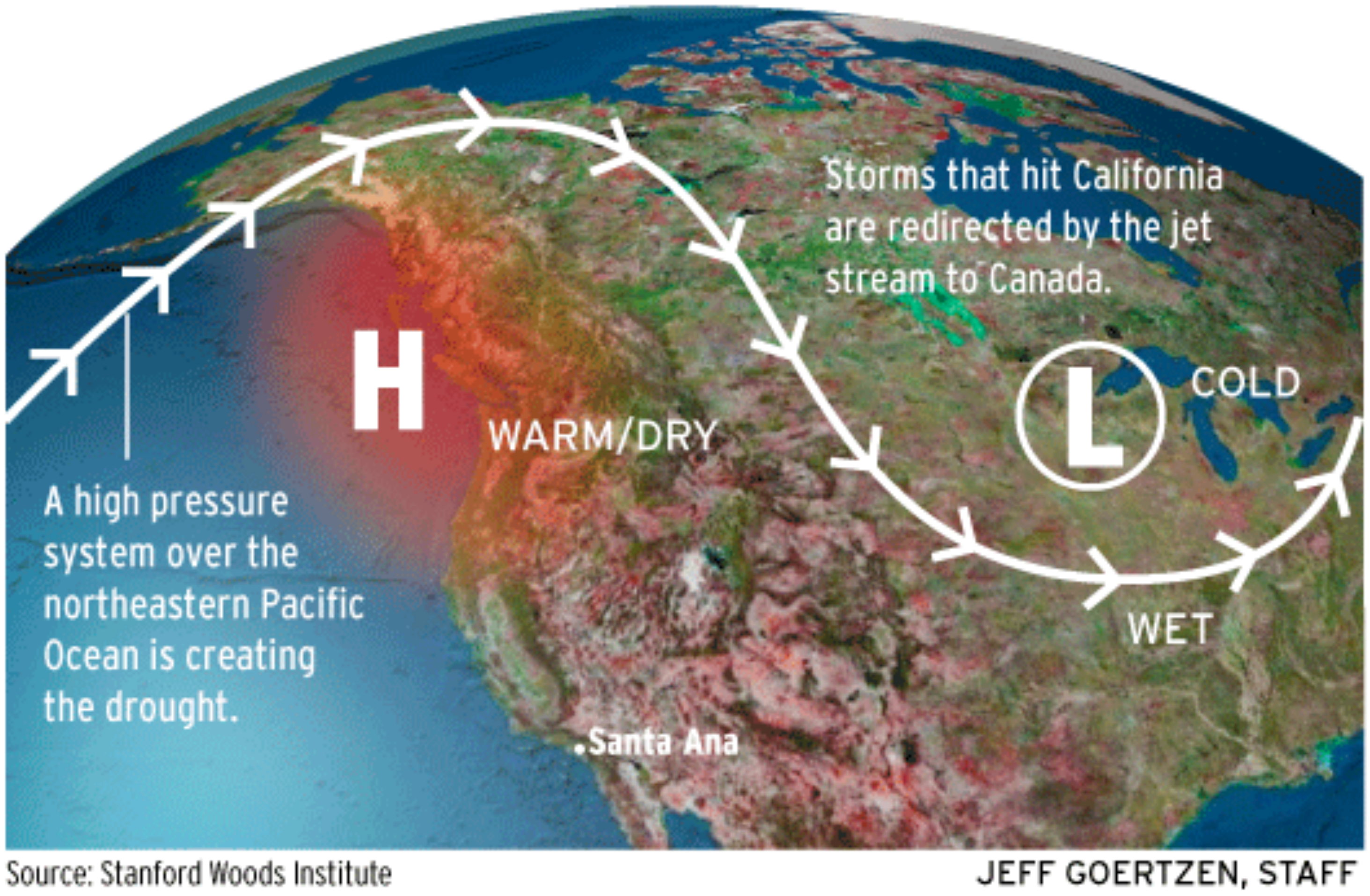
High sea level pressure: (1) diverts rain storms
(2) causes subsidence and therefore drying



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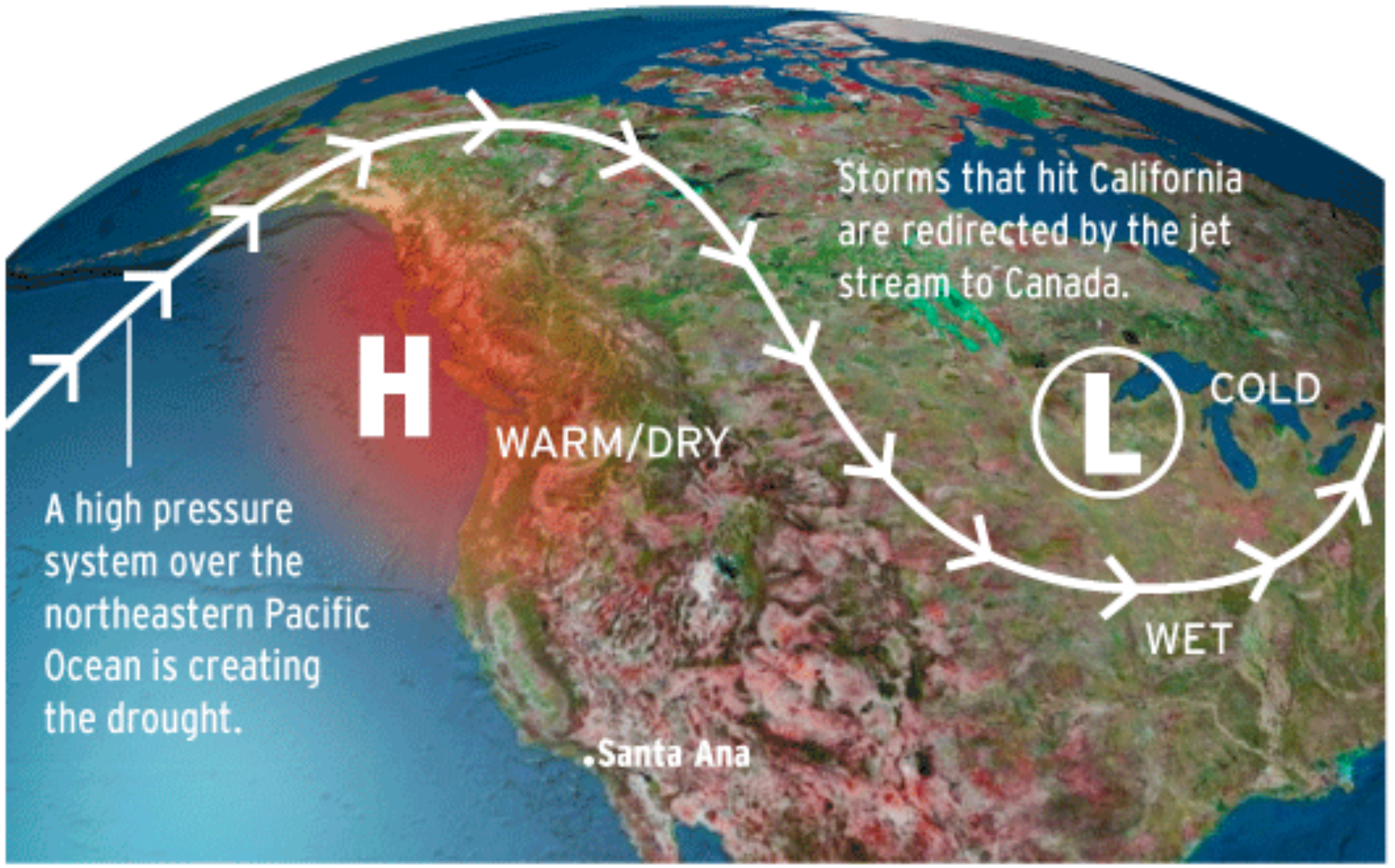
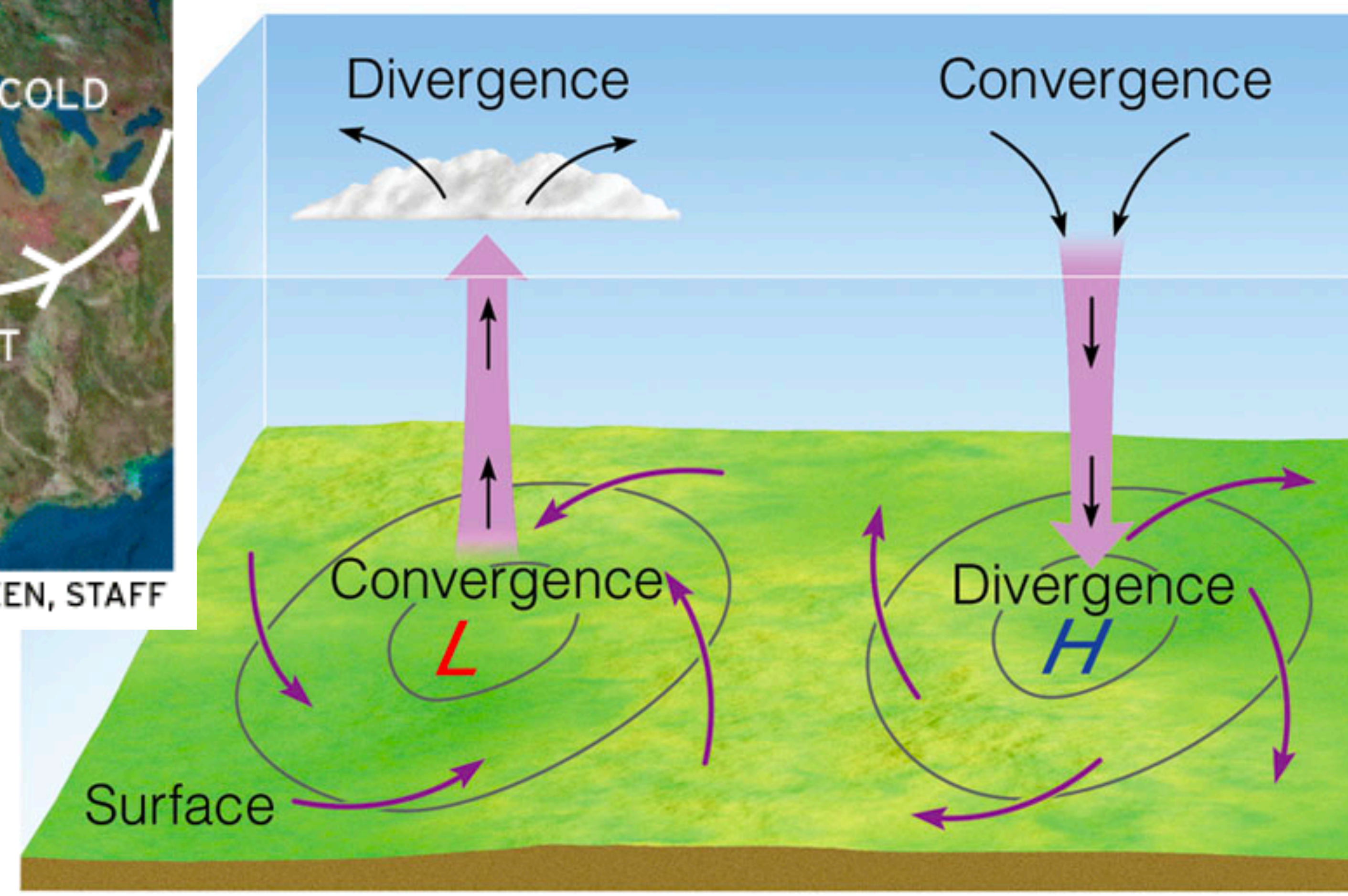


Source: Stanford Woods Institute JEFF GOERTZEN, STAFF

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



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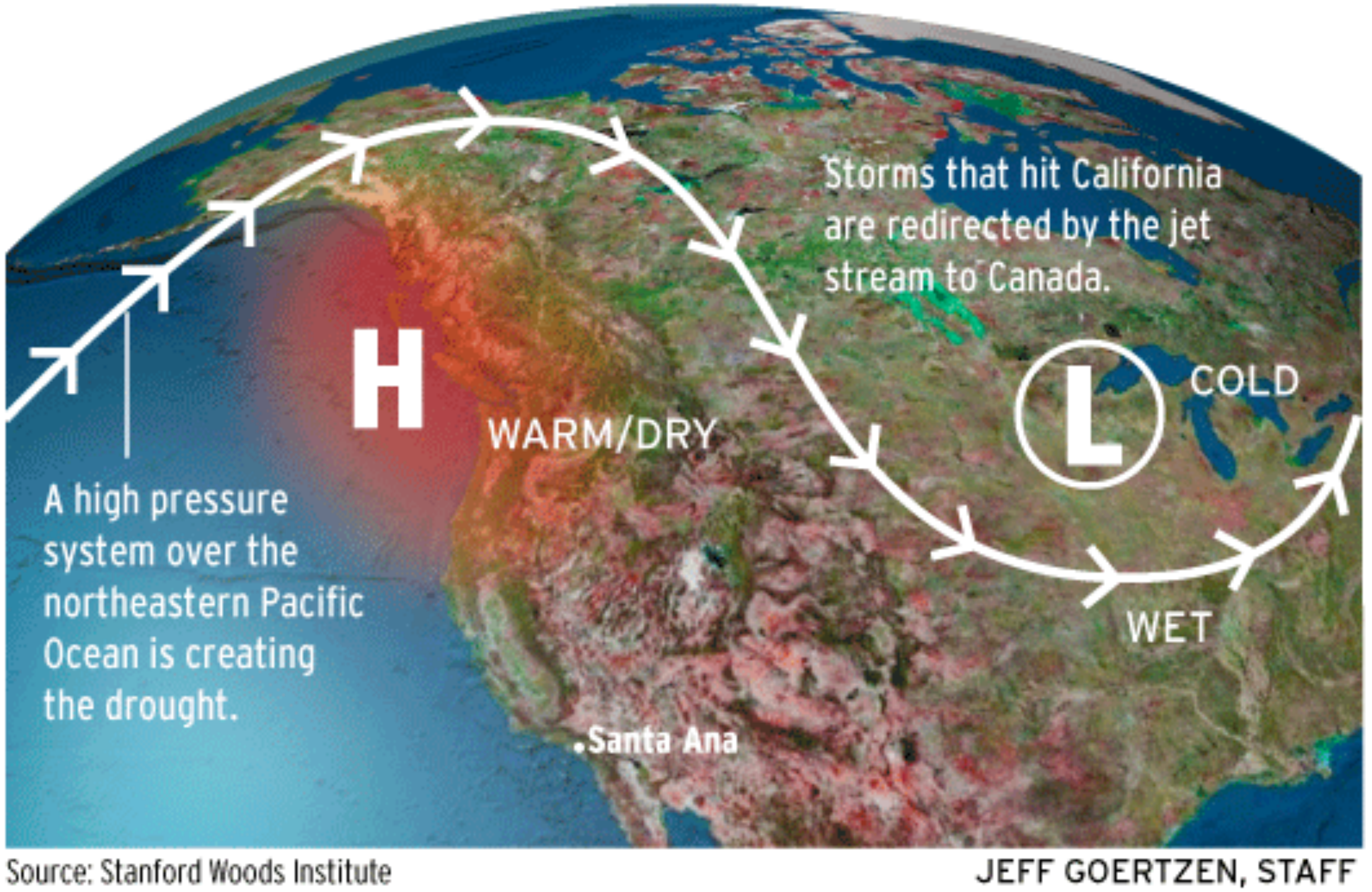

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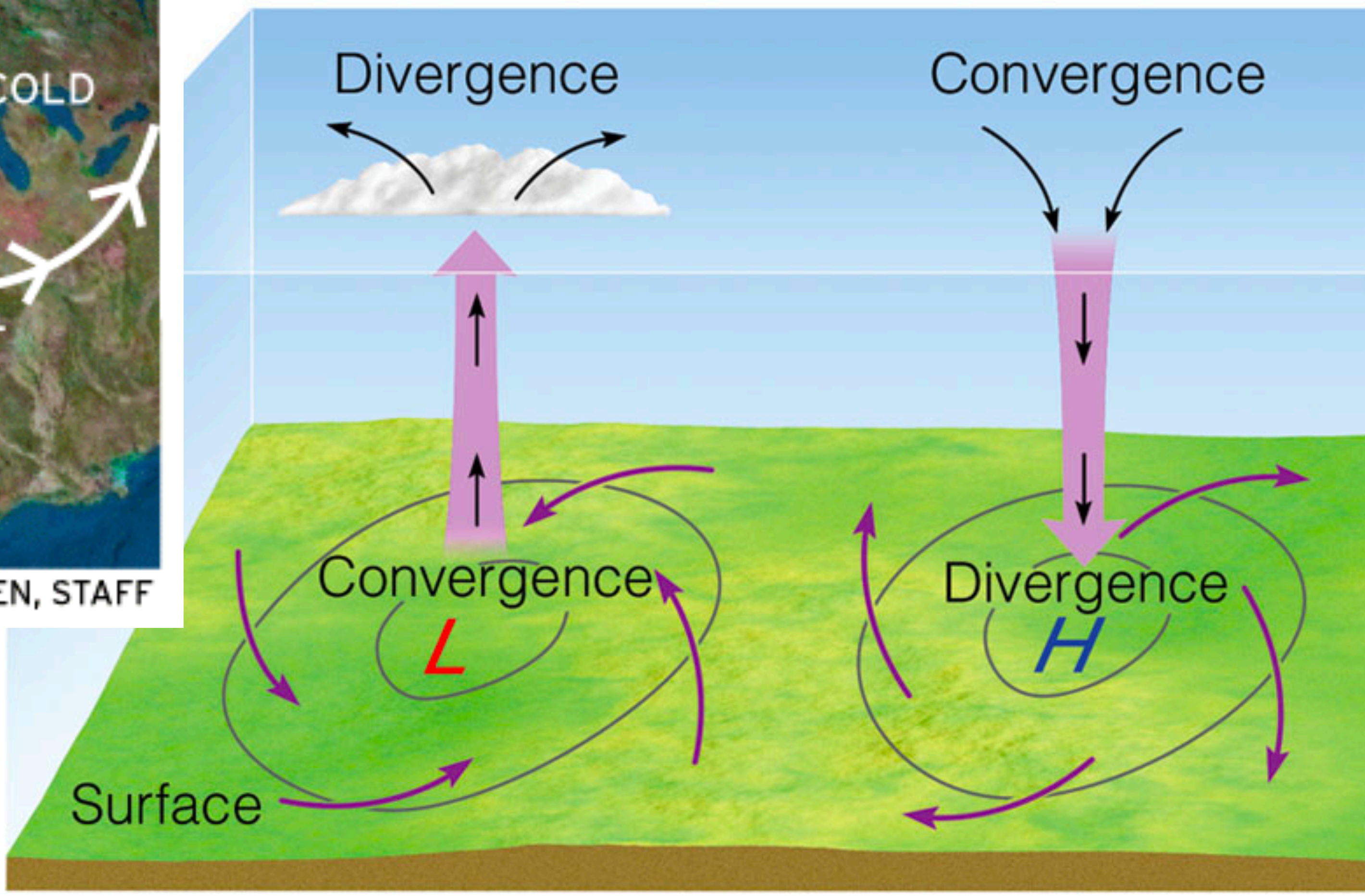


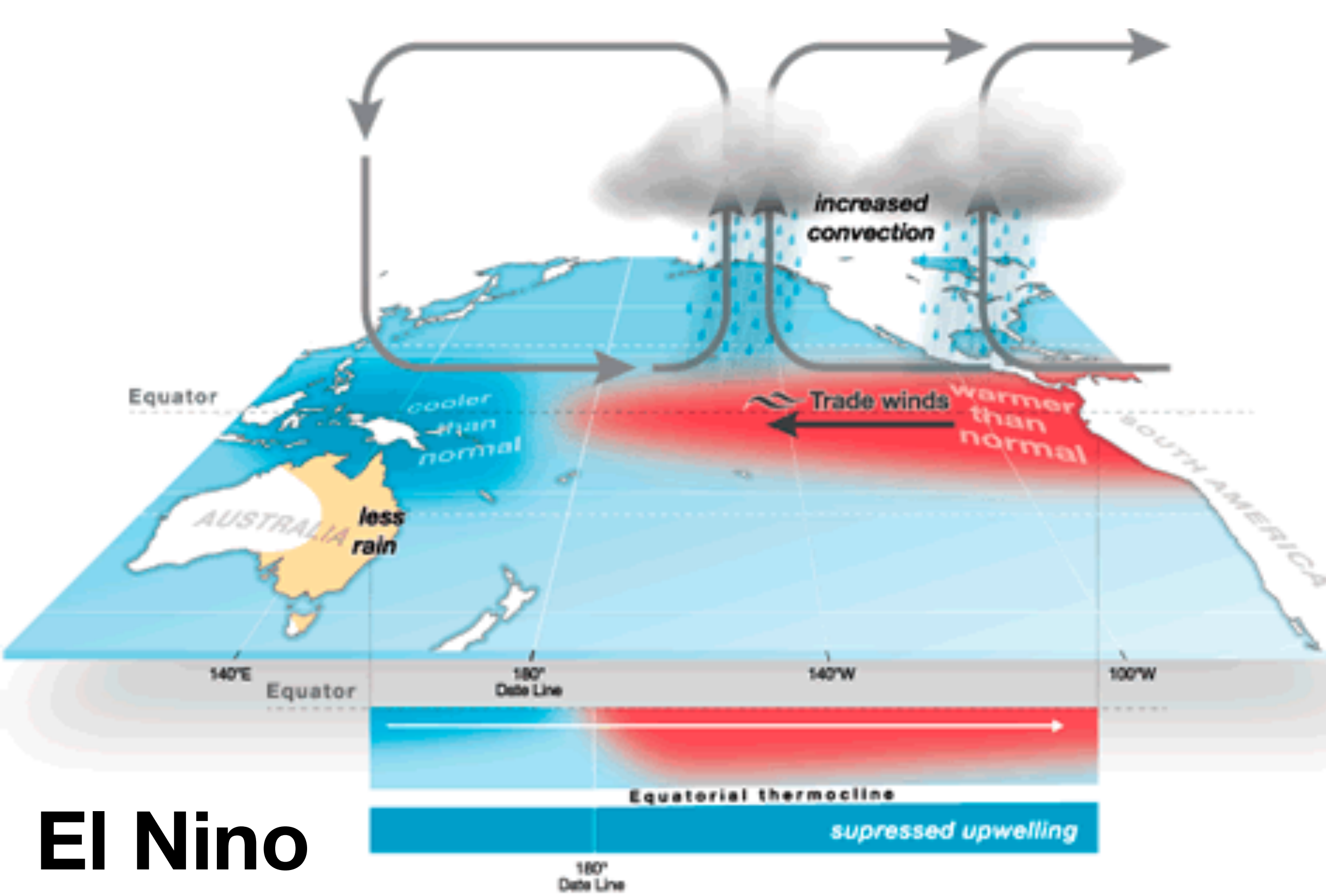
Cause of high pressure? Sea surface temperature anomalies

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

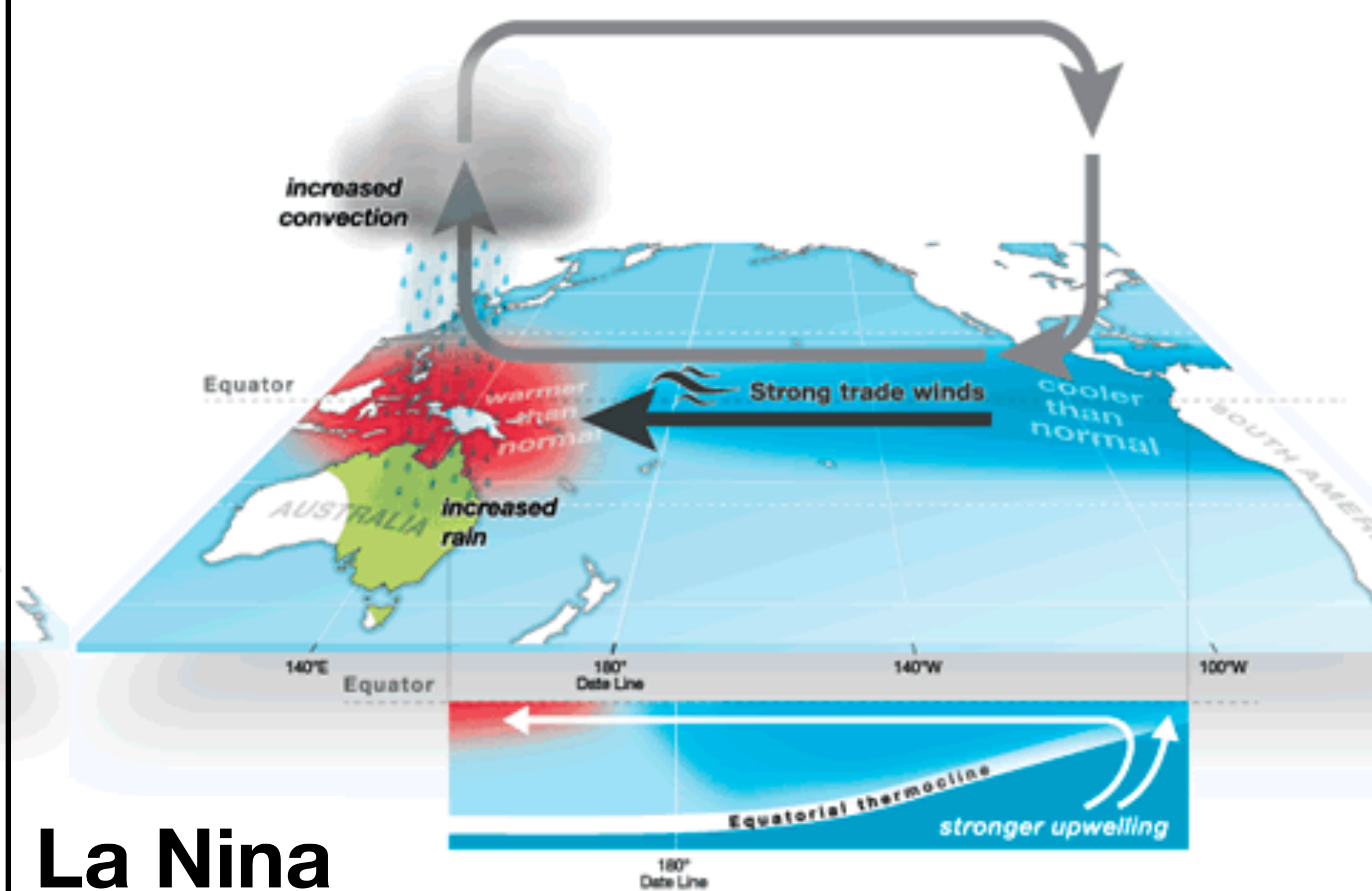
Three examples of processes that lead to sea surface temperature anomalies, leading to drought-causing high pressure signals:

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

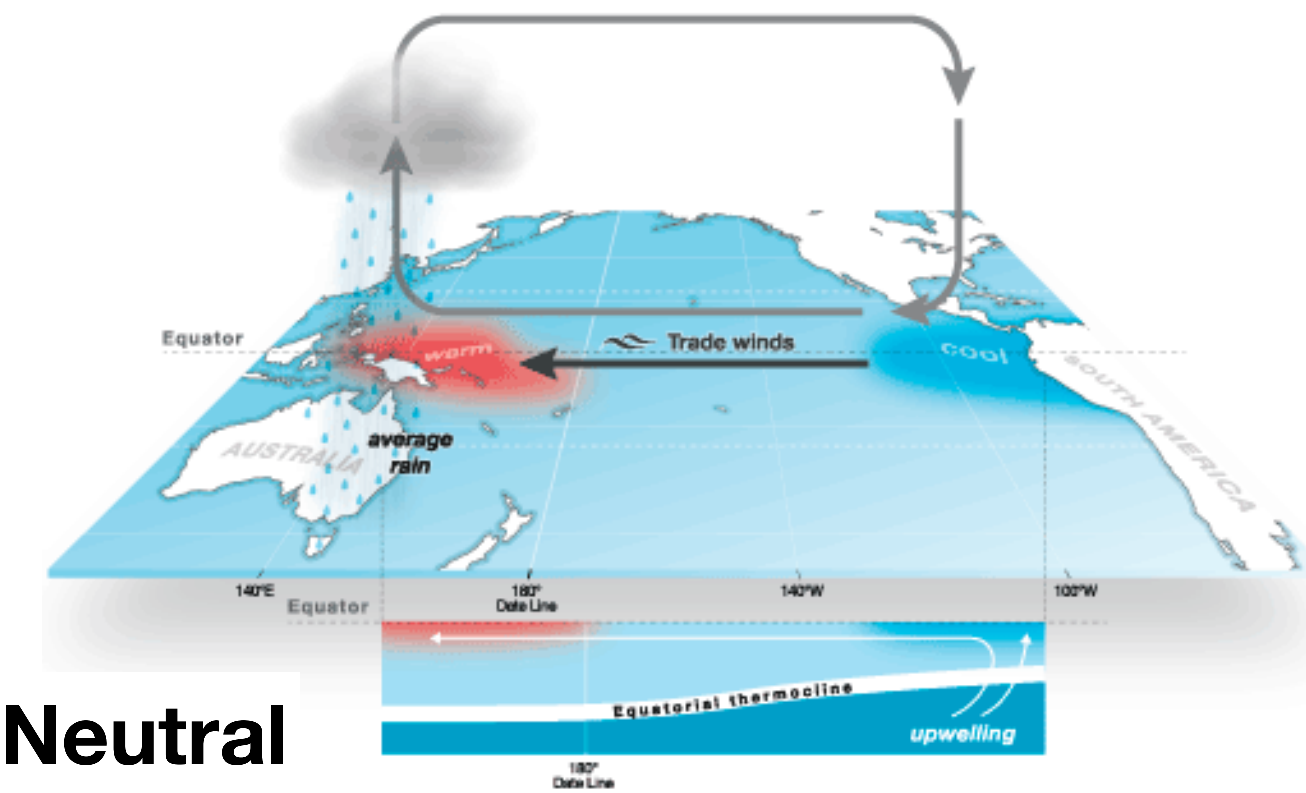
El Nino - Southern Oscillation (ENSO)



El Nino



La Nina



Neutral

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

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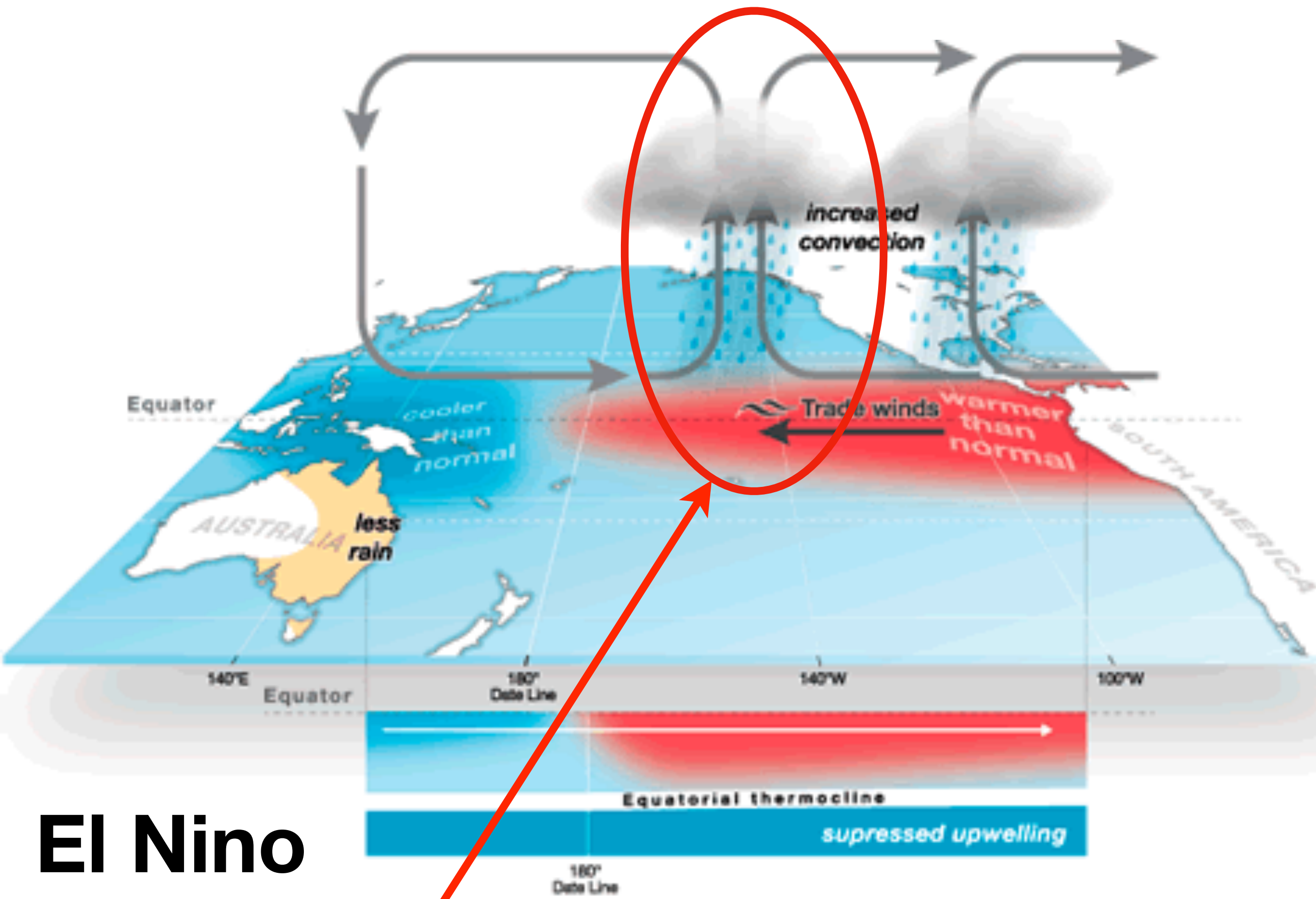
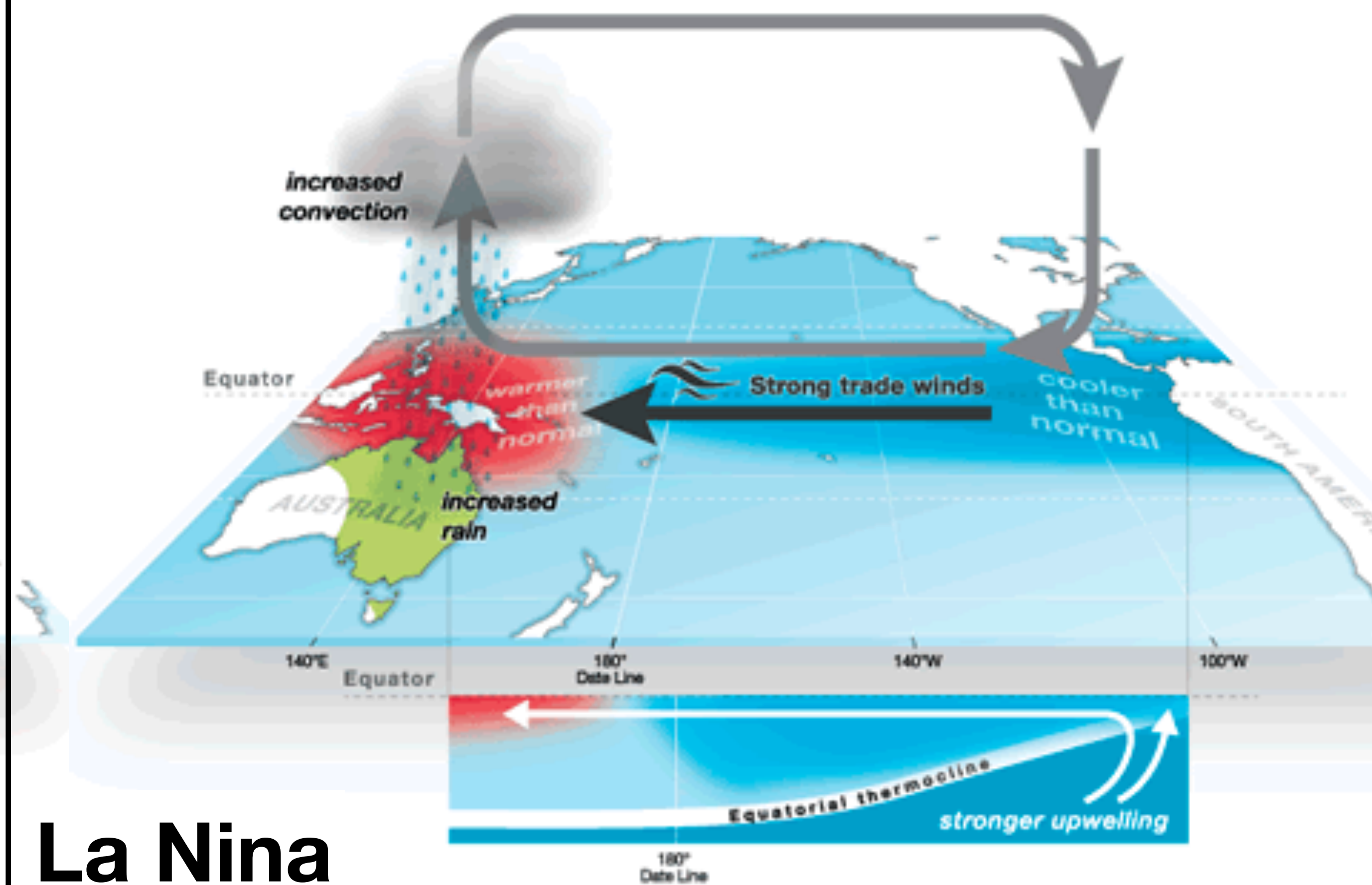
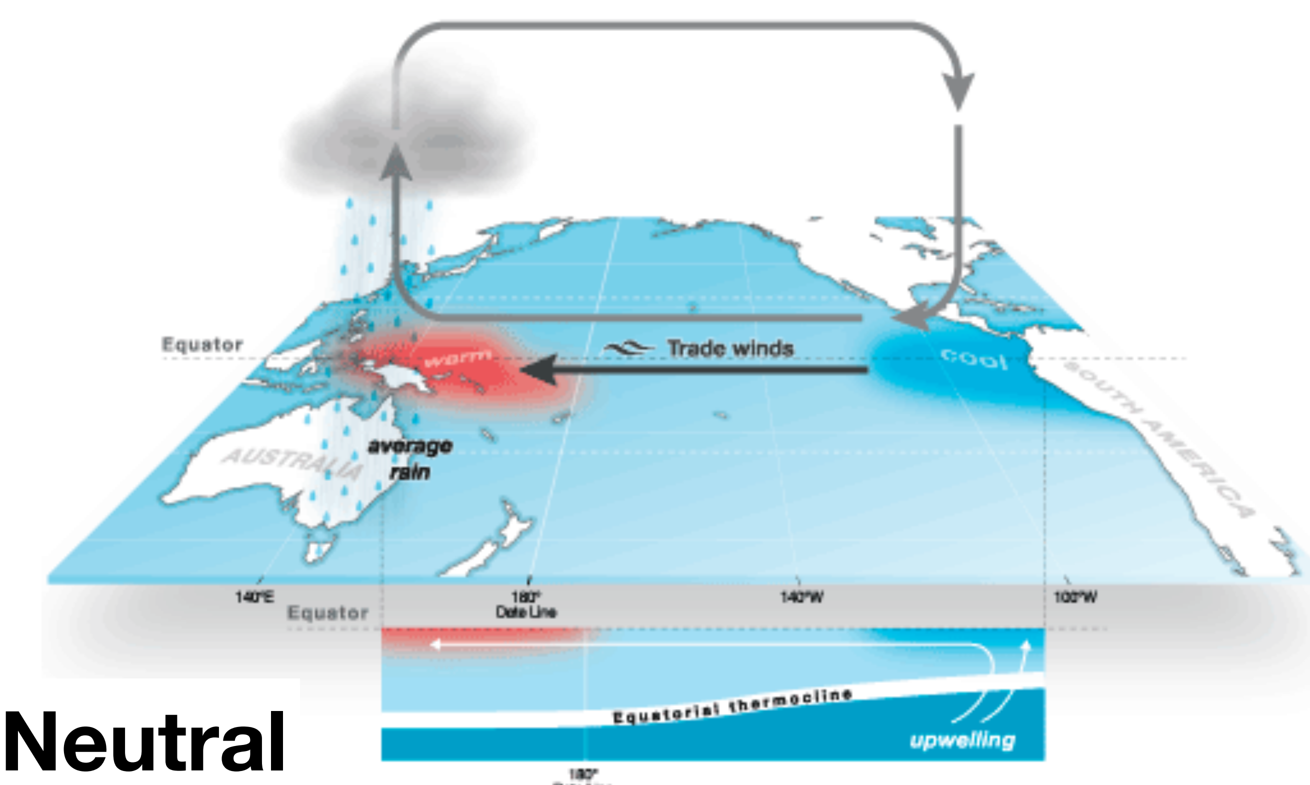


El Nino



La Nina

precipitation and atmospheric heating which forces atmospheric waves



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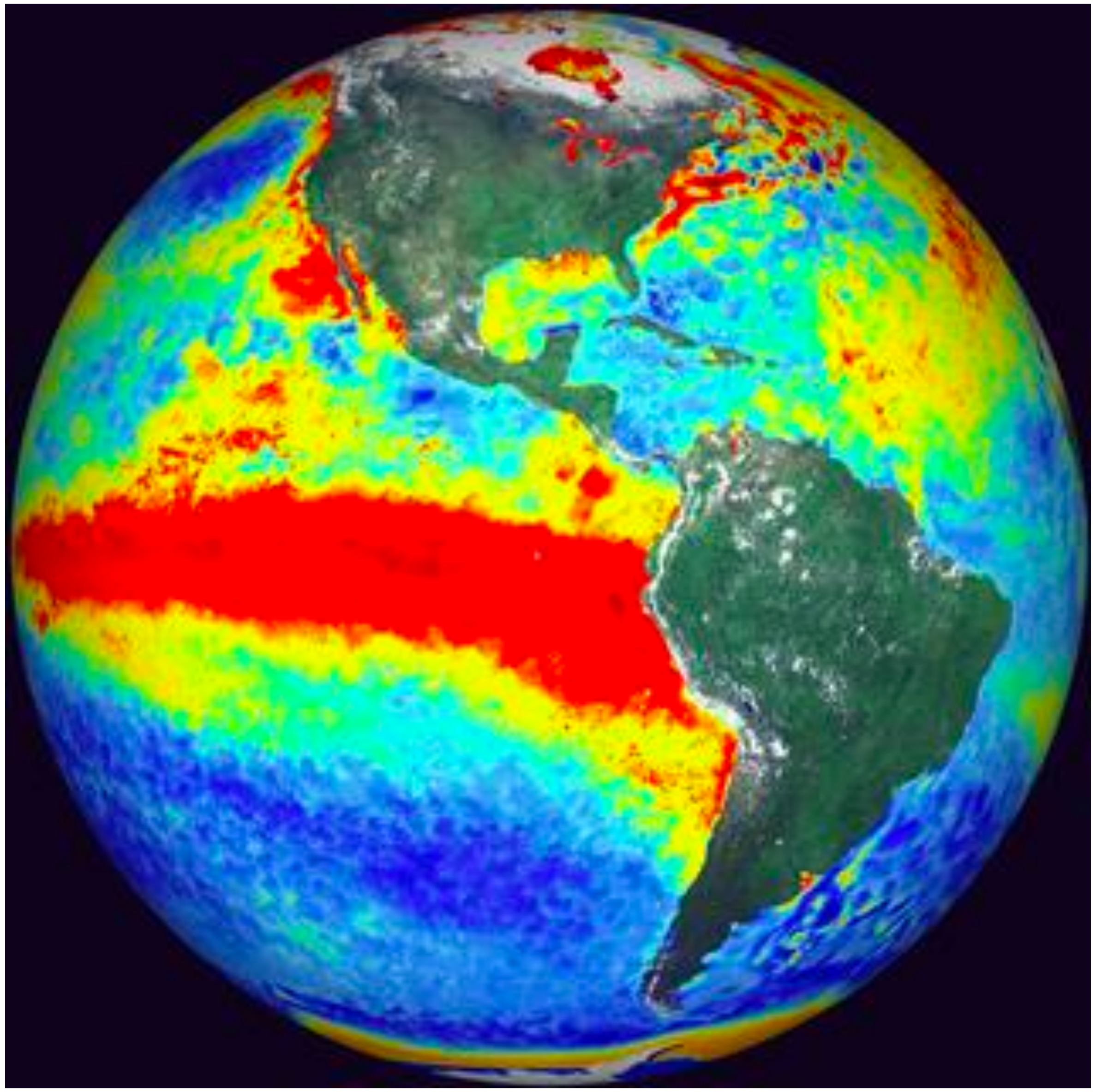
Atmospheric teleconnections: **Rossby wave** train forced by ENSO



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

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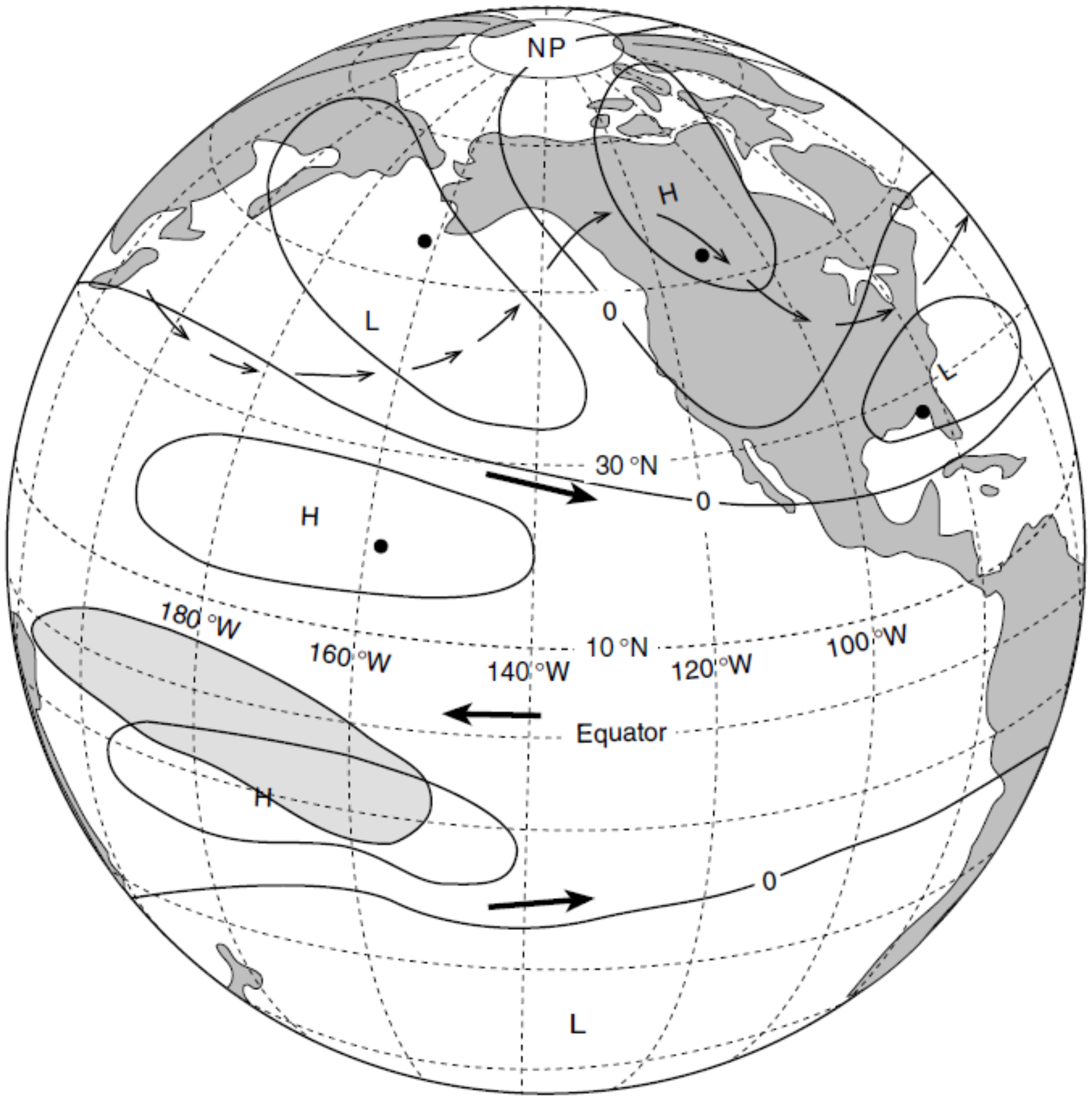
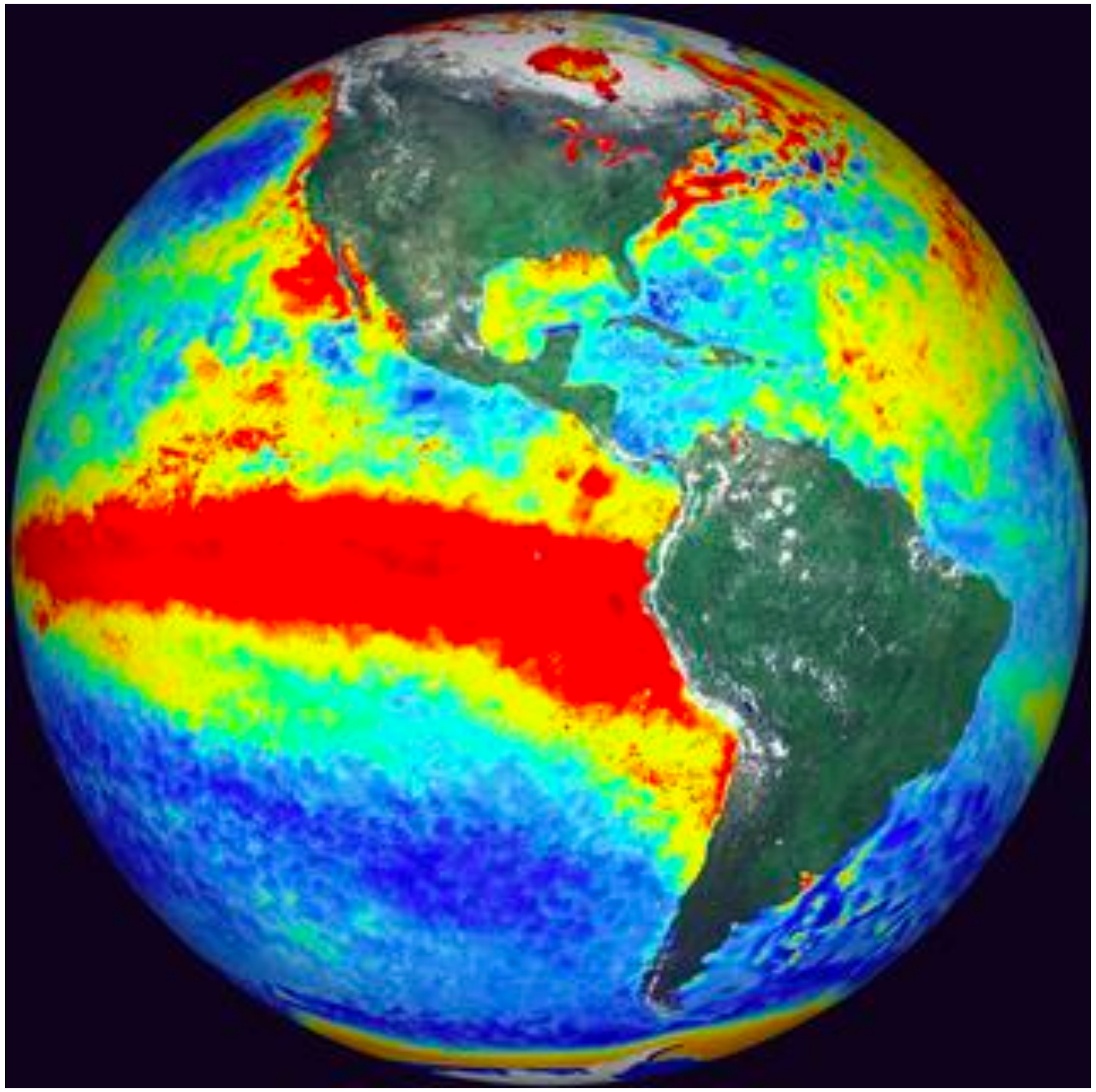


solid contours: schematic upper atmosphere geopotential height anomaly; shaded area at equator: enhanced cloudiness and rain. Light arrows: mid-tropospheric stream line distorted by wave pattern. (Horel & Wallace 1981)



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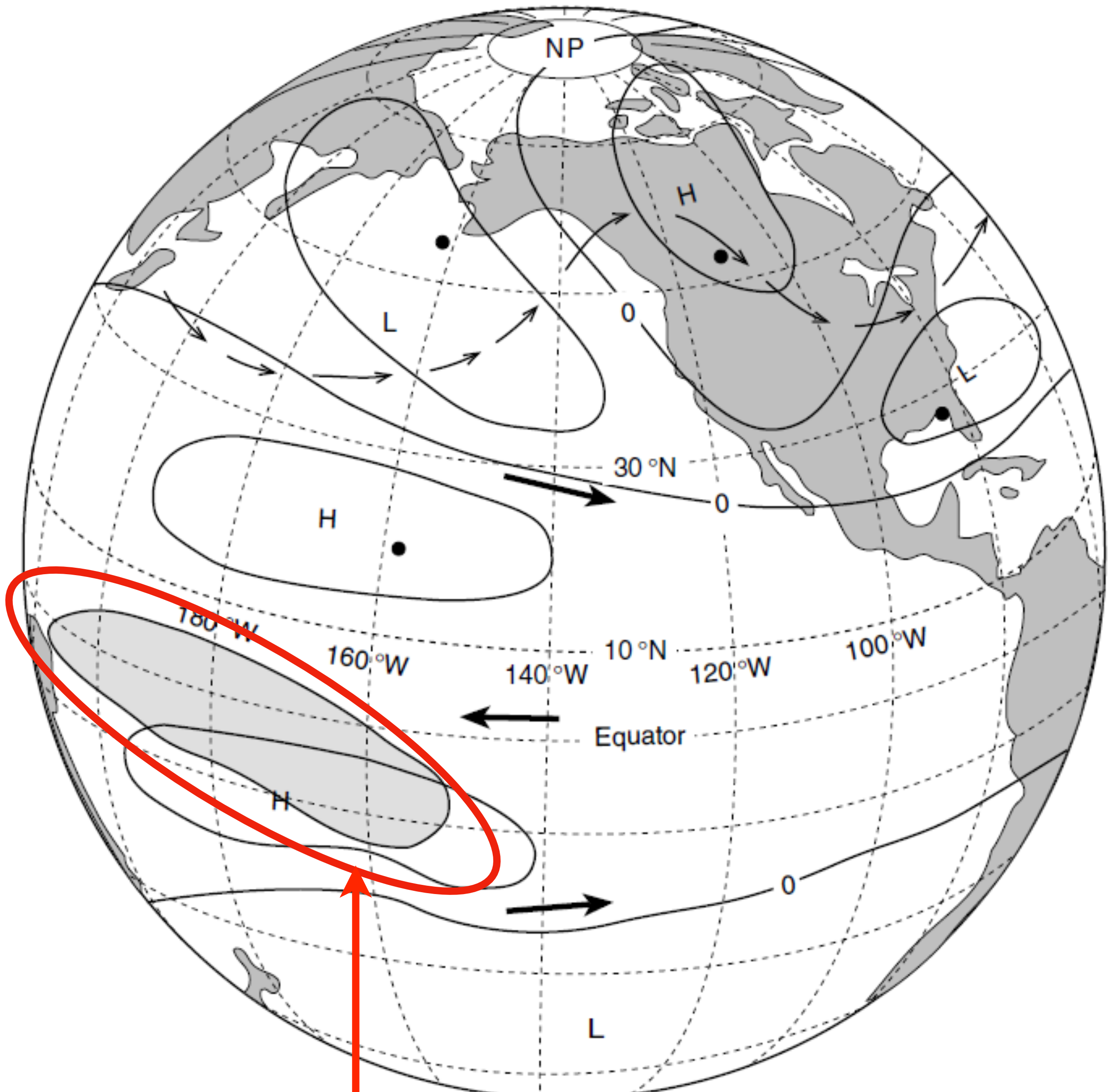

precipitation and atmospheric heating due to El Nino, which forces atmospheric waves

solid conto
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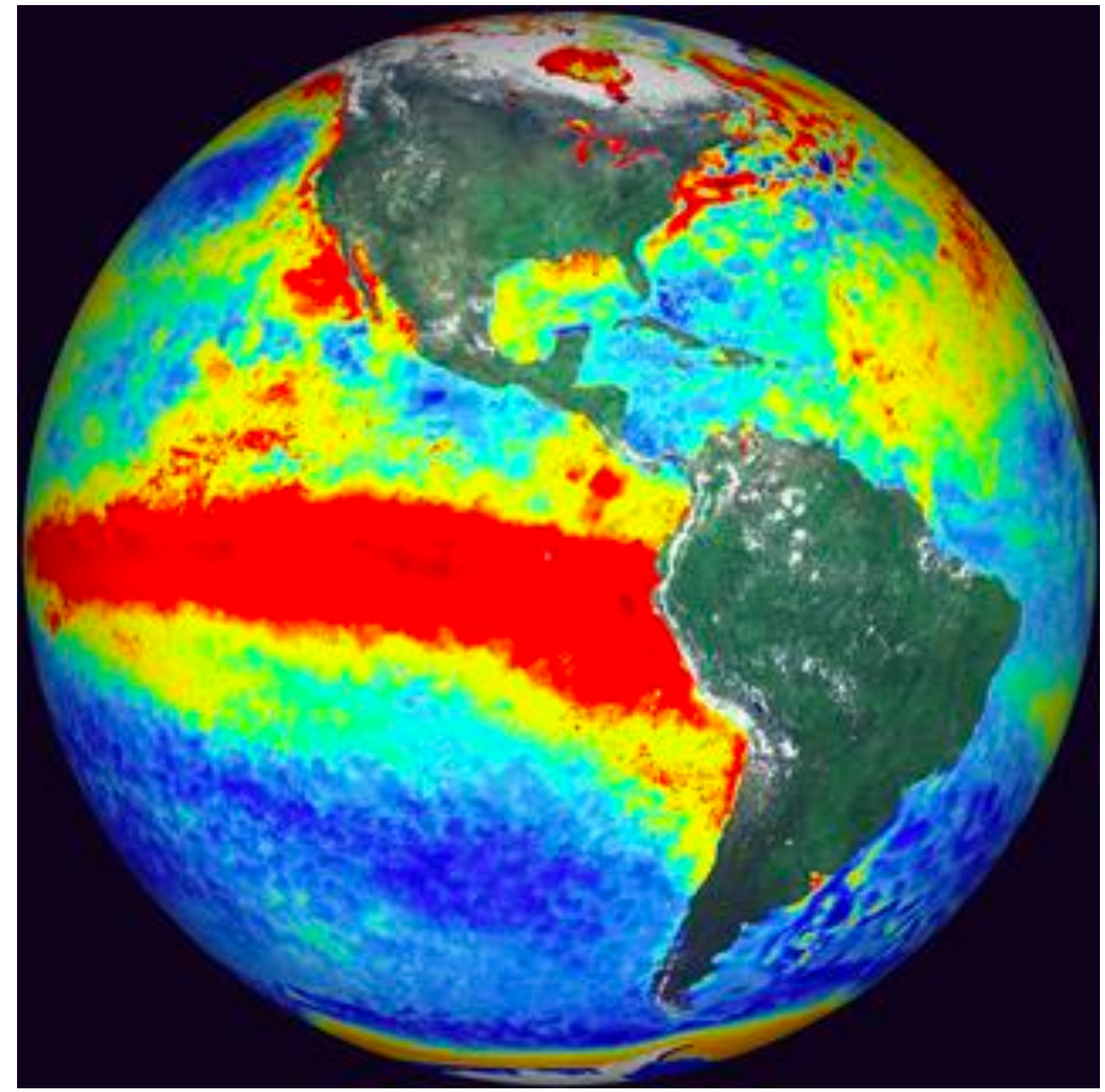

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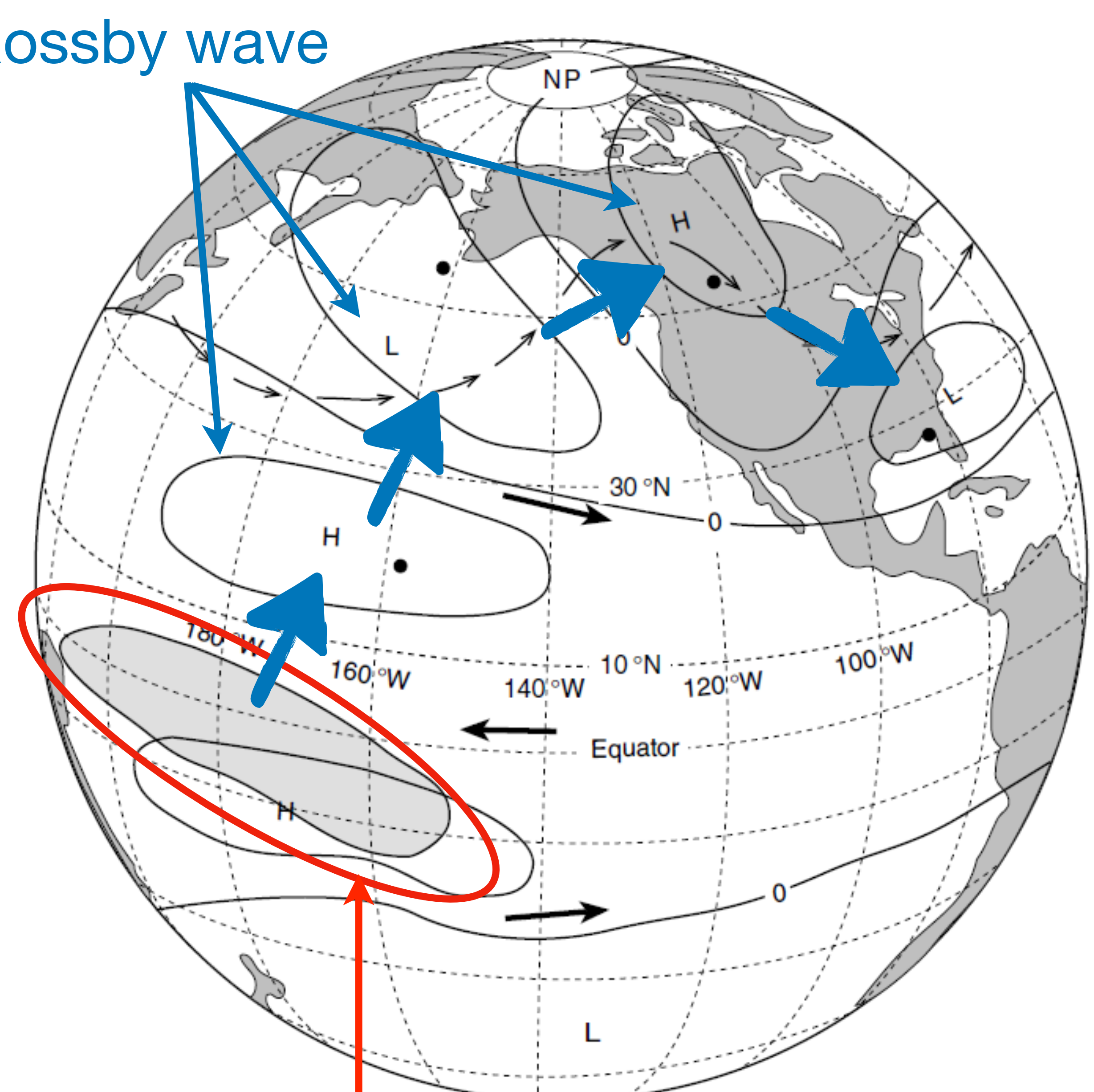

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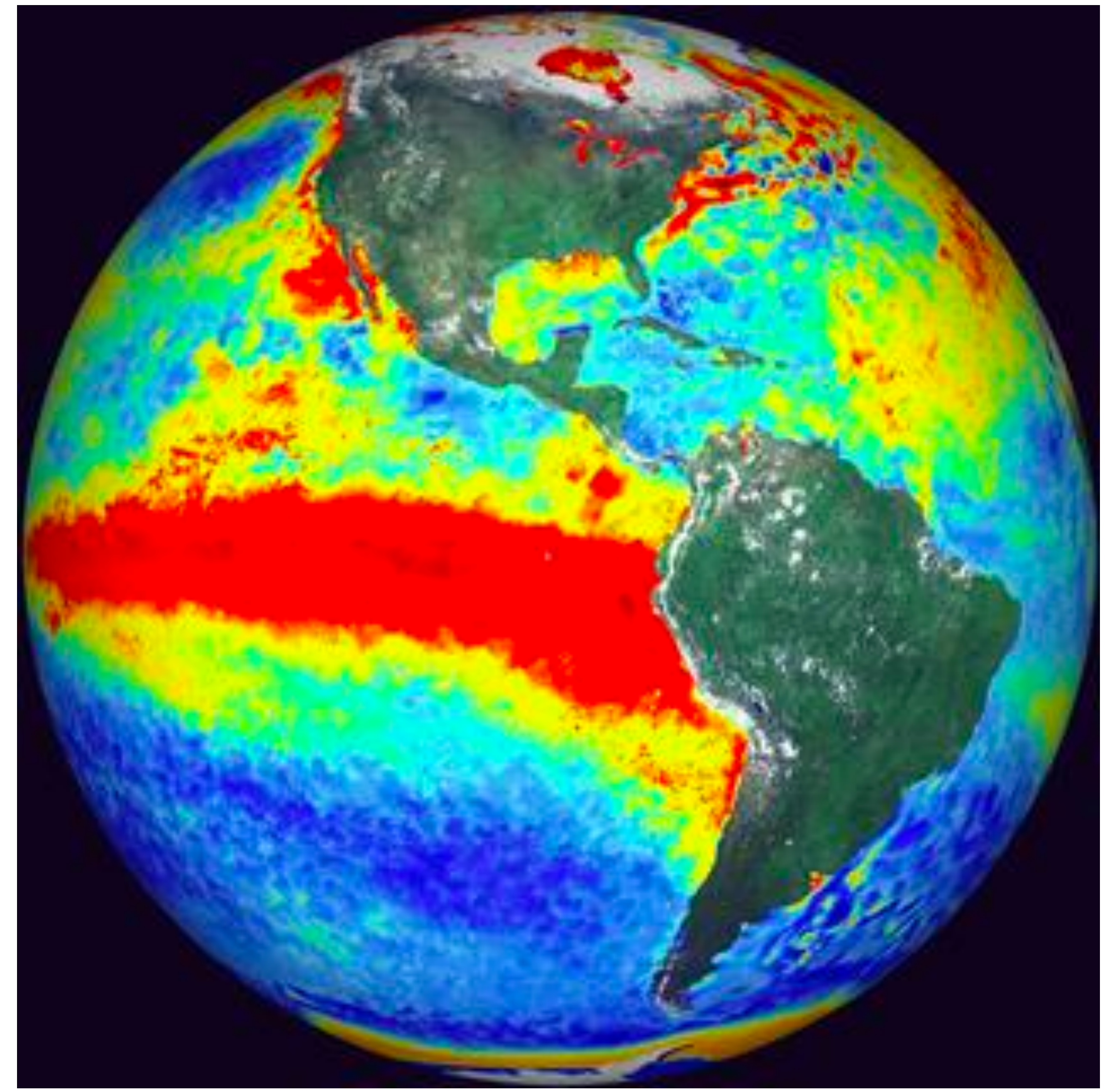

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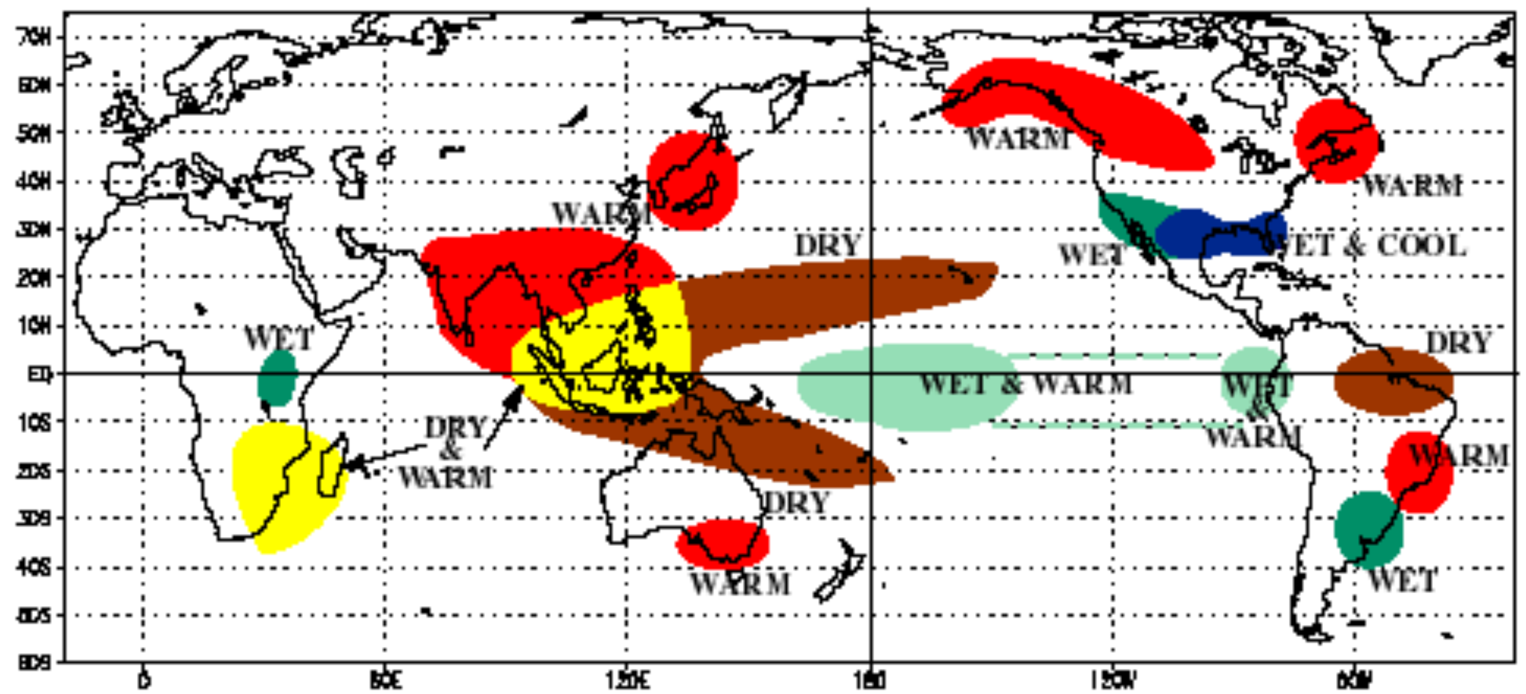
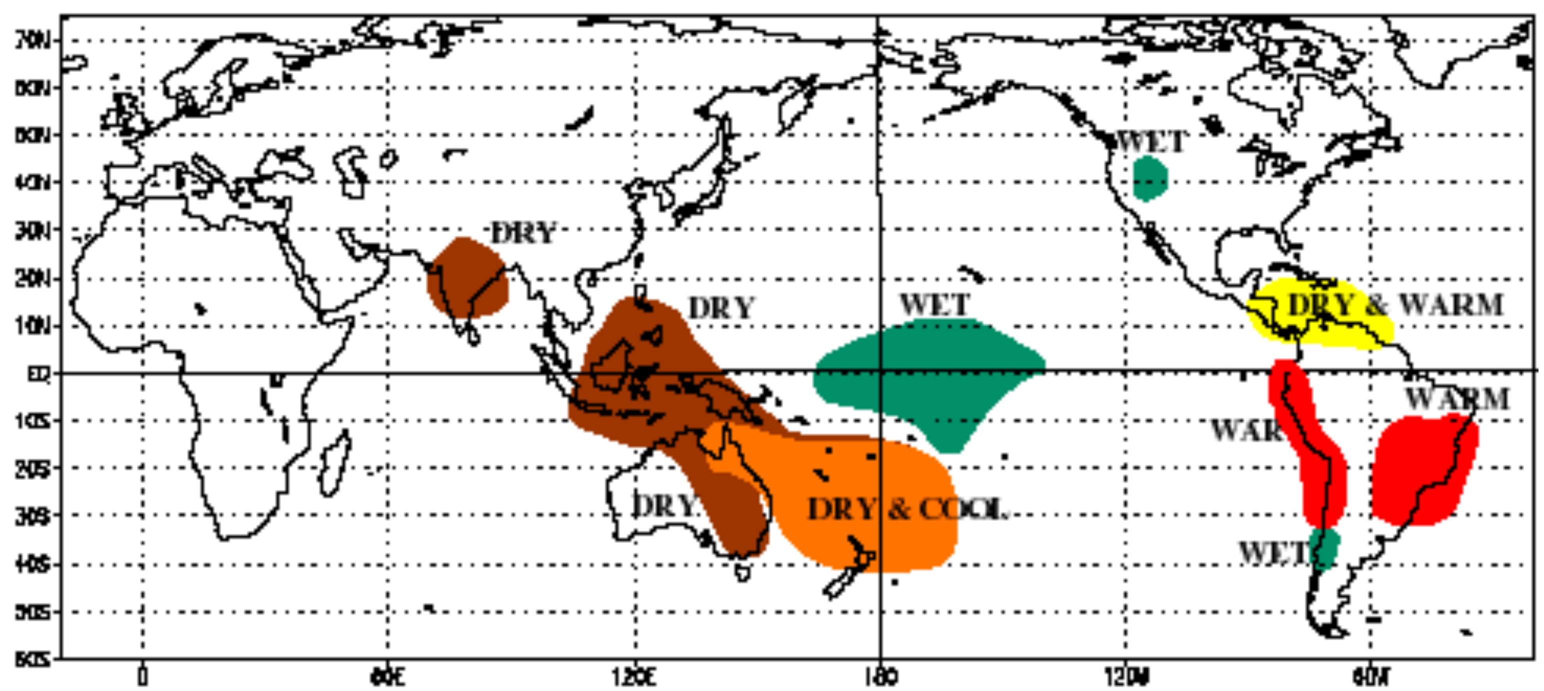
El Nino - Southern Oscillation (ENSO) teleconnections: **El Nino**

WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



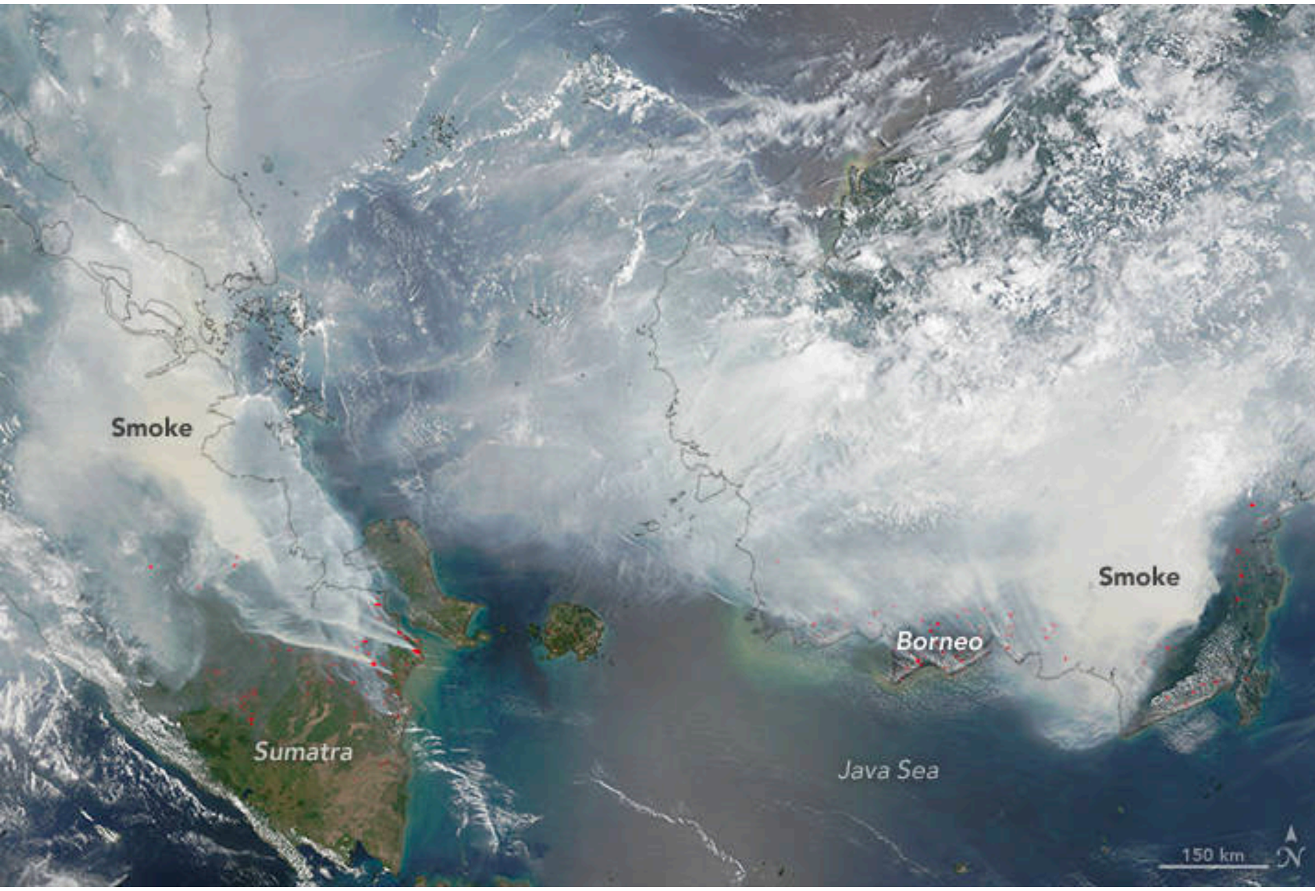
WARM EPISODE RELATIONSHIPS JUNE - AUGUST



Regional impacts of warm ENSO episodes (El Niño)

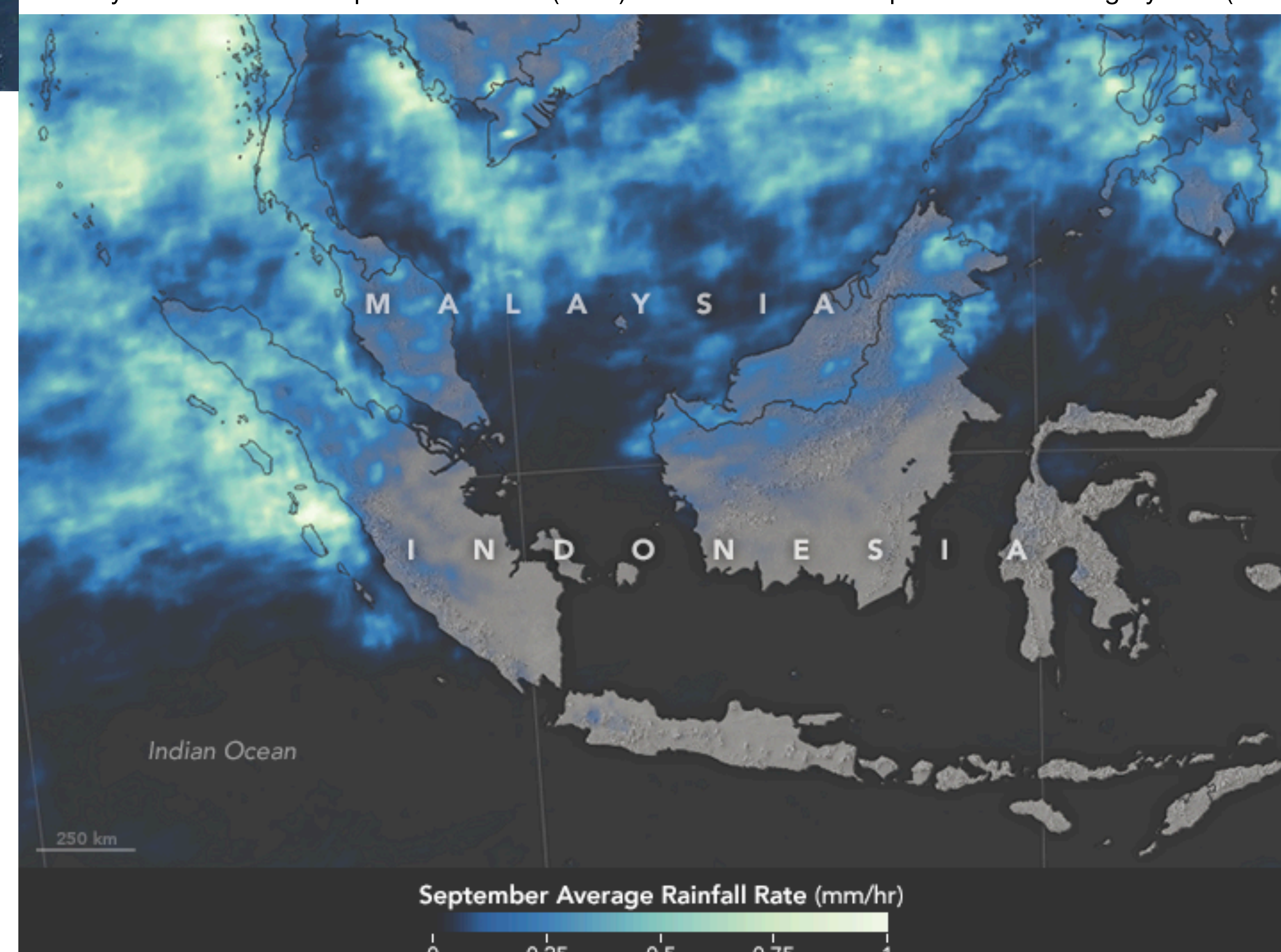
https://en.wikipedia.org/v

“El Niño Brought Drought and Fire to Indonesia” 2005, NASA



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

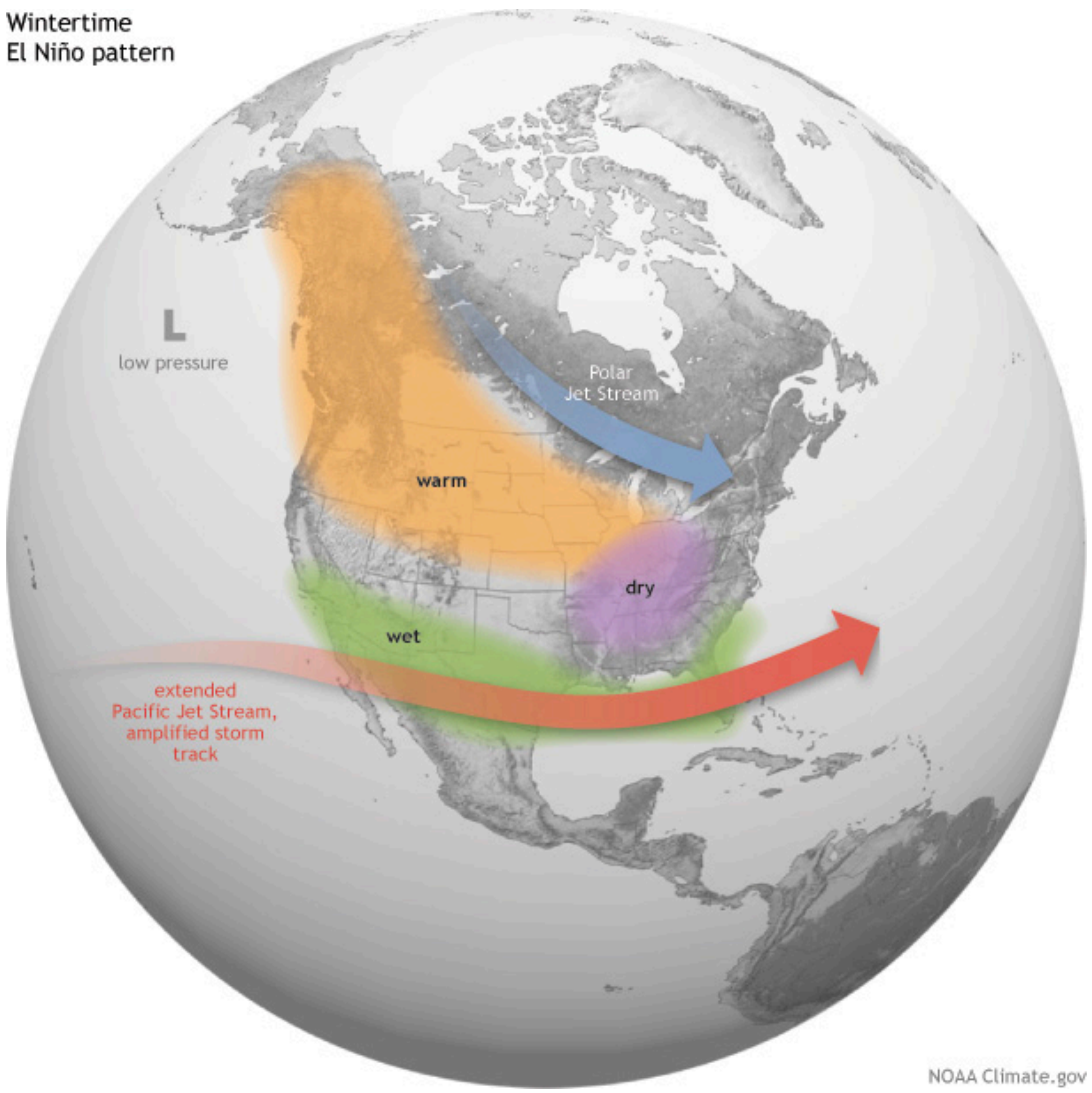
NASA Earth Observatory map (top) by Joshua Stevens and Jesse Allen, using IMERG data provided courtesy of the Global Precipitation Mission (GPM) Science Team’s Precipitation Processing System (PPS).



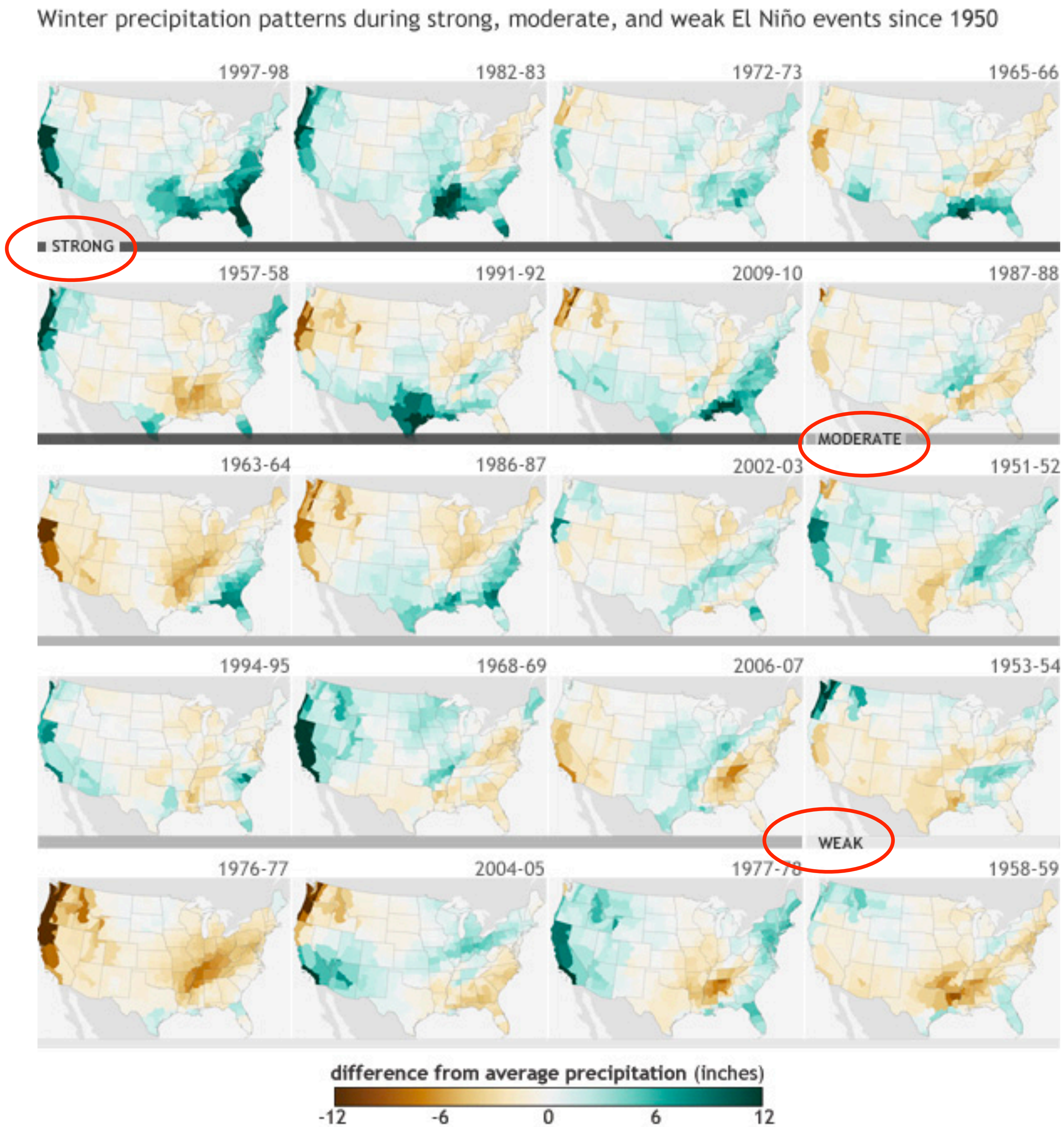
“One of the most predictable consequences of a strong El Niño is a change in rainfall patterns over Indonesia. During El Niño years, rain that is normally centered over Indonesia and the far western Pacific shifts eastward into the central Pacific; as a result, parts of Indonesia experience drought.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



Map by Fiona Martin for NOAA Climate.gov.



https://www.climate.gov/news-features/blogs/enso/united-states-el-ni%C3%B1o-impacts-0

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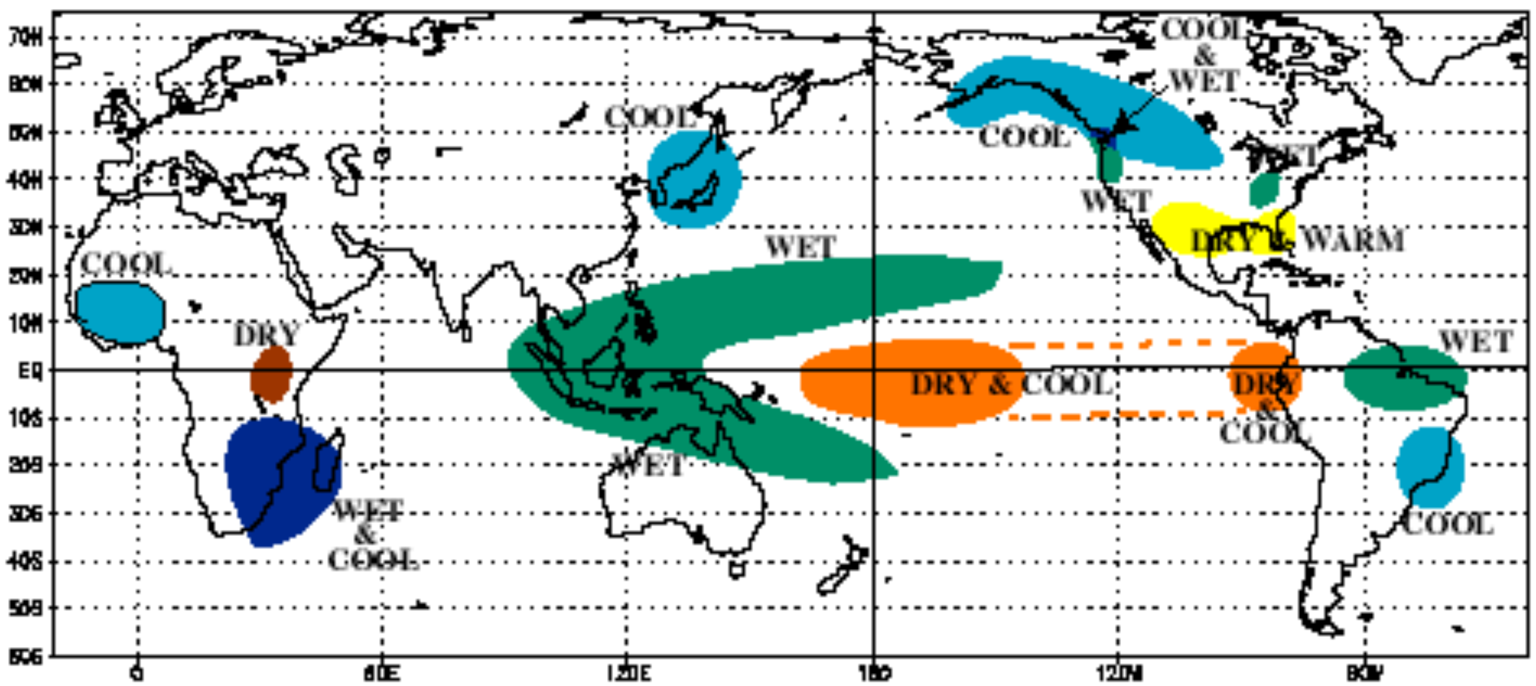
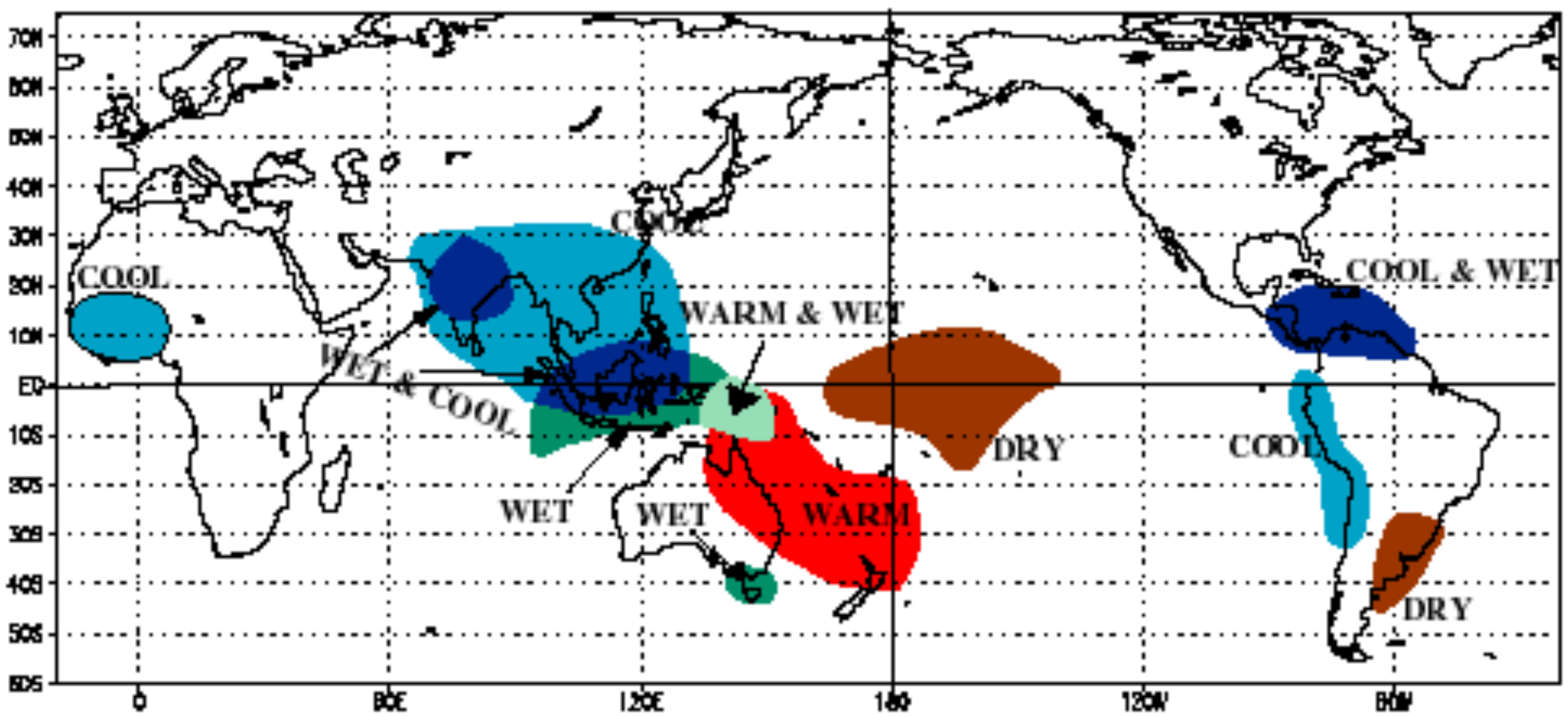
COLD EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



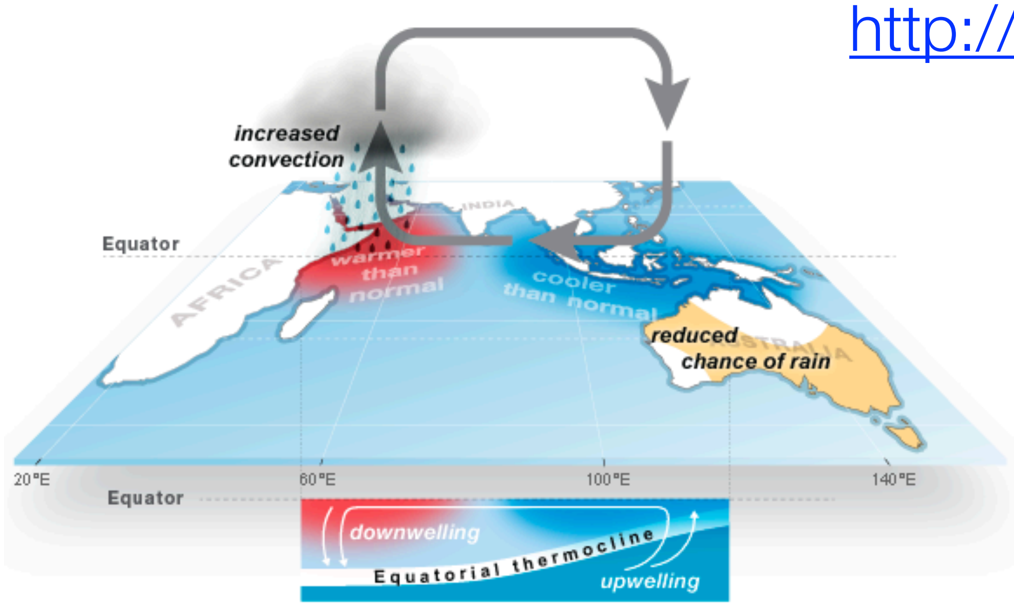
COLD EPISODE RELATIONSHIPS JUNE - AUGUST



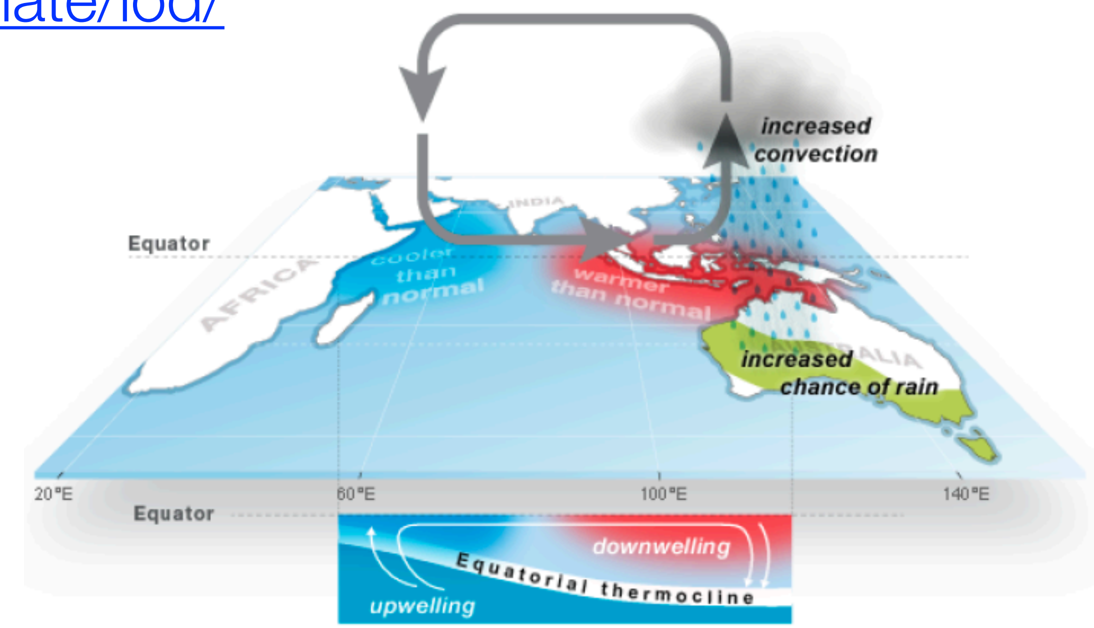
https://commons.wikimedia.org/wiki/File:La_Nina_regional_impacts.gif

Indian Ocean Dipole

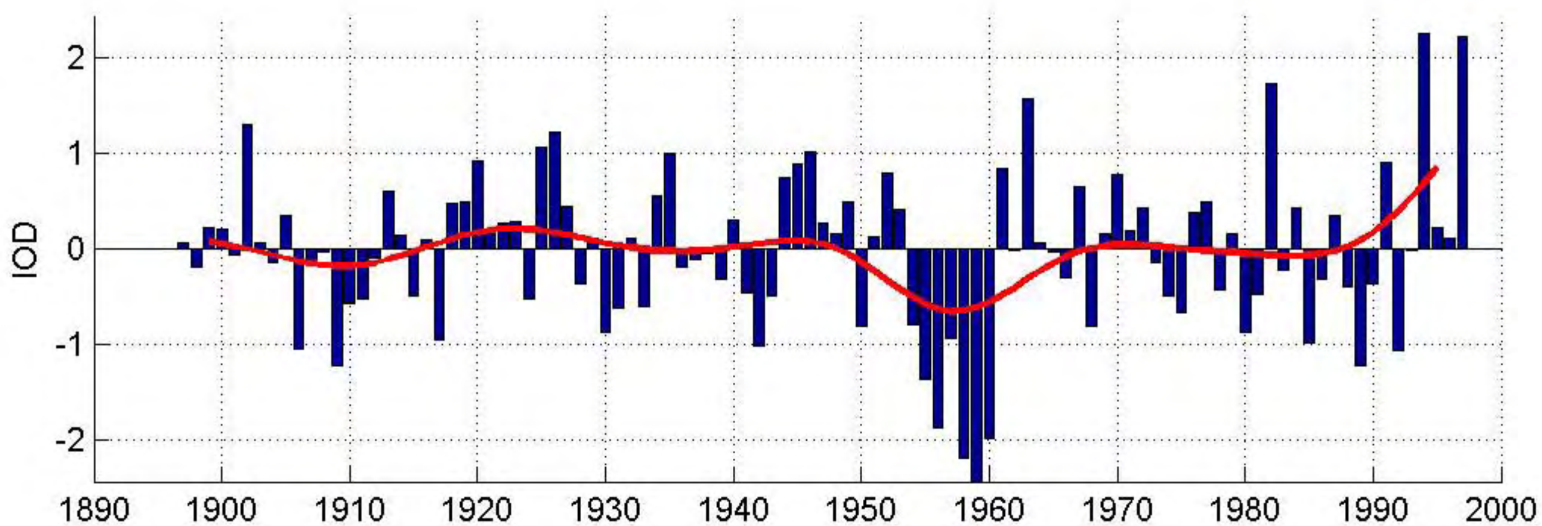
http://www.bom.gov.au/climate/iod/



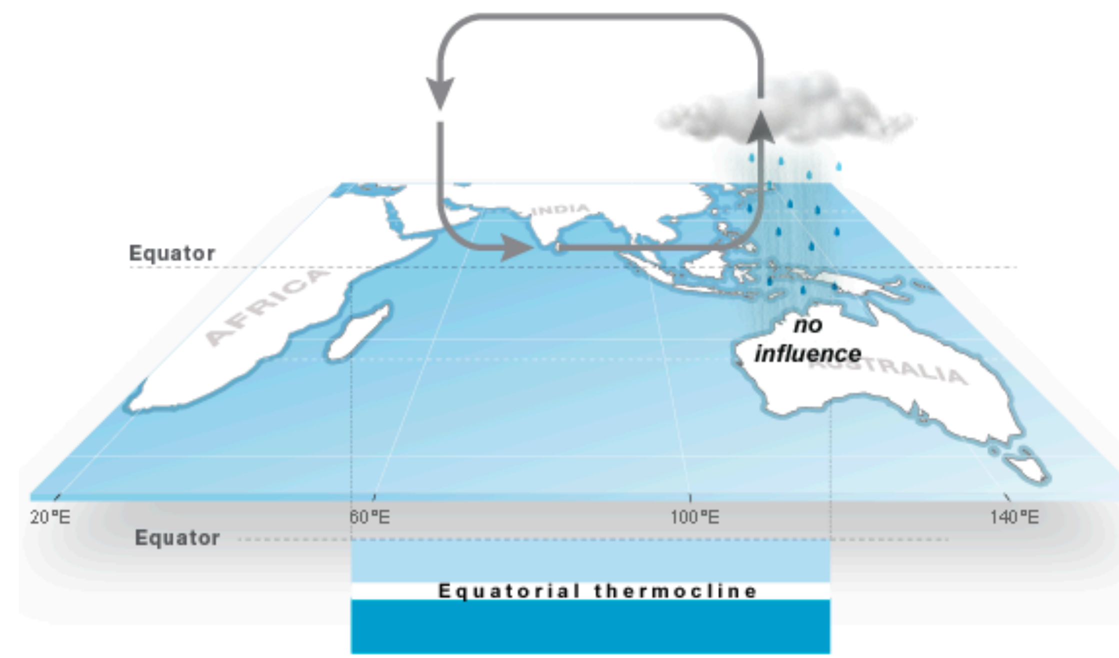
Indian Ocean Dipole (IOD): **Positive phase**



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



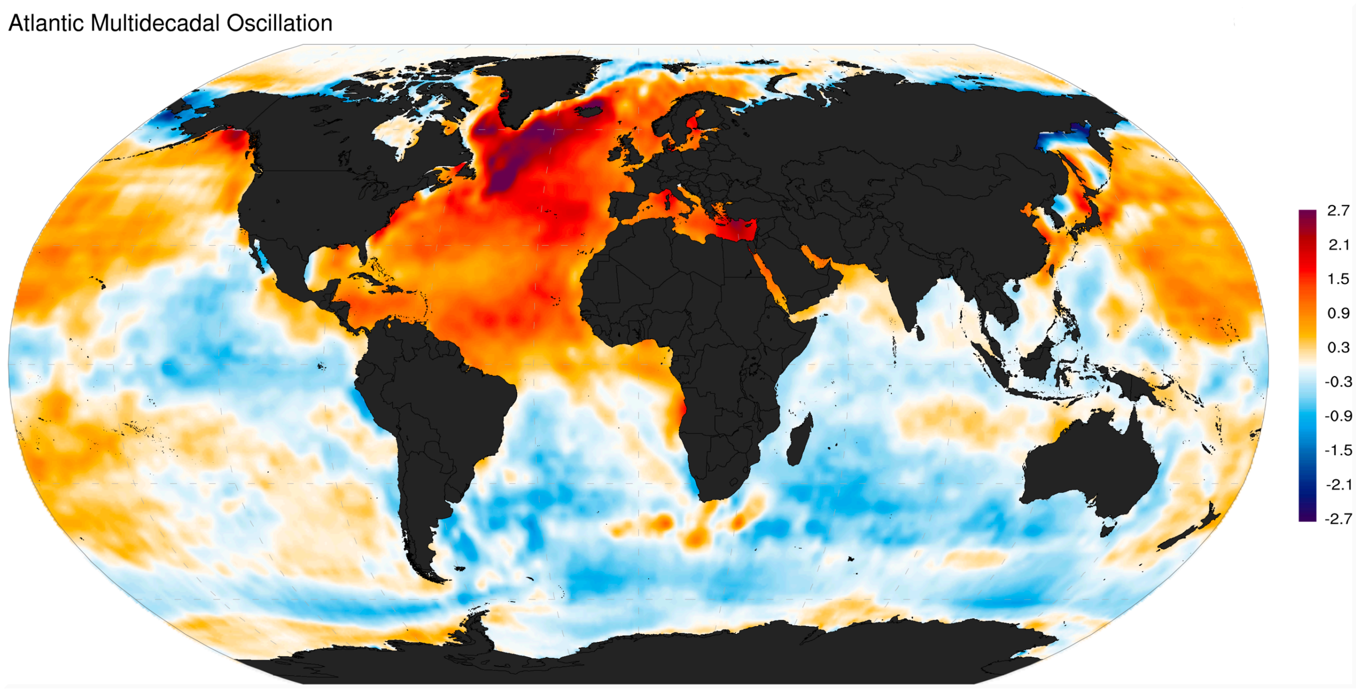
IOD time series, Berthot et al, 2017

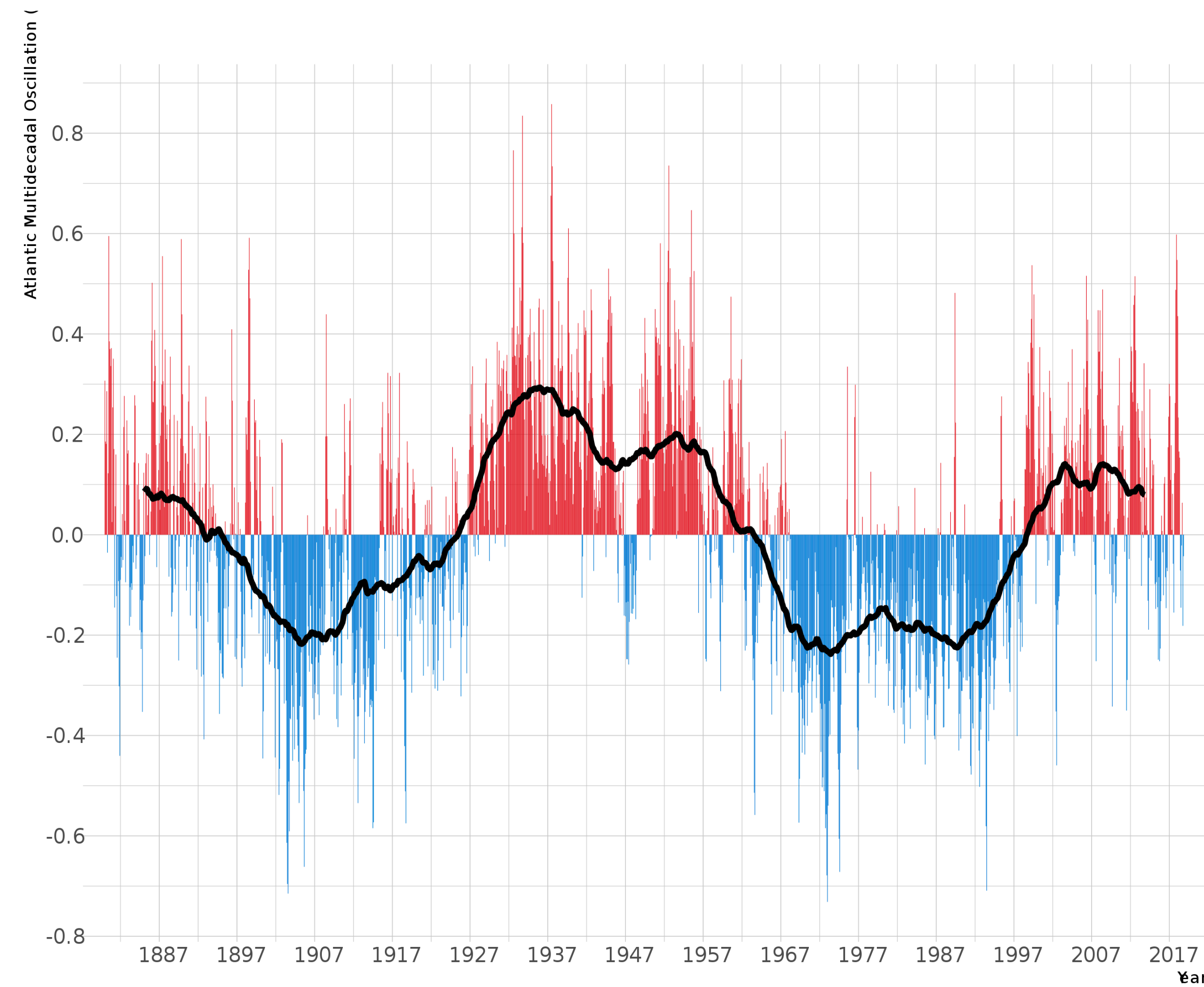


Indian Ocean Dipole (IOD): **Neutral phase**

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.

https://en.wikipedia.org/wiki/Atlantic_multidecadal_oscillation

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

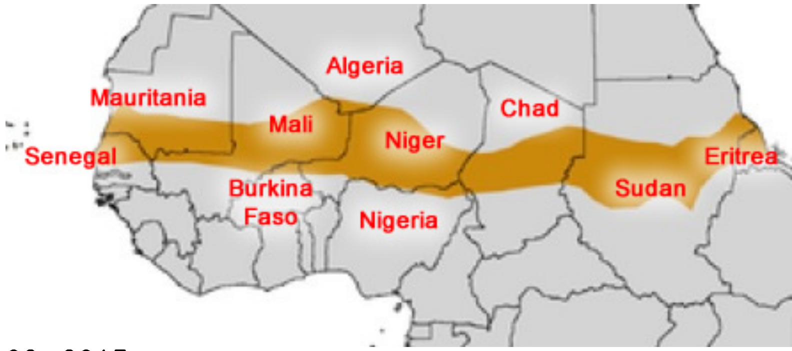
two test cases:

1. South-West US
2. Sahel

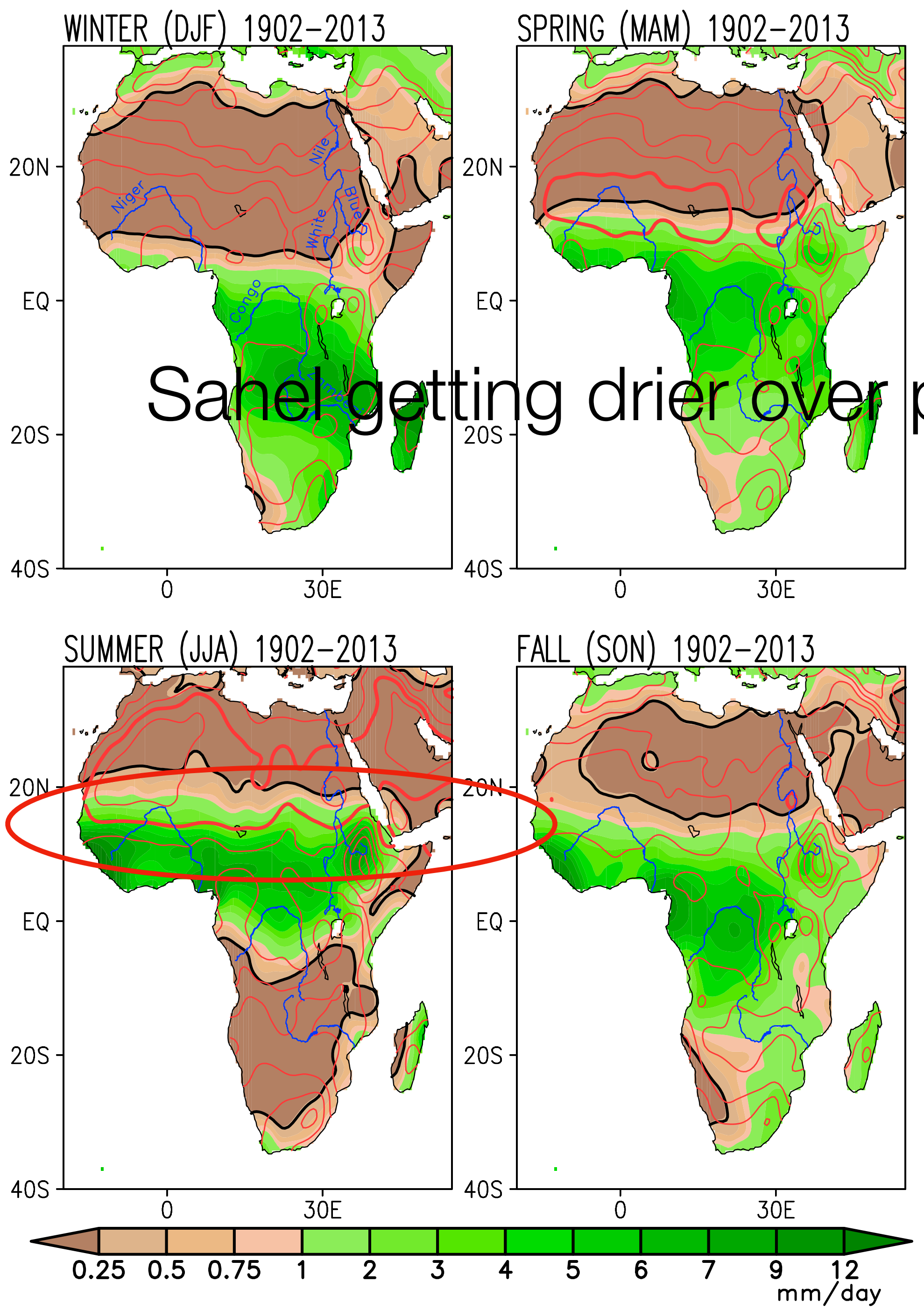
and then a global perspective

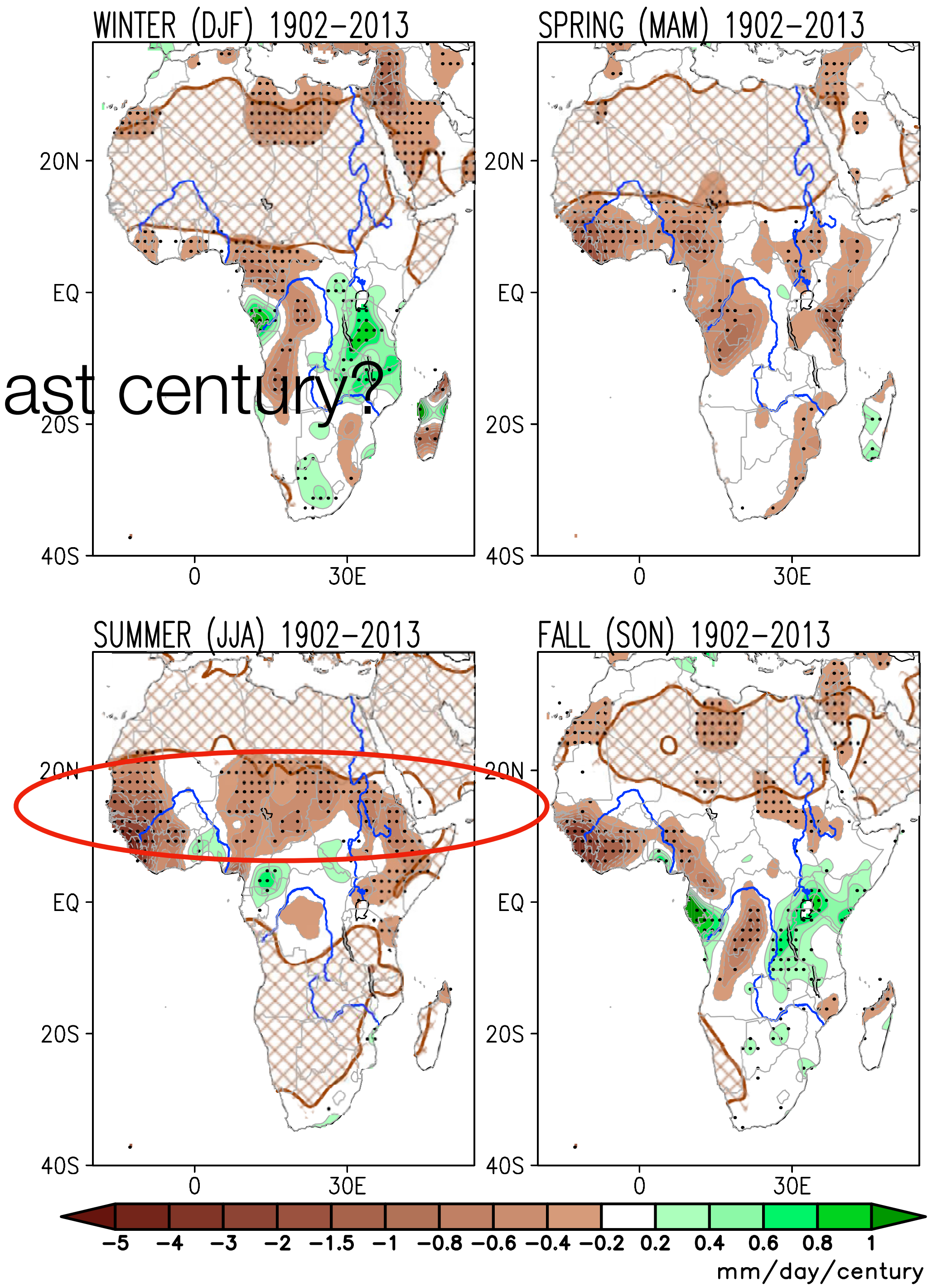
Sahel Droughts

Sahel Droughts



THOMAS AND NIGAM, 2018



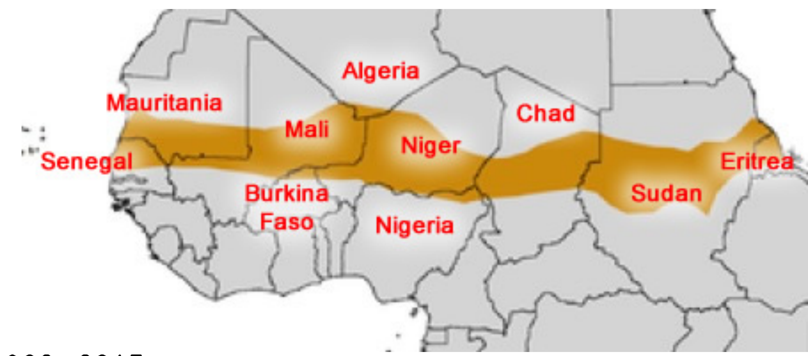


Sahel getting drier over past century?

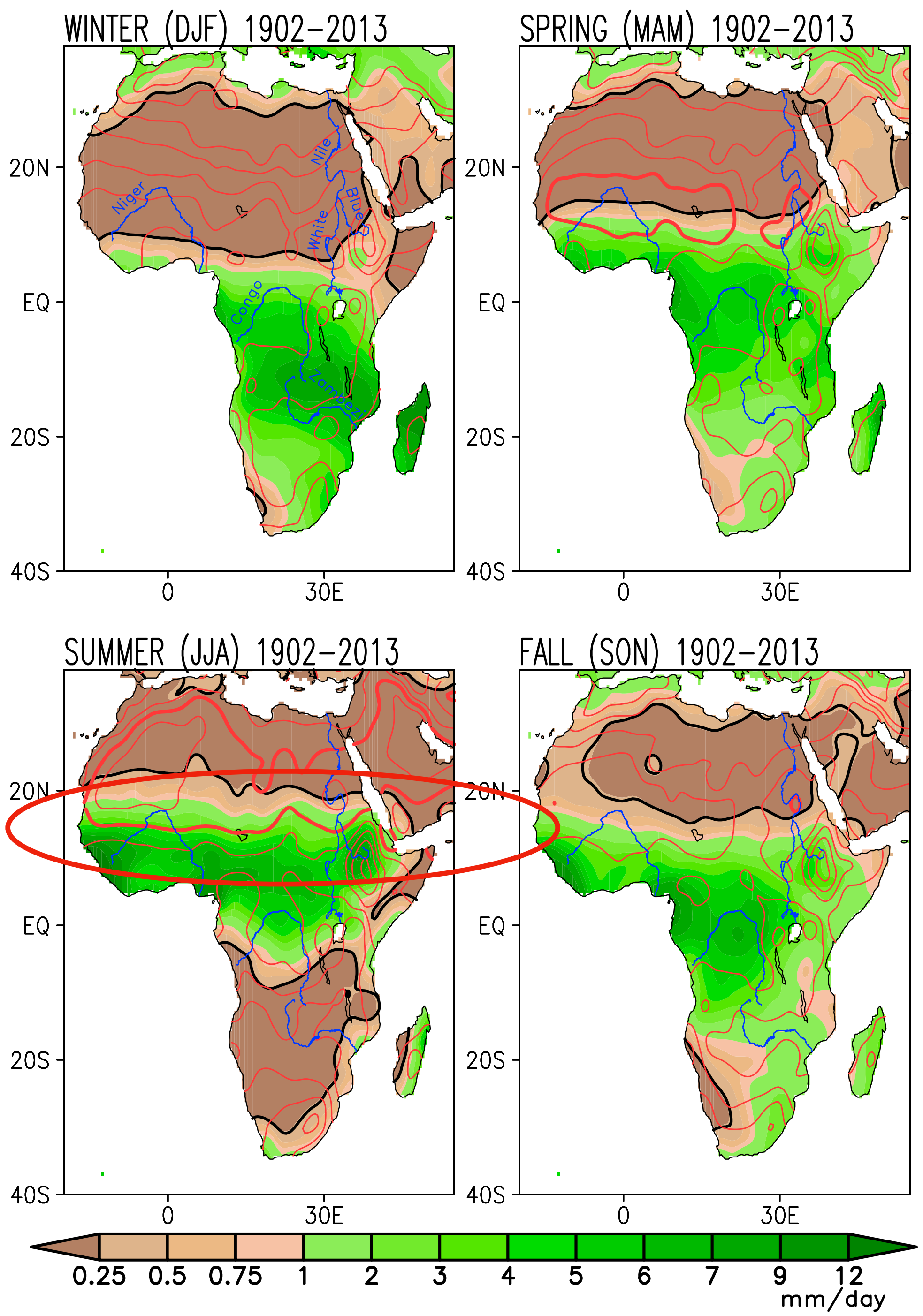
averaged precipitation & surface air temperature (red contours). 1902–2013

Linear trends in seasonal precipitation over the African continent during 1902–2013

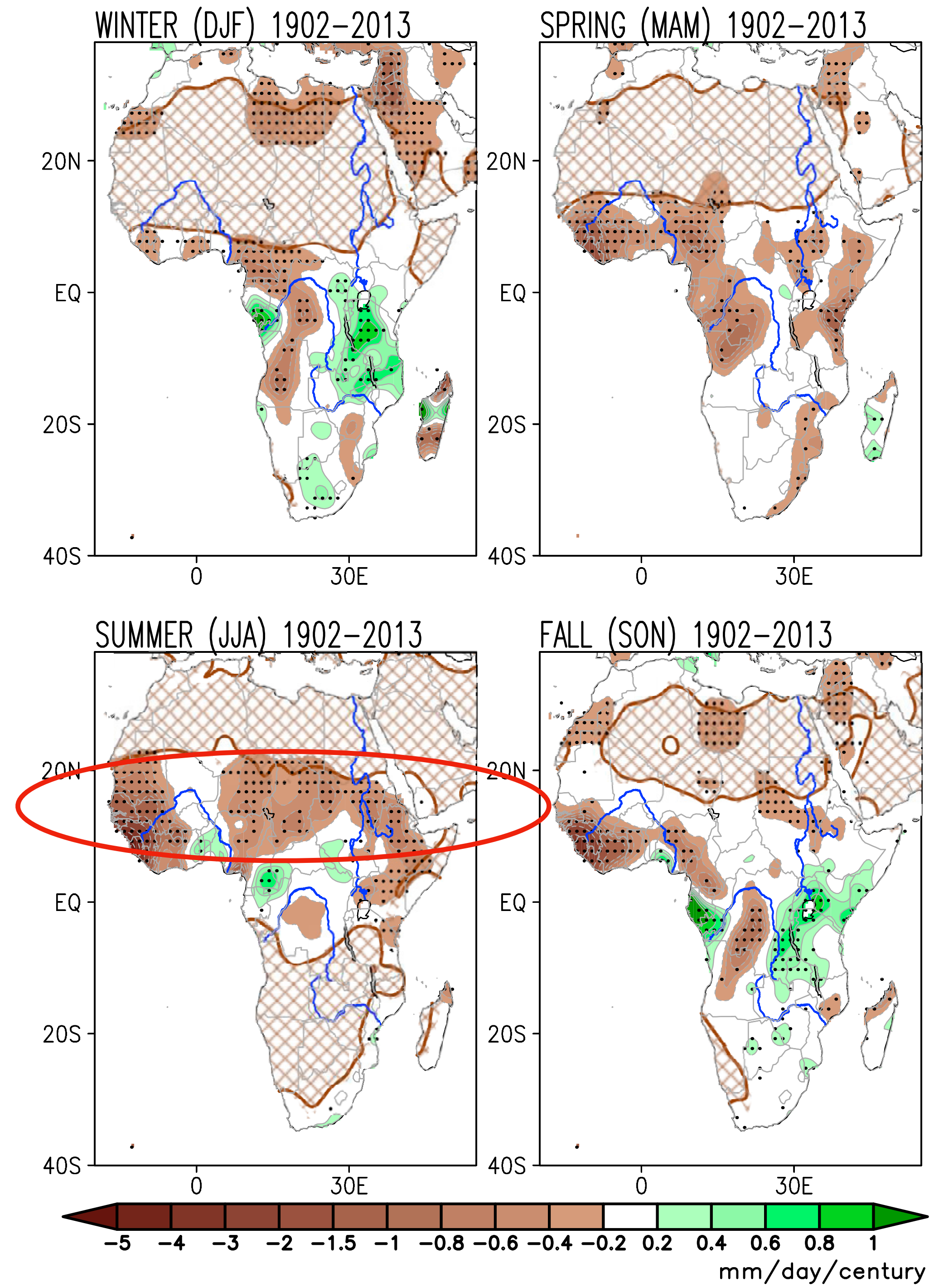
Sahel Droughts



THOMAS AND NIGAM, 2018



averaged precipitation & surface air temperature (red contours). 1902–2013



Linear trends in seasonal precipitation over the African continent during 1902–2013

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Sahel Droughts

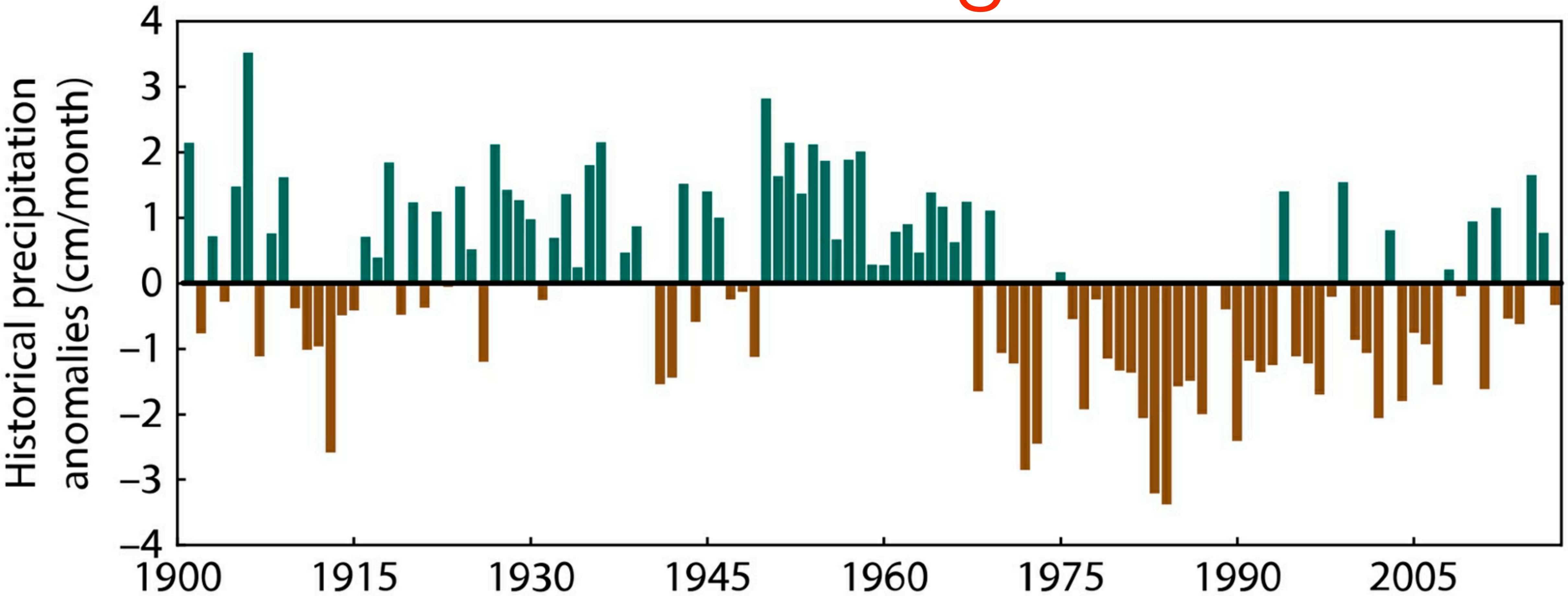

FIGURE 6.7 Monsoon season (June–October; JJASO) historical precipitation anomalies (relative to the 1901–2017 mean) averaged across the Sahel (10°N–20°N, 20°W–10°E) from 1901 to 2017. Anomalously wet conditions affected the Sahel for most of the 1950s and 1960s, but the region experienced an abrupt shift toward drought in 1968. Despite some recovery from the peak precipitation deficits in the 1970s and 1980s, this late 20th-century drought persisted well into 1990s, resulting in a mostly continuous ~30-year period of low precipitation. Source: Data from the University of Washington Joint Institute for Study of the Atmosphere and Oceans, doi:10.6069/H5MW2F2Q, http://research.jisao.washington.edu/data_sets/sahel/. Underlying data are from the Global Precipitation Climatology Centre Full Data Reanalysis Version 7 [Schneider et al., 2015] and First Guess Product [Ziese et al., 2011], https://www.dwd.de/EN/ourservices/gpcc/gpcc.html. Cook, Ben. Drought . Columbia University Press. Kindle Edition.

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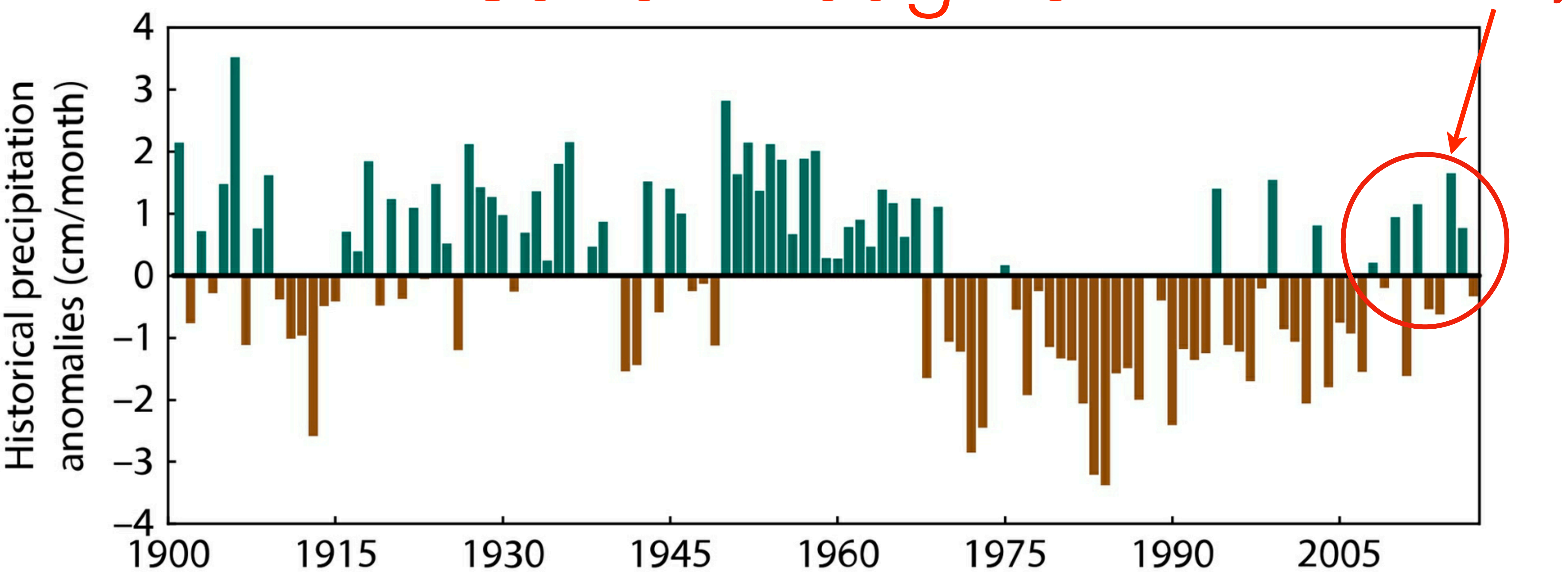
Sahel Droughts



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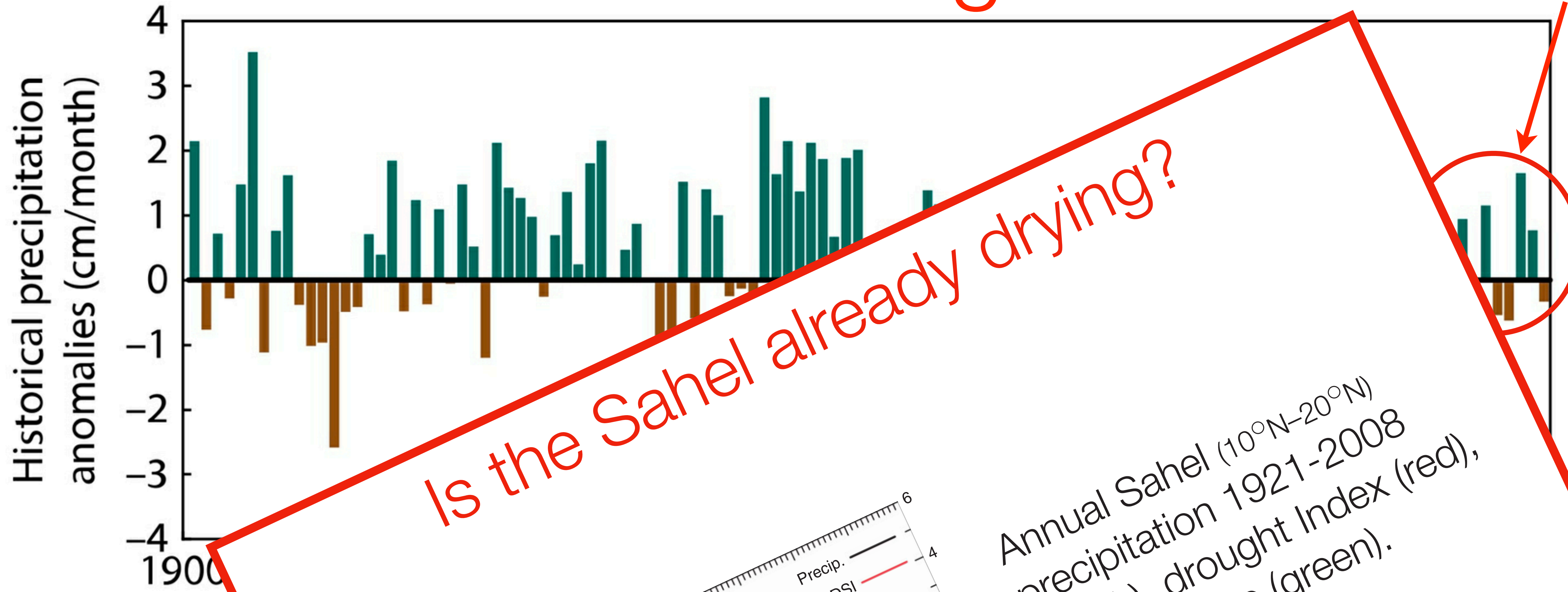
Sahel Droughts

recent recovery?



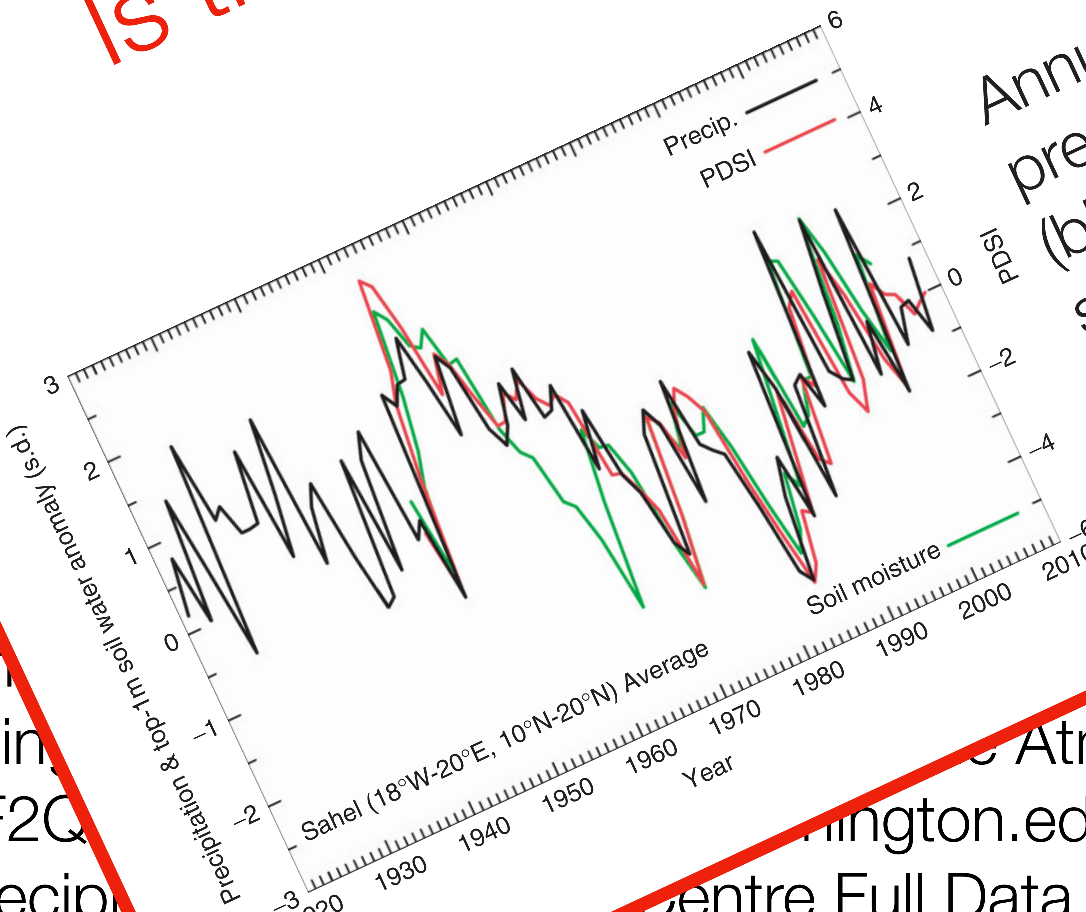


FIGURE 6.7 Mo ... ve
to the 1901–201 ... 01 to
2017. Anomalously ... 960s, but the
region experienced a ... covery from the peak
precipitation deficits i ... ought persisted well into
1990s, resulting in a m ... precipitation. Source: Data from
the University of Washin ... e Atmosphere and Oceans,
doi:10.6069/H5MW2F2Q ... ington.edu/data_sets/sahel/. Underlying data
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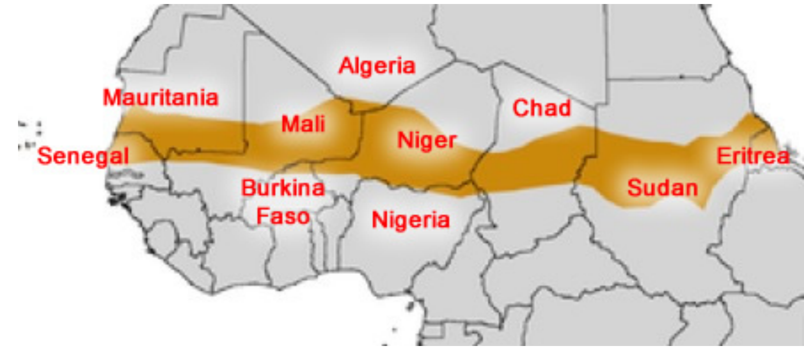
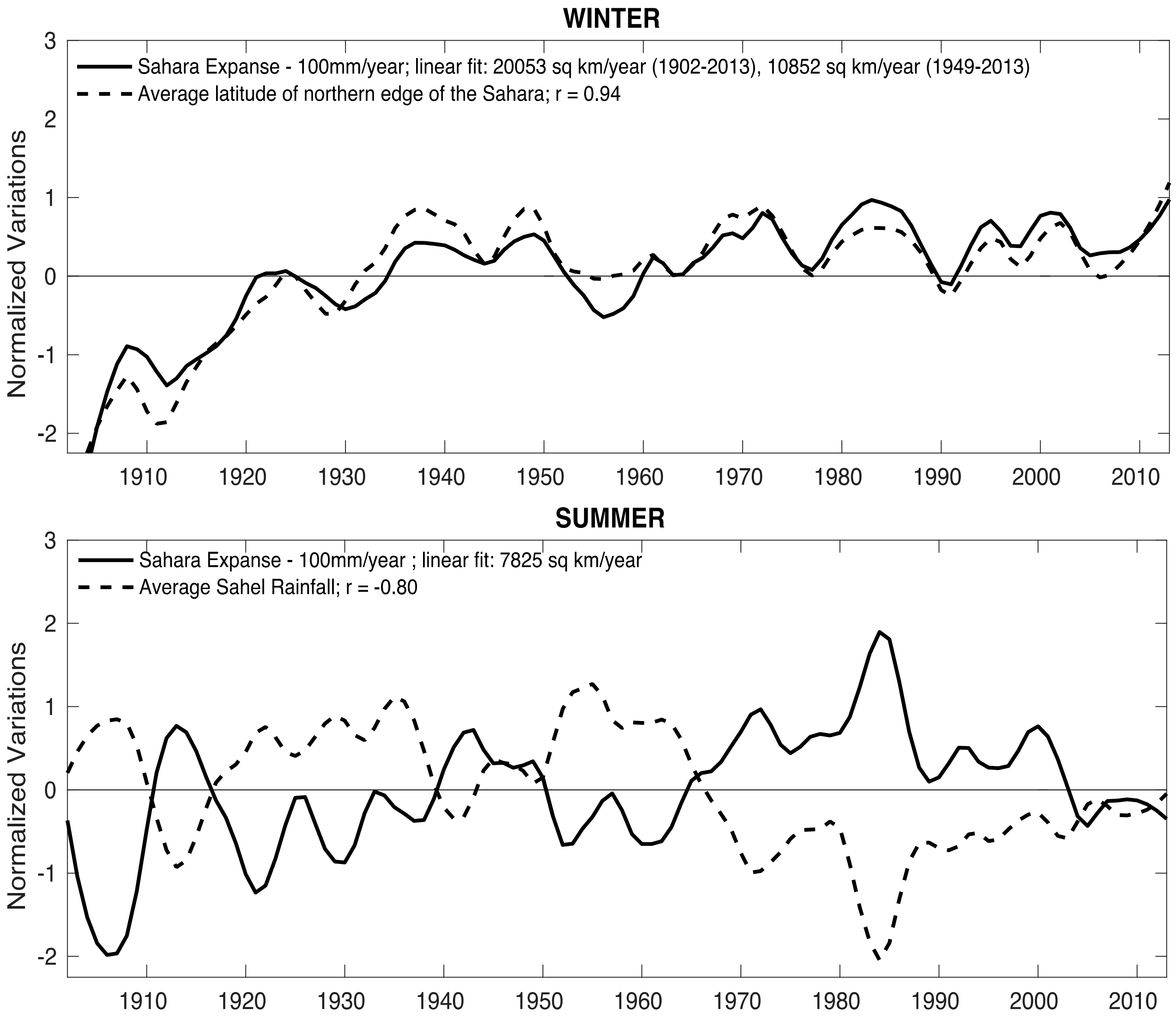
Sahel Droughts

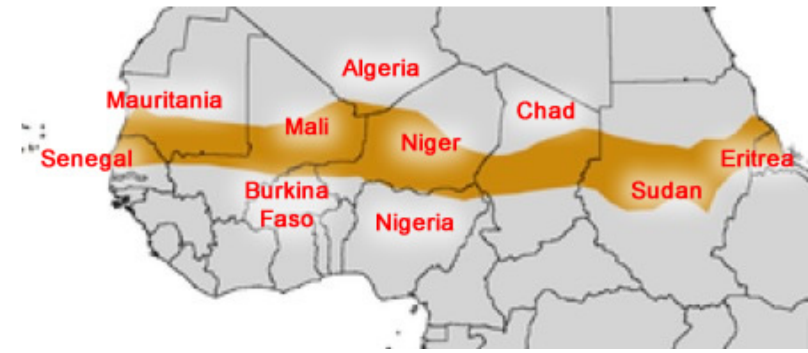


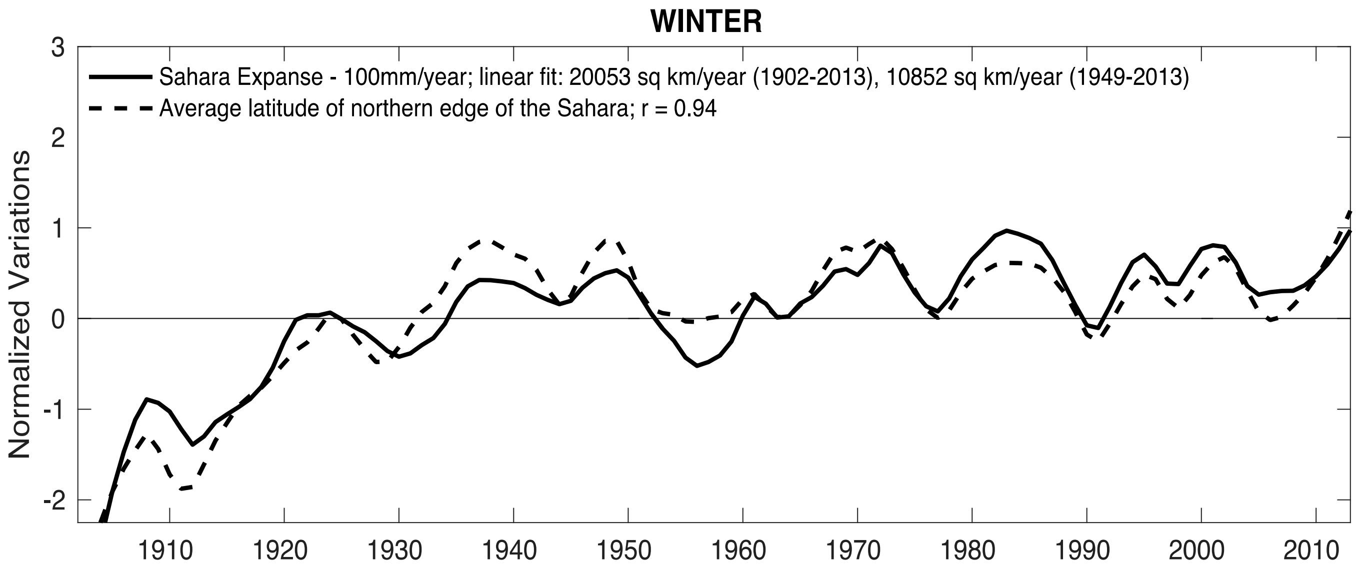


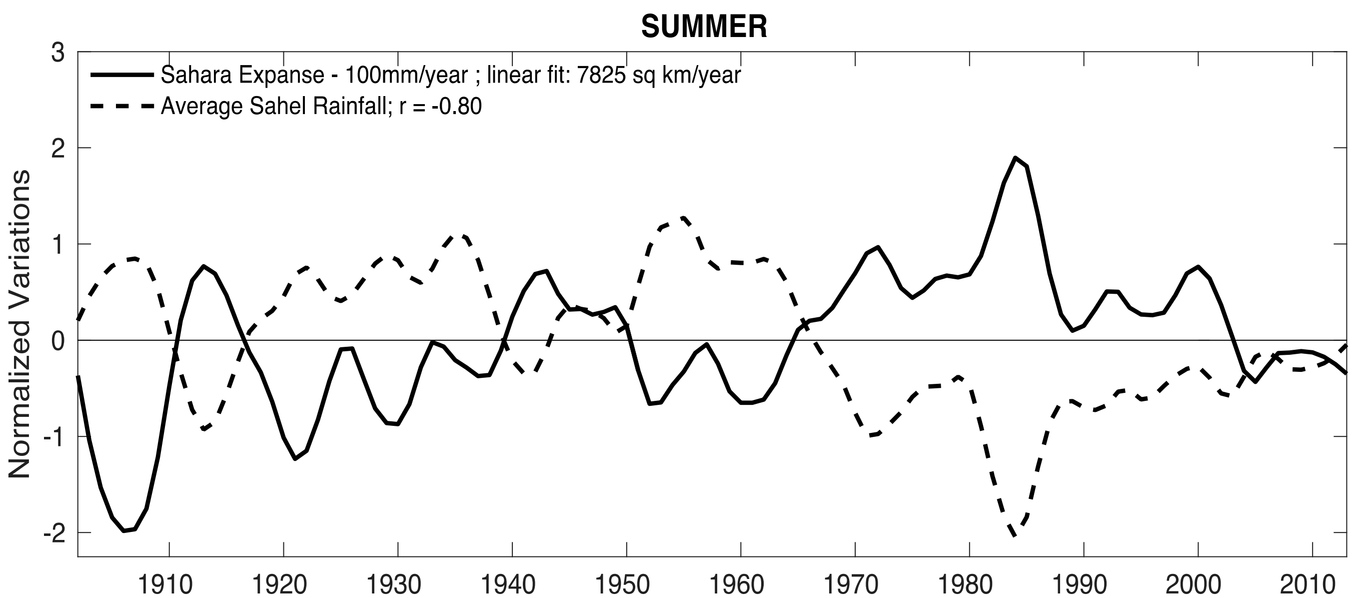
Not clear that the Sahel has been getting drier over recent decades

(Thomas and Nigam, 2018)

Sahel Droughts







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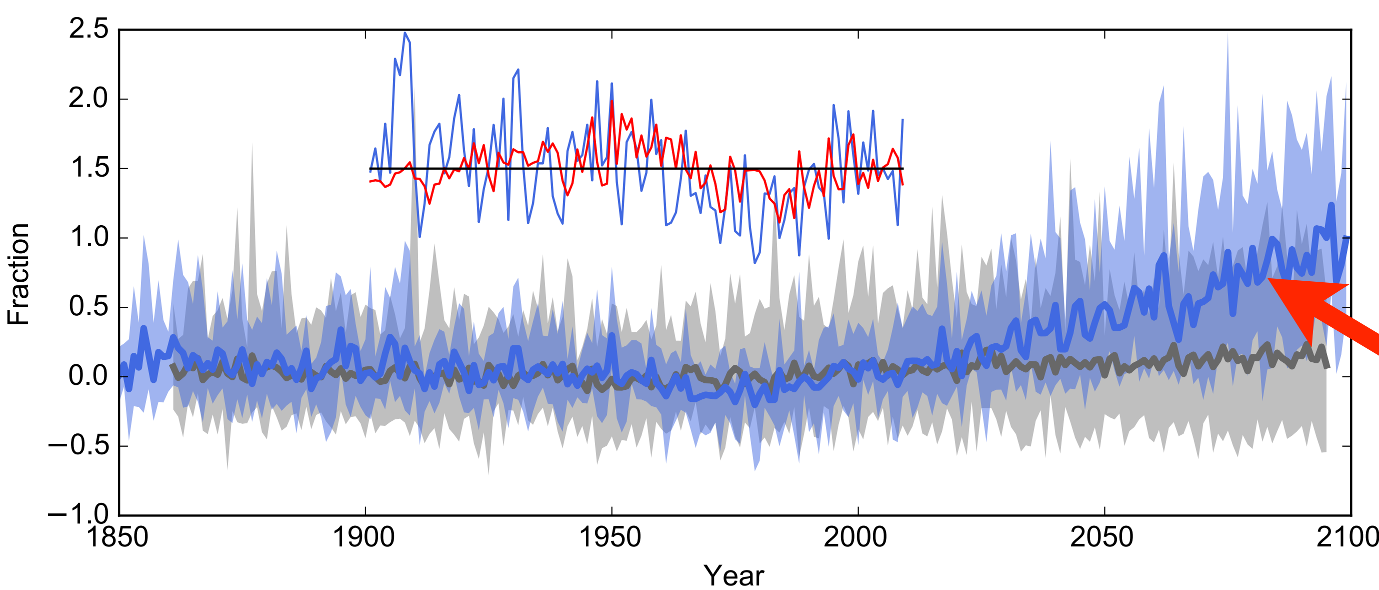


Sahel summer rainfall. Wet 7 (blue), 23 other models (grey), historical forcing & RCP8.5. Shading: model min/max.

(Schewe & Levermann 2017)

And some (7/30) climate models predict a wetter future Sahel…

South-West US Droughts

California droughts and La Nina

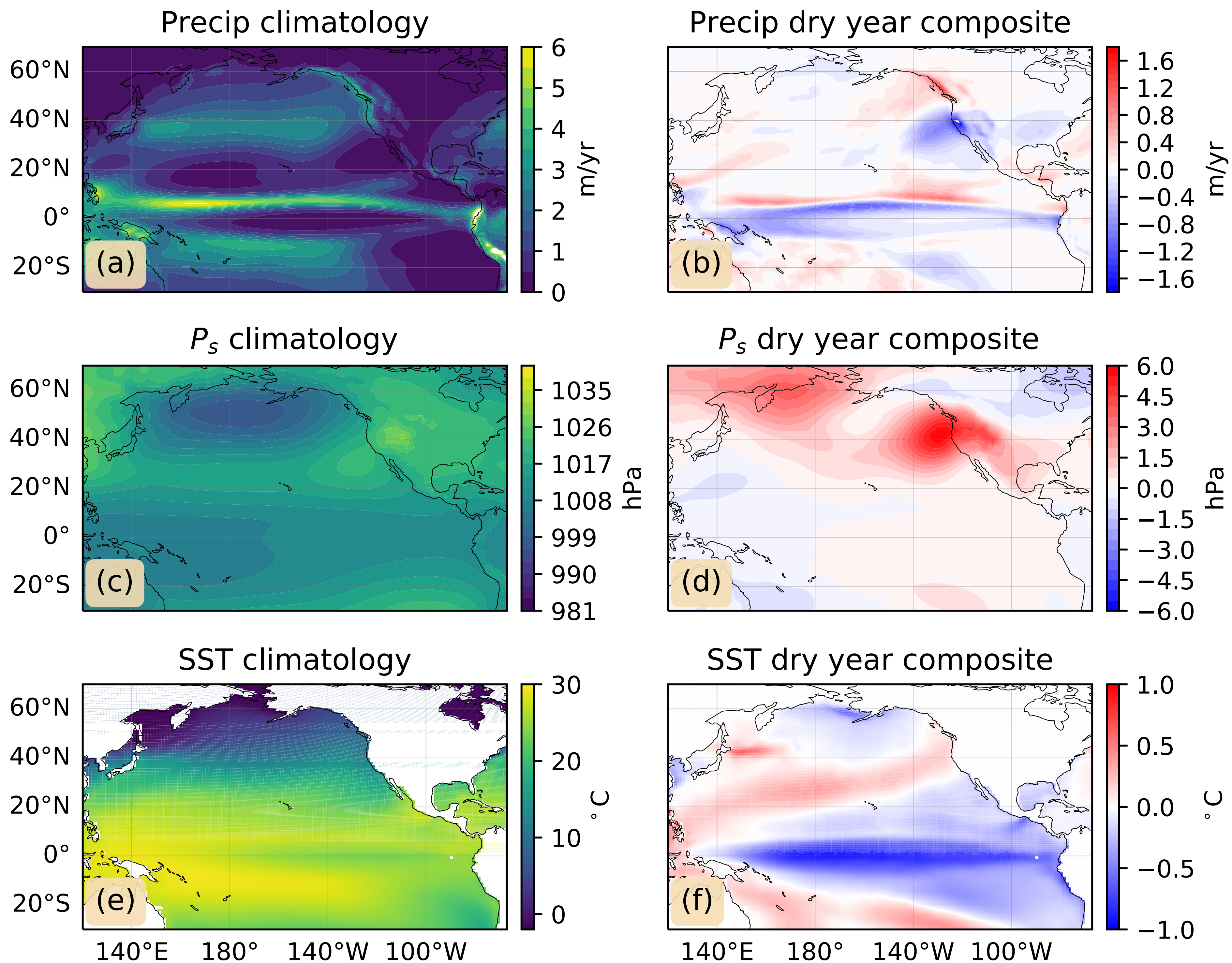


Figure 12.2: Analysis of California droughts in a climate model run at preindustrial CO_2 concentration. Climatological January averages (left) and the composites over dry California Januaries (right), for (upper) precipitation, (middle) sea level pressure, (lower) SST. While the general idea of remote sea surface temperature patterns driving teleconnections that can force drought conditions is robust, the details shown here may deviate from those in observations of California droughts due to various model biases.

How unusual was the 2012–2014 California drought?

Griffin & Anchukaitis, 2014: the current event is **the most severe drought in the last 1200 years…** driven by reduced though not unprecedented precipitation and record high temperatures.

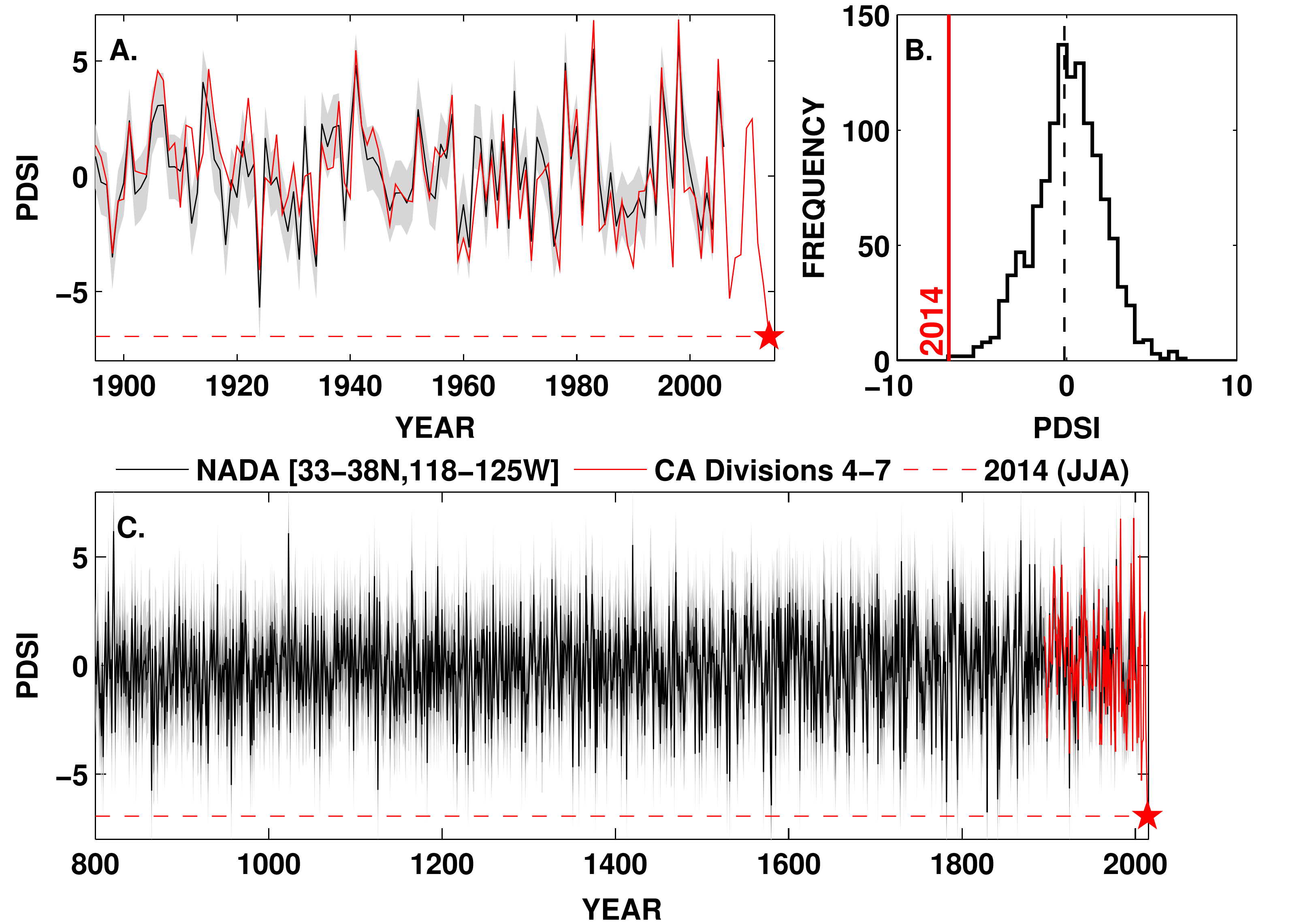


Figure 1. (a) Regional mean North American Drought Atlas (NADA) PDSI for Central and Southern California (33°N to 38°N and 118°W to 125°W; black line) and instrumental June through August NOAA Climate Division 4–7 PDSI (solid red line) for the observational period 1895 to 2014 [Vose et al., 2014]. The JJA season is chosen to match the NADA reconstruction target. Uncertainty (1σ) calculated as the root-mean-squared error from the residual fit of the NADA to the instrumental series shown as the shaded gray region. The red line and star indicate the 2014 value. (b) Distribution of the composite NADA-NOAA JJA PDSI values for the period 800 to 2014. The 2014 value is indicated by the red line and is labeled. (c) Long-term (800 to 2014) composite NADA-NOAA (black line) and instrumental (solid red line) PDSI. The horizontal dashed red line and star indicate the 2014 value. Uncertainty on the composite calculated as the root-mean-squared error from the residual fit of the NADA to the NOAA instrumental series shown as light (2σ) and dark (1σ) shaded gray regions.

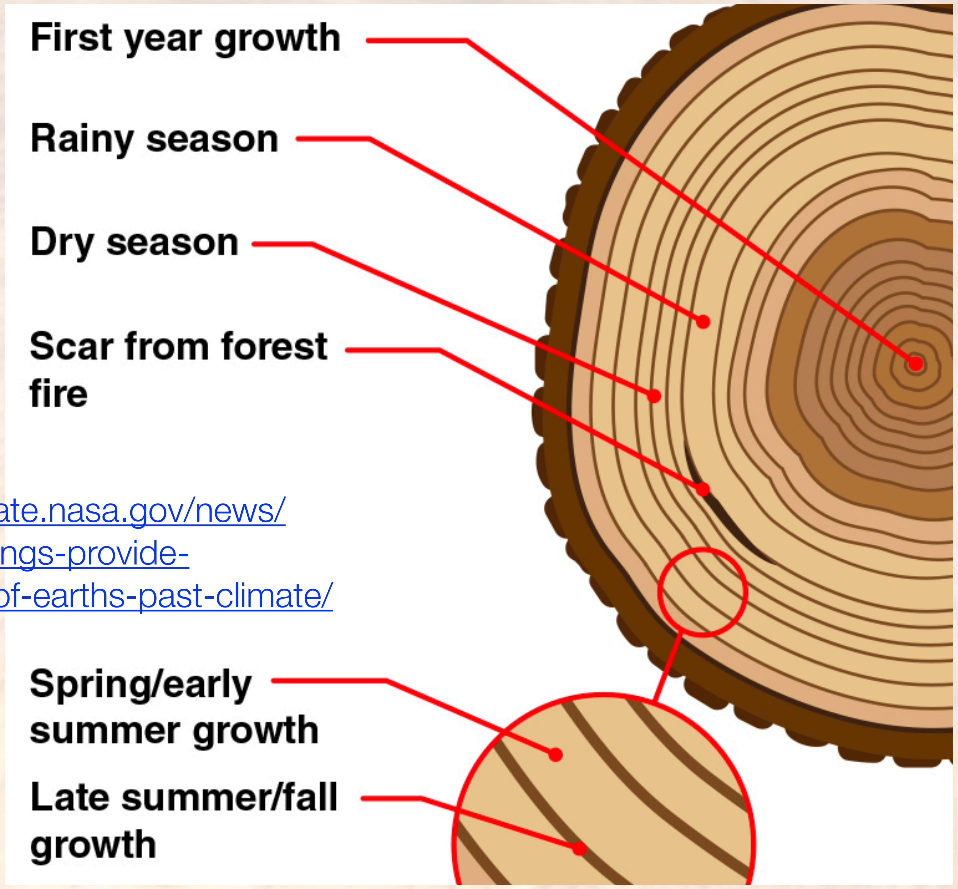
notes section 12.3:
Detection of climate change signal in droughts using “non-parametric” statistical analysis

Workshop #2:
Identifying ACC in a long-term SW US drought record

Reconstructing past droughts from tree ring data

https://www.nature.com/news/2010/100707/full/news.2010.335.html

Concentric rings of various widths mark the annual growth of trees. Peter Brown, Rocky Mountain Tree-Ring Research.



https://climate.nasa.gov/news/2540/tree-rings-provide-snapshots-of-earths-past-climate/

Reconstructing past droughts from tree ring data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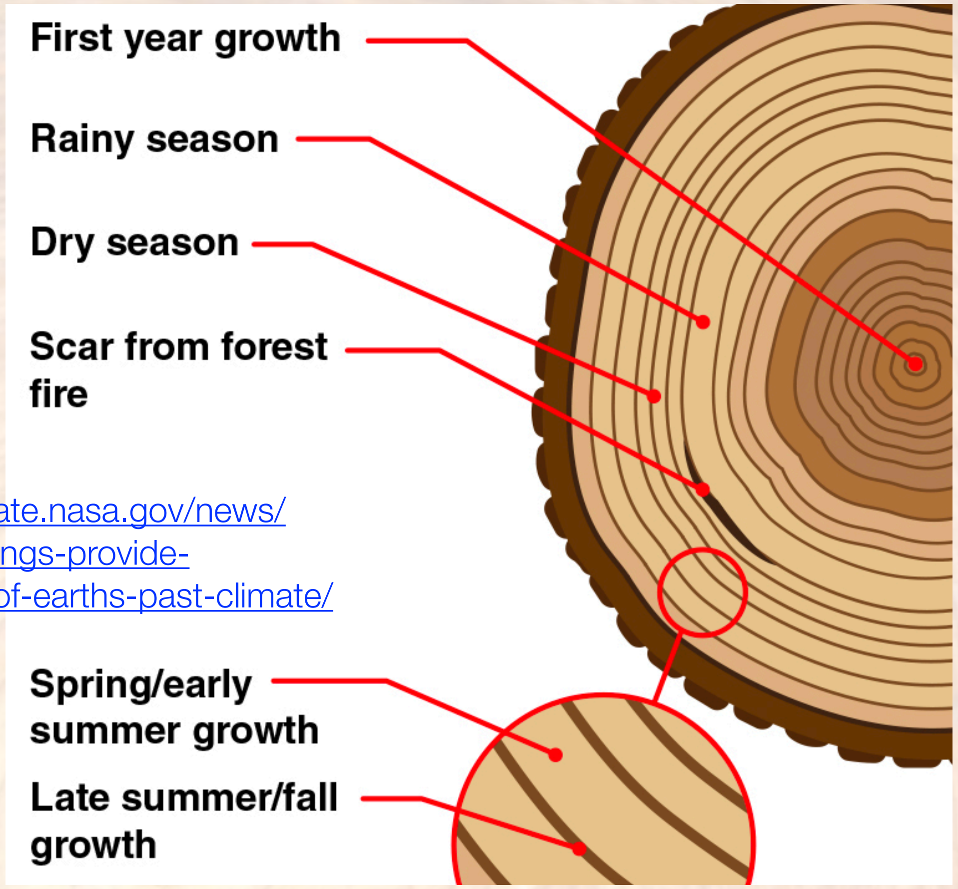

https://climate.nasa.gov/news/2540/tree-rings-provide-snapshots-of-earths-past-climate/

https://ites.ethz.ch/events/highlights/tree-ring-lab.html

coring and counting rings

Reconstructing past droughts from tree ring data

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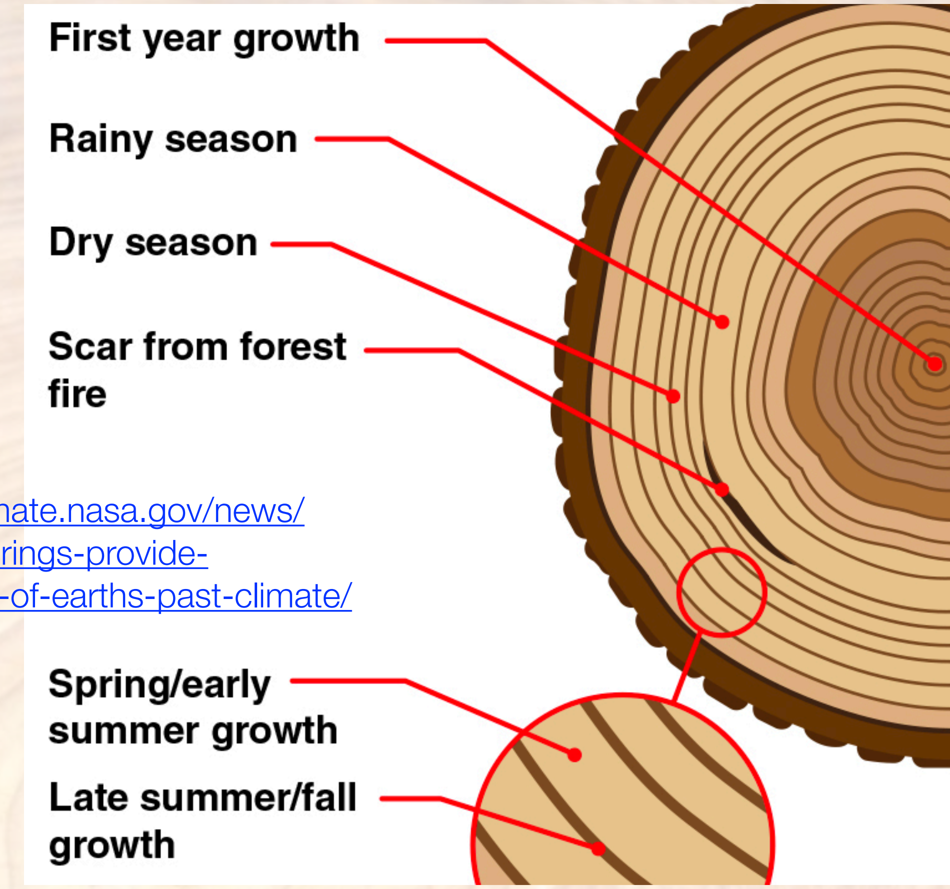

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https://ites.ethz.ch/events/highlights/tree-ring-lab.html

http://pvcblog.blogspot.com/2013/11/tree-ring-analysis-at-pleasant-valley.html

coring and counting rings

Workshop #3: Getting to know tree-ring data

http://nathistoc.bio.uci.edu/plants/Pinaceae/Pseudotsuga%20macrocarpa.htm

* Plot data from the many-tree Bigcone Douglas Fir records as function of year, as grey thin lines or dots
* Superimpose the bin-average as a thicker color line
* discuss the scatter around the average

Bigcone douglas fir

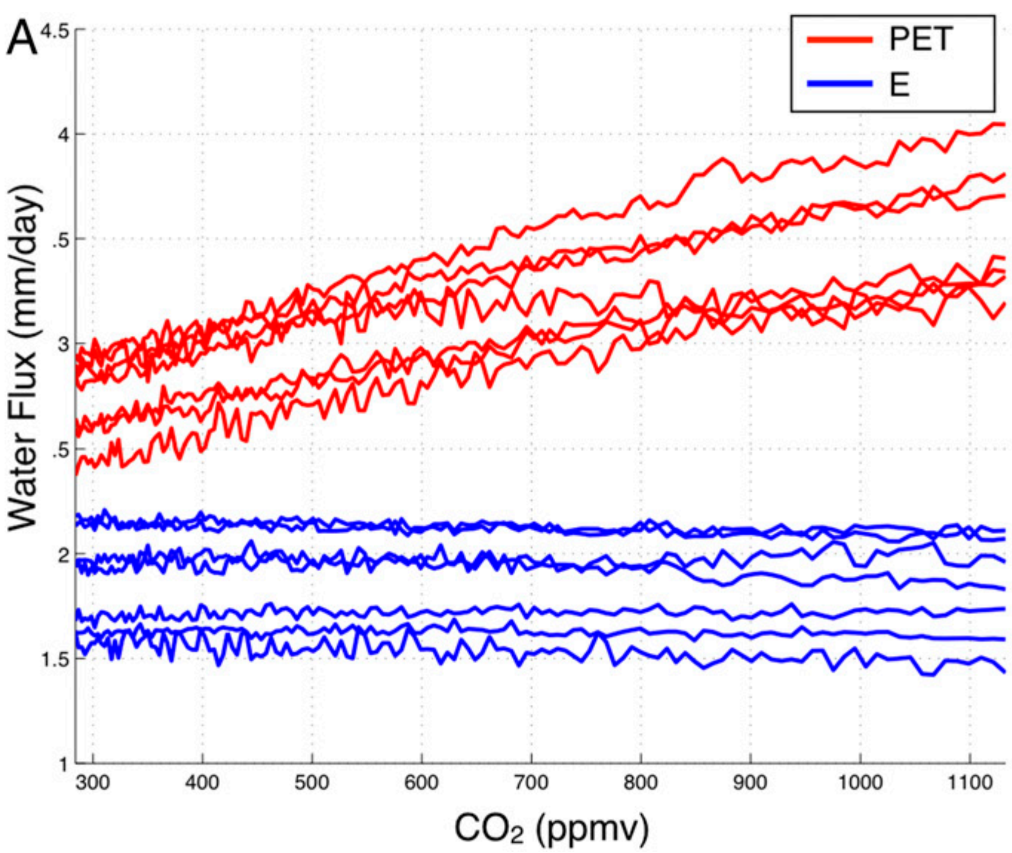
wikipedia

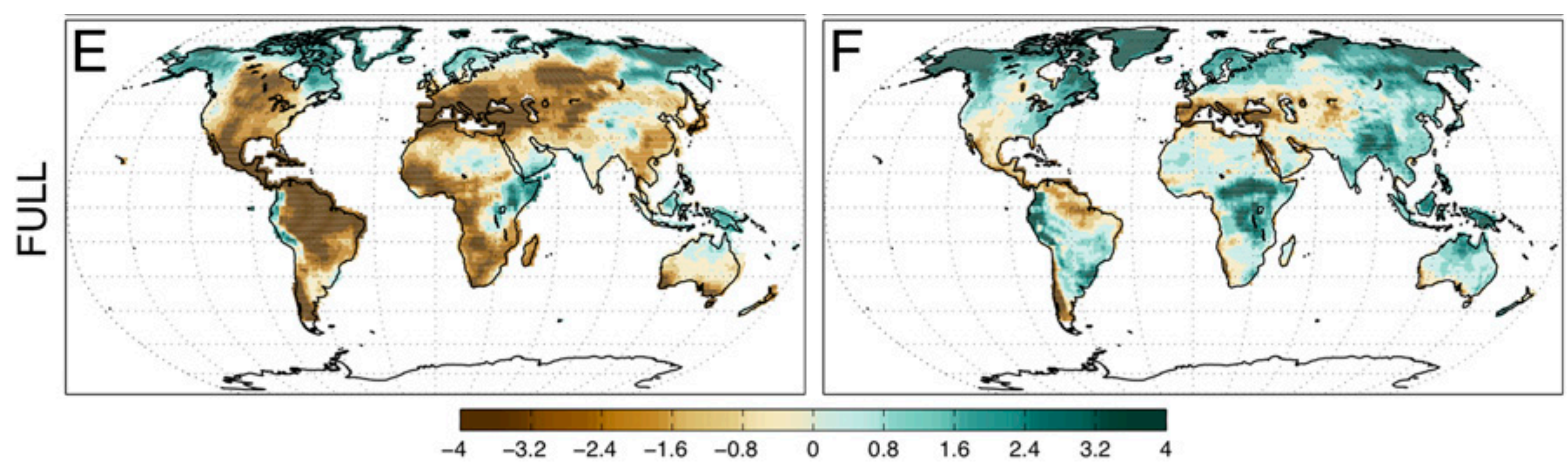
Vegetation feedbacks to increased CO_2 reduce drought danger

“Higher atmospheric CO2 ➨ plants limit stomatal opening while absorbing CO2. ➨ reduces water losses from land surface, increases soil moisture, reduces plant water stress, & reduces drought.

Plant-centric variables: precipitation minus evapotranspiration (P-E), runoff, and soil moisture.
Atmosphere-centric: no change to surface conductance with CO2: potential evapotranspiration (PET) and Palmer Drought Severity Index (PDSI).

Models: 84% of P-E change at mid&lower latitudes is due to physiological response to higher CO2





Maps of the multimodel mean difference over a quadrupling of CO_2 for PDSI (left) and P-E (right) normalized by the SD of the multimodel mean at each point. Green indicates more water on land; brown less.

Plant responses to increasing CO_2 reduce estimates of climate impacts on drought severity
Abigail L. S. Swann, Forrest M. Hoffman, Charles D. Koven, and James T. Randerson, 2016, PNAS

Soil moisture is critical for agriculture

AgriLand
IRELAND'S LARGEST FARMING NEWS PORTAL

HOME » ENVIRONMENT » LITTLE CHANGE EXPECTED IN SOIL MOISTURE DEFICITS THIS WEEK

Little change expected in soil moisture deficits this week

Conor Finnerty | Jul 23, 2018, 8:37am

There is very little change expected in soil moisture deficits this week, apart from some slight relief in the north-west of the country, Met Eireann confirmed.

Some rain is forecast this week due to more of an **Atlantic influence** on our weather.

https://indianexpress.com/article/india/india-others/drought-likely-in-parts-of-west-india-agriculture-minister/

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Credit: NOAA

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USDA/FAS/Curt Reynolds
https://climate.nasa.gov/news/2888/when-drought-threatens-crops-nasas-role-in-famine-warnings/

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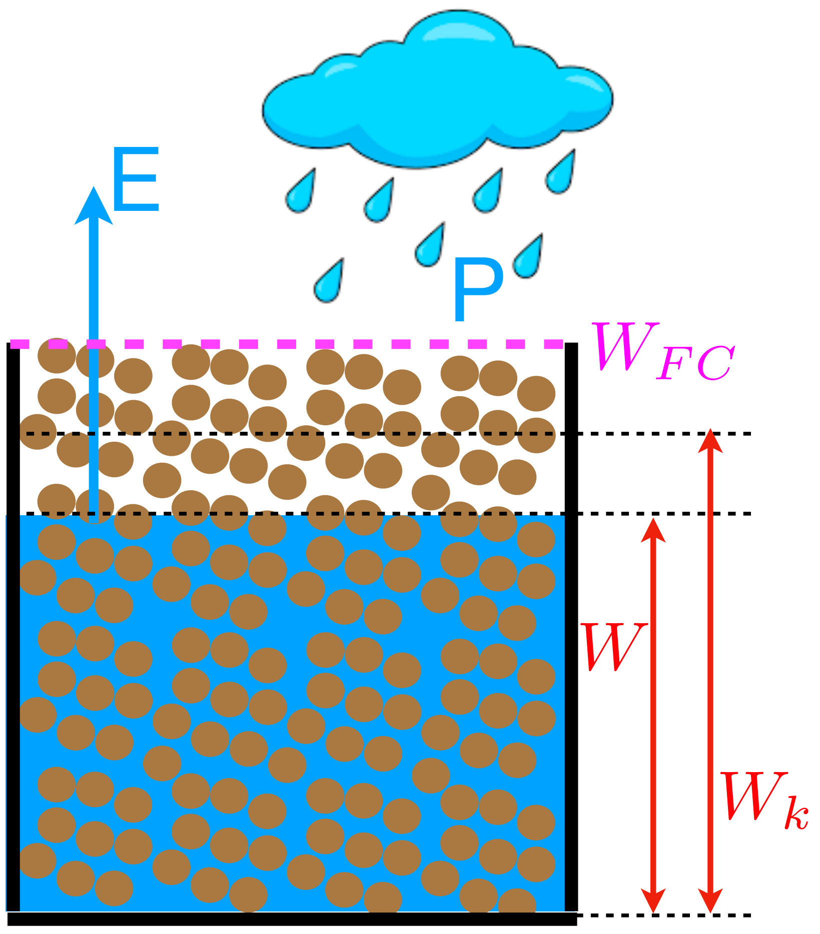
How is soil moisture calculated/ predicted from precipitation?

...parts-of-west-india-agriculture-minister/

USDA/FAS/Curt Reynolds
https://climate.nasa.gov/news/2888/when-drought-threatens-crops-nasas-role-in-famine-warnings/

Question: Suppose ground water level is maintained at some level by a balance of Evaporation and Precipitation. What do you expect will happen to the ground water level if precipitation is reduced by 20% due to global warming.



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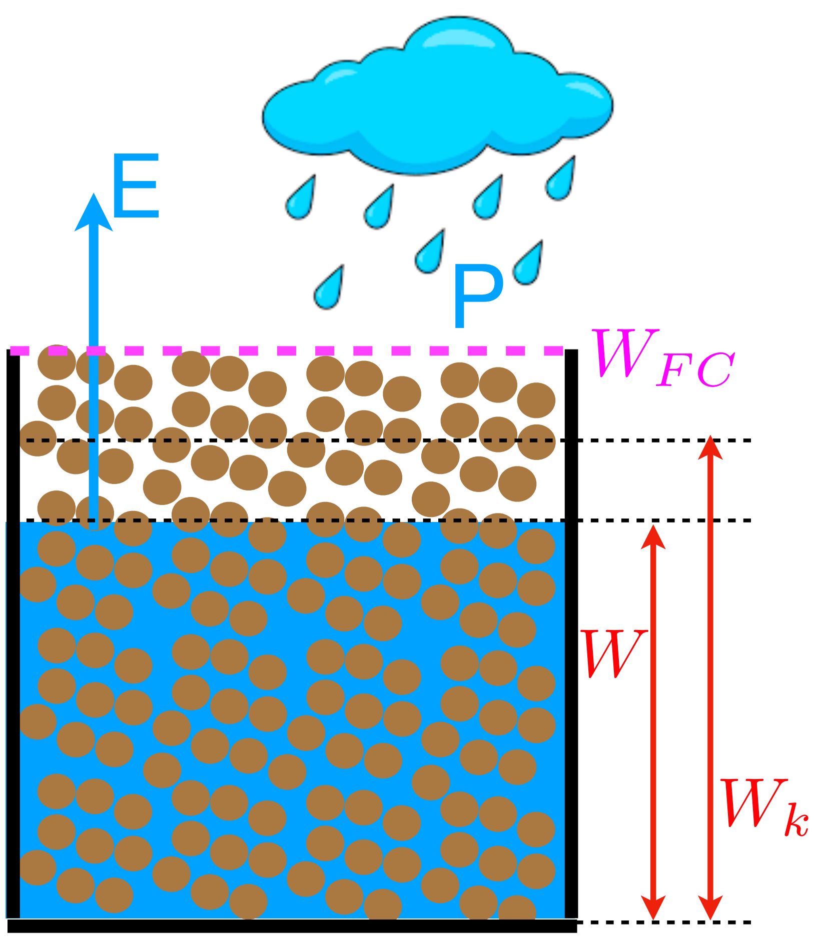
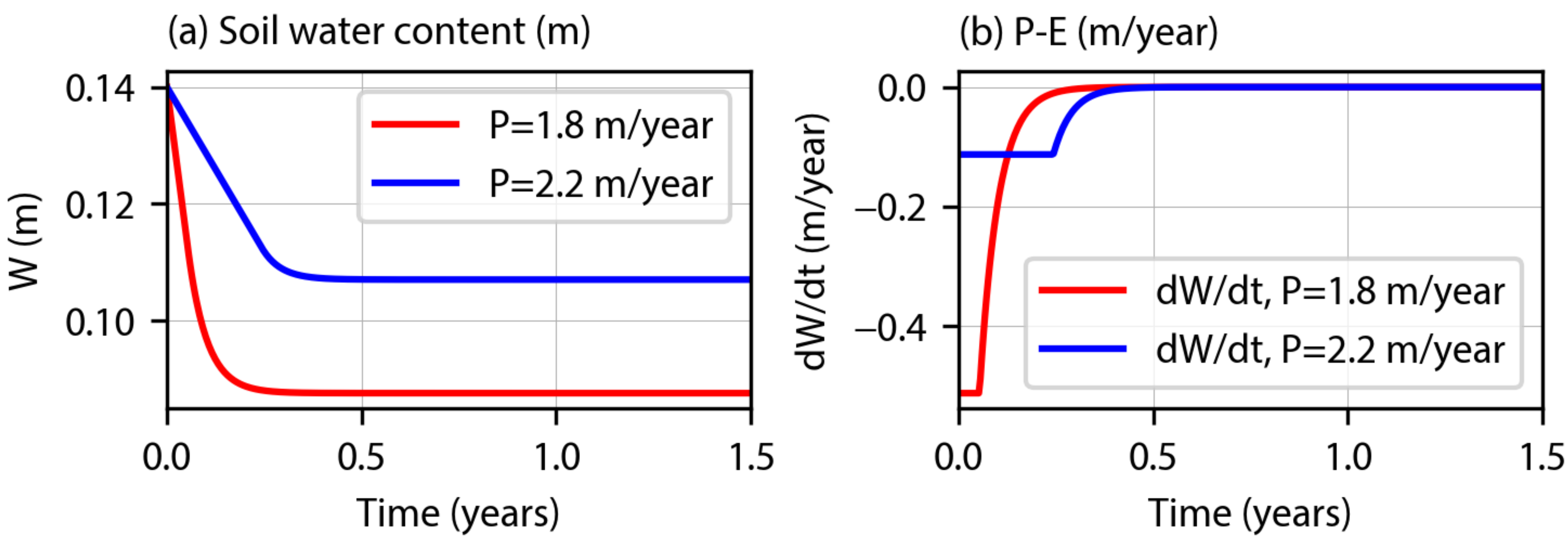
notes section 12.7:
Bucket model for soil moisture



workshop #6
Bucket model for soil moisture

workshop #6
Bucket model for soil moisture



Syria's civil war and drought

Climate change in the Fertile Crescent and implications of the recent Syrian drought

Colin P. Kelley[a,1], Shahrzad Mohtadi[b], Mark A. Cane[c], Richard Seager[c], and Yochanan Kushnir[c]

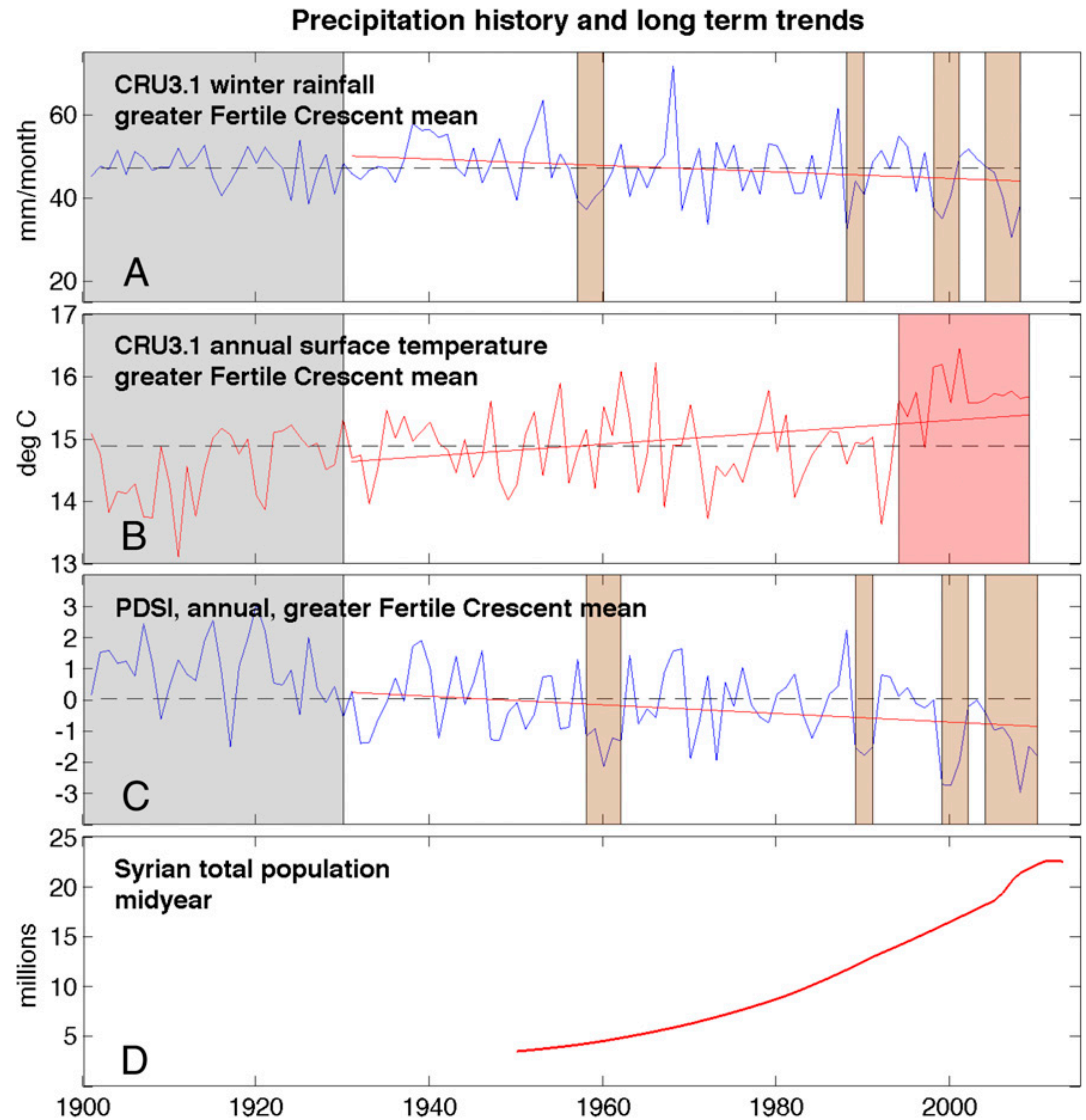


Fig. 1. (A) Six-month winter (November–April mean) Syria area mean precipitation, using CRU3.1 gridded data. **(B)** CRU annual near-surface temperature (red shading indicates recent persistence above the long-term normal). **(C)** Annual self-calibrating Palmer Drought Severity Index. **(D)** Syrian total midyear population. Based on the area mean of the FC as defined by the domain 30.5°N–41.5°N, 32.5°E–50.5°E (as shown in Fig. 2). Linear least-squares fits from 1931 to 2008 are shown in red, time means are shown as dashed lines, gray shading denotes low station density, and brown shading indicates multiyear (≥3) droughts.

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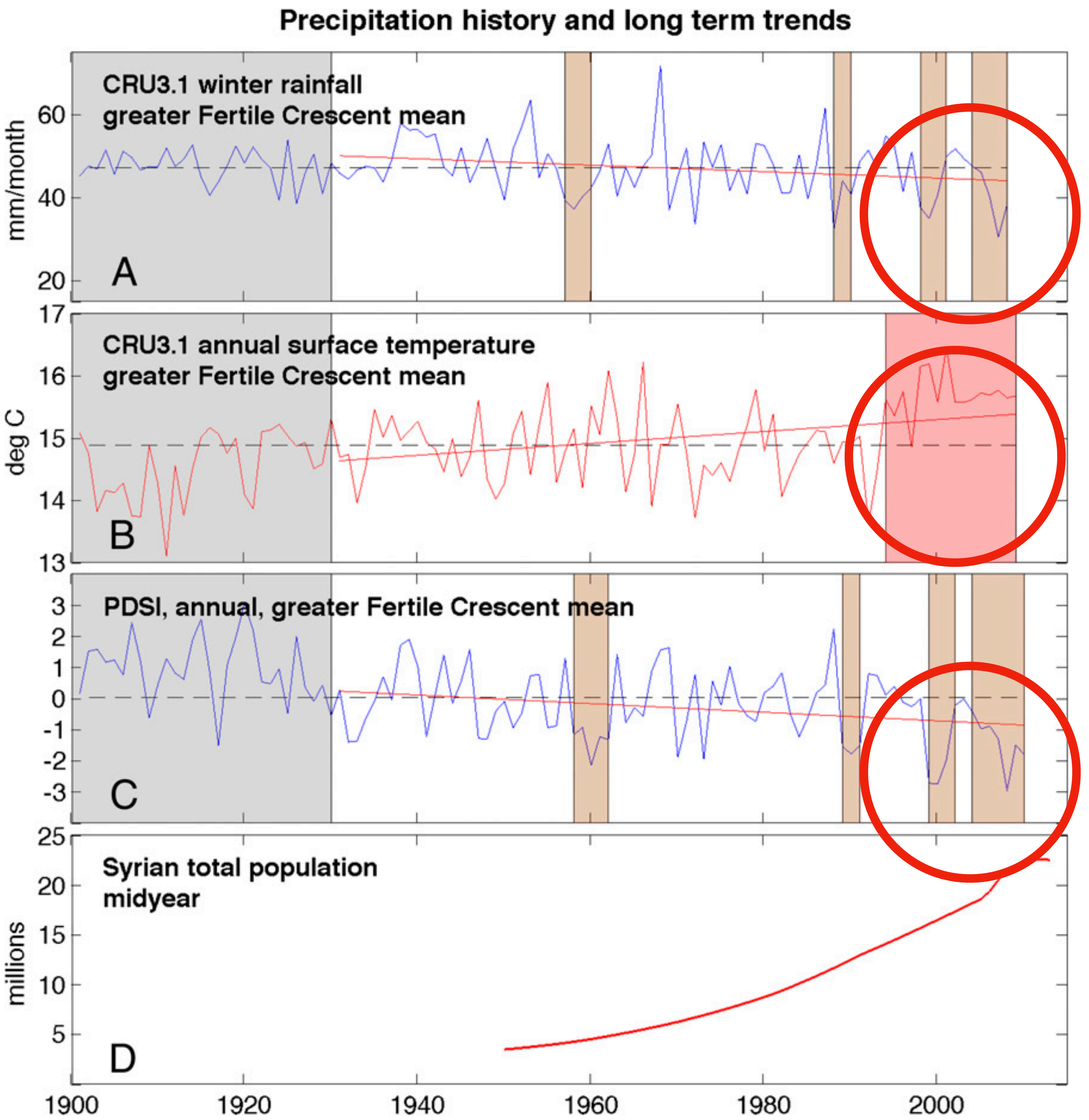

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The 2000s were especially dry, warm and low PDSI!

Syria's civil war and drought

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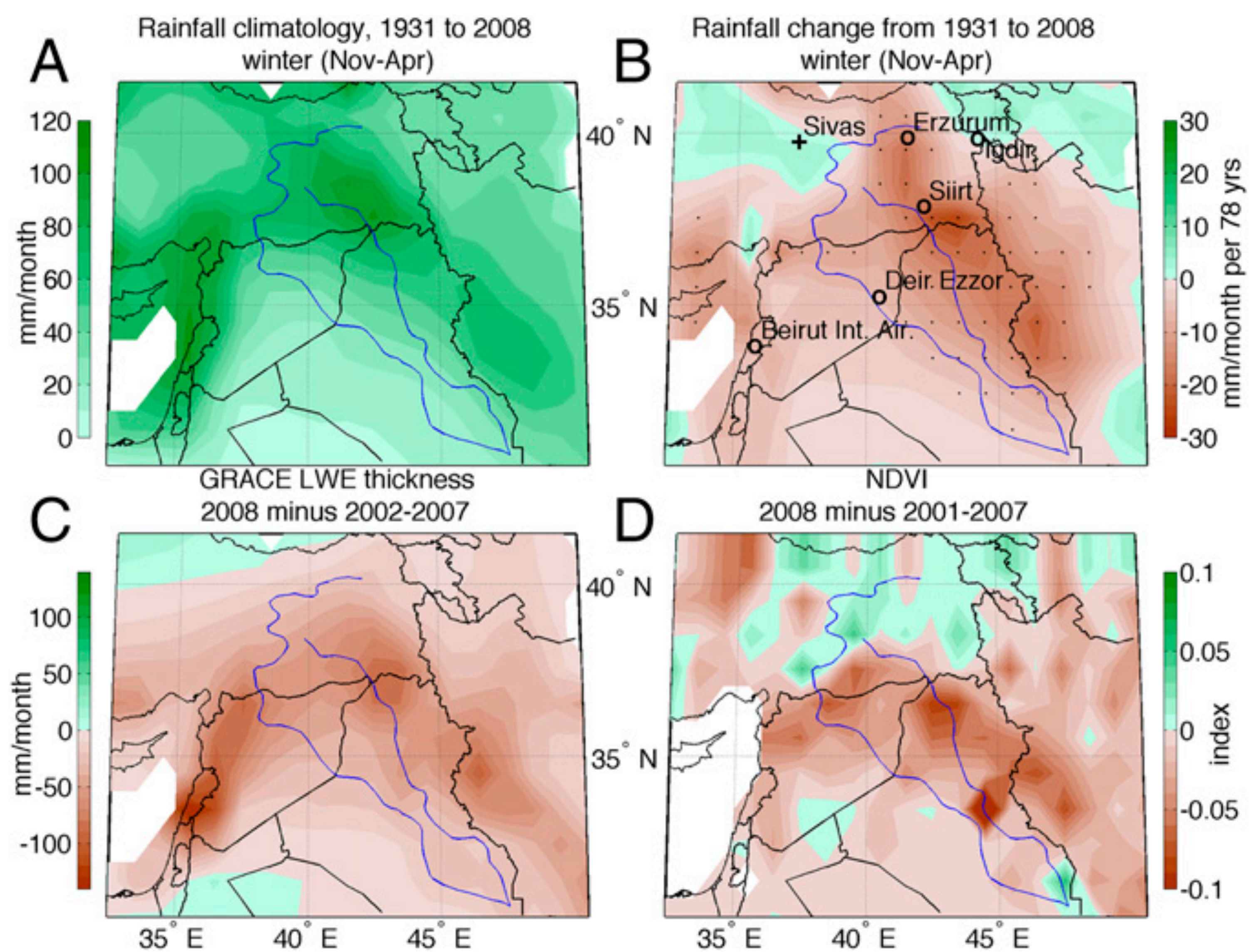
Fig. 2. (A) Observed winter (November–April) precipitation climatology, 1931–2008, UEA CRU version 3.1 data. (B) The spatial pattern of the CRU change in 6-month winter precipitation from 1931 to 2008 based on a linear fit (shading); those GHCN stations that indicate a significant ($P < 0.1$) trend over their respective records are shown as circles and crosses (indicating drying/wetting). (C) The difference in liquid water equivalent (LWE) between 2008 (annual) and the mean of the previous 6 years using the NASA GRACE Tellus project data. (D) The difference in the Normalized Difference Vegetation Index (NDVI) between 2008 (annual) and the mean of the previous 7 years.



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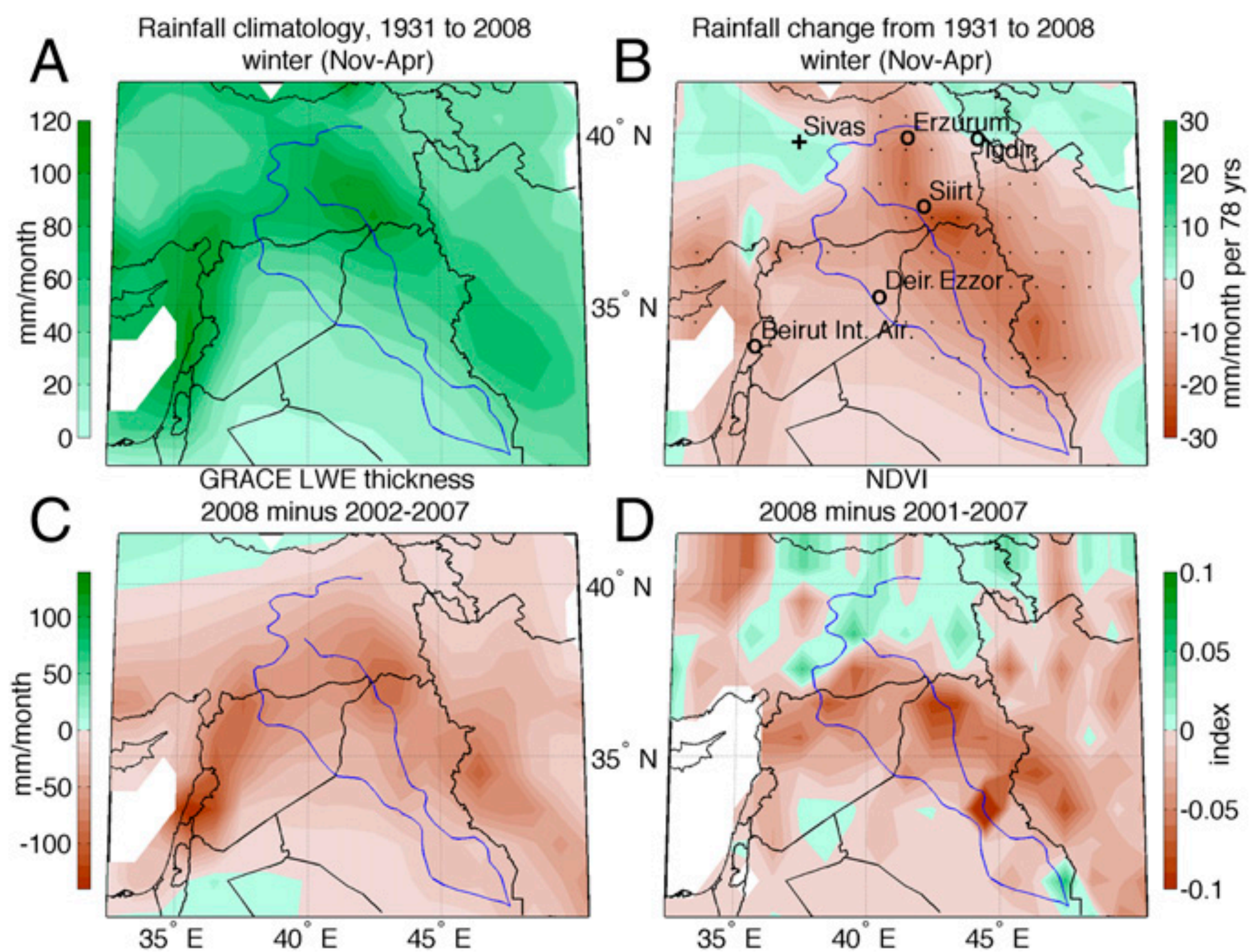


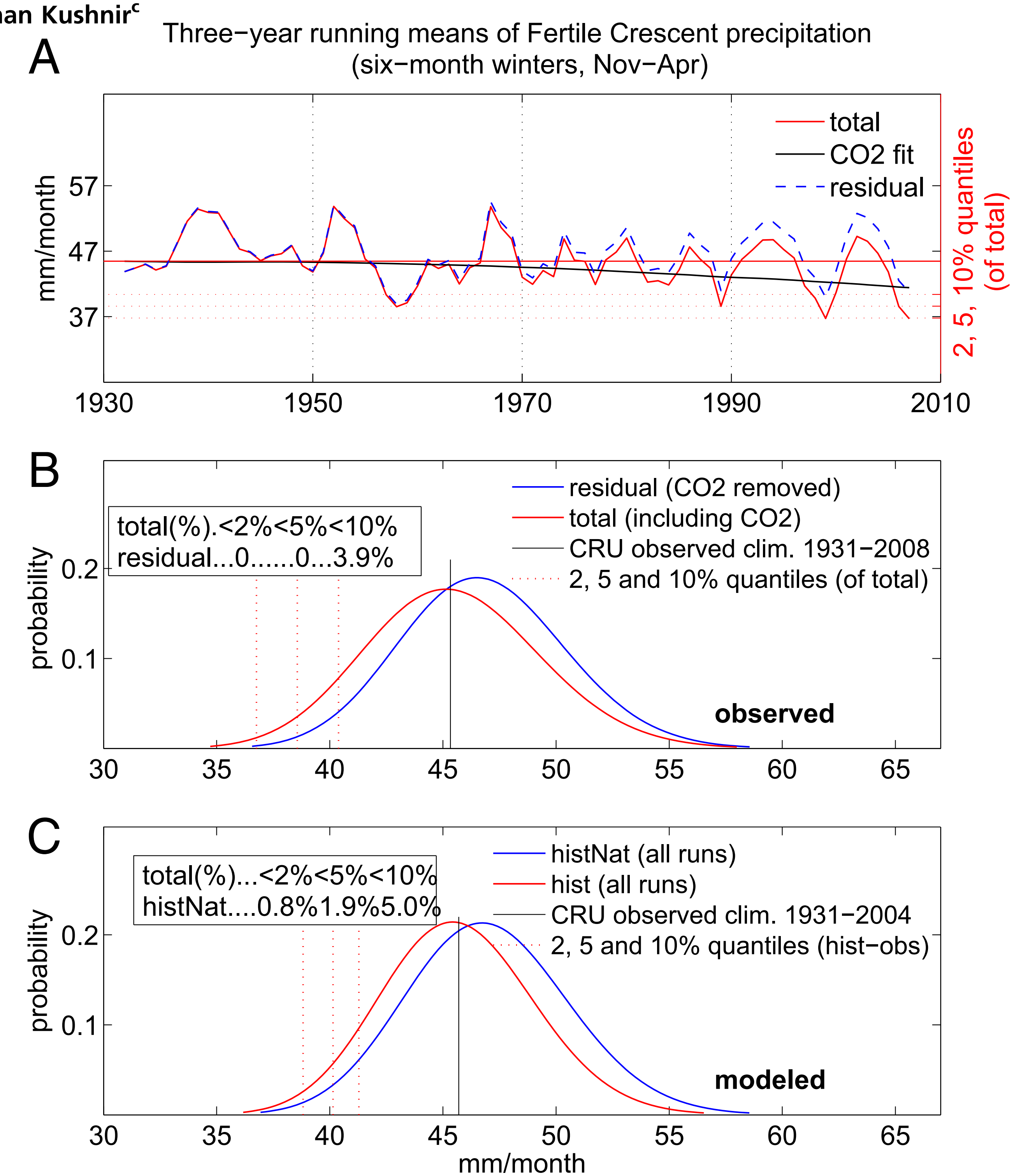
Syria was affected by a strong drying trend during the 2000s

Syria's civil war and drought

Climate change in the Fertile Crescent and implications of the recent Syrian drought

Colin P. Kelley[a,1], Shahrzad Mohtadi[b], Mark A. Cane[c], Richard Seager[c], and Yochanan Kushnir[c]

Fig. 3. (A) Timeseries of observed (CRU) 3-year running mean 6-month winter Fertile Crescent (FC) (area mean) precipitation: total (red), CO2 fit from regression (black), and the residual or difference between these (dashed blue). Frequency distributions based on gamma fits of 3-year running mean 6-month winter FC (area mean) precipitation, for the **(B)** observed data (corresponding with above) and **(C)** CMIP5 model simulations, comparing historical and histNat runs. Quantile thresholds based on the total (in B) and historical (in C) are shown at 2%, 5%, and 10% (dotted lines). **The tables** indicate the percentage of actual (B) observed (sample size 76) and (C) model simulated (sample size 46 × 72 for histNat and 69 × 72 for historical) occurrences exceeding the respective thresholds.



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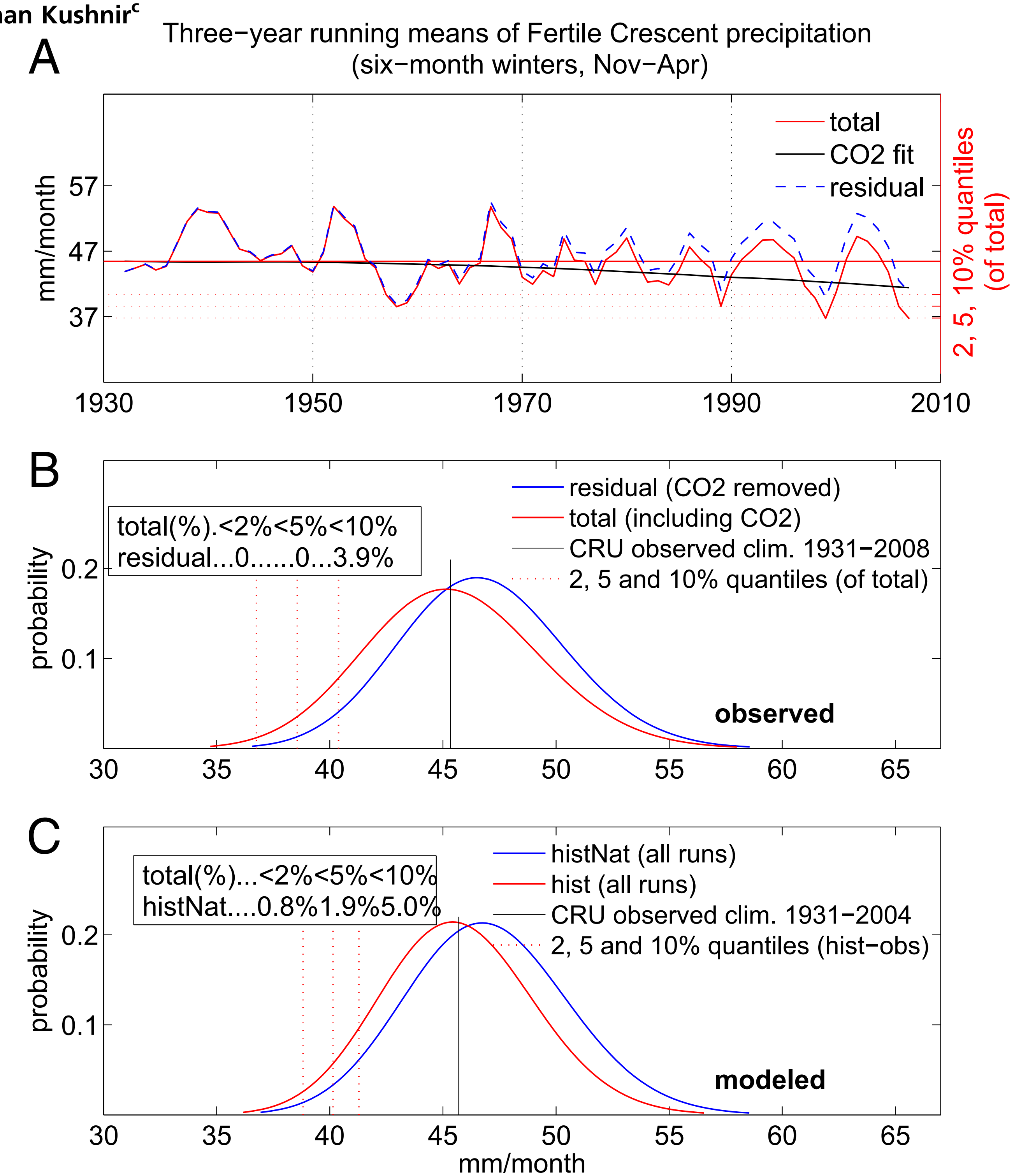

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Statistical analysis suggests that greenhouse forcing affected drought

More on observed & projected droughts in the IPCC report

Droughts in the 2013 IPCC report

TFE.9, Table 1 | Extreme weather and climate events: Global-scale assessment of recent observed changes, human contribution to the changes and projected further changes for the early (2016–2035) and late (2081–2100) 21st century. Bold indicates where the AR5 (black) provides a revised* global-scale assessment from the Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, blue) or AR4 (red). Projections for early 21st century were not provided in previous assessment reports. Projections in the AR5 are relative to the reference period of 1986–2005, and use the new RCP scenarios unless otherwise specified. See the Glossary for definitions of extreme weather and climate events.

Phenomenon and direction of trend	Assessment that changes occurred (typically since 1950 unless otherwise indicated)	Assessment of a human contribution to observed changes	Likelihood of further changes	
			Early 21st century	Late 21st century
Warmer and/or fewer cold days and nights over most land areas	*Very likely* {2.6} *Very likely* *Very likely*	***Very likely*** {10.6} *Likely* *Likely*	*Likely* {11.3}	*Virtually certain* {12.4} *Virtually certain* *Virtually certain*
Warmer and/or more frequent hot days and nights over most land areas	*Very likely* {2.6} *Very likely* *Very likely*	***Very likely*** {10.6} *Likely* *Likely* (nights only)	*Likely* {11.3}	*Virtually certain* {12.4} *Virtually certain* *Virtually certain*
Warm spells/heat waves. Frequency and/or duration increases over most land areas	***Medium confidence*** on a global scale *Likely* in large parts of Europe, Asia and Australia {2.6} *Medium confidence* in many (but not all) regions *Likely*	***Likely***[a] {10.6} Not formally assessed *More likely than not*	Not formally assessed[b] {11.3}	*Very likely* {12.4} *Very likely* *Very likely*
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation	*Likely* more land areas with increases than decreases[c] {2.6} *Likely* more land areas with increases than decreases *Likely* over most land areas	***Medium confidence*** {7.6, 10.6} *Medium confidence* *More likely than not*	*Likely* over many land areas {11.3}	***Very likely*** over most of the mid-latitude land masses and over wet tropical regions {12.4} *Likely* over many areas *Very likely* over most land areas
Increases in intensity and/or duration of drought	***Low confidence*** on a global scale *Likely* changes in some regions[d] {2.6} *Medium confidence* in some regions *Likely* in many regions, since 1970[e]	***Low confidence*** {10.6} *Medium confidence*[f] *More likely than not*	*Low confidence*[g] {11.3}	***Likely*** *(medium confidence)* on a regional to global scale[h] {12.4} *Medium confidence* in some regions *Likely*[e]
Increases in intense tropical cyclone activity	***Low confidence*** in long term (centennial) changes *Virtually certain* in North Atlantic since 1970 {2.6} *Low confidence* *Likely* in some regions, since 1970	***Low confidence***[i] {10.6} *Low confidence* *More likely than not*	*Low confidence* {11.3}	***More likely than not*** in the Western North Pacific and North Atlantic[j] {14.6} *More likely than not* in some basins *Likely*
Increased incidence and/or magnitude of extreme high sea level	*Likely* (since 1970) {3.7} *Likely* (late 20th century) *Likely*	***Likely***[k] {3.7} *Likely*[k] *More likely than not*[k]	*Likely*[l] {13.7}	***Very likely***[l] {13.7} *Very likely*[m] *Likely*

* The direct comparison of assessment findings between reports is difficult. For some climate variables, different aspects have been assessed, and the revised guidance note on uncertainties has been used for the SREX and AR5. The availability of new information, improved scientific understanding, continued analyses of data and models, and specific differences in methodologies applied in the assessed studies, all contribute to revised assessment findings.

Notes:

a Attribution is based on available case studies. It is *likely* that human influence has more than doubled the probability of occurrence of some observed heat waves in some locations.

b Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells.

c In most continents, *confidence* in trends is not higher than *medium* except in North America and Europe where there have been *likely* increases in either the frequency or intensity of heavy precipitation with some seasonal and/or regional variation. It is *very likely* that there have been increases in central North America.

d The frequency and intensity of drought has *likely* increased in the Mediterranean and West Africa and *likely* decreased in central North America and north-west Australia.

e AR4 assessed the area affected by drought.

f SREX assessed *medium confidence* that anthropogenic influence had contributed to some changes in the drought patterns observed in the second half of the 20th century, based on its attributed impact on precipitation and temperature changes. SREX assessed *low confidence* in the attribution of changes in droughts at the level of single regions.

g There is *low confidence* in projected changes in soil moisture.

h Regional to global-scale projected decreases in soil moisture and increased agricultural drought are *likely* (*medium confidence*) in presently dry regions by the end of this century under the RCP8.5 scenario. Soil moisture drying in the Mediterranean, Southwest USA and southern African regions is consistent with projected changes in Hadley circulation and increased surface temperatures, so there is *high confidence* in *likely* surface drying in these regions by the end of this century under the RCP8.5 scenario.

i There is *medium confidence* that a reduction in aerosol forcing over the North Atlantic has contributed at least in part to the observed increase in tropical cyclone activity since the 1970s in this region.

Droughts in 2013 IPCC report

Floods and Droughts: Compelling arguments both for and against significant increases in the land area affected by drought and/or dryness since the mid-20th century have resulted in a ***low confidence* assessment of observed and attributable large-scale trends**. This is due primarily to a lack and quality of direct observations, dependencies of inferred trends on the index choice, geographical inconsistencies in the trends and difficulties in distinguishing decadal scale variability from long term trends. On millennial time scales, **there is *high confidence* that proxy information provides evidence of droughts of greater magnitude and longer duration than observed during the 20th century in many regions**. There is *medium confidence* that more megadroughts occurred in monsoon Asia and wetter conditions prevailed in arid Central Asia and the South American monsoon region during the Little Ice Age (1450 to 1850) compared to the Medieval Climate Anomaly (950 to 1250). {2.6.2, 5.5.4, 5.5.5, 10.6.1}

Under the Representative Concentration Pathway RCP8.5: projections by the end of the century indicate **an increased risk of drought is *likely* (*medium confidence*)** in presently dry regions linked to regional to global-scale projected decreases in soil moisture. Soil moisture drying is most prominent in the Mediterranean, Southwest USA, and southern Africa, consistent with projected changes in the Hadley Circulation and increased surface temperatures, and **surface drying in these regions is *likely* (*high confidence*) by the end of the century under RCP8.5**. {12.4.5}

IPCC 2013: changes in droughts since the middle of the 20th century

Table 2.13 **Regional observed changes in a range of climate indices since the middle of the 20th century.** Assessments are based on a range of 'global' studies and assessments (Groisman et al., 2005; Alexander et al., 2006; Caesar et al., 2006; Sheffield and Wood, 2008; Dai, 2011a, 2011b, 2013; Seneviratne et al., 2012; Sheffield et al., 2012; Donat et al., 2013a, 2013c; van der Schrier et al., 2013) and selected regional studies as indicated. Bold text indicates where the assessment is somewhat different to SREX Table 3-2. In each such case a footnote explains why the assessment is different. See also Figures 2.32 and 2.33.

Region	Warm Days (e.g., TX90p[a])	Cold Days (e.g., TX10p[a])	Warm Nights (e.g., TN90p[a], TR[a])	Cold Nights/Frosts (e.g., TN10p[a], FD[a])	Heat Waves / Warm Spells[g]	Extreme Precipitation (e.g., RX1day[a], R95p[a], R99p[a])	Dryness (e.g,. CDD[a]) / Drought[h]
North America and Central America	*High confidence*: *Likely* overall increase but spatially varying trends[1,2]	*High confidence*: *Likely* overall decrease but with spatially varying trends[1,2]	*High confidence*: *Likely* overall increase[1,2]	*High confidence*: *Likely* overall decrease[1,2]	*Medium confidence*: increases in more regions than decreases[1,3] but 1930s dominates longer term trends in the USA[4]	*High confidence*: *Likely* overall increase[1,2,5] but some spatial variation *High confidence*: *Very likely* increase central North America[6,7]	*Medium confidence*: decrease[1] but spatially varying trends ***High confidence*[b]: *Likely* decrease central North America[4]**
Africa and Middle East	***Low to medium confidence*[b,d]: limited data in many regions but increases in most regions assessed** ***Medium confidence*[b]: increase North Africa and Middle East[19,20]** ***High confidence*[b]: *Likely* increase southern Africa[21,22,23]**	***Low to medium confidence*[b,d]: limited data in many regions but decreases in most regions assessed** ***Medium confidence*[b]: decrease North Africa and Middle East[19,20]** ***High confidence*[b]: *Likely* decrease southern Africa[21,22,23]**	***Medium confidence*[b,d]: limited data in many regions but increases in most regions assessed** ***Medium confidence*[b]: increase North Africa and Middle East[19,20]** ***High confidence*[b]: *Likely* increase southern Africa[21,22,23]**	***Medium confidence*[b,d]: limited data in many regions but decreases in most regions assessed** ***Medium confidence*[b]: decrease North Africa and Middle East[19,20]** ***High confidence*[b]: *Likely* decrease southern Africa[21,22,23]**	*Low confidence*[d]: insufficient evidence (lack of literature) *Medium confidence*: increase in North Africa and Middle East and southern Africa[3,19,21,22]	*Low confidence*[d]: insufficient evidence and spatially varying trends ***Medium confidence*[b]: increases in more regions than decreases in southern Africa but spatially varying trends depending on index[5,21,22]**	*Medium confidence*[d]: increase[19,22,24] ***High confidence*[b]: *Likely* increase in West Africa[25,26] although 1970s Sahel drought dominates the trend**

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.

The End