California Water Research

“Known unknowns” about increases in extreme events, climate dynamics, and deep uncertainty about climate model projections

DRAFT

February 2023 Deirdre Des Jardins

In the field of climate science, researchers use the term "known unknowns" to describe the factors that remain unclear despite ongoing research. The impacts of climate change have been accelerating over the past decade, and the current generation of climate models do not fully capture the increases in extreme events. The underlying climate dynamics are the focus of active research and model experiments by teams of researchers around the world the current generation of climate models. the current generation of climate models.

In this synthesis, we focus on some of the most significant "known unknowns" about the climate dynamics affecting California's precipitation. The goal is to show how combining evidence across scales from global to regional can provide a more comprehensive assessment of current knowledge about impacts of climate change. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group I (IPCC AR6 WG1 2021) emphasizes the importance of this approach, as it can increase confidence in attributing observed climate change to human influence and reduce uncertainties associated with single-variable assessments.

1. **Increases in frequency of extreme events**

The IPCC Working Group I (IPCC AR6 WG1 2021) found:

> Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5.
> (p. 25.)

In western North America, the Southwest has seen a megadrought, the driest two decades for soil moisture in the last 1200 years (Williams et al. 2020; Williams et al. 2022). California saw driest four year period in the observational record in 2012-2015 (CDWR 2016). The extreme heatwave in the Pacific Northwest in 2021 (Philip et al. 2021) was followed by extreme flooding in British Columbia (Gillett et al. 2022). In South America, Central Chile has been experiencing a prolonged dry period since 2010, with mean rainfall deficits from 20–40% (Garreaud et al. 2020). In Europe, there has been a steady increase in wetness in Central and Eastern Europe, Britain and Scandinavia, since 1983, the wettest 30 year period in the past 1000 years (Markonis et al. 2018). Western Europe saw extreme flooding in June 2021(Kreienkamp et al.

2021). With the same kind of north-south dipole as western North America, the Mediterranean region and Spain have had three dry decades since 1983 (Markonis et al. 2018). The Mediterranean region suffered an extreme heatwave in summer 2021 (Lhotka and Kyselý 2022). In 2022, there was an extreme Northern Hemisphere drought, affecting regions in North America, Europe, and Asia. (Schumacher et al. 2022).

The same year that the IPCC Working Group 1 report came out, European researchers published a study (Robinson et al. 2021) that found a staggering increase in the most extreme heat waves and precipitation events. The research team found that 3-sigma and 4-sigma extremes - events that are three and four standard deviations from the mean, respectively - became much more common in the first decade of this century, covering about 5% of the global land area from 2001 to 2010. This percentage increased rapidly to about 9% over the subsequent decade, representing a roughly 90-fold increase compared to the period from 1951 to 1980. What is particularly alarming is that the occurrence of 4-sigma extremes, which were nearly absent in the first decade of the century, affected about 3% of the land area from 2011 to 2020, reflecting a roughly 1000-fold increase compared to 1951 to 1980. (See Figure 1.)

(Robinson et al. 2021) found huge increases in extreme heat events on every continent, and statistically significant increases in precipitation extremes in Europe, Asia, eastern South America, and the central US. However, they found a statistically significant decrease in precipitation extremes in western North America. The IPCC Working Group 1 found low confidence in the direction of change in precipitation extremes in western and northwestern North America. Nevertheless, Working Group 1 found medium confidence in the human contribution to the increase in drought in western North America, the Mediterranean, and South Africa, as well as central Asia (IPCC AR6 WG1 Figure SPM.3)

The declining trend in extreme precipitation in western North America for 2011-2020 is anomalous in that extreme precipitation is expected to increase as the planet warms due to an increase in the water holding capacity of the atmosphere as represented by the Clausius–Clapeyron relationship, and has been increasing in most other regions. (IPCC AR6 WG1 2021) states that the projected increase in the magnitude of extreme precipitation is estimated at about 7% per 1°C warming, states “although this rate shows seasonal and geographical variations and is slightly less for five-day than for one-day precipitation maxima.”

While coupled climate models predict an increase in wet extremes in western North America (Swain et al. 2018; Gershunov et al. 2019; Rhoades et al. 2021), observations have shown a long term declining trend in extreme precipitation in this region. For instance, (Lamjiri et al. 2020) analyzed trends in annual 3-day maximum precipitation totals in the continental US from 2050-2019 and found a declining trend in western North America. As discussed later in this report, this anomalous trend may be related to major shifts in ocean / atmosphere dynamics that impact the number and duration of landfalling atmospheric rivers on the west coast of North America and California.

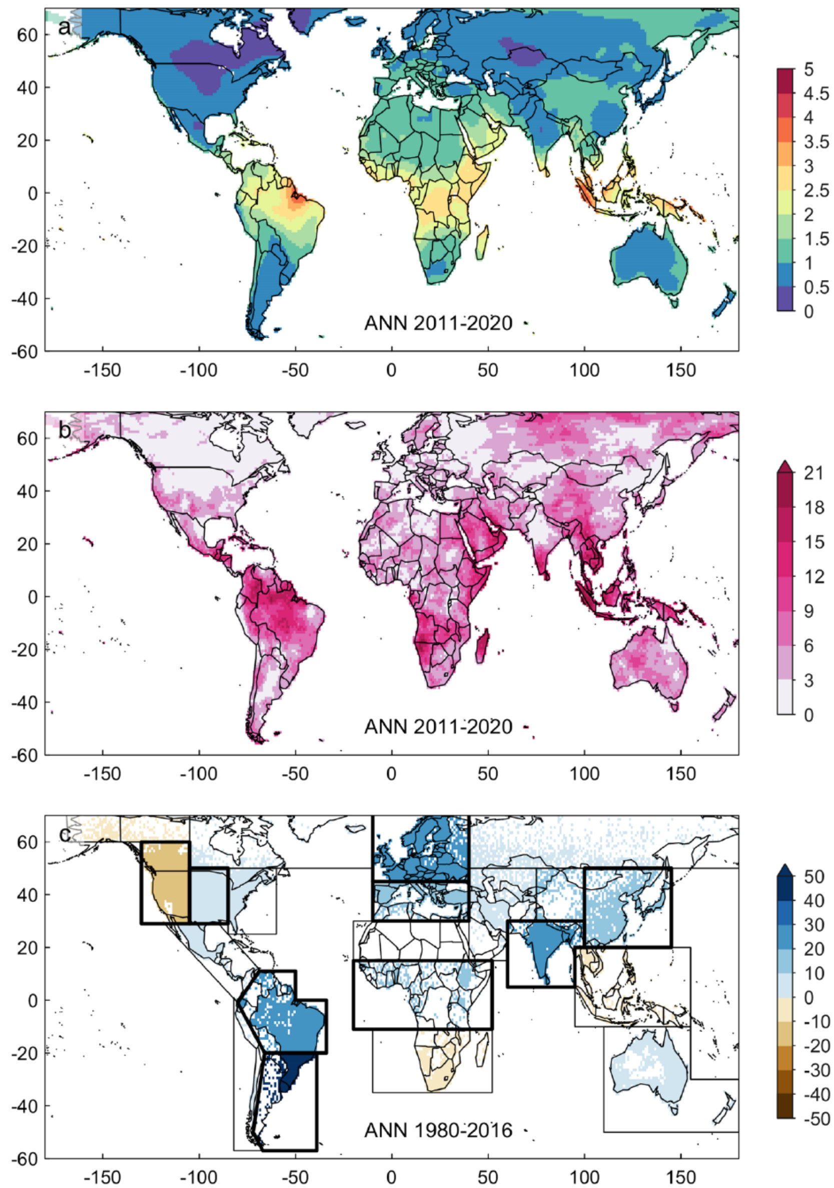

Figure 1 (Robinson et. al. 2021) Caption: Extremes and records of the last decade. Top panel: annual mean temperature anomalies (units of σ) for 2011−2020. Middle panel: total number of monthly temperature records for 2011−2020 (the maximum possible value at each grid point is 120 = 12 months × 10 years). Bottom panel: Deviation of observed daily-rainfall records from those expected in a stationary climate (in %), aggregated for SREX regions and averaged between 1980 and 2016. Regions with statistically significant deviations from a stationary climate are highlighted with bold frames. ([Creative Commons 4.0 license](#))

2. **Climate adaptation under increasing uncertainty**

The California Department of Water Resources last convened a general Climate Change Technical Advisory Group (CCTAG) from 2012-2015. The report (CCTAG et al. 2015) emphasized the importance of understanding underlying hydrologic and atmospheric processes and identifying knowledge gaps about how the processes integrate to produce floods or droughts. The group also recommended further investigation into variability across different scales:

> Finally, the CCTAG recognizes that variability across different space and time scales, including decadal scale variability, is an important part of the climate system that may not be adequately understood or captured in the observed historical record. Its incorporation into stress tests and extremes has a clear tie to evaluating water system shortages resulting from droughts of various magnitudes and durations. Further investigation and discussion should be included in future efforts.

Recent years have seen increasing uncertainty about the causes of reduced precipitation in western North America. An influential mid-drought attribution study of the 2012-2016 California drought by (Seager et al. 2014) attributed the reduced precipitation to decadal variability, as the coupled global climate models projected only weak drying. The authors noted "[t]he other point of faith in the model projections is that they correctly represent the radiatively-forced SST change" and that observed trends in the tropical Pacific were contrary to model projections.

Since 2015, there has been a huge investment in supercomputer time to run large ensembles of global climate models, enabling much better evaluation of internal variability of the models and greatly improving our understanding of the relative roles of internal variability and forced change in the climate dynamical system (Kay et al. 2015; Deser 2020; Deser et al. 2020; Mankin et al. 2020). (IPCC AR6 WG1 2021) highlighted the increased use of large ensembles as a significant improvement, allowing a better quantification of uncertainty in projections due to internal climate variability, stating:

> Simulations and understanding of modes of climate variability, including teleconnections, have improved since AR5 (medium confidence), and larger ensembles allow a better quantification of uncertainty in projections due to internal climate variability.

Large ensembles have been critical in recent years in advancing our understanding of the uncertainty of climate model projections due to model structural uncertainty, which comes from our incomplete understanding of the complex dynamics of the climate system, and imperfect representation of known processes (Deser 2020). The recent study by Seager et al. (2022), co-authored by two of the authors of the influential 2014 California drought attribution study, significantly undermines the conclusion that the drought was caused by natural variability. The authors used large ensembles to evaluate climate models' ability to reproduce observations-based trends in tropical Pacific Sea surface temperature. The study found that the latest generation of models still failed to reproduce these trends, leading the authors to conclude that the observed trends are extremely unlikely to be consistent with modeled internal variability.

Seager also co-authored a review with leading researchers (Lee et al. 2022), which concluded that there is major uncertainty about the affect of climate change on the complex dynamics of the tropical Pacific and the future evolution of the El Niño / Southern Oscillation (ENSO.) In the face of low confidence in future projections, the researchers suggested that a storyline approach could provide a pathway for describing risks to users, with climate adaptation practitioners outlining the divergent possible futures based on model projections and observational trajectories. The Delta Independent Science Board (Delta Independent Science Board 2022) also recommended a scenario-based approach for uncertainties about water resources that cannot be reliably predicted, stating:

Non-probabilistic scenarios and sensitivity analyses are useful to explore the stability, impacts, and adaptability of water management solutions under uncertainties that cannot be reliably predicted.

Recent years have also seen cascading climate impacts of extreme heat, drought, increasing aridity, wildfires, increased storm intensity and flooding. The ocean / atmosphere and land / atmosphere interactions and feedbacks causing these cascading impacts are incompletely understood. (IPCC AR6 WG1 2021) found that:

> Very rare extremes and compound or concurrent events, such as the 2018 concurrent heatwaves across the Northern Hemisphere, are often associated with large impacts. The changing climate state is already altering the likelihood of extreme events, such as decadal droughts and extreme sea levels, and will continue to do so under future warming. Compound events and concurrent extremes contribute to increasing probability of low-likelihood, high-impact outcomes and will become more frequent with increasing global warming (high confidence).

(Dettinger and Culberson 2008) observed rather presciently that "human-induced climate changes, mostly in the form of long-term trends, are projected to be larger and more sustained than those long-term fluctuations in the historical period, and comparable to—or larger than—natural climate excursions in the past several millennia."

Analyses of recent trends are also complicated by the fact that the climate during the observational record from the 19th to the 21st Century is likely nonstationary. The accelerating increase in global surface temperature seen in the 20th Century started around 1950 at the end of the Little Ice Age. See Figure 2, reproduced from (IPCC AR6 WG1 2021).

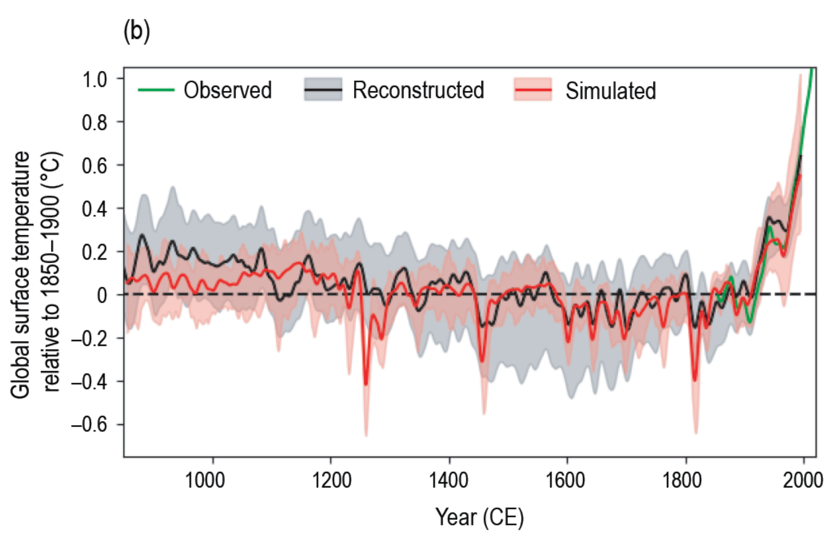

Figure 2 Global surface temperature (IPCC AR6 WG1 2021) Box TS2, Fig 2B

In the face of such uncertainty, (Dettinger and Culberson 2008) urged California researchers and climate adaptation practitioners to:

- Address more certain projections directly and less certain changes by increasing flexibility

- Pursue risk-based decision-making
- Support competing hypotheses
- Explore contradictions

The rest of this report explores the recent multidecadal shifts in modes of climate variability that affect precipitation in California, going from global to synoptic to regional scale.

1. A trend in increasing monthly ocean and land temperature autocorrelations and variability since mid-century
2. A possible slowdown in the Atlantic Meridional Overturning Circulation
3. A (temporary?) slowdown in the Pacific Meridional Overturning Circulation
4. Shifts in the Atlantic Multidecadal Variability (AMV)
5. Shifts in the El Niño / Southern Oscillation, including
    a. A shift to a more La-Niña like pattern in the tropical Pacific, starting around 1999 / 2000
    b. A shift in the types of El Niños, starting in the mid-1970s
6. Shifts in the Pacific Decadal Variability (PDV)
7. A decrease in atmospheric rivers landfalling on the west coast and California since mid-century
8. An increase in atmospheric ridging in the Northeast Pacific associated with drought

We also explore recent research which shows that some major knowledge gaps persist with the current generation of coupled global climate models. Coupled climate models fully integrate representations of the physical processes that form the climate dynamical system, including the atmosphere, oceans, land surface, and cryosphere. Coupled climate models are referred to by generation of the Coupled Model Intercomparison Project. The fifth CMIP (CMIP5) was conducted from 2008 to 2014 and involved 20 modeling groups and more than 30 models. The California Department of Water Resources has been using models from CMIP5 for climate change studies.

The sixth CMIP (CMIP6) was conducted from 2016 to 2022 and involved more than 40 modeling groups and more than 100 models. CMIP6 includes significant improvements over CMIP5, including higher spatial resolution and more detailed representations of atmospheric and oceanic processes. However, significant gaps in our knowledge remain, and are the focus of experiments by Model Intercomparison Projects (MIPs) which focus on representations of major components such as the atmosphere, oceans, or cryosphere. This report also inventories major knowledge gaps related to differences between coupled climate model projections and observations, from the global to the regional scale.

1. Coupled climate models are unable to replicate global climate variability in observed sea surface temperatures in the Atlantic and Pacific.
2. Coupled climate models are unable to reproduce current multidecadal trends in the El Niño / Southern Oscillation towards a La-Nina like pattern.
3. CMIP5 coupled climate models systematically underestimate the low frequency multidecadal variability in the Pacific Ocean. It is slightly improved in CMIP6 but remains a concern.

4. Declining trends in maximum annual precipitation and landfalling atmospheric rivers on the west coast of North America are contrary to coupled climate model ensemble projections.
5. The “drier, extreme warming” HadGem2-ES climate model was one of the climate models found to best model atmospheric ridging in the North Pacific associated with the 2012-2016 drought.

The final section of this report looks at recent multidecadal trends in precipitation in California. Distinguishing recent multidecadal shifts in precipitation and increased frequency of extreme events from natural variability is complex and difficult. In California, paleoclimate reconstructions also show much larger variability across timescales than found in the observational record (Malamud-Roam et al. 2007).

However, as noted by (Palmer 1999) changing probability distributions for regional climate variations is expected to be the first response to external forcing by anthropogenic climate change. Recent changes observed in climate variables are therefore consistent with the behavior of coupled, nonlinear dynamical systems perturbed by external forcing. While the shifts may be consistent with known patterns of natural variability over millennial timescales, this does not necessarily disprove an anthropogenic cause.

3. **Global shifts in ocean dynamics**

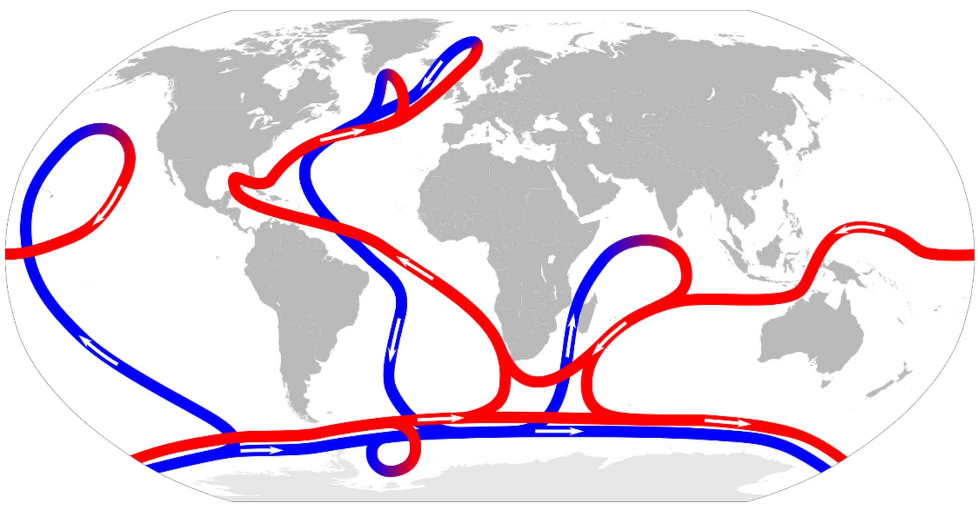

Figure 3 Global meridional overturning circulation (Robert Simmon, NASA. Minor modifications by Robert A. Rohde)

This section looks at global, decadal scale variability in ocean dynamics. In complex systems theory, it has been found that when simplified models of large, coupled systems approach tipping points, they tend to exhibit increased autocorrelation, meaning that the behavior of the system in its current time step becomes more dependent on its behavior in previous time steps. The system also becomes increasingly sensitive to small perturbations and feedback mechanisms (Lenton et al. 2008; Scheffer et al. 2009; Lenton 2011).

It is therefore potentially highly significant that (Lenton et al. 2017) found that monthly temperature variability and autocorrelation increased over the period of 1957-2002 in large parts of the North Pacific, North Atlantic, North America, and the Mediterranean. The increased autocorrelation may be associated with the slowdown of the Atlantic part of the global Meridional Overturning Circulation, called the AMOC. (Figure 3 shows the global Meridional Overturning Circulation.)

(Caesar et al. 2021) examined multiple different proxy indicators of the AMOC and found evidence that there was an unprecedented decline in the 20th century, concluding that “the AMOC is currently in its weakest state in over a millennium.” However, (Kilbourne et al. 2022) argued that the conclusions of (Caesar et al. 2021) could be different if a more data from the North Atlantic region was analyzed, and that the strength of the AMOC over recent centuries is still poorly constrained.

(IPCC AR6 WG1 2021) found it “very likely” that the AMOC will weaken by 2100 and only medium confidence that there will not be an abrupt collapse before 2100. (p. 1165.)

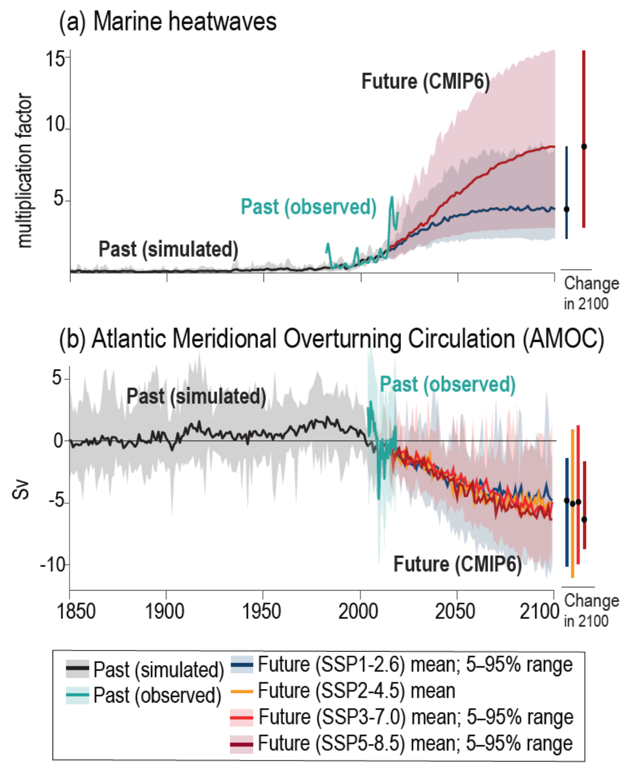

Figure 4 Marine Heatwaves and AMOC (IPCC AR6 WG1 2021) Figure TS.11

Compared to the AMOC, the Pacific Meridional Overturning Circulation (PMOC) has had few studies, but (McPhaden and Zhang 2002) analyzed hydrographic data and found a slowdown starting in the mid-1970s, which was confirmed by later studies of dissolved oxygen (Deutsch et al. 2006) and chlorofluorocarbons ((Sonnerup et al. 2007). The slowdown coincided with a warming of the eastern equatorial Pacific by 1°C, a shift in El Niño types, and with a shift in North Pacific dynamics that was later determined to be part of the Pacific Decadal Variability (Miller et al. 1994; Trenberth and Hurrell 1994; Mantua et al. 1997).

(McPhaden and Zhang 2004) found a rebound in PMOC after the strong La Niña of 1998 through 2003. SSTs in the eastern equatorial Pacific dropped by more than 0.6°C. The shift occurred after a positive shift in the Atlantic Multidecadal Variability, a pattern of slow variations in Atlantic sea surface temperatures over about 60-80 years. The warm phase of the AMV is associated with warm SST anomalies in the North Atlantic, and the cool phase with cool SST anomalies. when sea surface temperatures in the North Atlantic are warmer than normal, and a cool phase, when sea surface temperatures in the North Atlantic are cooler than normal, but there are associated variations in the Pacific Ocean (Figure 5).

(IPCC AR6 WG1 2021) found evidence for "two-way teleconnections between the tropical Atlantic and Pacific on interannual to decadal time scales, such that the tropical Atlantic variability responds and feeds back to the Pacific." (Yang et al. 2020) found that Pacific SST anomalies are driven by a coupling of the variation in surface SSTs in the tropical Atlantic with the tropical Pacific via surface wind anomalies in the central and eastern Pacific.

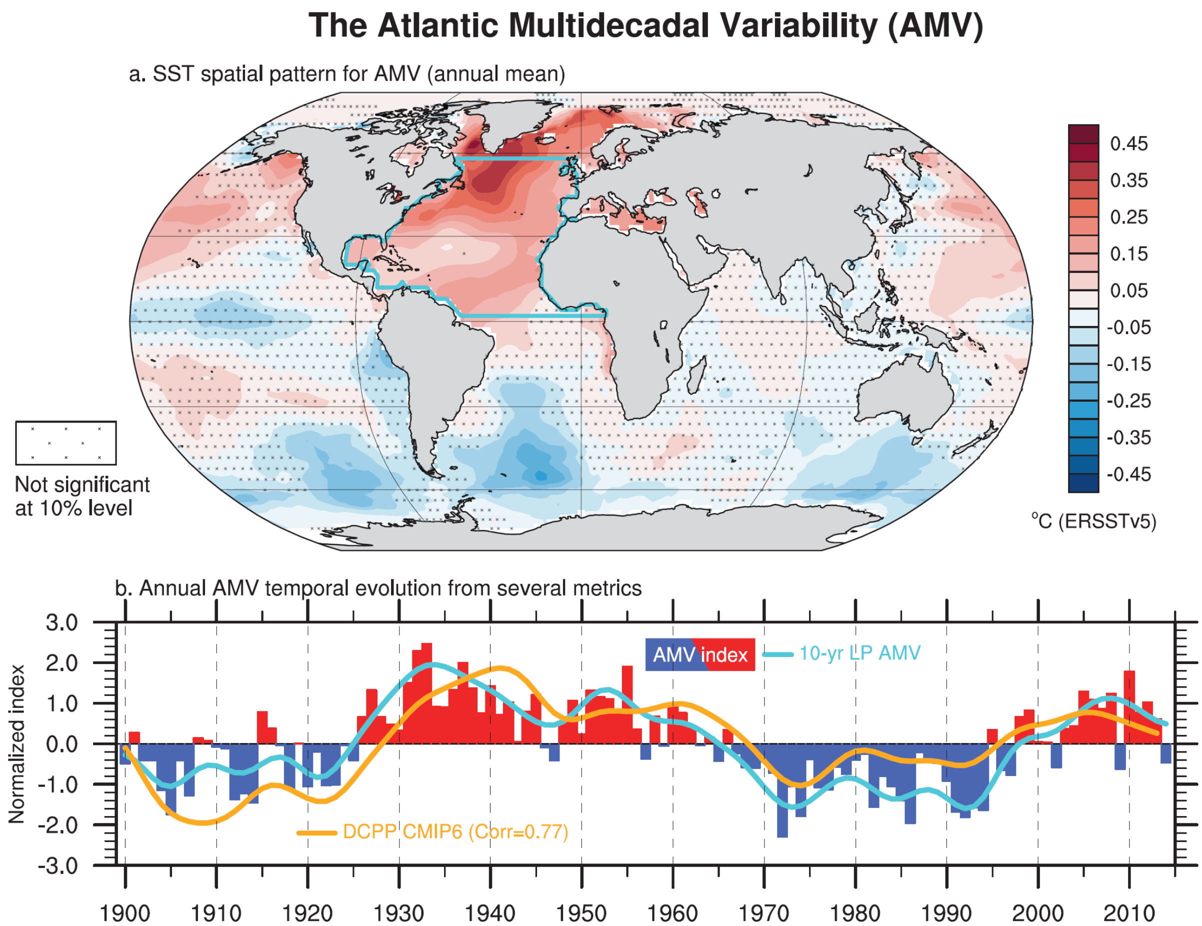

Figure 5 Atlantic Multidecadal Variability (IPCC AR6 WG1 Annex IV)

(Orihuela-Pinto et al. 2022) forced a global climate model with fresh water added to the Atlantic to analyzed impacts of AMOC shutdown on the Pacific. They found that ENSO variability decreased by about 30%, with a stronger Walker circulation and a shift toward more central Pacific El Niño than eastern Pacific El Niño events, and a 95% reduction in extreme El Niños. As will be discussed, similar changes have been seen in recent years, except for the reduction in extreme El Niños.

(Kravtsov et al. 2018) found that global climate models are unable to replicate global decadal-scale climate variability (DCV):

global DCV modes are likely to be due to a combination of multiple slow, regional-to-basin-scale oceanic processes defining dynamical memory of the climate system in the presence of fast, large-scale atmospheric processes. The latter fast processes can both supply energy for DCV and provide means for intra- and inter-basin communication and synchronisation of decadal climate modes.

Controlled coupled climate model experiments nudged to replicate the observed surface temperatures in the Atlantic or Pacific sector are able to simulate observed global teleconnections associated with DCV… However, free runs of these models are much less skillful in reproducing these teleconnections… our results summarise and rigorously document pronounced quantitative discrepancies between models and observations…

4. **Shifts in the El Niño / Southern Oscillation**

The El Niño / Southern Oscillation (ENSO) is the dominant global mode of interannual variation in sea surface temperatures. (Tung et al. 2019). The La Niña has warm anomalies in the Pacific warm pool, a large area of shallow seas around the Indonesian archipelago. During La Niña, the trade winds and the Walker circulation are stronger than usual, and the eastern Tropical Pacific Ocean is cooler than usual. See Figure 6, from (Halpert et al. 2016).

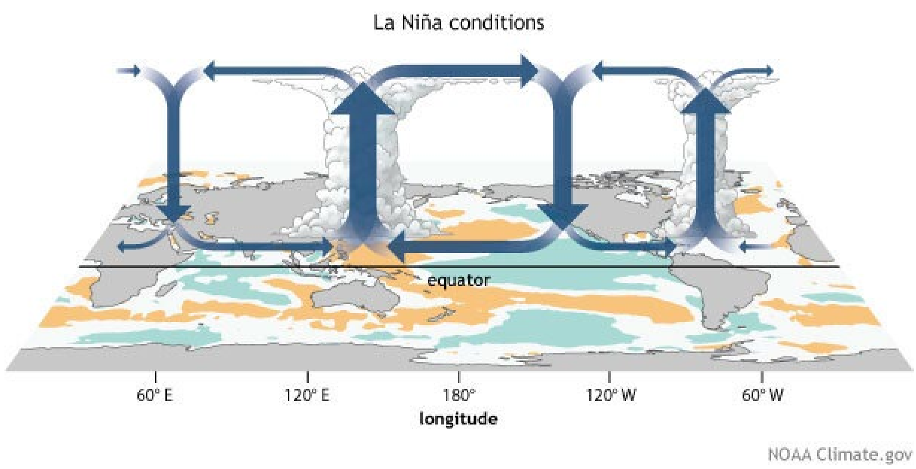

Figure 6 La Niña conditions *Source: NOAA Climate.gov*

During El Niño, it's the opposite. Trade winds are weaker than usual. There is less upwelling, and the sea surface temperatures in the central and eastern tropical Pacific are warmer than average. Rainfall is above average over the central or eastern Pacific, and below average over the Indonesian archipelago. (See Figure 7, from (Halpert et al. 2016)

This section looks in detail at the 21st Century shift to La-Nina like patterns in the tropical Pacific, which happened after the strong 1998 La Niña. The pattern shift has been associated with the 21st Century megadrought in the Southwest, the worst soil moisture drought in the last 1200 years (Williams et al. 2020; Williams et al. 2022).

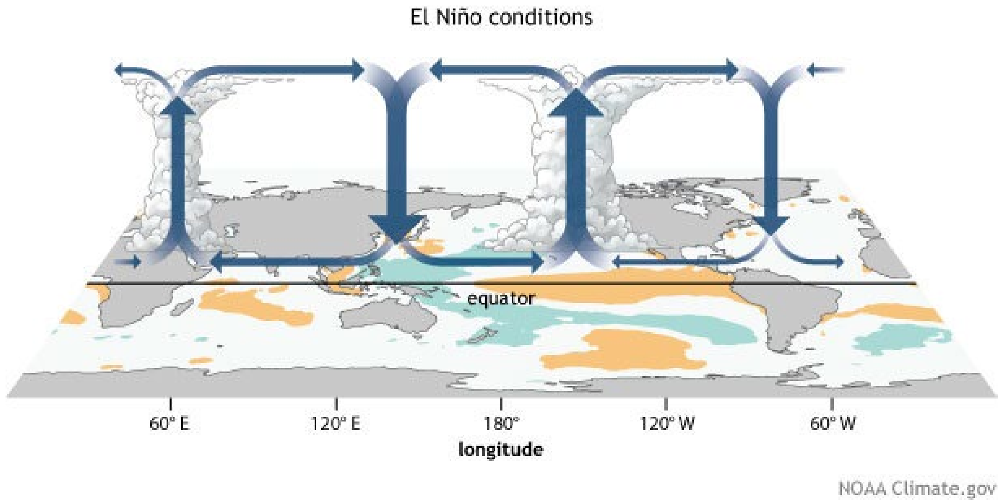

Figure 7 El Niño conditions (Halpert et. al. 2016)

La Niña-like patterns in the tropical Pacific have been associated with persistent droughts in the Southwest in the mid to late 19th century, the Dust Bowl era drought in the 1930s, and drought in the late 1940s to mid-1950s. (Schubert et al. 2004; Seager et al. 2005; Herweijer and Seager 2008). A study of reconstructed paleo drought data by (Steiger et al. 2019) suggested that Southwest decadal scale megadroughts between AD 800 and 1600 were "primarily driven by anomalously frequent and cold, unforced La Niña conditions, with contributions from a partially forced warm Atlantic and a forced local temperature increase."

Figure 8 shows the Multivariate ENSO Index, designed to capture persistent patterns in "sea level pressure, sea surface temperature, zonal and meridional components of the surface wind, and outgoing longwave radiation over the tropical Pacific basin." (NOAA Physical Sciences Laboratory 2023). Negative (blue) values of the index are La Niña patterns, and positive (red) values are El Niño patterns. The blue on the chart after 2000 shows the prolonged shift to predominantly La Niña-like patterns in the 21st Century.

The report of the IPCC AR6 WG1 (IPCC AR6 WG1 2021) describes a long term trend towards La-Nina like conditions, starting in the late 19th Century:

> Since 1870, observed SSTs in the tropical western Pacific Ocean have increased while those in the tropical eastern Pacific Ocean have changed less… Much of the resultant strengthening of the equatorial Pacific temperature gradient has occurred since about 1980 due to strong warming in the west and cooling in the east... concurrent with an intensification of the surface equatorial easterly trade winds and Walker circulation. (p. 988)

The intensification of the eastern trade winds and the Walker Circulation is anomalous; climate models project that the circulation will weaken. The assessment in Chapter 3 in (IPCC AR6 WG1 2021) concludes:

> The causes of the observed strengthening of the Pacific Walker circulation since the 1980s are not well understood, and the observed strengthening trend is outside the range of trends simulated in the coupled models (medium confidence).

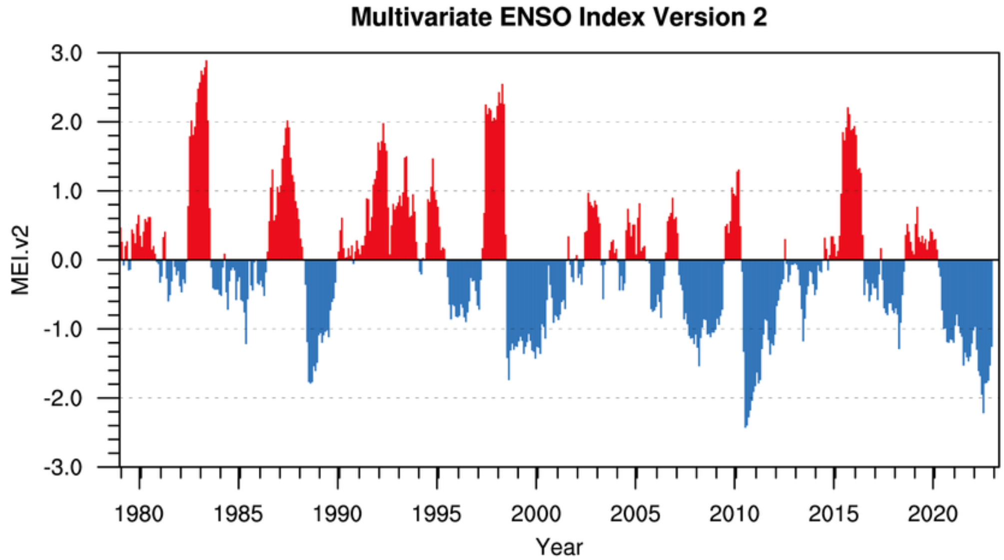

Figure 8 Multivariate ENSO Index (NOAA Physical Science Laboratory)

However, (IPCC AR6 WG1 2021) also concludes:

> Because the causes of observed equatorial Pacific temperature gradient and Walker circulation trends are not well understood… there is low confidence in their attribution to anthropogenic influences…while there is medium confidence that the observed changes have resulted from internal variability.

The failure of climate models to capture recent trends in the tropical Pacific is a major focus of current research. There have been several new studies published since the (IPCC AR6 WG1 2021) report, which significantly reduce confidence that the observed changes have resulted from internal variability as represented by current climate models.

In a review article, (Lee et al. 2022) describe the known issues with the climate models from the fifth and sixth phases of the Coupled Model Intercomparison Project (CIMP5 and CMIP6), and Large Ensembles of those models (Kay et al. 2015).

> During 1958-2017, observed trends in the Niño-3.4 index… lie either on the cold fringe, or entirely outside of, the spread of CMIP5 historical simulations (Seager et al. 2019) [associated figure reproduced as Figure 9.] Discrepancies… persist in the CMIP6 models… Moreover, notable discrepancies were found between the observations and 35 runs of the NCAR Large Ensemble (LENS) project (Seager et al. 2022). These analyses indicate that the observed SST trends ending in the current decade are at the very limit of the range of trends in individual CMIP5, CMIP6, and LENS model runs. The disparity

between CMIP5 trends and the observational data has also been noted in the acceleration of the Pacific Walker circulation (Li et al. 2019) [footnote citations converted.]

(Wills et al. 2022) used 16 initial-condition large ensembles to explore whether the mismatch between observed and modeled trends of SSTs between 1979–2020 could be explained by internal variability. The authors found "large-scale differences that were very unlikely (<5% probability) to occur due to internal variability as represented in models."

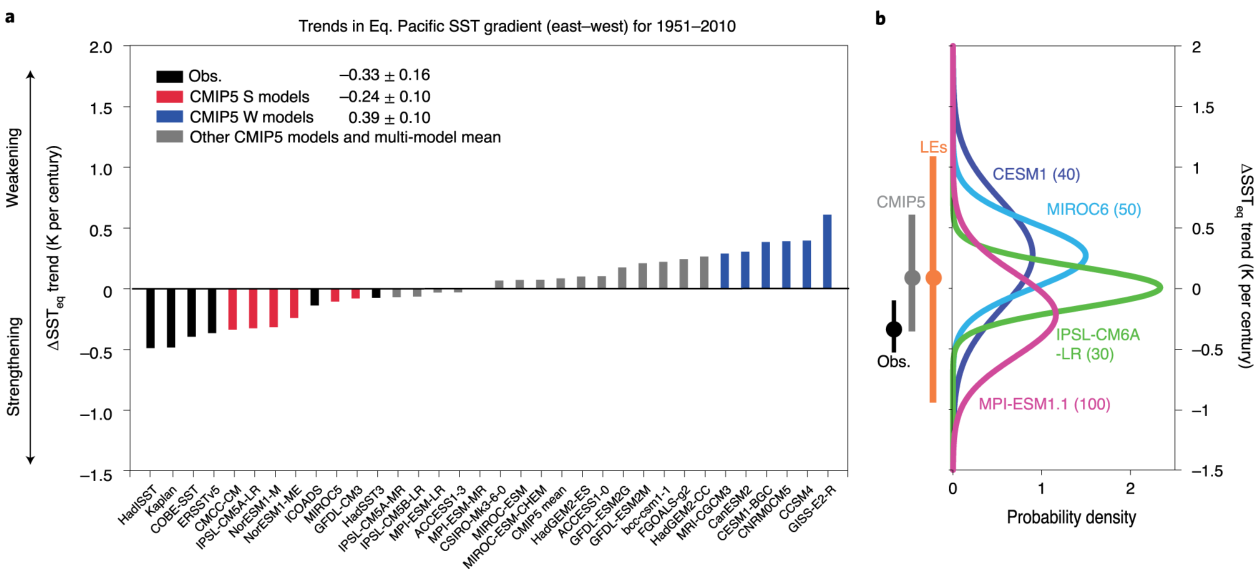

Figure 9 CMIP5 models and Observed SST trends (Lee et. al. 2022)
***a** Linear trends for 1951–2010 of the equatorial Pacific zonal SST gradient from six observational data sources (Obs), and 27 CMIP5 models… **b** Probability density function of the 1951-2010 SST gradient trends in four large ensemble simulations indicated in the figure. The ensemble size is indicated in parentheses. Dots and bars in the left margin of b indicate the means and 5–95% ranges. (Creative Commons 4.0 license)*

In conclusion, several thorough analyses of CMIP5, CMIP6, large ensembles, and initial-condition large ensembles have been published since the IPCC 2021 report, with significant findings that it is very unlikely that the discrepancy between observed and modeled trends in the tropical Pacific are due to modeled internal variability. Even before this research, the IPCC only gave medium confidence that recent trends are due to internal variability.

5. **"Known unknowns" about physical processes in the tropical Pacific**

(Lee et al. 2022) has a comprehensive review of "known unknowns" about physical processes in the tropical Pacific. According to the authors, "[t]heories exist that support the model projections and argue that the zonal SST gradient should weaken while other theories are consistent with the observed trajectories and argue that the zonal SST gradient should strengthen."

(Lee et al. 2022), considers three leading theories. In an El-Nino like future, the Walker circulation slows down, weakening upwelling in the eastern Pacific, leading to more warming. The second alternative has continued upwelling of cold water in the eastern Pacific, because the deepest ocean waters will be slower to warm due to climate change. This leads to a La-Nina like future. A third process creates a La-Nina like future by convection feed backs. Warming causes stronger convection over the Pacific warm pool, strengthening circulation. Reduction in cloud cover on the periphery of the Pacific warm pool allows more infrared radiation to space. Air over the western Pacific Ocean becomes moister, promoting even stronger convection, and therefore strengthening the Walker circulation. See the accessible and informative discussion by leading researchers on NOAA's ENSO blog (Lee et al. 2023).

In the same discussion on NOAA's ENSO blog, Ulla Heede states:

> It is entirely possible that the La Niña-like trends in the Pacific we are observing now are transient (short-term) and will reverse at some point in the next 100 years and start to look more like the modeled projections, with the eastern Pacific Ocean warming faster than the rest of the tropical oceans (9). Even if it is just transient, we need to understand these trends better: is it a response to global warming? (I tend to think so!), natural variability, or some mix of the two?

(Heede et al. 2020) forced the Community Earth System Model with a "wide range of both abrupt and gradual CO2 increases" and found "a robust transient response to CO2 forcing across all simulations, lasting between 20 and 100 years, depending on how abruptly the system is perturbed." The initial response is a La-Nina like pattern, and the equilibrium response, emerging after 50-100 years, is an El Niño-like pattern. The rather staggering implication is that if the current La-Nina like pattern in the tropical is strongly influenced by transient effects of anthropogenic forcing, it could continue for as long as another 30-70 years.

(Lee et al. 2022) consider such uncertainties and conclude

> Climate models have been extensively used for climate risk mitigation planning. In contrast, observational trends that deviate from model consensus projections have been widely regarded as being caused by internal variability, and hence have not been considered for climate risk assessments. However, given the possibility that observed tropical Pacific SST trends that deviate from the model consensus projection might include a forced response, observed SST trends should also be considered when assessing climate risks. Faced with this emerging evidence, not taking observed trajectories into consideration increases the possibility of making a type 2 error, i.e. a missed warning.

6. **The Pacific Decadal Variability**

Pacific Decadal Variability (PDV) has been found to be a third leading mode of global multidecadal variability in sea surface temperatures, along with global warming and the AMV (Yang et al. 2020). The PDV was also found to be the leading mode of variability associated with unforced decadal global surface air temperature fluctuations, with additional influence from the AMV (IPCC AR6 WG1 2021).

The PDO was first defined by (Mantua et al. 1997), as the dominant pattern (first mode in an Empirical Orthogonal Function) in decadal scale variations in monthly SSTs in the North Pacific.(Power et al. 1999) defined an Interdecadal Pacific Oscillation, which encompasses the entire Pacific. There are a number of other indices which collectively represent Pacific Decadal Variability, but are not independent (IPCC AR6 WG1 2021). (IPCC AR6 WG1 2021) noted that the instrumental record is too short to robustly characterize multidecadal cycles in the PDV, and proxy reconstructions disagree:

> There is little coherence between the various paleo-proxy indices prior to the instrumental record, and neither these nor the instrumental records provide indications of a clearly defined spectral peak (Chen and Wallace, 2015; M. Newman et al., 2016; Henley, 2017; L. Zhang et al., 2018; Buckley et al., 2019).

Because of the difficulty of proving or disproving theories about the PDV, it has been the subject of active research and debate for decades.

(Roe 2009) famously observed that the PDV "should be characterized as neither decadal nor an oscillation (though it is in Pacific)." Roe used feedback analysis to show that earth systems which have a sensitive response to forcing will have inherently long oscillatory response times to either internal or external forcing. Since the PDV does not have a clearly defined spectral peak, an alternative hypothesis is that it is a red noise process caused by external forcing from volcanos, aerosols, or greenhouse gas emissions.

(Mann et al. 2020) recently provided more evidence for the external forcing hypothesis, for both the PDV and the AMV. A multivariate signal detection algorithm was used to search for spectral signatures in observational data and climate model control runs. They found "no compelling evidence… for any robust interdecadal or multidecadal climate oscillations, with the only signals that are distinct from coloured noise found within the interannual ENSO frequency band. (Mann et al. 2021) analyzed CMIP5 runs, and found a "robust multidecadal, narrowband (50- to 70-year) oscillatory 'AMO-like' signal in simulations of the past millennium; the oscillation is driven by episodes of high-amplitude explosive volcanism that happen, in past centuries, to display a multidecadal pacing."

The role of external forcing in the AMV is the subject of active research and vigorous debate. (IPCC AR6 WG1 2021) described the current state of knowledge as follows:

> The transition between phases has been shown to involve various atmospheric and oceanic processes, leading to some predictability, but also influences from external forcing (both anthropogenic and natural), whose respective weight and interplay remain outstanding issues,

For the PDV, (Sun et al. 2022) clarified the conjecture by (Mann et al. 2020) by using wavelet analysis on a paleo reconstruction to show that the 50-70 year variation in the PDV pattern could be the result of volcanic forcing during the Little Ice Age (1250-1850), but that a 20-40 year cycle appears to be due to internal variability. In a synthesis of proxy reconstructions, (Fang et al. 2019) also found persistent 50–100 year variability during the Little Ice Age.

There has also been continuing debate about whether PDV is due to decadal-scale variability of ENSO. (Wills et al. 2018) used a sophisticated pattern recognition method (Low Frequency Component Analysis) to show while the first mode of decadal variability in the North Pacific is global warming, there is a second mode, independent of the El Niño / Southern Oscillation and is similar to the PDO pattern found by (Mantua et al. 1997), and has variability on the 20-40 year timescale found by (Sun et al. 2022). See Figure 10.

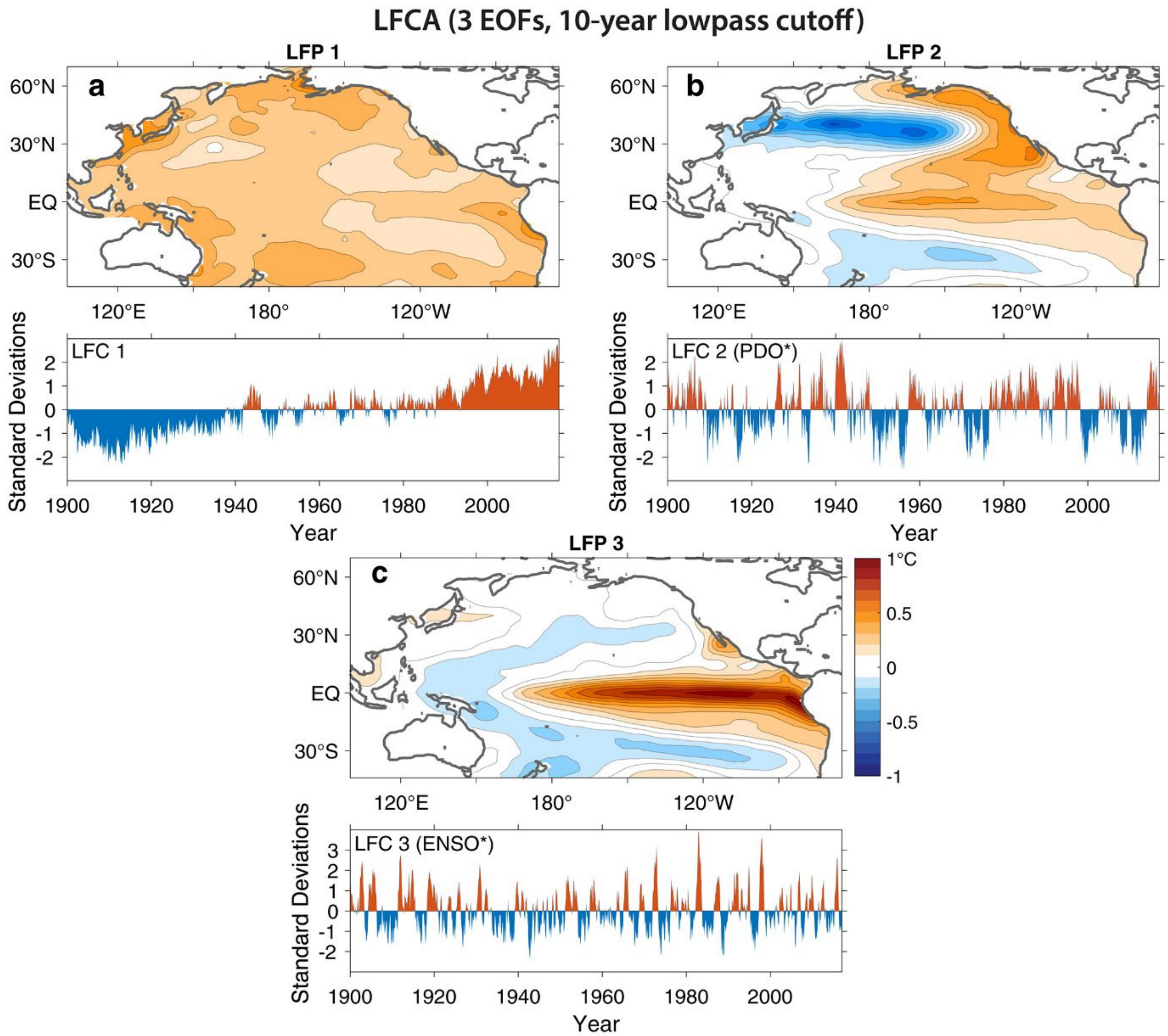

Figure 10 (Wills et al 2018) Low-frequency components (LFCs) of Pacific sea surface temperature anomalies. (a)–(c) Low-frequency patterns (LFPs) and the corresponding LFCs…. They represent (a) global warming, (b) the Pacific Decadal Oscillation (PDO), and (c) the El Niño–Southern Oscillation (ENSO).

(Heede and Fedorov 2023) found two similar patterns to the first two found by (Wills et al. 2018). The uniform warming pattern was similar; their PDO pattern was the reverse of the PDO pattern found by Wills et. al. The third mode shows a pattern of warming in the Northeastern Pacific that appears to include persistent warm blob seen in connection with atmospheric ridging connected to drought in California.

(Heede and Fedorov 2023) found one climate model (CESM2-FV2) that “shows a late 20th century trend similar to the observed in the 21st century in terms of changes in the east–west equatorial SST gradient” and that “it is the simultaneous occurrence of this [residual warming] pattern and the negative PDO that helps simulate the strengthening of the Walker circulation in this model.”

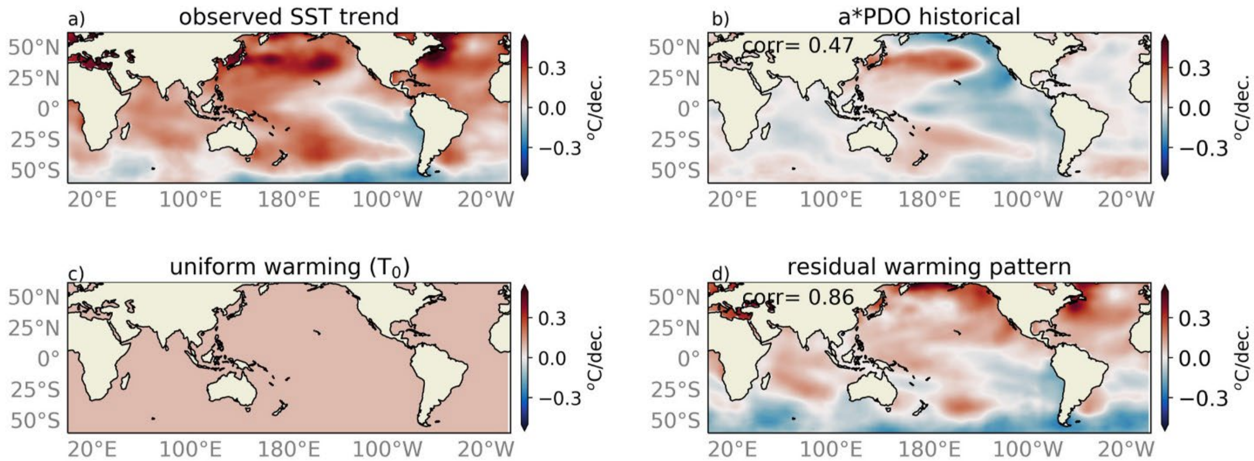

Figure 11 (Heede and Federov 2022, [Creative Commons 4.0 license](#))

The residual warming pattern found by (Heede and Fedorov 2023) is similar to the Pacific Meridional Mode, which was linked to California drought by (Hartmann 2015), who found that it had become second mode of variability in monthly temperatures in the North Pacific and the tropical Pacific since 1979, and was 2-3 standard deviations higher than normal in the winter of 2013-2014.

(Fasullo et al 2020) used large ensembles to evaluate the representation of Pacific Decadal Variability (PDV) in the current generation of models from the fifth and sixth Coupled Model Intercomparison Project (CMIP5 and CMIP6). (IPCC AR6 WG1 2021) found that the observed PDV is "in the tails of the model distributions," and that

> even if one cannot rule out that the observed PDV over the instrumental era represents an exceptional period of variability, it is plausible that the tendency of the CMIP5 models to systematically underestimate the low frequency variance is due to an incomplete representation of decadal-scale mechanisms in these models. This situation is slightly improved in CMIP6 historical simulations but remains a concern…

7. Links between the Pacific and drought on the west coast of North America

The following details some of the attribution studies that linked the North Pacific pattern popularly known as the "Ridiculously Resilient Ridge" to climate shifts.

A study of 1949-2015 reanalysis data by (Swain et al. 2016) found large and statistically significant increases in the frequency of atmospheric ridging patterns associated with drought. (Swain et al. 2014) looked at which CMIP5 models best correlated with observed ridging, and found that GISS-E2-H, HadGEM2-ES, and NorESM1-M models had the highest correlation. Runs for these three models were compared with pre-industrial control runs, with the finding that anthropogenic forcing runs had greatly increased the probability of ridging.

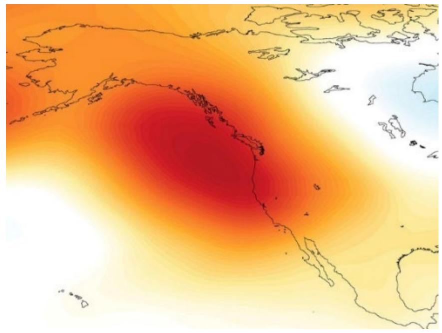

Figure 12 Ridiculously Resilient Ridge (PAL, Wikipedia)

More work needs to be done to understand why the HadGEM2-ES model best correlates with observed ridging. Evaluations have shown that the HadGEM2-ES model has some of the warmest and driest projections of the ten CMIP5 models selected by DWR's Climate Change Technical Advisory Group for use in California water resources planning (CCTAG et al. 2015). The model was also selected by the California Water Commission for the "Drier, Extreme Warming" scenario at 2070 ((California Water Commission 2016 Aug), and was selected for the 20 year extreme drought scenario for California's Fourth Climate Assessment (Pierce et al. 2018), because it projected a dry spell from 2051-2070 with 78% of historical median annual precipitation, averaged over the North Coast and Sierra California Climate Tracker regions.

Research has also found feedbacks between sea ice loss in the Arctic and the ridging seen in the North Pacific. (Lee et al. 2015) et al. forced a coupled model with the observed SST anomalies in the western Pacific and eastern North Pacific, and found a wave-like pattern similar to the observed perturbation, and that reduced sea ice in the Bering Sea and the Sea of Okhostk enhanced the perturbation at high latitudes. (Cvijanovic et al. 2017) investigated a fast atmospheric response to sea ice loss expected over the next few decades and found that it "could induce largescale atmospheric circulation changes across the Northern hemisphere, resulting in significant drying over California."

7. **Increased precipitation variability and trends in the El Niño / Southern Oscillation (ENSO)**

(IPCC AR6 WG1 2021) found that rainfall variability related to the El Niño–Southern Oscillation (ENSO) is projected to be amplified by the second half of the 21st Century:

> A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought (high confidence), but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks. It is very likely that rainfall variability related to the El Niño–Southern Oscillation is projected to be amplified by the second half of the 21st century in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios.

(IPCC AR6 WG1 2021) also found that observations show that ENSO amplitude has increased since 1950, and "The El Niño events of 1982–1983, 1997–1998 and 2015–2016 had the strongest anomalies in the Niño 3.4 SST index since 1950." (Hu et al. 2020) clarify that in the mid- to late 1970s ENSO amplitude increased and the period became longer, but around 1999/2000 there was a reduction of ENSO variability and an increase in the frequency of the oscillation.

The discrepancy can be explained as shift in the kind of El Niño events. Central Pacific El Niño, also known as El Niño Modoki (Ashok et al. 2007) , is a type of El Niño event that occurs when the warmest sea surface temperature anomaly is located in the central Pacific rather than the eastern Pacific. Central Pacific El Niños have weaker deep convection in the eastern Pacific.

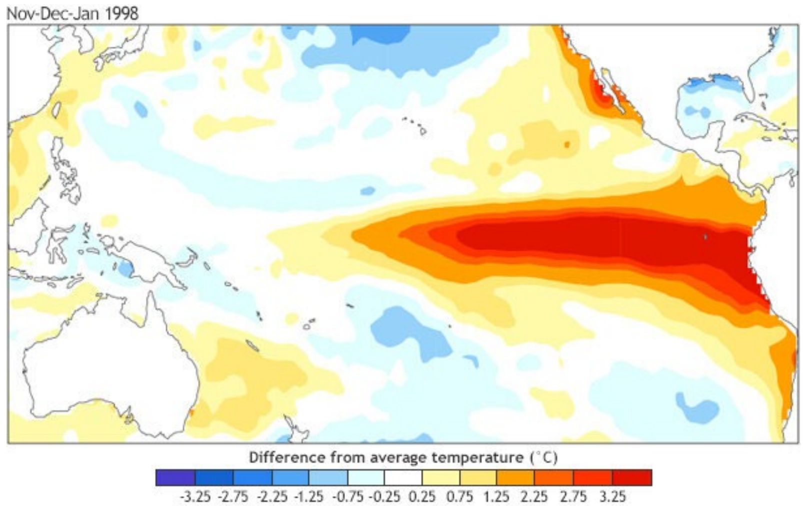

Figure 13 Eastern Pacific El Niño (L'Hereux 2014) NOAA climate.gov

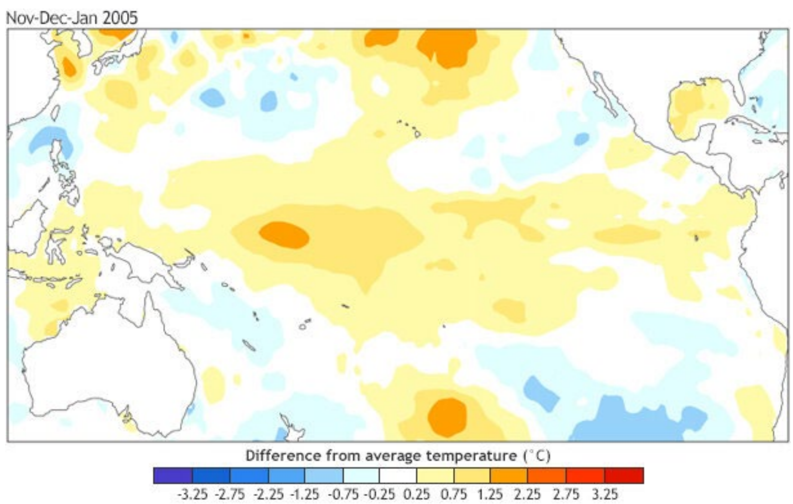

Figure 14 Central Pacific El Niño (L'Hereaux 2014) NOAA Climate.gov

The 2015-2016 El Niño was a Central Pacific El Niño, and although it was associated with sea surface temperature anomalies in the Niño3.4 region that were comparable to those during the extreme 1997-1998 and 1982-1983 El Niño events, it did not result in above average precipitation in the western US (Paek et al. 2017; Lee et al. 2018). (Patricola et al. 2020) hypothesized that "the zonal shift of tropical deep convection can substantially modify the extratropical wave-train response through which the ENSO-western US precipitation teleconnection operates (Hoerling and Kumar 2002; Yeh et al. 2018)."

(Wang et al. 2019) used a cluster analysis to classify El Niños based on onset and amplification processes. The cluster analysis found five types of El Niño: Moderate Central Pacific,Neutral warm, Moderate Eastern Pacific, and Strong basin-wide. The authors found that "the regime has changed from eastern Pacific origin to western Pacific origin with more frequent occurrence of extreme events since the 1970s.” The regime change was attributed to the same background warming in the western Pacific and increased sea-surface temperature gradients that are associated with the increased incidence of the La Niña-like pattern.

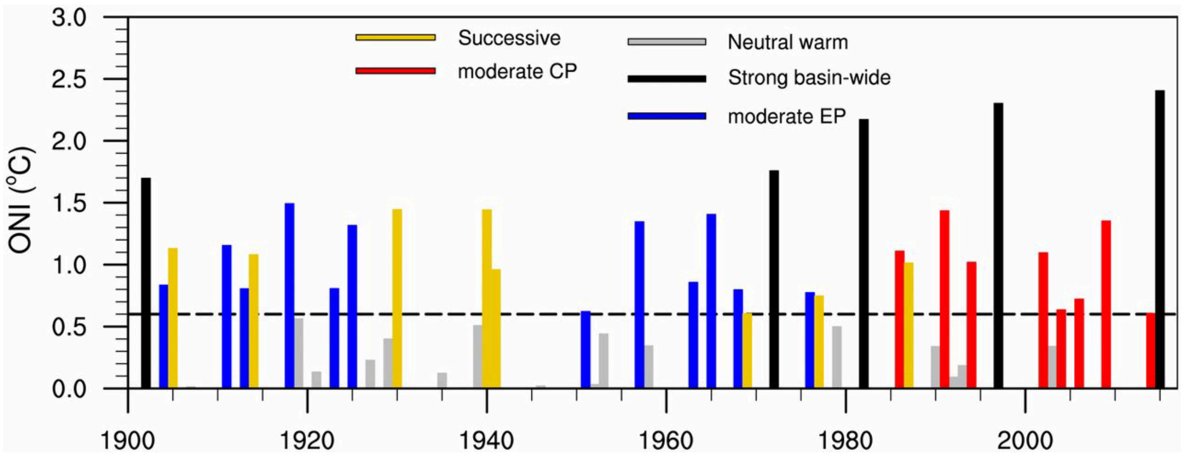

Figure 15 (Wang et. al. 2019.) Types of El Niño events

(IPCC AR6 WG1 2021) also found a change in the type of El Niño events:

> … A number of studies, using a range of indicators, have found an increase in recent decades of the fraction of CP El Niño events, particularly after 2000 (Yu and Kim, 2013; Lübbecke and McPhaden, 2014; Pascolini-Campbell et al., 2015; Jiang and Zhu, 2018). Johnson (2013) found that the frequency of CP El Niño events had increased (although not significantly) over the 1950–2011 period, being accompanied by a significant increase in the frequency of La Niña events with a warm (as opposed to cool) western Pacific warm pool. A coral-based reconstruction starting in 1600 CE (Freund et al., 2019) found that the ratio of CP to EP events in the last 30 years was substantially higher than at any other time over the last 400 years.

(Joh et al. 2021) found that the coupling between the Kuroshio Extension current in the western North Pacific and the CP El Niño is nonstationary and has intensified since the mid-1980s.

6. Trends in precipitation on the west coast of North and South America

With respect to global changes in the hydrologic cycle, (IPCC AR6 WG1 2021) found that

> Greenhouse gas forcing has driven increased contrasts in precipitation amounts between wet and dry seasons and weather regimes over tropical land areas (medium confidence) and a detectable precipitation increase in the northern high latitudes (high confidence). Greenhouse gas forcing has also contributed to drying in dry summer climates, including the Mediterranean, south-western Australia, south-western South America, South Africa, and western North America (medium to high confidence).

In a study of 1950-2020 ERA5 reanalysis data (Benestad et al. 2022) found that the average wet day precipitation has been increasing for many regions at mid-latitudes, but has been decreasing on the west coast of North and South America and in Africa (Figure 16).

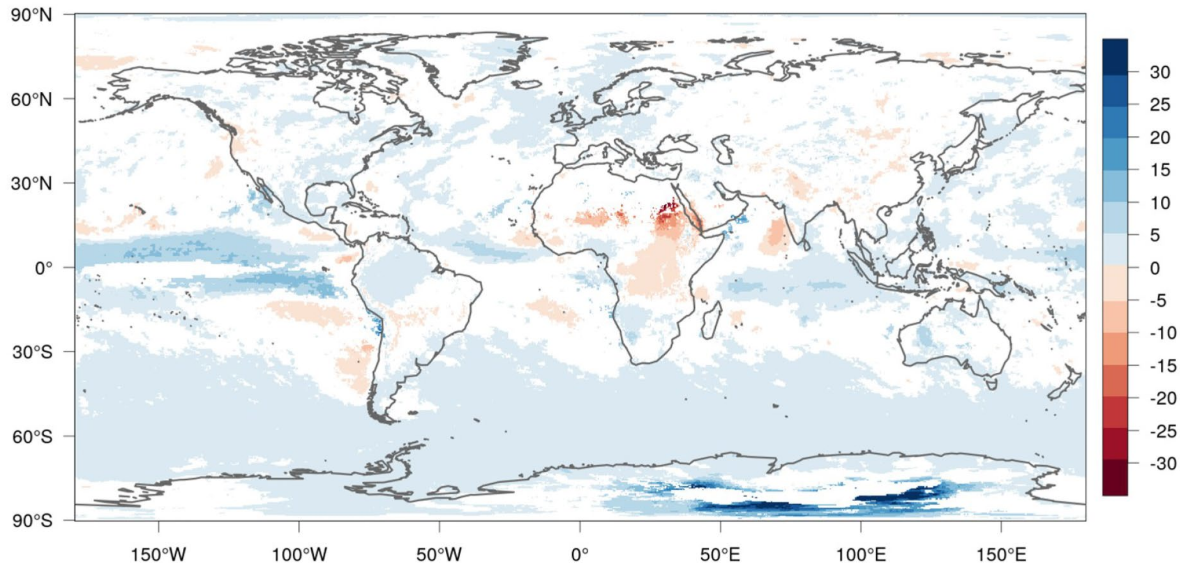

Figure 16 (Benestad et. al. 2022) Map of relative linear trend in average wet-day mean precipitation with units of %/decade for the period 1950–2020, based on the ERA5 reanalysis. Only statistically significant trends are shown (α = 0.05). (Creative Commons 4.0 license)

The trends found by (Benestad et al. 2022) are consistent with the IPCC AR6 synthesis, which found:

> Observed precipitation records since the early 1900s show increases in precipitation totals over central and north-eastern North America that are attributable to anthropogenic warming but larger in magnitude than found in CMIP5 simulations… Decreases in precipitation amount over the central and south-western USA and increases over the north-central USA during 1983–2015… are not clearly associated with forced responses in CMIP6 simulations.
>
> Over South America, there is observational and paleoclimate evidence of declining precipitation amount during the past 50 years over the Altiplano and central Chile, primarily explained by the PDO but with at least 25% of the decline attributed to anthropogenic influence…

(Benestad et al. 2022) also found a long-term decreasing trend in the frequency of wet days in western North and South America. (Figure 17).

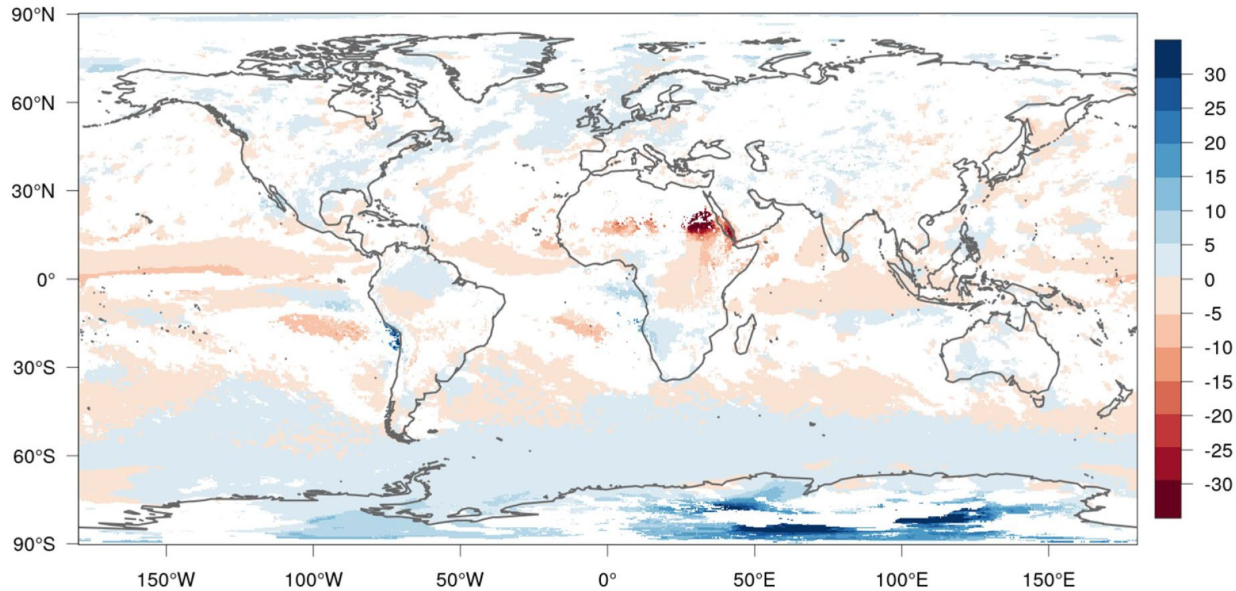

Figure 17 (Benestad et. al. 2022, Creative Commons license 4.0) Map of average wet-day frequency in terms of relative linear trend of %/decade (bottom) for the period 1950–2020 based on ERA5 reanalysis. Only statistically significant trends are shown figure (α = 0.05). The wet-day frequency is calculated for each year by dividing the number of 'wet days' (days with more than 1 mm recorded precipitation) with the total number of days per year. (Creative Commons 4.0 license)

Climate change is expected to reduce wet days in western North and South America, as well as increase interannual variability, but not until the latter half of the century, (Polade et al. 2014). (Wood et al. 2021) found a robust agreement in Single Model Large Ensemble (SMILE) projections of increased variability on scales from annual to decadal.

(Jain et al. 2005) documented increased variability of streamflow in the 30-year period from 1972-2000 in major catchments in western North America, including the Fraser, Columbia, Sacramento–San Joaquin, and Upper Colorado, as well as synchronous low flows in all basins, which the authors associated with warming in the western Pacific.

The reduction in wet days on the West coast of North America appears to coincide with a declining trend in landfalling atmospheric rivers. (Gershunov et al. 2019) used automated detection methods on reanalysis data from 1951-2000 to find landfalling ARs from January to March. Surprisingly, the supplemental information shows a reduction in the number of landfalling ARs on the west coast, and an even larger reduction in California, as well as a reduction in duration of ARs. The authors found:

> a change in the average number of landfalling ARs on the west coast of -1 (1%), and a reduction in duration of 0.27 days (14%) (Table S3)
>
> a change in the average number of landfalling ARs in California of -2(15%) and a reduction in duration of 0.21 days (9%) (Table S4)

The authors also found an overall decrease in AR-related precipitation on the west coast of North America, and more in California.

a reduction in annual AR precipitation on the west coast of -16 mm (14%), compensated for by an increase in non-AR precipitation of +47 mm (9 %) (Table S6)

a reduction in annual AR precipitation in California of -70 mm (32%), compensated for by an increase in non-AR precipitation of +112 mm (28%). (Table S5)

Given the reduction in precipitation in the 21st Century, it seems quite possible that some of the increase in non-AR related precipitation may have reversed in the 21st Century. Non-AR related precipitation is expected to decrease due to climate change, but not until the latter half of the century. Figure 18 is reproduced from (Dettinger 2016). All CMIP 5 models project a decrease in precipitation below the 95th percentile in the latter half of the 21st Century, however the models disagree on the sign and magnitude of changes in the wettest 5% days, which are associated with ARs.

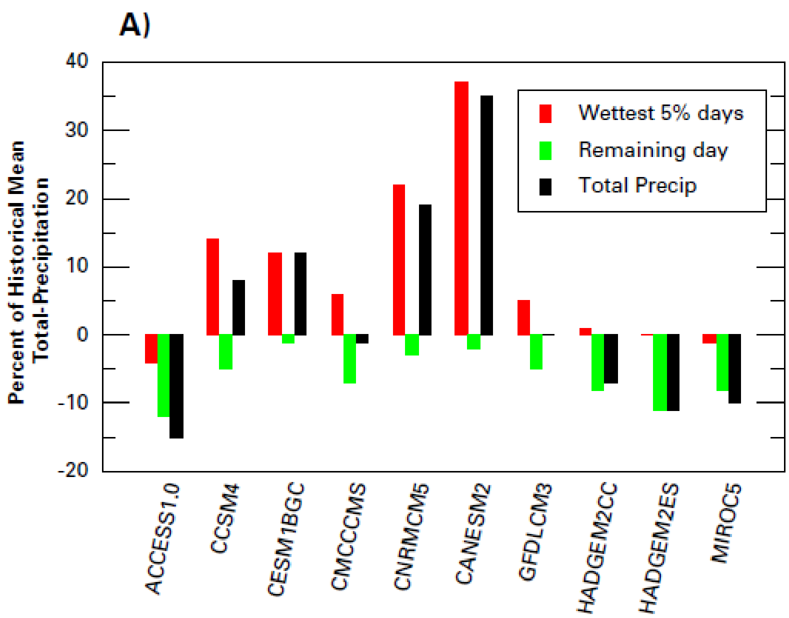

Figure 18 (Dettinger 2016), projected changes from historical mean total precipitation on the wettest 5% days, and the remaining days, between 1951–2000 and 2046–2095 for ten CMIP5 models, forced with the highest GHG emissions scenario (RCP 8.5). (Creative Commons 4.0 license)

8. Decadal-scale variations in California precipitation

(CCTAG et al. 2015) has a detailed discussion of decadal trends in precipitation in Northern California, and states:

> The early 20th century rainfall “trough” is clearly seen in the 30-year trailing average, as plotted in Figure 3-3 by the heavy dark line. In 1896, the trailing 30-year average peaked at 20.42 inches (51.87 centimeters [cm]), then fell steadily to the 1937 minimum of 14.51 inches (36.86 cm). Over the next 70 years, Sacramento rebounded sufficiently for the 30-year average to recover to a peak of 20.63 inches (52.40 cm) in 2007. What is disturbing is the significant decline in the 30-year average precipitation in Sacramento since the 2007 peak. This drop is as steep or steeper than any decline over a similar period in well over a century. Developing adaptive capacity to this decadal-scale variability appears to be an important element of extremes planning processes.

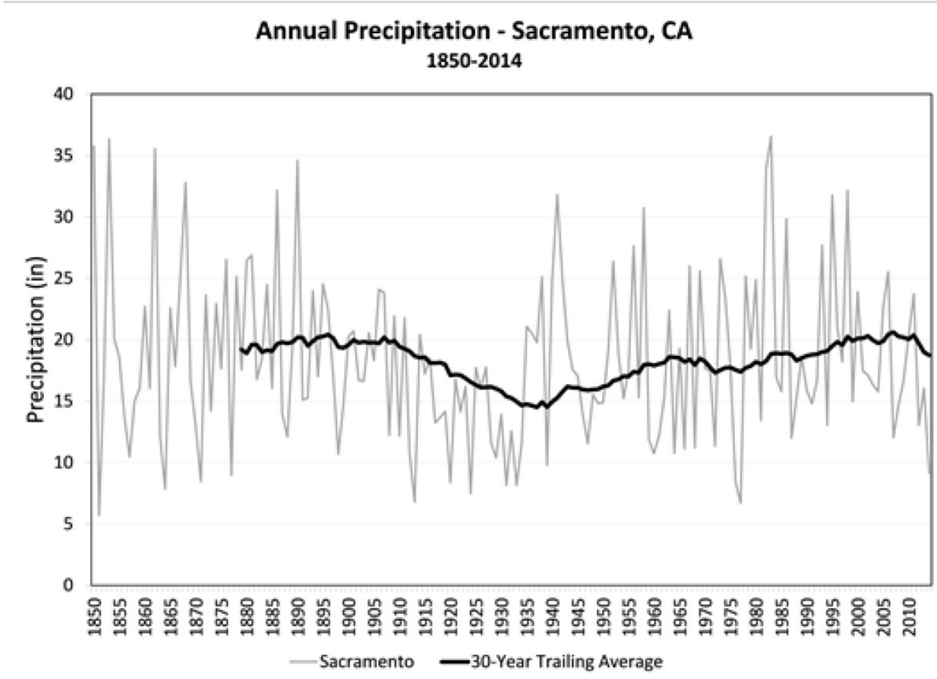

Figure 19 (CCTAG et. al. 2015, reproduced from figure 3.3)

Figure 20 shows California annual precipitation from 1895-2022 (NOAA NCEI 2023 Feb). A linear regression over the entire period shows a slight declining trend of -0.08 in / decade. However, linear methods are known to fail in characterizing time series of nonlinear, chaotic dynamical systems. (Packard et al. 1980; Casdagli et al. 1990; Bradley and Kantz 2015). A LOESS curve (Cleveland 1979) shows the recent decline in precipitation, as well as the Dust Bowl era drought and the pluvial from the 1970s through the 1990s.

(Razavi et al. 2015) found that the hydrology of the Saskatchewan basin had significant shifts at different points in the region's history. They suggested that the observational record in the region was a poor representation of the long-term properties of the hydrologic regime, and shorter periods, such as 30-year periods, are not representative.

Figure 21 shows annual precipitation over the 42-year period from 1980-2022, and the recent multidecadal declining trend of -1.42 in/decade as California moved from a pluvial period to a dry period.

The Northern Sierra Eight Station precipitation index combines precipitation at eight high-altitude stations in the Northern Sierra Nevada (CDWR 2023). Because the stations are in the watershed of the Sacramento River, it is an important index of water supply for the State Water Project and Central Valley Project. Figure 22 shows the decline in Northern Sierra Eight Station annual precipitation since 1980, which is even larger than the decline in California annual precipitation.

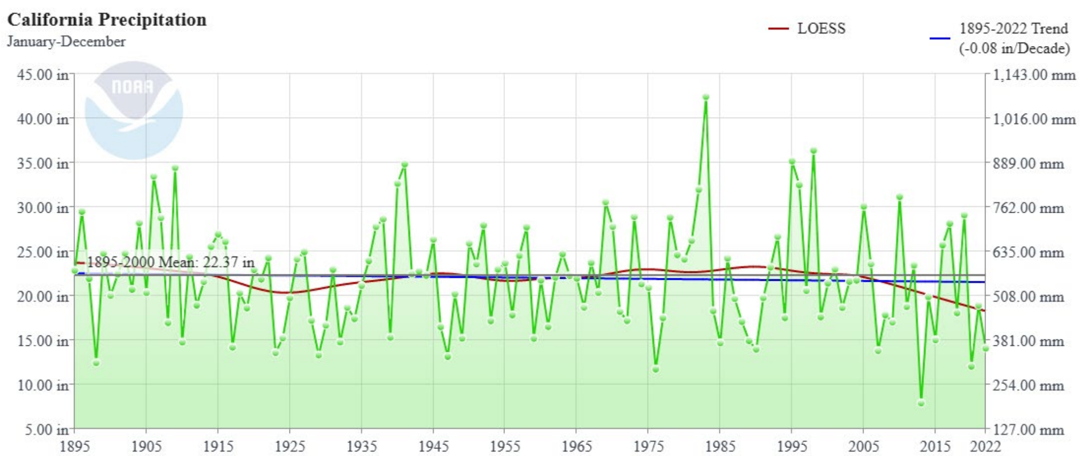

Figure 20 California Annual Precipitation 1895-2022   Source: NOAA NCEI

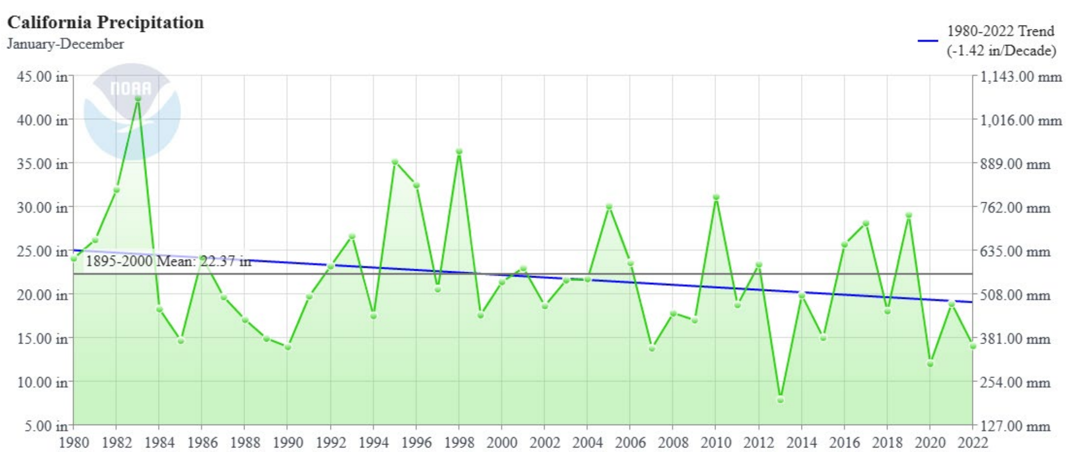

Figure 21   California Annual Precipitation 1980-2022   Source: NOAA NCEI

Recent four decade trends may be a better representation of the impacts of climate shifts on California's social and ecological systems than the trend over the last 125 years. (Dettinger and Culberson 2008) observed:

> The general rapidity of the coming changes—and the extent to which we have weakened the state's ecosystems and have pushed engineered systems to near their limits—are likely to hinder the ability of many geomorphic, ecological, engineered, and even political systems to accommodate the climate changes without significant internal reorganization.

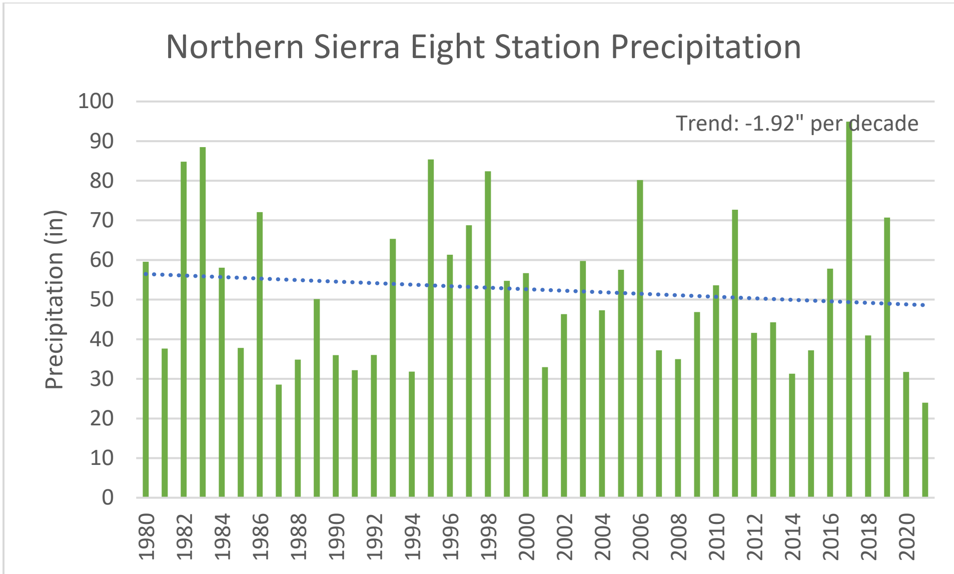

Figure 22 Northern Sierra Eight Station Precipitation 1980-2022

A study by the California Department of Water Resources (He and Gautam 2016) used a Mann-Kendall test and found no statistically significant trend in mean precipitation in California hydrologic regions. The Mann-Kendall test is designed to test for monotonic trends and may not detect nonmonotonic shifts. As observed by (Wang et al. 2020), although the Mann-Kendall test has been widely used to test for trends in hydrologic time series, the possibility of a Type II error of failing to recognize recent trends is as important as a Type I error of statistical significance against the null hypothesis of “no trend.”

(He and Gautam 2016) did find increased variability since 1980 in precipitation across California hydrologic regions. Current data also shows a continuing trend of increased variability. Figure 15 shows the 30-year variance ratio for California annual precipitation from 1895-2022. (The variance ratio is the variance of the 30-year window divided by the variance of the whole time series.) One can see that the variance ratio was reduced during an unusually stable period in the 1950s and 1960s but increased greatly from the 1970s to the 21st Century.

Figure 16 shows the precipitation and the moving variance ratio over 30-year periods. The variance increases dramatically starting in the mid-1960s, and declines somewhat after the 1990s, but stays significantly higher than the earlier period.

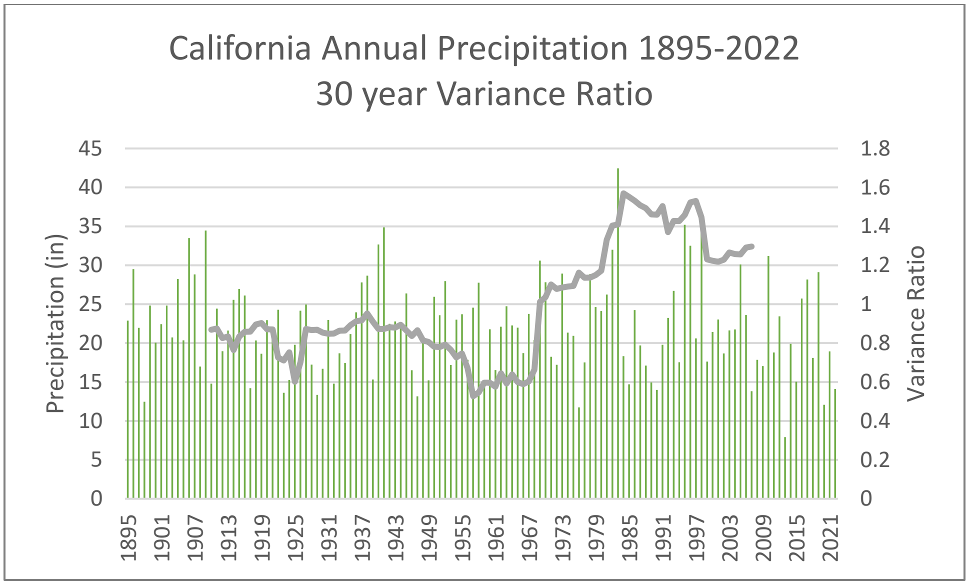

Figure 23 California annual precipitation 1895-2022 with moving variance ratio over 30-year periods. (Variance of 30-year window divided by total variance.) Date is center of 30-year period. Data: NOAA NCEI

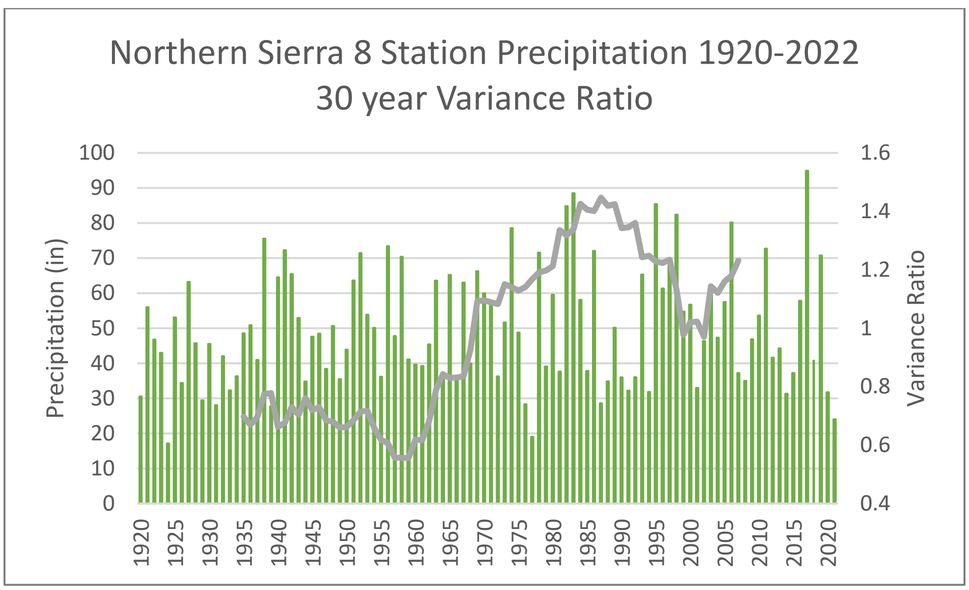

Figure 24 Northern Sierra 8 Station Precipitation 1920-2022 with moving variance ratio over 30-year periods. (Variance of 30-year window divided by total variance.) Date is center of 30-year period.

The possibility that the increased frequency of dry years in the Northern Sierra in the 21st Century was due to accelerating impacts of climate change was initially rejected by most researchers because coupled climate models do not project drying until the latter half of the 21st Century. For example, (Berg and Hall 2015) wrote:

> … Only by the end of the century does a signal of enhanced frequency of dry extremes emerge past natural variability levels. Thus, this analysis finds no model evidence that

> the 2013/14 low wet season precipitation, and perhaps the remaining extremely dry wet seasons over California that will surely occur throughout the first half of the twenty-first century, can be clearly linked to climate change.

Regardless of whether recent trends are due to anthropogenic forcing, the 30 year probability distribution is clearly changing. (Koutsoyiannis 2003) argued that “hydrological statistics, the branch of hydrology that deals with uncertainty, in its current state is not consistent with the varying character of climate,” and that hydrologic time series are “better modelled as stochastic fluctuations on many time scales.”

References

Ashok K, Behera SK, Rao SA, Weng H, Yamagata T. 2007. El Niño Modoki and its possible teleconnection. Journal of Geophysical Research: Oceans. 112(C11). doi:10.1029/2006JC003798. [accessed 2023 Feb 17]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2006JC003798.

Benestad RE, Lussana C, Lutz J, Dobler A, Landgren O, Haugen JE, Mezghani A, Casati B, Parding KM. 2022. Global hydro-climatological indicators and changes in the global hydrological cycle and rainfall patterns. PLOS Climate. 1(5):e0000029. doi:10.1371/journal.pclm.0000029. [accessed 2022 Nov 8]. https://journals.plos.org/climate/article?id=10.1371/journal.pclm.0000029.

Berg N, Hall A. 2015. Increased Interannual Precipitation Extremes over California under Climate Change. Journal of Climate. 28(16):6324–6334. doi:10.1175/JCLI-D-14-00624.1. [accessed 2023 Feb 12]. https://journals.ametsoc.org/view/journals/clim/28/16/jcli-d-14-00624.1.xml.

Bradley E, Kantz H. 2015. Nonlinear time-series analysis revisited. Chaos. 25(9):097610. doi:10.1063/1.4917289. [accessed 2023 Feb 11]. https://aip.scitation.org/doi/abs/10.1063/1.4917289.

Caesar L, McCarthy GD, Thornalley DJR, Cahill N, Rahmstorf S. 2021. Current Atlantic Meridional Overturning Circulation weakest in last millennium. Nat Geosci. 14(3):118–120. doi:10.1038/s41561-021-00699-z. [accessed 2022 Dec 1]. https://www.nature.com/articles/s41561-021-00699-z.

California Water Commission. 2016 Aug. Climate Change Projections for Water Storage Investment Program (WSIP) - Technical Reference Appendix A - Climate Change and Sea-Level Rise - California Open Data. [accessed 2022 Dec 16]. https://data.ca.gov/dataset/climate-change-projections-for-water-storage-investment-program-wsip/resource/919f39d7-8626-4843-9c64-f105bba399f6.

Casdagli M, Eubank S, Farmer JD, Gibson J, Des Jardins D, Hunter N, Theiler J. 1990. Nonlinear modeling of chaotic time series: Theory and applications. Los Alamos National Lab., NM (USA) Report No.: LA-UR-91-1637; CONF-901246-4. [accessed 2023 Feb 11]. https://www.osti.gov/biblio/5569352.

CCTAG, Lynn E (Chair), Schwarz A, Anderson J, Correa M, O'Daly W. 2015. Perspectives and Guidance for Climate Change Analysis. Climate Change Technical Advisory Group.

CDWR. 2016. Drought and Water Year 2016: Hot and Dry Conditions Continue. California Department of Water Resources, Natural Resources Agency.

CDWR. 2023. Northern Sierra Eight Station Precipitation. [accessed 2023 Feb 10]. https://cdec.water.ca.gov.

Cleveland WS. 1979. Robust Locally Weighted Regression and Smoothing Scatterplots. Journal of the American Statistical Association. 74(368):829–836. doi:10.1080/01621459.1979.10481038. [accessed 2023 Feb 11]. https://www.tandfonline.com/doi/abs/10.1080/01621459.1979.10481038.

Cvijanovic I, Santer BD, Bonfils C, Lucas DD, Chiang JCH, Zimmerman S. 2017. Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall. Nat Commun. 8(1):1947. doi:10.1038/s41467-017-01907-4. [accessed 2022 Dec 5]. https://www.nature.com/articles/s41467-017-01907-4.

Delta Independent Science Board. 2022. Review of Water Supply Reliability Estimation Related to the Sacramento-San Joaquin Delta. Sacramento, CA: Delta Independent Science Board.

Deser C. 2020. "Certain Uncertainty: The Role of Internal Climate Variability in Projections of Regional Climate Change and Risk Management." Earth's Future. 8(12):e2020EF001854. doi:10.1029/2020EF001854. [accessed 2022 Nov 2]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2020EF001854.

Deser C, Lehner F, Rodgers KB, Ault T, Delworth TL, DiNezio PN, Fiore A, Frankignoul C, Fyfe JC, Horton DE, et al. 2020. Insights from Earth system model initial-condition large ensembles and future prospects. Nat Clim Chang. 10(4):277–286. doi:10.1038/s41558-020-0731-2. [accessed 2023 Feb 22]. https://www.nature.com/articles/s41558-020-0731-2.

Dettinger M. 2016. Historical and Future Relations Between Large Storms and Droughts in California. SFEWS. 14(2). doi:10.15447/sfews.2016v14iss2art1. [accessed 2022 Dec 1]. http://escholarship.org/uc/item/1hq3504j.

Dettinger M, Culberson S. 2008. Internalizing Climate Change—Scientific Resource Management and the Climate Change Challenges. SFEWS. 6(2). doi:10.15447/sfews.2008v6iss2art5. [accessed 2022 Nov 25]. http://escholarship.org/uc/item/64z013q3.

Deutsch C, Emerson S, Thompson L. 2006. Physical-biological interactions in North Pacific oxygen variability. Journal of Geophysical Research: Oceans. 111(C9). doi:10.1029/2005JC003179. [accessed 2023 Feb 22]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2005JC003179.

Fang K, Chen D, Ilvonen L, Pasanen L, Holmström L, Seppä H, Huang G, Ou T, Linderholm H. 2019. Oceanic and atmospheric modes in the Pacific and Atlantic Oceans since the Little Ice Age (LIA): Towards a synthesis. Quaternary Science Reviews. 215:293–307. doi:10.1016/j.quascirev.2019.05.014. [accessed 2023 Feb 23]. https://www.sciencedirect.com/science/article/pii/S0277379118308886.

Garreaud RD, Boisier JP, Rondanelli R, Montecinos A, Sepúlveda HH, Veloso-Aguila D. 2020. The Central Chile Mega Drought (2010–2018): A climate dynamics perspective. International Journal of Climatology. 40(1):421–439. doi:10.1002/joc.6219. [accessed 2023 Feb 12]. https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.6219.

Gershunov A, Shulgina T, Clemesha RES, Guirguis K, Pierce DW, Dettinger MD, Lavers DA, Cayan DR, Polade SD, Kalansky J, et al. 2019. Precipitation regime change in Western North America: The role of Atmospheric Rivers. Sci Rep. 9(1):9944. doi:10.1038/s41598-019-46169-w. [accessed 2022 Oct 31]. https://www.nature.com/articles/s41598-019-46169-w.

Gillett N, Cannon A, Malinina E, Schnorbus M, Anslow F, Sun Q, Kirchmeier-Young M, Zwiers F, Seiler C, Zhang X, et al. 2022. Human Influence on the 2021 British Columbia Floods. doi:10.2139/ssrn.4025205. [accessed 2023 Feb 14]. https://papers.ssrn.com/abstract=4025205.

Halpert M, Barnston A, L'Hereaux M, Becker E. 2016. El Niño and La Niña: Frequently asked questions. ENSO blog. [accessed 2023 Feb 7]. http://www.climate.gov/news-features/understanding-climate/el-ni%C3%B1o-and-la-ni%C3%B1a-frequently-asked-questions.

Hartmann DL. 2015. Pacific sea surface temperature and the winter of 2014. Geophysical Research Letters. 42(6):1894–1902. doi:10.1002/2015GL063083. [accessed 2023 Feb 6]. https://onlinelibrary.wiley.com/doi/abs/10.1002/2015GL063083.

He M, Gautam M. 2016. Variability and Trends in Precipitation, Temperature and Drought Indices in the State of California. Hydrology. 3(2):14. doi:10.3390/hydrology3020014. [accessed 2023 Feb 11]. https://www.mdpi.com/2306-5338/3/2/14.

Heede UK, Fedorov AV. 2023. Colder Eastern Equatorial Pacific and Stronger Walker Circulation in the Early 21st Century: Separating the Forced Response to Global Warming from Natural Variability. Geophysical Research Letters. 50(3):e2022GL101020. doi:10.1029/2022GL101020. [accessed 2023 Jan 31]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2022GL101020.

Heede UK, Fedorov AV, Burls NJ. 2020. Time Scales and Mechanisms for the Tropical Pacific Response to Global Warming: A Tug of War between the Ocean Thermostat and Weaker Walker. Journal of Climate. 33(14):6101–6118. doi:10.1175/JCLI-D-19-0690.1. [accessed 2023 Jan 31]. https://journals.ametsoc.org/view/journals/clim/33/14/JCLI-D-19-0690.1.xml.

Herweijer C, Seager R. 2008. The global footprint of persistent extra-tropical drought in the instrumental era. Int J Climatol. 28(13):1761–1774. doi:10.1002/joc.1590. [accessed 2023 Feb 6]. https://onlinelibrary.wiley.com/doi/10.1002/joc.1590.

Hu Z-Z, Kumar A, Huang B, Zhu J, L'Heureux M, McPhaden MJ, Yu J-Y. 2020. The Interdecadal Shift of ENSO Properties in 1999/2000: A Review. Journal of Climate. 33(11):4441–4462. doi:10.1175/JCLI-D-19-0316.1. [accessed 2023 Feb 16]. https://journals.ametsoc.org/view/journals/clim/33/11/jcli-d-19-0316.1.xml.

IPCC AR6 WG1. 2021. Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/assessment-report/ar6/.

Jain S, Hoerling M, Eischeid J. 2005. Decreasing Reliability and Increasing Synchroneity of Western North American Streamflow. Journal of Climate. 18(5):613–618. doi:10.1175/JCLI-3311.1. [accessed 2023 Feb 12]. https://journals.ametsoc.org/view/journals/clim/18/5/jcli-3311.1.xml.

Joh Y, Di Lorenzo E, Siqueira L, Kirtman BP. 2021. Enhanced interactions of Kuroshio Extension with tropical Pacific in a changing climate. Sci Rep. 11(1):6247. doi:10.1038/s41598-021-85582-y. [accessed 2023 Feb 22]. https://www.nature.com/articles/s41598-021-85582-y.

Kay JE, Deser C, Phillips A, Mai A, Hannay C, Strand G, Arblaster JM, Bates SC, Danabasoglu G, Edwards J, et al. 2015. The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability. Bulletin of the American Meteorological Society. 96(8):1333–1349. doi:10.1175/BAMS-D-13-00255.1. [accessed 2023 Feb 8]. https://journals.ametsoc.org/view/journals/bams/96/8/bams-d-13-00255.1.xml.

Kilbourne KH, Wanamaker AD, Moffa-Sanchez P, Reynolds DJ, Amrhein DE, Butler PG, Gebbie G, Goes M, Jansen MF, Little CM, et al. 2022. Atlantic circulation change still uncertain. Nat Geosci. 15(3):165–167. doi:10.1038/s41561-022-00896-4. [accessed 2023 Feb 21]. https://www.nature.com/articles/s41561-022-00896-4.

Koutsoyiannis D. 2003. Climate change, the Hurst phenomenon, and hydrological statistics. Hydrological Sciences Journal. 48(1):3–24. doi:10.1623/hysj.48.1.3.43481. [accessed 2023 Feb 10]. https://doi.org/10.1623/hysj.48.1.3.43481.

Kravtsov S, Grimm C, Gu S. 2018. Global-scale multidecadal variability missing in state-of-the-art climate models. npj Clim Atmos Sci. 1(1):1–10. doi:10.1038/s41612-018-0044-6. [accessed 2023 Feb 23]. https://www.nature.com/articles/s41612-018-0044-6.

Kreienkamp F, Philip S, Tradowsky J, Kew S, Lorenz P, Arrighi J, Belleflamme A, Bettmann T, Caluwaerts S, Chan S, et al. 2021. Heavy rainfall which led to severe flooding in Western Europe made more likely by climate change – World Weather Attribution. World Weather Attribution. [accessed 2023 Feb 14]. https://www.worldweatherattribution.org/heavy-rainfall-which-led-to-severe-flooding-in-western-europe-made-more-likely-by-climate-change/.

Lamjiri MA, Ralph FM, Dettinger MD. 2020. Recent Changes in United States Extreme 3-Day Precipitation Using the R-CAT Scale. Journal of Hydrometeorology. 21(6):1207–1221. doi:10.1175/JHM-D-19-0171.1. [accessed 2022 Dec 2]. https://journals.ametsoc.org/view/journals/hydr/21/6/JHM-D-19-0171.1.xml.

Lee M-Y, Hong C-C, Hsu H-H. 2015. Compounding effects of warm sea surface temperature and reduced sea ice on the extreme circulation over the extratropical North Pacific and North America during the 2013–2014 boreal winter. Geophysical Research Letters. 42(5):1612–1618. doi:10.1002/2014GL062956. [accessed 2023 Feb 17]. https://onlinelibrary.wiley.com/doi/abs/10.1002/2014GL062956.

Lee S, Karnauskas K, Heede U, L'Hereaux M. 2023. How the pattern of trends across the tropical Pacific Ocean is critical for understanding the future climate. ENSO blog. [accessed 2023 Feb 7]. http://www.climate.gov/news-features/blogs/how-pattern-trends-across-tropical-pacific-ocean-critical-understanding-future.

Lee S, L'Heureux M, Wittenberg AT, Seager R, O'Gorman PA, Johnson NC. 2022. On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. npj Clim Atmos Sci. 5(1):1–15. doi:10.1038/s41612-022-00301-2. [accessed 2023 Jan 27]. https://www.nature.com/articles/s41612-022-00301-2.

Lee S-K, Lopez H, Chung E-S, DiNezio P, Yeh S-W, Wittenberg AT. 2018. On the Fragile Relationship Between El Niño and California Rainfall. Geophysical Research Letters. 45(2):907–915. doi:10.1002/2017GL076197. [accessed 2023 Feb 17]. https://onlinelibrary.wiley.com/doi/abs/10.1002/2017GL076197.

Lenton TM. 2011. Early warning of climate tipping points. Nature Clim Change. 1(4):201–209. doi:10.1038/nclimate1143. [accessed 2022 Nov 26]. https://www.nature.com/articles/nclimate1143.

Lenton TM, Dakos V, Bathiany S, Scheffer M. 2017. Observed trends in the magnitude and persistence of monthly temperature variability. Sci Rep. 7(1):5940. doi:10.1038/s41598-017-06382-x. [accessed 2023 Feb 18]. https://www.nature.com/articles/s41598-017-06382-x.

Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ. 2008. Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences. 105(6):1786–1793. doi:10.1073/pnas.0705414105. [accessed 2023 Feb 24]. https://www.pnas.org/doi/10.1073/pnas.0705414105.

Lhotka O, Kyselý J. 2022. The 2021 European Heat Wave in the Context of Past Major Heat Waves. Earth and Space Science. 9(11):e2022EA002567. doi:10.1029/2022EA002567. [accessed 2023 Feb 14]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2022EA002567.

Li Y, Chen Q, Liu X, Li J, Xing N, Xie F, Feng J, Zhou X, Cai H, Wang Z. 2019. Long-Term Trend of the Tropical Pacific Trade Winds Under Global Warming and Its Causes. Journal of Geophysical Research: Oceans. 124(4):2626–2640. doi:10.1029/2018JC014603. [accessed 2023 Feb 7]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2018JC014603.

Mankin JS, Lehner F, Coats S, McKinnon KA. 2020. The Value of Initial Condition Large Ensembles to Robust Adaptation Decision-Making. Earth's Future. 8(10):e2012EF001610. doi:10.1029/2020EF001610. [accessed 2022 Nov 21]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2020EF001610.

Mann ME, Steinman BA, Brouillette DJ, Miller SK. 2021. Multidecadal climate oscillations during the past millennium driven by volcanic forcing. Science. 371(6533):1014–1019. doi:10.1126/science.abc5810. [accessed 2022 Dec 6]. https://www.science.org/doi/full/10.1126/science.abc5810.

Mann ME, Steinman BA, Miller SK. 2020. Absence of internal multidecadal and interdecadal oscillations in climate model simulations. Nat Commun. 11(1):49. doi:10.1038/s41467-019-13823-w. [accessed 2022 Dec 13]. https://www.nature.com/articles/s41467-019-13823-w.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production*. Bulletin of the American Meteorological Society. 78(6):1069–1080. doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2. [accessed 2022 Nov 26]. https://journals.ametsoc.org/view/journals/bams/78/6/1520-0477_1997_078_1069_apicow_2_0_co_2.xml.

Markonis Y, Hanel M, Máca P, Kyselý J, Cook ER. 2018. Persistent multi-scale fluctuations shift European hydroclimate to its millennial boundaries. Nat Commun. 9(1):1767. doi:10.1038/s41467-018-04207-7. [accessed 2023 Jan 22]. https://www.nature.com/articles/s41467-018-04207-7.

McPhaden MJ, Zhang D. 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. Nature. 415(6872):603–608. doi:10.1038/415603a. [accessed 2023 Feb 22]. https://www.nature.com/articles/415603a.

McPhaden MJ, Zhang D. 2004. Pacific Ocean circulation rebounds. Geophysical Research Letters. 31(18). doi:10.1029/2004GL020727. [accessed 2023 Feb 22]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2004GL020727.

Miller A, Cayan D, Barnett T, Graham N, Oberhuber J. 1994. The 1976-77 Climate Shift of the Pacific Ocean. oceanog. 7(1):21–26. doi:10.5670/oceanog.1994.11. [accessed 2023 Feb 22]. https://tos.org/oceanography/article/the-1976-77-climate-shift-of-the-pacific-ocean.

NOAA NCEI. 2023 Feb. Climate at a Glance: Statewide Time Series. [accessed 2023 Feb 11]. https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series/4/pcp/ann/11/1895-2023?base_prd=true&begbaseyear=1895&endbaseyear=2000&trend=true&trend_base=100&begtrendyear=1895&endtrendyear=2023&filter=true&filterType=loess.

NOAA Physical Sciences Laboratory. 2023. Multivariate ENSO Index Version 2 (MEI.v2). El Niño Southern Oscillation (ENSO). [accessed 2023 Feb 5]. https://psl.noaa.gov/enso/mei/.

Orihuela-Pinto B, England MH, Taschetto AS. 2022. Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation. Nat Clim Chang. 12(6):558–565. doi:10.1038/s41558-022-01380-y. [accessed 2023 Feb 20]. https://www.nature.com/articles/s41558-022-01380-y.

Packard NH, Crutchfield JP, Farmer JD, Shaw RS. 1980. Geometry from a Time Series. Phys Rev Lett. 45(9):712–716. doi:10.1103/PhysRevLett.45.712. [accessed 2023 Feb 11]. https://link.aps.org/doi/10.1103/PhysRevLett.45.712.

Paek H, Yu J-Y, Qian C. 2017. Why were the 2015/2016 and 1997/1998 extreme El Niños different? Geophysical Research Letters. 44(4):1848–1856. doi:10.1002/2016GL071515. [accessed 2023 Feb 17]. https://onlinelibrary.wiley.com/doi/abs/10.1002/2016GL071515.

Palmer TN. 1999. A Nonlinear Dynamical Perspective on Climate Prediction. J Climate. 12(2):575–591. doi:10.1175/1520-0442(1999)012<0575:ANDPOC>2.0.CO;2. [accessed 2023 Feb 18]. http://journals.ametsoc.org/doi/10.1175/1520-0442(1999)012<0575:ANDPOC>2.0.CO;2.

Patricola CM, O'Brien JP, Risser MD, Rhoades AM, O'Brien TA, Ullrich PA, Stone DA, Collins WD. 2020. Maximizing ENSO as a source of western US hydroclimate predictability. Clim Dyn. 54(1):351–372. doi:10.1007/s00382-019-05004-8. [accessed 2022 Nov 26]. https://doi.org/10.1007/s00382-019-05004-8.

Philip SY, Kew SF, van Oldenborgh GJ, Anslow FS, Seneviratne SI, Vautard R, Coumou D, Ebi KL, Arrighi J, Singh R, et al. 2021. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. Earth system change: climate scenarios. [accessed 2023 Feb 14]. https://esd.copernicus.org/preprints/esd-2021-90/esd-2021-90.pdf.

Pierce DW, Kalansky J, Cayan DR. 2018. Climate, Drought, and Sea Level Rise Scenarios for California's Fourth Climate Change Assessment. California's Fourth Climate Change Assessment.

Polade SD, Pierce DW, Cayan DR, Gershunov A, Dettinger MD. 2014. The key role of dry days in changing regional climate and precipitation regimes. Sci Rep. 4(1):4364. doi:10.1038/srep04364. [accessed 2022 Oct 29]. https://www.nature.com/articles/srep04364.

Power S, Casey T, Folland C, Colman A, Mehta V. 1999. Inter-decadal modulation of the impact of ENSO on Australia. Climate Dynamics. 15(5):319–324. doi:10.1007/s003820050284. [accessed 2023 Feb 13]. https://doi.org/10.1007/s003820050284.

Razavi S, Elshorbagy A, Wheater H, Sauchyn D. 2015. Toward understanding nonstationarity in climate and hydrology through tree ring proxy records. Water Resources Research. 51(3):1813–1830. doi:10.1002/2014WR015696. [accessed 2022 Nov 26]. https://onlinelibrary.wiley.com/doi/abs/10.1002/2014WR015696.

Rhoades AM, Risser MD, Stone DA, Wehner MF, Jones AD. 2021. Implications of warming on western United States landfalling atmospheric rivers and their flood damages. Weather and Climate Extremes. 32:100326. doi:10.1016/j.wace.2021.100326. [accessed 2023 Feb 17]. https://www.sciencedirect.com/science/article/pii/S2212094721000244.

Robinson A, Lehmann J, Barriopedro D, Rahmstorf S, Coumou D. 2021. Increasing heat and rainfall extremes now far outside the historical climate. npj Clim Atmos Sci. 4(1):1–4. doi:10.1038/s41612-021-00202-w. [accessed 2023 Jan 27]. https://www.nature.com/articles/s41612-021-00202-w.

Roe G. 2009. Feedbacks, Timescales, and Seeing Red. Annu Rev Earth Planet Sci. 37(1):93–115. doi:10.1146/annurev.earth.061008.134734. [accessed 2022 Nov 27]. https://www.annualreviews.org/doi/10.1146/annurev.earth.061008.134734.

Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, Held H, van Nes EH, Rietkerk M, Sugihara G. 2009. Early-warning signals for critical transitions. Nature. 461(7260):53–59. doi:10.1038/nature08227. [accessed 2023 Feb 24]. https://www.nature.com/articles/nature08227.

Schubert SD, Suarez MJ, Pegion PJ, Koster RD, Bacmeister JT. 2004. On the Cause of the 1930s Dust Bowl. Science. 303(5665):1855–1859. doi:10.1126/science.1095048. [accessed 2023 Feb 6]. https://www.science.org/doi/10.1126/science.1095048.

Schumacher DL, Zachariah M, Otto F, Barnes C, Philip S, Kew S, Vahlberg M, Singh R, Heinrich D, Arrighi J, et al. 2022. High temperatures exacerbated by climate change made 2022 Northern Hemisphere soil moisture droughts more likely. Imperial College London, Royal Netherlands Meterological Institute: World Weather Attribution.

Seager R, Henderson N, Cane M. 2022. Persistent Discrepancies between Observed and Modeled Trends in the Tropical Pacific Ocean. Journal of Climate. 35(14):4571–4584.

doi:10.1175/JCLI-D-21-0648.1. [accessed 2023 Feb 5]. https://journals.ametsoc.org/view/journals/clim/35/14/JCLI-D-21-0648.1.xml.

Seager R, Kushnir Y, Herweijer C, Naik N, Velez J. 2005. Modeling of Tropical Forcing of Persistent Droughts and Pluvials over Western North America: 1856–2000. Journal of Climate. 18(19):4065–4088. doi:10.1175/JCLI3522.1. [accessed 2023 Feb 6]. https://journals.ametsoc.org/view/journals/clim/18/19/jcli3522.1.xml.

Sonnerup RE, Bullister JL, Mecking S. 2007. Circulation rate changes in the eastern subtropical North Pacific based on chlorofluorocarbon ages. Geophysical Research Letters. 34(8). doi:10.1029/2006gl028813.

Steiger NJ, Smerdon JE, Cook BI, Seager R, Williams AP, Cook ER. 2019. Oceanic and radiative forcing of medieval megadroughts in the American Southwest. Science Advances. 5(7):eaax0087. doi:10.1126/sciadv.aax0087. [accessed 2023 Feb 6]. https://www.science.org/doi/10.1126/sciadv.aax0087.

Sun W, Liu J, Wang B, Chen D, Gao C. 2022. Pacific multidecadal (50–70 year) variability instigated by volcanic forcing during the Little Ice Age (1250–1850). Clim Dyn. 59(1):231–244. doi:10.1007/s00382-021-06127-7. [accessed 2023 Feb 21]. https://doi.org/10.1007/s00382-021-06127-7.

Swain DL, Horton DE, Singh D, Diffenbaugh NS. 2016. Trends in atmospheric patterns conducive to seasonal precipitation and temperature extremes in California. Science Advances. 2(4):e1501344. doi:10.1126/sciadv.1501344. [accessed 2023 Feb 4]. https://www.science.org/doi/10.1126/sciadv.1501344.

Swain DL, Langenbrunner B, Neelin JD, Hall A. 2018. Increasing precipitation volatility in twenty-first-century California. Nature Clim Change. 8(5):427–433. doi:10.1038/s41558-018-0140-y. [accessed 2022 Nov 2]. https://www.nature.com/articles/s41558-018-0140-y.

Swain DL, Tsiang M, Haugen M, Singh D, Charland A, Rajaratnam B, Diffenbaugh NS. 2014. 2. THE EXTRAORDINARY CALIFORNIA DROUGHT OF 2013/2014: CHARACTER, CONTEXT, AND THE ROLE OF CLIMATE CHANGE.

Trenberth KE, Hurrell JW. 1994. Decadal atmosphere-ocean variations in the Pacific. Climate Dynamics. 9(6):303–319. doi:10.1007/BF00204745. [accessed 2023 Feb 16]. https://doi.org/10.1007/BF00204745.

Tung K-K, Chen X, Zhou J, Li K-F. 2019. Interdecadal variability in pan-Pacific and global SST, revisited. Clim Dyn. 52(3):2145–2157. doi:10.1007/s00382-018-4240-1. [accessed 2023 Feb 23]. https://doi.org/10.1007/s00382-018-4240-1.

Wang B, Luo X, Yang Y-M, Sun W, Cane MA, Cai W, Yeh S-W, Liu J. 2019. Historical change of El Niño properties sheds light on future changes of extreme El Niño. Proceedings of the National Academy of Sciences. 116(45):22512–22517. doi:10.1073/pnas.1911130116. [accessed 2023 Jan 13]. https://www.pnas.org/doi/10.1073/pnas.1911130116.

Wang F, Shao W, Yu H, Kan G, He X, Zhang D, Ren M, Wang G. 2020. Re-evaluation of the Power of the Mann-Kendall Test for Detecting Monotonic Trends in Hydrometeorological Time

Series. Frontiers in Earth Science. 8. [accessed 2023 Feb 16]. https://www.frontiersin.org/articles/10.3389/feart.2020.00014.

Wills RC, Schneider T, Wallace JM, Battisti DS, Hartmann DL. 2018. Disentangling Global Warming, Multidecadal Variability, and El Niño in Pacific Temperatures. Geophysical Research Letters. 45(5):2487–2496. doi:10.1002/2017GL076327. [accessed 2023 Feb 21]. https://onlinelibrary.wiley.com/doi/abs/10.1002/2017GL076327.

Wills RCJ, Dong Y, Proistosecu C, Armour KC, Battisti DS. 2022. Systematic Climate Model Biases in the Large-Scale Patterns of Recent Sea-Surface Temperature and Sea-Level Pressure Change. Geophysical Research Letters. 49(17):e2022GL100011. doi:10.1029/2022GL100011. [accessed 2022 Nov 21]. https://onlinelibrary.wiley.com/doi/abs/10.1029/2022GL100011.

Wood RR, Lehner F, Pendergrass AG, Schlunegger S. 2021. Changes in precipitation variability across time scales in multiple global climate model large ensembles. Environ Res Lett. 16(8):084022. doi:10.1088/1748-9326/ac10dd. [accessed 2022 Oct 31]. https://dx.doi.org/10.1088/1748-9326/ac10dd.

Yang Y-M, An S-I, Wang B, Park JH. 2020. A global-scale multidecadal variability driven by Atlantic multidecadal oscillation. Natl Sci Rev. 7(7):1190–1197. doi:10.1093/nsr/nwz216. [accessed 2023 Feb 23]. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8288868/.