Quantifying drought risk through multiple large-ensembles: the case of Cape Town 2015-17 and Central America 2015-19 multiyear droughts

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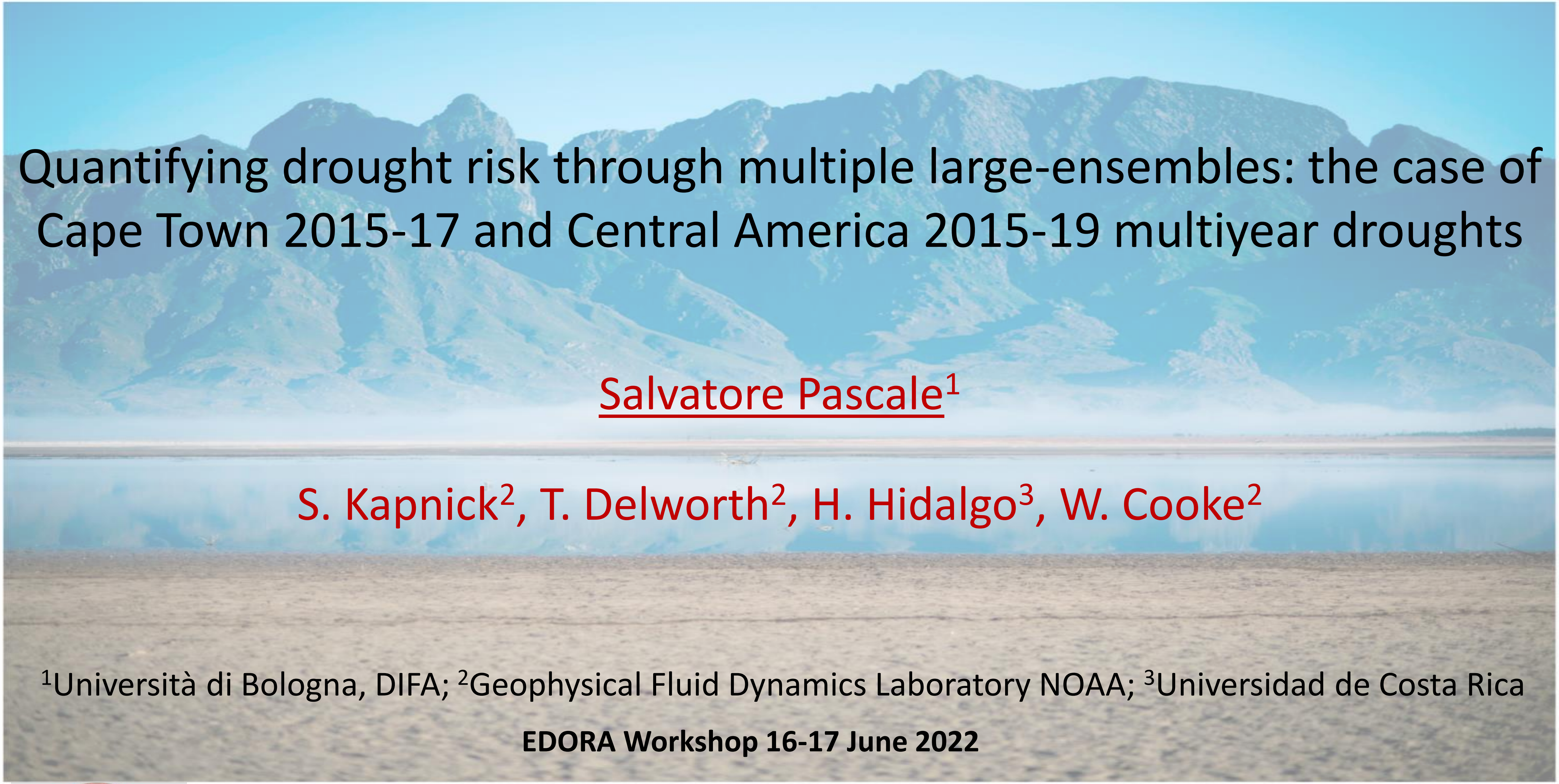
EDORA Workshop 16-17 June 2022



Theewaterskloof Dam, April 2018

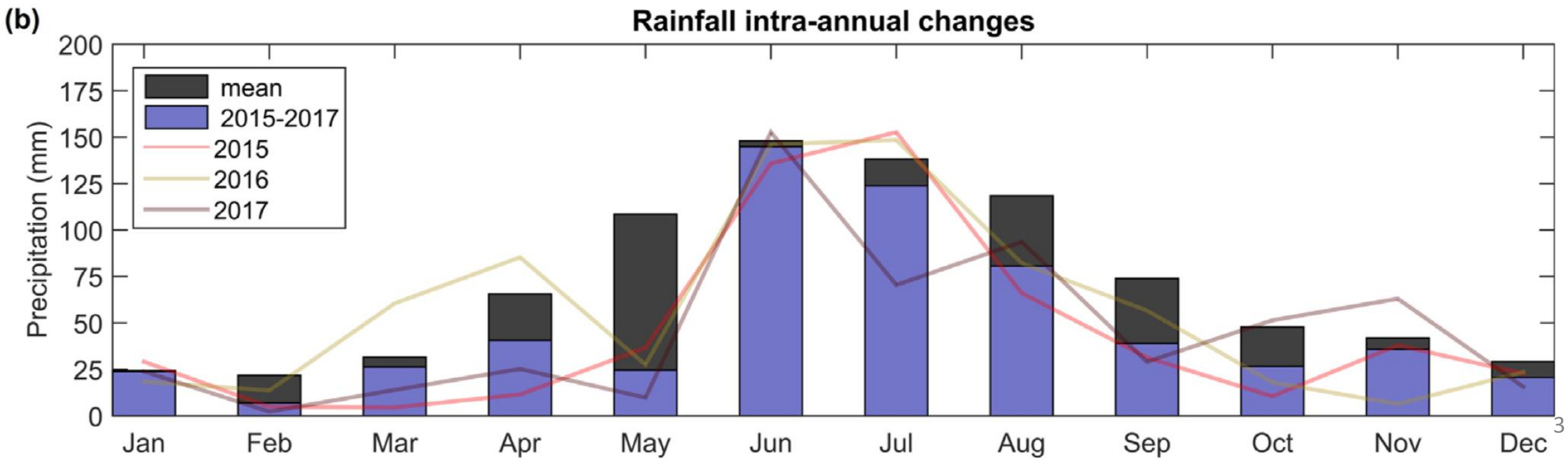
Case 1: the Cape Town "Day Zero" water crisis

Cape Town, South Africa, Feb. 8, 2018 *(Image credit: fivepointsix/iStock)*

- Extensive economic impacts (37k jobs lost in WC Province, 50k people pushed into poverty)
- Agriculture: 13-20% drop in exports; Tourism: 10% drop
- Public health concerns
- Stringent water restrictions: ban of outdoor and non-essential water use; consumption restricted to about 50 gallons per person in February 2018.

The Cape Town "Day Zero" drought

- **Multi-year meteorological drought** (2015-17) **unprecedented** in the centennial record (Wolski 2018; Otto et al. 2018) over most of Southwestern South Africa (**SSA**)
- April-September rainfall totals at 35%-50% below average in most of SSA. Rainfall deficit during the **shoulder season**
- **Hydrological drought**: dams supplying Cape Town ≈ **20% in austral fall 2017/2018**
- If below **13.5%** "**Day Zero**": disconnect much of the municipal water supplies

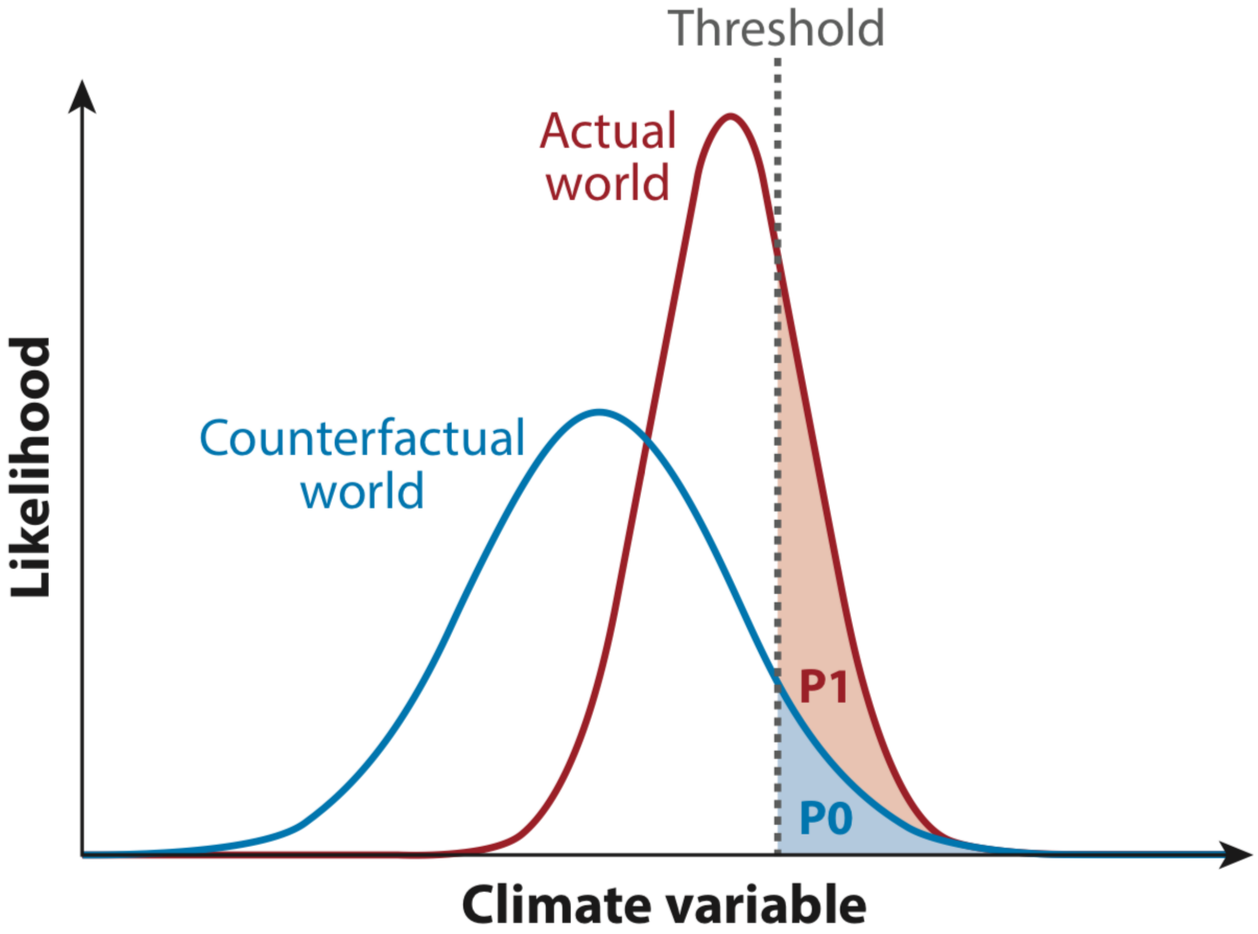


Sousa et al., 2018

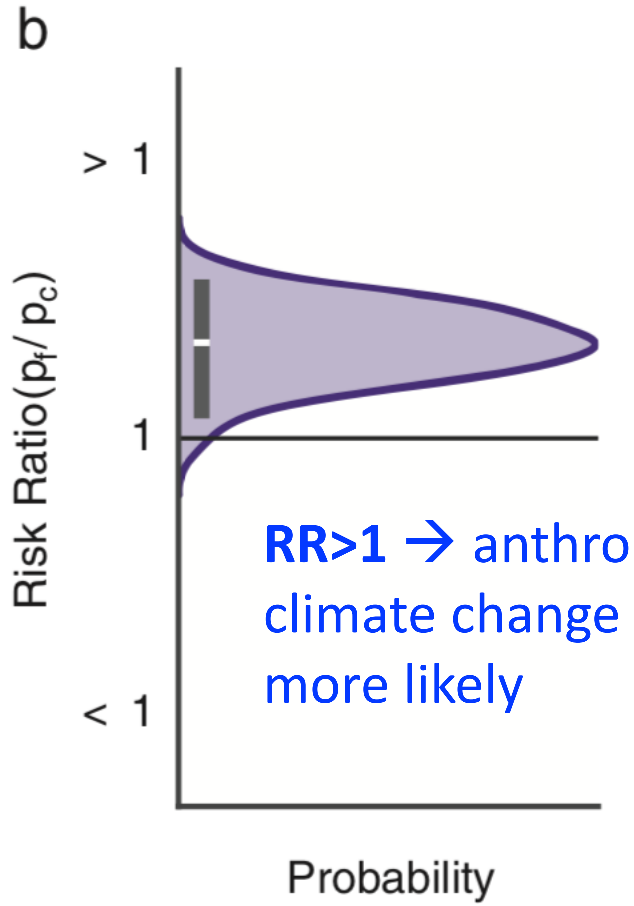
1. To what extent did anthropogenic global warming make the Day Zero drought more likely (**event attribution**)?

2. How will the probability of occurrence of another similar or worse meteorological drought change in the coming decades (**coming decades**)?

How to attribute extremes to anthropogenic climate change?



Otto F.E.L., Ann. Rev. Env. Res.. 2017. 42:627-46



RR>1 → anthropogenic climate change made it more likely

Hauser et al., *Earth's future*, 2017

Probabilistic event attribution: Risk Ratio

Large ensembles suite

- Large Ensemble simulations from the **S**eamless System for **P**rediction and **Ea**rth System **R**esearch (**SPEAR_MED,** 2020): 0.5 degree resolution, (Delworth et al., 2020, https://www.gfdl.noaa.gov/spear)

- **Additional** large ensembles at same or coarser resolution to test model uncertainties**:**

  - **SPEAR_LO:** 1 degree resolution (Delworth et al., 2020)
  - **FLOR, FLOR_FA:** 0.5 degree resolution (Vecchi et al., 2014)
  - **CESM1**: 1.3 x 0.9 degree resolution (Kay et al., 2015**)**
  - **MPI-GE:** 1.9 degree resolution (Mahler et al., 2019)

The SPEAR_MED large ensemble

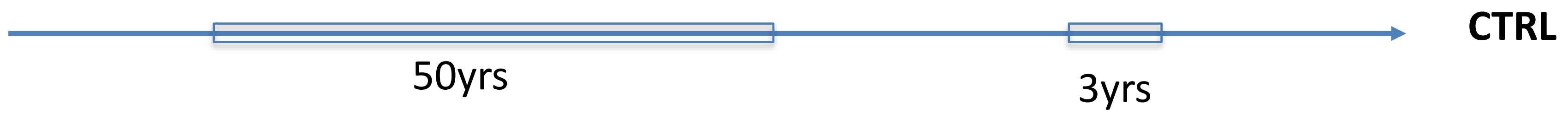
- **CTRL**: forcing kept constant at 1850 (pre-industrial) levels: **3000** yrs

- **ALLFORC**, 30 ensemble members: 1921-2100 SPEAR_MED:
  - Historical forcing up to 2014
  - **SSP5-8.5** (high-emission) and **SSP2-4.5** (intermediate) scenarios 2015-2100

- **NATURAL**, 30 ensemble members: natural historical forcing (solar+volcanic) until 2014, idealized solar after 2015

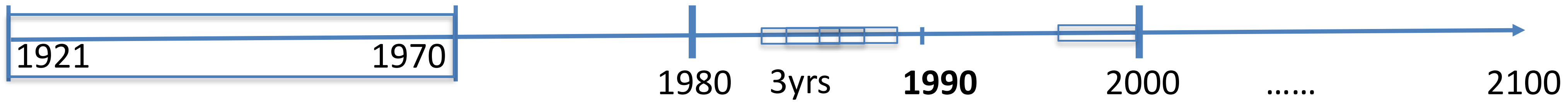
Estimation of PDFs

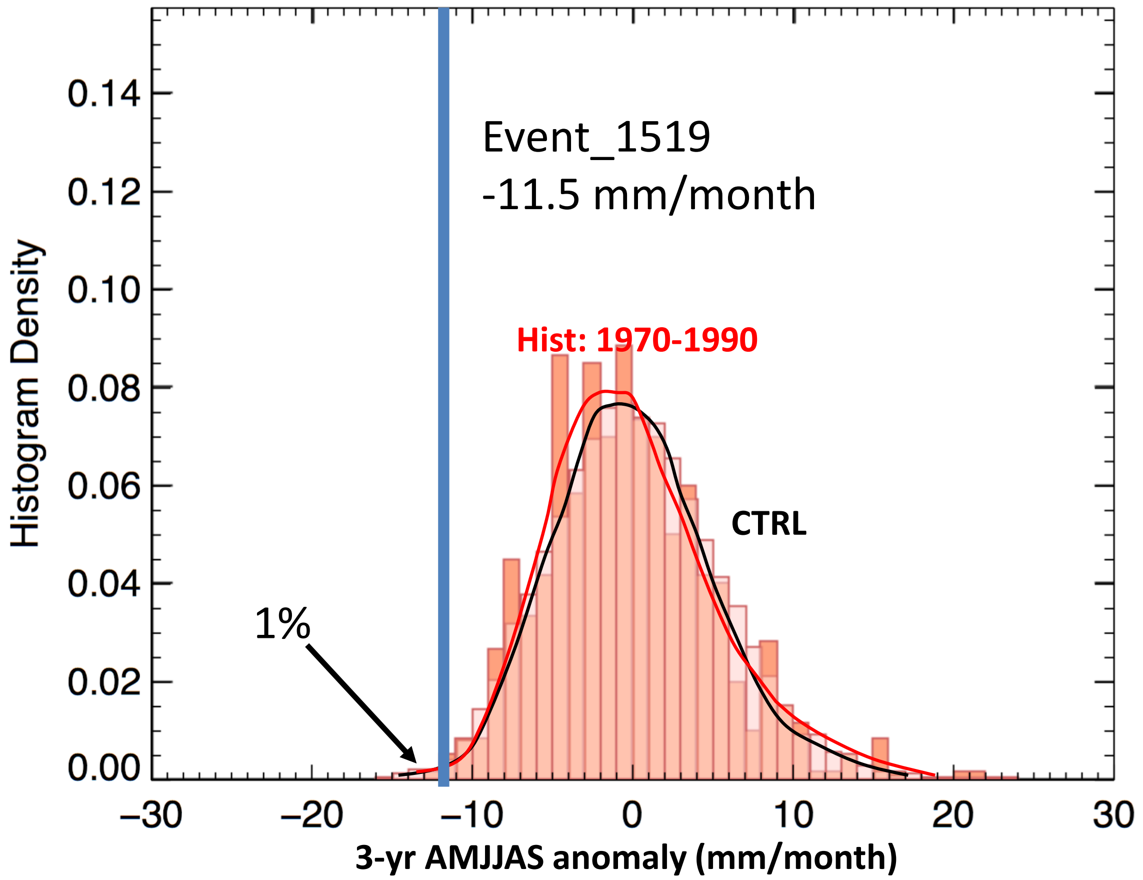
- 3-yr Winter Rainfall Index anomaly (relative to 1921-70) for 2015-2017 ≈ **-12** mm/month
- **CTRL's PDF** (3yr mean anomalies) : randomly select non-overlapping 50yr and a 3yr time windows and take the mean difference (repeat it 10,000 times)

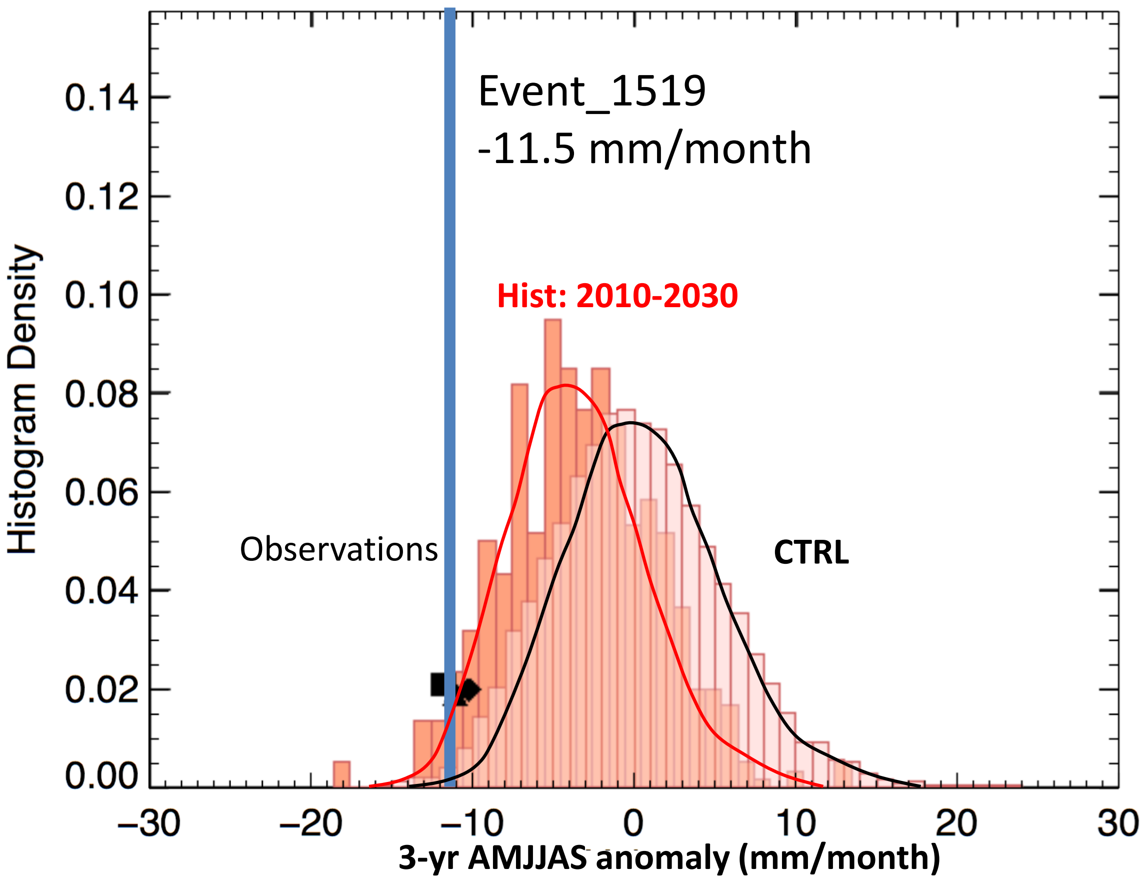


Estimation of PDFs

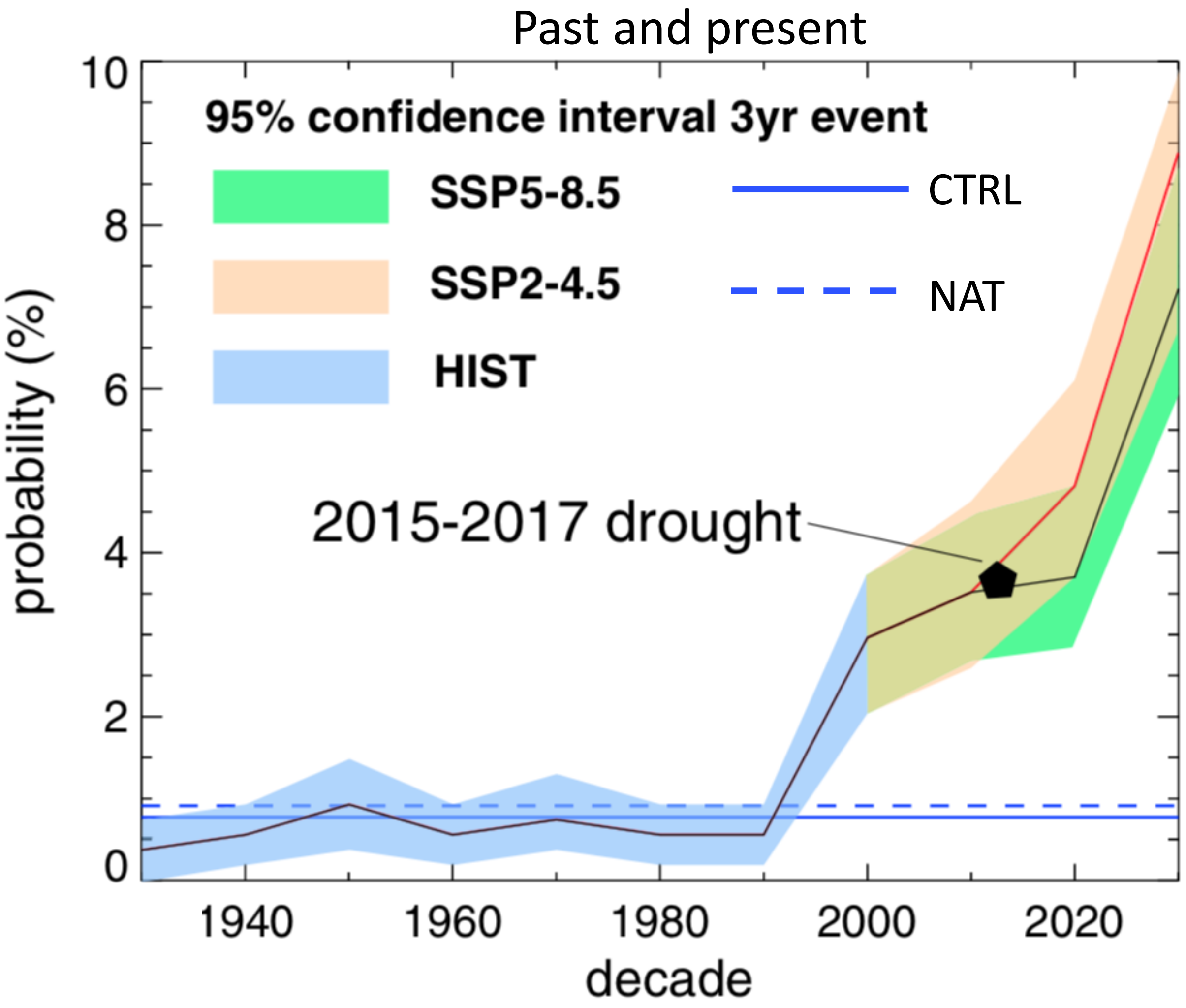
- 3-yr Winter Rainfall Index anomaly (relative to 1921-70) for 2015-2017 ≈ **-11.5** mm/month
- **Decadal PDF** (3yr mean anomalies) for each 20-yr window (18x30=**540** different sequences)

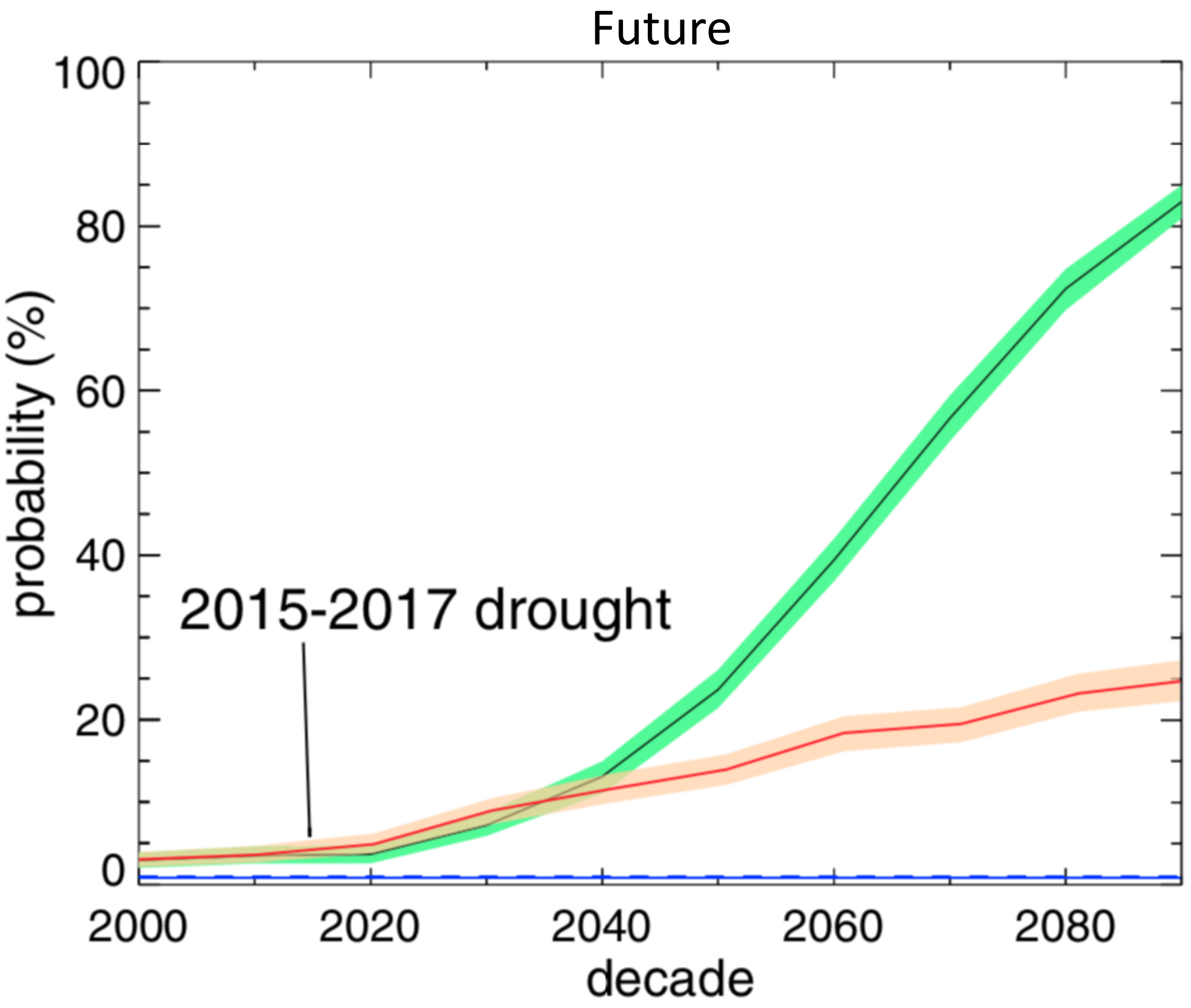




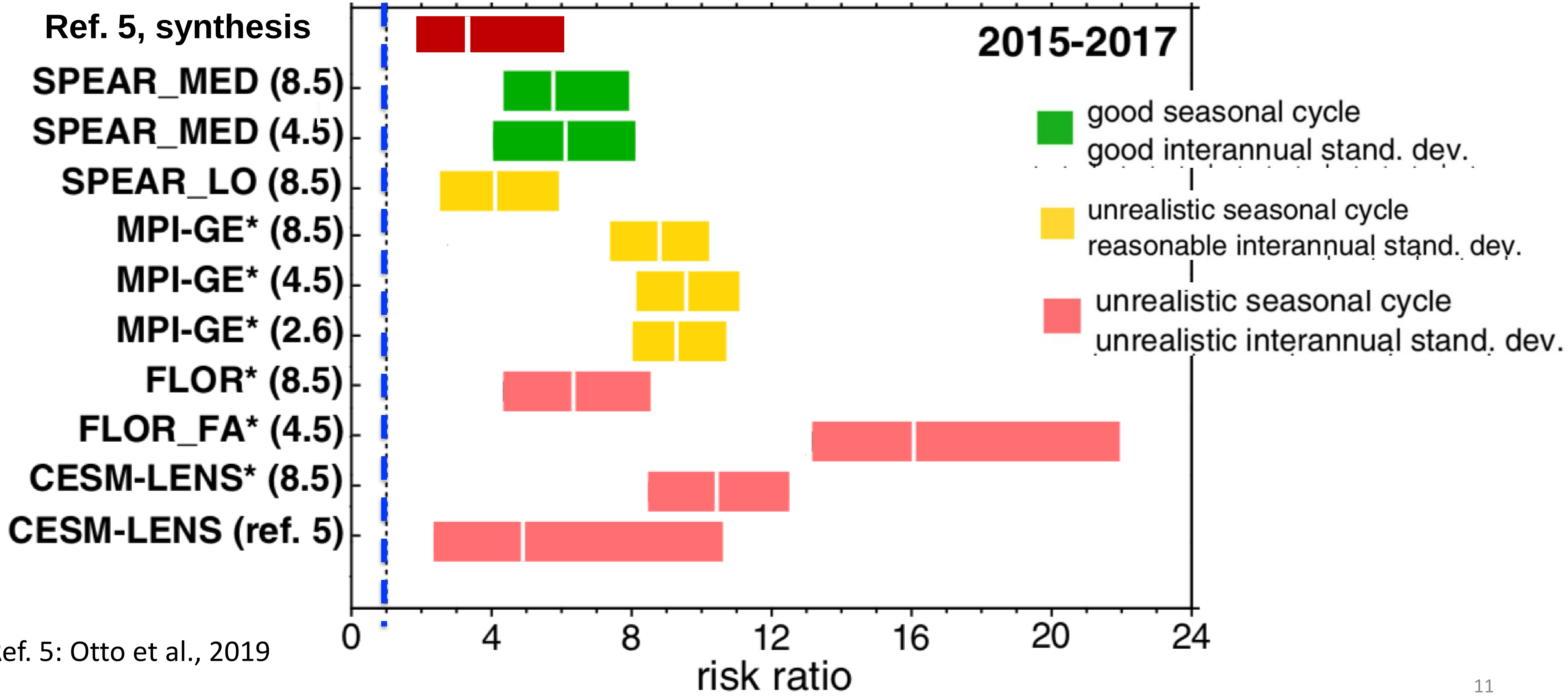


How likely event_1519 in the next decades?





Risk ratios



Ref. 5: Otto et al., 2019

Case 2: the 2015-19 Central American megadrought

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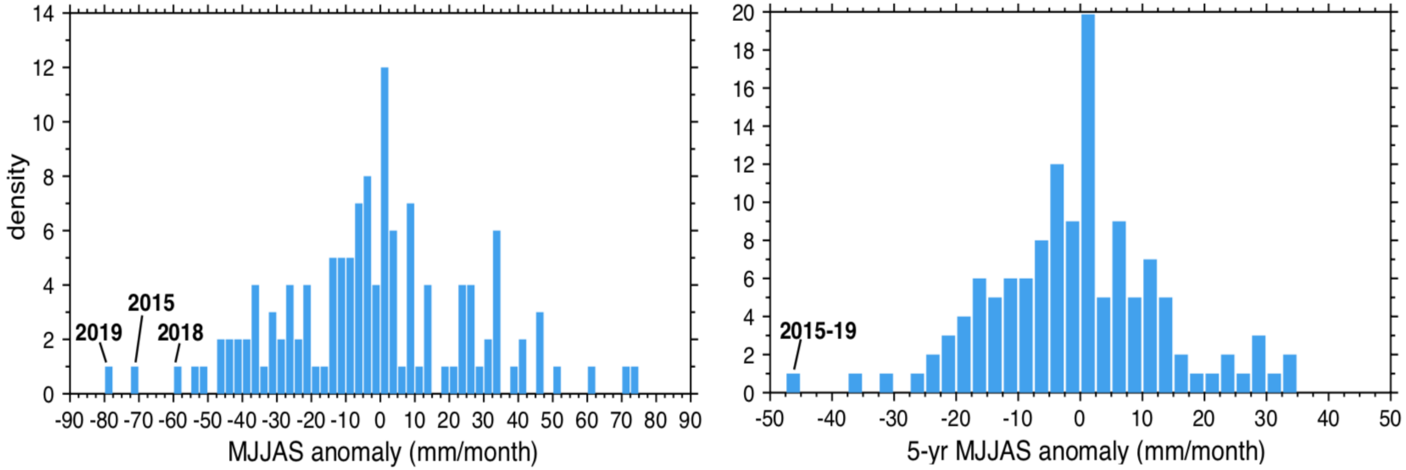
Eye of the Storm

Fifth Straight Year of Central American Drought Helping Drive Migration

Recent rains have helped, but long-term climate change is likely to significantly increase migration

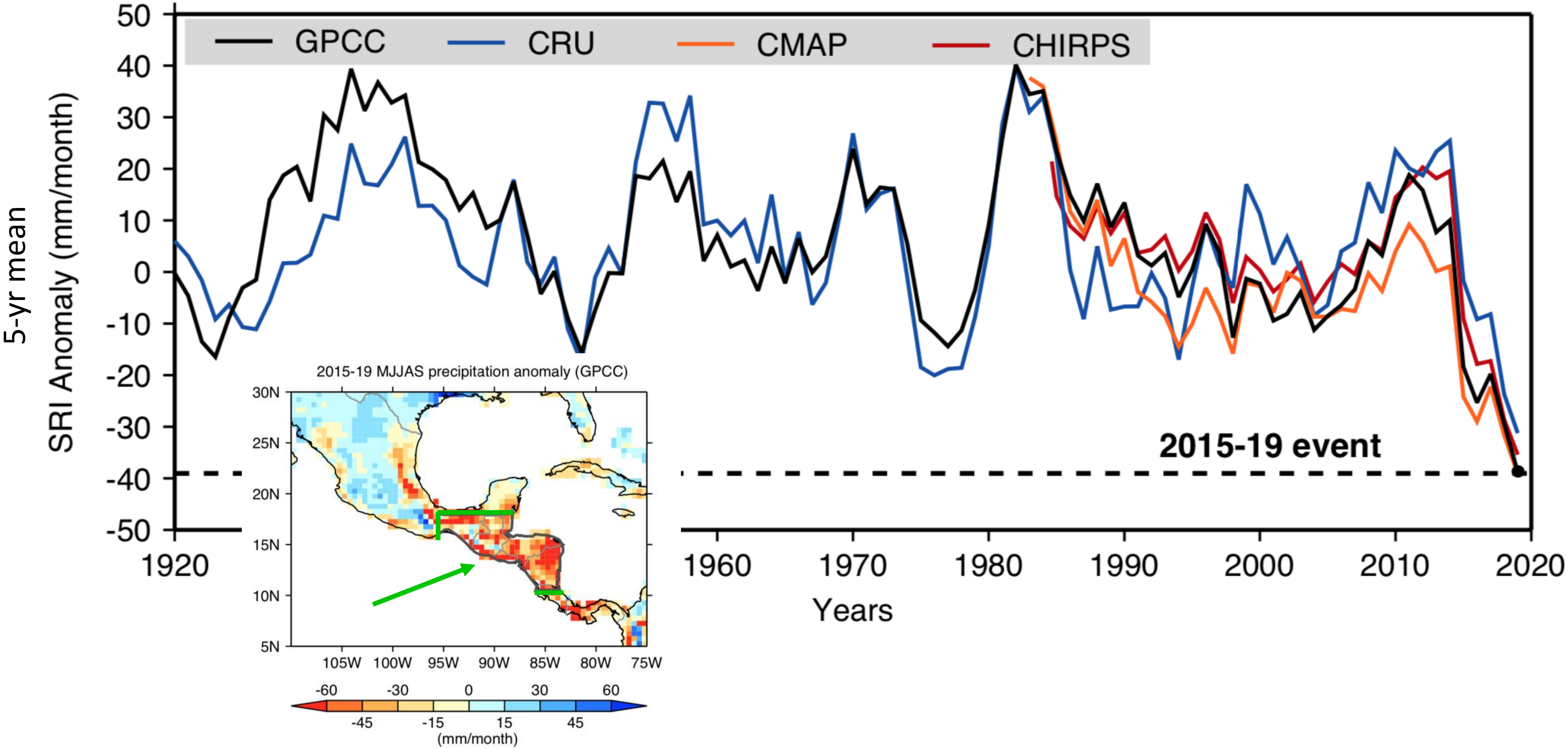
By Jeff Masters on December 23, 2019



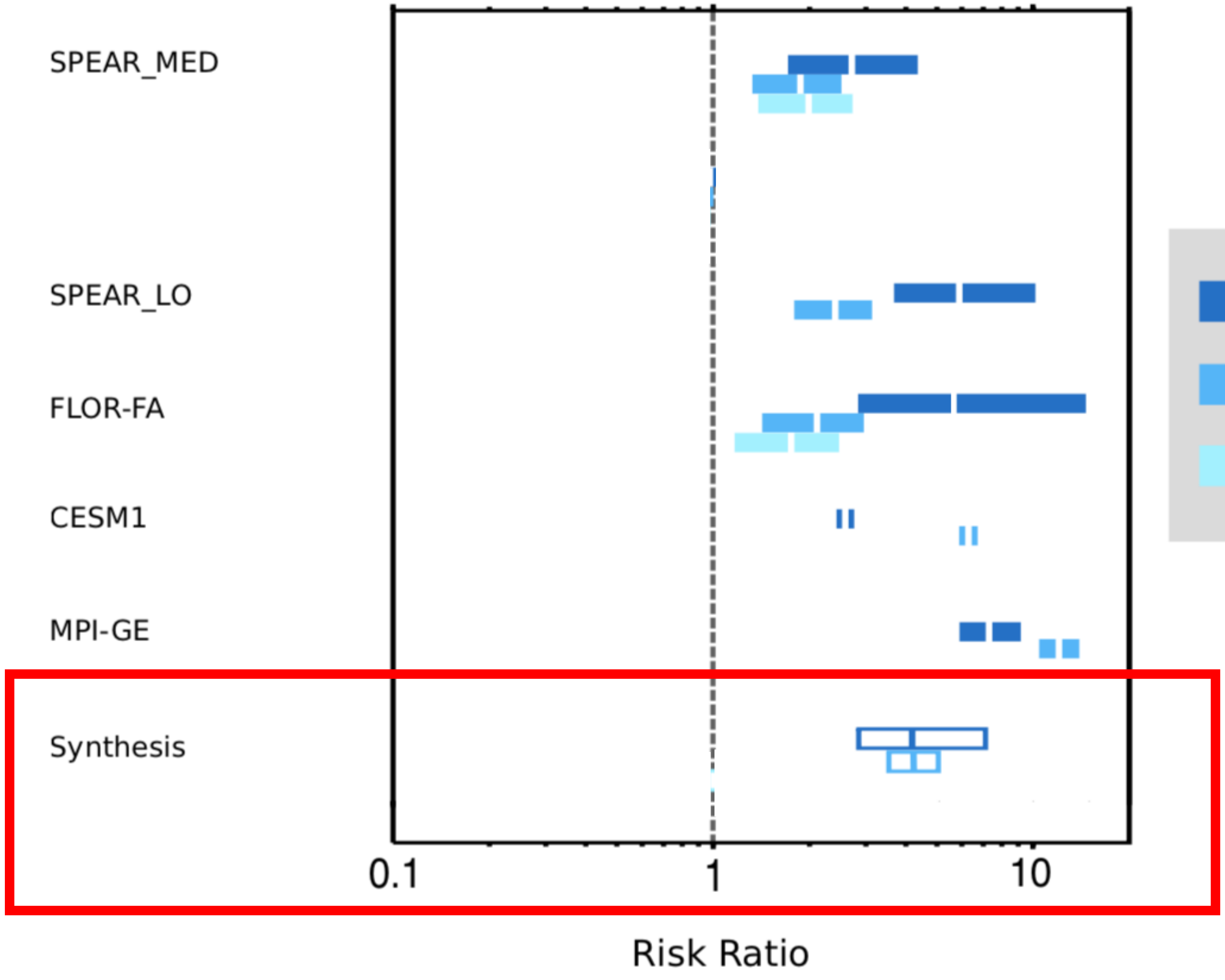
- Prolonged droughts in Honduras, El Salvador, Guatemala, Nicaragua led to massive loss of major crops (beans, coffee, corn), which are a fundamental part of the livelihoods of the population in the region.
- 2014, 2015, 2016, 2018, 2019 were dry. The 2015-2019 mean exceptionally dry

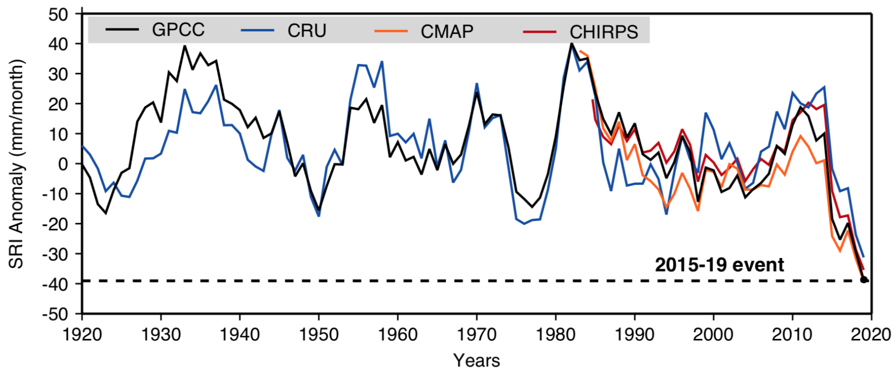
Pascale et al., Climatic Change, under review

The 2015-19 event



RR for event_1519





PRES. vs. PAST (1921-1970)

PRES. vs. CTRL

PRES. vs. NATURAL

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Increasing risk of another Cape Town "Day Zero" drought in the 21st century

Salvatore Pascale, Sarah B. Kapnick, Thomas L. Delworth, and William F. Cooke

PNAS first published November 9, 2020; https://doi.org/10.1073/pnas.2009144117
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Edited by Dennis L. Hartmann, University of Washington, Seattle, WA, and approved September 28, 2020 (receive
review May 7, 2020)

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Thank you!

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Natural variability vs forced signal in the 2015–2019 Central American drought

Salvatore Pascale, Sarah B. Kapnick, Thomas L. Delworth, Hugo G. Hidalgo & William F. Cooke

Climatic Change **168**, Article number: 16 (2021) | Cite this article

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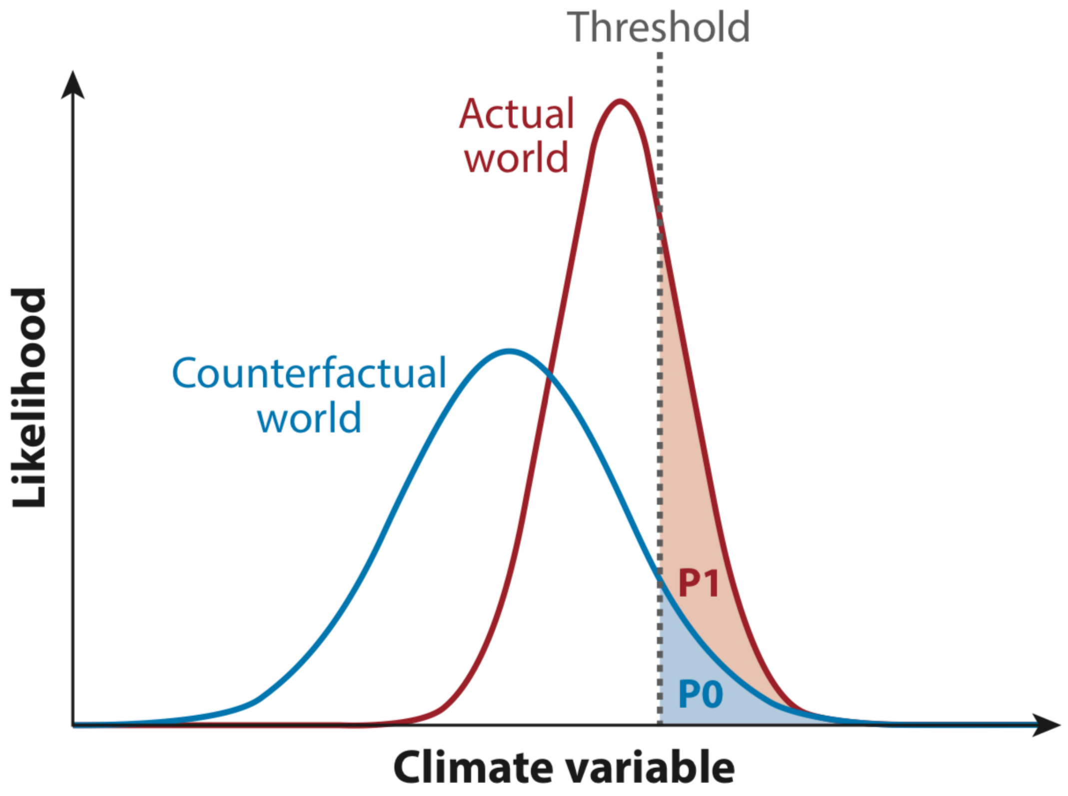
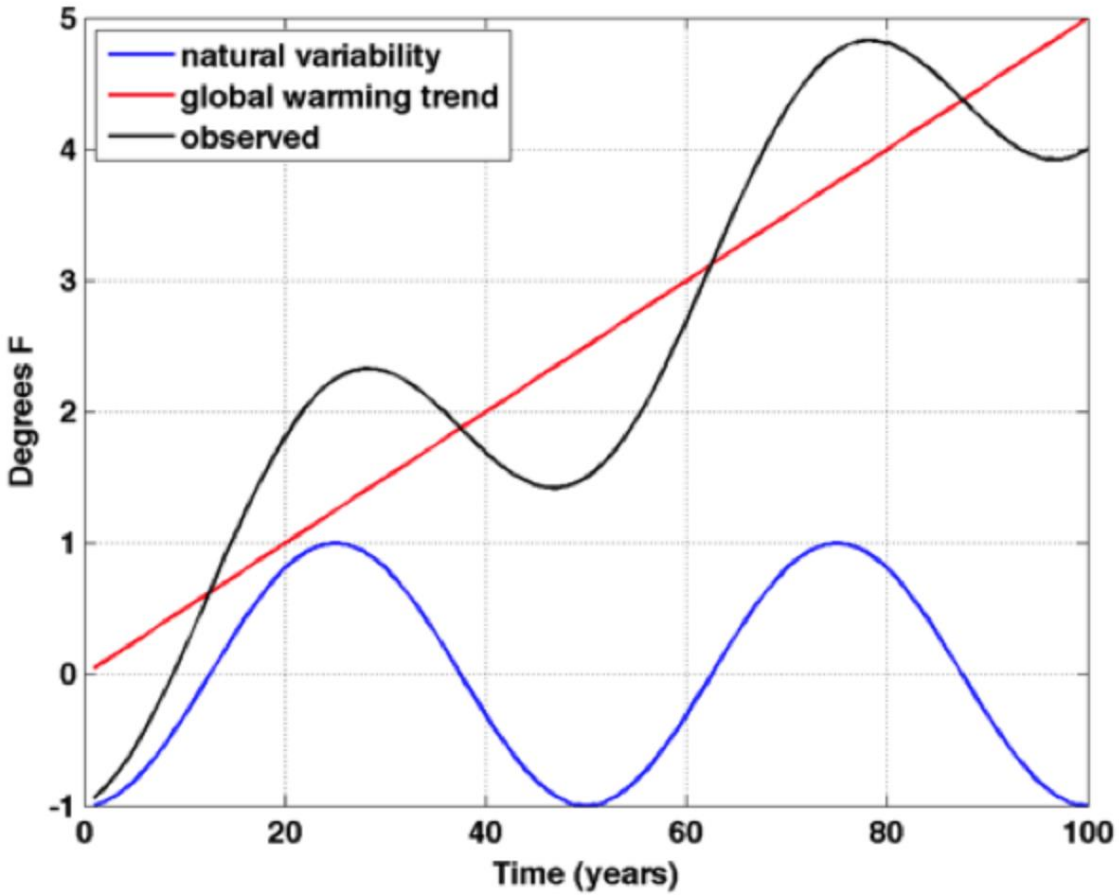
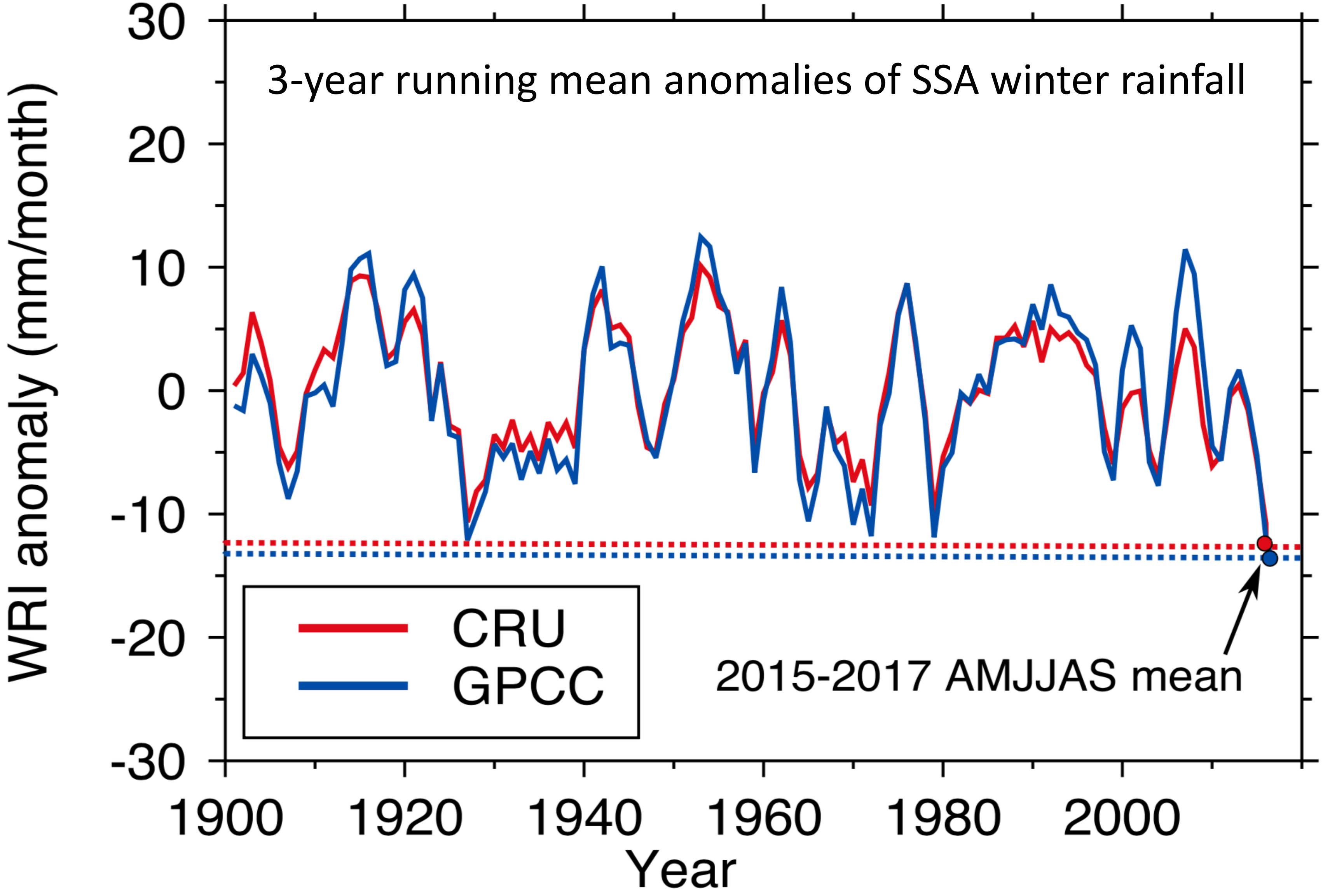




natural variability
global warming trend
observed
Degrees F
Time (years)
5
4
3
2
1
0
-1
0
20
40
60
80
100

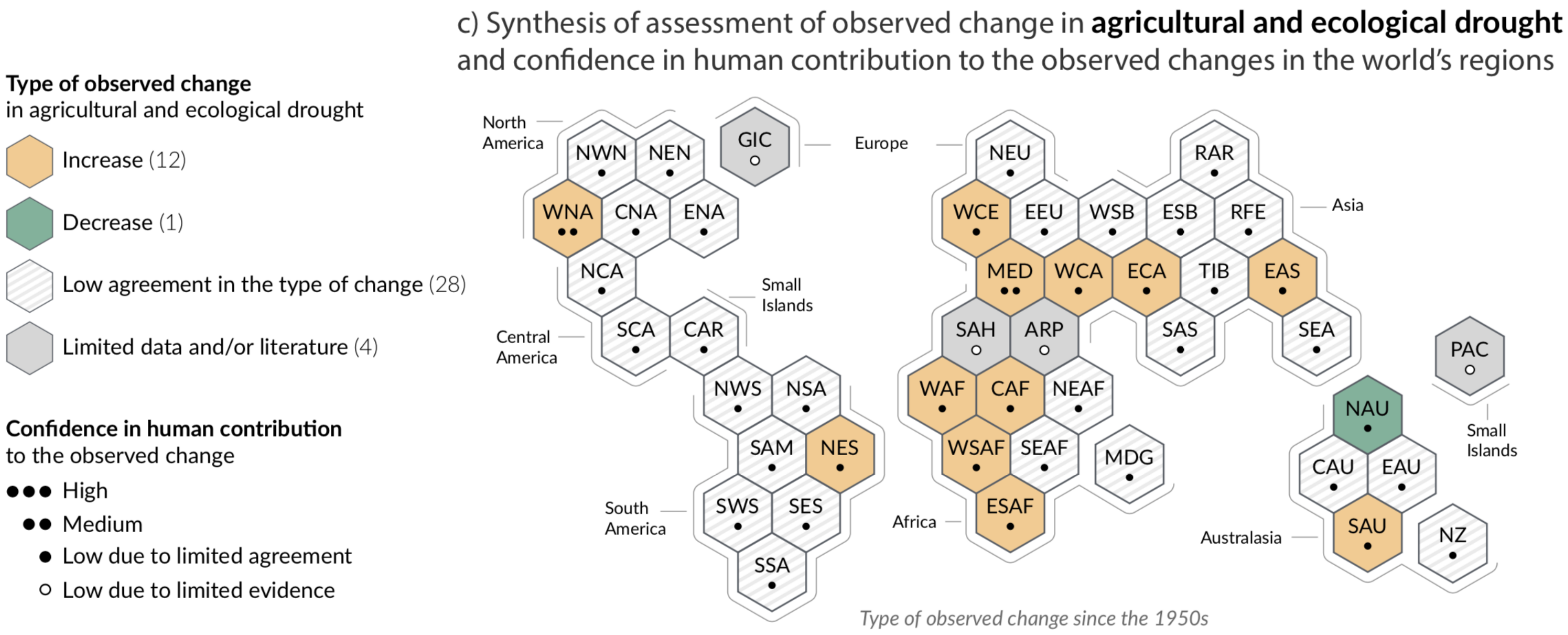
Definition of event_1517



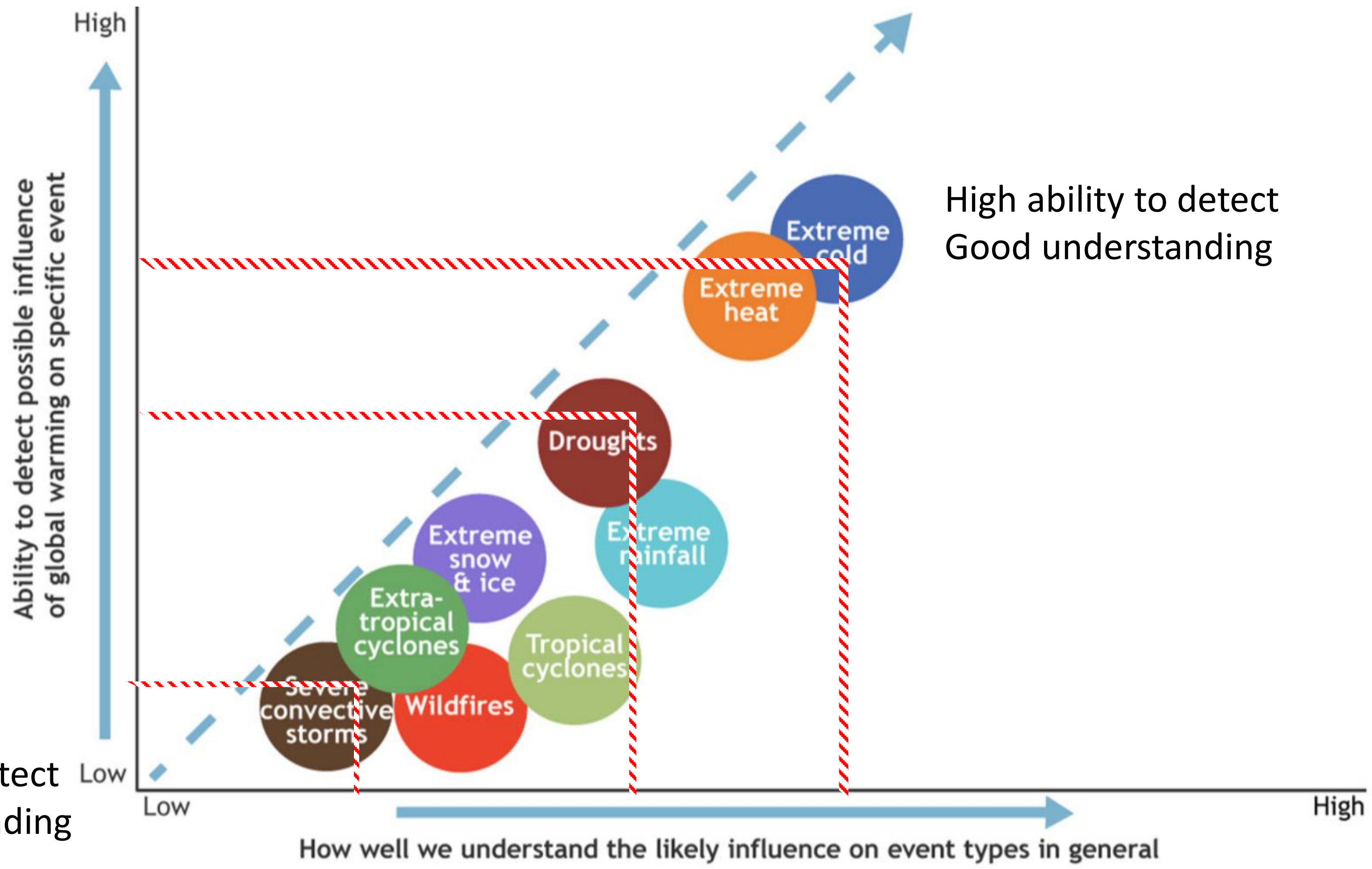
2015-17 anomaly
-12 mm/month

Weather and climatic extremes: present and future

Climate change is already affecting every inhabited region across the globe with human influence contributing to many observed changes in weather and climate extremes



Confidence in attributing different events

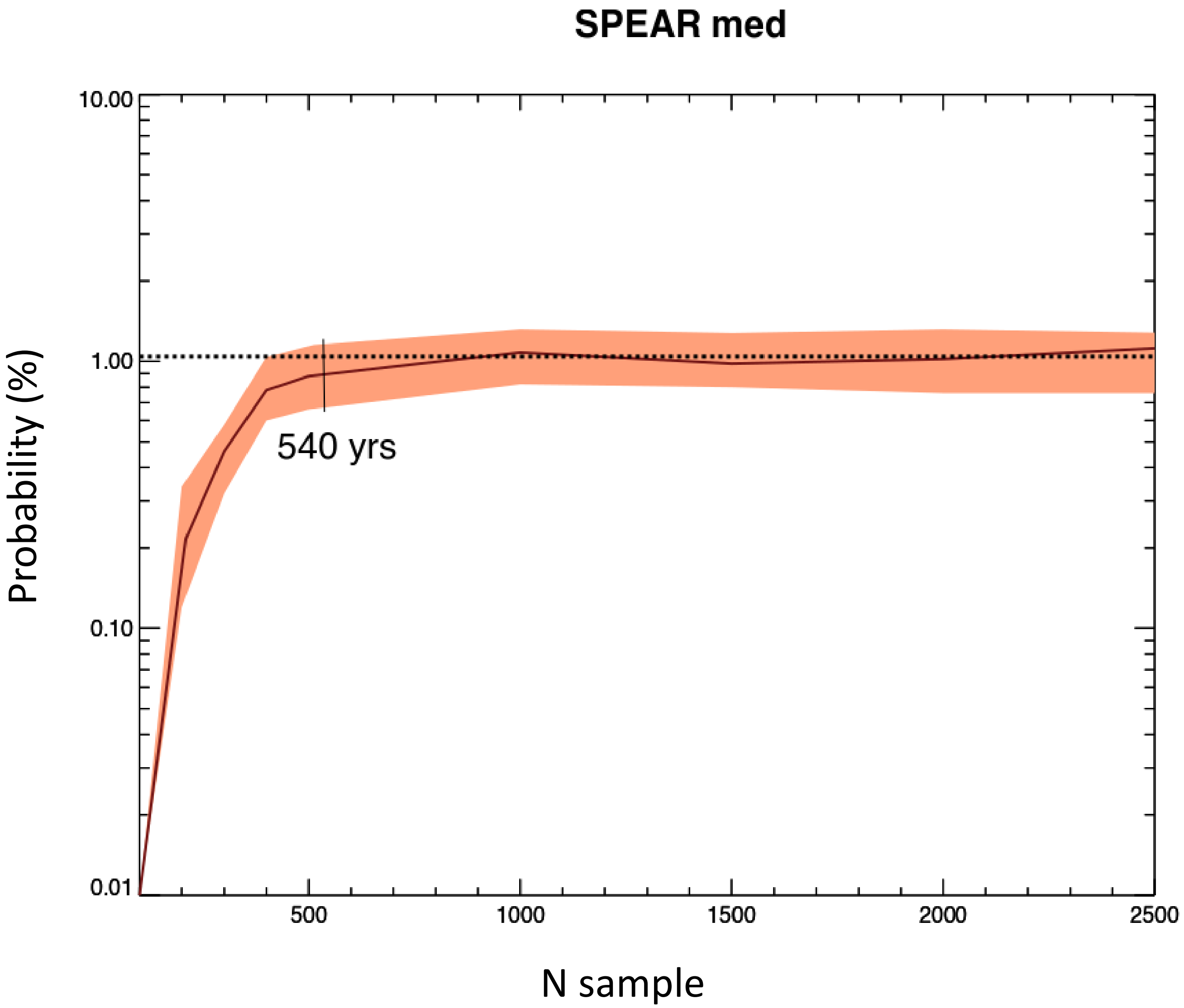


High ability to detect
Good understanding

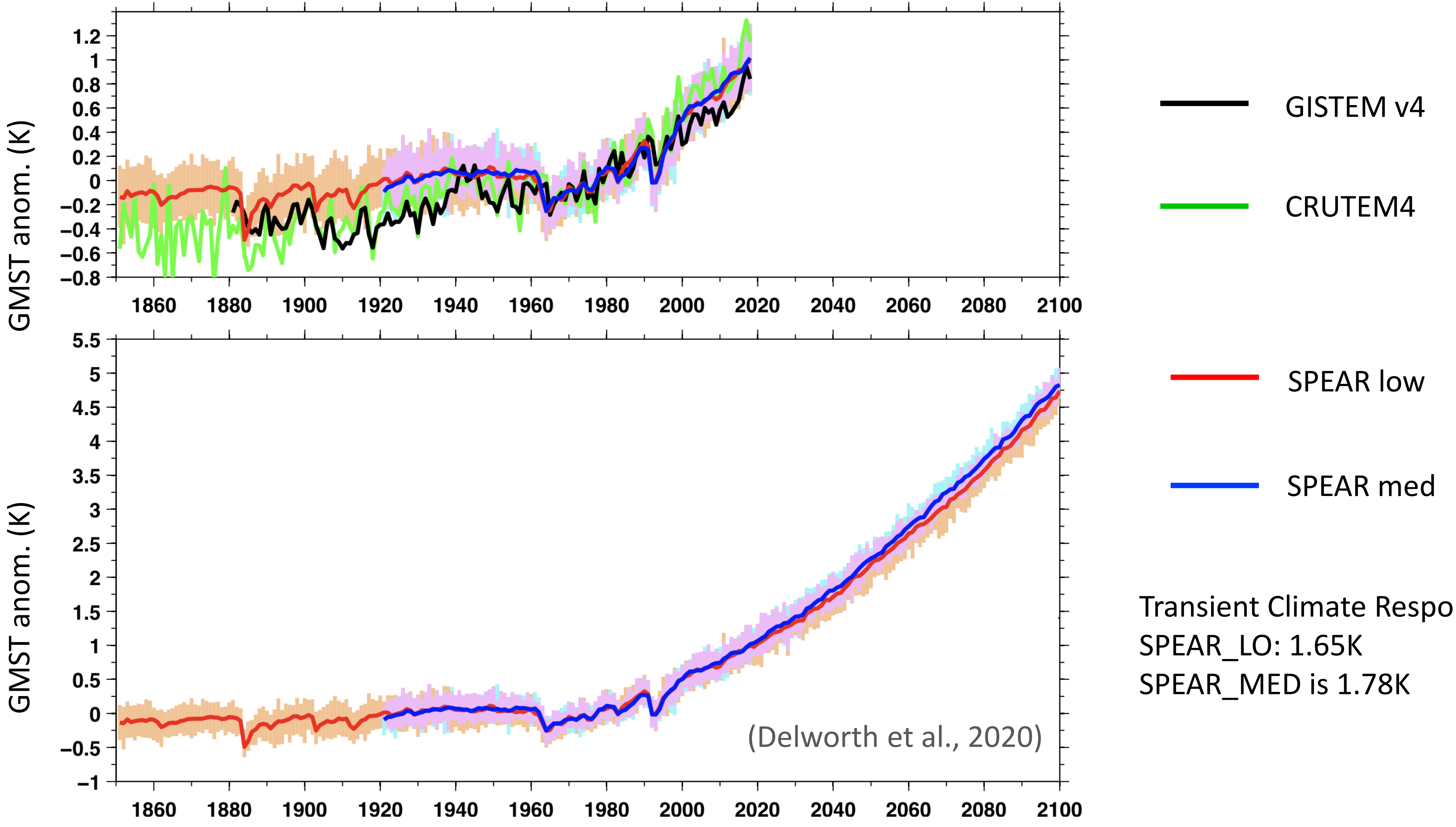
Low ability to detect
Lower understanding

NOAA Climate.gov, adapted from NAS 2016

Enough to estimate tails?

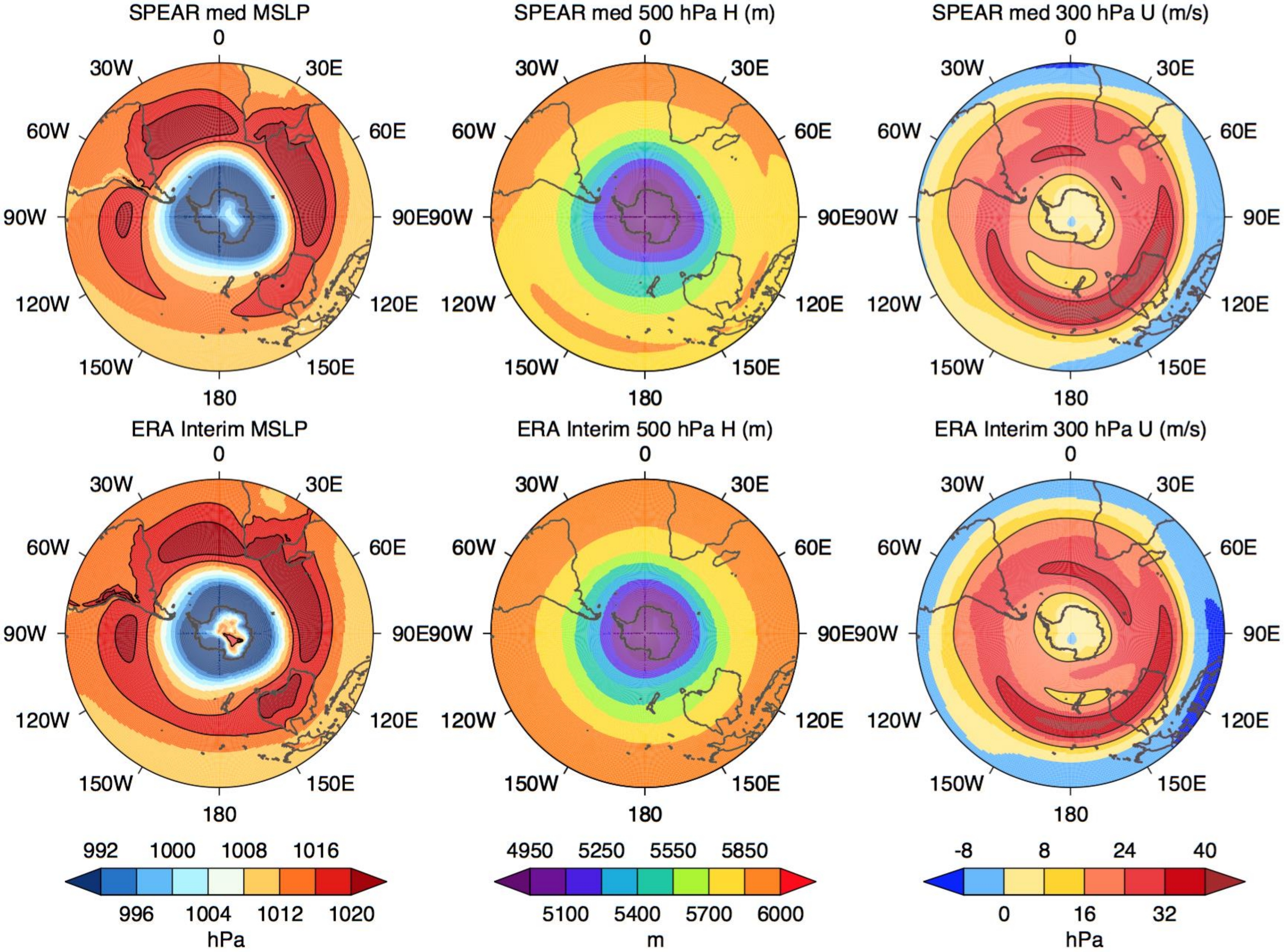


SPEAR: global mean surface temperature evaluation

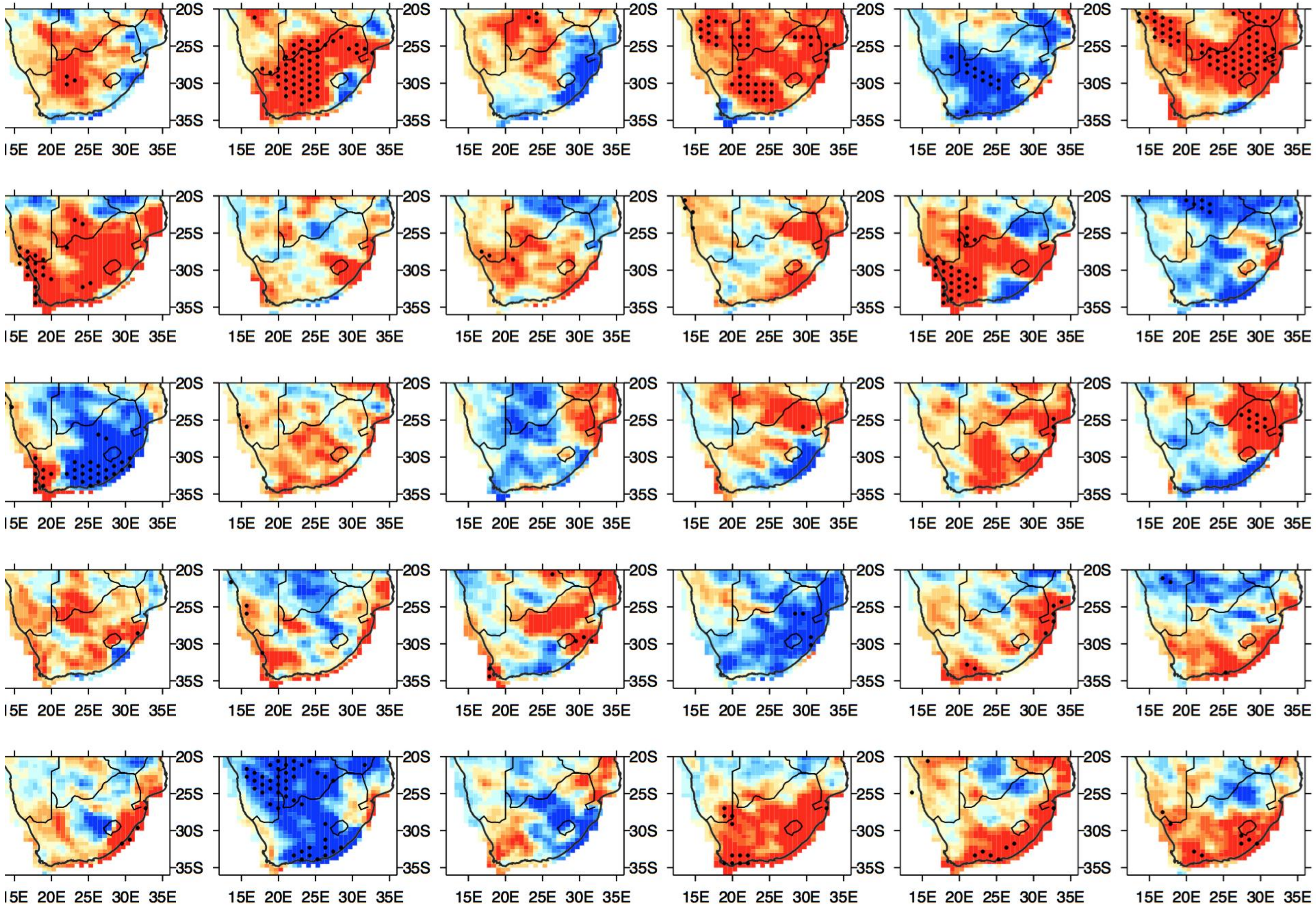


Transient Climate Response
SPEAR_LO: 1.65K
SPEAR_MED is 1.78K

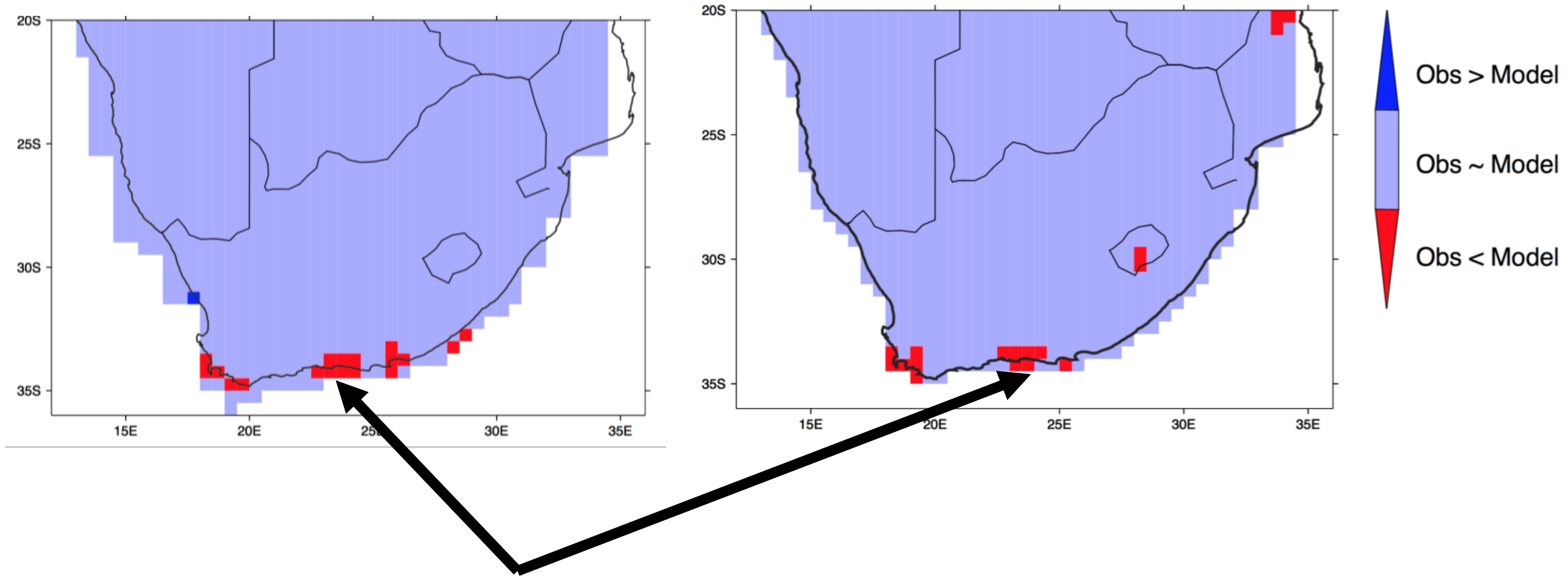
MSLP 500 Geop. Height 300 hPa zonal wind



1951-2017 linear trends (AMJJAS precip)
Individual members



Range of AMJJAS trends consistent (i.e., within the range of natural variability) with observed trends over most of SA

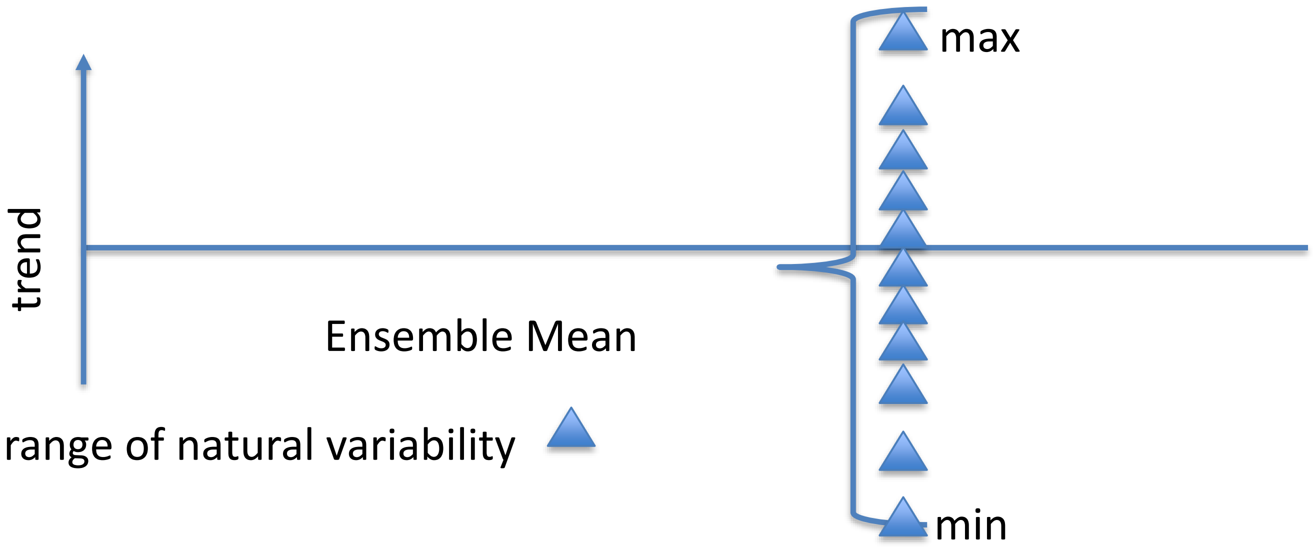


Here observed negative trends exceed the ensemble minimum

Are observed trends attributable to anthropogenic forcing?

To estimate natural variability range: Trends calculated over a 67-yr period picked up randomly 30 times to form the ensemble mean △ (this process is then repeated 3000 times).

Natural variability range
(from CTRL)



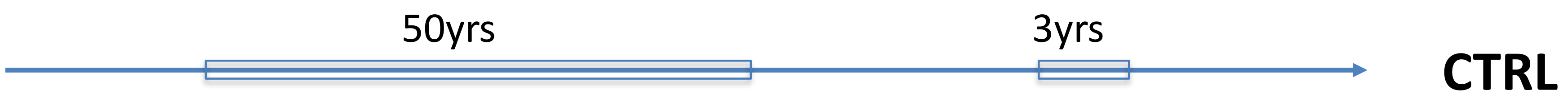
within the range of natural variability △

outside the range of natural variability △

Method

How exceptional the mean 2015-17 drought was?

Randomly select non-overlapping 50yr and a 3yr time windows..



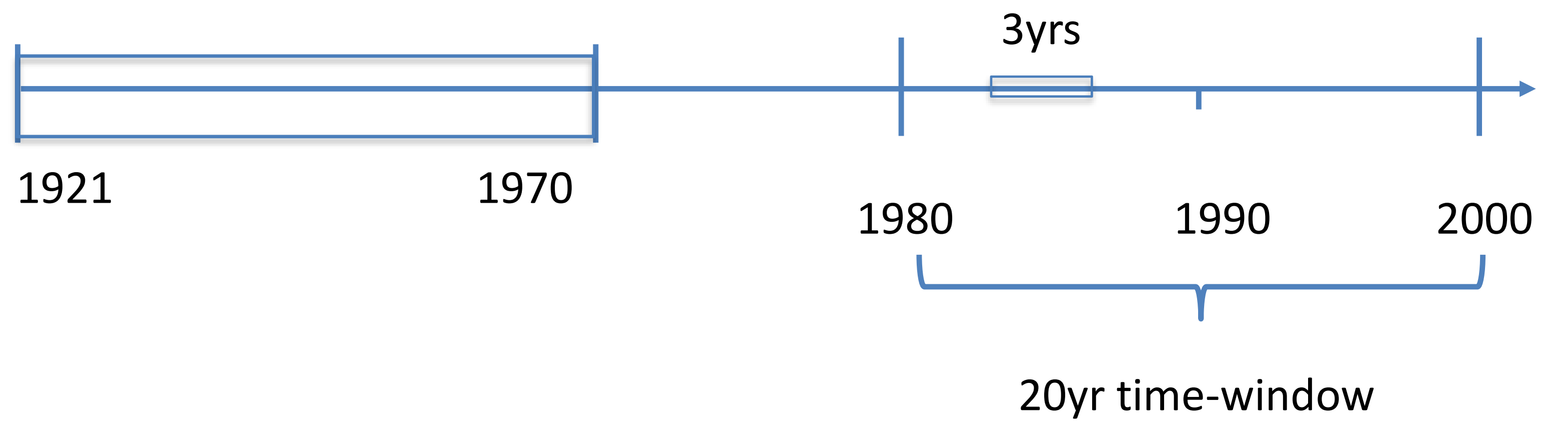
Get an anomaly

Repeat it 10,000 times

Method

How exceptional the mean 2015-17 drought was?

Randomly select 3 consecutive years

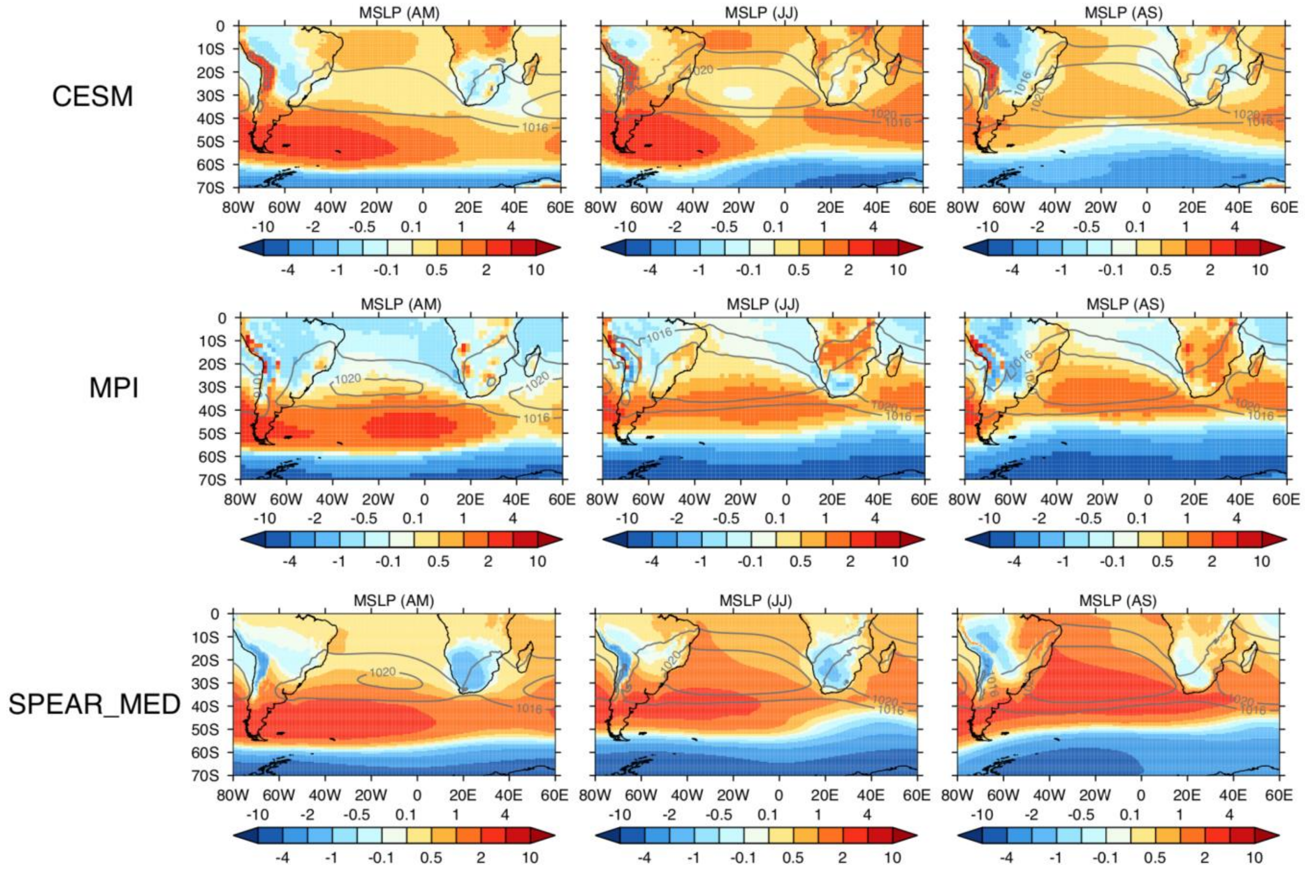


Hist

Proj

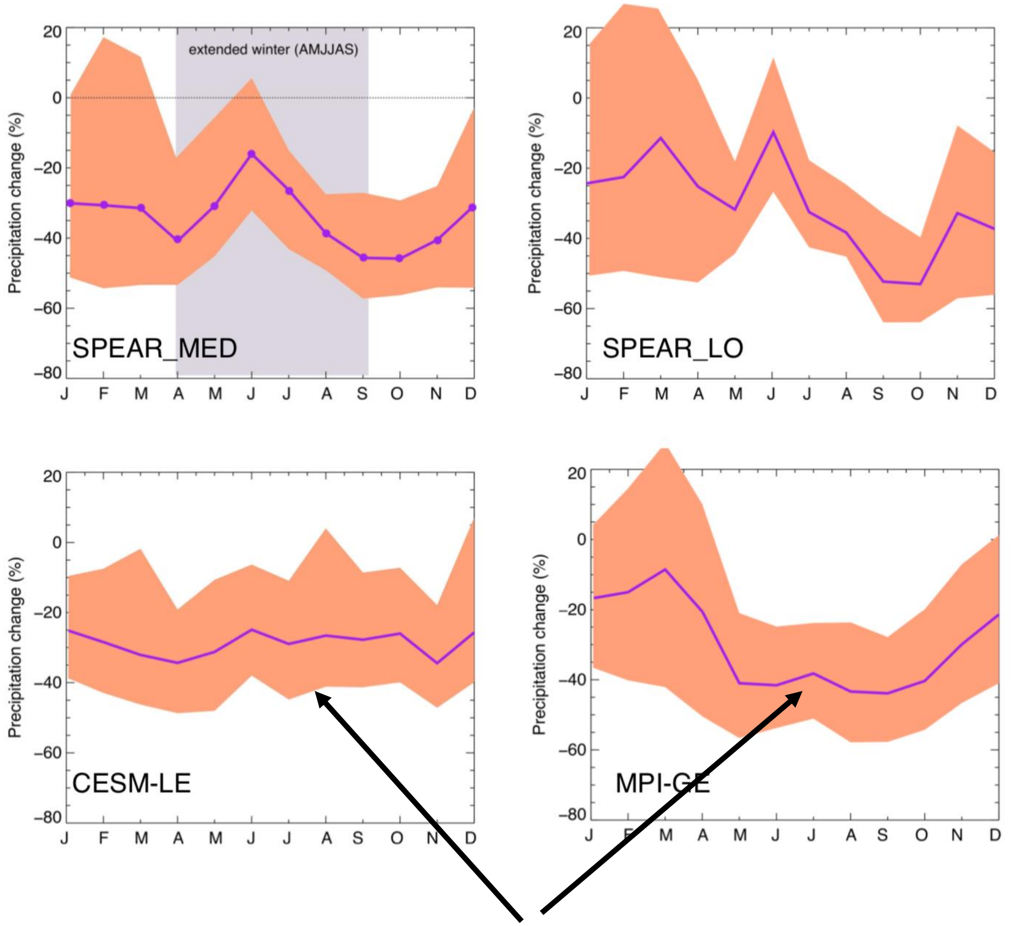
Repeat 20 times, for each ensemble member (20x30=600)

Other Large Ensembles?



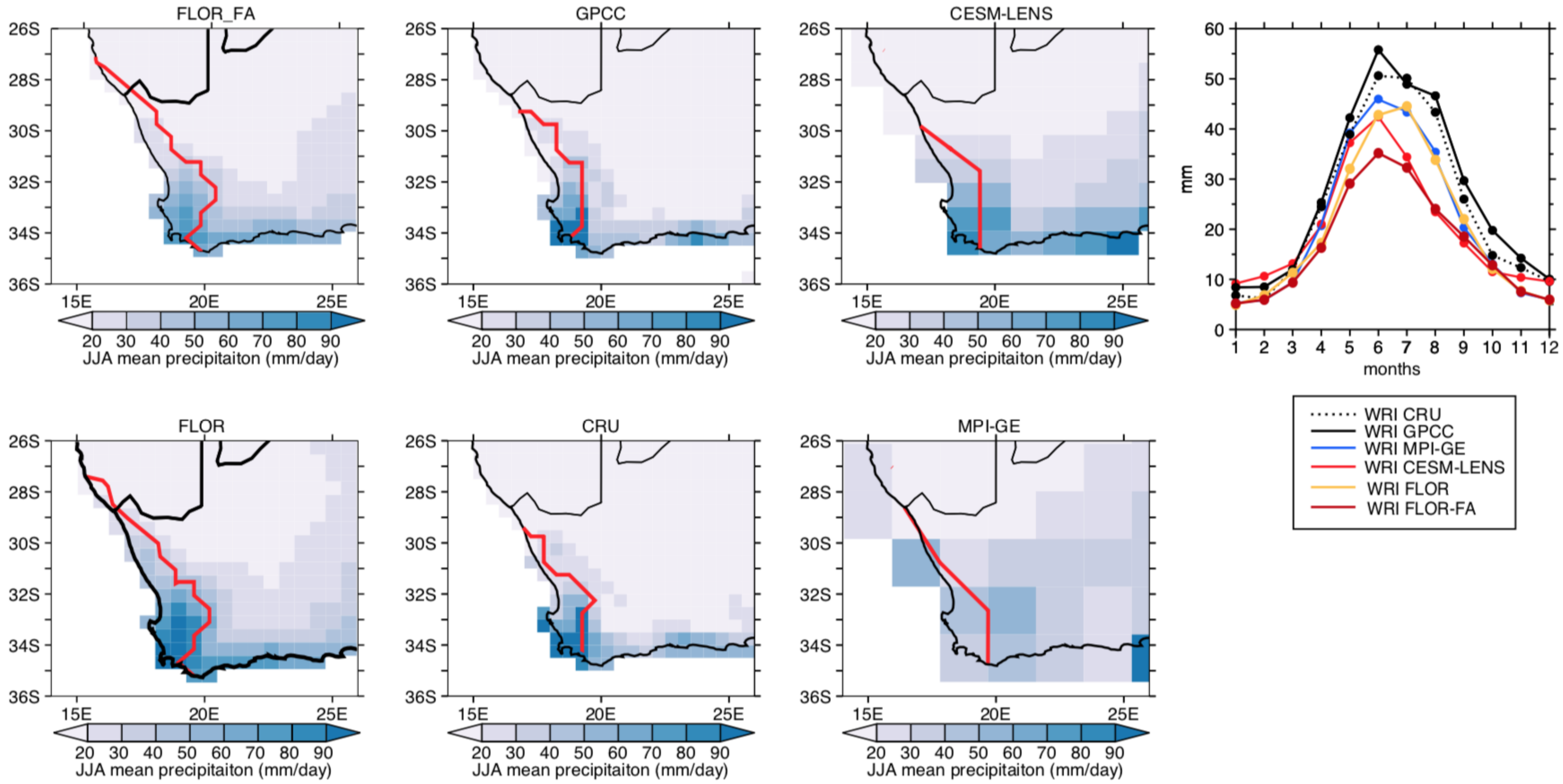
Ensemble mean difference MSLP
(**2070-2100 vs.1921-2000**)

Fraction of WRI reduction (2071-2100 vs 1921-1970)

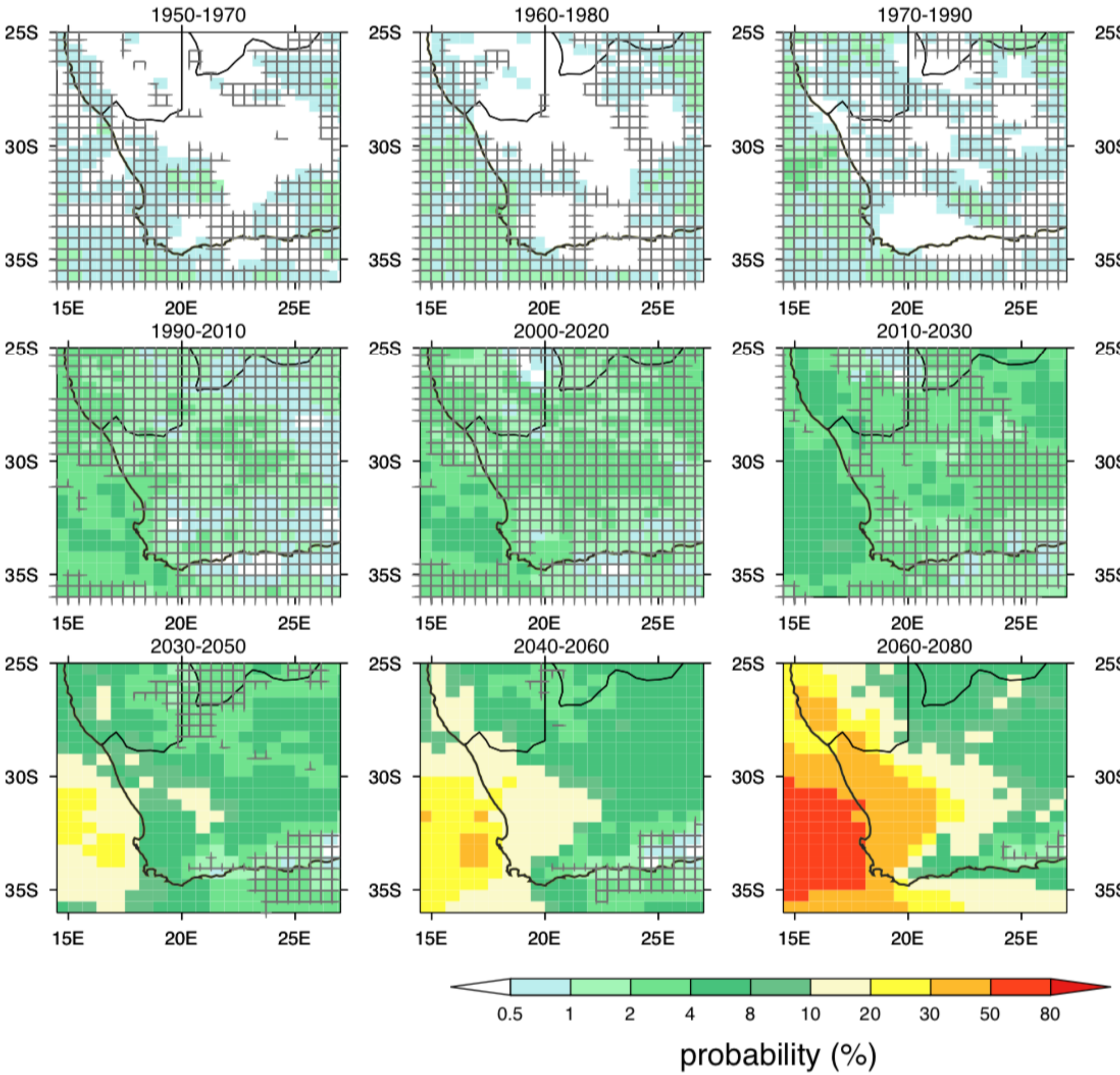


Forced signal less seasonal

Model evaluation of SSA precipitation



How likely event_1519 in the next decades?



Grid point view

Probability of exceeding the 1st percentile from the CTRL probability distribution of the three-year winter rainfall anomalies.

Approach to event attribution: high-resolution LE

- Large Ensemble simulations from the newly developed **S**eamless System for **P**rediction and **Ea**rth System **R**esearch at 0.5 degree resolution: **SPEAR_MED**

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RESEARCH ARTICLE
10.1029/2019MS001895

Special Section:
Geophysical Fluid Dynamics Laboratory CMIP6 Models

Rich Gudgel retired at the end of March 2019.
Shian-Jiann Lin retired in May 2019.

Key Points:
- Development and performance of the next generation GFDL seasonal to decadal prediction model is documented
- The response of this model to realistic radiative forcing changes is shown via a large ensemble of climate simulations for 1921–2100

SPEAR: The Next Generation GFDL Modeling System for Seasonal to Multidecadal Prediction and Projection

Thomas L. Delworth[1], William F. Cooke[1,2], Alistair Adcroft[1,3], Mitchell Bushuk[1,2], Jan-Huey Chen[1,2], Krista A. Dunne[4], Paul Ginoux[1], Richard Gudgel[1], Robert W. Hallberg[1], Lucas Harris[1], Matthew J. Harrison[1], Nathaniel Johnson[1,3], Sarah B. Kapnick[1], Shian-Jian Lin[1], Feiyu Lu[1,3], Sergey Malyshev[1], Paul C. Milly[4], Hiroyuki Murakami[1,2], Vaishali Naik[1], Salvatore Pascale[1,3,5], David Paynter[1], Anthony Rosati[1,2], M.D. Schwarzkopf[1], Elena Shevliakova[1], Seth Underwood[1], Andrew T. Wittenberg[1], Baoqiang Xiang[1,3], Xiaosong Yang[1,2], Fanrong Zeng[1], Honghai Zhang[1,3,6], Liping Zhang[1,2], and Ming Zhao[1]

[1]Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, NJ, USA, [2]University Corporation for Atmospheric Research, Boulder, CO, USA, [3]Department of Geosciences, Princeton University, Princeton, NJ, USA, [4]Integrated Modeling and Prediction Division, U.S. Geological Survey, Princeton, NJ, USA, [5]Department of Earth System Science, Stanford University, Stanford, CA, USA, [6]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA

https://www.gfdl.noaa.gov/spear

- **Large decadal/interdecadal variability** of winter SSA rains (Dieppois et al. 2016, Reason et al., 2002; Philippon et al., 2012) → Large Ensembles powerful method to isolate internal natural variability from forced signal

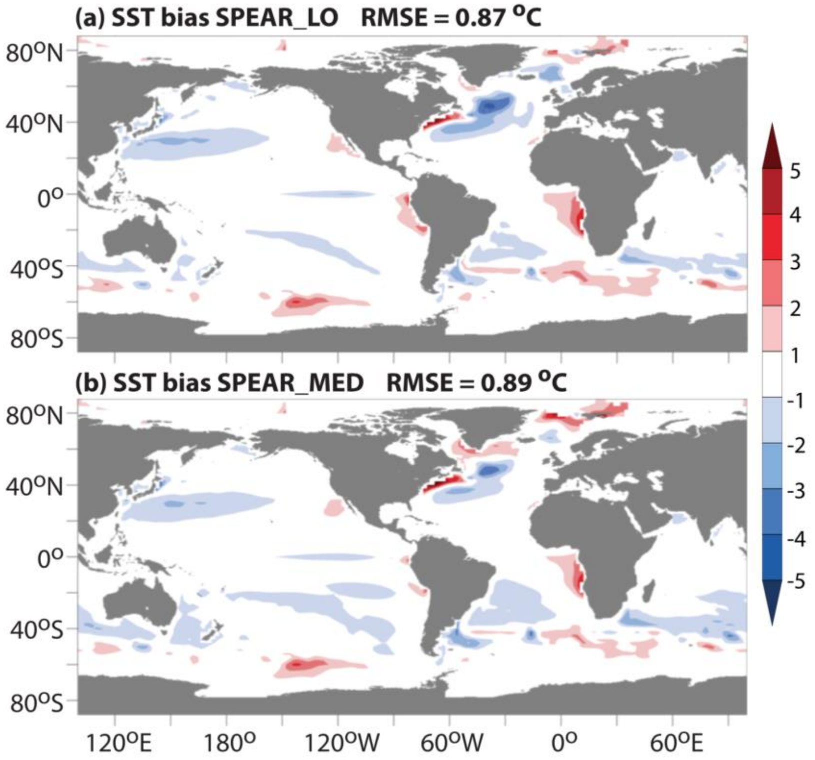
- **Additional** large ensembles at same or coarser resolution to test model uncertainties: SPEAR_LO, FLOR, FLOR_FA (Vecchi et al., 2014), CESM1 (Kay et al., 2015), MPI-GE (Mahler et al., 2019)

SPEAR: The next generation GFDL modeling system

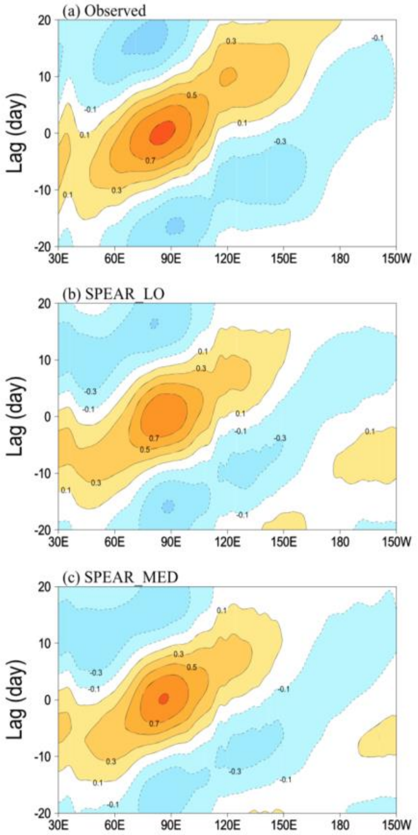
- Built from component models of GFDL CM4: **AM4** (atmosphere), **MOM6** (ocean), **LM4** (land surface), **SIS2** (sea ice)

- Ocean: 1 degree; Atmosphere 0.25 (**SPEAR_HI**), 0.5 (**SPEAR_MED**), 1 (**SPEAR_LOW**) degree: thought for regional climate and extremes

Reduced SST biases

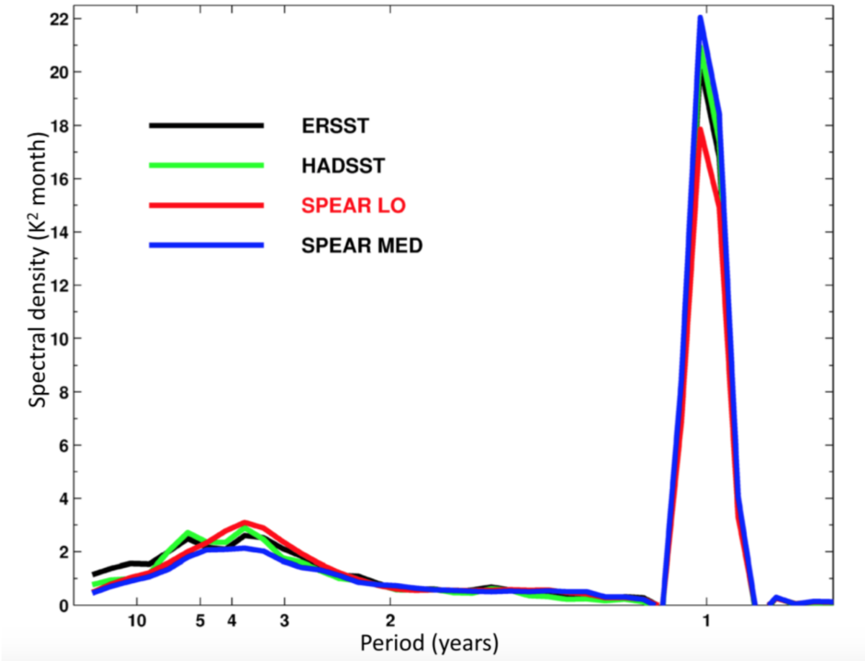


Improved MJO



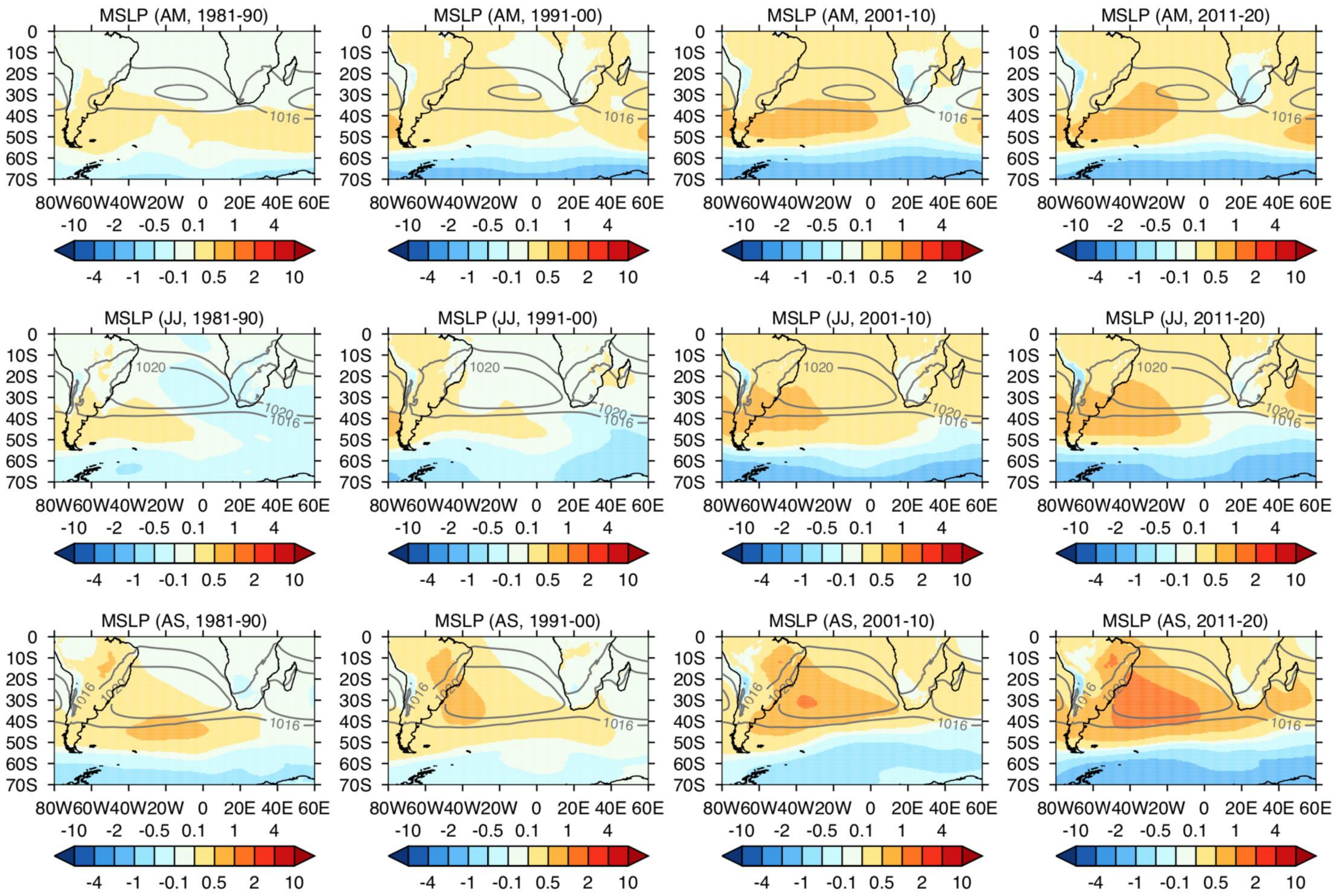
Realistic ENSO

(SST averaged 150°W-90°W, 5°S-5°N)

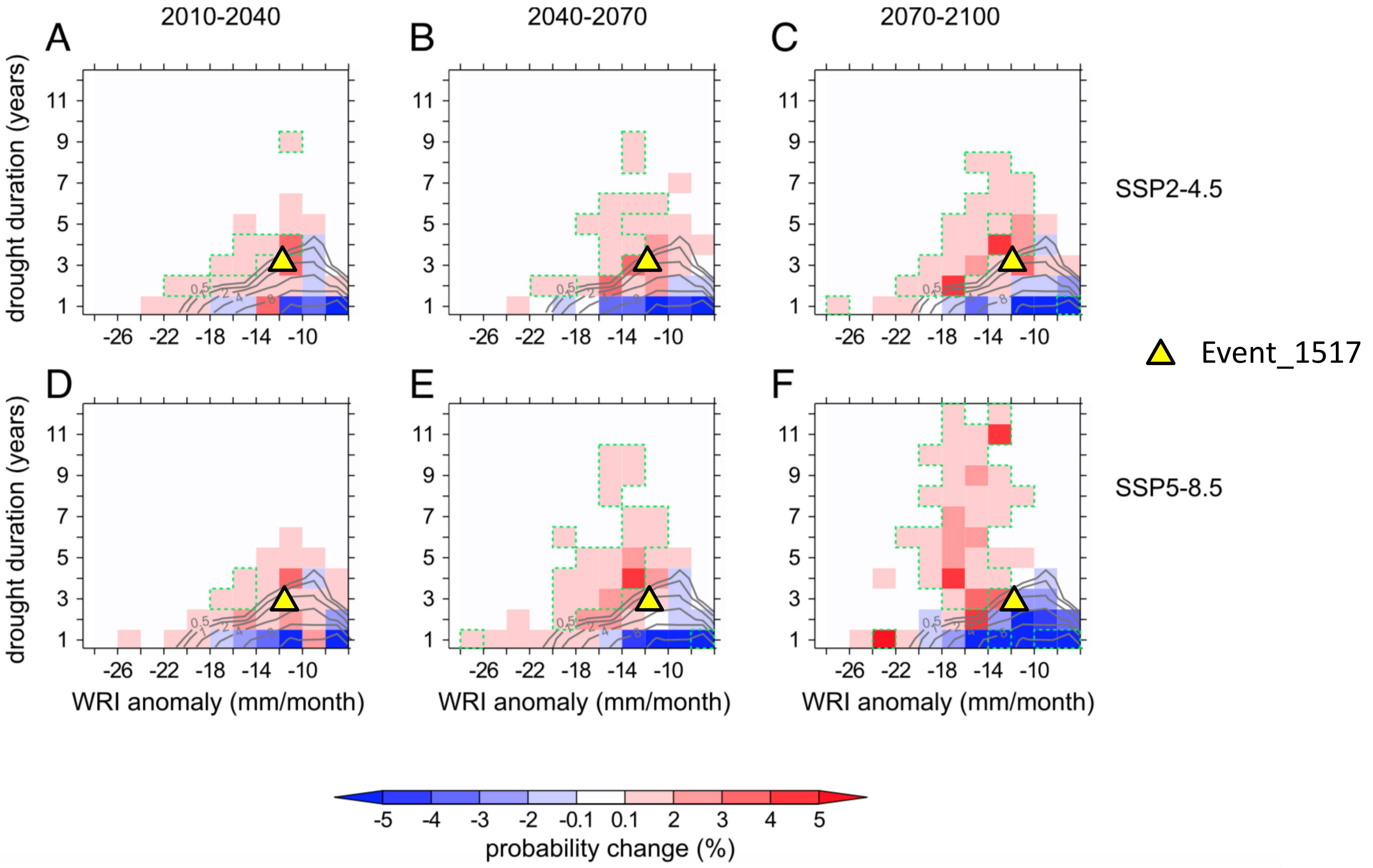


Delworth et al., 2020

Decadal MSLP forced anomalies

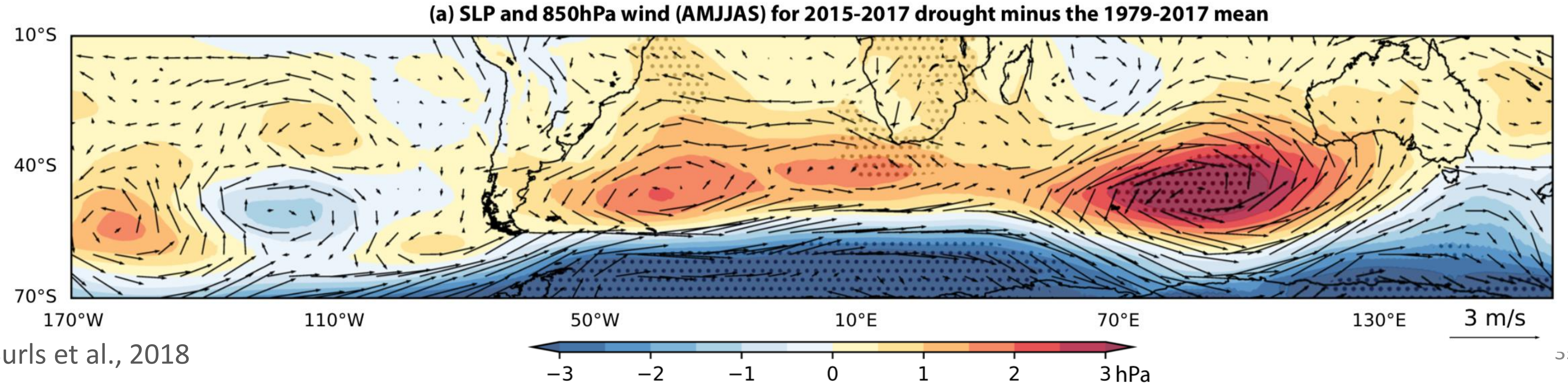


Duration of large AMJJAS rainfall anomalies



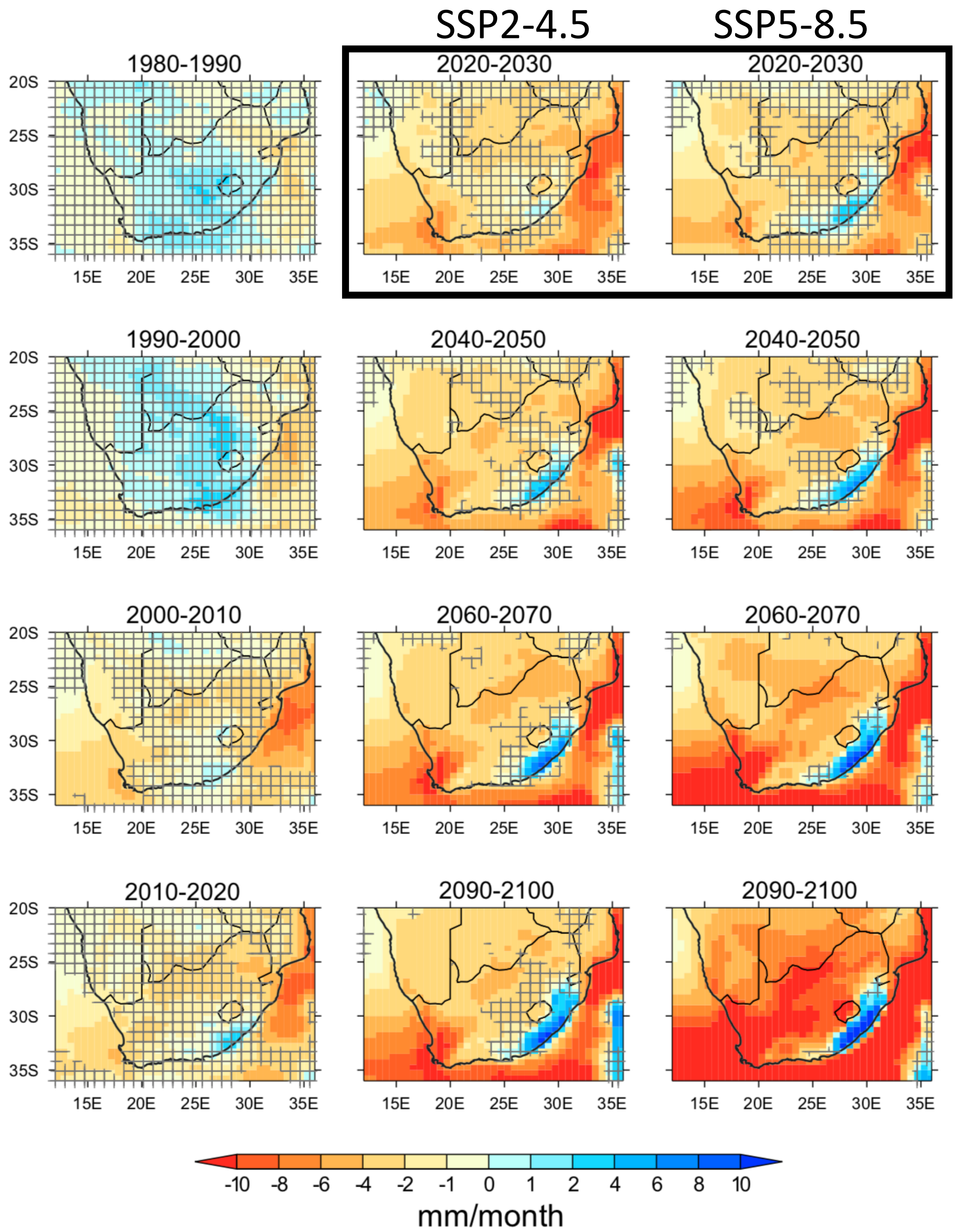
Why did this happen?

- Prolonged **rainfall deficit** the main factor (Otto et al., 2018; Sousa et al., 2018); **poor water management** co-factor (Muller 2018).
- It's been suggested a southward shift of extratropical cyclones (Sousa et al., 2018; Mahlela et al., 2018)
- Others found no anomaly in # front, but higher post-frontal MSLP → Less rainy days, shorter duration of wet spells (Burls et al., 2019)
- Hadley Cell expansion?



Burls et al., 2018

Time of detectability

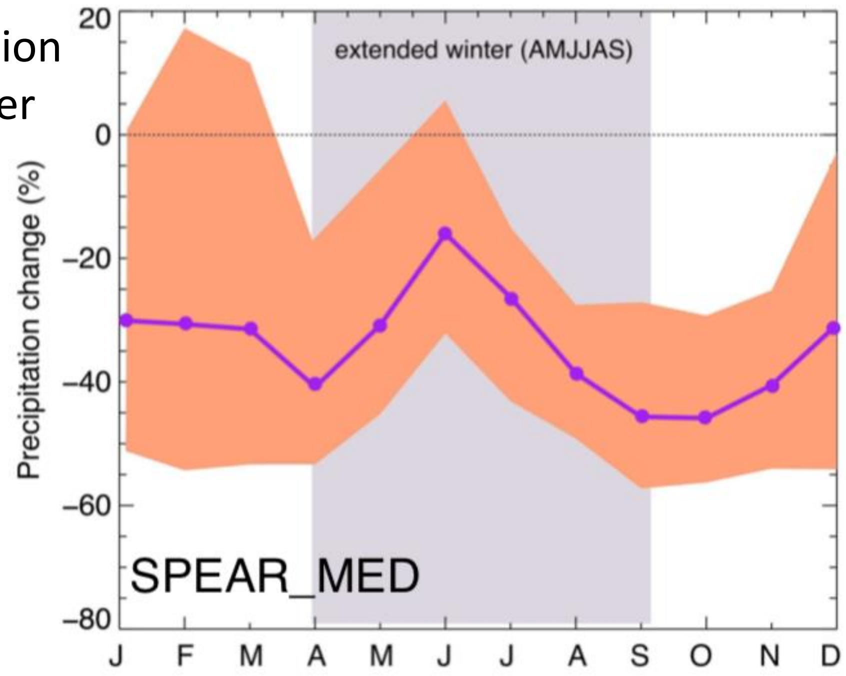


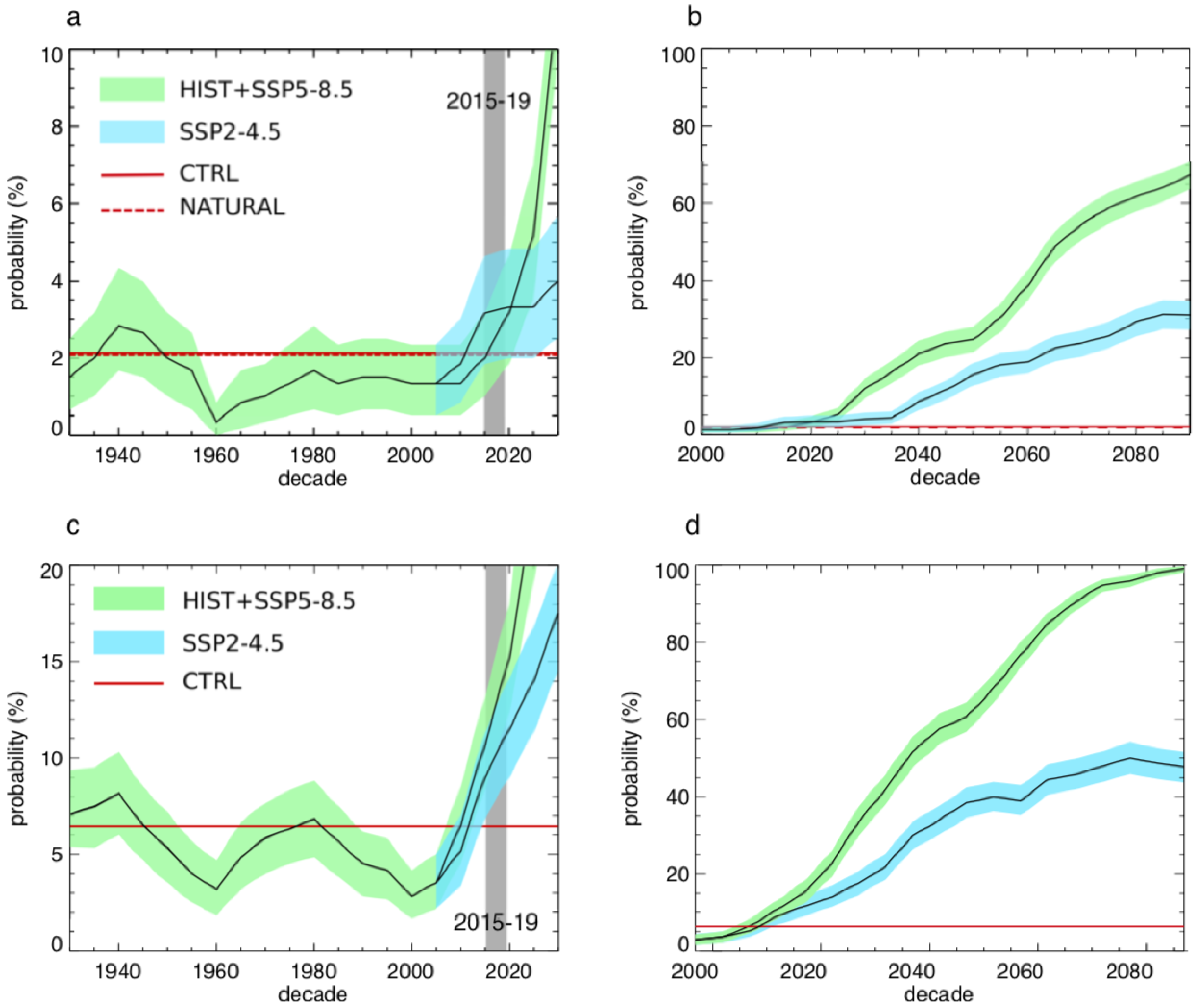
Decadal precipitation differences relative to 1921-1970
Non-stippled: signal detectable from internal natural variability

Anthropogenic signal in the **mean** clearly emerges after 2020-30 in the Western Cape province.

Stronger % reduction during the shoulder seasons

End-of-21st-century WRI anomaly




a
HIST+SSP5-8.5
SSP2-4.5
CTRL
NATURAL
2015-19
probability (%)
decade
b
probability (%)
decade
c
HIST+SSP5-8.5
SSP2-4.5
CTRL
2015-19
probability (%)
decade
d
probability (%)
decade

What is the role of humans in extremes

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Published: 02 December 2004

Human contribution to the European heatwave of 2003

Peter A. Stott, D. A. Stone & M. R. Allen

Nature **432**, 610–614 (2004) | Cite this article

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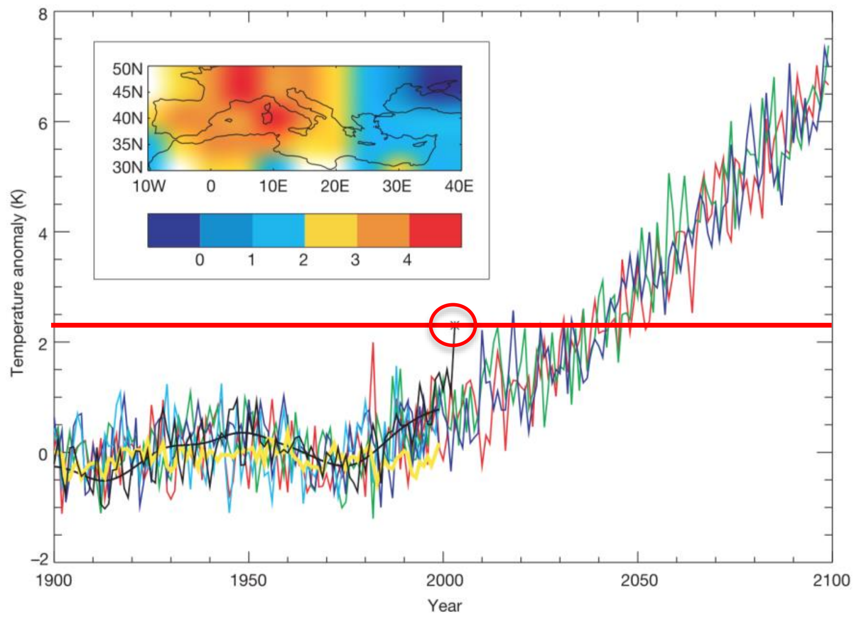
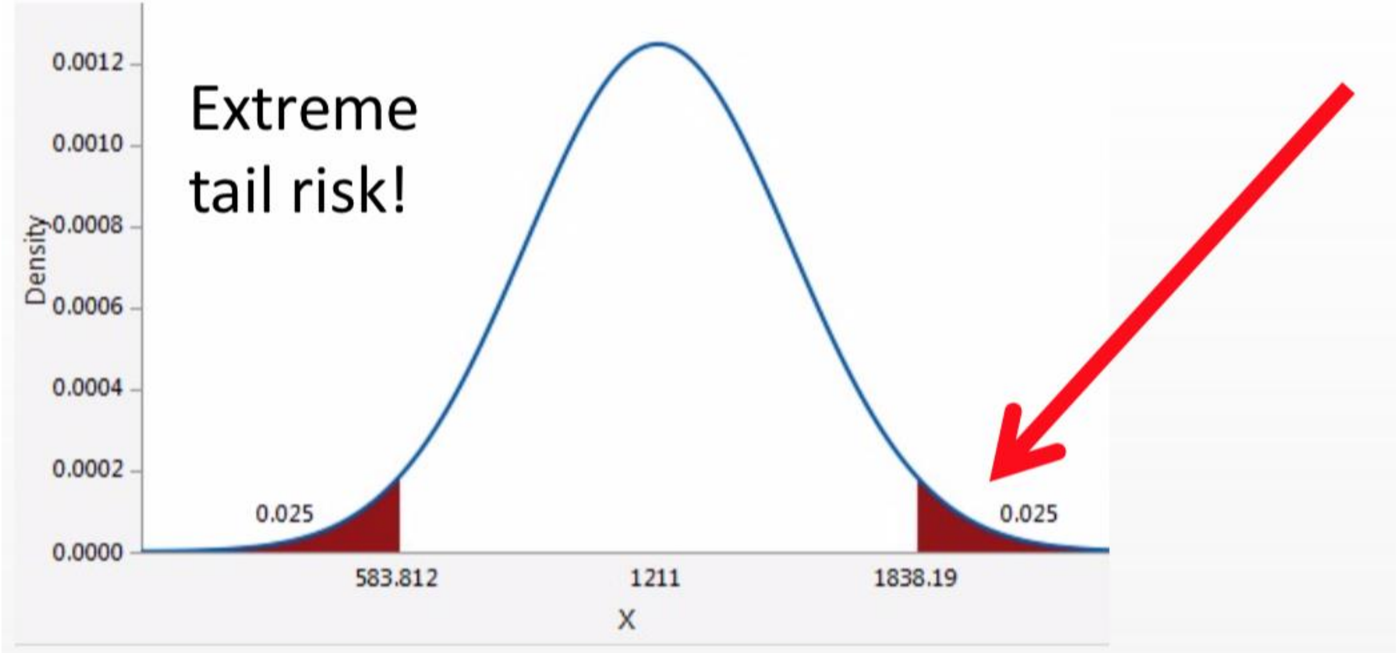


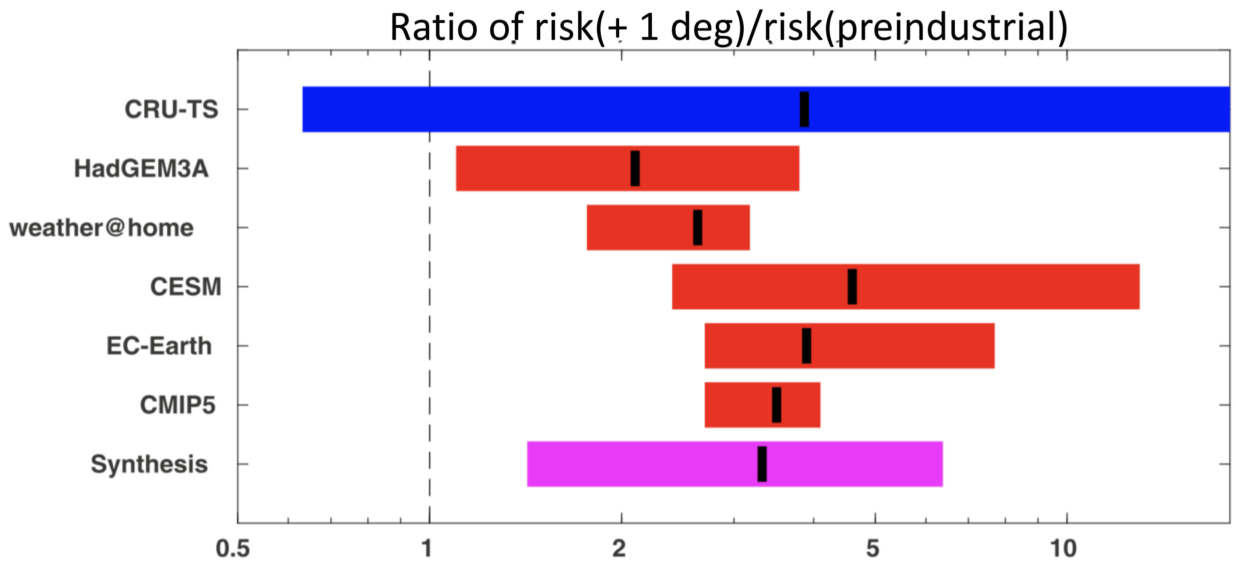
How do we study extreme climate event risk?



Climate models can be used to generate sufficiently large datasets (i.e., 100s to 1000s to 10,000s of years) to explore extreme event probabilities for different moment in times)

Did Anthropogenic Global Warming make it worse?

- 3-yr mean precipitation (observations, AGCM ensembles, GCM ensembles) fitted to a Gaussian or GEV whose parameters scale with temperature
- **1.4 to 6.4 times** more likely at +1 deg of GW



Otto et al., 2018

but..

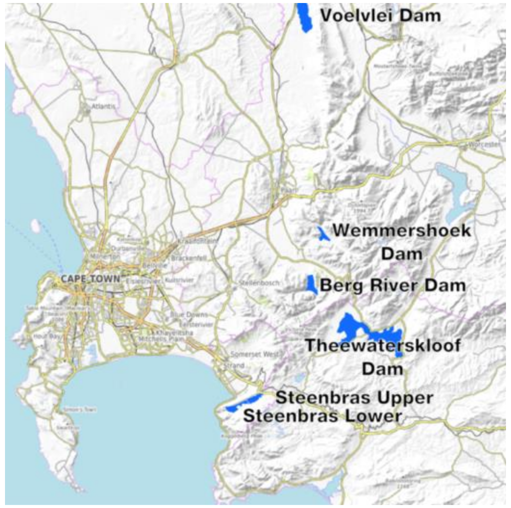
- Older generation models (e.g., CMIP3/5) have systematic biases in SH jet stream position (Curtis et al., 2020)
- Small extent of the SSA region & difficulty to get regional features (e.g., orography)
- Dynamical mechanisms ?

Other Large Ensemble experiments

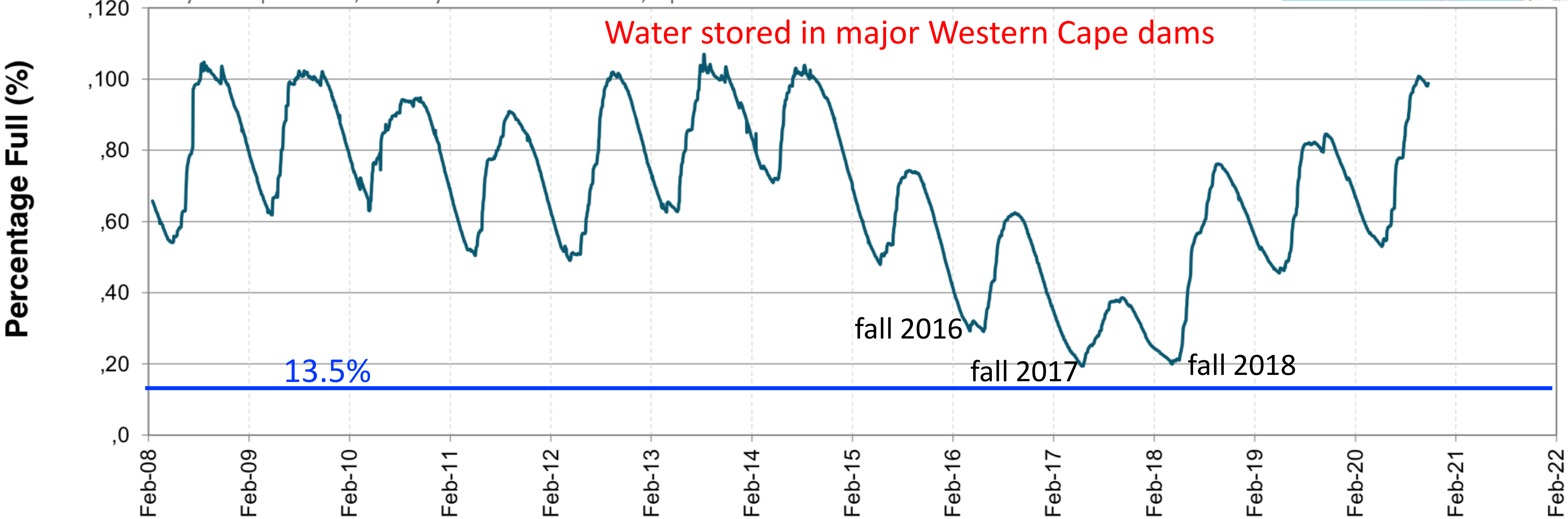
Experiment	Years	Members	Atm. res.	Description
SPEAR_LO CTRL	5000	1	$1^\circ \times 1^\circ$	Preindustrial (1850) forcing
SPEAR_LO NATURAL	1921-2100	30	$1^\circ \times 1^\circ$	Natural historical forcing before 2014; solar variability only after 2014.
SPEAR_LO ALLFORC8.5	1921-2100	30	$1^\circ \times 1^\circ$	All historical forcing before 2014; **SSP5-8.5** afterwards.
FLOR_FA CTRL	3500	1	$0.5^\circ \times 0.5^\circ$	Preindustrial (1860) forcing
FLOR_FA NATURAL	1941-2050	30	$0.5^\circ \times 0.5^\circ$	Natural historical forcing before 2005; solar variability only after 2005;
FLOR_FA ALLFORC4.5	1941-2050	30	$0.5^\circ \times 0.5^\circ$	All historical forcing before 2005; **RCP4.5** afterwards.
FLOR CTRL	2200	1	$0.5^\circ \times 0.5^\circ$	Preindustrial forcing (1860)
FLOR NATURAL	1921-2100	30	$0.5^\circ \times 0.5^\circ$	Natural historical forcing before 2005; solar variability only after 2005.
FLOR ALLFORC8.5	1921-2100	30	$0.5^\circ \times 0.5^\circ$	All historical forcing before 2005; **RCP8.5** afterwards.
CESM-LENS CTRL	1800	1	$1.3^\circ \times 0.9^\circ$	Preindustrial forcing
CESM-LENS ALLFORC8.5	1921-2100	40	$1.3^\circ \times 0.9^\circ$	All historical forcing before 2005; **RCP8.5** afterwards.
MPI-GE CTRL	2000	1	$1.9^\circ \times 1.9^\circ$	Preindustrial forcing (1850)
MPI-GE ALLFORC8.5	1850-2100	100	$1.9^\circ \times 1.9^\circ$	All historical forcing before 2005; **RCP8.5** afterwards.
MPI-GE ALLFORC4.5	1850-2100	100	$1.9^\circ \times 1.9^\circ$	Same as MPI-ESM1 ALLFORC8.5 before 2005; **RCP4.5** afterwards.
MPI-GE ALLFORC2.6	1850-2100	100	$1.9^\circ \times 1.9^\circ$	Same as MPI-ESM1 ALLFORC8.5 before 2005; **RCP2.6** afterwards.

The Cape Town "Day Zero" hydrological drought

- Dams supplying Cape Town ≈ **20% in austral fall 2017/2018**
- If below **13.5% "Day Zero"**: disconnect much of the municipal water supplies



City of Cape Town, weekly water dashboard, updated Nov 9



Extreme events' attribution

nature

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nature › letters › article

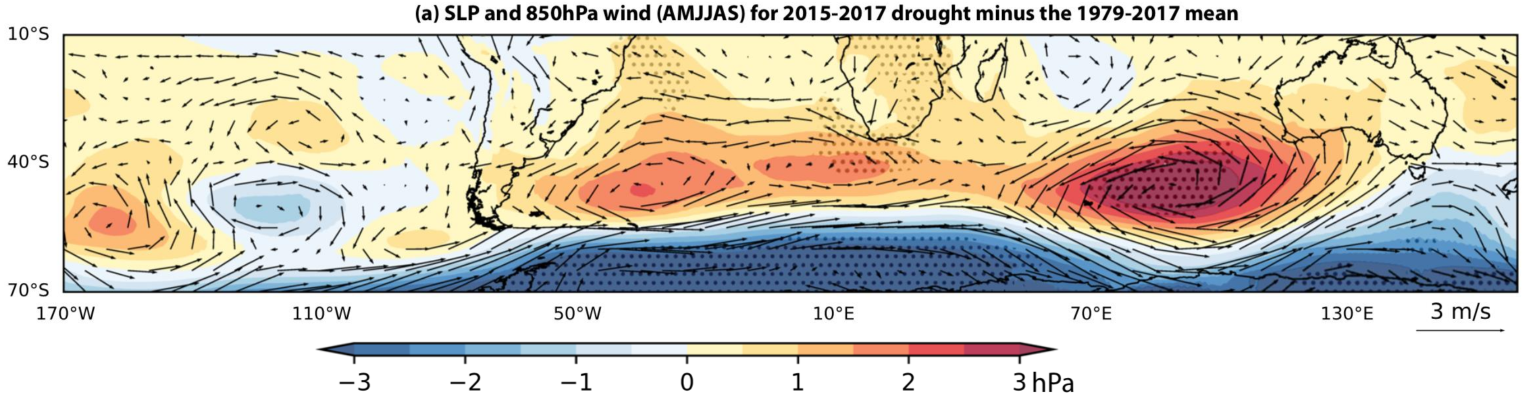
Published: 02 December 2004

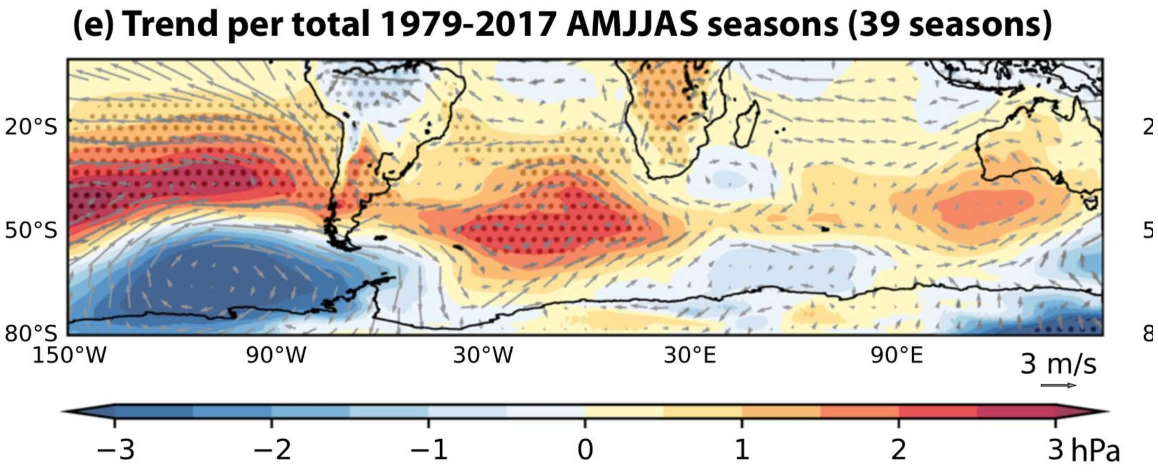
Human contribution to the European heatwave of 2003

Peter A. Stott, D. A. Stone & M. R. Allen

Nature **432**, 610–614 (2004) | Cite this article

Link to large scale circulation shifts?

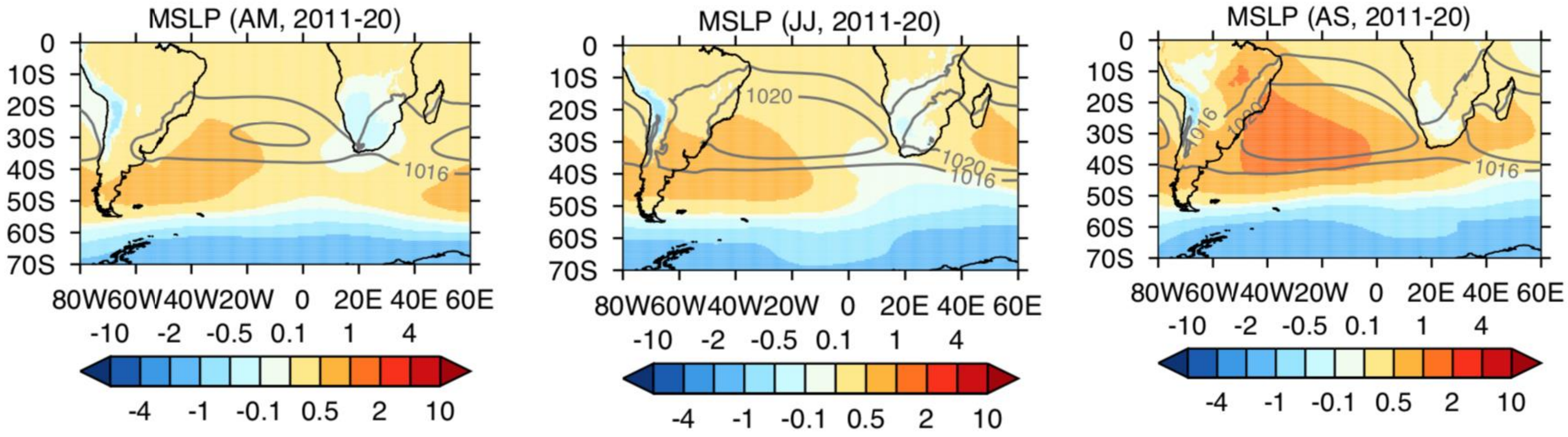




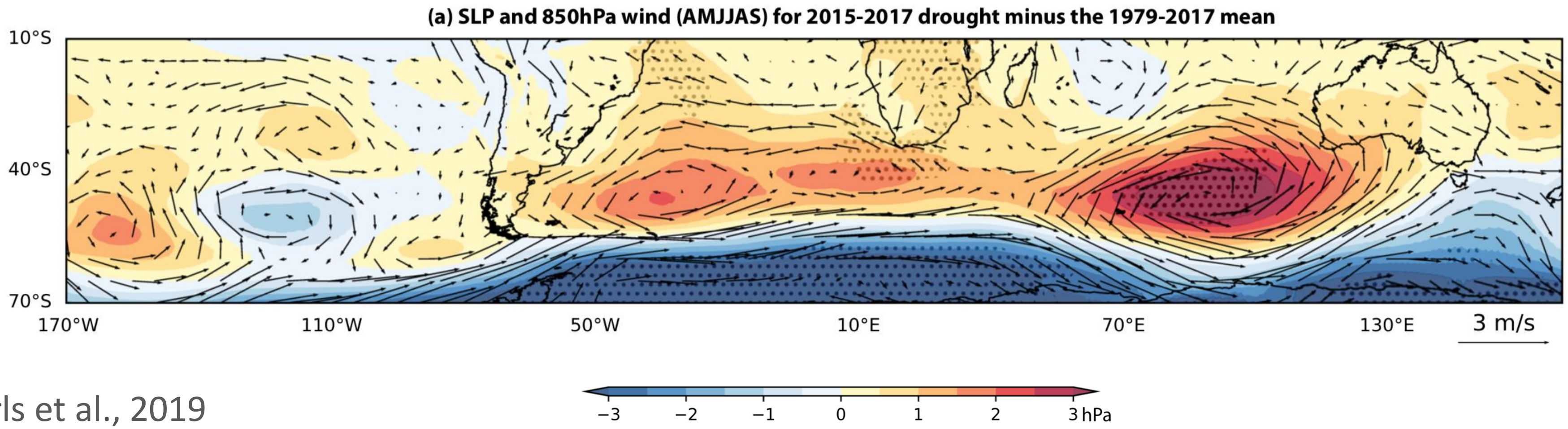
- **Higher sea-level pressure in 2015-17** invoked as the cause of a southward shift of the moisture corridors, contributing to winter rainfall (Sousa et al., 2018).
- Burls et al. (2019): no significant regional trends over the **last 40 y** in the number of cold fronts making landfall over SSA; shorter duration of rainfall events due to larger sea-level pressure during postfrontal days.
- Hadley Cell expansion? For the SH, indication forced signal in Hadley Cell emerging around 2020 (Amaya et al., 2018; Grise et al., 2019). If CO_2 keeps increasing, not a matter of if, but of **when**. But how **seasonally**?

Burls et al., 2019

Decadal MSLP forced anomalies



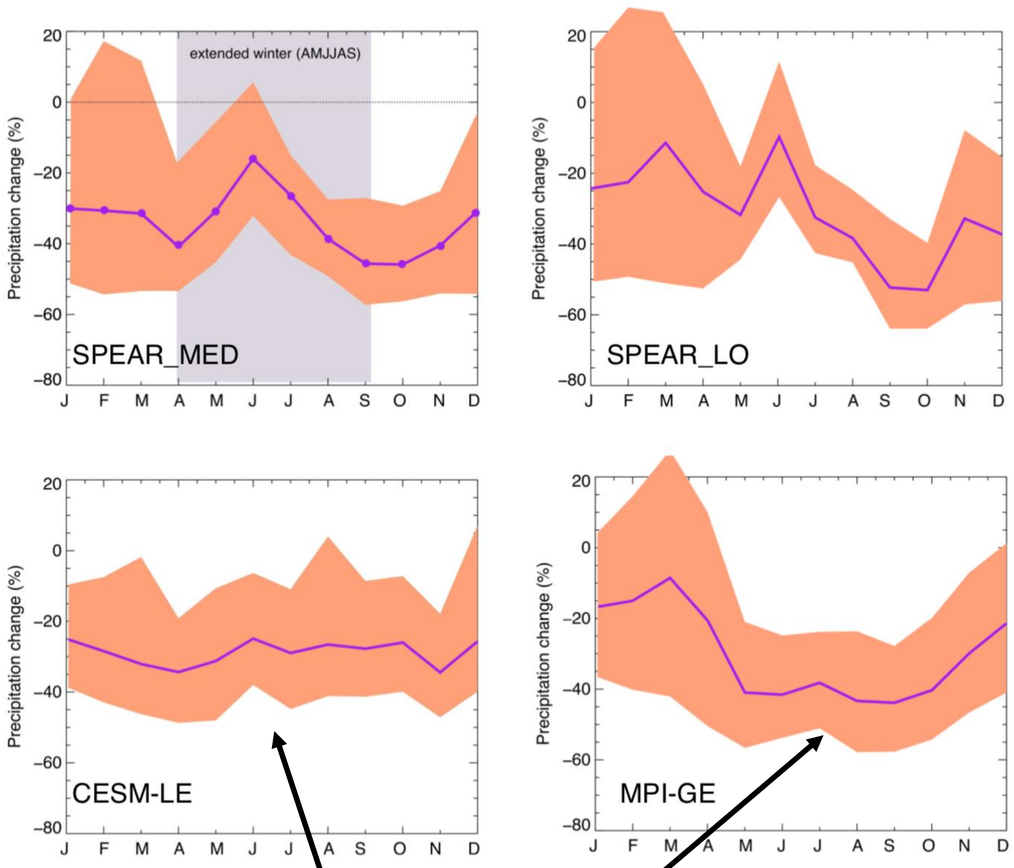
Similarities, but **challenging to discern forced signal** in the observational record (Staten et al., 2018)



Burls et al., 2019

Other Large Ensembles?

Fraction of WRI reduction (2071-2100 vs 1921-1970)

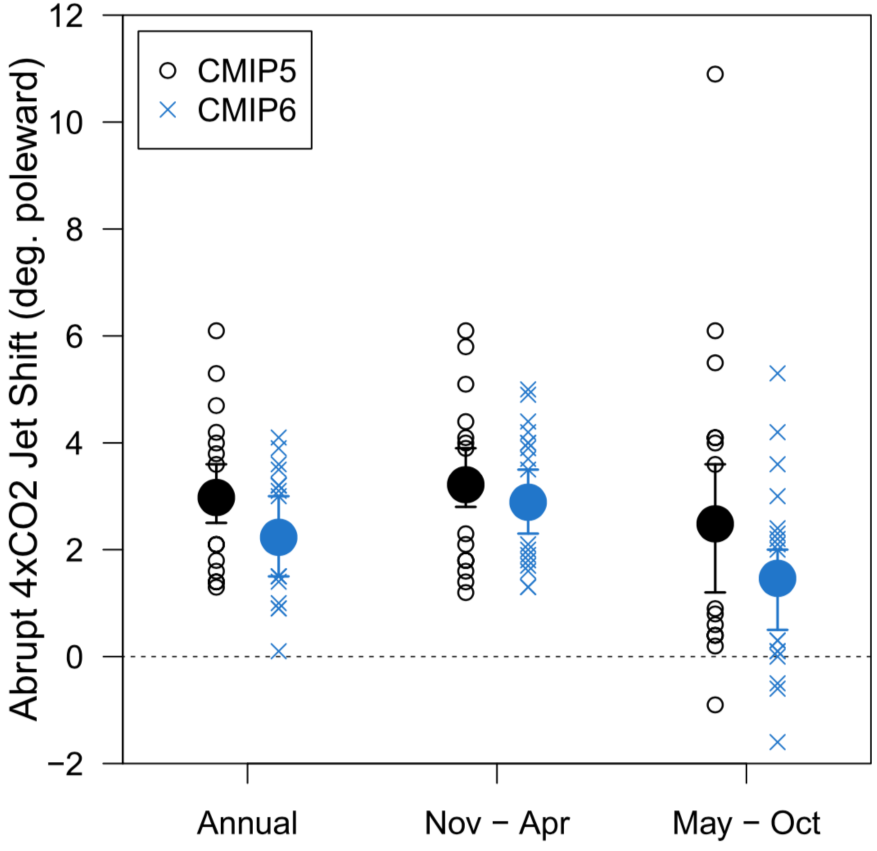


CMIP6 family

CMIP3/5 family

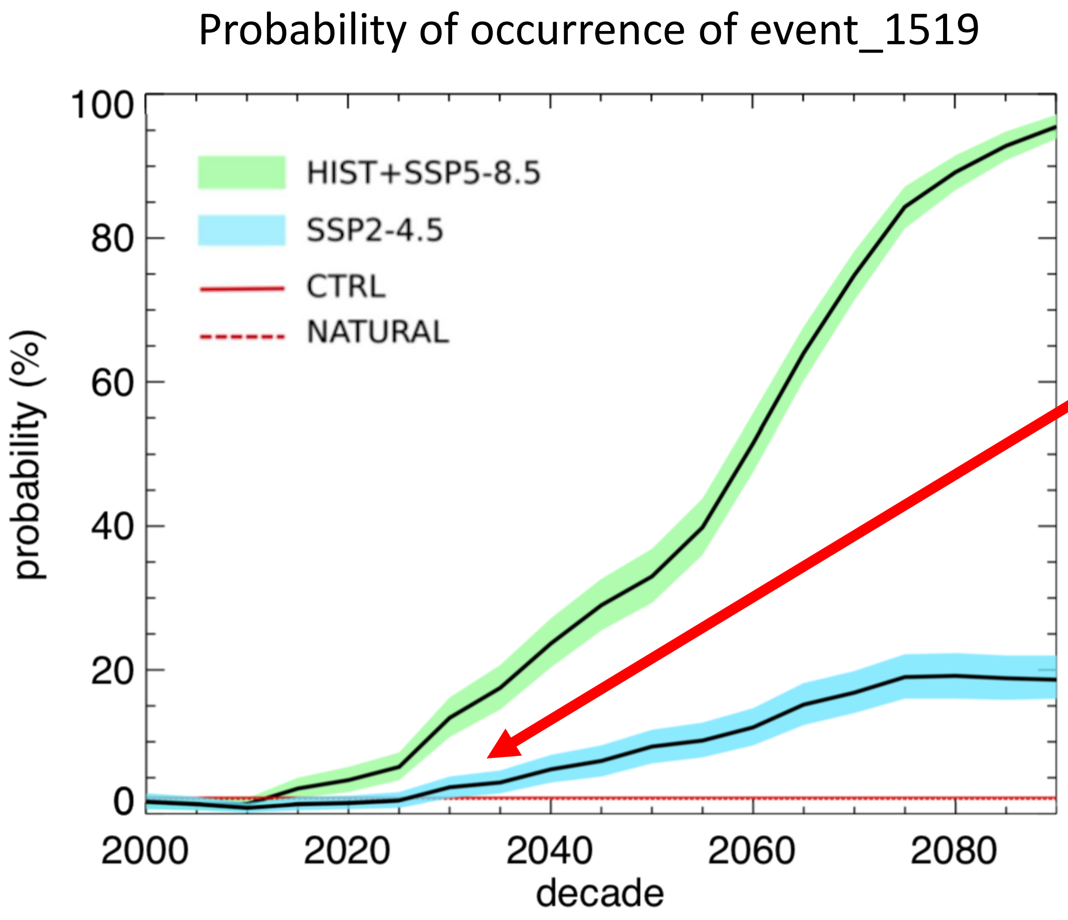
Forced signal less seasonal

The shift is substantially muted in CMIP6 during the austral winter compared with previous generation of GCMs

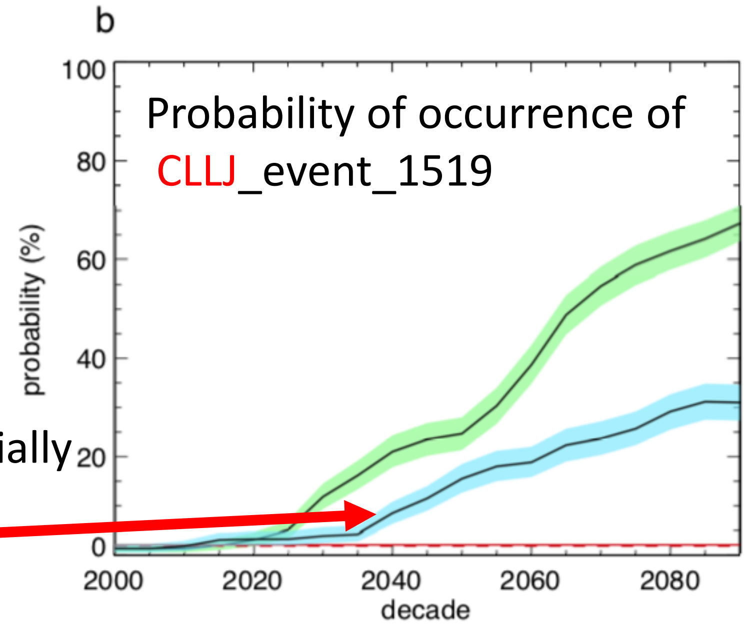


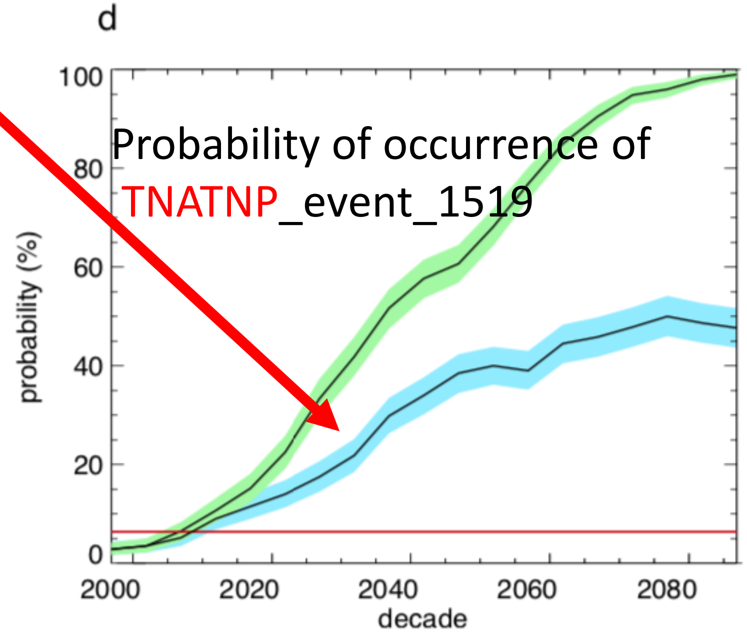
Curtis et al., 2020

Future?

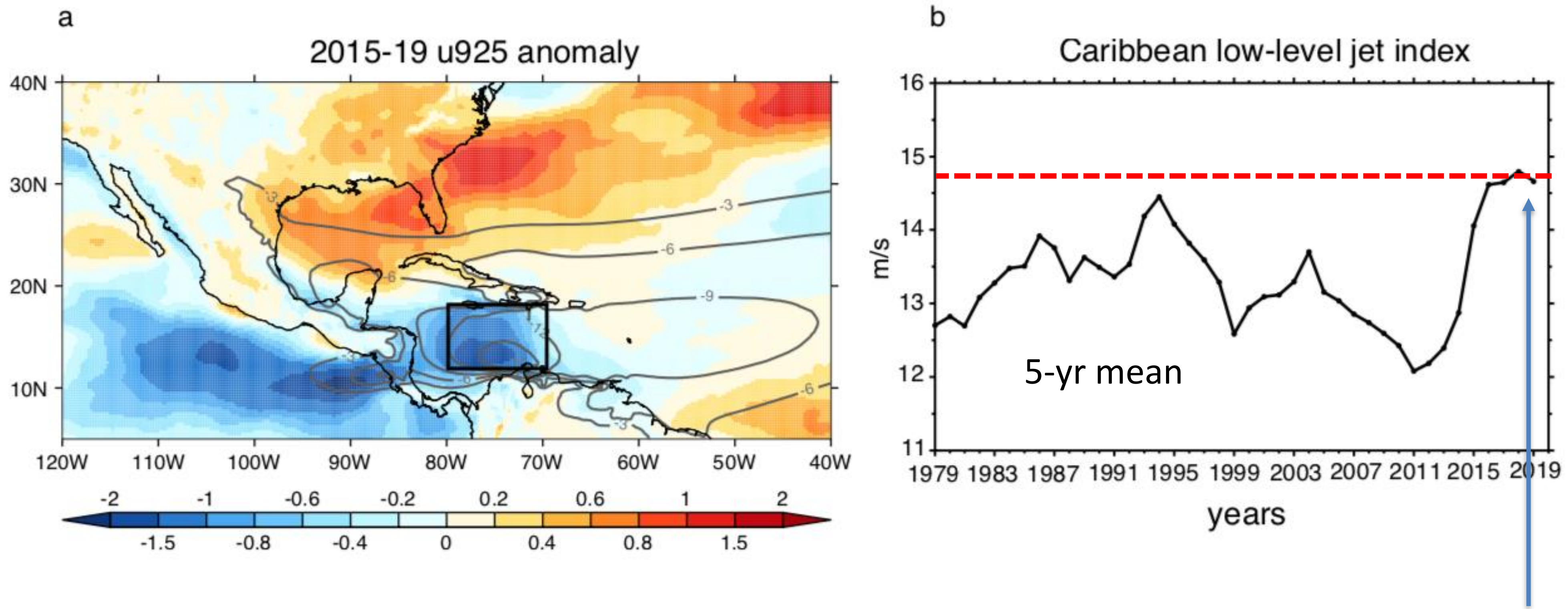


differing substantially after 2030-40





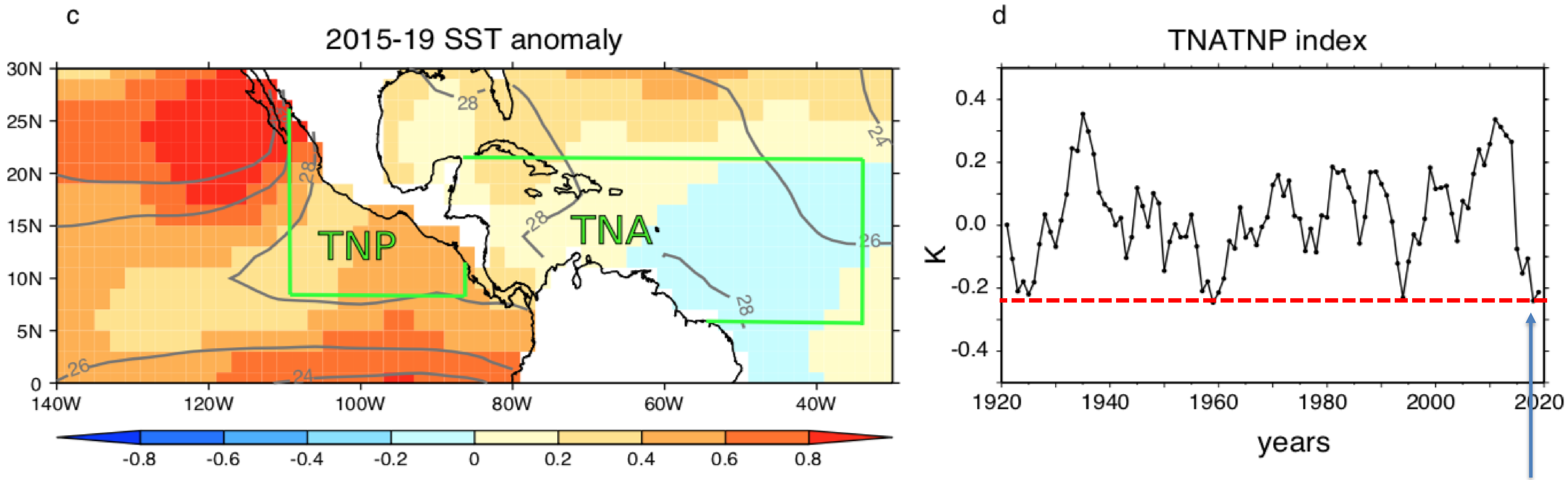
Large scale anomalies: the Caribbean Low-Level Jet



Strong, persistent CLLJ

The stronger the CLLJ, the drier CA (CLLJ index: Wang et al., 2007, JCLIM)

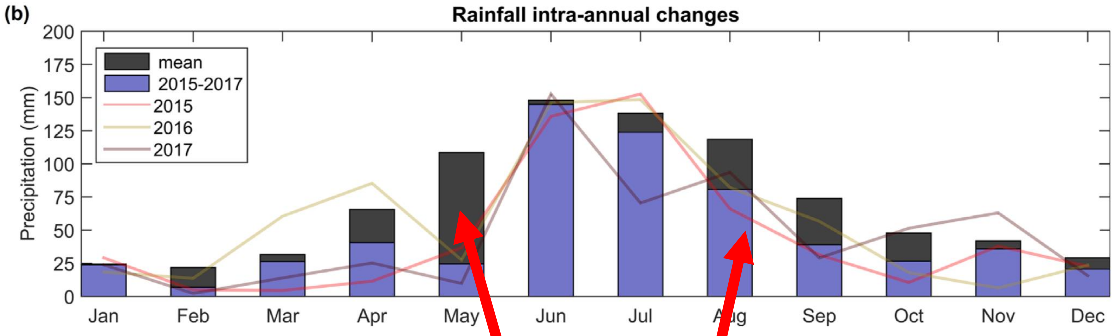
Large scale anomalies: the Atlantic-Pacific SST difference



Warmer TNP and colder TNA→ drier over Central America
(Taylor et al., 2002; Fuentes-Franco et al., 2015)

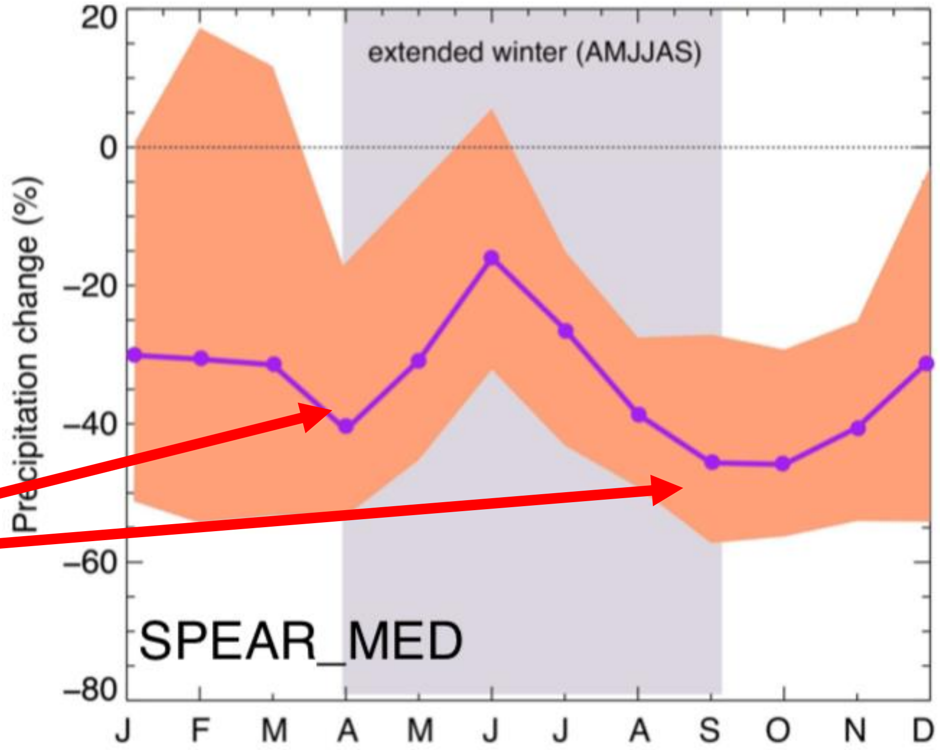
Persistent –ve TNATNP index
(TNA colder than TNP)

Seasonality of the anomaly/change



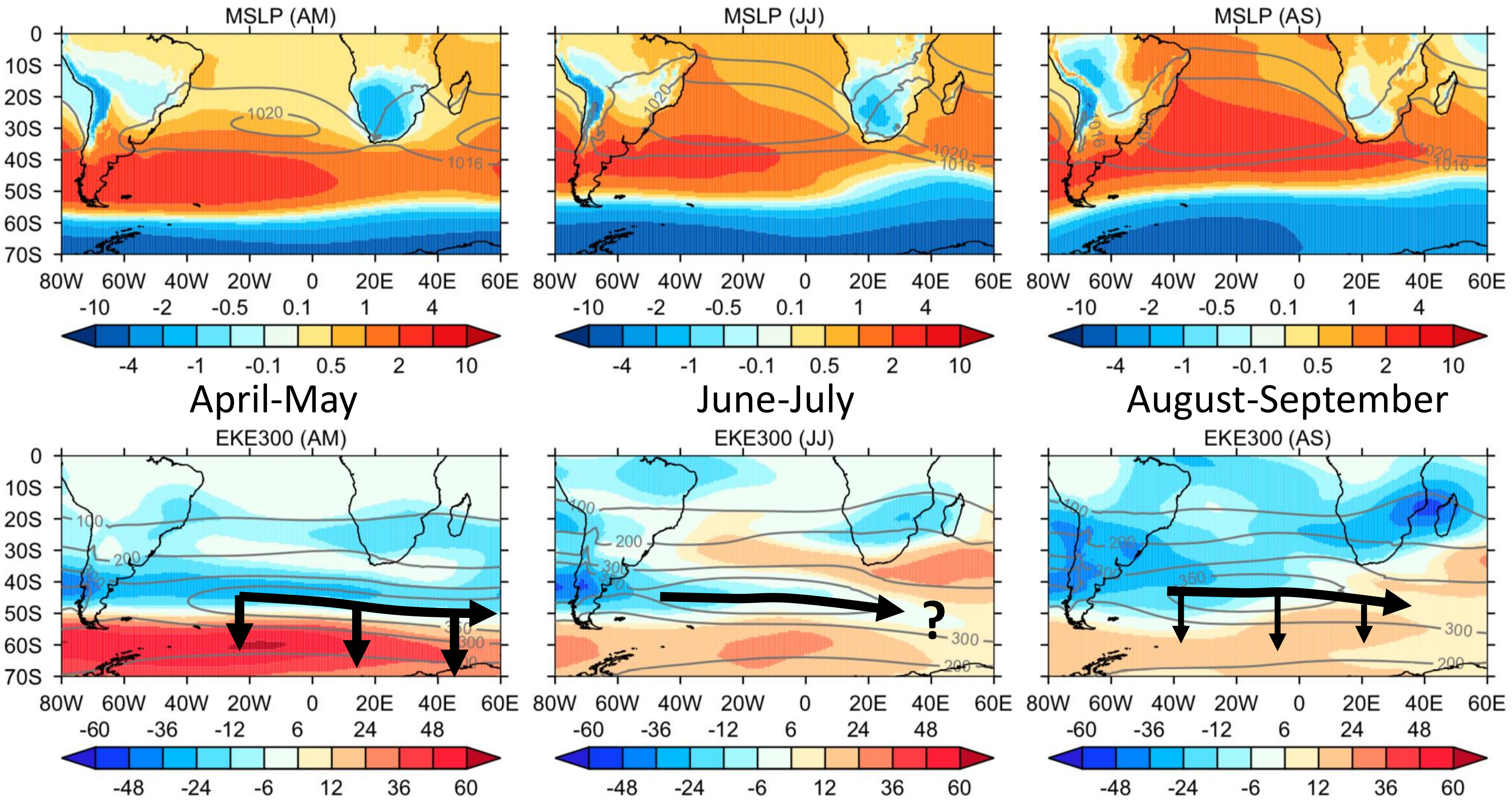
Sousa et al., 2018

End-of-21st-century WRI anomaly



Stronger % reduction during the shoulder seasons

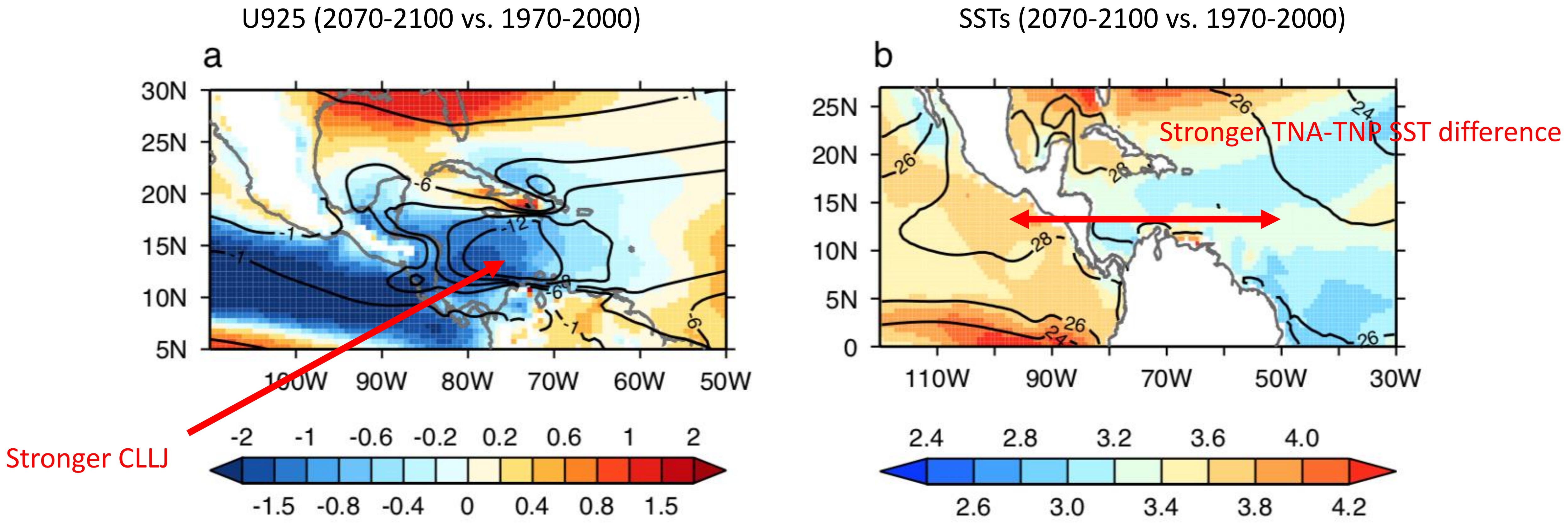
Poleward shift of the SH jet stream?



Ensemble mean difference in MSLP and EKE300 (**2070-2100 vs.1921-2000**)

The most evident forced signals in April-March and August–September (AS)

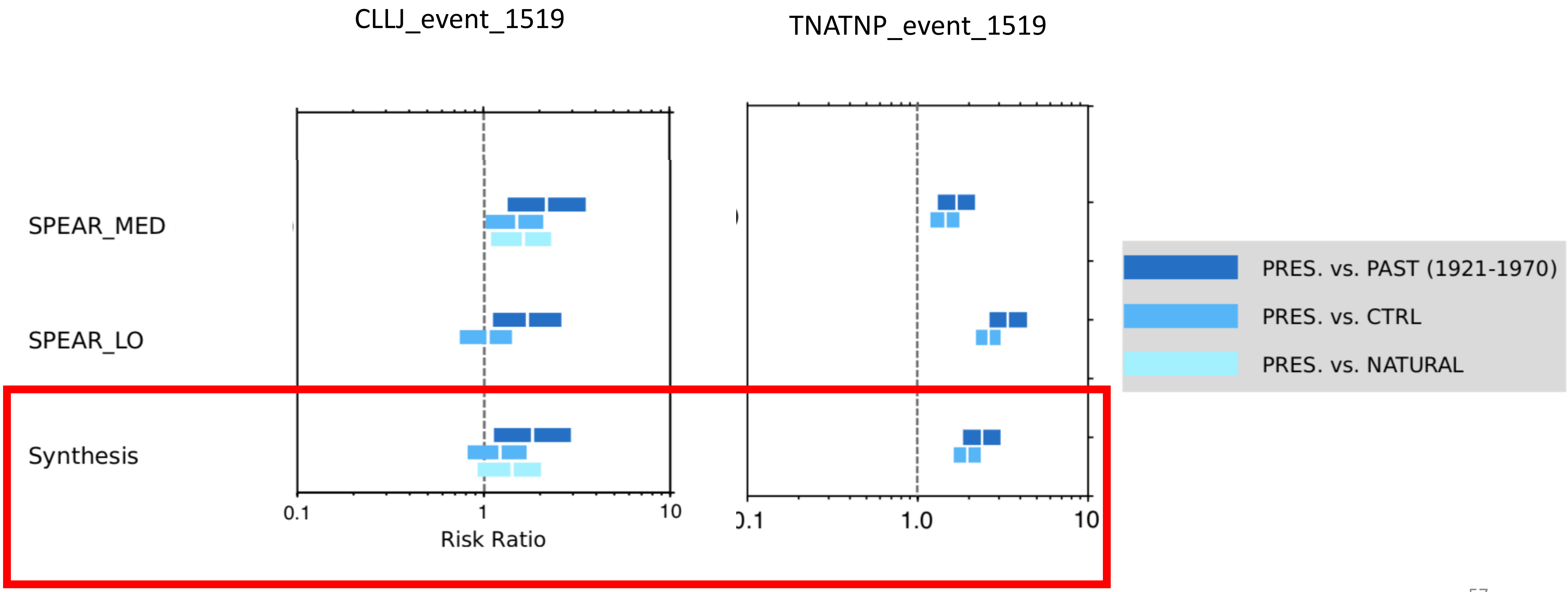
CLLJ and TNATNP projections (SPEAR_MED, SSP5-8.5)



Already known and discussed (e.g., Rauscher et al.,2008, 2011; Fuentes-Franco et al., 2015)

Are these configurations already more likely because of ACC?

Changes in CLLJ and TNATNP attributable?

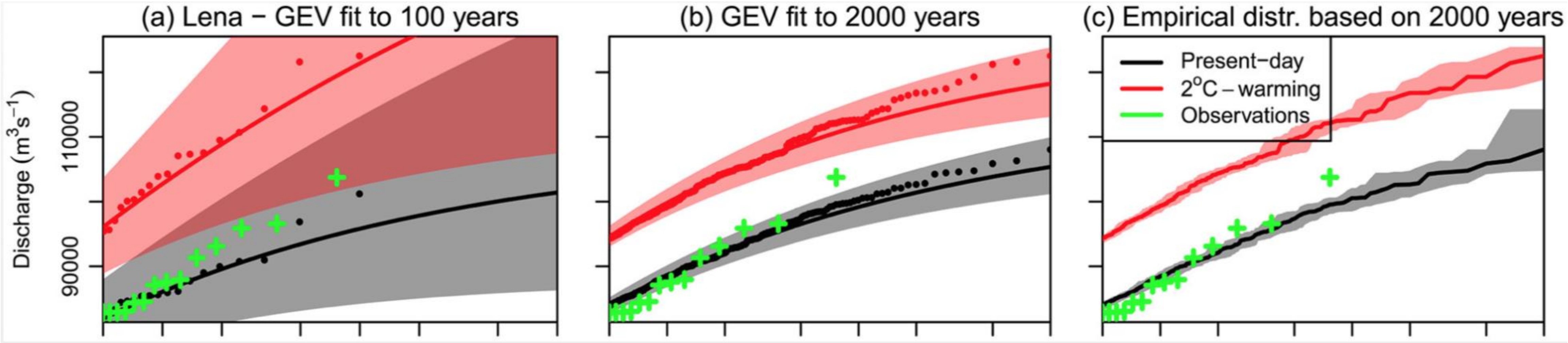


How do we study extreme climate event risk?

- **Observations alone:** using observations alone can lead to high uncertainty for historic events (LEFT).
  - observations have limited records
  - statistical methods fill in gaps to create uncertainty range

- **Climate models+Statistical methods to estimate extreme values:** increased data (2000yrs) from climate models can be used to reduce the uncertainty (CENTRE)

- **Climate models+Direct calculations of probabilities:** with a sufficient number of years, probabilities can be calculated directly, reducing uncertainty added by statistical methods (RIGHT)

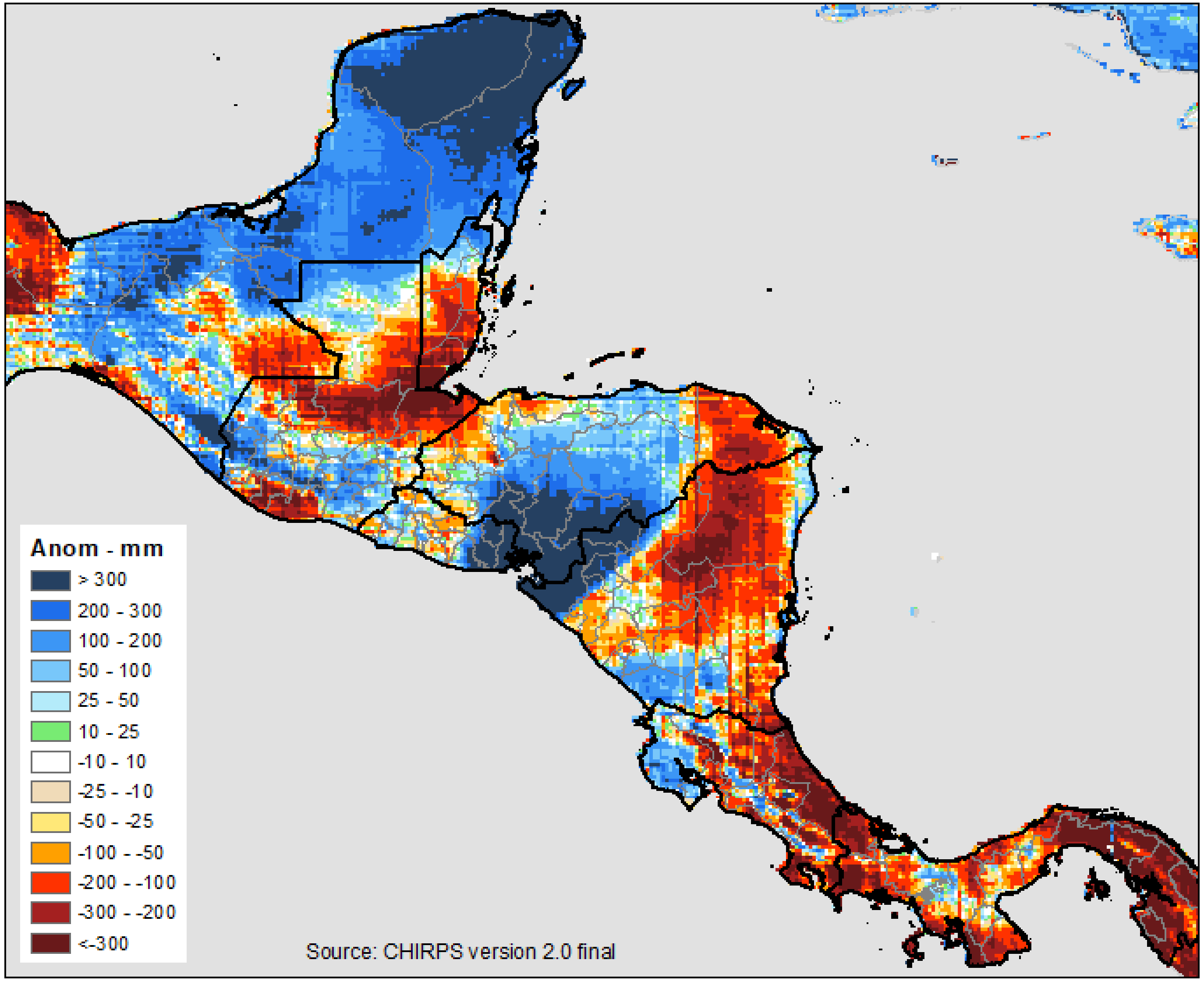


Van der Wiel et al., 2019, GRL

Seasonal Rainfall Accumulation Anomaly by pentad

2020 season May - Aug

(May pentad 1 thru Aug pentad 6) - Average (1981-2010)

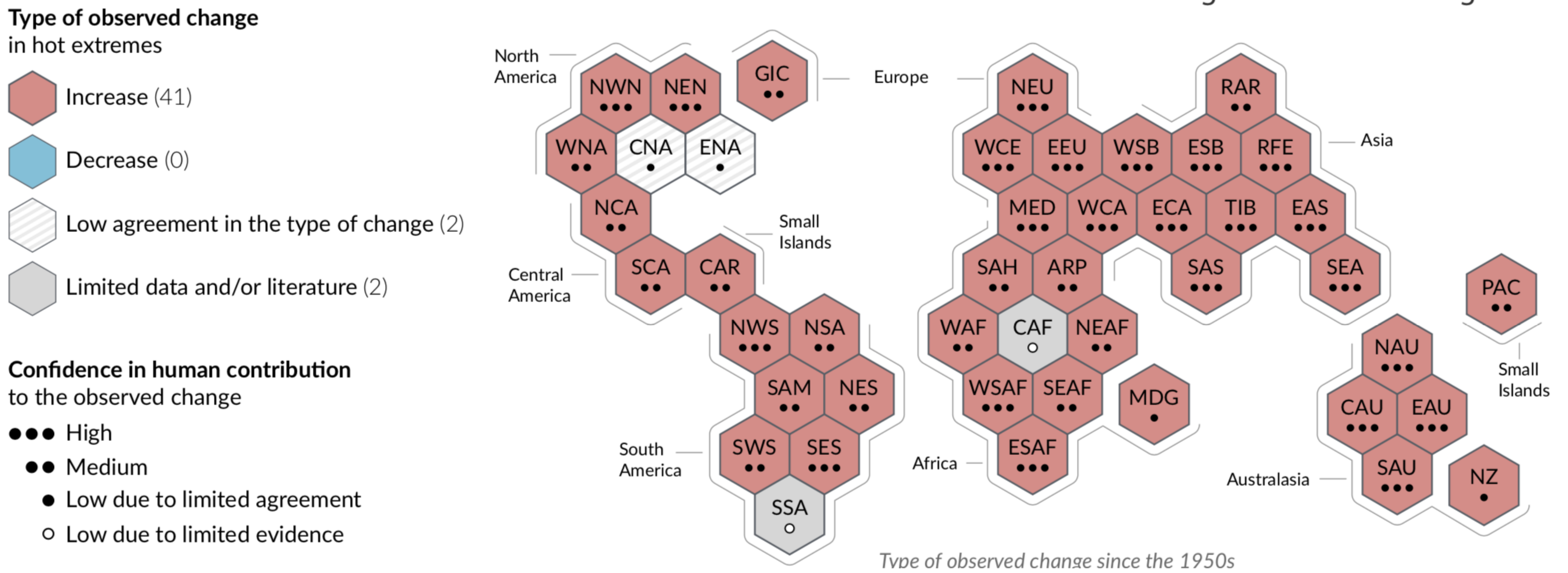


Map produced by USGS/EROS

Weather and climatic extremes: present and future

Climate change is already affecting every inhabited region across the globe with human influence contributing to many observed changes in weather and climate extremes

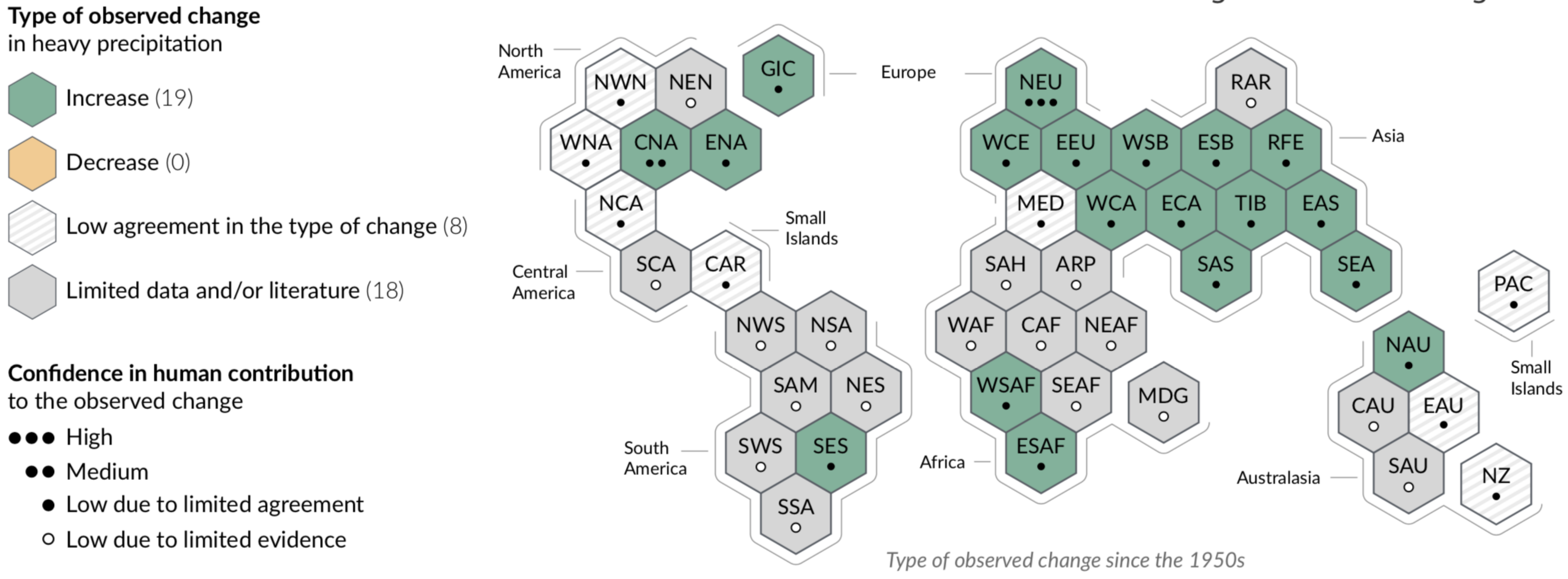
a) Synthesis of assessment of observed change in **hot extremes** and confidence in human contribution to the observed changes in the world's regions



Weather and climatic extremes: present and future

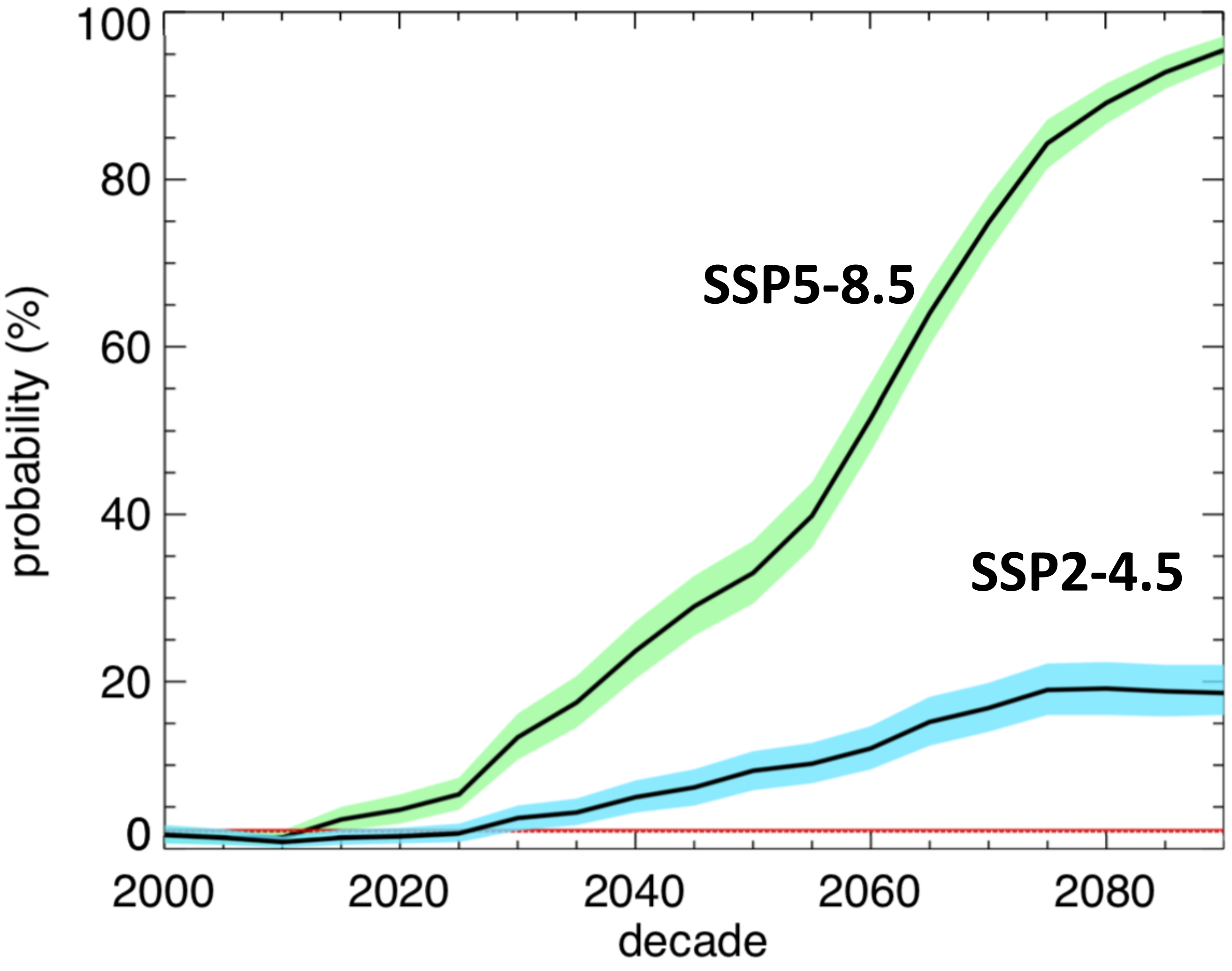
Climate change is already affecting every inhabited region across the globe with human influence contributing to many observed changes in weather and climate extremes

b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions



AR6, Summary for policymakers, IPCC, 2021

Future?

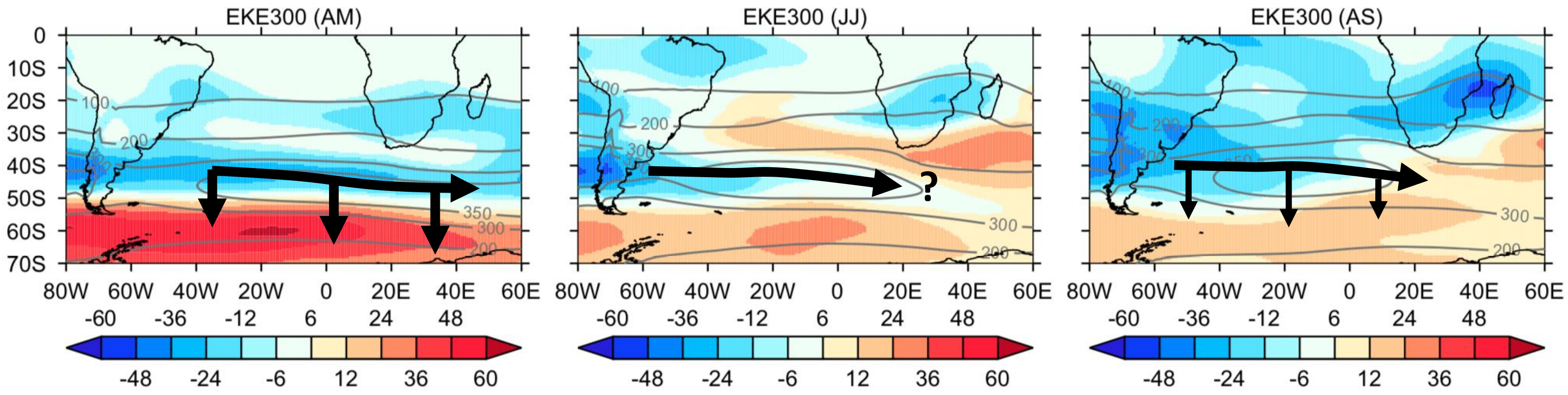

100
80
60
40
20
0
probability (%)
2000
2020
2040
2060
2080
decade
SSP5-8.5
SSP2-4.5

1. To what extent did anthropogenic global warming make 2015-19 Central America rainfall deficit more likely (**event attribution**)?

2. How will the probability of occurrence of another similar or worse meteorological drought change in the **coming decades**?

Conclusions (I): “Day Zero” drought

1. The PDF has **already shifted**: AGW made it ≈**5.5 times more likely (CI [4.5-8])**. Further constrain the risk ratio of SSA drought at and above the original [1.4, 6.4] by Otto et al. (2018)..
2. RR ~110 (30) by the end of 21st century in SSP5-8.5 (SSP2-4.5). RR>80 in any high emiss. scenarios, >30 in RCP4.5 (MPI), ~12 in RCP2.6 (MPI)
3. Shift due to increasing MSLP and southward storm track shift: regional Hadley cell expansion? Robust indication for late fall/early winter and spring.
4. 2015-17 conditions may be a glimpse of what the future will look like in SSA

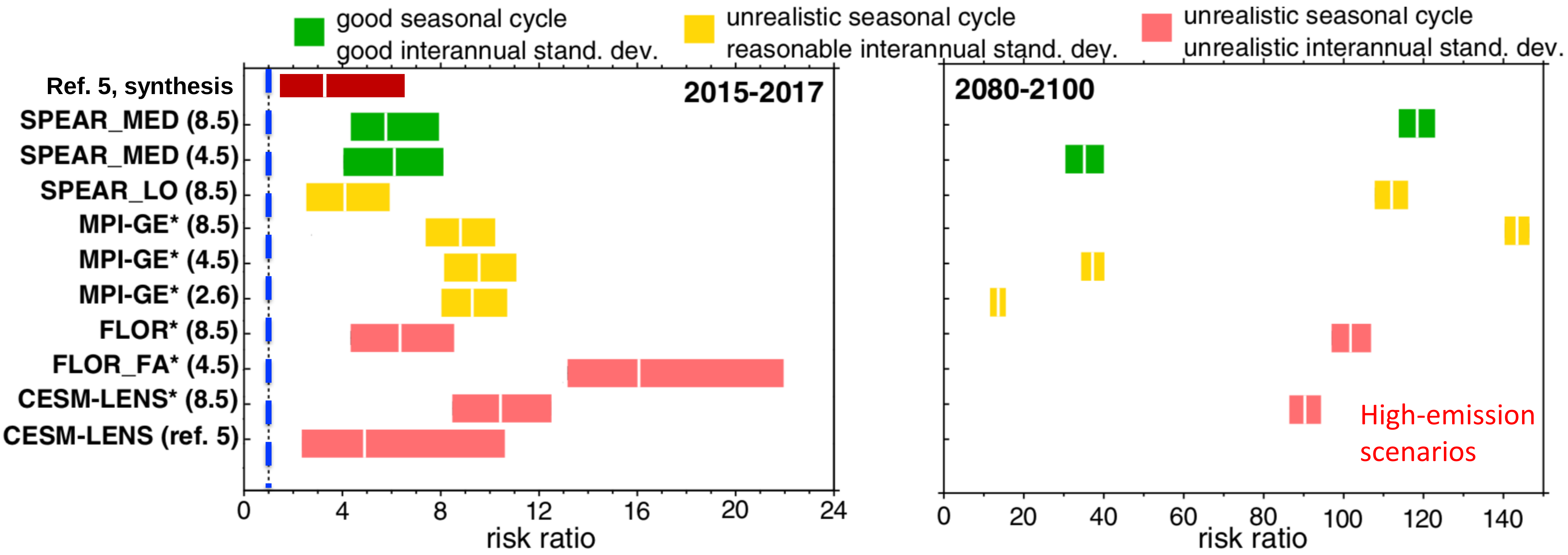


Conclusions (II): Central American drought

- Convincing evidence that the 2015-19 rainfall deficit has been made more likely by ACC by a factor 4

- % of similar or worse megadrought increasing rapidly without actions to reduce GHGs

Risk ratios



Ref. 5: Otto et al., 2019

Conclusions (I): “Day Zero” drought

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