Mechanisms of changes in precipitation and droughts driven by natural variability and external forcings

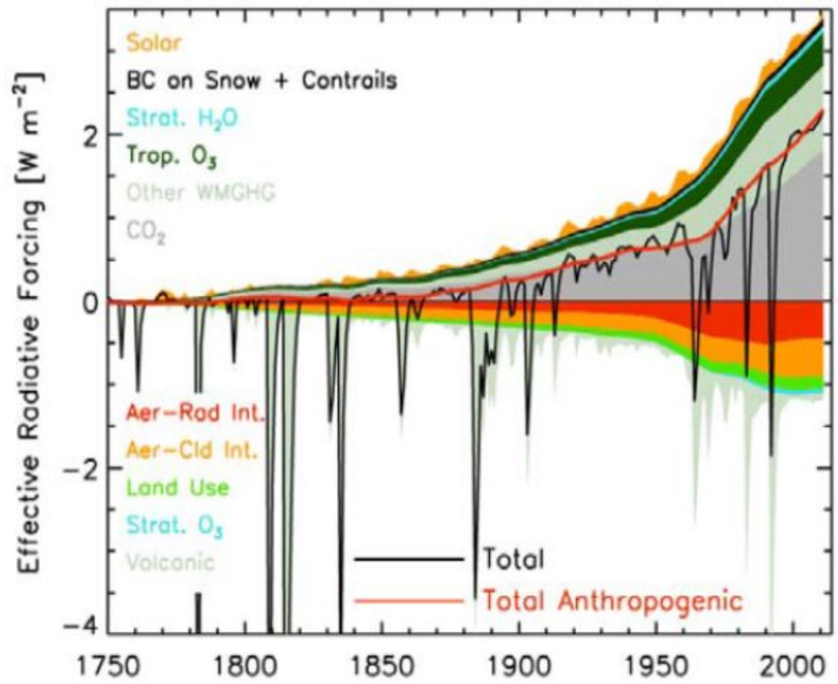
Celine Bonfils
Sept 12, 2018
AGCI, Aspen, Colorado
When the Rain Stops: Drought on Subseasonal and Longer timescales

Lawrence Livermore National Laboratory

LLNL-PRES-740731

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Variation with Time of Climate Forcings:



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Young Buck

"when the, rain stops
I'm doughnut ridin'
and I can't stop"

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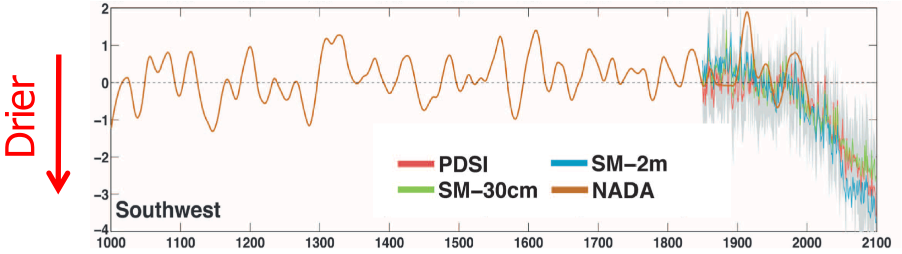
Starts with a flood in a desert region in Australia in 2039 "About self-identity, forgiveness and love"

Motivation

Unprecedented 21st century drought risk in the American SW (Cook et al. 2015)



Climate models project unprecedented drought risk and increased aridity

Science questions:

- Are changes in drought behavior becoming increasingly driven by human forcing?
- Can we identify these human-induced changes in observed climate records?

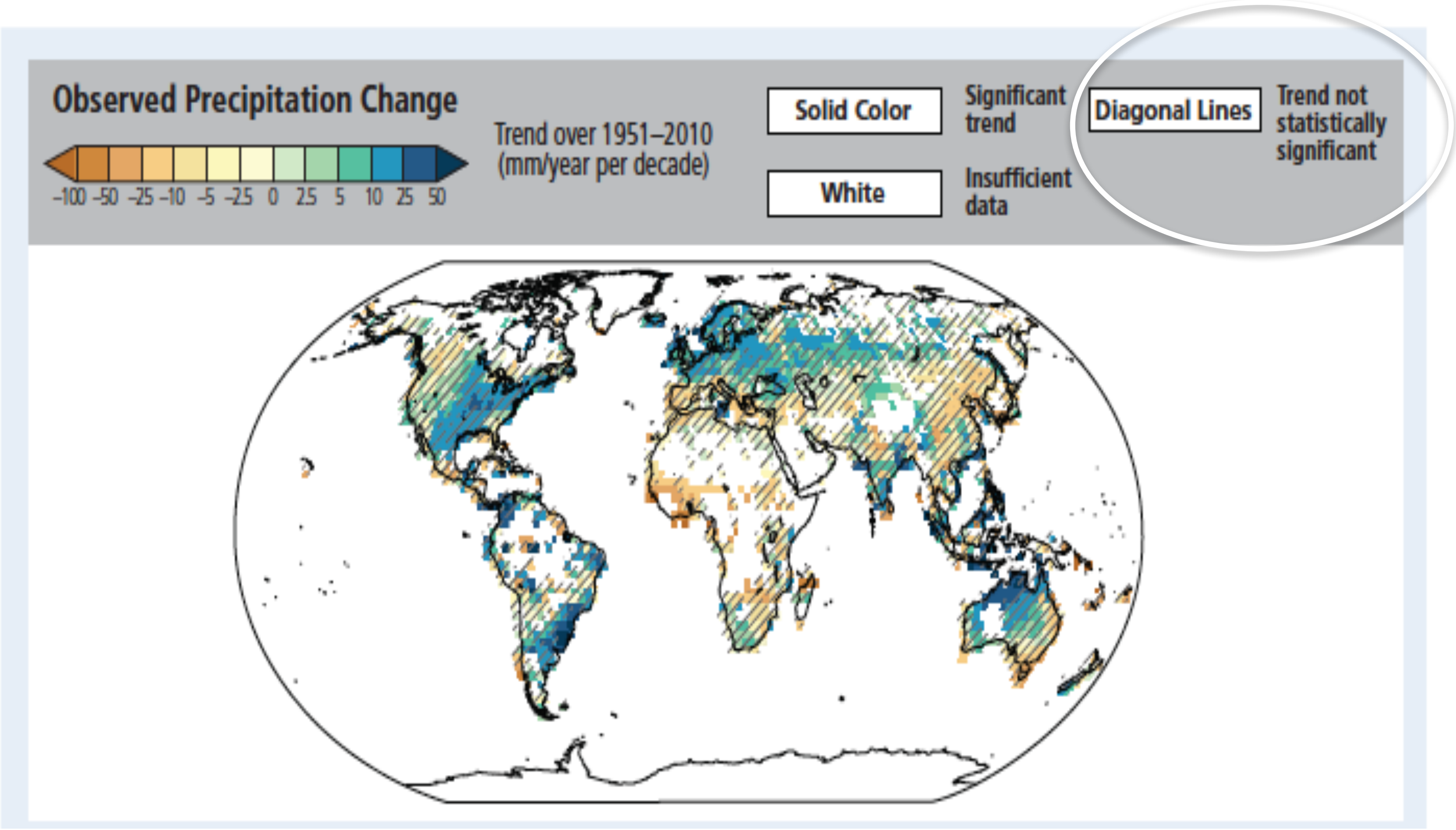
→ Focused first on large-scale precursors of droughts and long-term trends

Improve our understanding of the nature and causes of past/future droughts

Influences on droughts/aridification

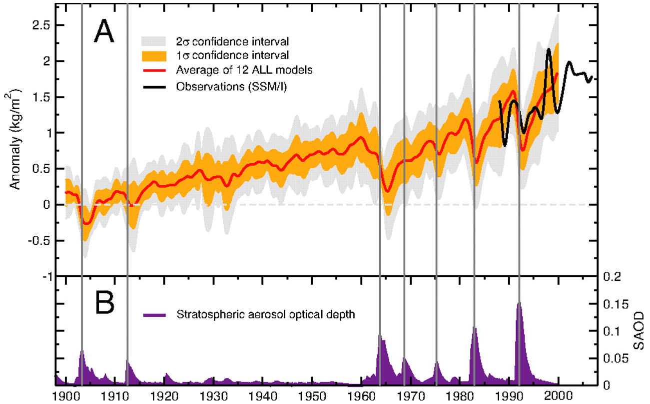
	Moisture supply: Precipitation	Evaporative demand
Gradual change in mean	#1. Discernable human-induced changes in the observed rainfall patterns Marvel and Bonfils 2013	
Gradual change in variance		

How do we identify a human influence on global precipitation?



First, we need to identify some mechanisms that are expected to drive the future changes in P

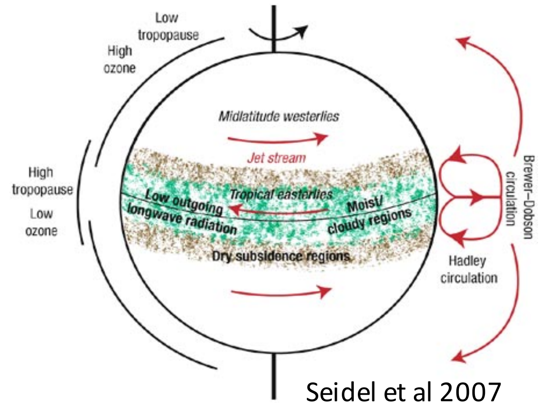
Thermodynamic



Santer et al 2007

Intensification of current zonal wet-dry patterns

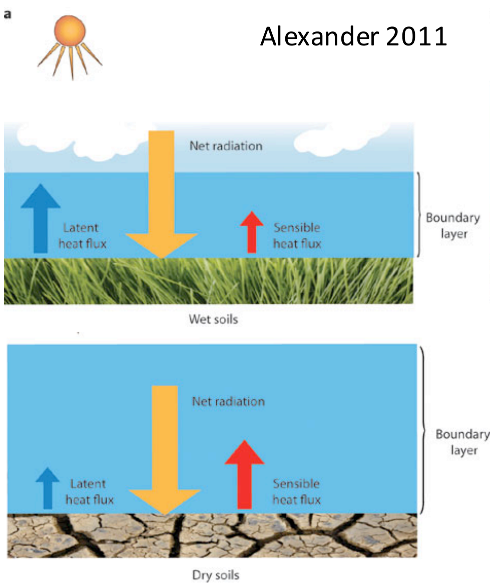
Dynamic



Seidel et al 2007

Latitudinal redistribution of global precipitation

Coupled



Land-atm feedbacks

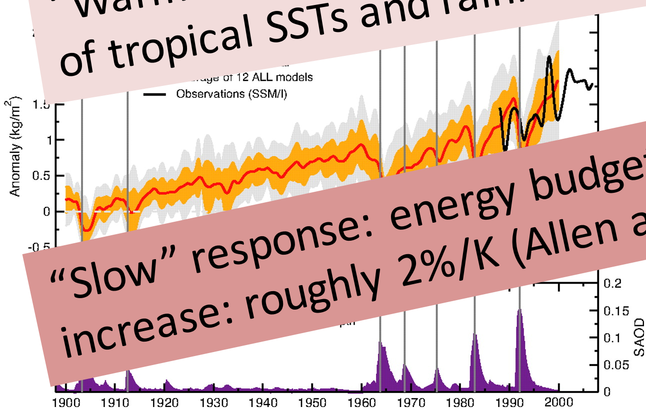
First, we need to identify some mechanisms that are expected to drive the future changes in P

Thermod... ...mic

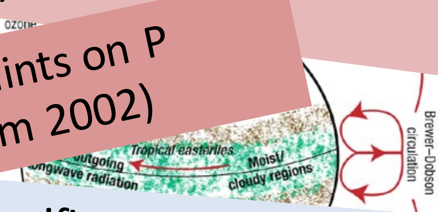
Coupled

“Warmer-gets-wetter” mechanism (link the patterns of tropical SSTs and rainfall change ...ie et al. 2010)

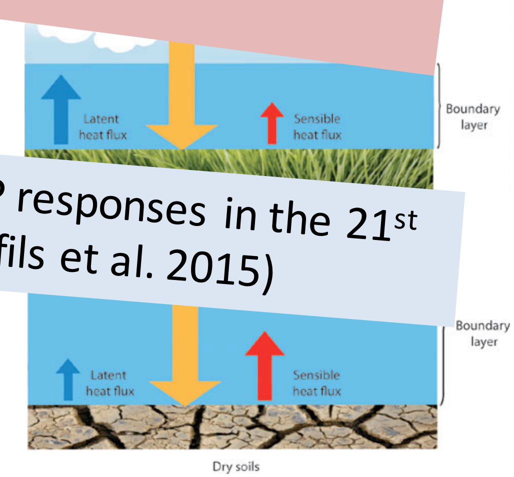
Fast P response to CO_2 forcing (e.g., Richardson et al. 2016)



Santer et al 2007



...Alexander 2011



“Slow” response: energy budget constraints on P increase: roughly 2%/K (Allen and Ingram 2002)

Intensification of ENSO-driven P responses in the 21st century (Power et al. 2013, Bonfils et al. 2015)

...et al 2007

Intensification of...

...tion of ... precipitation

...feedbacks

WWDD theory does not work well over land (Greve et al. 2014)...

... unless seasonality is considered (Kumar et al. 2015)

Changes in annual cycle of P, shift in ITCZ...

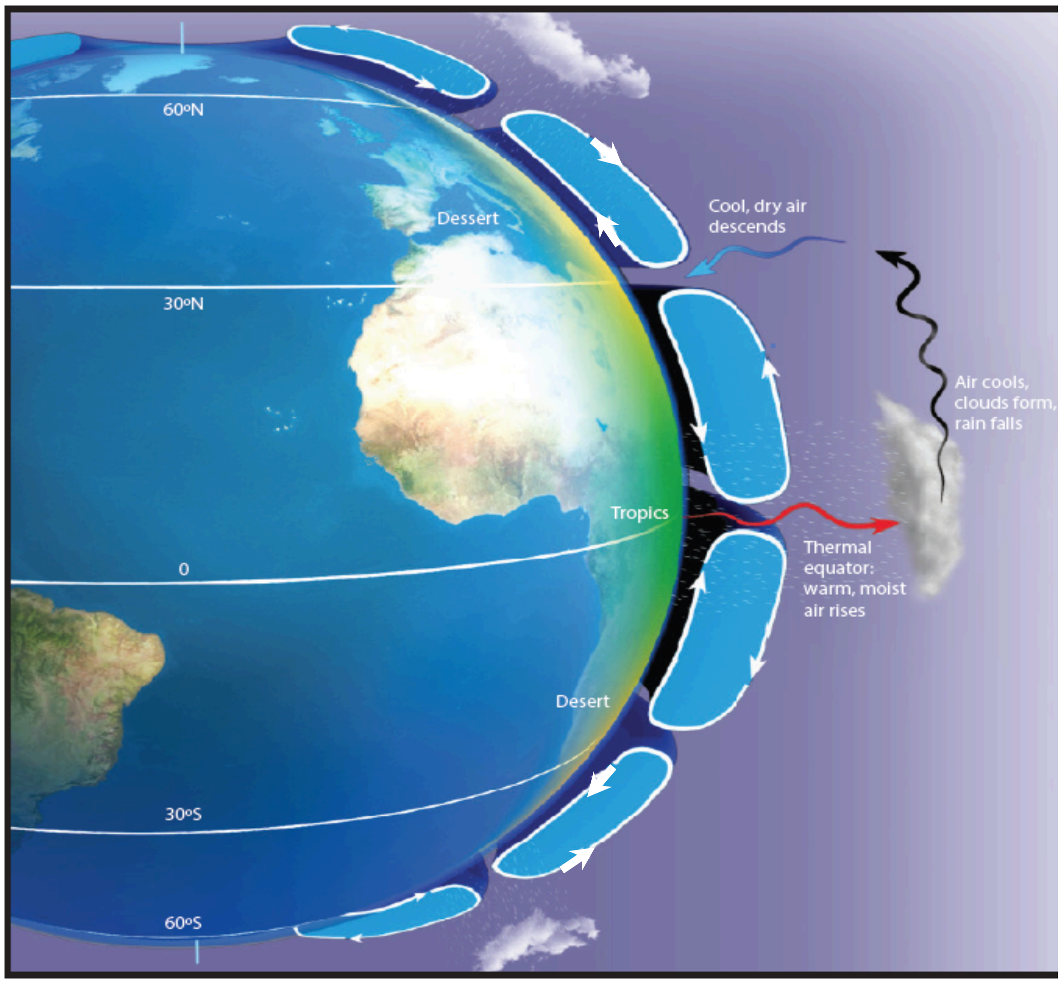
Then, we pick a mechanism and tried to detect a human influence

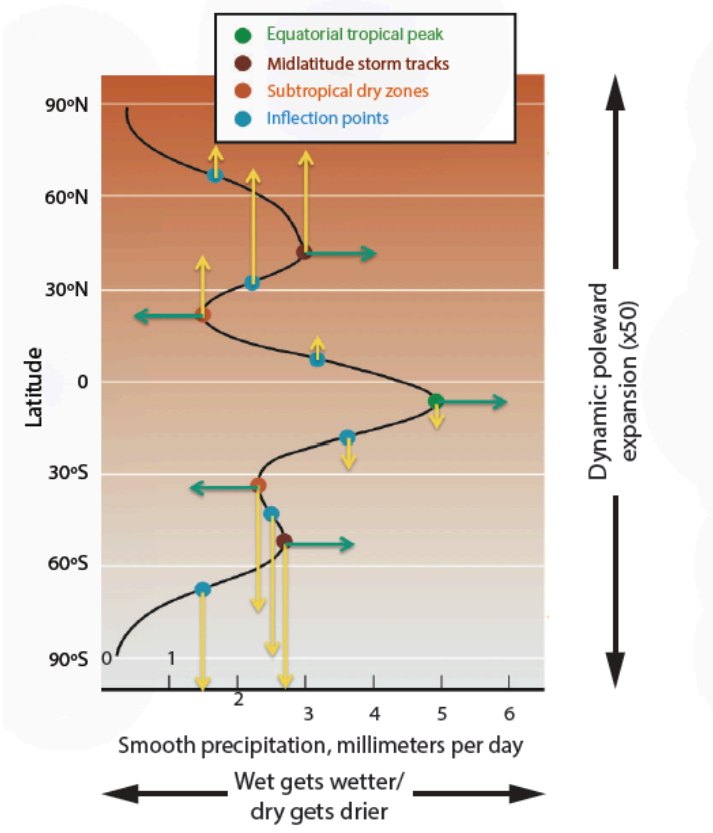
Eg: Natural and Human Influences on Changing Zonal-Mean Precipitation (Marvel & Bonfils, 2013 PNAS)

Theories and climate projections predict a latitudinal intensification and poleward shifts of global precipitation

Human fingerprint = expected response to human forcings from 70+ CMIP5 runs of historical climate change (1980-2012)

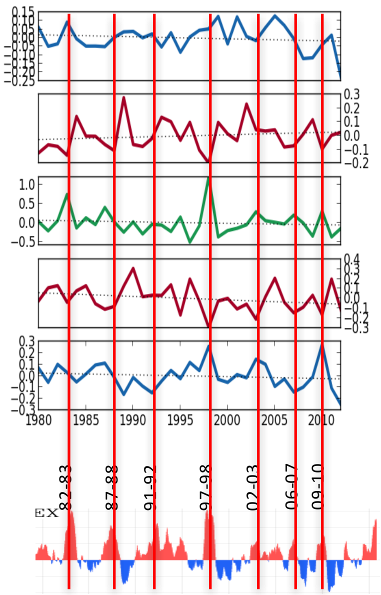
= Distortion of the curve in response to human forcing





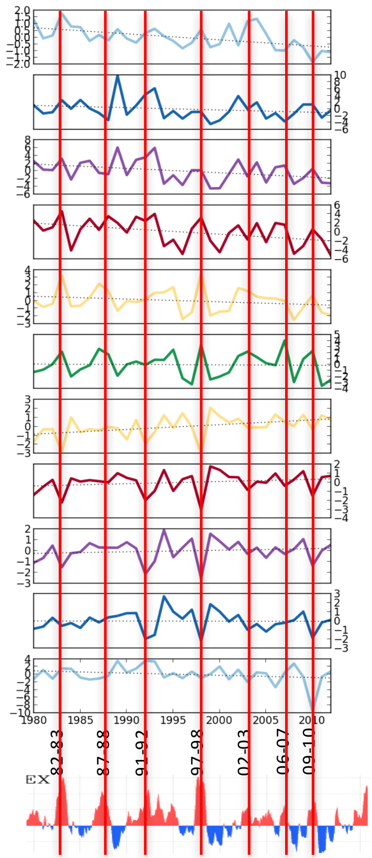
Projection of observed Intensity and Position anomalies

Intensity



Niño3.4

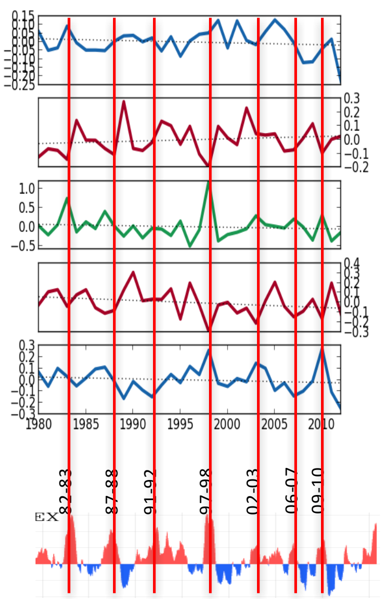
Position



Niño3.4

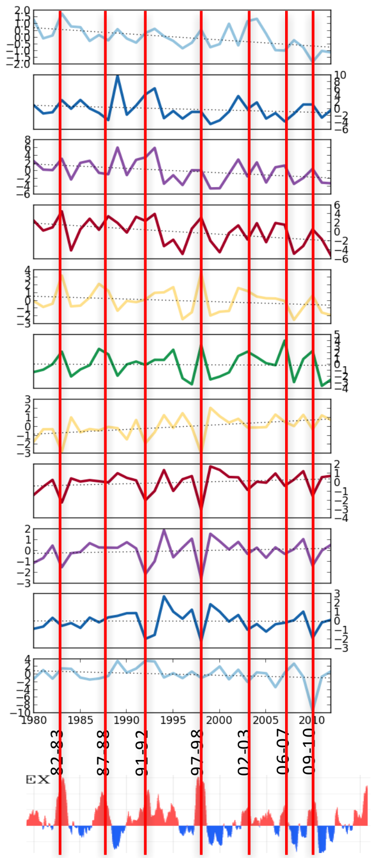
Projection of observed Intensity and Position anomalies

Intensity

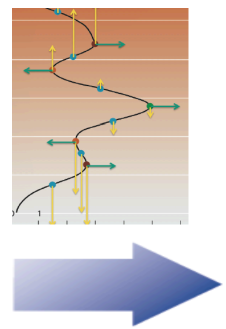


Niño3.4

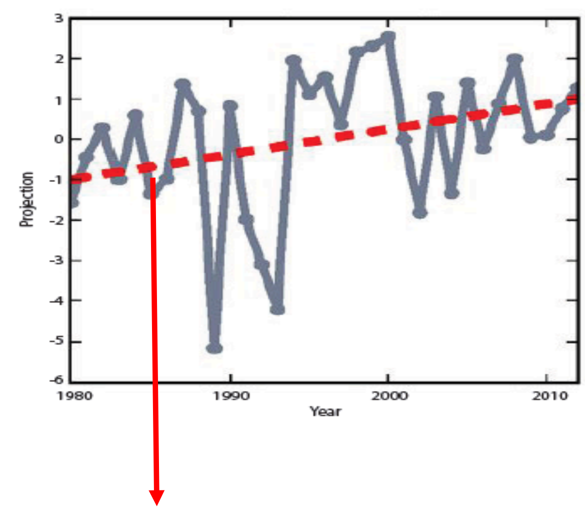
Position



Niño3.4



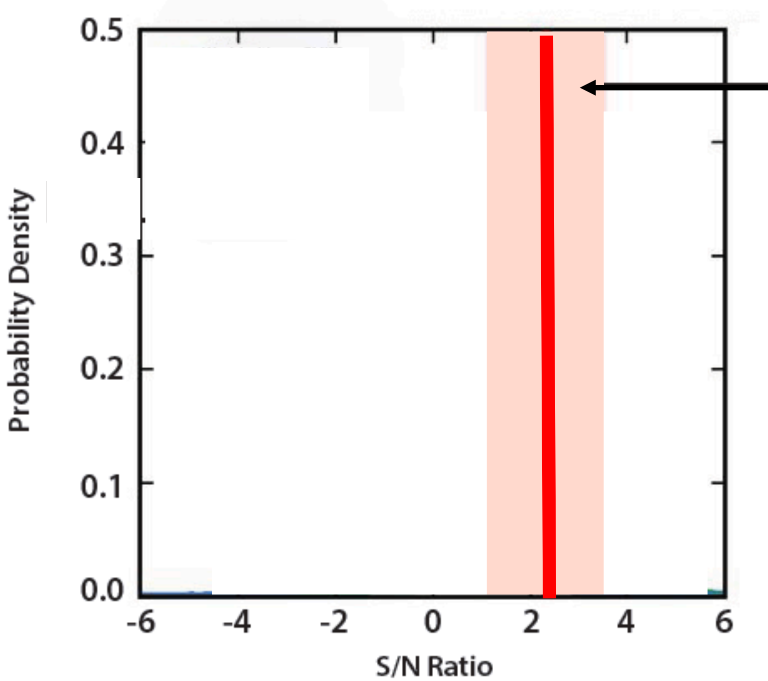
SIGNAL time-series = measure of similarity between obs and fingerprint



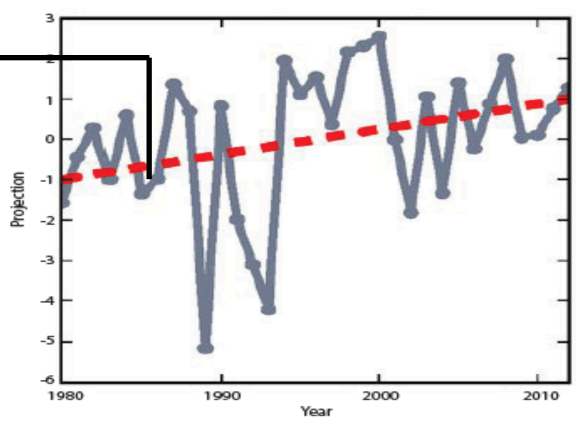
Positive trend: fingerprint is present and growing in the observations

Projection of observed Intensity and Position anomalies

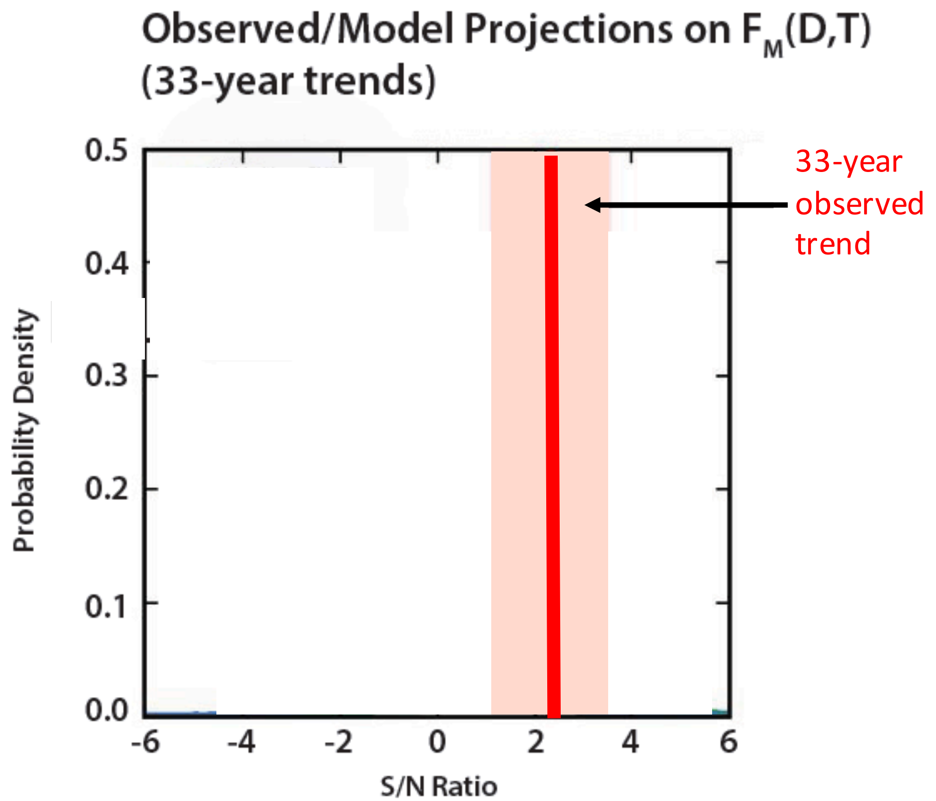
Observed/Model Projections on $F_M(D,T)$
(33-year trends)



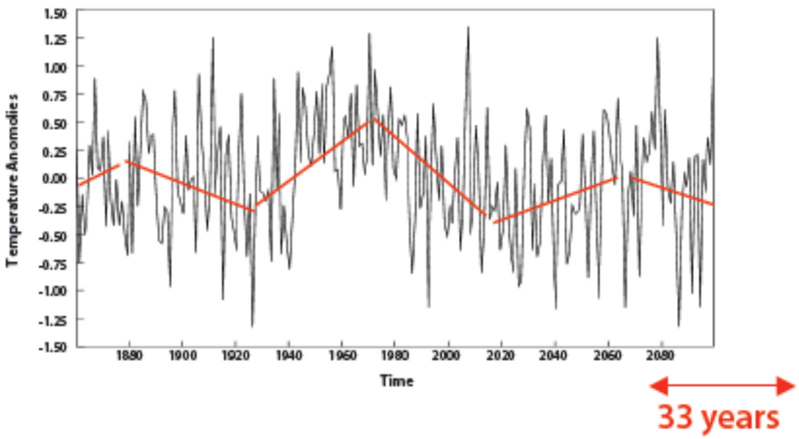
SIGNAL time-series = measure of similarity between obs and fingerprint



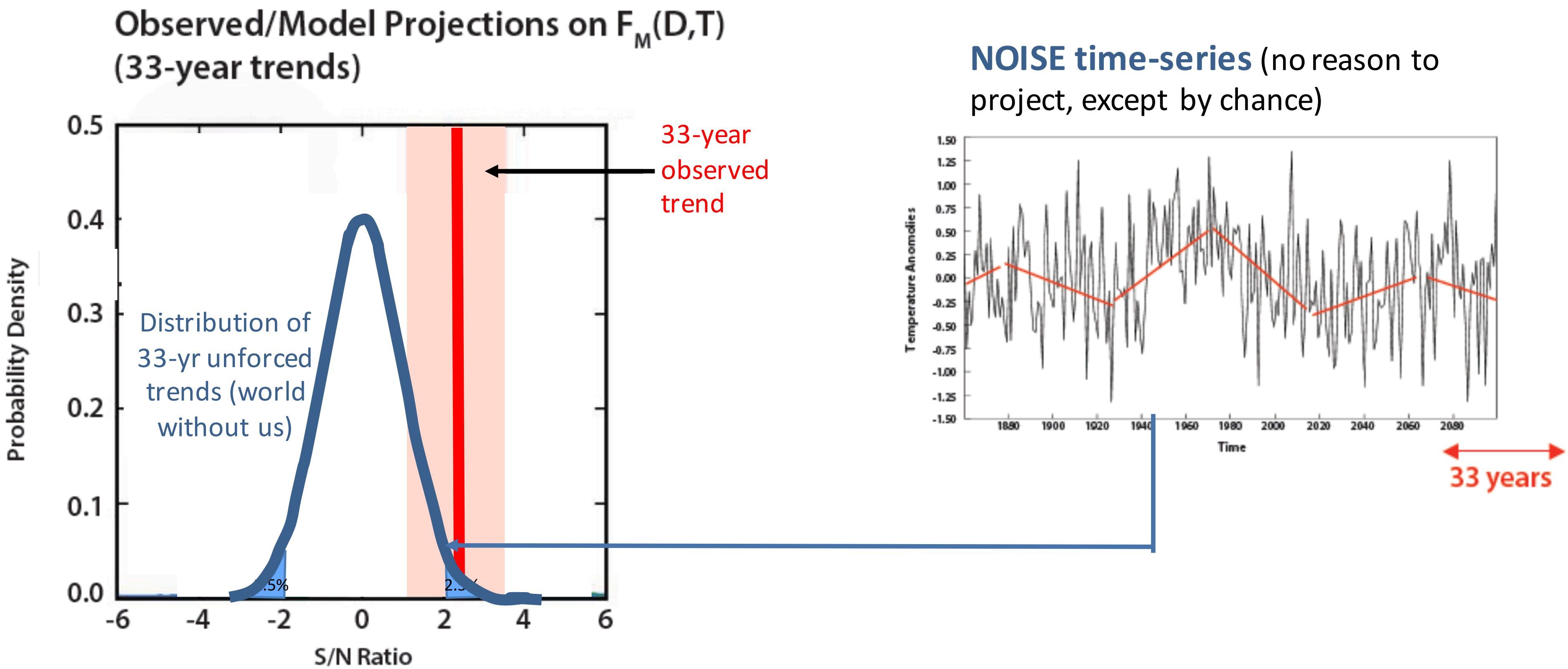
Projection of 20k yrs of unforced Intensity and Position anomalies



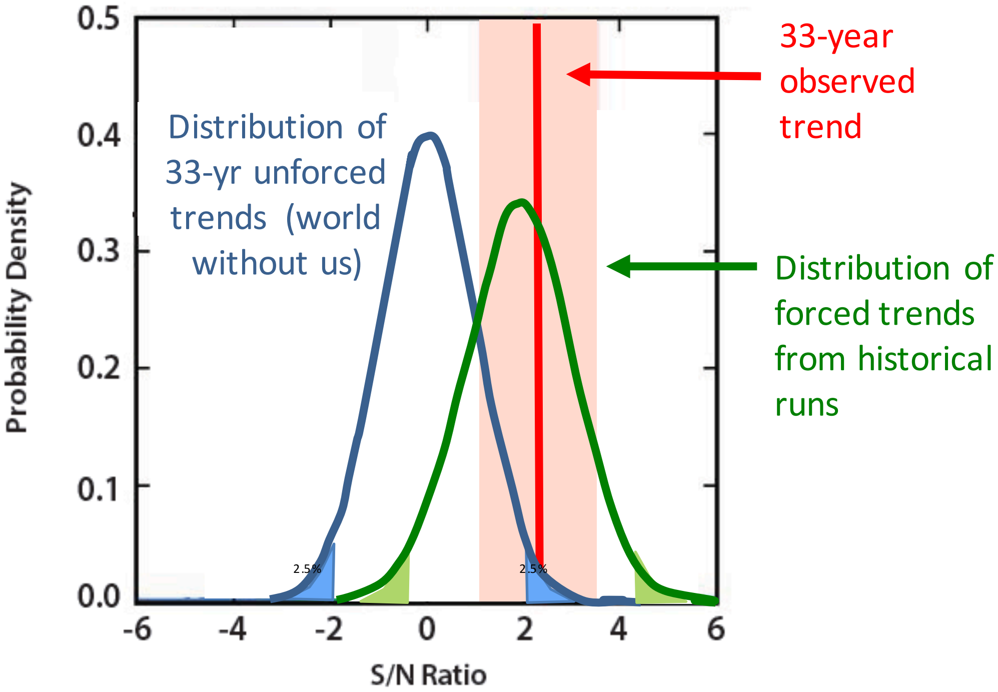
NOISE time-series (no reason to project, except by chance)



Observed trend cannot be explained by internal variability



#1 We detected a human influence on changing zonal-mean precipitation



- **Detection:** The observed intensification + poleward expansion of zonal P cannot be explained by climate noise alone.
- **Attribution:** The observations matches predictions from simulations with combined natural and human forcings

Marvel K and C Bonfils 2013: Identifying External Influences on Global Precipitation. *PNAS*

Influences on droughts

	Moisture supply: Precipitation	Evaporative demand
Gradual change in mean	Marvel and Bonfils 2013	
Gradual change in variance	#2. Increase in ENSO-driven precipitation variability Bonfils et al. 2015	

In the 21st century, ENSO-driven precipitation variability is intensified

Goal

ENSO is the main trigger of precipitation variability

- Models do not agree on how ENSO characteristics will evolve in the future

Unclear whether the precipitation response to ENSO will change in the future, even if ENSO remains unchanged

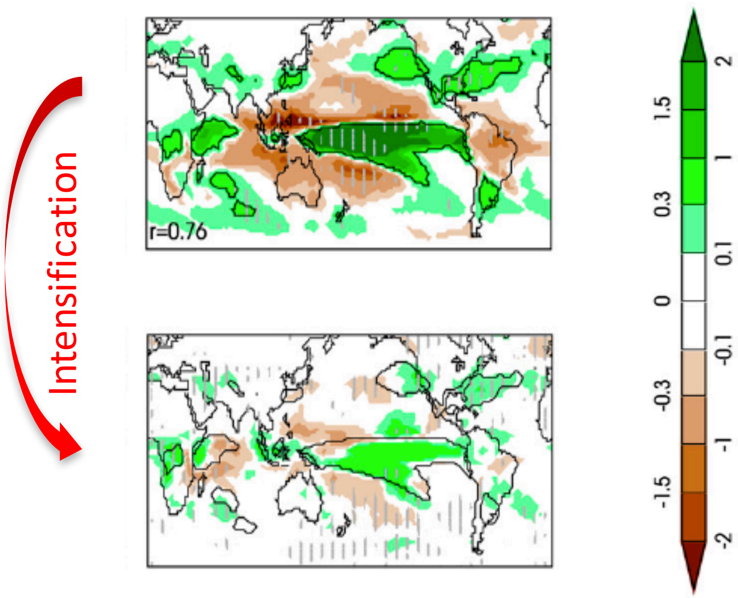
- Non-uniform warming in tropical Pacific Ocean
- Atmospheric circulation change
- Moister atmosphere

Results

<u>Basic</u> 20th century P response to ENSO events

<u>Additional</u> P response to ENSO in the future

El Niño



Bonfils C, B Santer, T Phillips, K Marvel, R Leung, C Doutriaux, A Capotondi, 2015. *J. Clim*

Influence on droughts

<table>
<tr><th></th><th>Moisture supply: Precipitation</th><th>Evaporative demand</th></tr>
<tr><td>Gradual change in mean</td><td>Marvel and Bonfils 2013</td><td rowspan="2">#3. Most regions where aridity/moistening is currently regulated by ENSO variability will become more arid in the future
Bonfils et al. 2016</td></tr>
<tr><td>Gradual change in variance</td><td>Bonfils et al. 2015</td></tr>
</table>

#3 Influence of anthropogenic climate change on regional aridity

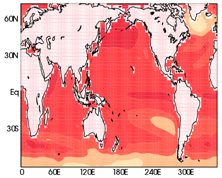
Objectives

Investigate the contributions from:

- changes in precipitation vs. evaporative demand
- Changes in mean aridity vs. ENSO variability

Use different sets of experiments to assess the impact of:

1) Ocean warming (+Warming, mean=4K)



2) Plant fertilization to rising CO2 (+VEG)

3) "fast" radiative forcing from enhanced CO2 (+RAD)

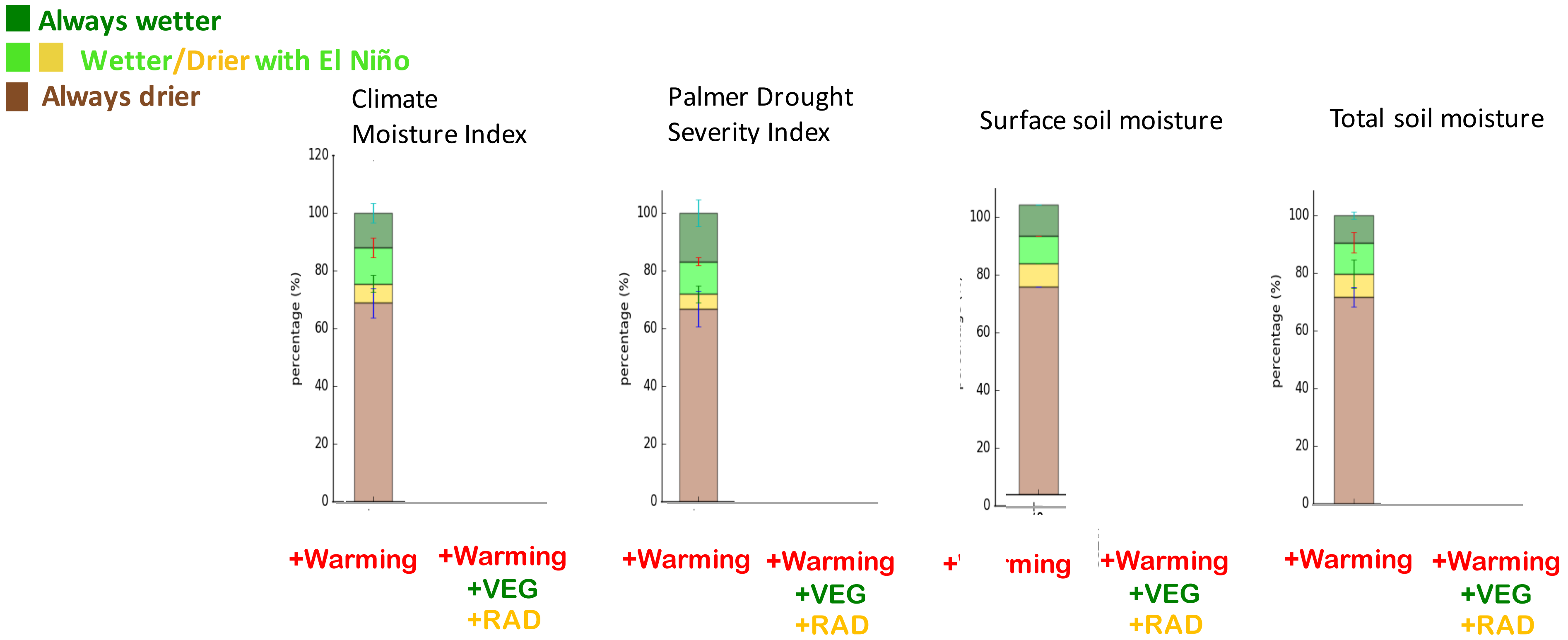
Approach

- Identify regions where aridity is historically sensitive to ENSO
- Find regions where the future changes in mean aridity exceeds the range of ENSO variability

→ 6 measures of terrestrial aridity
→ P/(P+Eo), CMI, PDSI, 2 SM indices, runoff

CMI= (P / PET) -1 when P < PET
CMI= 1- (PET / P) when P > PET

#3 Influence of anthropogenic climate change on regional aridity

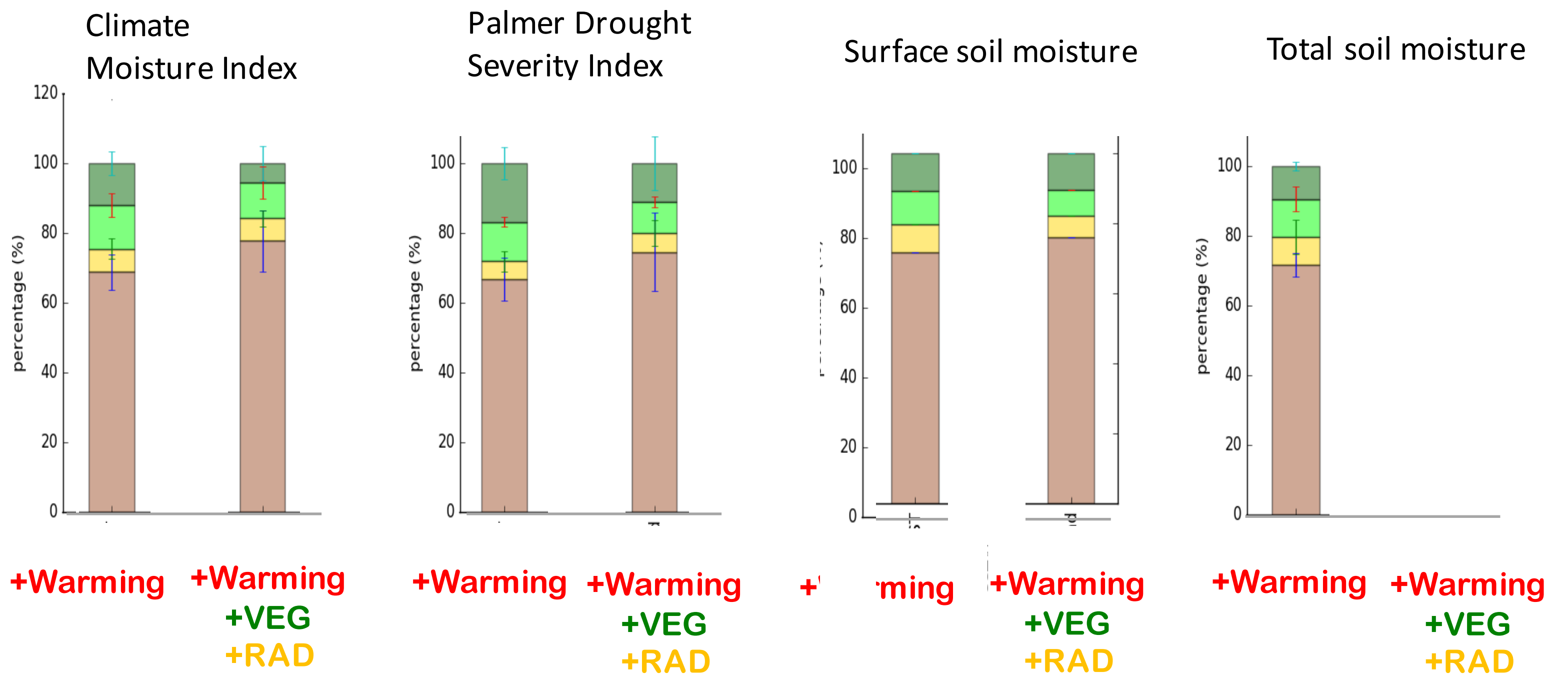


Results

- Future aridity predicted in ~67-72% of the regions where aridity is currently driven by ENSO variability

#3 Influence of anthropogenic climate change on regional aridity

Always wetter
Wetter/Drier with El Niño
Always drier

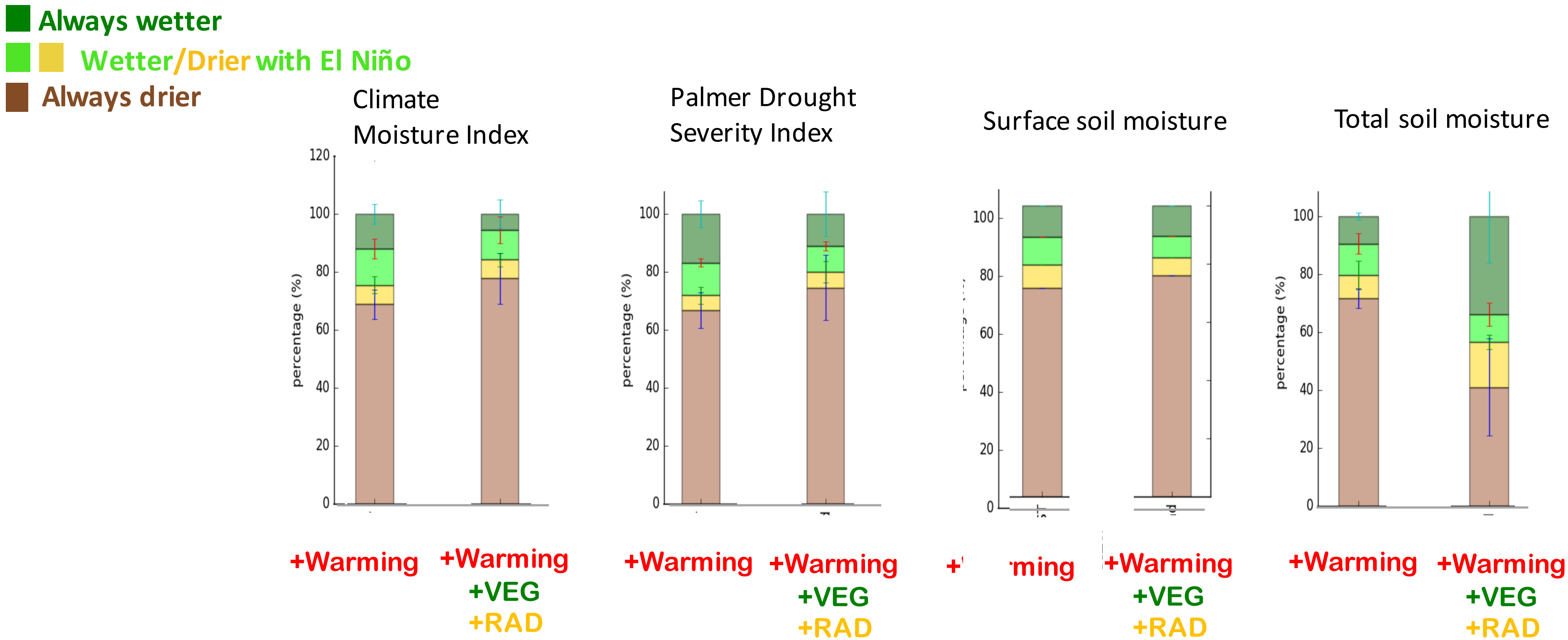


Results

- Future aridity predicted in ~67-72% of the regions where aridity is currently driven by ENSO variability
- It reaches ~75-78% when the vegetation and radiative effects are included

Bonfils, C., G. Anderson, B. Santer, T. Phillips, K. Taylor, M. Cuntz, M. Zelinka, K. Marvel, B. Cook, I. Cvijanovic, P. Durack, 2017. *J. Clim*

#3 Influence of anthropogenic climate change on regional aridity



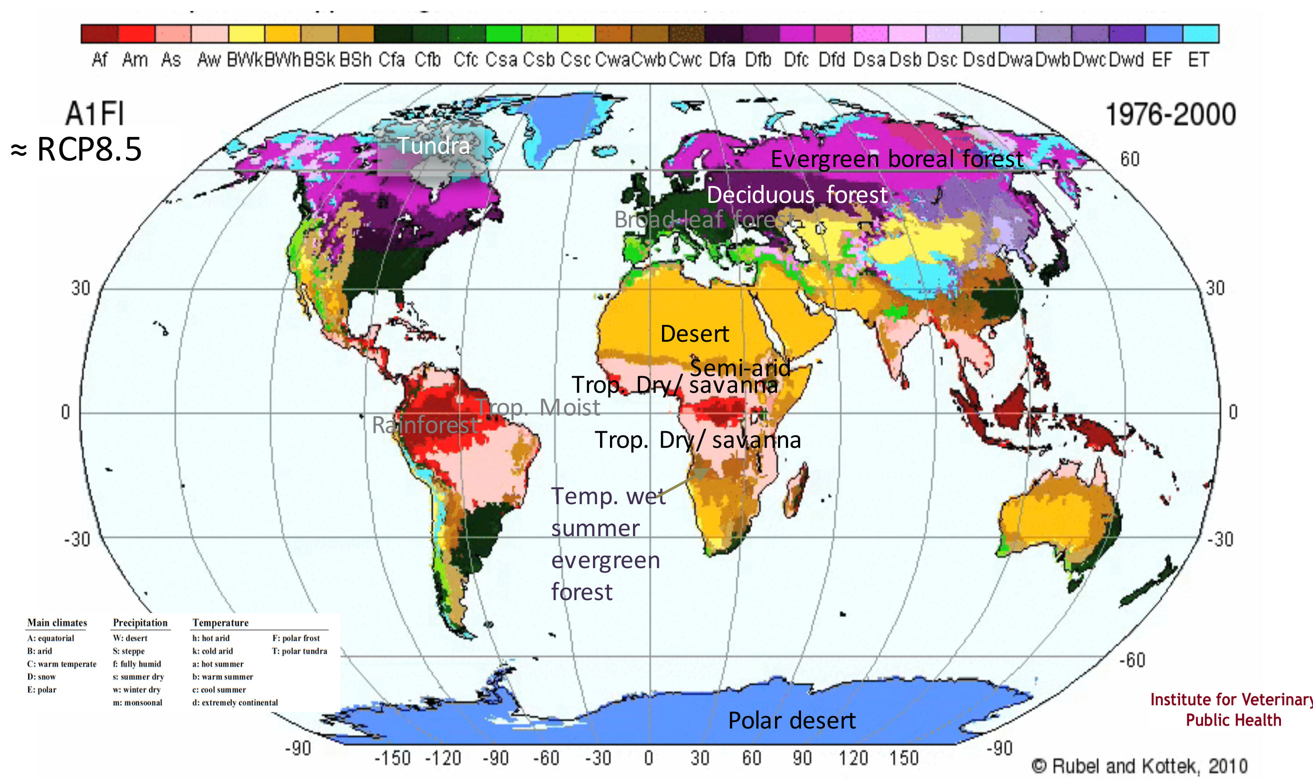
Results

- Future aridity predicted in ~67-72% of the regions where aridity is currently driven by ENSO variability
- It reaches ~75-78% when the vegetation and radiative effects are included
- This prediction is much weaker when total soil moisture is considered (41%): stomatal closure prevents soil desiccation

Bonfils, C., G. Anderson, B. Santer, T. Phillips, K. Taylor, M. Cuntz, M. Zelinka, K. Marvel, B. Cook, I. Cvijanovic, P. Durack, 2017. *J. Clim*

On the natural and human influences in changes in aridity /droughts?

- **Changes in latitudinal distribution of Köppen vegetation types. Single metric that:**
  - Summarizes the changes in climate that are ecologically relevant
  - Is sensitive to thresholds and features of the seasonal cycle in temperature and precipitation



http://koeppen-geiger.vu-wien.ac.at/

On the natural and human influences in changes in aridity /droughts?

- **Changes in latitudinal distribution of Köppen vegetation types.**

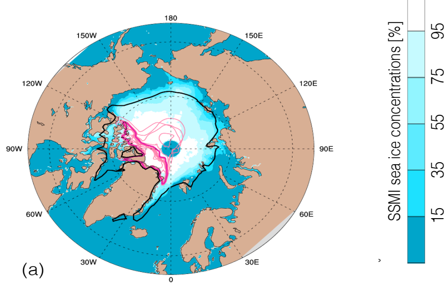
- **Arctic sea ice loss could favor drying in California (Cvijanovic et al 2017)**

CESM ensemble of simulations with seasonally ice free Arctic (by sampling model uncertainty in 3 sea-ice physics parameters + initial conditions) -

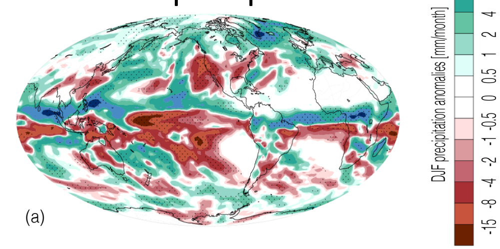
2-step teleconnection:

1. Northward shift in ITCZ
2. Tropical convection reorganization favors a persistent ridge over North Pacific coast

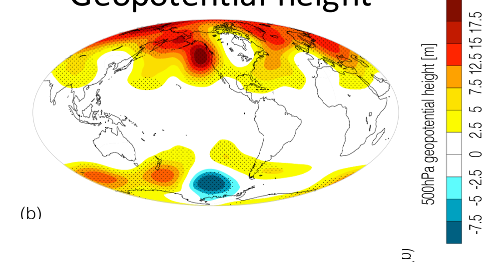
Sea ice (September)



Winter precipitation



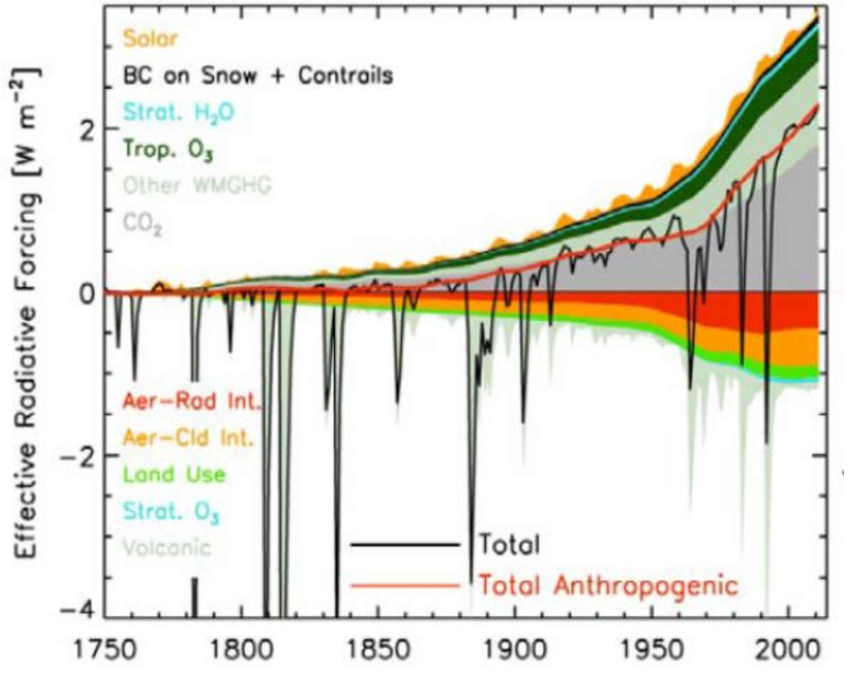
Geopotential height



On the natural and human influences in changes in aridity /droughts?

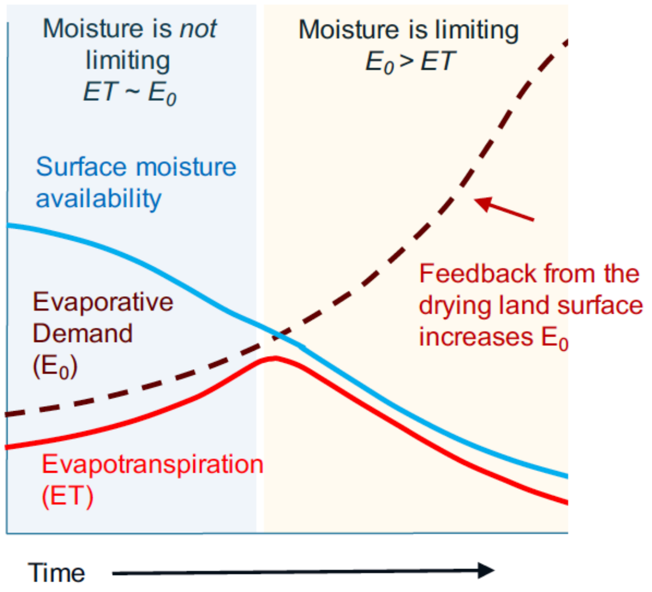
- **Changes in latitudinal distribution of Köppen vegetation types.**
- **Arctic sea ice loss could favor drying in California (Cvijanovic et al 2017)**
- **D&A considering the impact of GHG, AA, volcanic activity on large-scale changes in P, T & drought index**

Variation with Time of Climate Forcings:



Flash droughts

- We find that the characterization of flash droughts can be regionally dependent
- However, within a same region, the characterization of flash droughts could change with time (i.e. forcings).
- A change in SM or Eo mean state could trigger flash droughts that could occur earlier and / or more frequently



Lukas, Hobbins, Rangwala

Large-scale precursors → changes occurring over land, at regional scale

Monthly → daily data

Change in variable → Change in frequency, duration and/or intensity

Ideal coverage period: ideally 1948 – 2017

Need a metric easy to capture in both CMIP simulations and observations

Supplemental Materiel

Another mechanisms: Arctic sea ice loss could favor drying in California

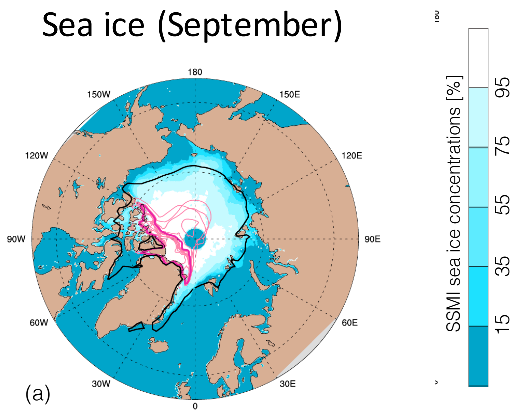
Approach

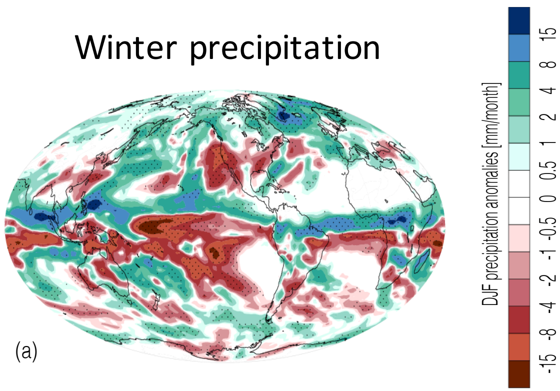
- CESM ensemble of simulations with seasonally ice free Arctic (by sampling model uncertainty in 3 sea-ice physics parameters + initial conditions)
- Framework allows coupling between sea-ice, ocean and atmosphere in an energetically consistent way

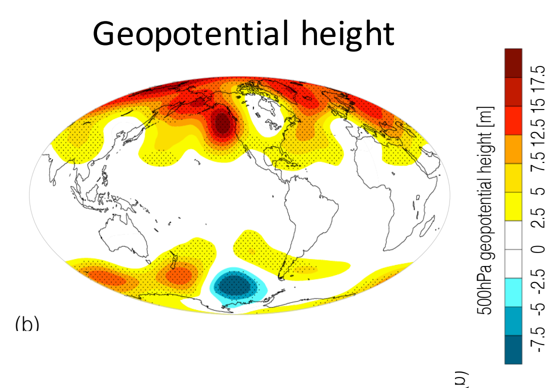
Impact

- ❑ 2-step teleconnection:
  1. Northward shift in ITCZ (Chiang and Bitz 2005)
  2. Tropical convection reorganization favors a persistent ridge over North Pacific coast

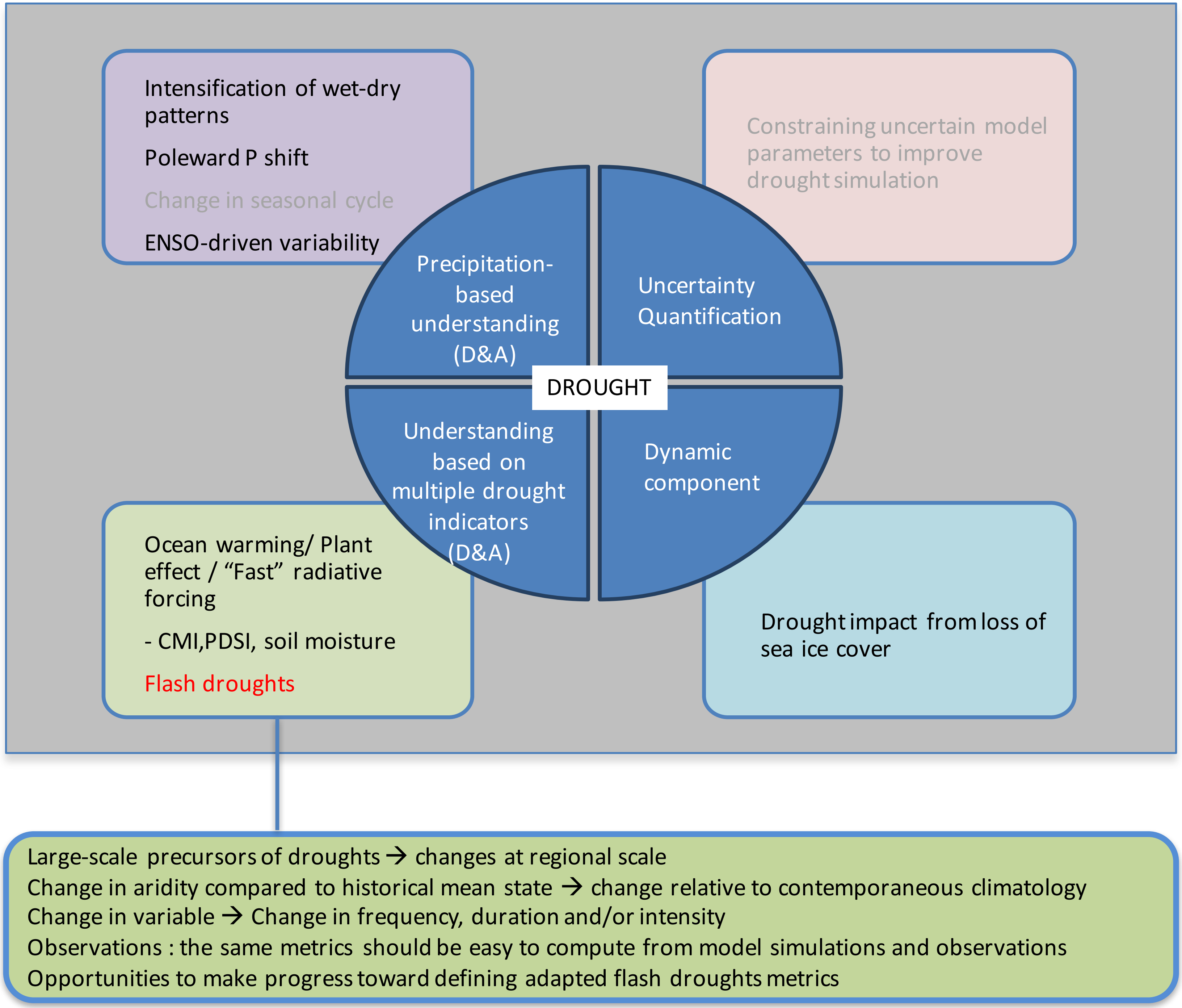
- ❑ A misrepresentation of future sea-ice changes has implications for the prediction of future drought risks







Cvijanovic I, B Santer, C Bonfils, D Lucas, S. Zimmerman, J Chiang 2017 Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall, *Nature Comm*


Intensification of wet-dry patterns
Poleward P shift
Change in seasonal cycle
ENSO-driven variability
Constraining uncertain model parameters to improve drought simulation
Precipitation-based understanding (D&A)
Uncertainty Quantification
DROUGHT
Understanding based on multiple drought indicators (D&A)
Dynamic component
Ocean warming/ Plant effect / “Fast” radiative forcing
- CMI,PDSI, soil moisture
Flash droughts
Drought impact from loss of sea ice cover
Large-scale precursors of droughts → changes at regional scale
Change in aridity compared to historical mean state → change relative to contemporaneous climatology
Change in variable → Change in frequency, duration and/or intensity
Observations : the same metrics should be easy to compute from model simulations and observations
Opportunities to make progress toward defining adapted flash droughts metrics

#5 Quantifying the effect of parameter uncertainties in simulations of drought in the Western United States

Goal

Can we more successfully simulate key features of observed drought behavior?

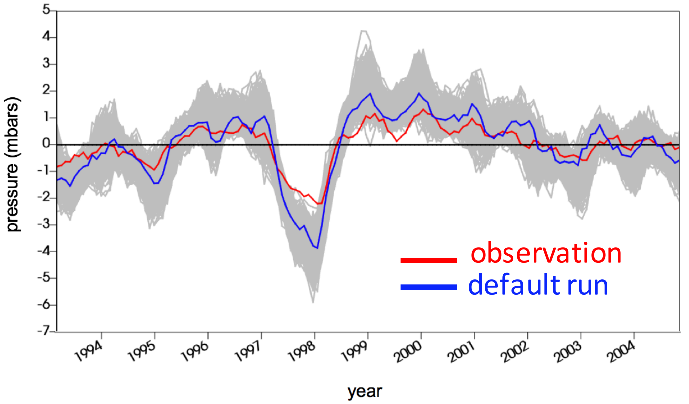
Approach

1317-member perturbed physics ensemble

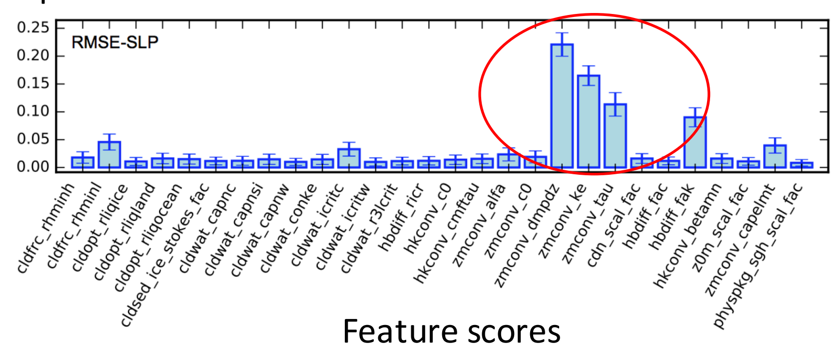
- Latin Hypercube Sampling to vary the values of 28 input parameters (e.g., clouds, P, convection & boundary layer) over allowable ranges
- Set of metrics that best characterize the drought and its drivers (tropical forcing, spatial extent of P and aridity bias)

- We perform a sensitivity analysis to identify the key parameters influencing drought metrics

Forcing metric derived from the difference in pressure anomalies in tropics



Forcing metric is most sensitive to deep convection parameters



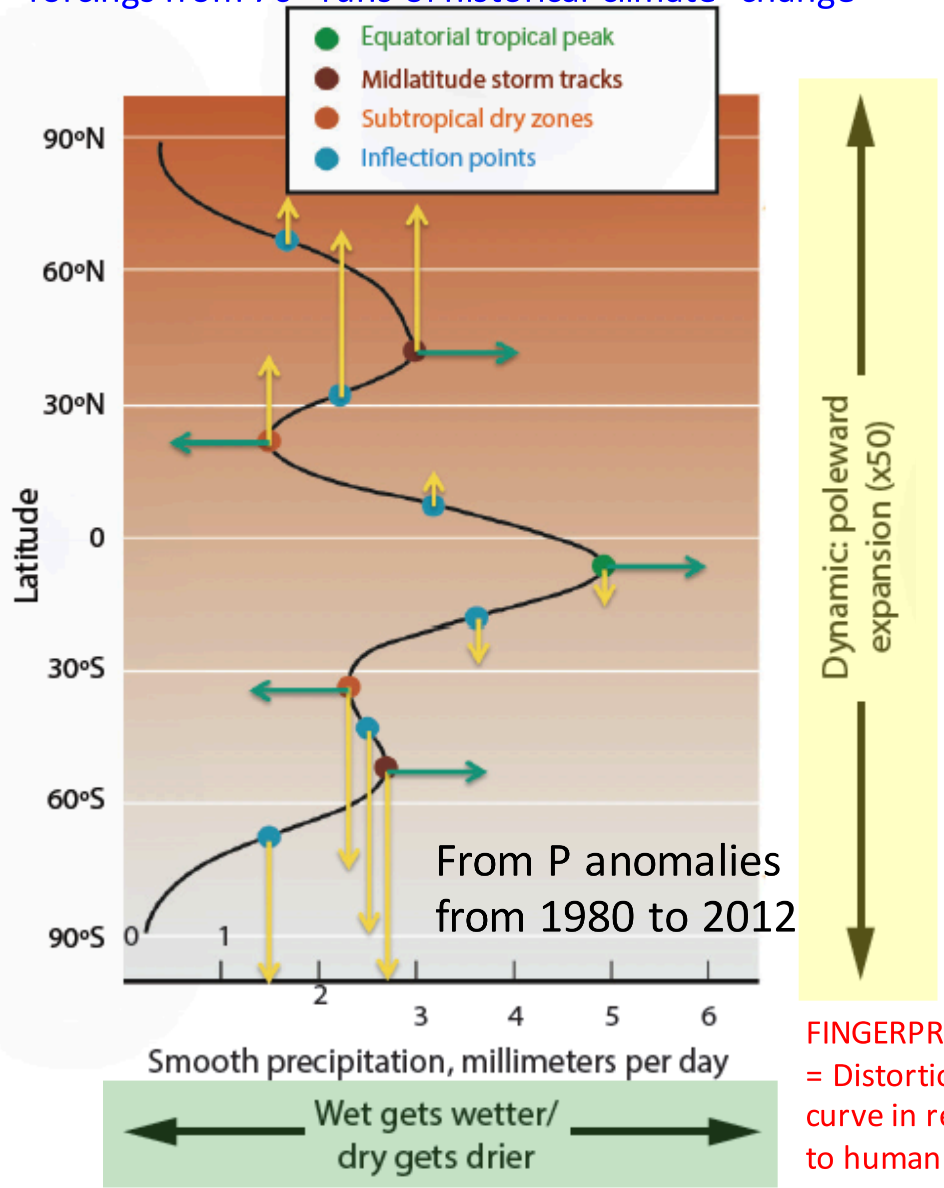
Feature scores

Köppen vegetation map after Ganadesikan and Stouffer (2006)

Köppen Regional Climate (Generic Vegetation Type)	**T/P Criteria***
Ef: Polar Desert (scant vegetation)	$T_{max} < 0$ Celsius (C)
Et: Tundra (dwarf trees, mosses)	0 C < T_{max} < 10 C and T_{min} < -3 C
Dc: Cold Winters/Cool Summers (evergreen boreal forest)	T_{min} < -3 C and < 4 months warmer than 10 C, but not types **BS** or **BW**
Dab: Cold Winters/Warm Summers (deciduous forest)	T_{min} < -3 C , T_{max} > 10 C and > 4 months warmer than 10 C, but not types **BS** or **BW**
Cw: Temperate, Wet Summers (evergreen forest)	-3 C< T_{min} < 18 C and $P_{max} > 10P_{min}$ with P_{max} occurring in summer and P_{min} in winter, but not types **BS** or **BW**
Cs: Temperate, Wet Winters (evergreen broad-leaf forest)	-3 C < T_{min} < -18 C and $P_{max} > 3P_{min}$, with P_{max} occurring in winter and P_{min} in summer, but not types **BS** or **BW**
Cfc: Temperate, Cool and Moist (needle-tree forest)	-3 C < T_{min} < 18 and T_{max} < 22 C, and with < 4 months warmer than 10 C, but not types **BS**, **BW**, **Cs**, or **Cw**
Cfb: Temperate, Warm and Moist (broad-leaf forest)	-3 C < T_{min} < 18 and T_{max} < 22 C, and with > 4 months warmer than 10 C, but not types **BS**, **BW**, **Cs**, or **Cw**
Cfa: Temperate, Hot and Moist (broad-leaf forest)	-3 C< T_{min} < 18 C and T_{max} > 22 C, but not types **BS**, **BW**, **Cs**, or **Cw**
BS: Semiarid (bush or grassland)	$(T_{avg} + P_{off}) < P_{year} < 2(T_{avg} + P_{off})$
BW: Desert (wasteland, cactus/seasonal Vegetation)	$P_{year} < (T_{avg} + P_{off})$
Af: Tropical Wet (tropical evergreen rain forest)	T_{min} > 18 C and P_{min} > 6 cm, but not types **BS** or **BW**
Am: Tropical Moist (tropical evergreen forest)	T_{min} > 18 C and $(250\ cm - P_{year})/25 < P_{min} < 6$ cm, but not types **BS** or **BW**
Aw: Tropical Dry (savanna/woodland)	T_{min} > 18 C and P_{min} < 6cm, $(250\ cm - P_{year})/25$, but not types **BS** or **BW**

#1 Natural and Human Influences on Changing Zonal-Mean Precipitation

Human fingerprint = expected response to human forcings from 70+ runs of historical climate change



FINGERPRINT = Distortion of the curve in response to human forcing

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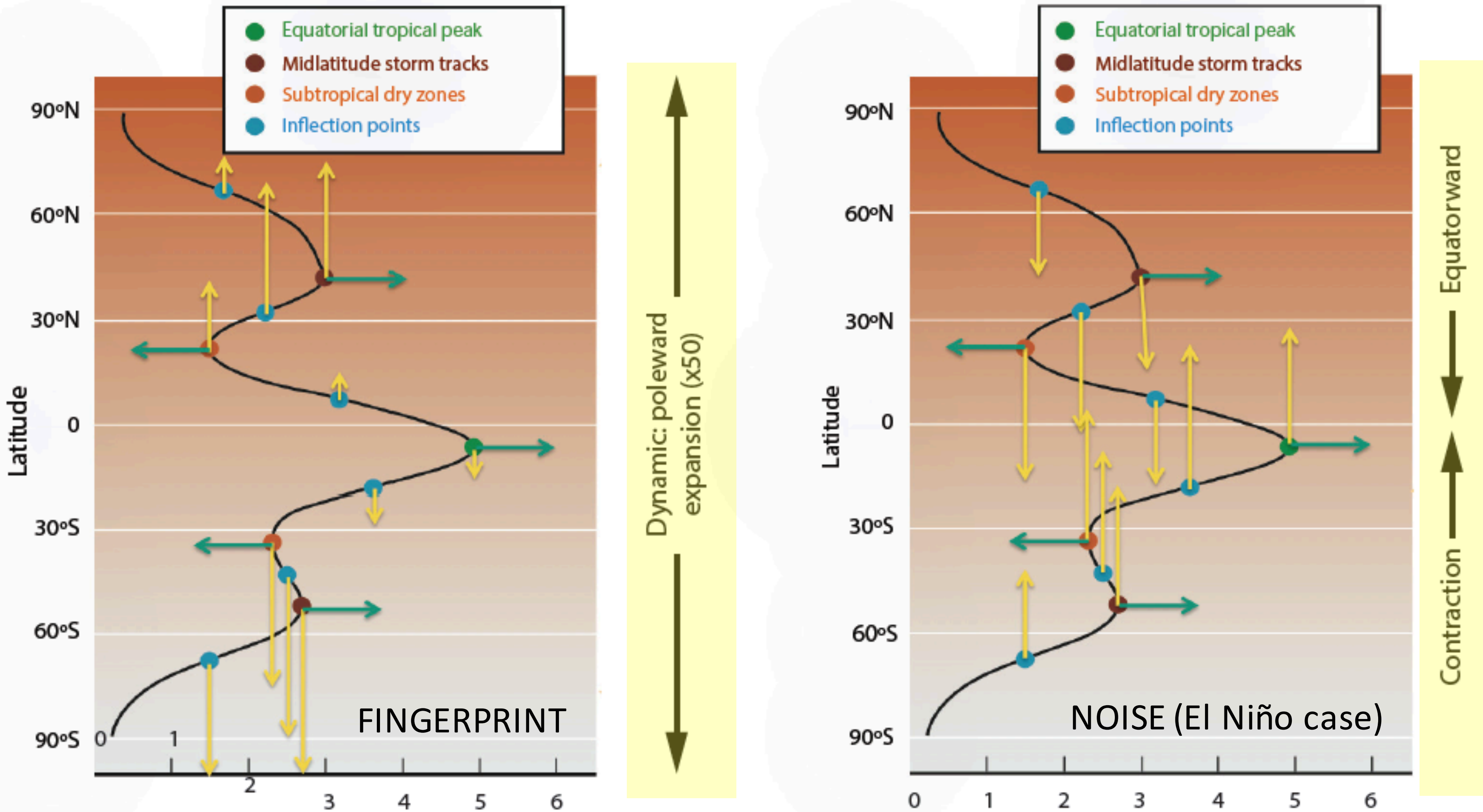

Human pattern ≠ Noise pattern

The intensification + poleward expansion of zonal P is found in observations and cannot be explained by climate noise alone