Early Career: Detection and Attribution of Regional Climate Change with a Focus on the Precursors of Droughts

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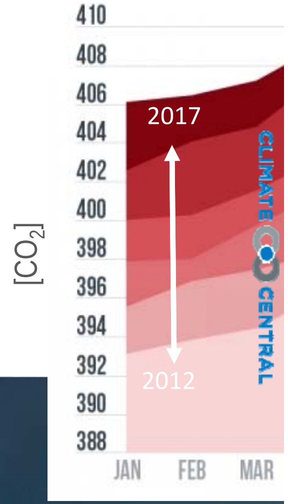
LLNL, NASA/GISS, NOAA, PNNL, INRA

DOE- Funded: ECRP, SFA



Lawrence Livermore
National Laboratory

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Gaithersburg, MD

LLNL PRES 740731

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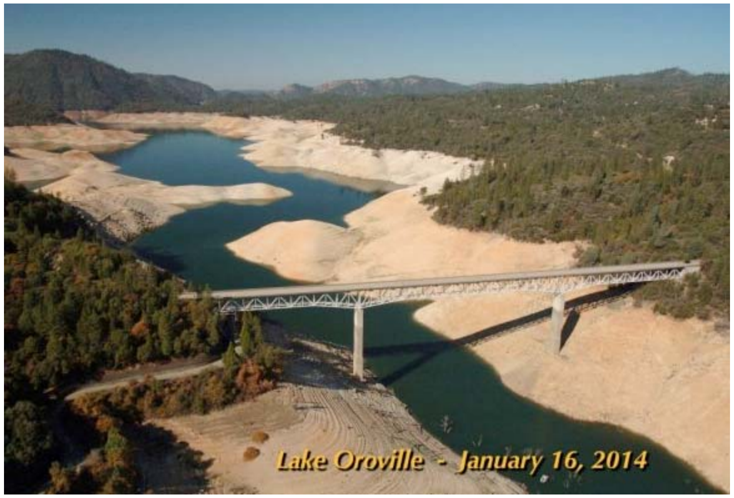
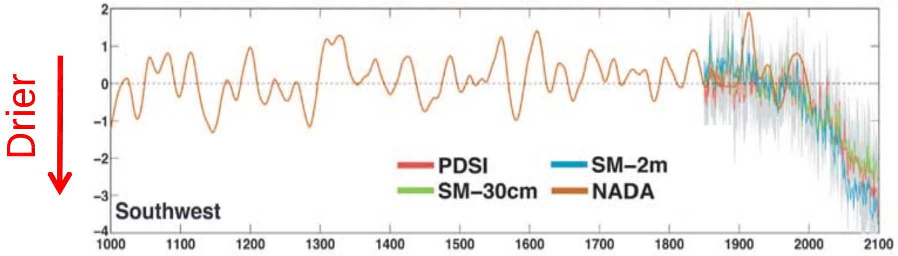
Motivation



- Water is the single most important natural resource
- 1/5 of the world's population live where water is scarce
- Climate models project unprecedented drought risk and increased aridity

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

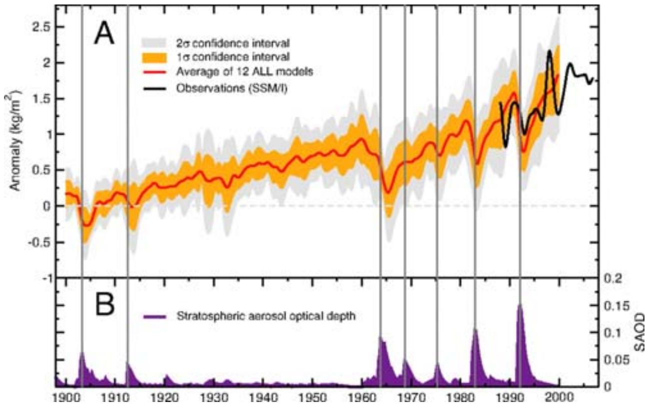


- Are changes in drought behavior becoming increasingly driven by human forcing?
- Can we identify human-induced changes in drought properties in observed climate records?

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

ENSO: primary source of drought variability in many regions of the globe
Other factors are also expected to affect drought in a warming world

Thermodynamic



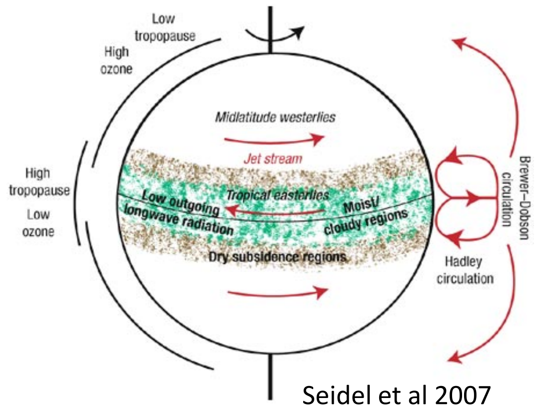
Santer et al 2007

Intensification of current zonal wet-dry patterns

Clausius-Clapeyron

Held and Soden 2006

Dynamic

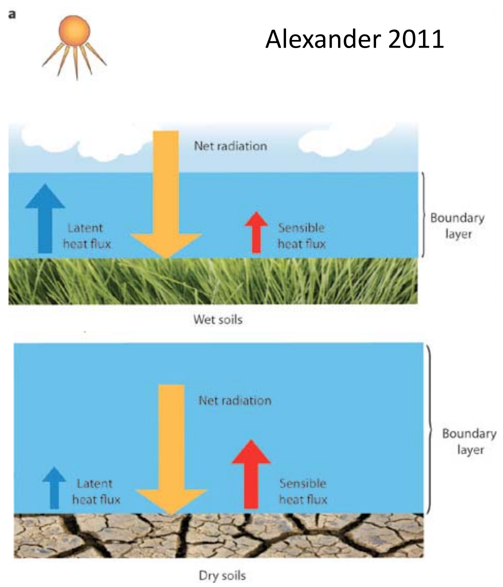


Seidel et al 2007

Latitudinal redistribution of global precipitation

Ozone depletion and increase in greenhouse gases both expected to shift circulation poleward

Coupled



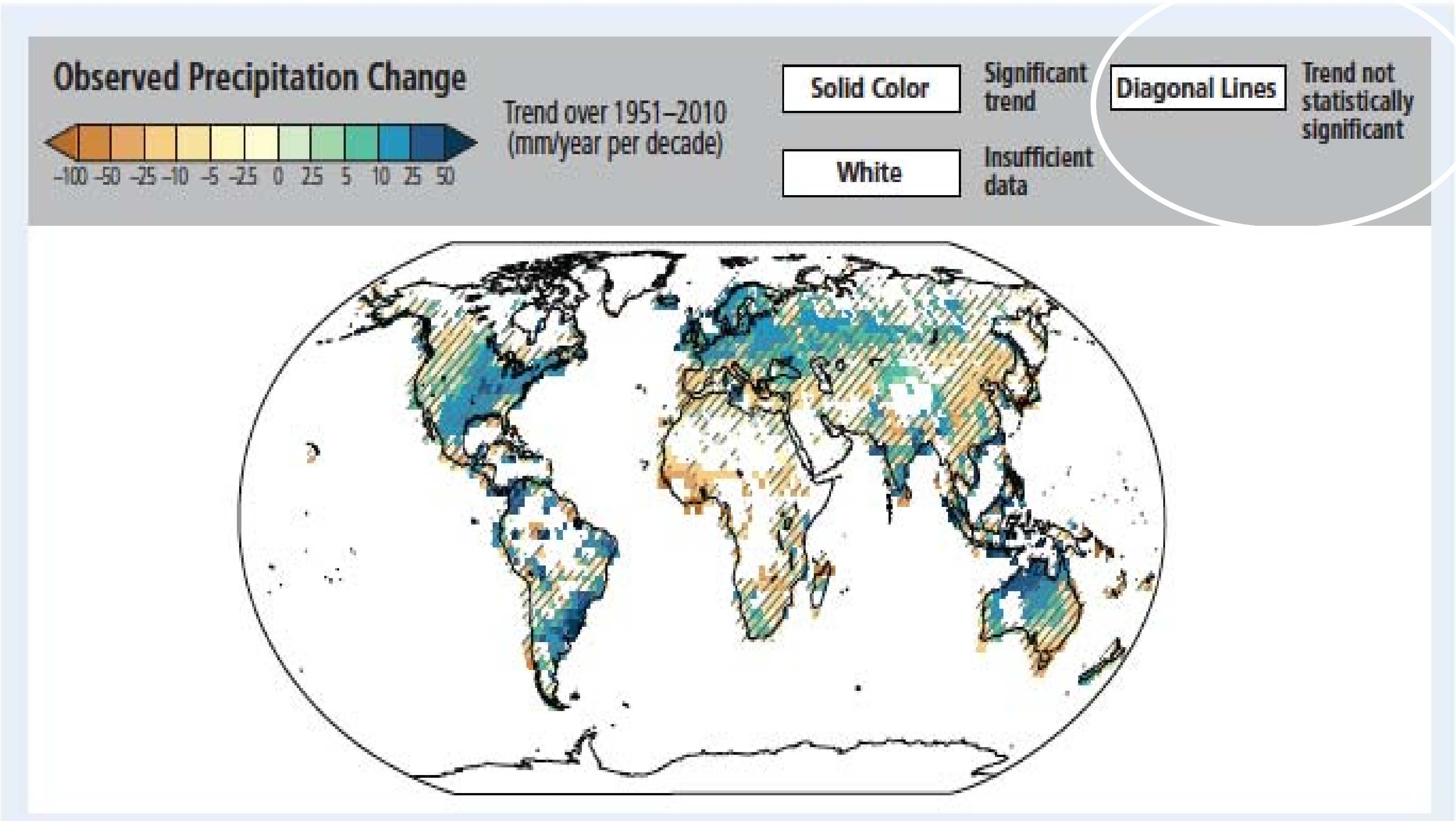
Alexander 2011

Land-atm feedbacks

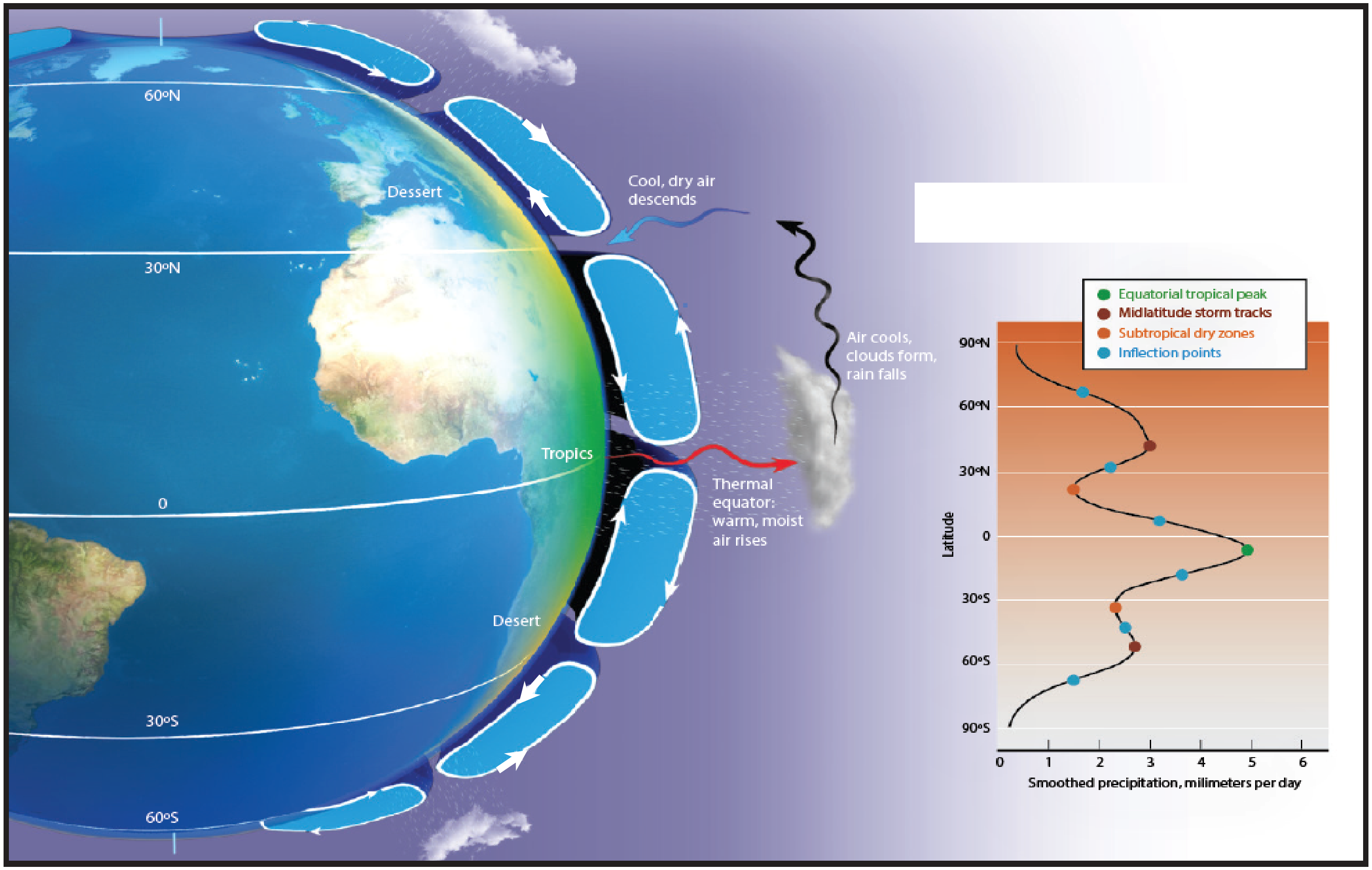
Influences on droughts

	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?

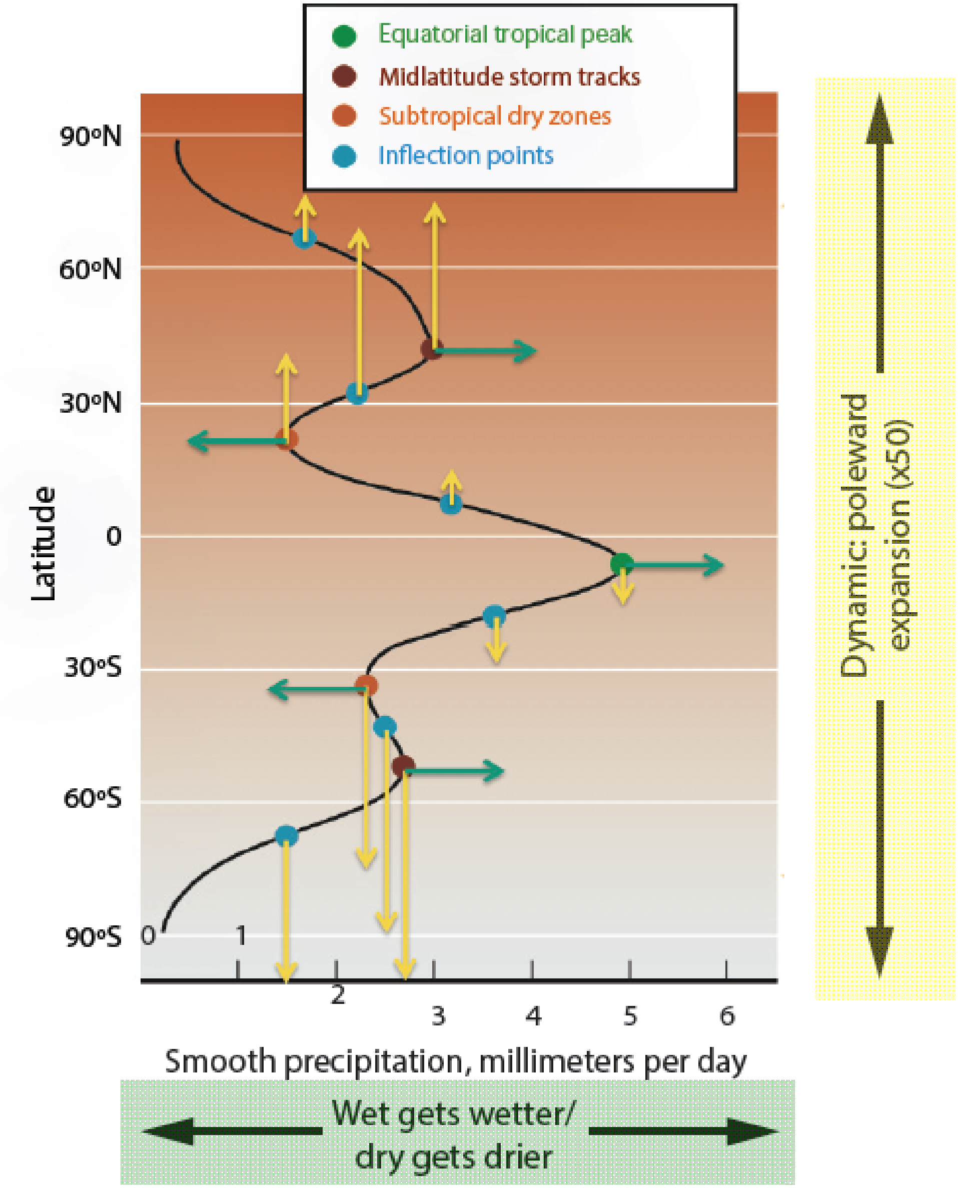


#1 Natural and Human Influences on Changing Zonal-Mean Precipitation



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

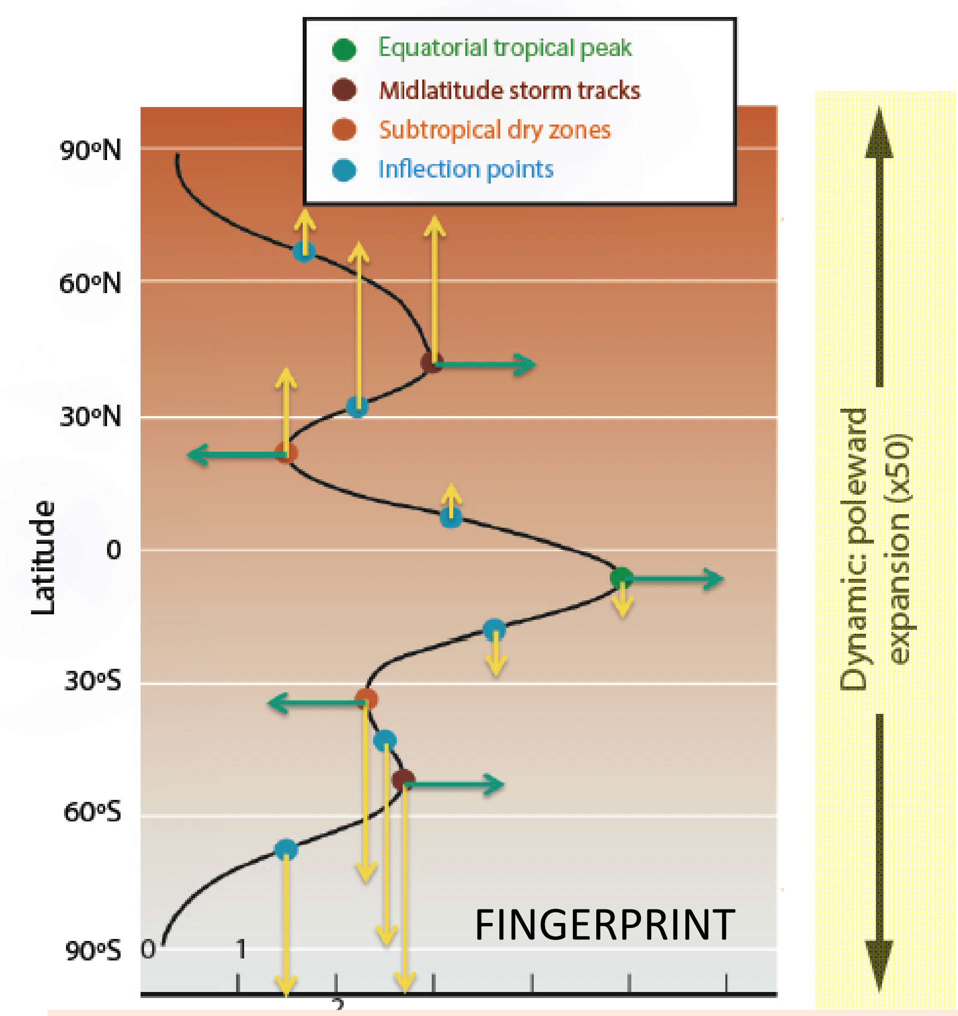
#1 Natural and Human Influences on Changing Zonal-Mean Precipitation

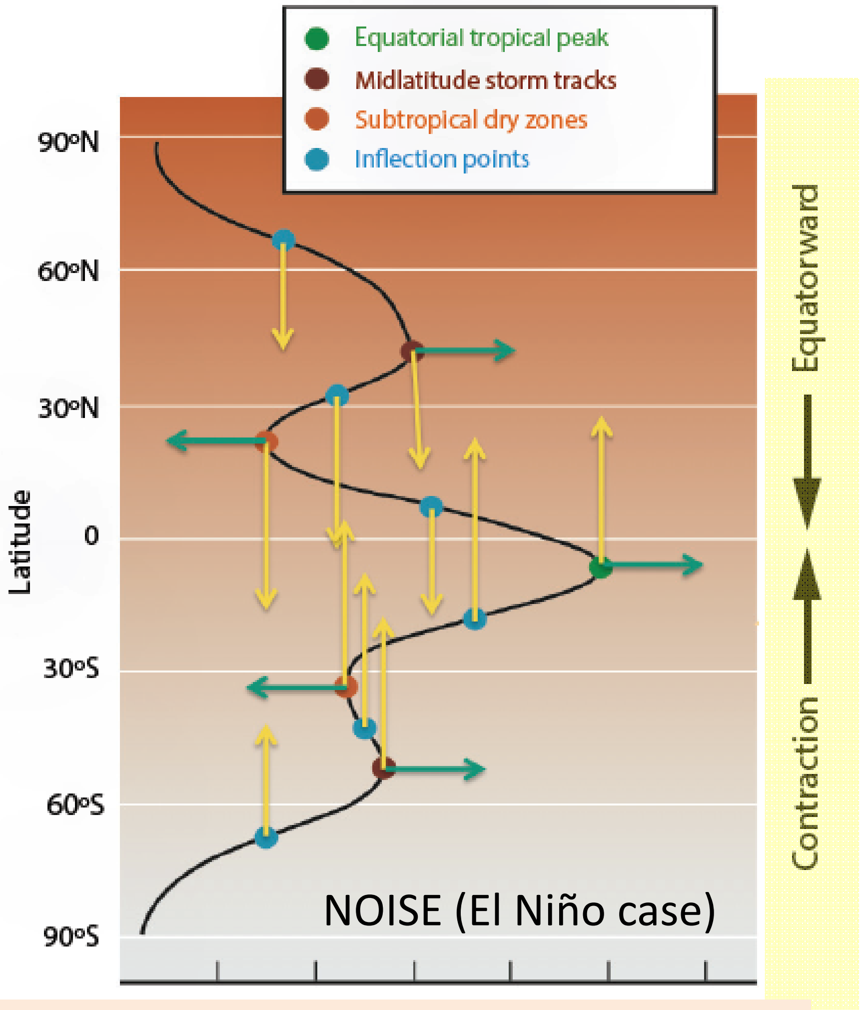


1. **Extract human fingerprint** = expected response to human forcings from 70+ runs of historical climate change

→ From precipitation anomalies from 1980 to 2012

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



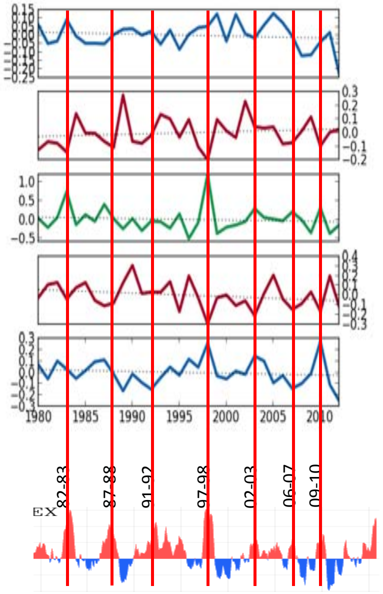


Human pattern ≠ Noise pattern

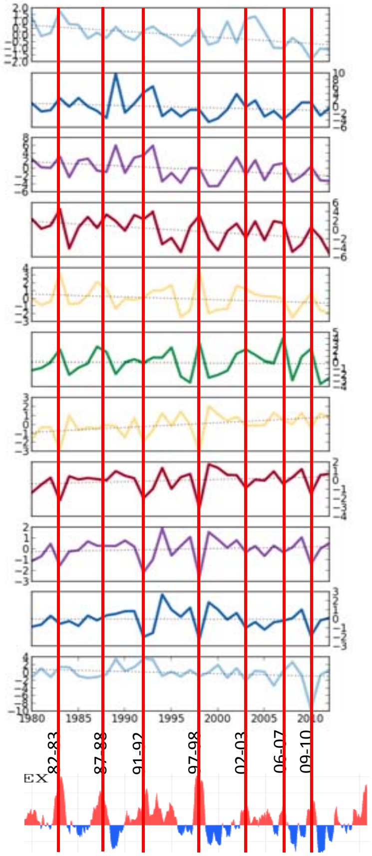
#1 Natural and Human Influences on Changing Zonal-Mean Precipitation

2. Measure the similarity between observations and fingerprint

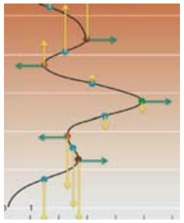
Intensity



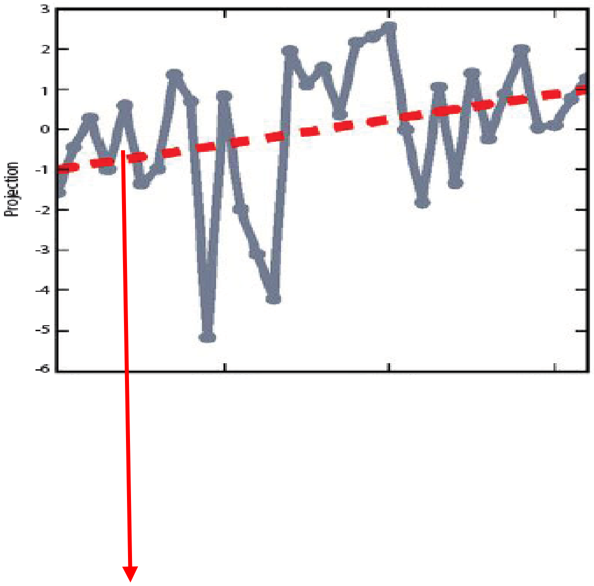
Niño3.4



Niño3.4

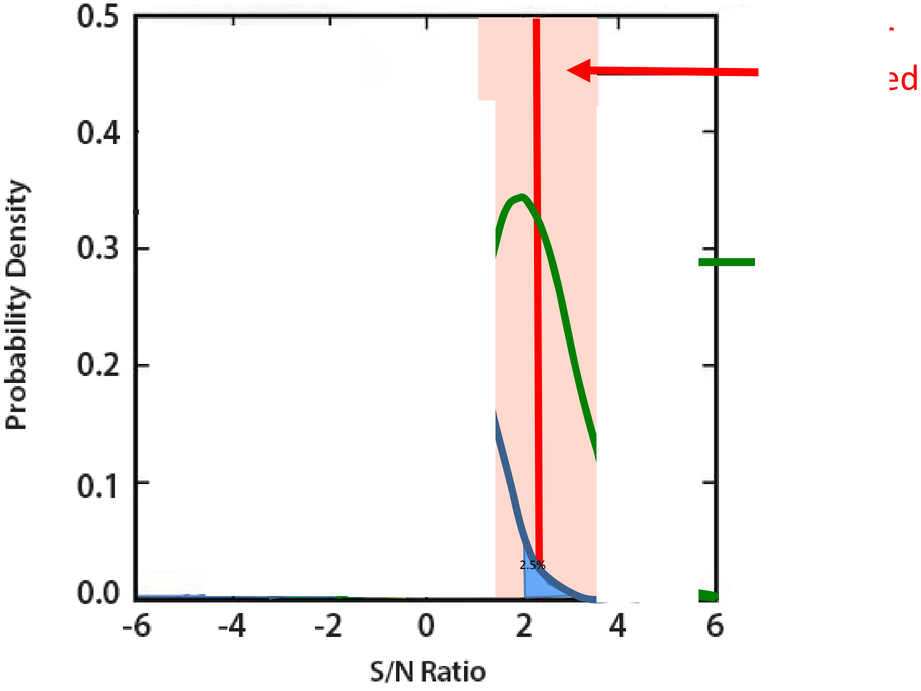


SIGNAL time-series



Positive trend: fingerprint is present and growing in the observations

#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 fingerprint 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	

#2 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 will evolve in the future

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

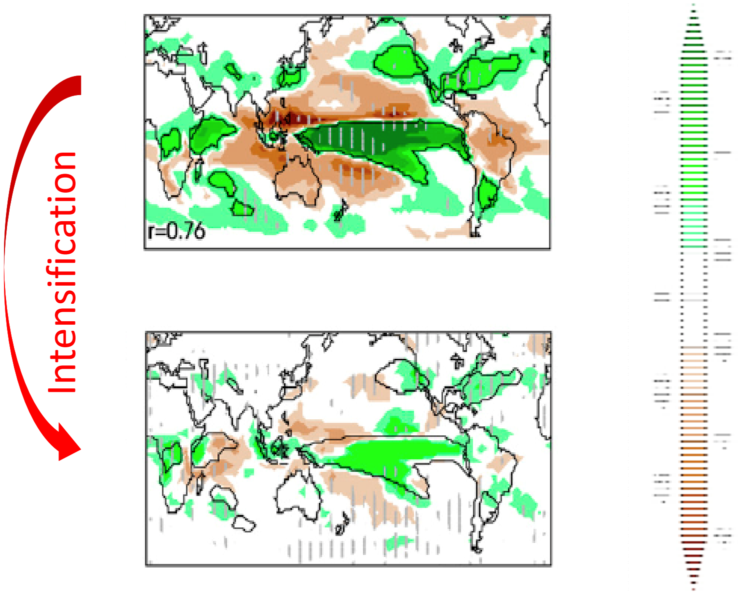
- Non-uniform warming in tropical Pacific Ocean
- Atmospheric circulation change
- Moister atmosphere

Results

Basic 20th century
P response to
ENSO events

Additional
P response to
ENSO
in the future

El Niño

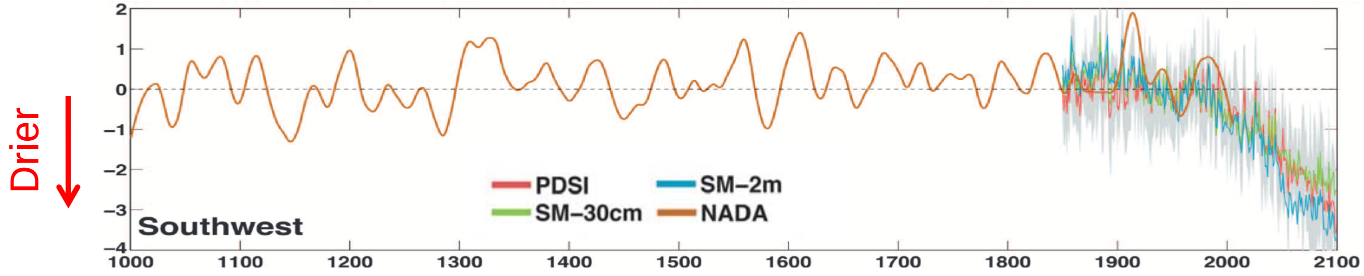


Bonfils C, B Santer, T Phillips, K Marvel, R Leung, C Doutriaux, A Capotondi, 2015. *J. Clim*

Influence on droughts

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

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



#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

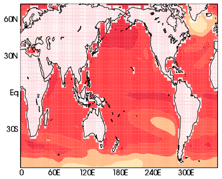
Approach

- 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

Use different sets of experiments to assess the impact of:

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



2) Plant fertilization to rising CO2 (+VEG)

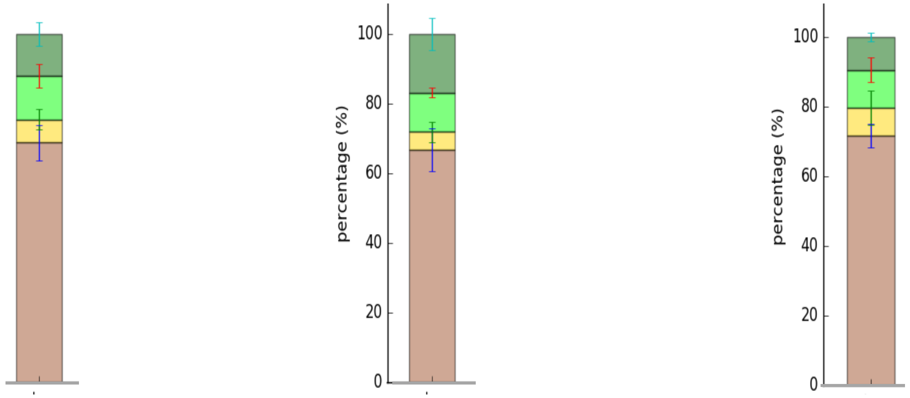
3) “fast” radiative forcing from enhanced CO2 (+RAD)

#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

#3 Influence of anthropogenic climate change on regional aridity

🟩 **Always wetter**

🟩 🟨 **Wetter/Drier with El Niño**

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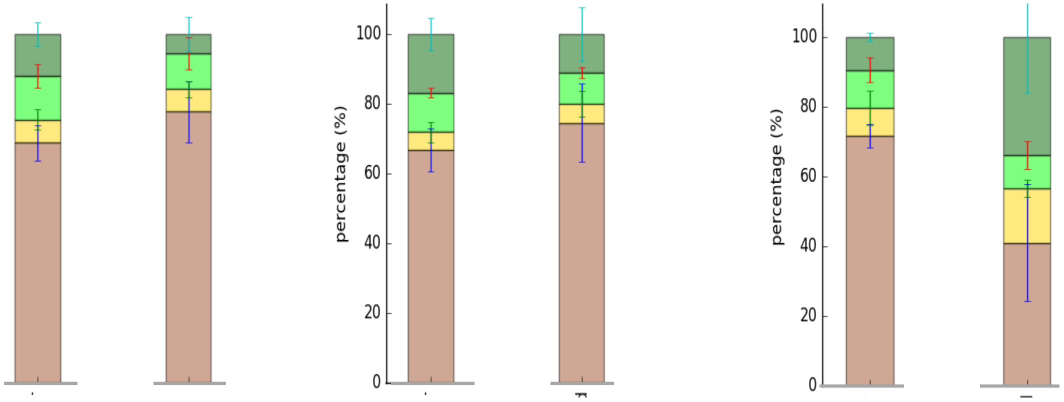
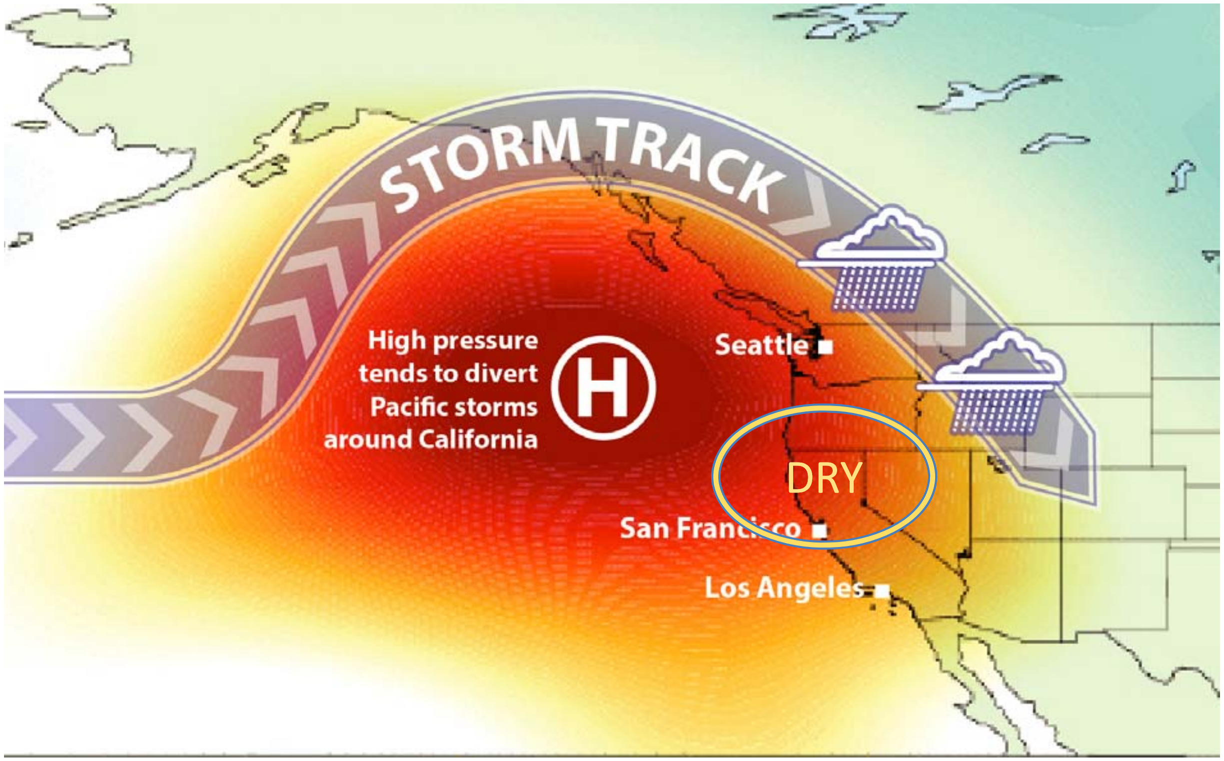


Results

- 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*

Other drought mechanisms?



Possible causes for a North Pacific Ridge (causing P deficit in CA) include:

1) Tropical Pacific ocean forcing of natural origin (Seager et al. 2015)
2) Human-induced change in geopotential height (Swain et al. 2016)
3) Arctic sea-ice cover loss (Sewall 2005)

#4 Arctic sea ice loss favors 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

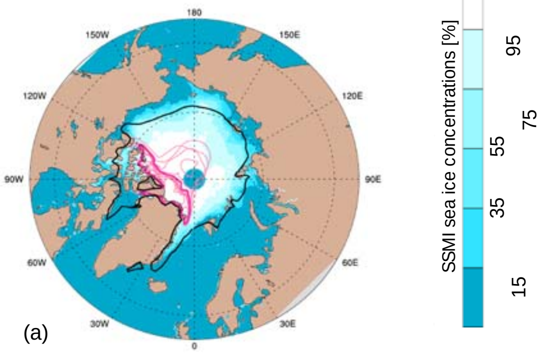
Impact

☐ 2-step teleconnection:

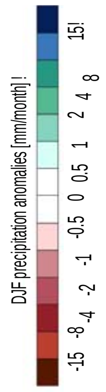
1. Northward shift in ITCZ (Chiang and Bitz 2005)
2. Tropical convection reorganization favors a persistent ridge over North Pacific coast

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

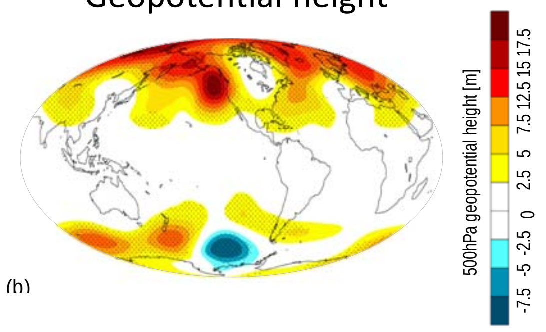
Sea ice (September)



Winter precipitation



Geopotential height



Cvijanovic et al. 2017

#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?

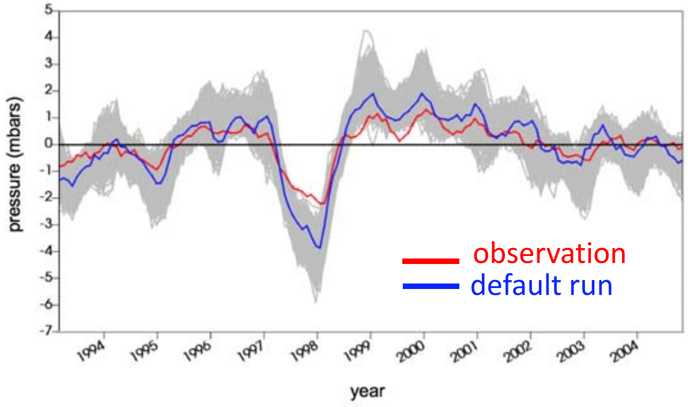
Approach

1317-member perturbed physics ensemble

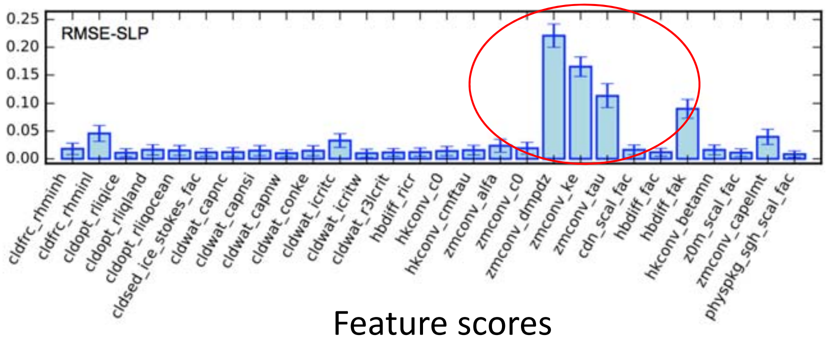
- Latin Hypercube Sampling to vary the values of 28 input parameters (e.g., clouds, P, convection & boundary layer) over allowable ranges
- Set of metrics that best characterize the drought and its drivers (tropical forcing, spatial extent of P and aridity bias)

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

Forcing metric derived from the difference in pressure anomalies in tropics



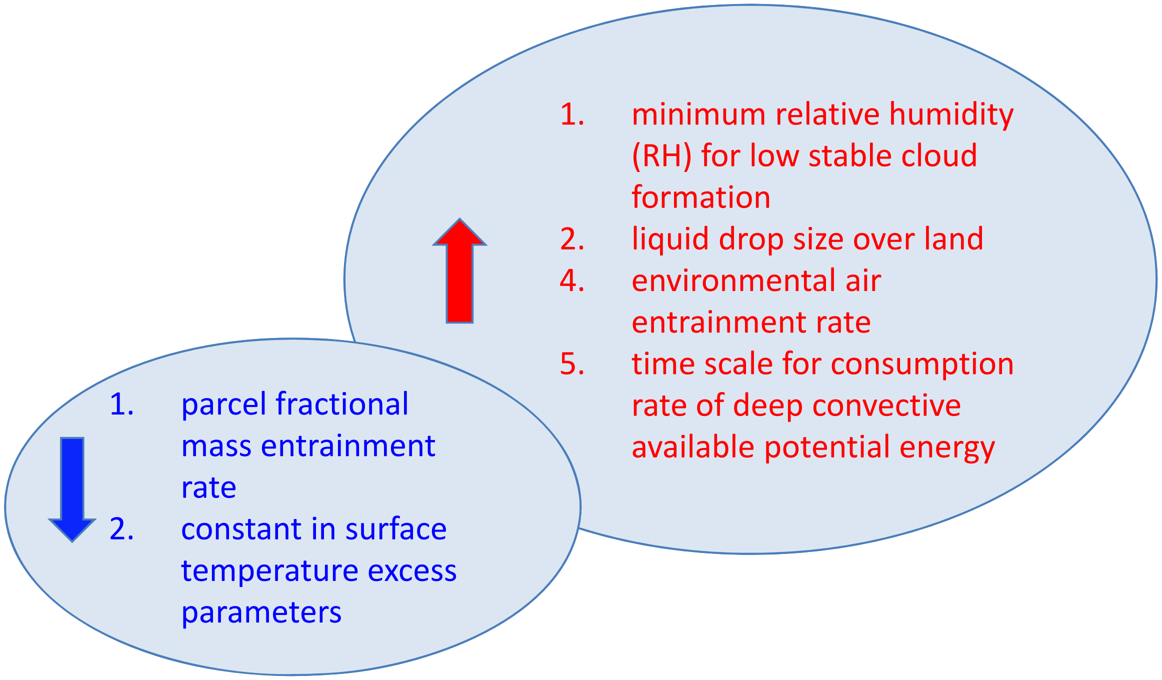
Forcing metric is most sensitive to deep convection parameters



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

Results

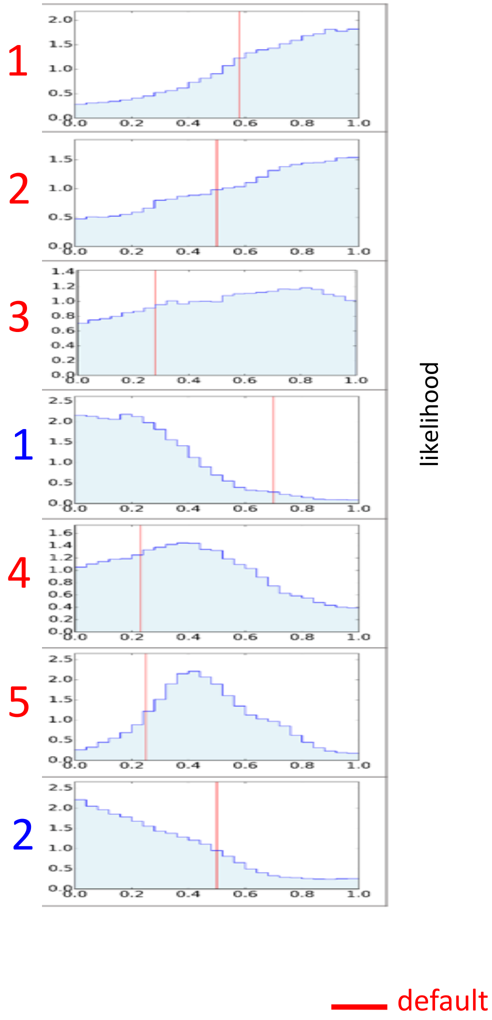
- We have identified the key parameters that influence the turn of century drought
- Deep convection parameters account for more than half the ensemble variance in metrics used to quantify drought
- We can improve upon the default values for those parameters



1. minimum relative humidity (RH) for low stable cloud formation
2. liquid drop size over land
4. environmental air entrainment rate
5. time scale for consumption rate of deep convective available potential energy

1. parcel fractional mass entrainment rate
2. constant in surface temperature excess parameters

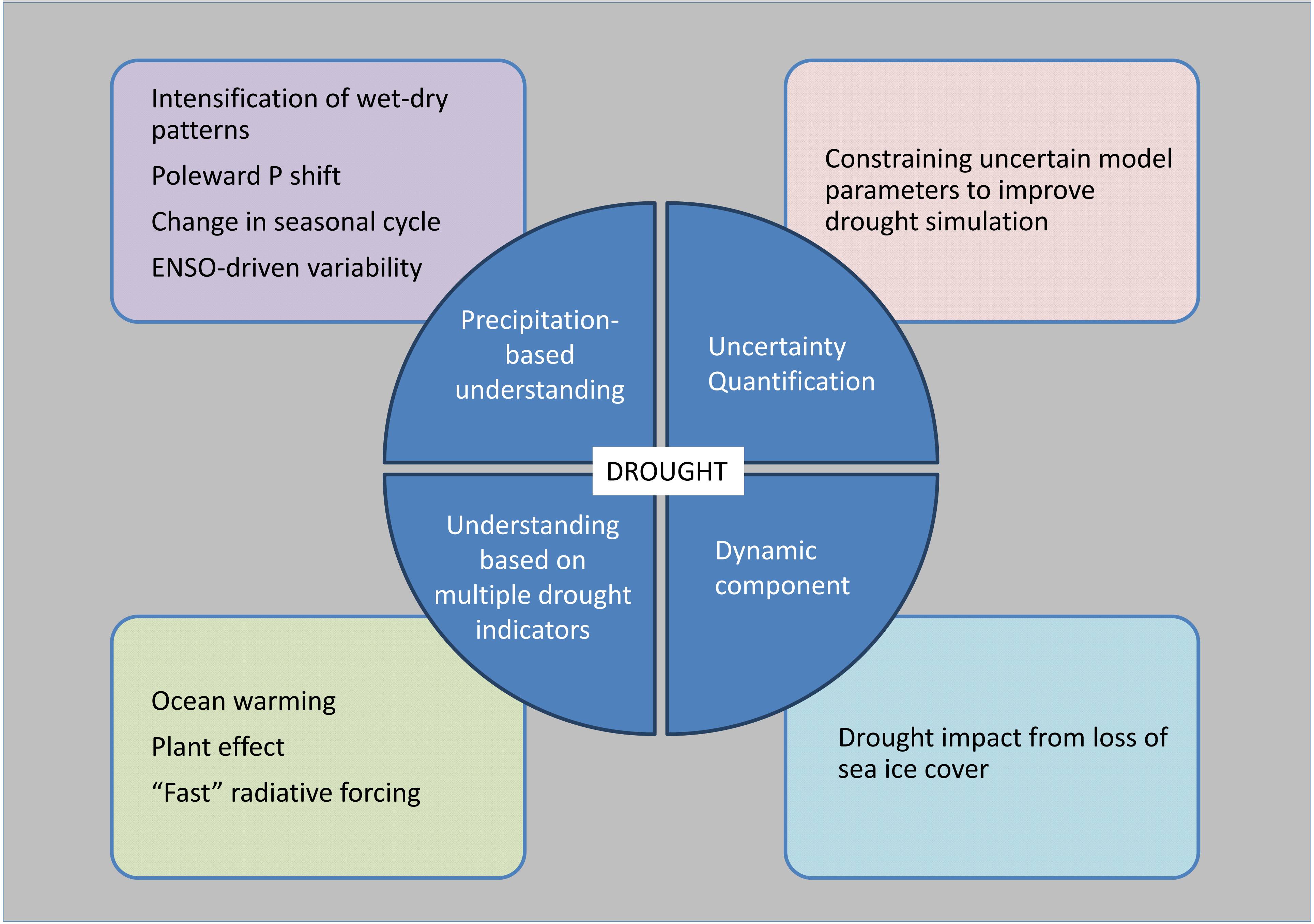
Optimal parameter values for all 3 metrics



Parameter Posterior Distributions

Anderson G, D Lucas, and C Bonfils, 2017: Uncertainty Analysis of Simulations of the Turn-of-the-Century Drought in the Western U.S. ***JGR-Atm (submitted)***

LLNL research on the precursors of droughts is strong



Intensification of wet-dry patterns

Poleward P shift

Change in seasonal cycle

ENSO-driven variability

Precipitation-based understanding

Uncertainty Quantification

Constraining uncertain model parameters to improve drought simulation

DROUGHT

Understanding based on multiple drought indicators

Dynamic component

Ocean warming

Plant effect

“Fast” radiative forcing

Drought impact from loss of sea ice cover

#6 Can we find a human fingerprint in bioclimatic estimates?

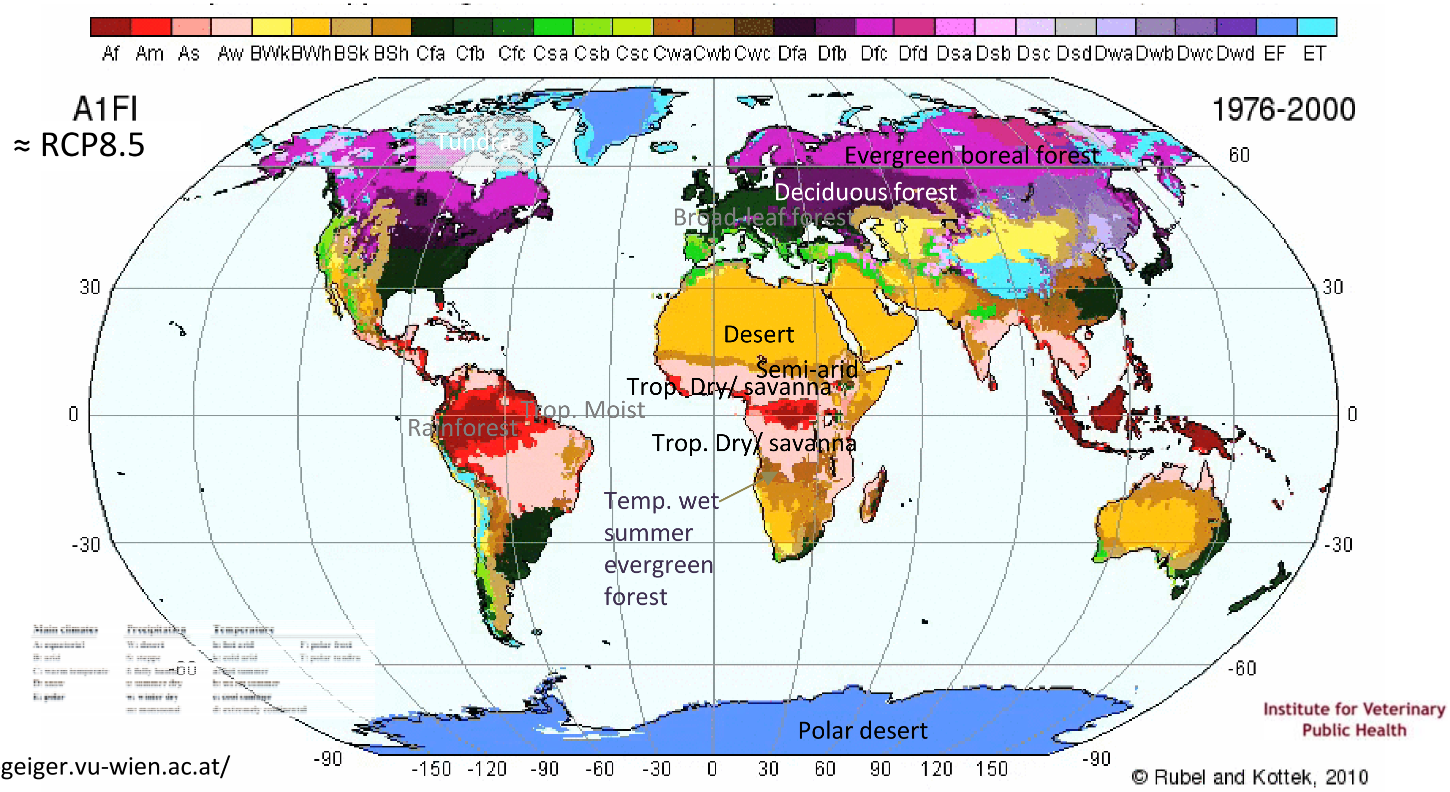
Objectives

- Many mechanisms drive the future changes in precipitation
- The Köppen vegetation scheme provides a 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

Approach

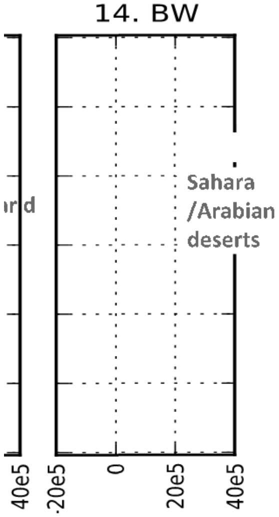
For each year over 1979-2015, we calculated:

1. The observed & modeled yearly vegetation distributions
2. The latitudinal area occupied by each vegetation type
3. The change in the areal extent of bioclimate zones every year



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

print = expected
uman forcings

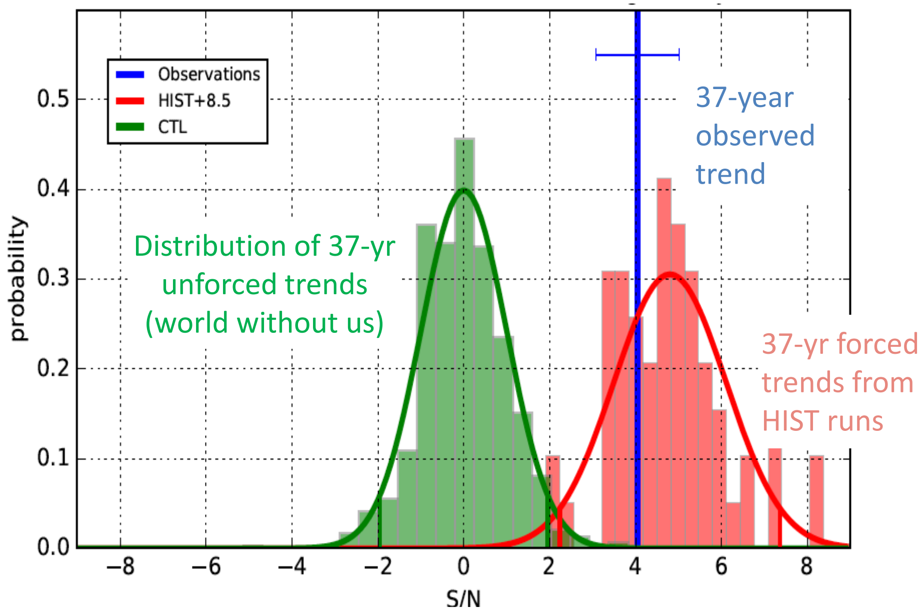


Area for individual vegetation types

#6 YES! We found a human fingerprint in observations

- **Detection:** The changes in the repartition (location, extent) of bioclimatic zones driven by observed T and P estimates are unlikely to arise purely from natural climate variability

- **Attribution:** Results compatible with predictions including both natural and human forcings
- Both the changes in temperature and precipitation contribute



37-year observed trend

Distribution of 37-yr unforced trends (world without us)

37-yr forced trends from HIST runs

1979-2015

Bonfils et al. 2018 Human-induced vegetation shifts based on bioclimatic estimates *In prep.*

PCMDI SFA – Detection and Attribution Activity

DE-FOA-0001036: Human influence on the hydrological cycle

LDRD

Milestones

Task 1: An analysis of drought behavior

#3 **Competitive influences on droughts** Bonfils et al 2017 J. Climate

#6 **Human-induced vegetation shifts based on bioclimatic estimates** Phillips and Bonfils 2015 ERL - Bonfils et al. in prep.

- **Comparing Tropospheric Warming In Climate Models and Satellite Data** Santer et al 2017 J Climate - Santer et al 2017 Scientific Reports - Santer et al 2017 Nat Geoscience

Task 2: Role of ocean / ENSO

#2 **Contributions of mean and ENSO variability to future P changes** Bonfils et al. 2015 J Climate

- **Role of volcanic activity on climate and tropical ocean temperatures** Santer et al 2014 Nat Geoscience - Santer et al 2015 GRL - Santer et al 2016 Nat CC - Santer et al 2017 in review

Task 3: A UQ analysis

#5 **Effect of parameter uncertainties on drought simulation** Anderson et al JGR in review

- **Quantify whether responses to different forcings add linearly in climate models?** Marvel et al 2015 ERL

15 articles published / accepted

2 manuscripts in review

3 manuscripts in preparation

Task 4: Drought-promoting changes in atm. circulation

#1 **Human influence on changing zonal-mean precipitation** Marvel and Bonfils 2013 PNAS

#4 **Arctic sea-ice loss favors dry CA** Cvijanovic et al 2017 Nat Comm

- **Human fingerprint in zonal-mean cloud** Marvel et al 2014 J Climate
- **Include for the first time the "total natural variability" in a D&A study** Santer et al 2013
- **D&A on the changes in phase and amplitude of atmospheric temperature** Santer et al in prep
- **D&A on changes in precipitation annual cycle** Marvel et al 2017 J Climate
- **D&A-derived study tracking tropical P** Bonfils et al in prep

ECRP: incubator of new ideas

- Multivariate D&A using zonal climate features:
  - D&A on cloud trends (GISS/LLNL collaboration)
  - Correlated precipitation/cloud behavior
- D&A technique:
  - Applied on geopotential height (SFA)
- Perform D&A study based on the recent changes in aridity using one or several indices
  - D&A in various drought indicators (GISS/LLNL collaboration?)
  - Use of the "total natural variability"
- Response of tropical P to other forcings and mid-latitudes teleconnections
  - ➢ D&A-derived technique
  - ➢ Implication of sea-ice loss
- End to End D&A in Western U.S. hydrology
- Continue to explore new directions motivated by ECRP work

10 proposals submitted [3 LDRDs - 2 FOA - 1 SFA renewal - 2 TechBase - 2 UC Lab-Fees]

D&A research at LLNL has successfully transitioned from looking at mean state changes to examining aspects of climate change of greater societal relevance

Publications status: Funded by SFA| LDRD| ECRP | DE-FOA-0001036

9 articles published / accepted:

Bonfils C, B Santer, T Phillips, K Marvel, R Leung, C Doutriaux, A Capotondi, 2015: Relative contributions of mean-state shifts and ENSO-driven variability to precipitation changes in a warming climate, *J. Clim* #2

Marvel K, G Schmidt, D Shindell, C Bonfils, et al. 2015: Do responses to different anthropogenic forcings add linearly in climate models? *ERL*

Santer B, S Solomon, D Ridley, J Fyfe, F Beltran, C Bonfils et al., 2016: Correspondence: Volcanic effects on climate, *Nature Clim Ch*.

Bonfils C, G Anderson, B Santer, T Phillips, I Cvijanovic, et al., 2017: Competing influences of anthropogenic warming, ENSO, and plant physiology on future terrestrial aridity, *J. Clim.* #3

Cvijanovic I, B Santer, C Bonfils, D Lucas, S. Zimmerman, J Chiang: Seasonally ice free Arctic favors dry California, *Nature Comm (accepted)* #4

Marvel, K, M Biasutti, C Bonfils, K Taylor, 2017: Observed and Projected Changes to the Precipitation Annual Cycle, *J. Clim.*

Santer B, S Solomon, F Wentz, Q Fu, […], C Bonfils, 2017b: Tropospheric Warming over the past two decades, *Scientific Reports*

Santer B, J Fyfe, […] C Bonfils, I Cvijanovic, […] 2017c: Causes of differences in model and satellite tropospheric warming rates, Nature Geosc.

Santer B […], I. Cvijanovic, C Bonfils, 2017a: Comparing Tropospheric Warming in climate models and satellite data, *J. Clim*

2 manuscripts in review:

Santer B […] D Ridley, C Bonfils et al., 2017b: Correspondence: Climate impact of volcanic forcing uncertainty, *Nature Comm*

Anderson G, C Bonfils, D Lucas, B Santer: Uncertainty Analysis of Simulations of the Turn-of-the-Century Drought in the Western U.S., *JGR* #5

3 manuscripts in preparation:

Bonfils C, T Phillips, B Santer Human-induced vegetation shifts based on bioclimatic estimates #6

Santer et al Human influence on the observed changes in the phase and amplitude of atmospheric temperature

Bonfils C, et al D&A-derived technique tracking tropical precipitation

6 articles published before Nov 2015:

Phillips T, C Bonfils, 2015: Köppen bioclimatic evaluation of CMIP historical climate simulations, *ERL*

Marvel K, M Zelinka, S Klein, C Bonfils, P Caldwell, C Doutriaux, et al. 2015: External influences on modeled and observed cloud trends, *J. Clim*

Santer B, S Solomon, C Bonfils, M Zelinka et al. 2015: Observed multi-variable signals of late 20th and early 21st century volcanic activity, *GRL*

Santer B, C Bonfils, JF Painter, M Zelinka et al., 2014: Volcanic contribution to decadal changes in tropospheric temperature, *Nature Geosc*

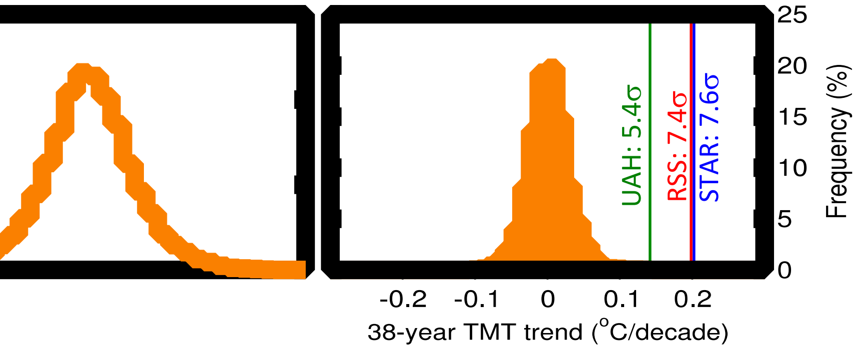
Marvel K, C Bonfils, 2013: Identifying external influences on global precipitation, *PNAS* #1

Santer B, JF Painter, C Bonfils et al. 2013: Human and natural influences on the changing thermal structure of the atmosphere, *PNAS*

Supplemental Materiel

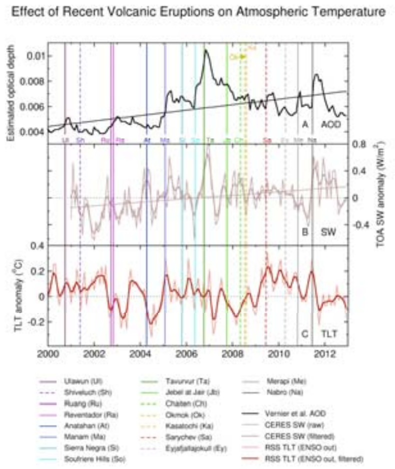
Milestones

Tropospheric warming in 2 out of 3 satellite datasets is “unprecedented”



Santer et al 2017 Scientific Reports

Volcanic contribution to decadal changes in tropospheric temperature



Santer et al 2014
Nat Geoscience

Trends are generally additive but nonlinearities appear in P trends with interactive chemistry

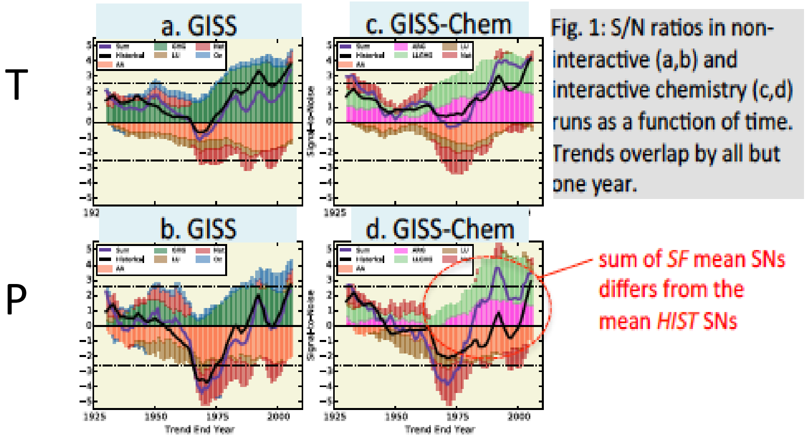
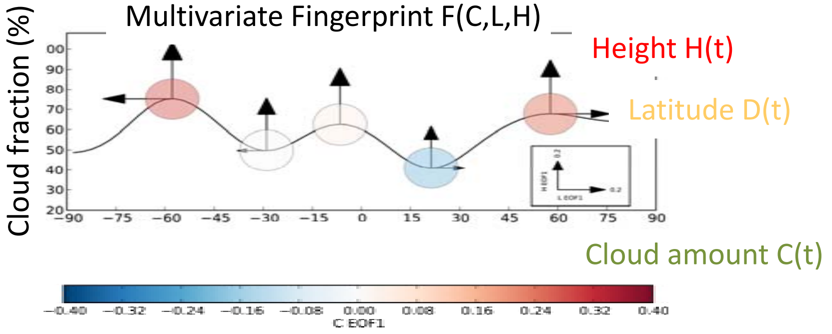


Fig. 1: S/N ratios in non-interactive (a,b) and interactive chemistry (c,d) runs as a function of time. Trends overlap by all but one year.

sum of *SF* mean SNs differs from the mean *HIST* SNs

Marvel et al 2015 ERL

Identifying the Human Fingerprint in Observed Cloud Trends



Marvel et al 2017 J. Climate

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)	$T_{min} > 18C$ and $P_{min} > 6$ cm, but not types **BS** or **BW**
Am: Tropical Moist (tropical evergreen forest)	$T_{min} > 18C$ and $(250\ cm - P_{year})/25 < P_{min} < 6$ cm, but not types **BS** or **BW**
Aw: Tropical Dry (savanna/woodland)	$T_{min} > 18C$ and $P_{min} < 6cm$, $(250\ cm - P_{year})/25$, but not types **BS** or **BW**