# Jetstream dynamics behind boreal summer hot-dry extremes: Sources of S2S predictability and long-term climate risks

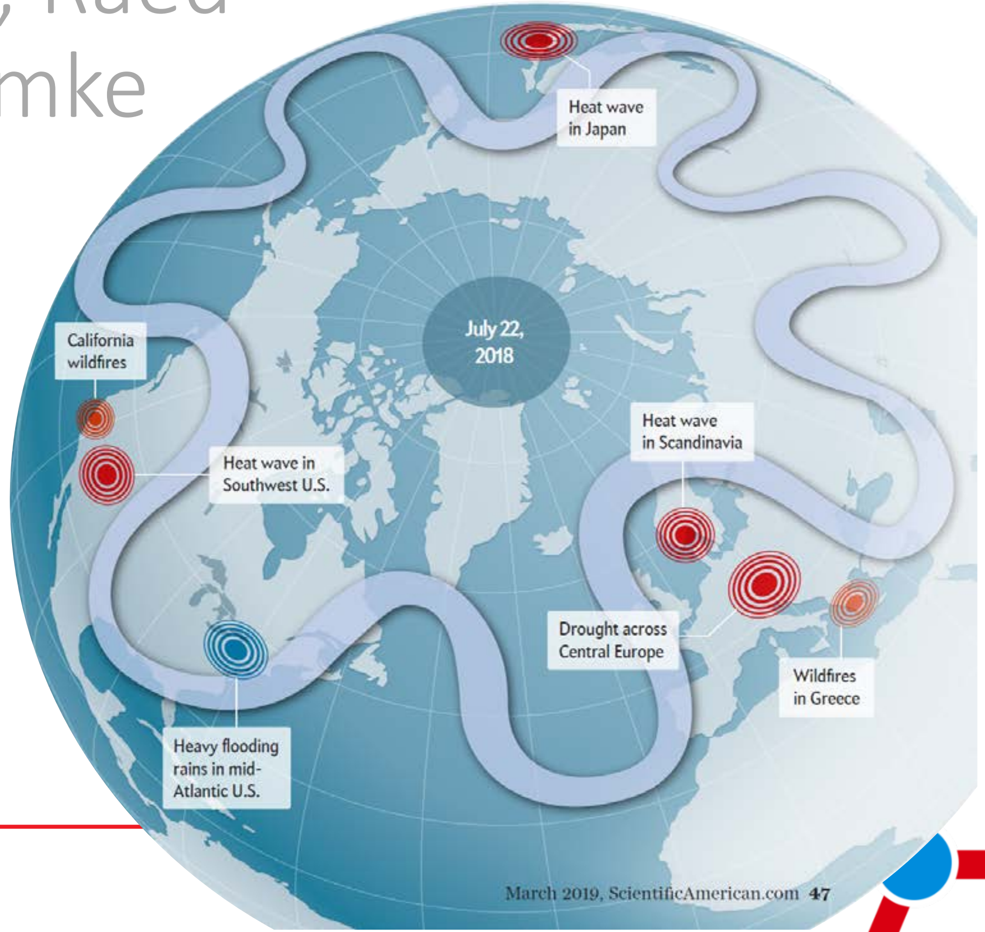
Dim Coumou, Efi Rousi, Giorgia di Capua, Chiem v Straaten, Sem Vijverberg, Raed Hamed, Kai Kornhuber, Rei Chemke

CAFÉ Final Conference,
Barcelona, 27-29 Sept 2022

@DimCoumou

Koninklijk Nederlands Meteorologisch Instituut
*Ministerie van Infrastructuur en Milieu*

VU VRIJE UNIVERSITEIT AMSTERDAM




CLIMATE EXTREMES

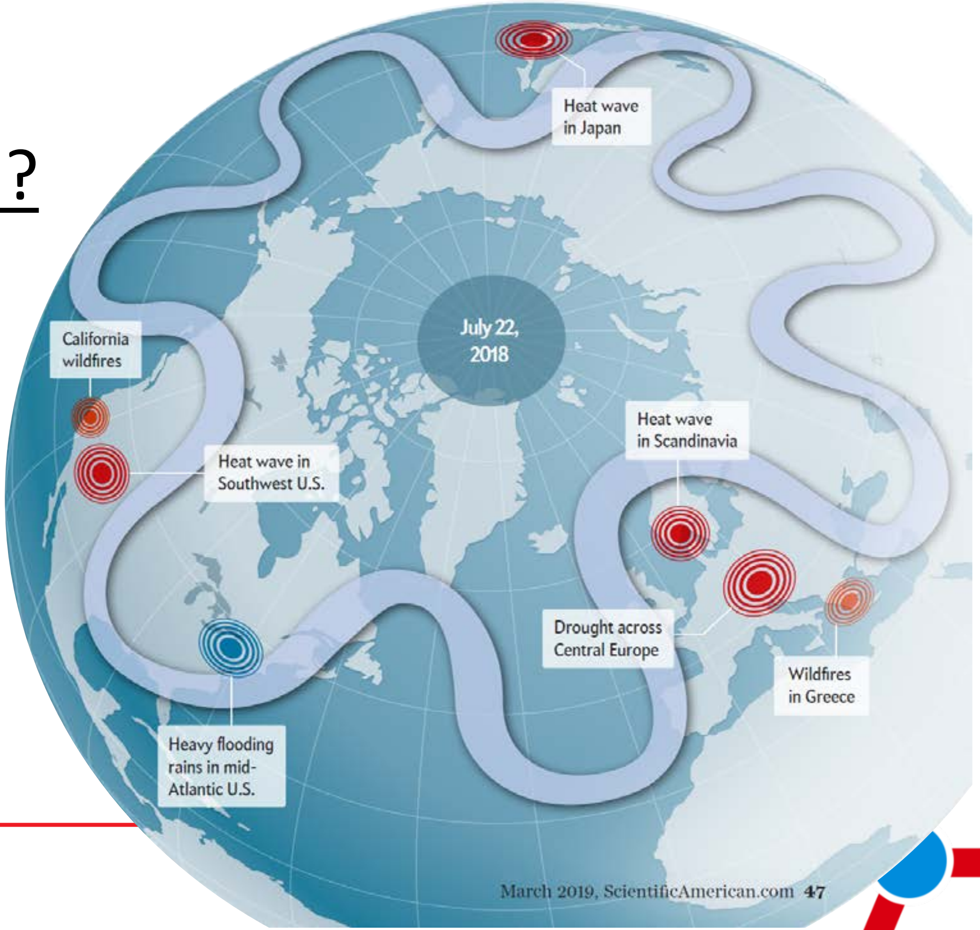
# Outline of this talk

1. Drivers of CGWT on S2S timescales

- Insights from climate models
- Insights from Explainable AI
- Insights from Causal Discovery Algorithms

2. How does AGW affect boreal summer circulation?

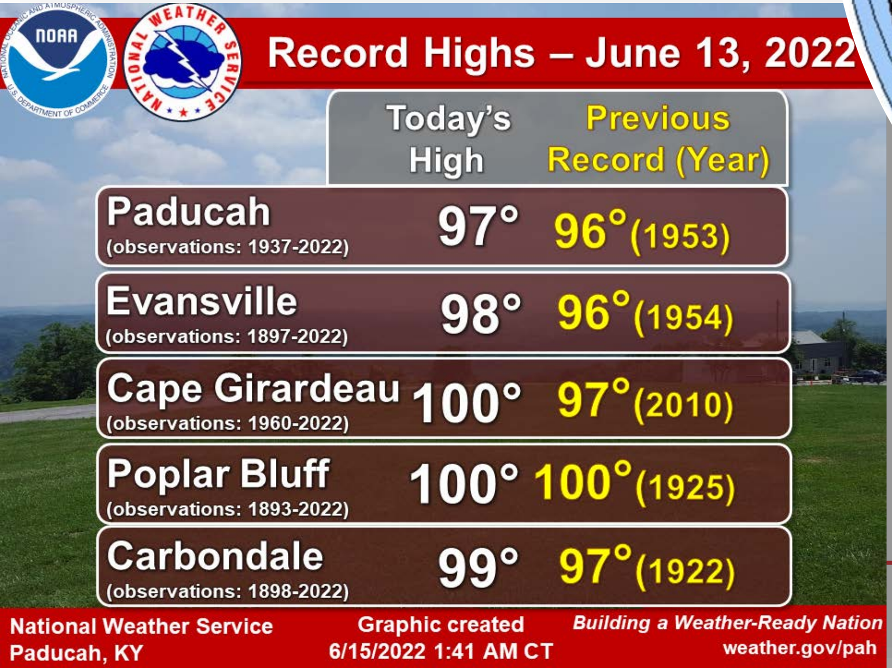
- Over last 40 years circulation has weakened
- This weakening is also seen in climate models: Is it attributable?
- Double jets & European heat waves

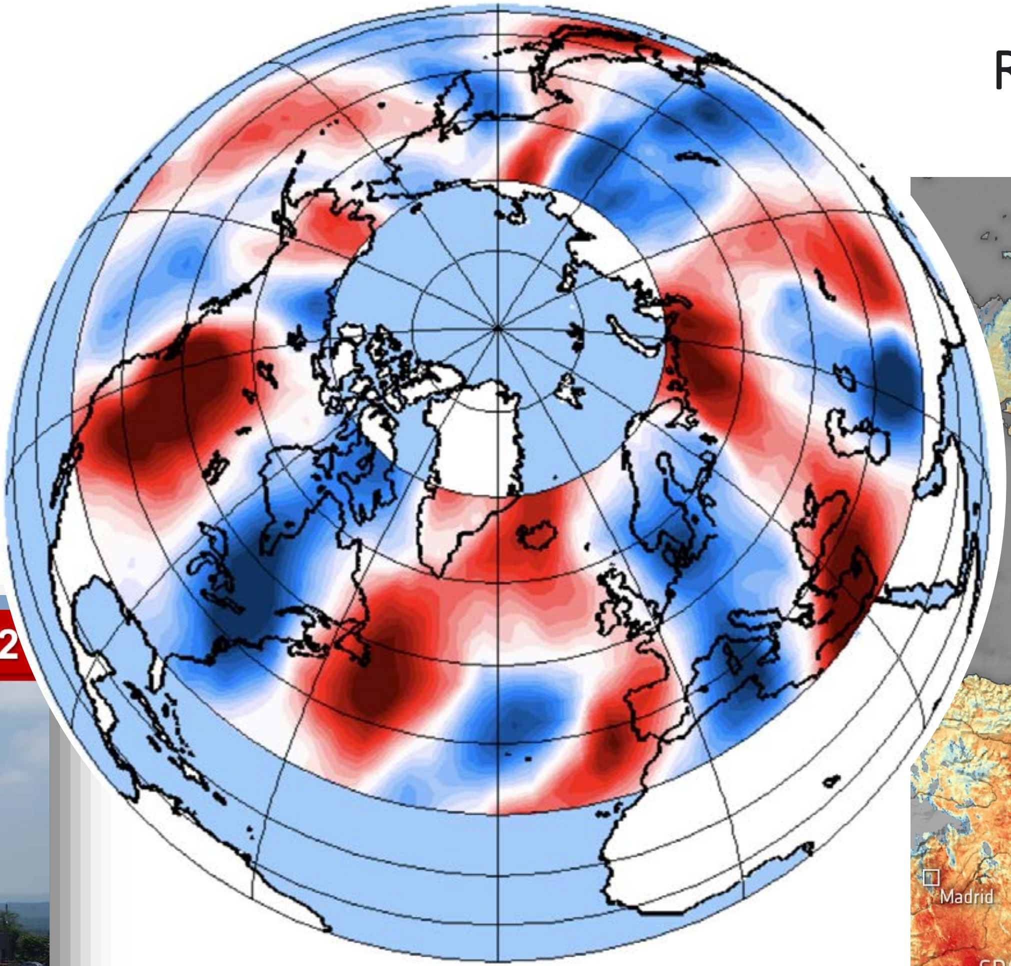



CLIMATE EXTREMES

# 2022 summer concurrent heat waves, wave-7 in June

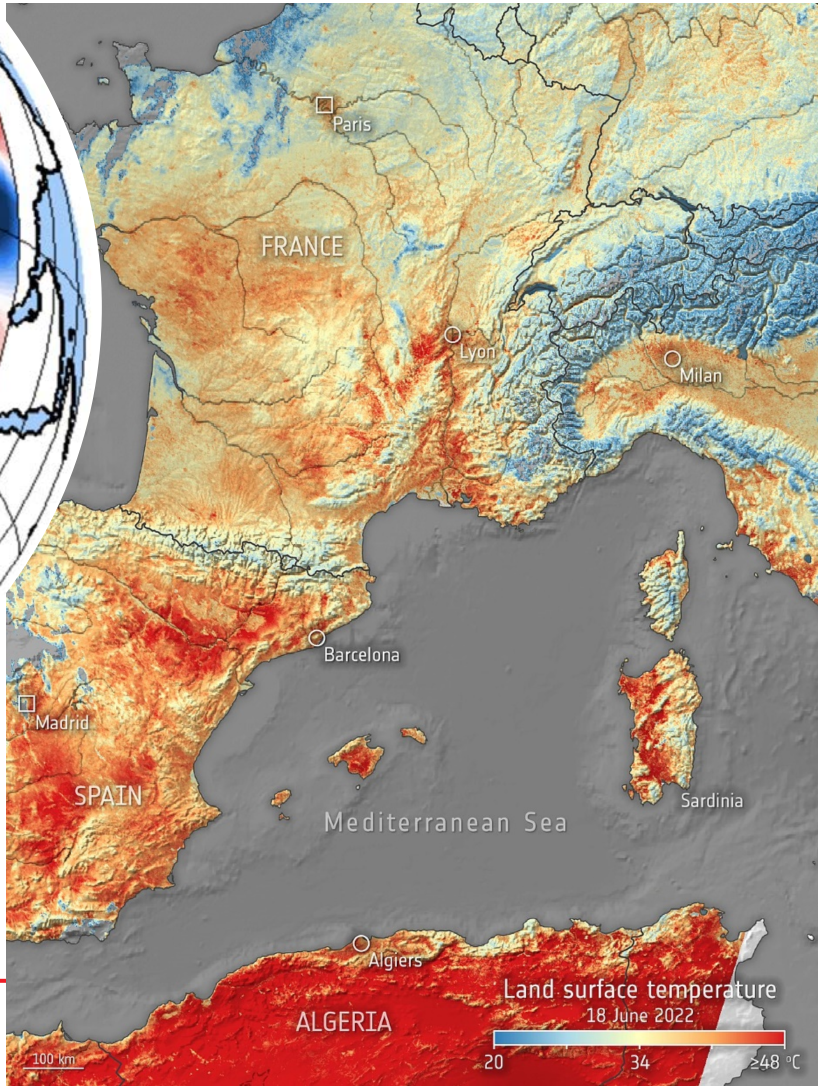
Historic heat wave affected the Midwestern United State



V-wind
(5-20 June 2022)

Record heat in western Europe
June 18




climateextremes.eu

# 2010 Food prices

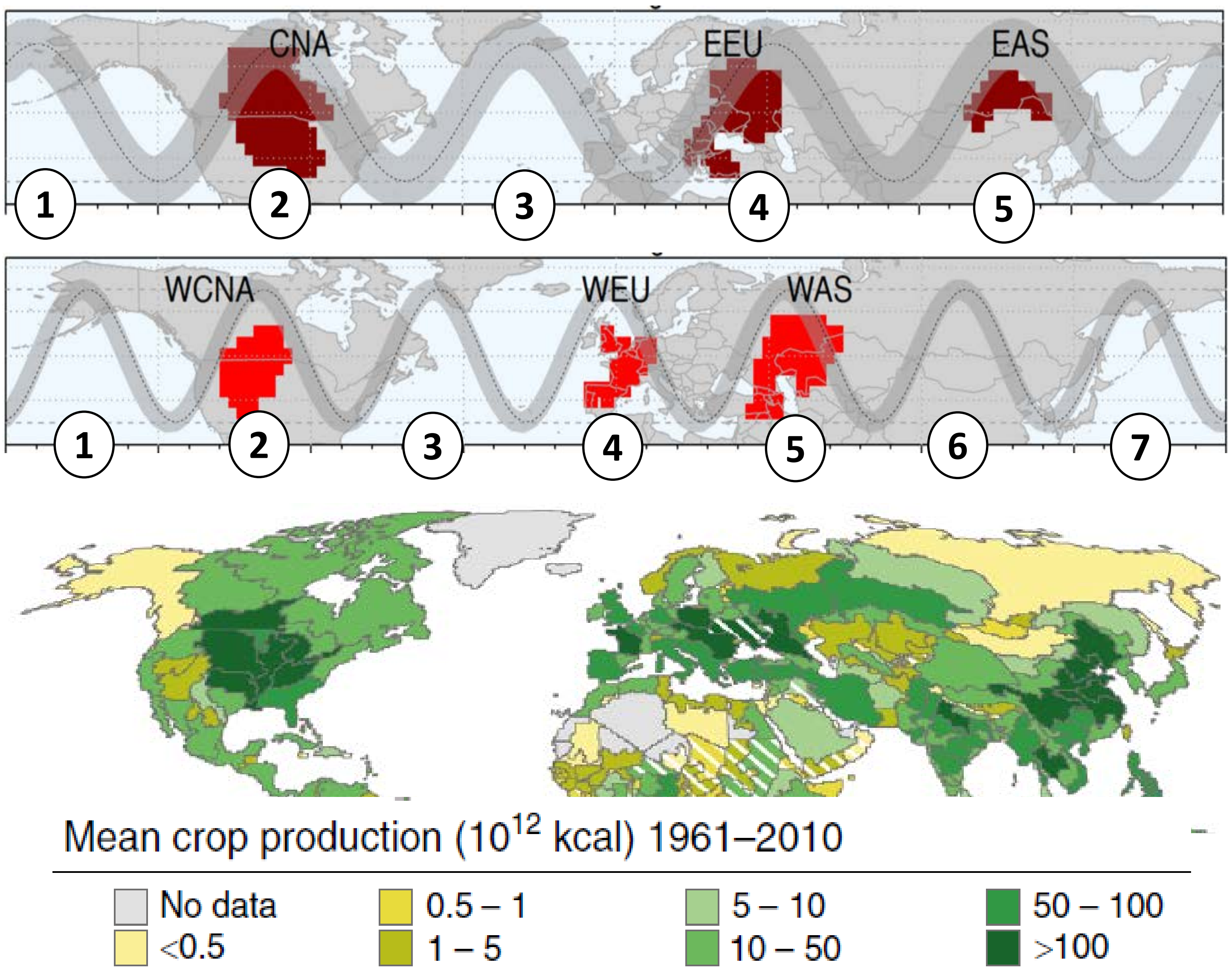
In summer, wave 5 and 7 can phase-lock causing hot-dry extremes in important breadbaskets

20-fold increase in chance of **simultaneous heatwaves** when waves are present

Signal also detectable in crop data

Kornhuber et al, *NCC* (2021)

# Circumglobal wave trains (CGWT)

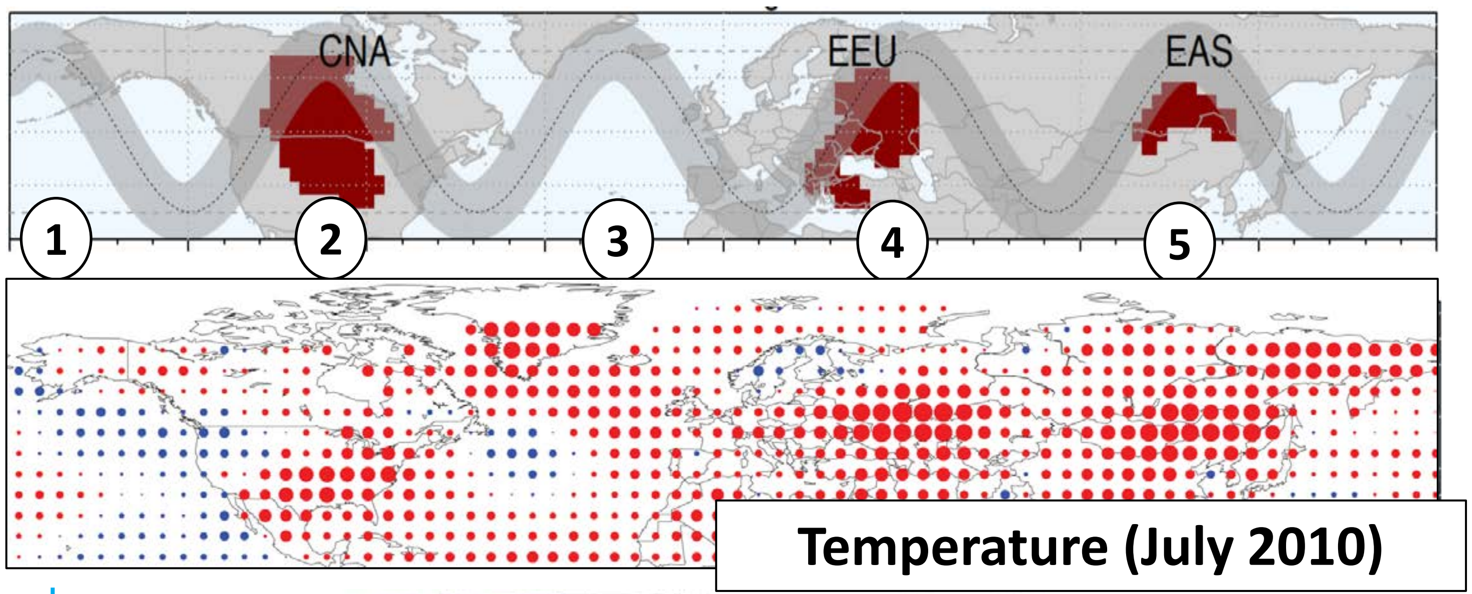


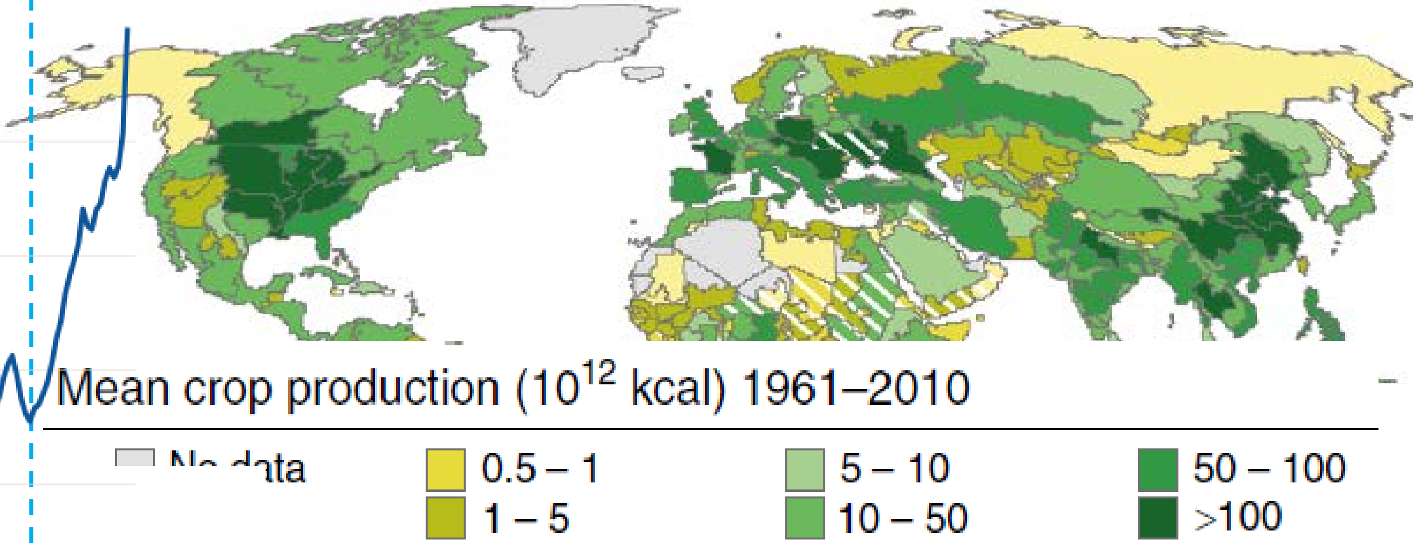
# 2010 Food prices

Failed harvests in Russia/Ukraine & poor harvest in US…

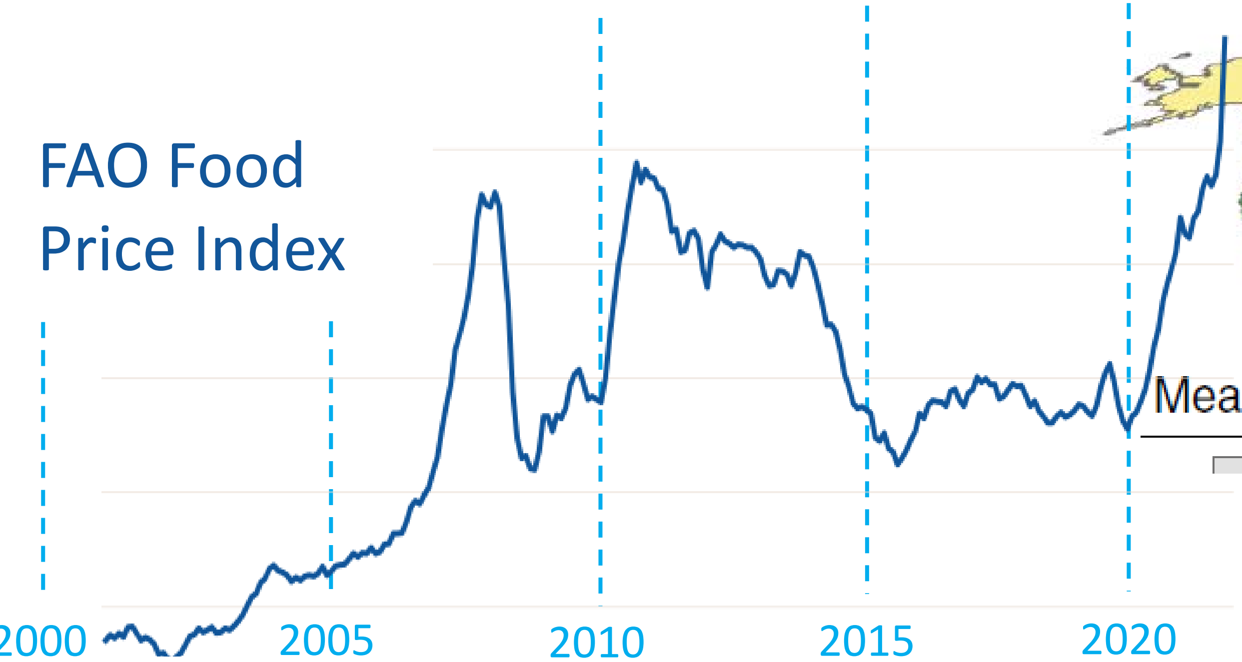
…driving food prices in 2011 (Arab Spring)

# Circumglobal wave trains (CGWT)



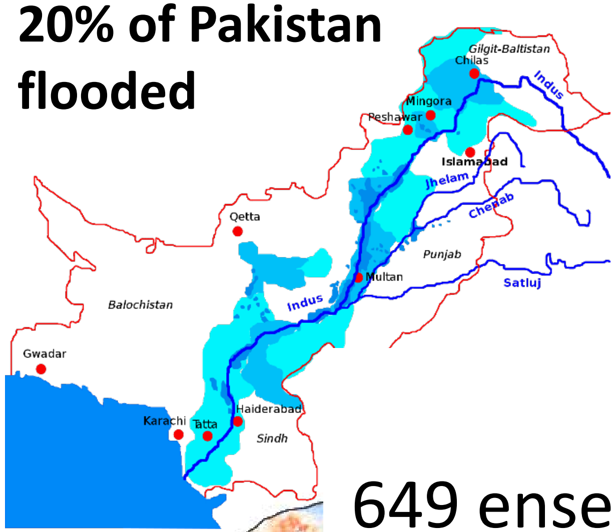




FAO Food Price Index



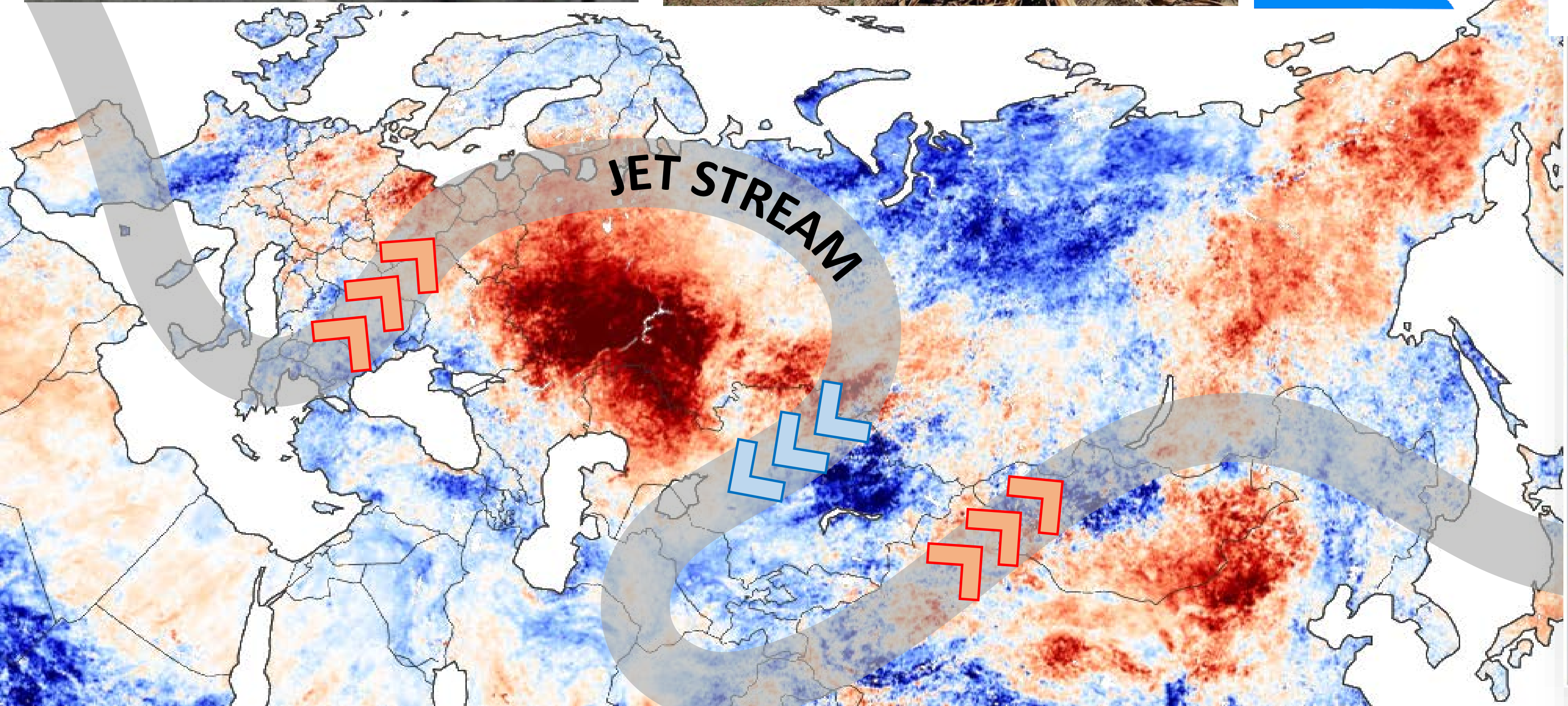
# 2010 Russian heatwave & Pakistan flooding





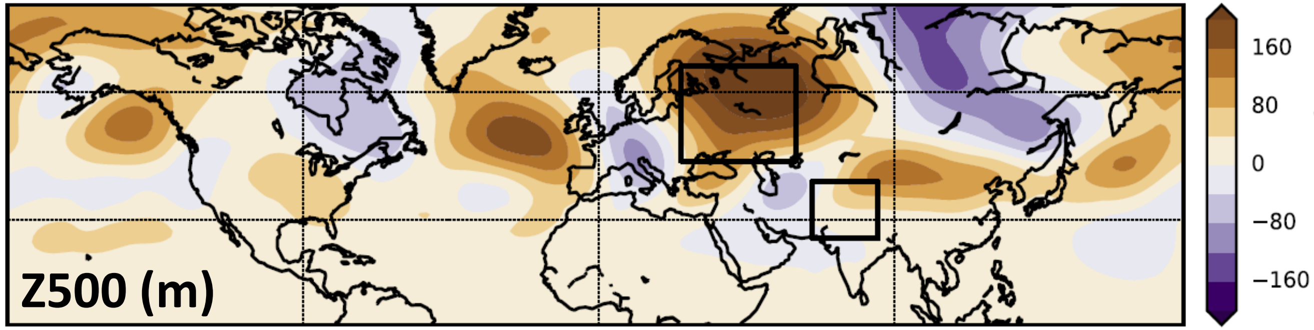

**HadAM3P**

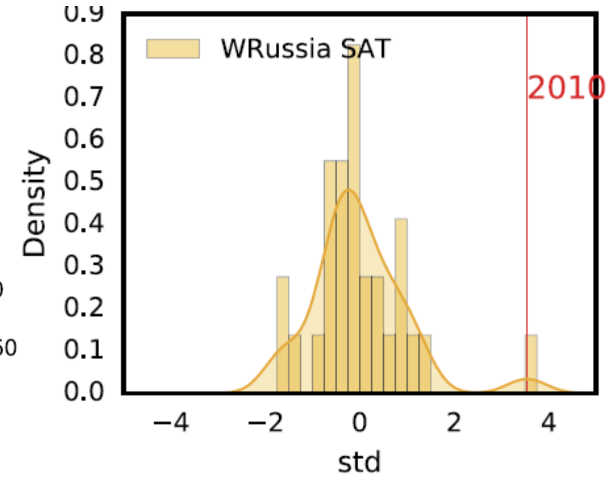
649 ensemble runs for 2010

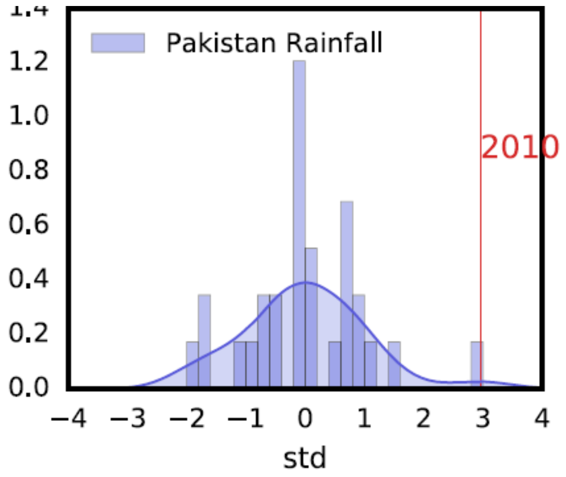



# Drivers of 2010 extremes: Russian Heatwave & Pakistan Flooding

ERA5 reanalyses (25 July – 8 Aug 2010)






Di Capua et al, *npj* (2021)

# Drivers of 2010 extremes: Russian Heatwave & Pakistan Flooding

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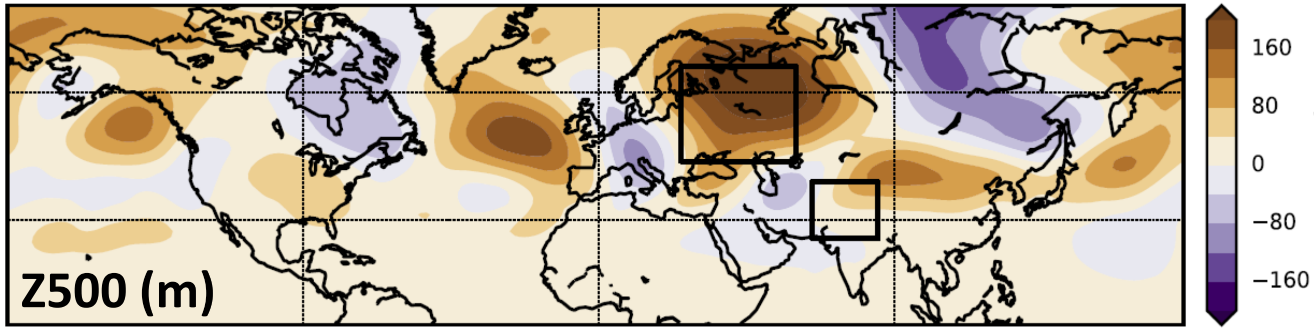
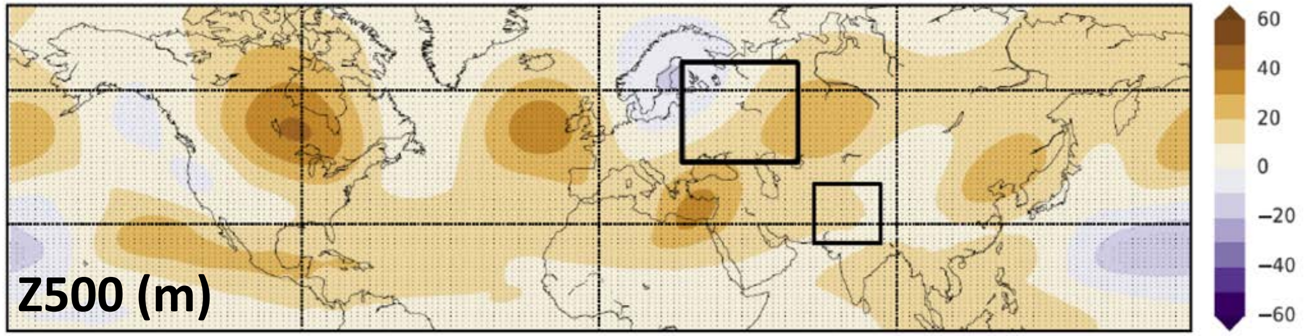
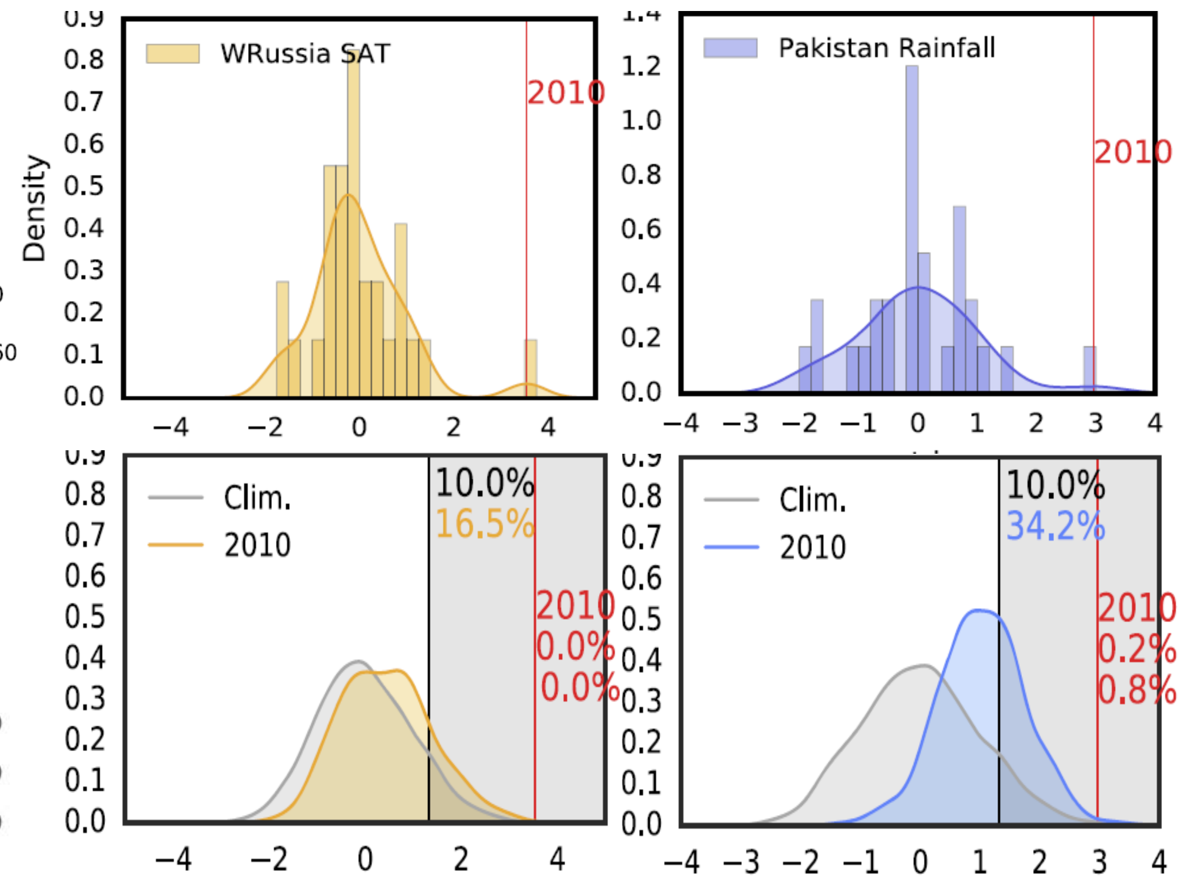
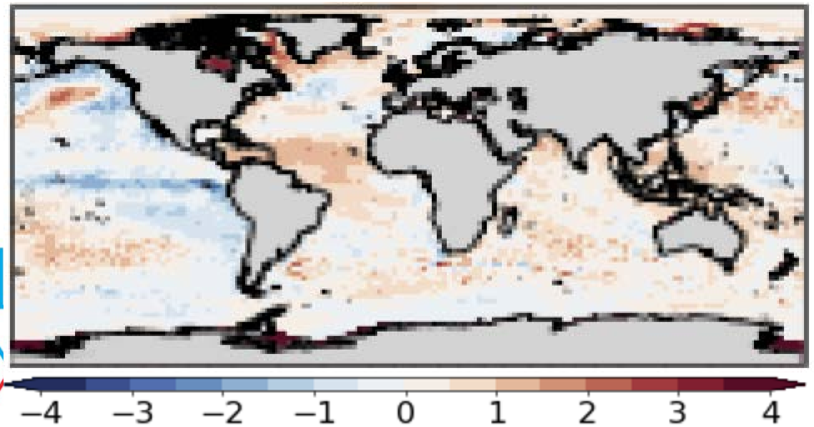



Model, ensemble mean for 2010



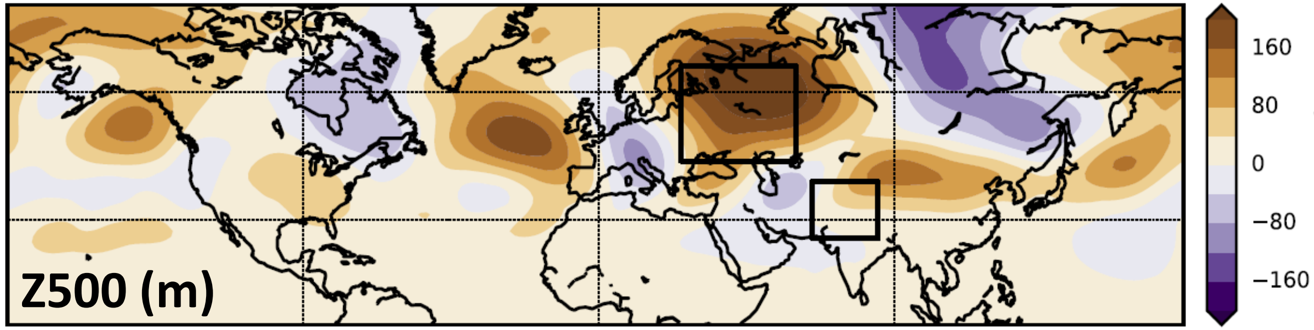




**2010 SSTs** (La Nina + warm tropical Atlantic) force wave-5 pattern, but phase-shifted

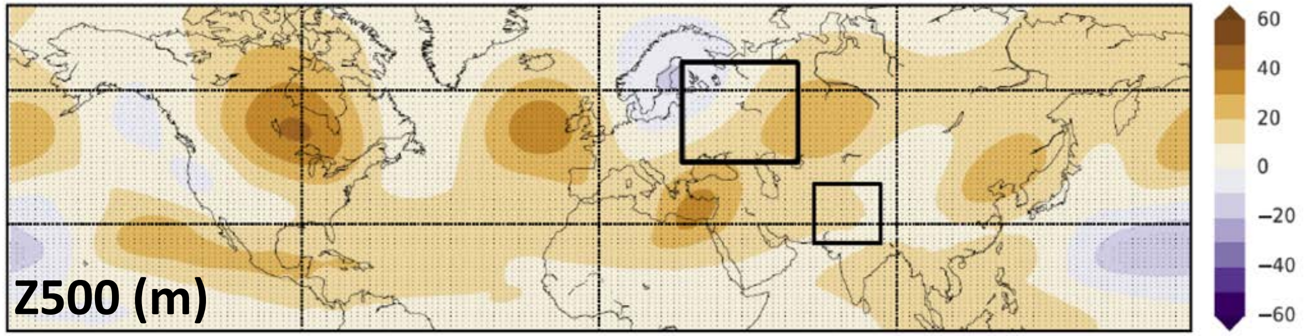
Di Capua et al, *npj* (2021), see also O'Reilly et al (2018)

# Drivers of 2010 extremes: Russian Heatwave & Pakistan Flooding

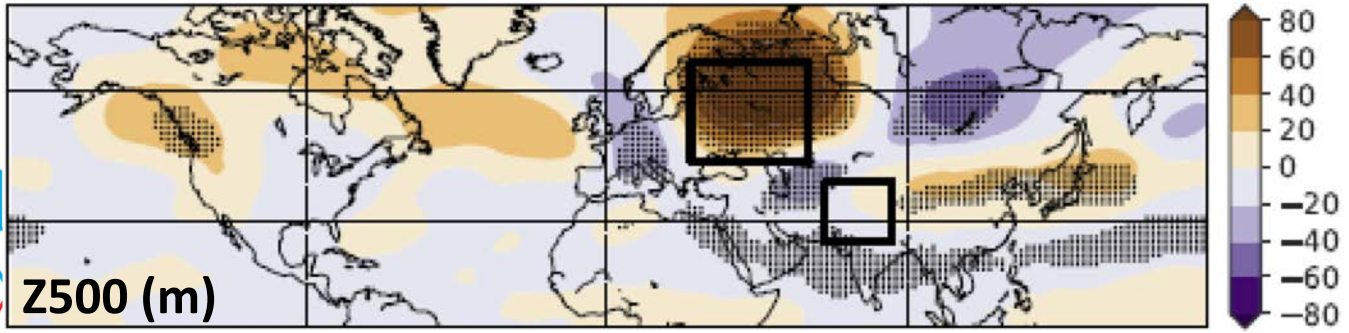
ERA5 reanalyses (25 July – 8 Aug 2010)

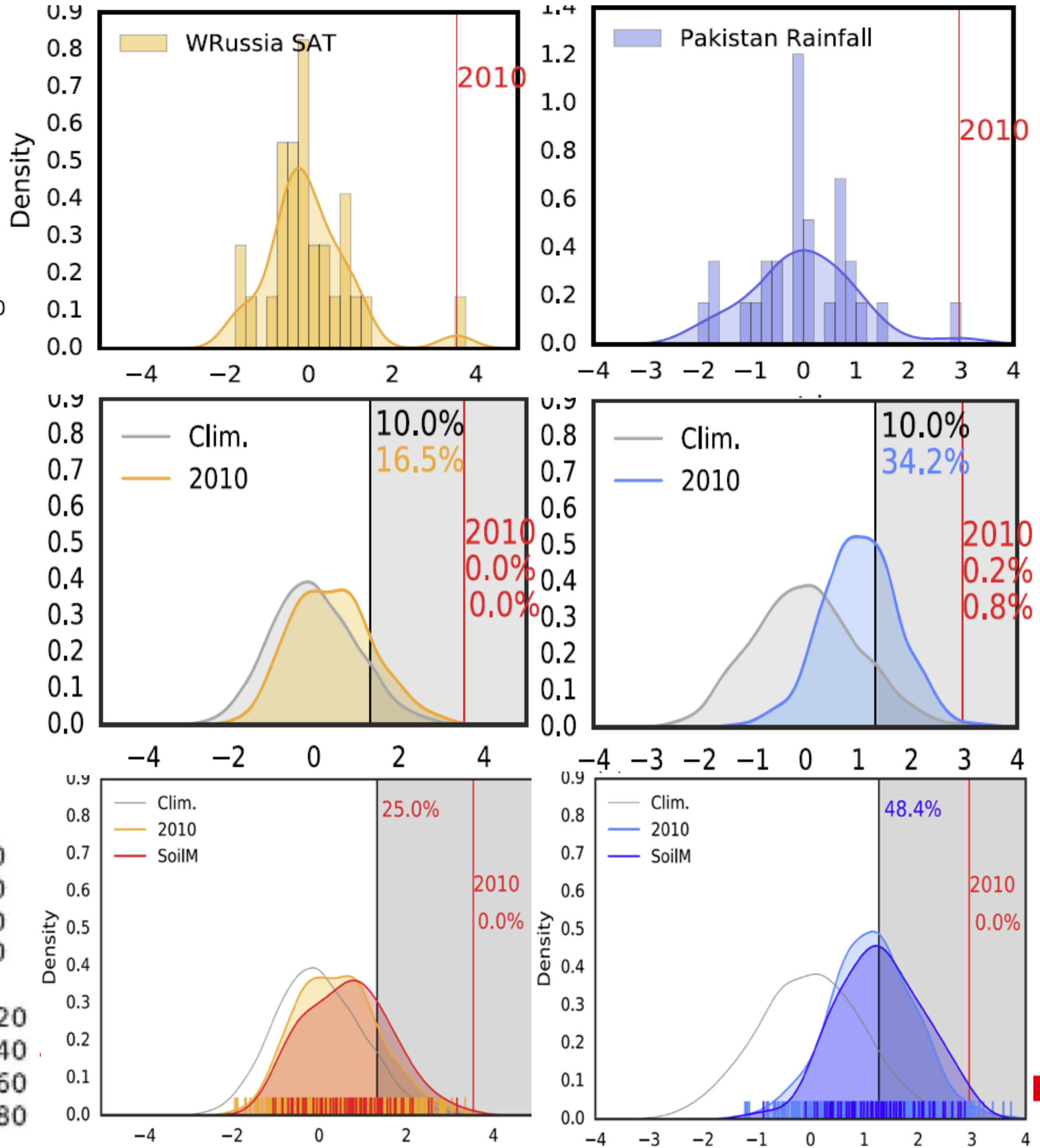



Model, ensemble mean for 2010

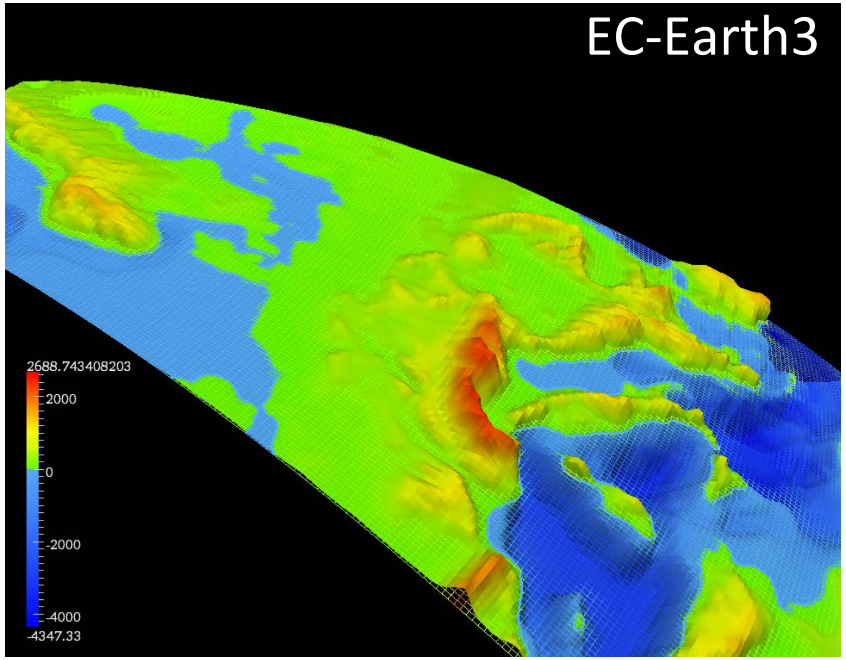



Model, 10% driest soils (June)



# Climate modeling




Obeys physical laws

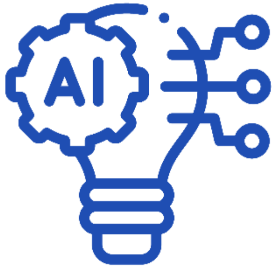
Large ensembles

Nudging experiments

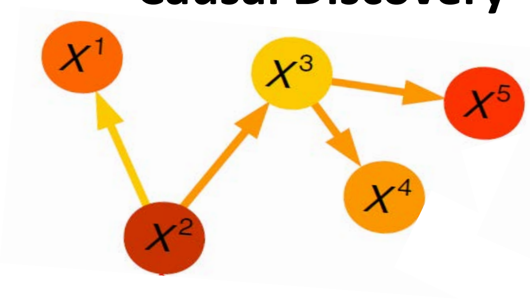
Suffer from model biases

# Data driven

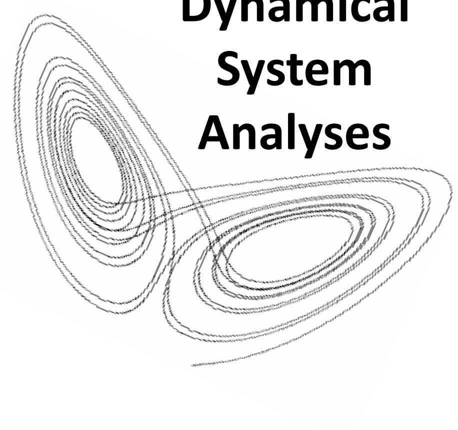
**Explainable AI**




**Causal Discovery**




**Dynamical System Analyses**



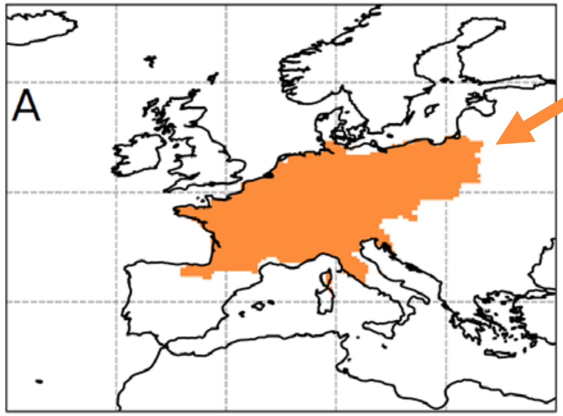
**Observational analyses**
sources of predictability
*causal* pathways
understand dynamical evolution

**Climate modeling**
Representation of processes in models
Understand model biases

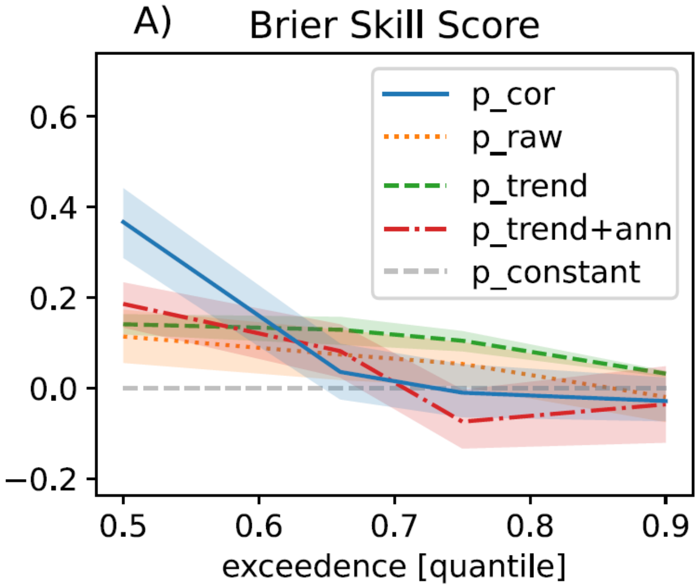
**Advanced data science methods**

CLIMATE EXTREMES

# Warm pool variability important source of predictability for European summer temperature, mitigated by CGWTs

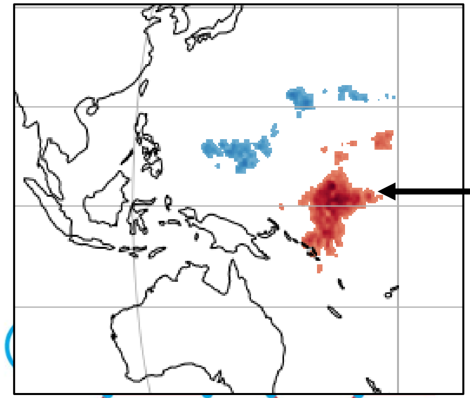



1. Target: Probability that T2m exceeds median (2 weeks gap + 30-day average)
2. Train Artificial Neural Network (ANN) to apply corrections to ECMWF forecast
3. Large set of regional and global precursors
4. Explainable AI to understand when & why corrections are needed

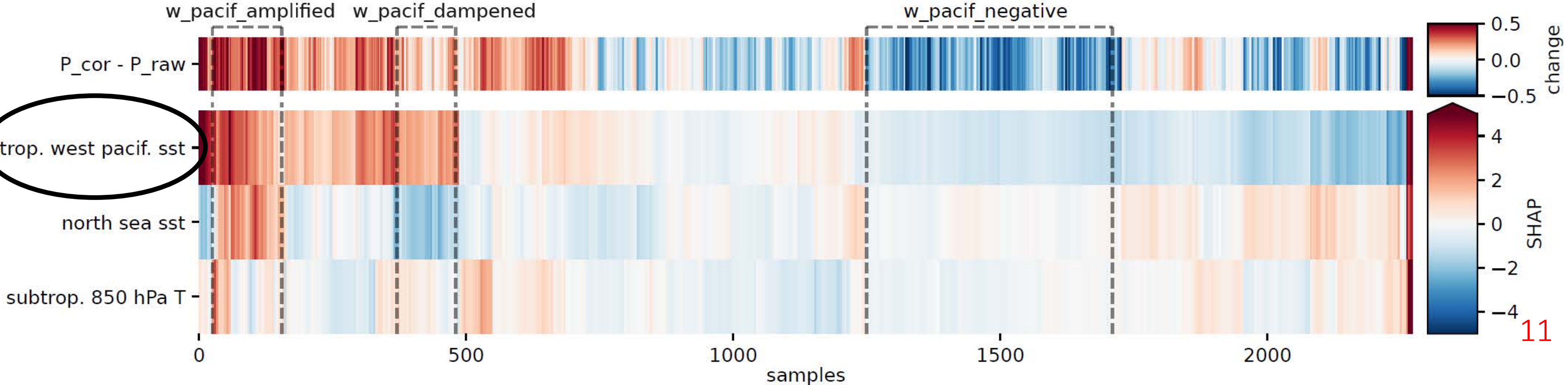



Van Straaten et al (in review)

Correlation pattern



Which precursor states are responsible for what corrections?




EXTREMES

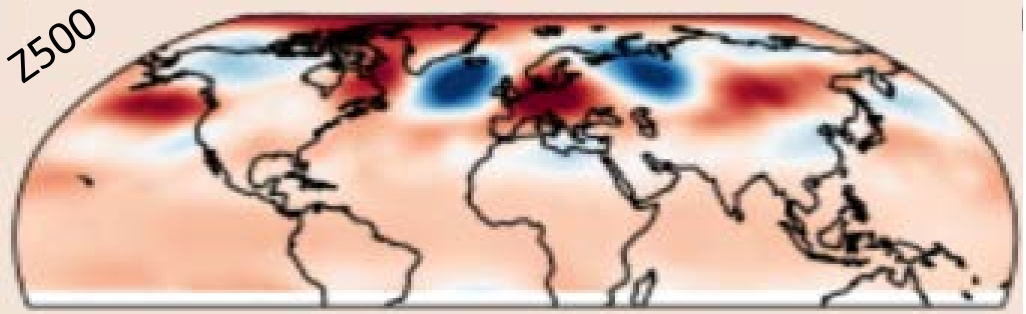
# Warm pool variability important source of predictability for European summer temperature, mitigated by CGWTs

Upward corrections predominantly during El Nino events, vice versa for La Nina

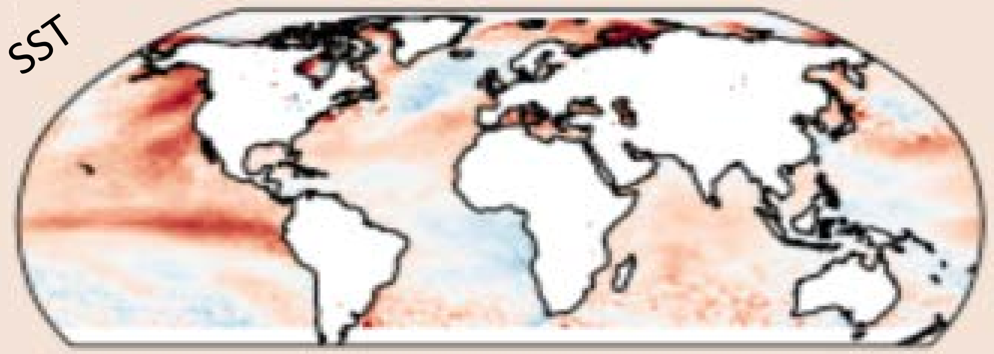
Signal appears mitigated via wavetrains in jetstream

Van Straaten et al (in review)

Upward correction needed

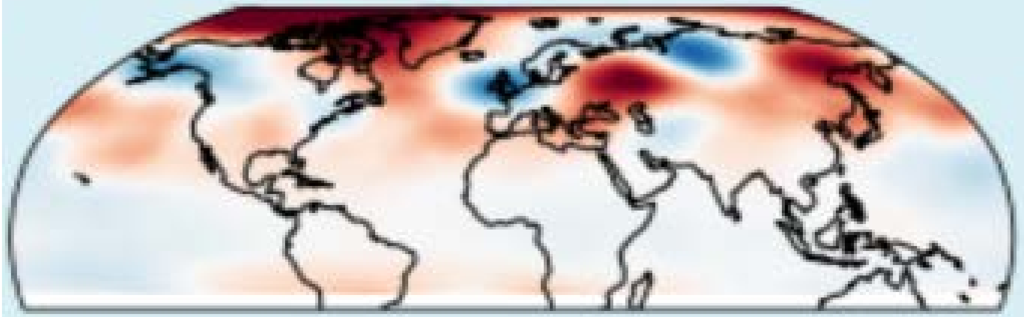



W-Europe hot & E-Europe cold

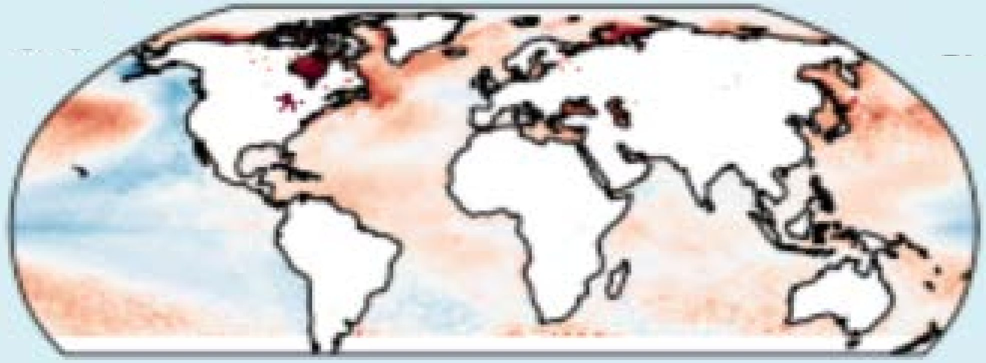



El Nino

Downward correction needed



W-Europe cold & E-Europe hot



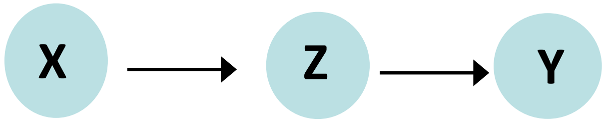
La Nina

# Correlation analyses

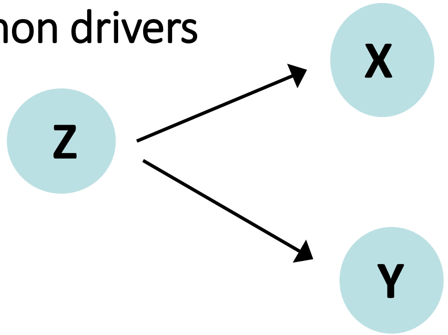
Problems with correlation:

X and Y are conditionally independent given Z

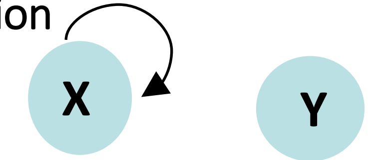
## Indirect links




## Common drivers

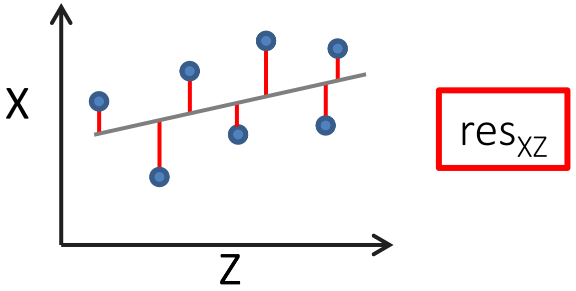


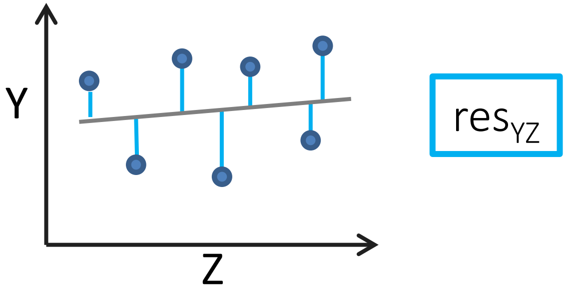

## Autocorrelation



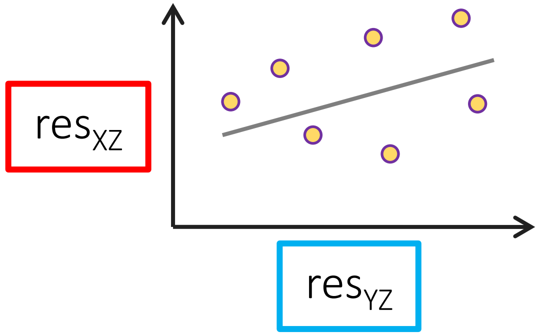

# Causal Discovery Algorithms

Regress X and Y on Z



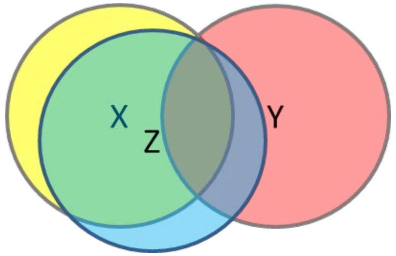

Regress the residuals




**Partial correlation**

$p(X, Y \mid Z) = p(res_{XZ}, res_{YZ})$

≈ 0, if X and Y are conditionally **independent** given Z

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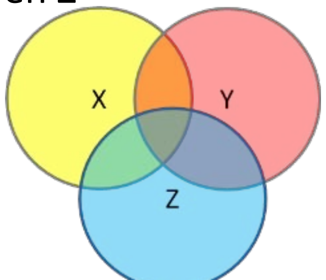


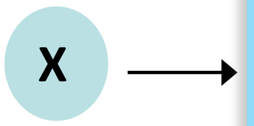
# Correlation analyses

# Causal Inference

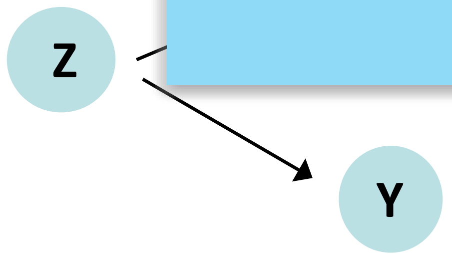
Problems with correlation:

X and Y are

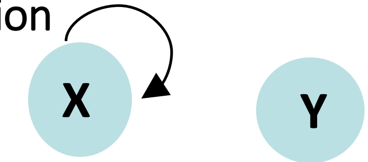
Indirect links




Common drive




Autocorrelation




Regress X and Y on Z

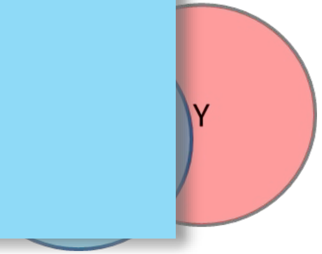
Partial correlation

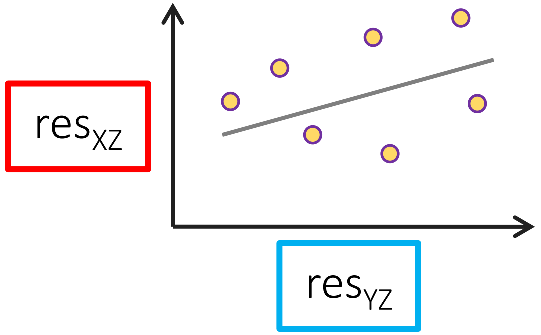
res$_{YZ}$)

**Iteratively loop over all *actors* at all *lags* and test whether any of the links is explained by spurious effects – if so remove them. What remains is a Causal Effect Network**

**Tigramite4.0 by Jakob Runge**

ionally

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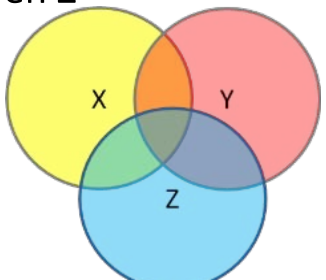
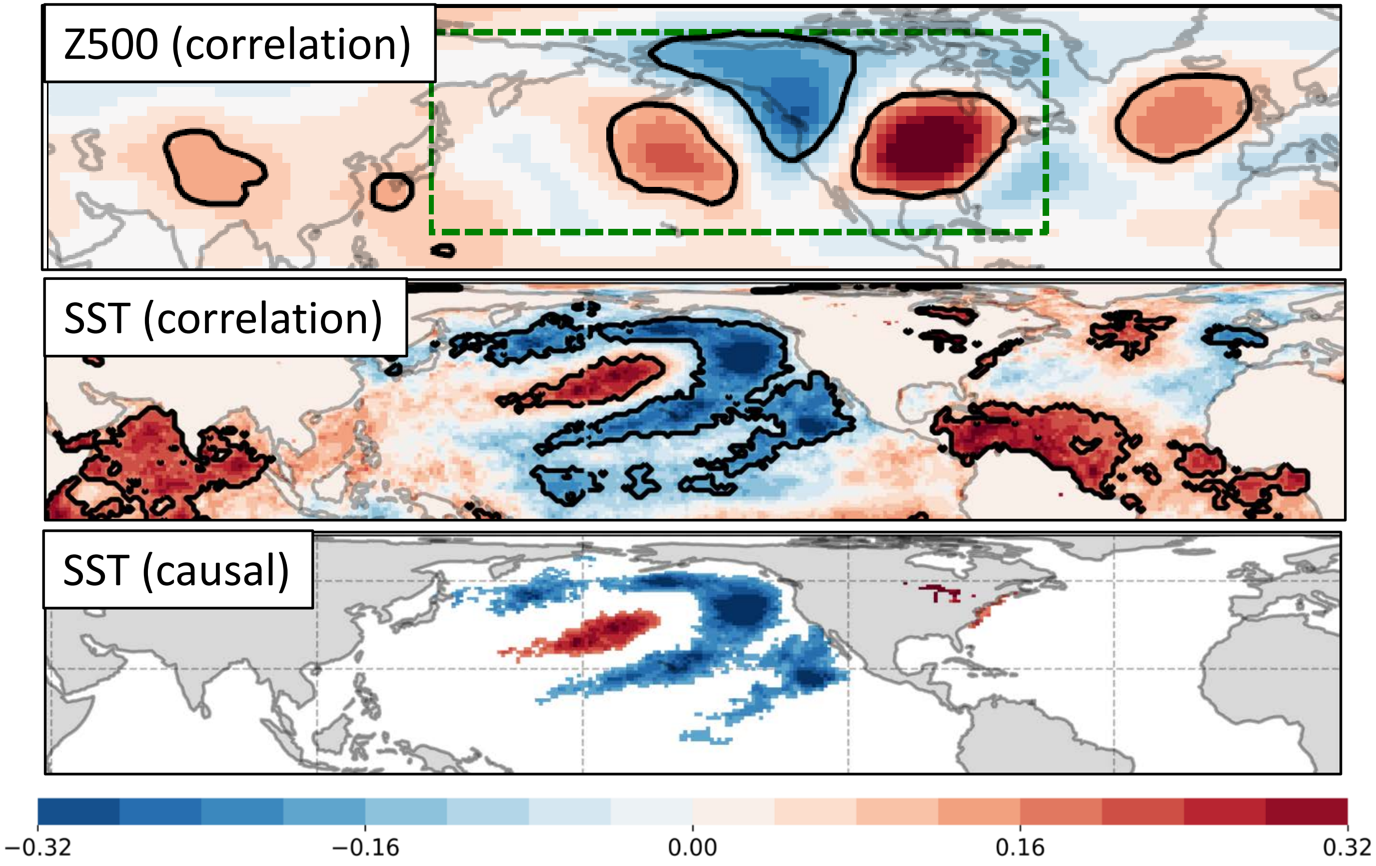
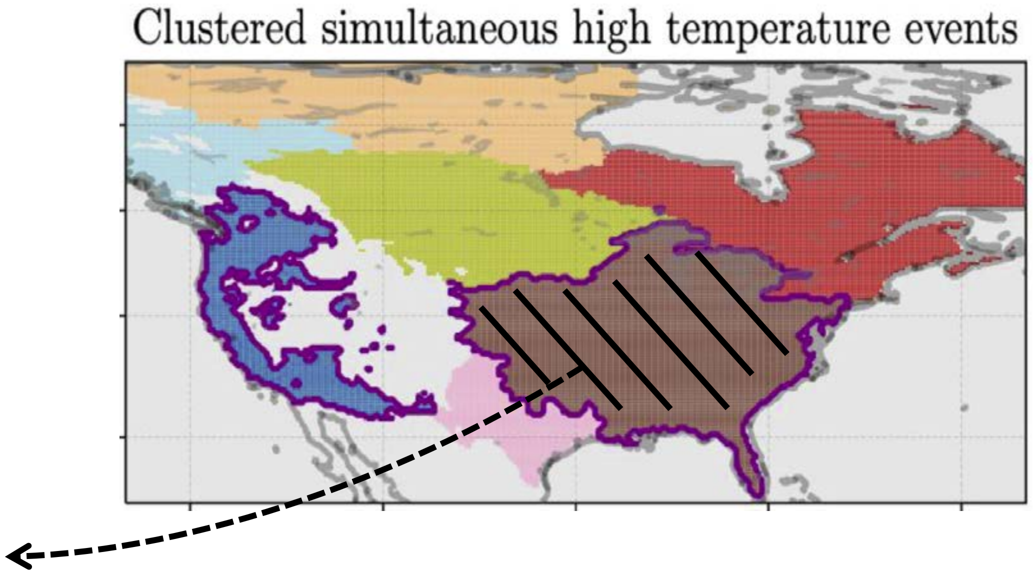


# Eastern US Heatwaves: Wavetrain – SST interactions



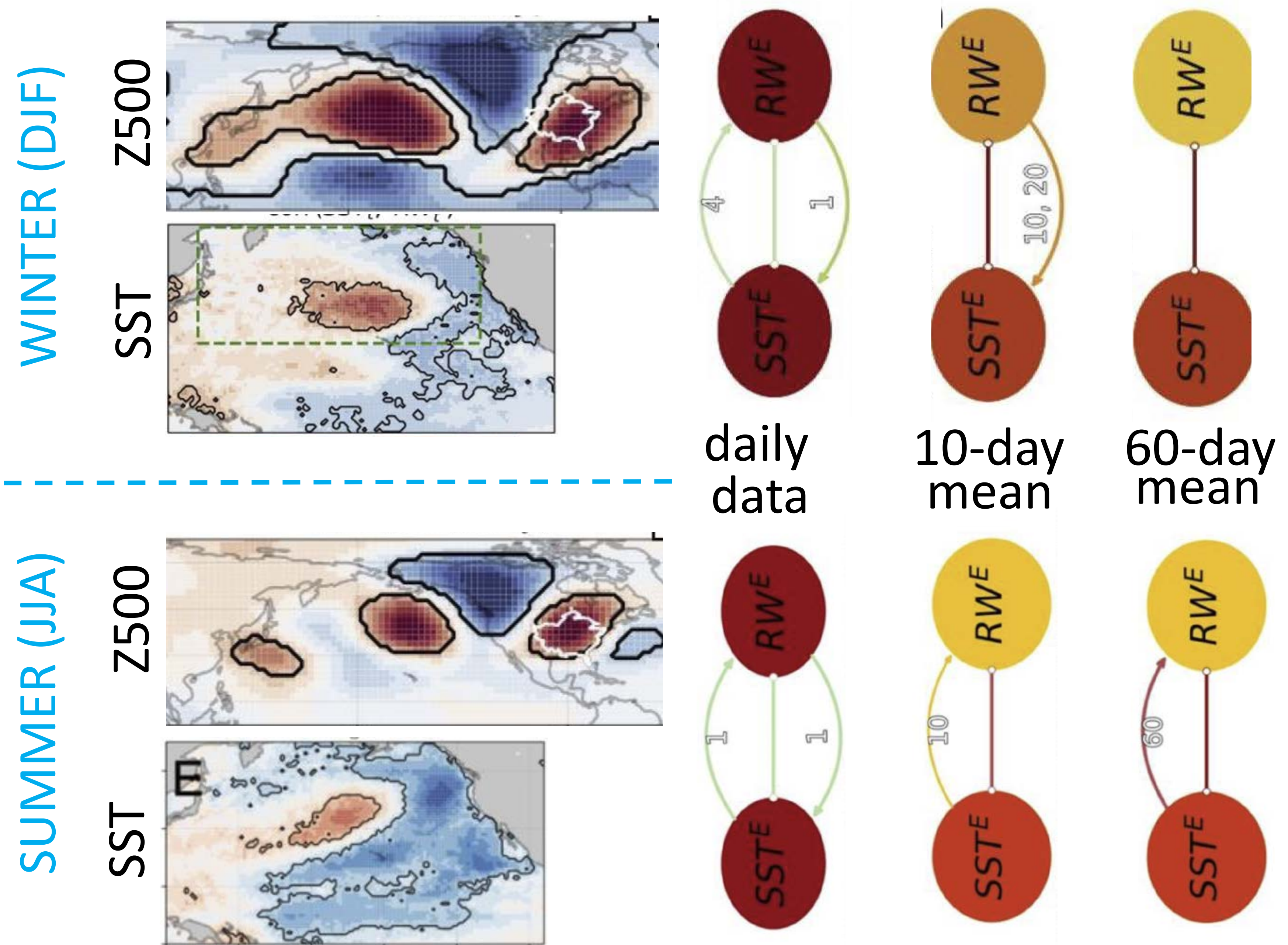




Eastern US heatwaves are causally linked to Pacific extra-tropical SSTs ('Horseshoe' SST pattern)

CLIMATE EXTREMES

McKinnon et al, 2016; Vijverberg et al, 2020; Vijverberg & Coumou, 2022

# Seasonal evolution of interactions between wave and SSTs

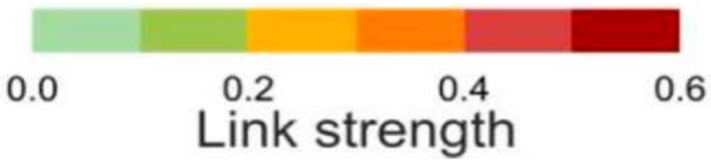



<u>Daily timescales:</u>

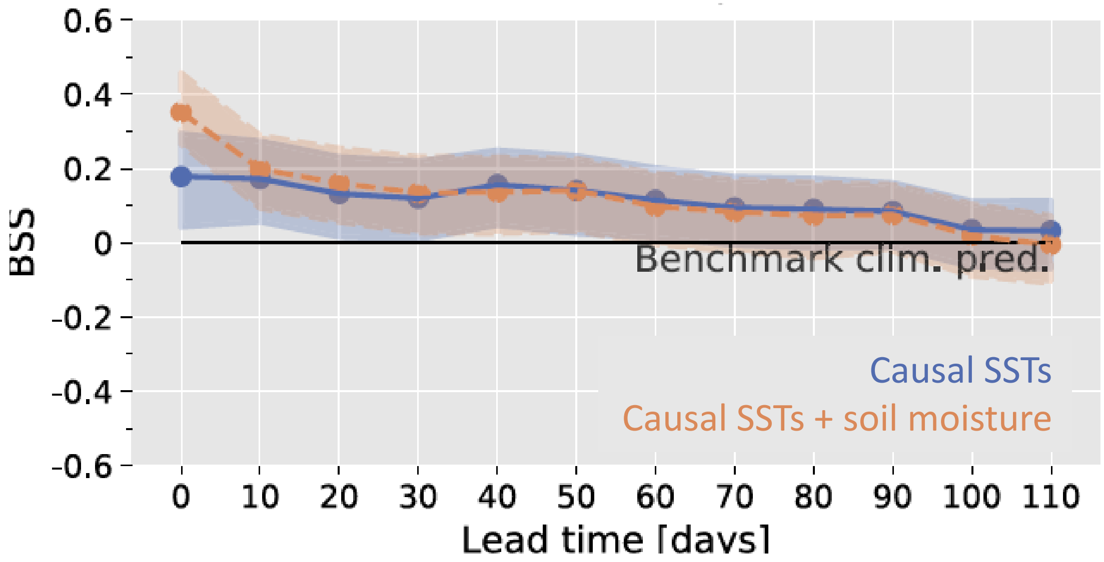
2-way positive feedbacks in both seasons

<u>10 days & longer:</u>

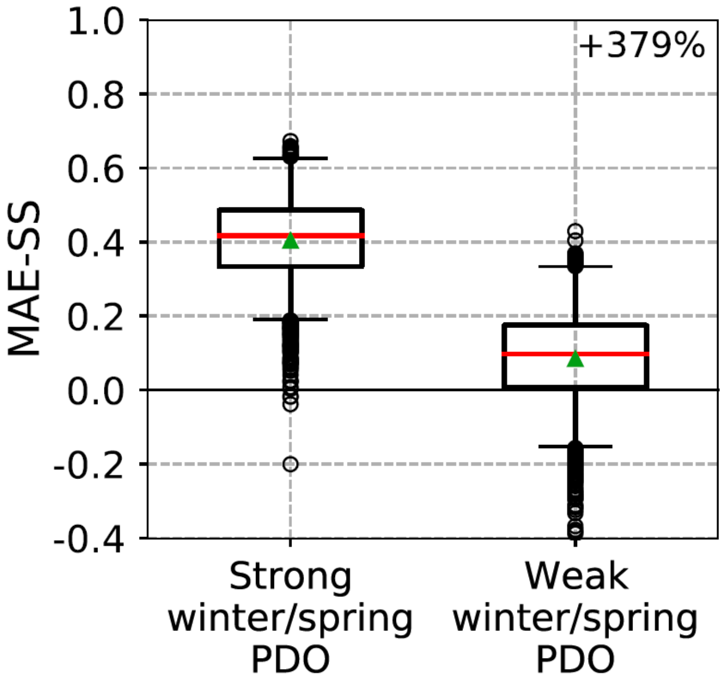
- Predominant downward forcing in winter
- Predominantly upward forcing in summer



# S2S predictability of hot-dry extremes in eastern US




Warm anomalies (upper tercile, 15 day window) are predictable up to ~60 days ahead using causal ‘Horseshoe’ SST pattern



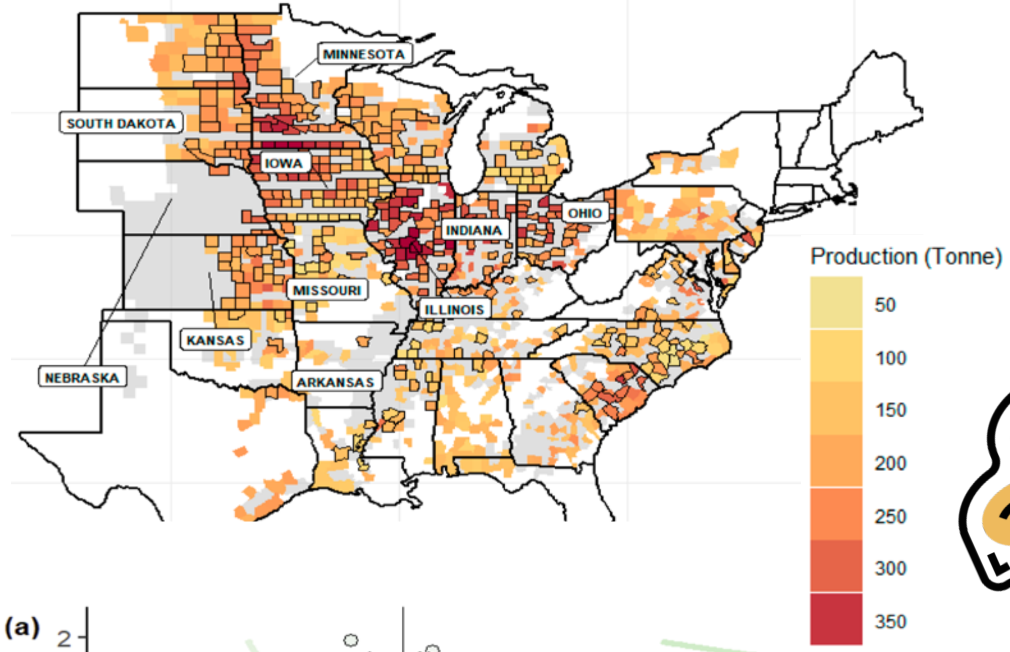

Pattern projects on PDO. Strong PDO years have enhanced predictability.

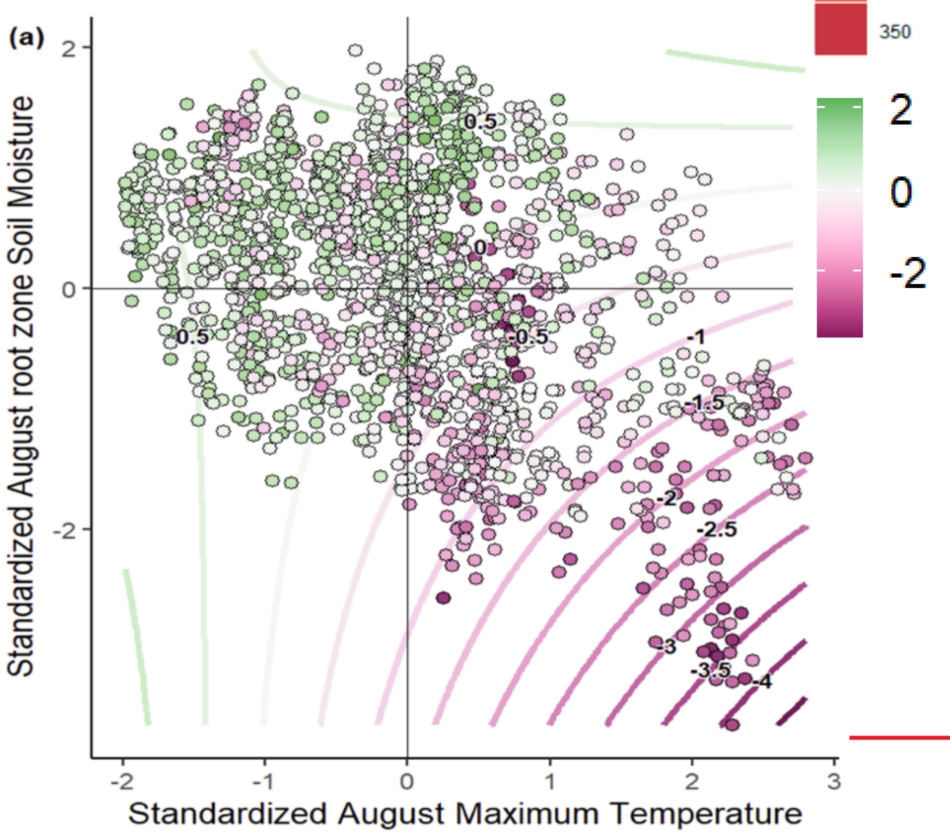
Window of predictability

CLIMATE EXTREMES

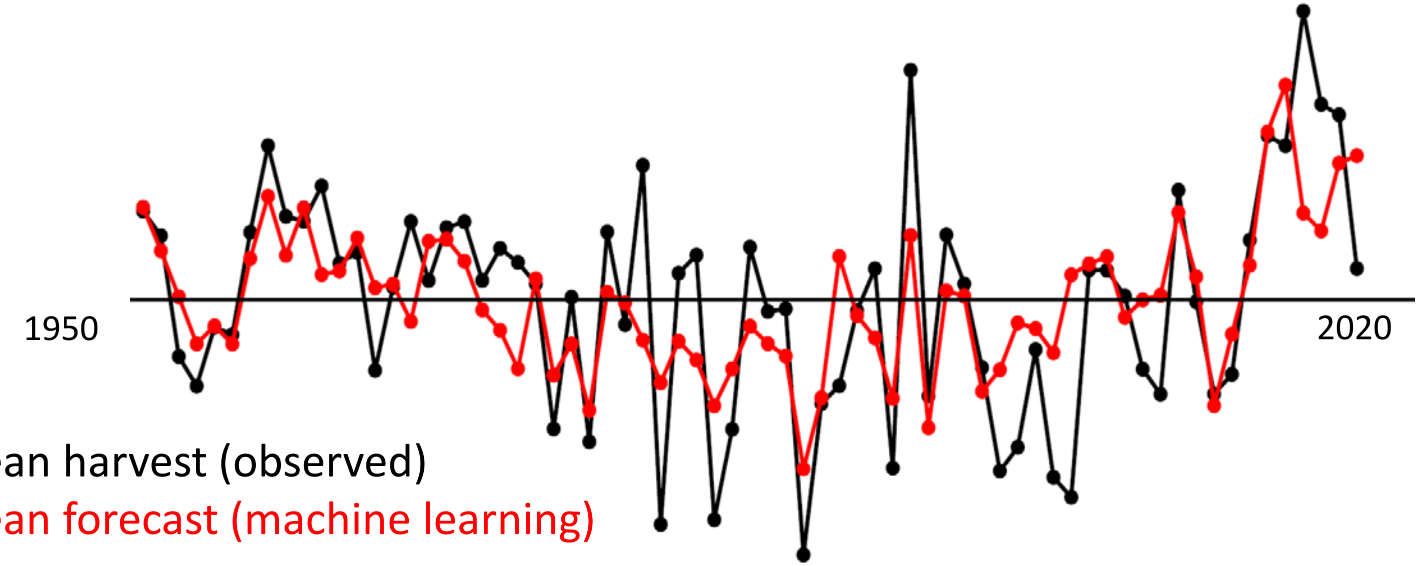
); Vijverberg & Coumou, 2022; Vijverberg et al, accepted

# Long-lead predictability of soybean




- Soybean harvest failures even *better predictab*le from 'Horseshoe' SST pattern
- Soybeans very sensitive to compound hot-dry conditions.
- Sometimes including impact-variables can make life easier




Hamed et al (2021); Vijverberg et al, accepted

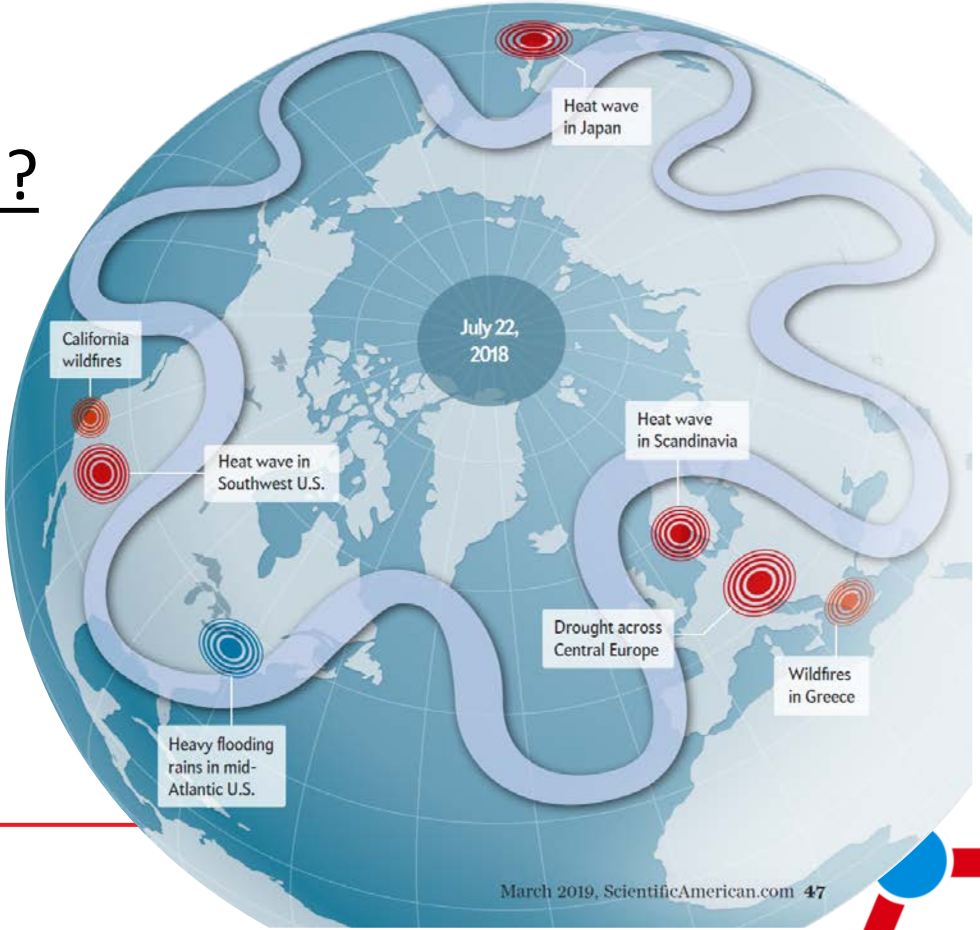
# Outline of this talk

## 1. Drivers of CGWT on S2S timescales

- Insights from climate models
- Insights from Explainable AI
- Insights from Causal Discovery Algorithms

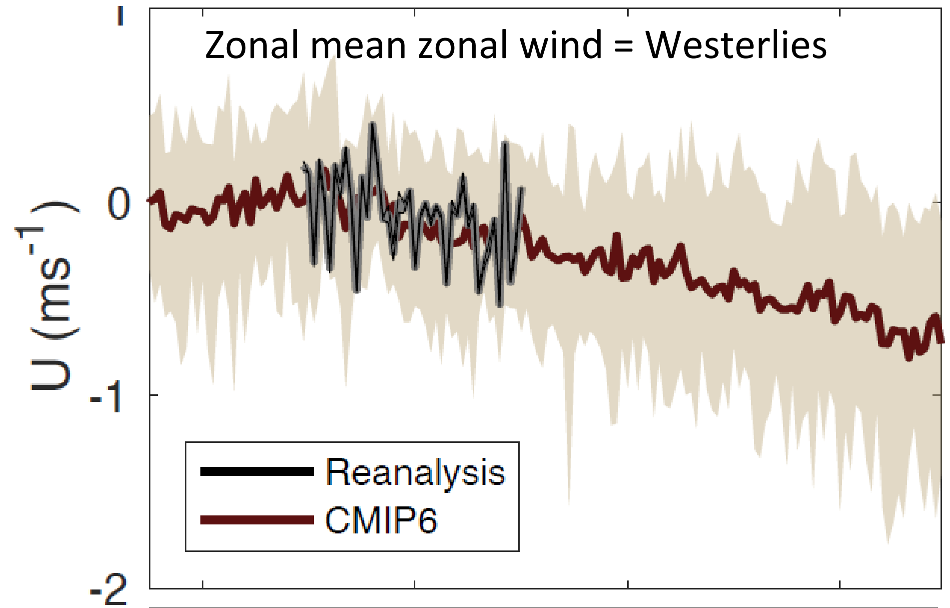
## 2. How does AGW affect boreal summer circulation?

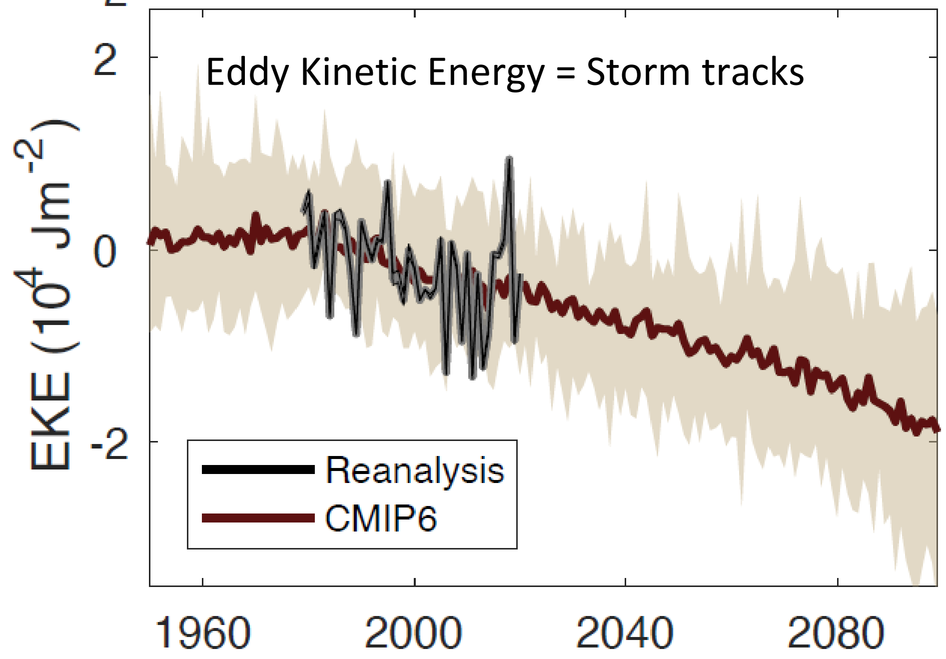
- Over last 40 years circulation has weakened
- This weakening is also seen in climate models: Is it attributable?
- Double jets & European heat waves

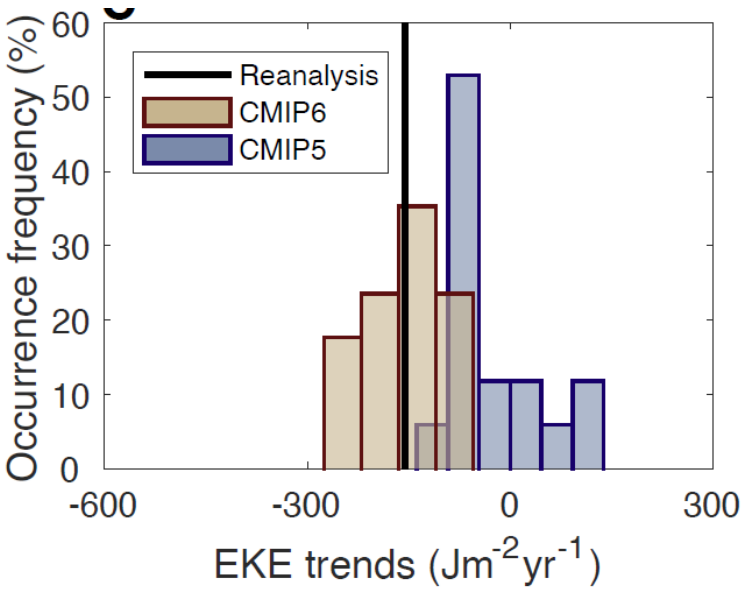


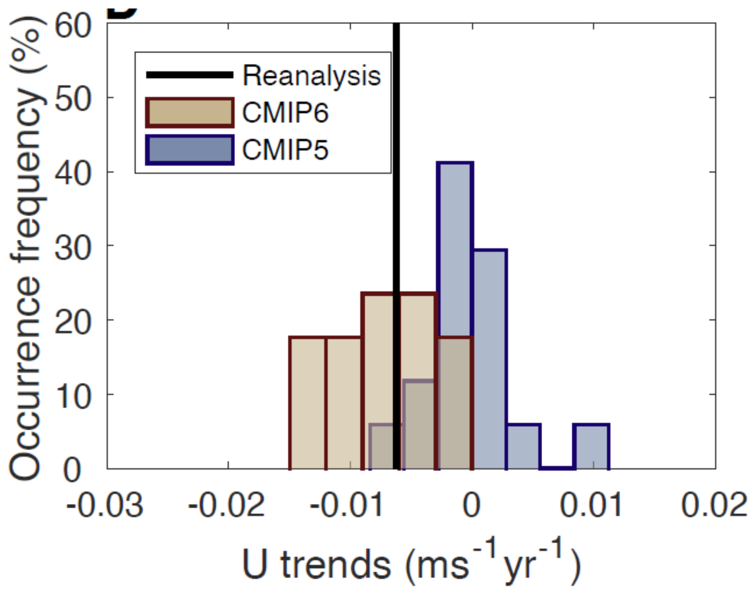

CLIMATE EXTREMES

# Is climate change affecting boreal summer circulation?



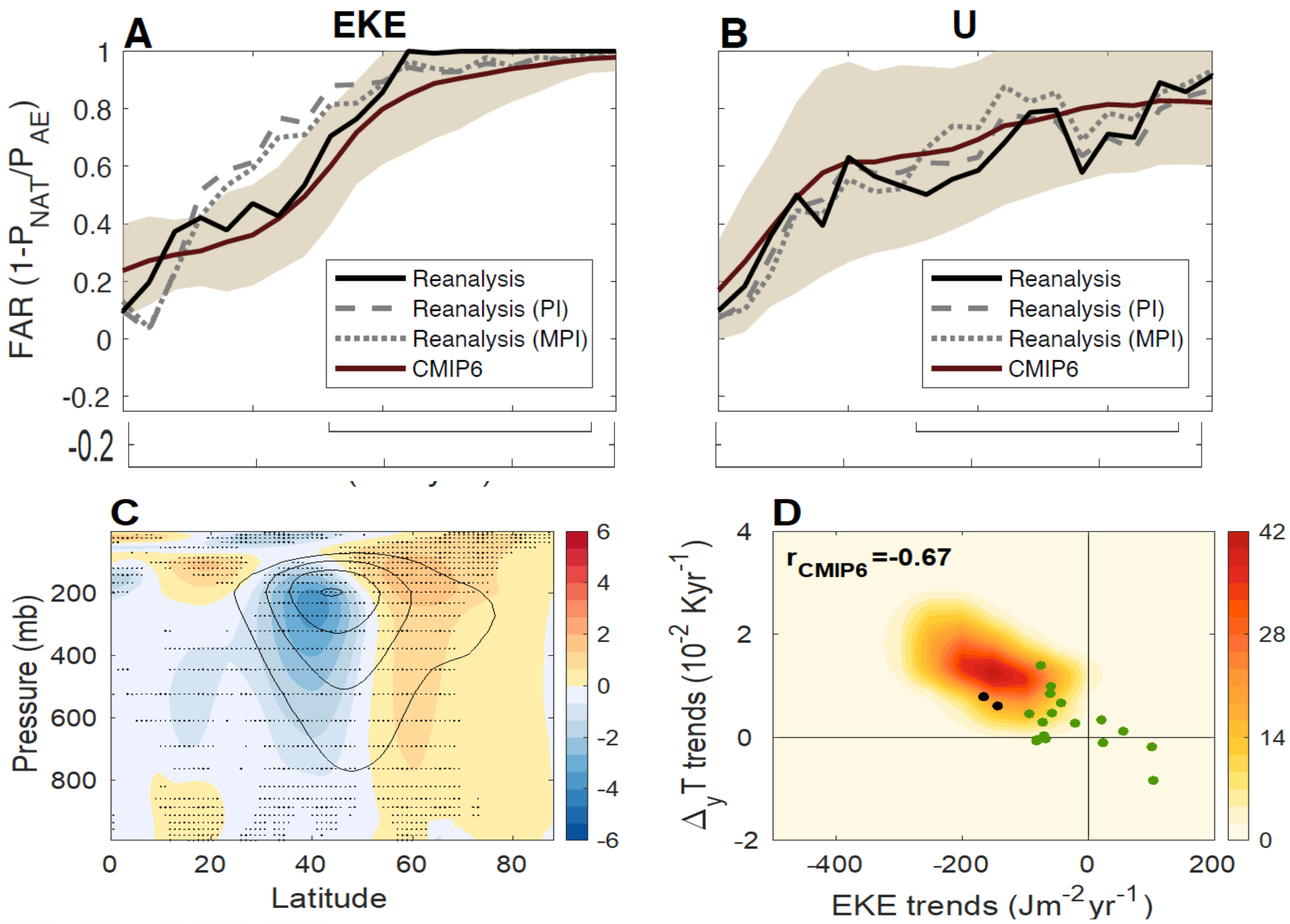




Both westerlies & storm tracks have been weakening since 1979

CMIP6 models capture this downward trend but CMIP5 models do not

Coumou et al (2015); Chemke & Coumou (in review)

# Weakening is attributable to anthropogenic emissions




Fractional Attributable Risk:

**FAR = 1 - $P_{NAT}$ / $P_{AE}$**

P = probability of trend with natural forcing only (NAT) or with natural + anthropogenic emissions (AE)

Reduction in equator-to-pole gradient results in weakening at jet core and in vertical shear (& thus baroclinicity)

CMIP5 models underestimate trends in equator-to-pole temperature gradient (i.e. Arctic Amplification).

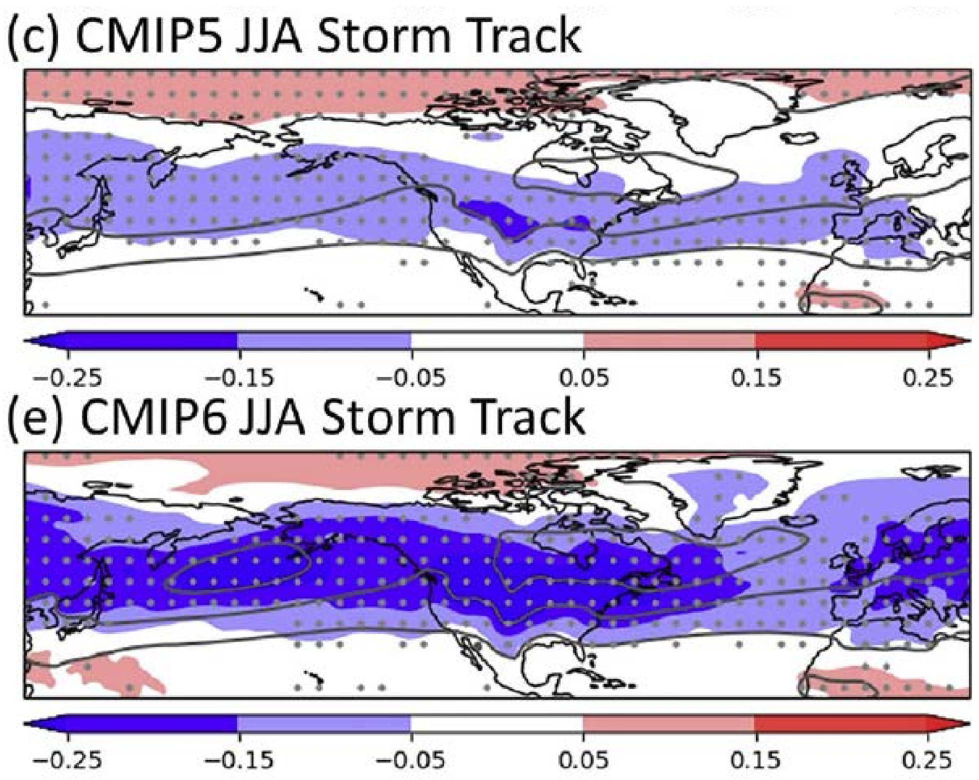
CLIMATE EXTREMES

Chemke & Coumou (in review)

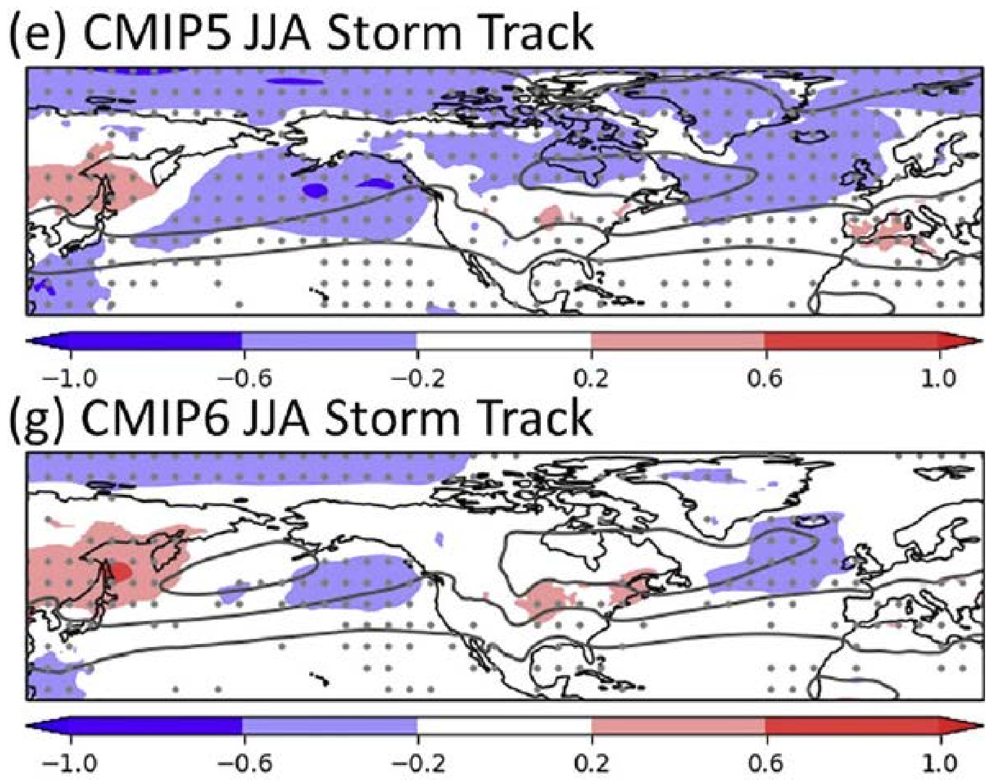
# Weakening of summer circulation: CMIP5 vs CMIP6

Climate models project same storm track weakening under future emissions

CMIP6: Improved storm track representation & stronger climate signal



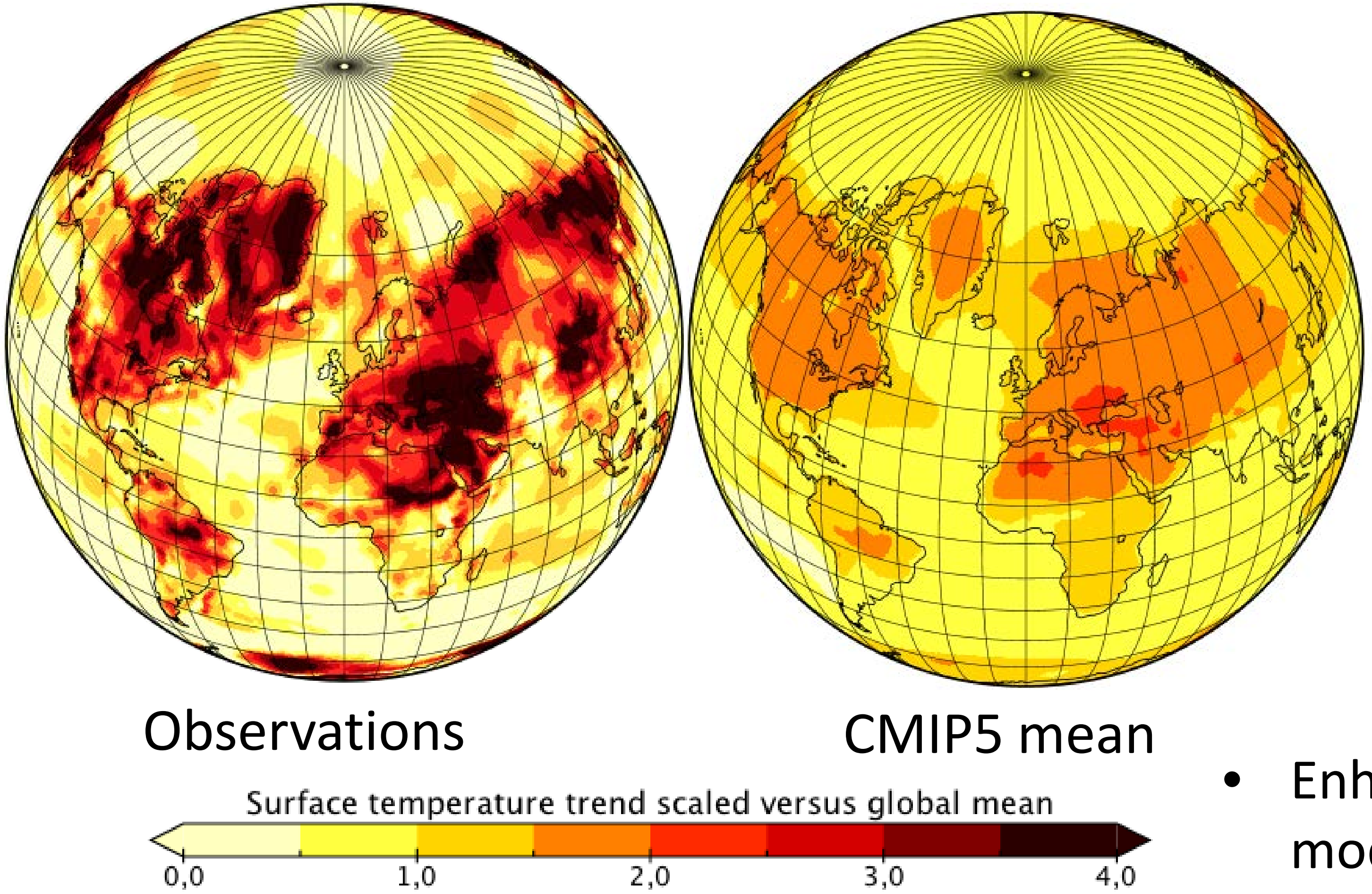

<u>FORCED RESPONSE</u>: JJA multimodel mean future minus present (RCP4.5)

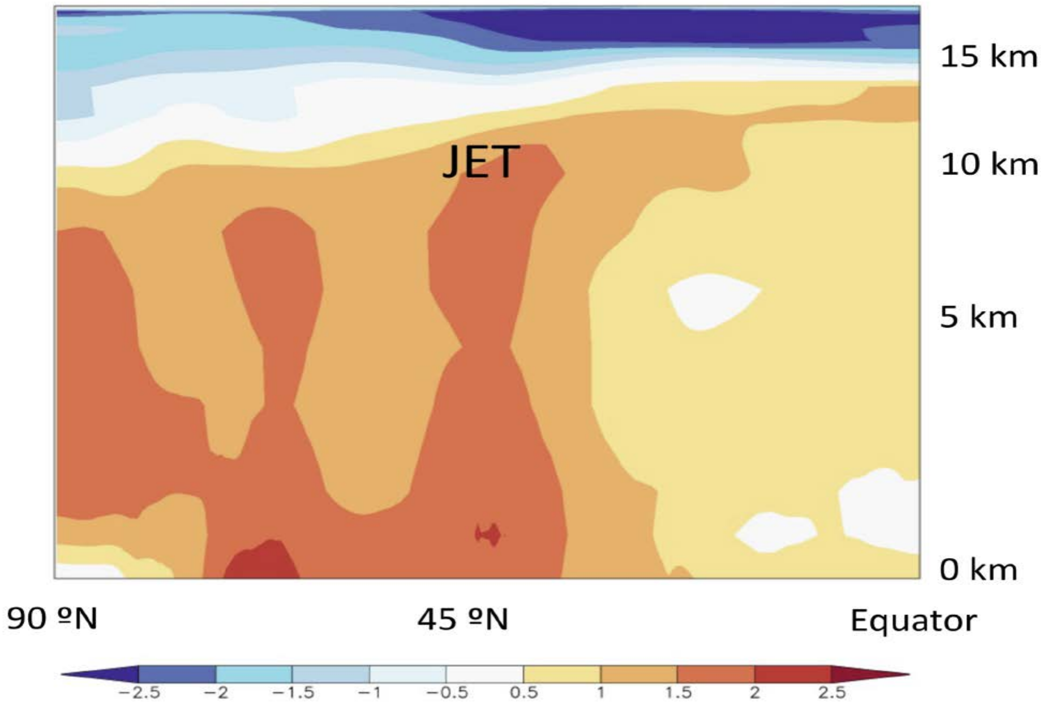



<u>MODEL BIAS</u>: JJA multimodel mean present minus ERA5

Harvey et al, JGR (2020)

# Warming trends in summer (1979-2017)



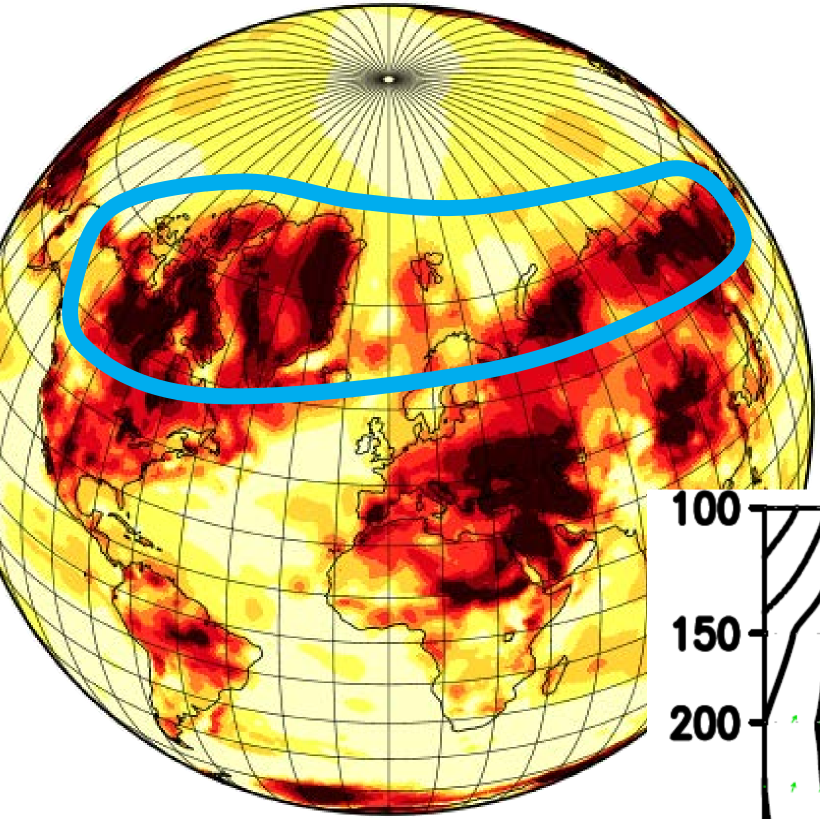




- Enhanced land-warming underestimated by models
- Amplification over high-latitude land (but not over Arctic ocean)
- Warming penetrates to higher levels, weakening mid-latitude gradient

CLIMATE EXTREMES

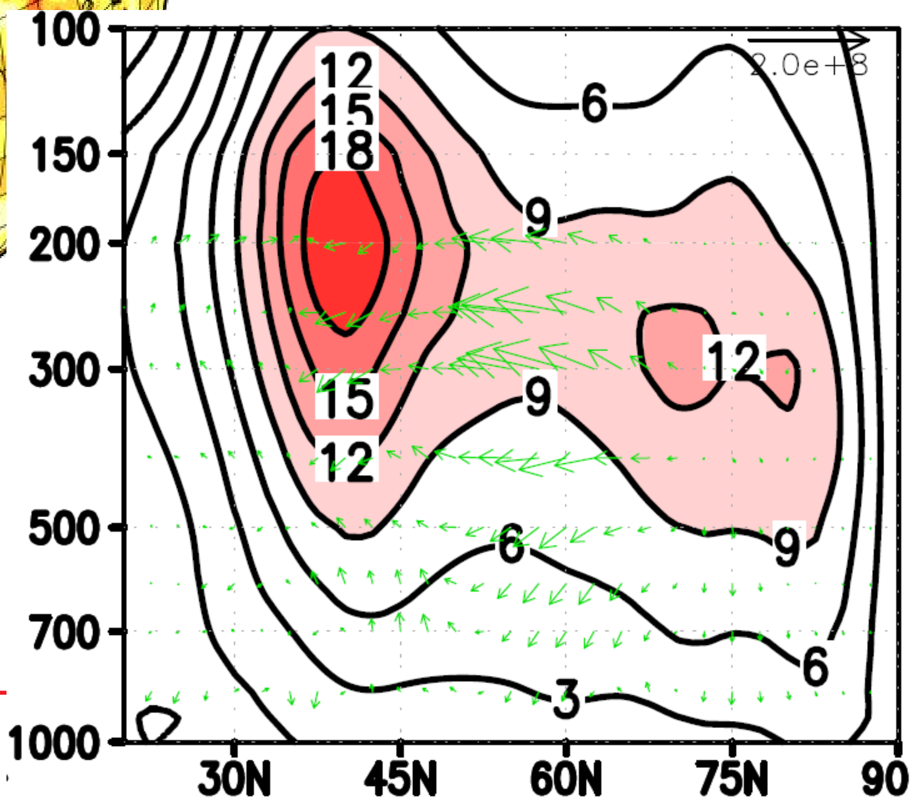
Philip et al (2021)

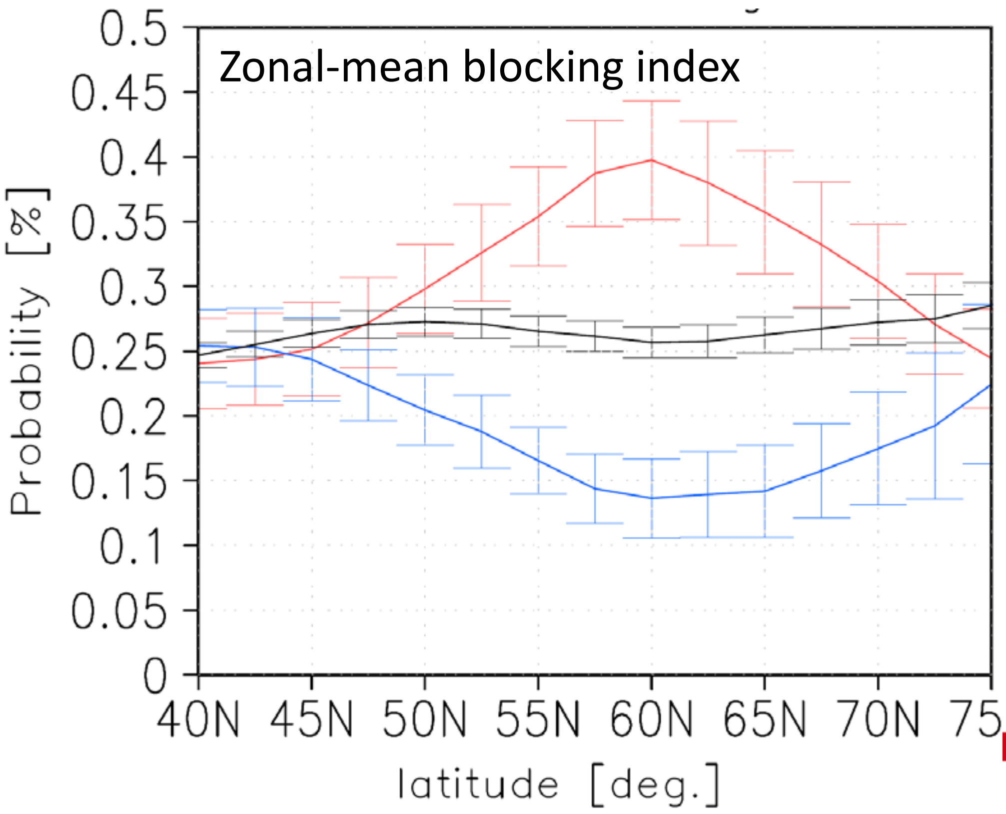
# High-latitude land-warming favors double jets



- Weakening mid-lat gradient but strengthening land-ocean gradient → Favors Arctic front jet / double jets
- Associated with enhanced mid-latitude blocking

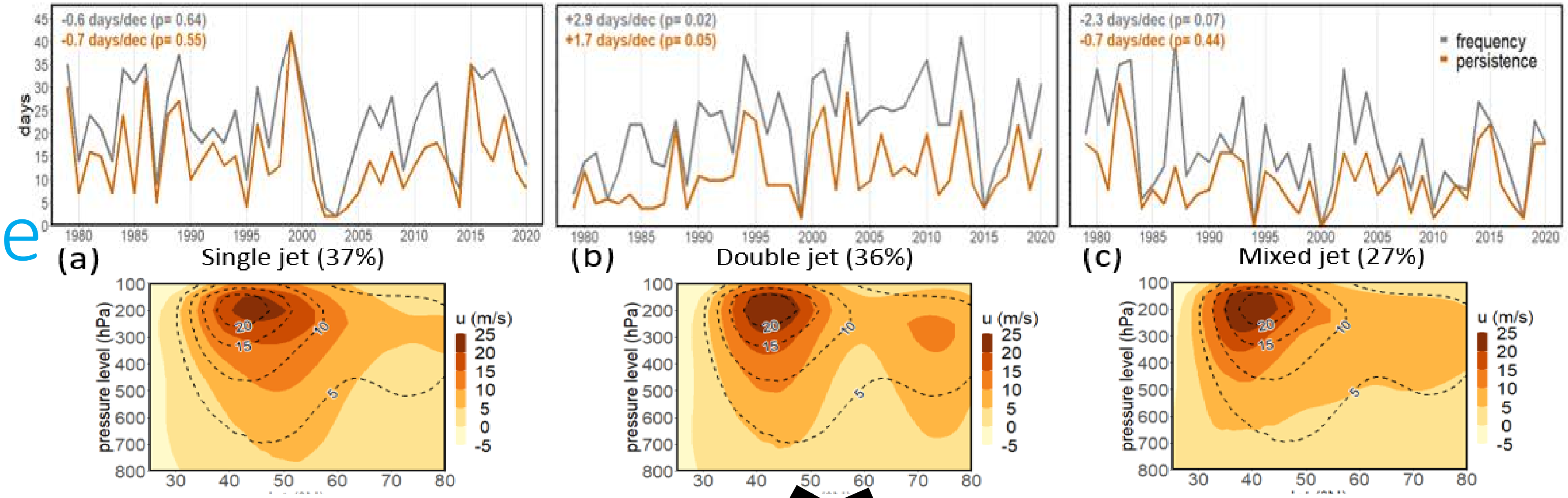
Tachibana *et al.* (2010)



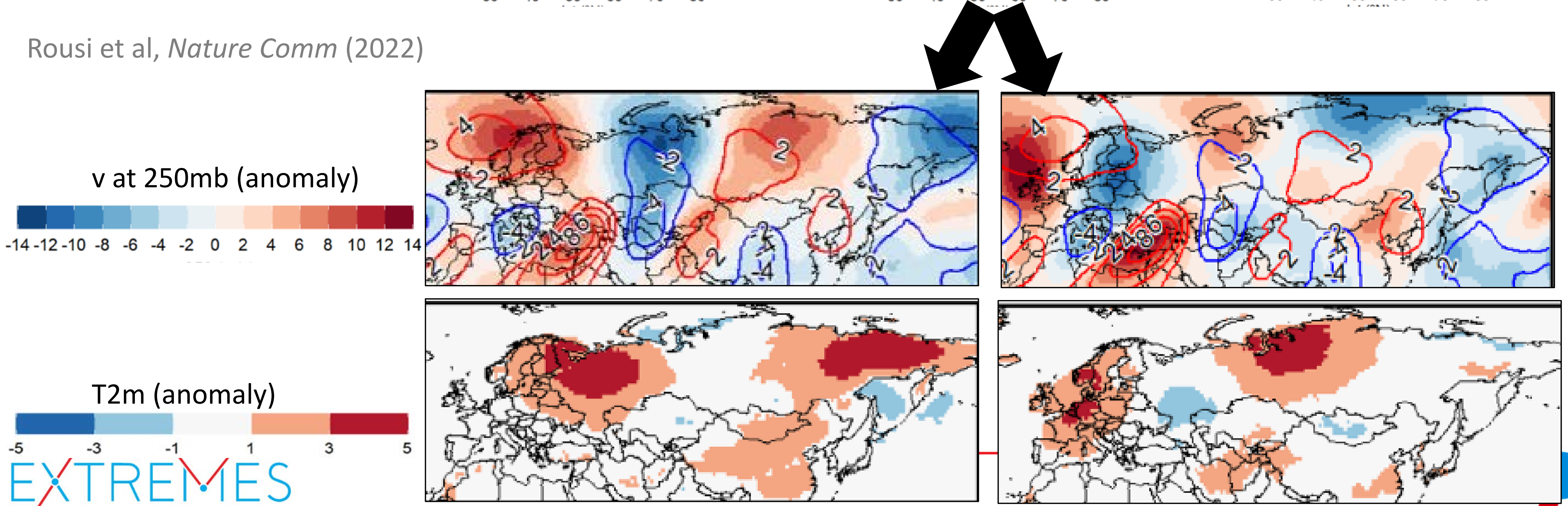




CLIMATE EXTREMES

# ‘Double jet states’ have become more persistent over Eurasia

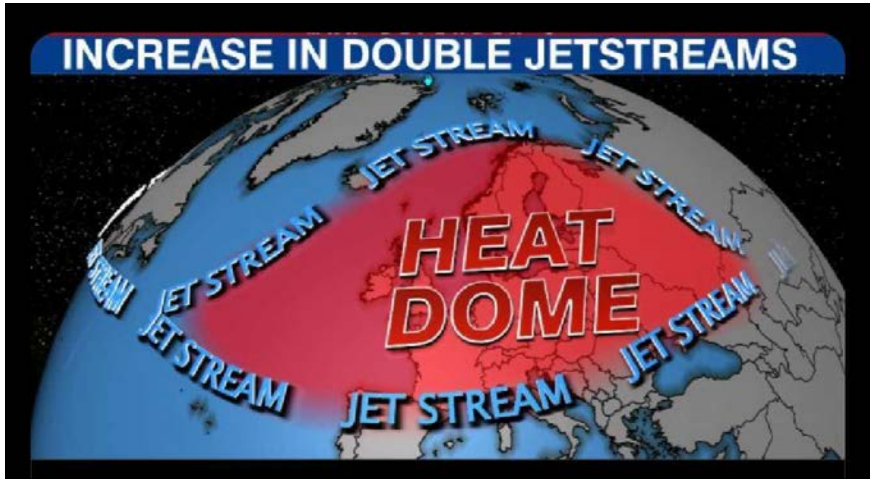



Rousi et al, *Nature Comm* (2022)

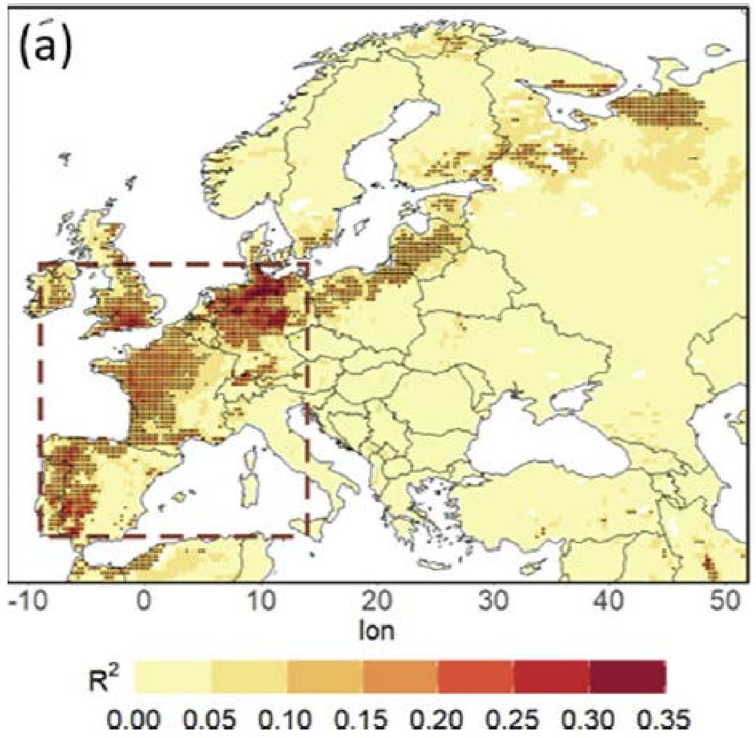



EXTREMES

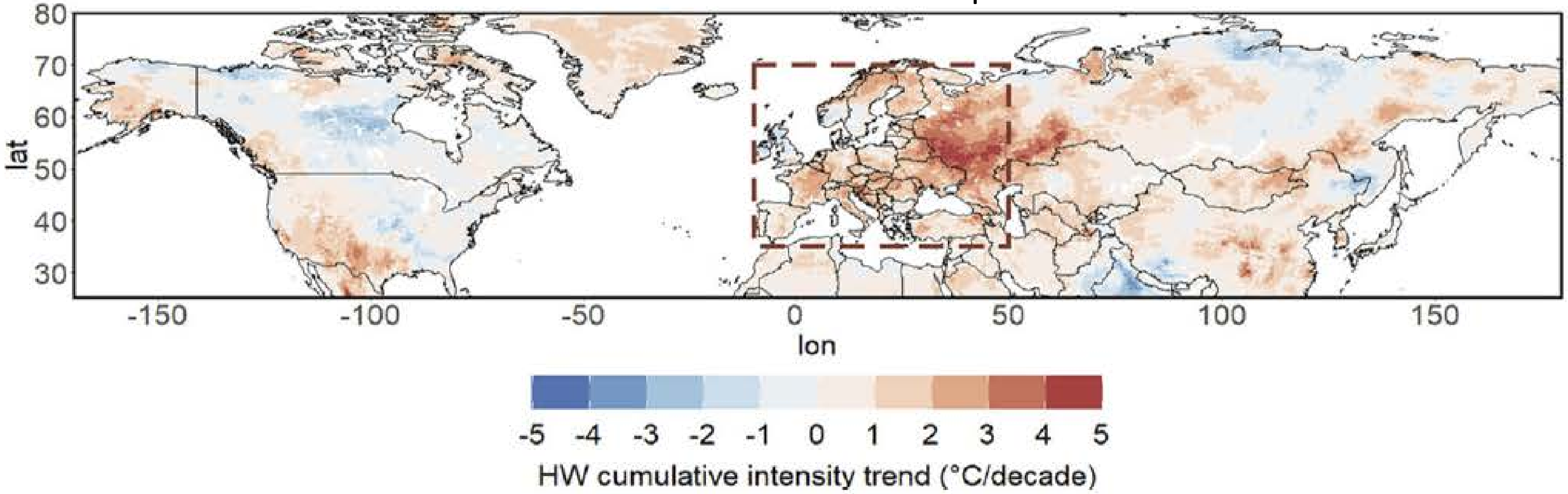
# Persistent double jet states particularly important for western Europe

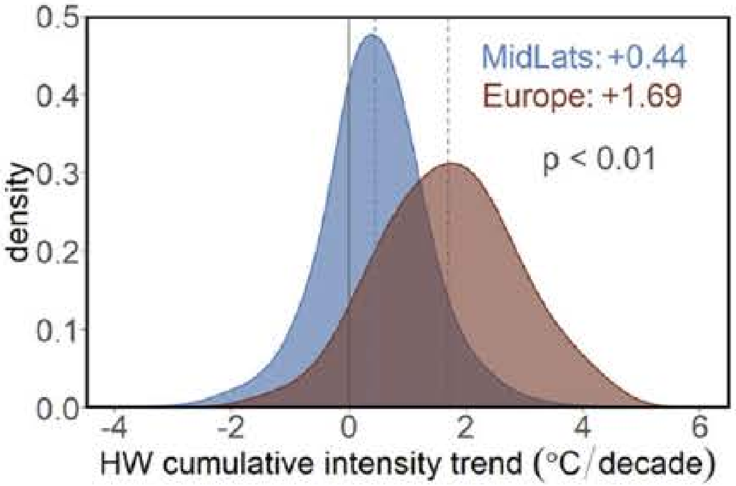



Explained variance ($R2$) of heatwave cumulative intensity based on linear regression on double jet persistence.




Heatwaves increase much faster in Europe than elsewhere

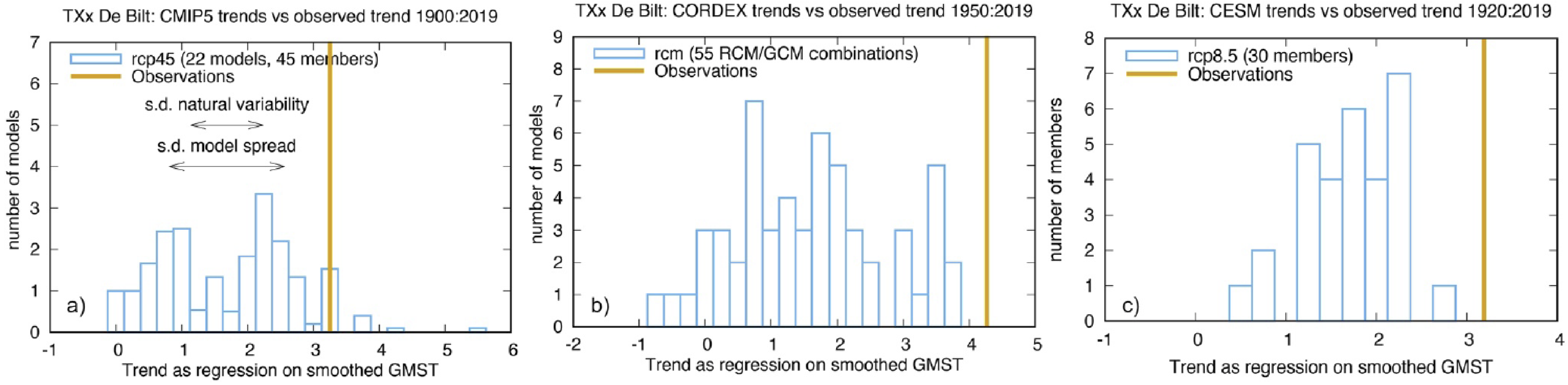


# Climate models do not capture pronounced trends in heatwaves over Europe

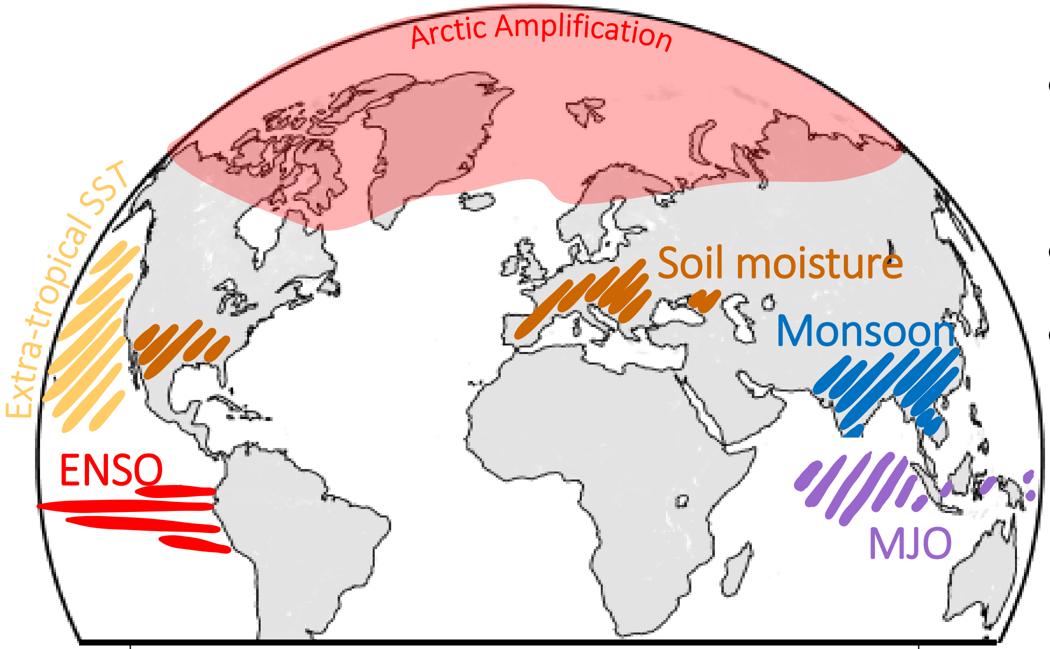
**Attributing and Projecting Heatwaves Is Hard: We Can Do Better**

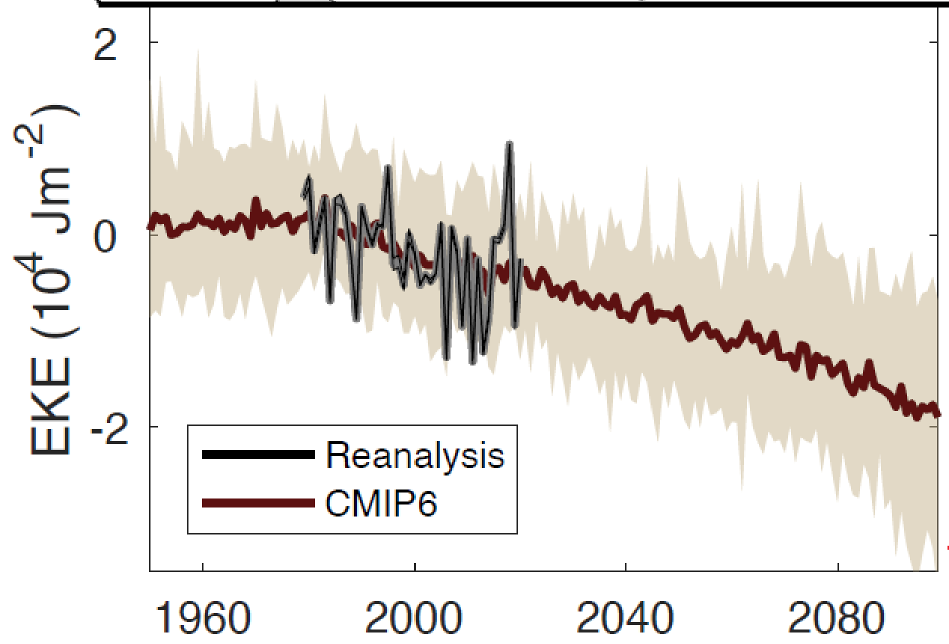
**Geert Jan Van Oldenborgh[1], Michael F. Wehner[2], Robert Vautard[3], Friederike E. L. Otto[4], Sonia I. Seneviratne[5], Peter A. Stott[6], Gabriele C. Hegerl[7], Sjoukje Y. Philip[1], and Sarah F. Kew[1]**




Histogram of the TXx trends at De Bilt in the CMIP5 ensemble compared to the observed trend 1900–2019

# Take away messages




## S2S predictability of CGWTs

- Tropical SSTs & monsoon variability important drivers of CGWTs
- Warm pool variability important for EU summers
- Extra-tropical SSTs & local soil-moisture patterns can cause 2-way feedback and thereby strengthen CGWT

## Climate risks

- Boreal summer stormtracks & westerlies weaken due to Arctic Amplification, likely attributable
- Trend towards more-persistent double jets, linked to increase in EU heatwaves. Causal drivers still unclear
- What about CGWTs? What about summer drought?

# Take away messages

**<u>Things are complex:</u>**
**Both tropics, Arctic and regional feedbacks are important for boreal summer circulation**

**<u>Beware of:</u>**
**Differences between seasons and differences between timescales**

**<u>Reasons for hope:</u>**
**Explainable AI & Causal Discovery can help to solve the puzzle (in addition to climate models)**

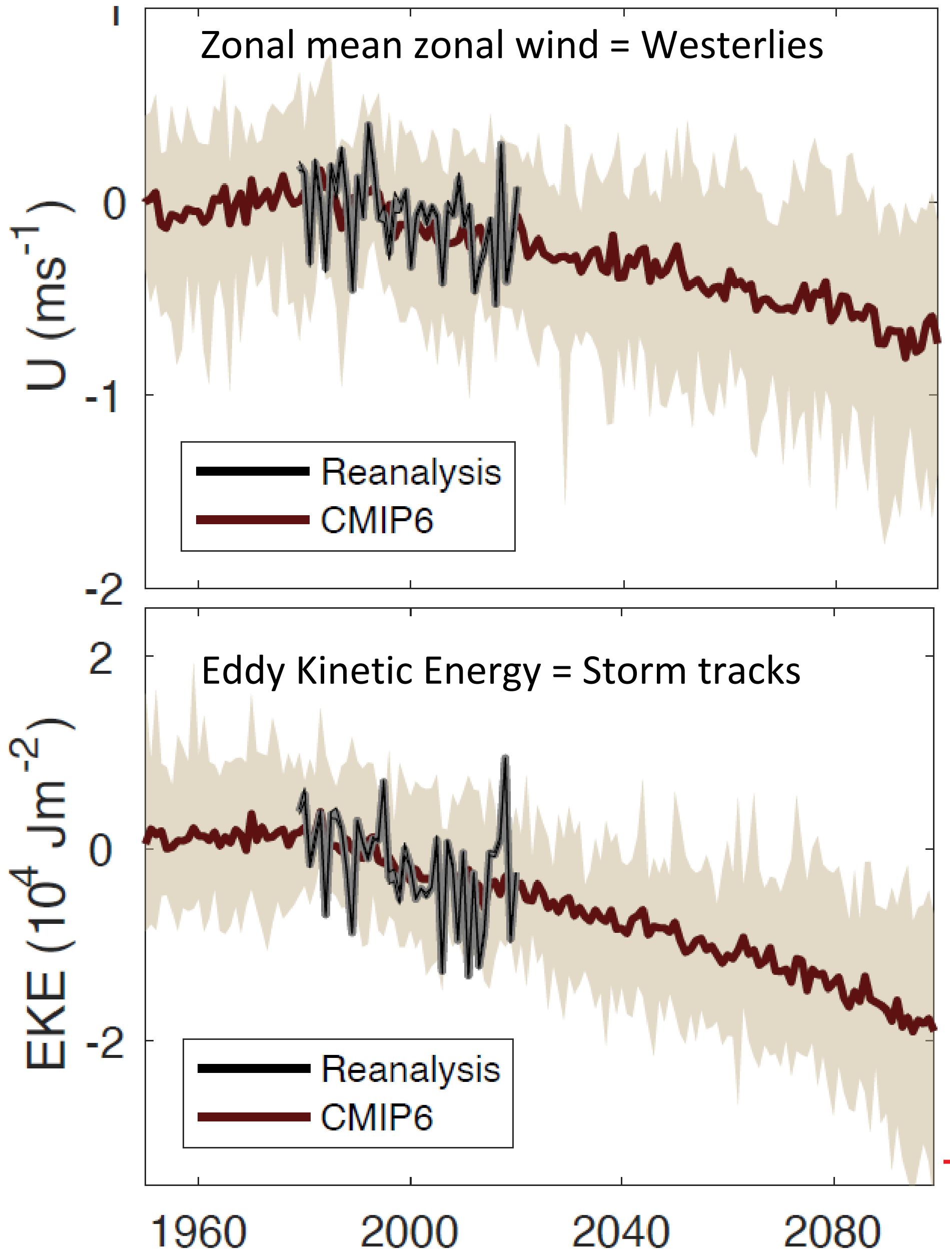
@DimCoumou

Koninklijk Nederlands Meteorologisch Instituut
*Ministerie van Infrastructuur en Milieu*

VU VRIJE UNIVERSITEIT AMSTERDAM

CLIMATE EXTREMES

# Is climate change affecting boreal summer circulation?

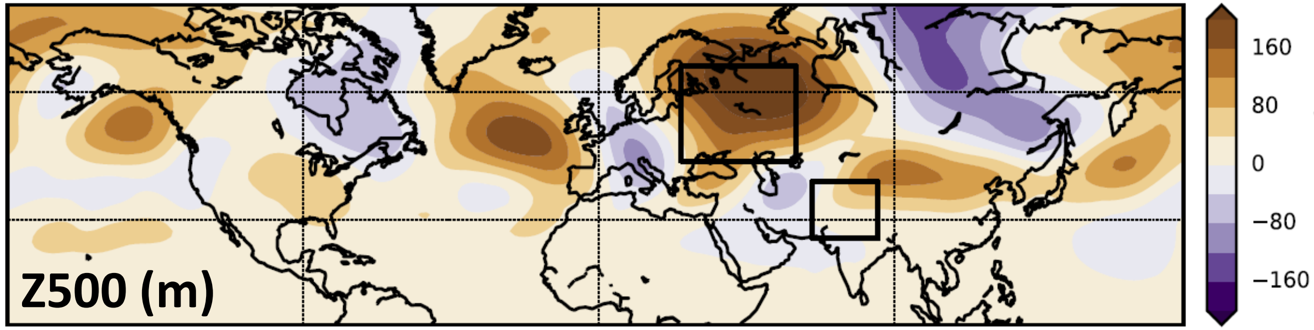



Both westerlies & storm tracks have been weakening since 1979. Internal variability or GHG forced?

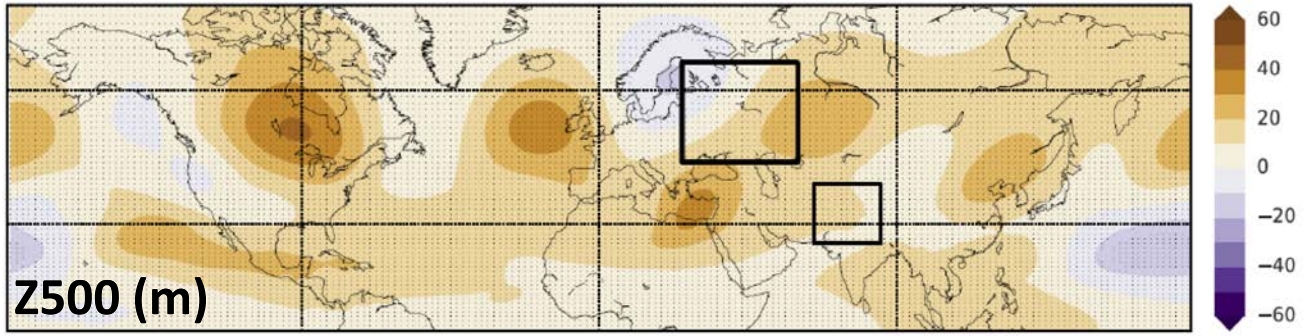
Coumou et al (2015); Chemke & Coumou (in review)

# Drivers of 2010 extremes: Russian Heatwave & Pakistan Flooding

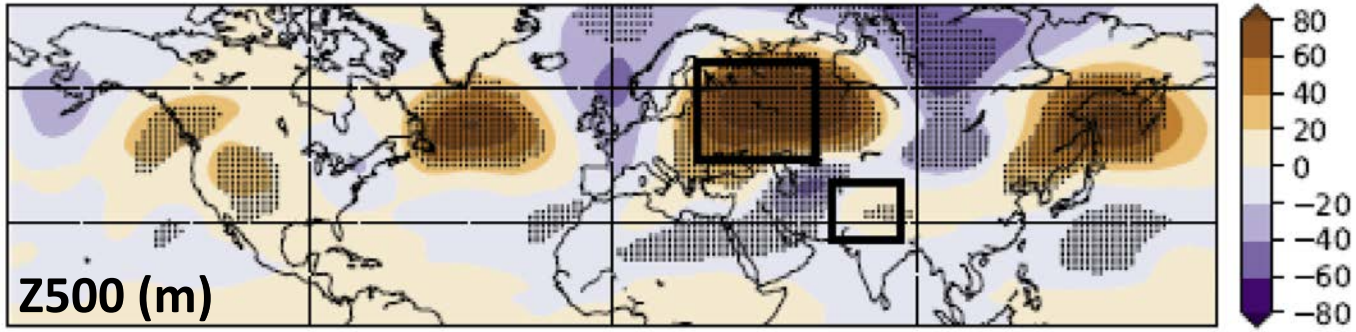
ERA5 reanalyses (25 July – 8 Aug 2010)

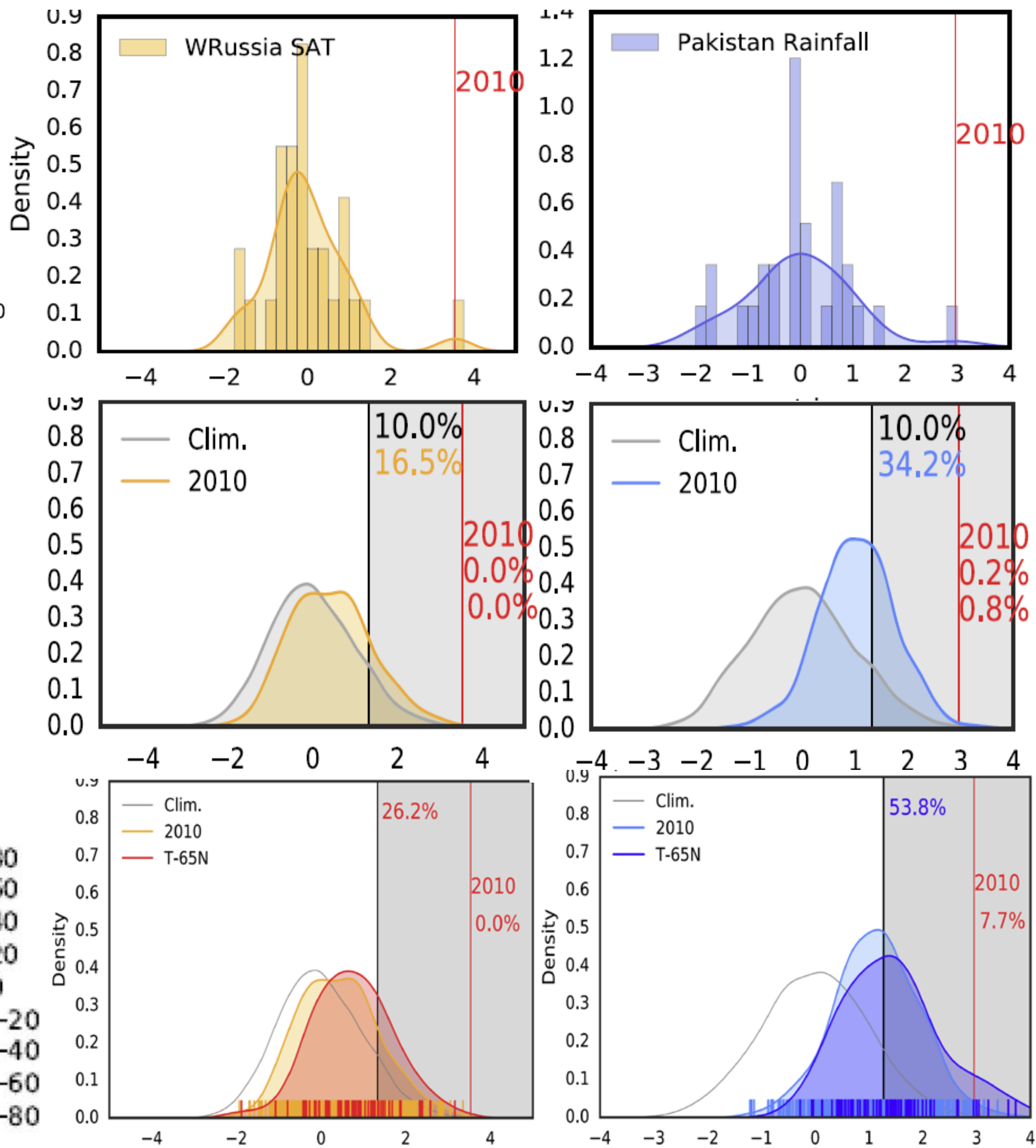



Model, ensemble mean

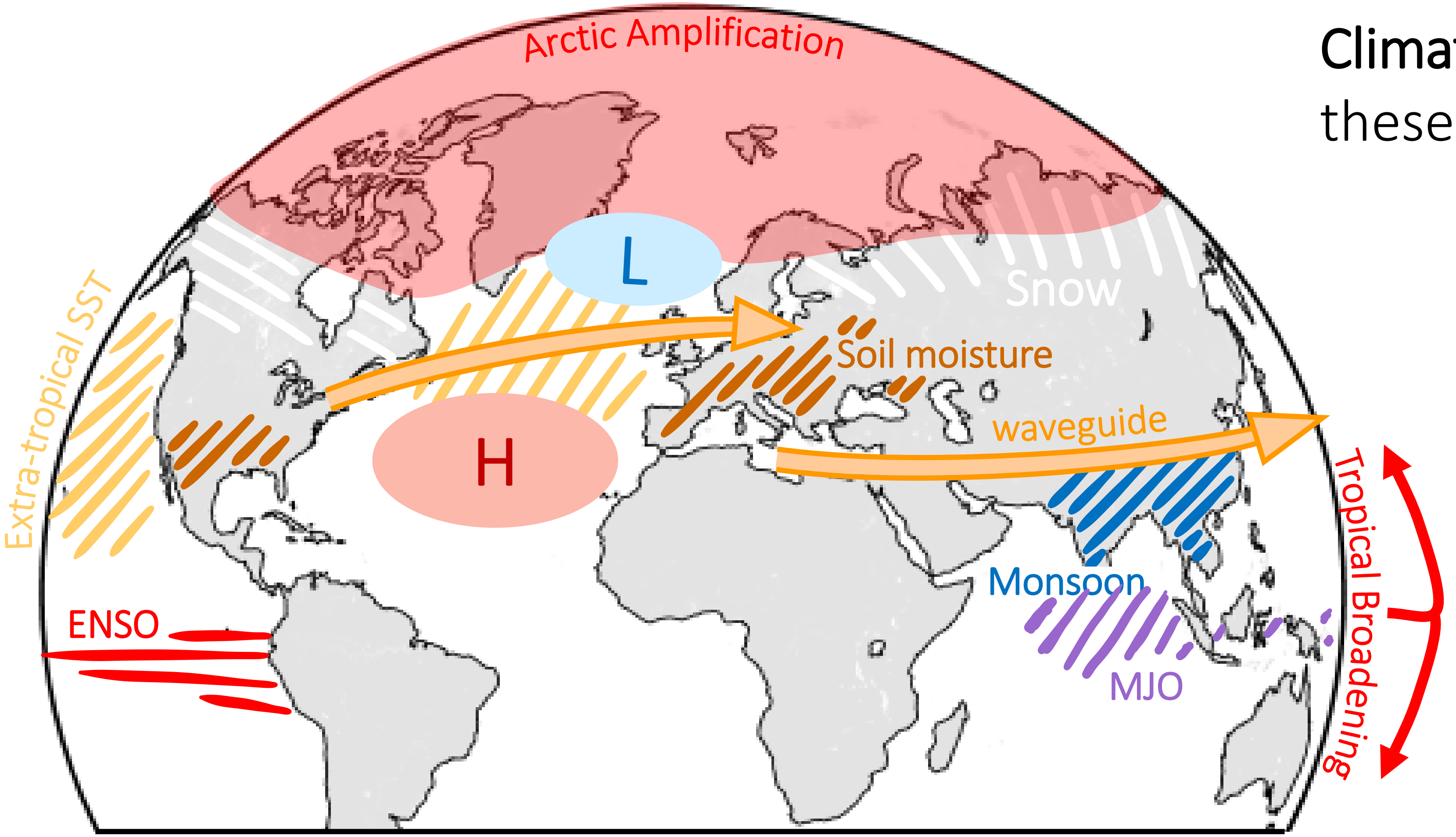



Model, 10% warmest Arctic



# Drivers of quasi-stationary CGWT in summer



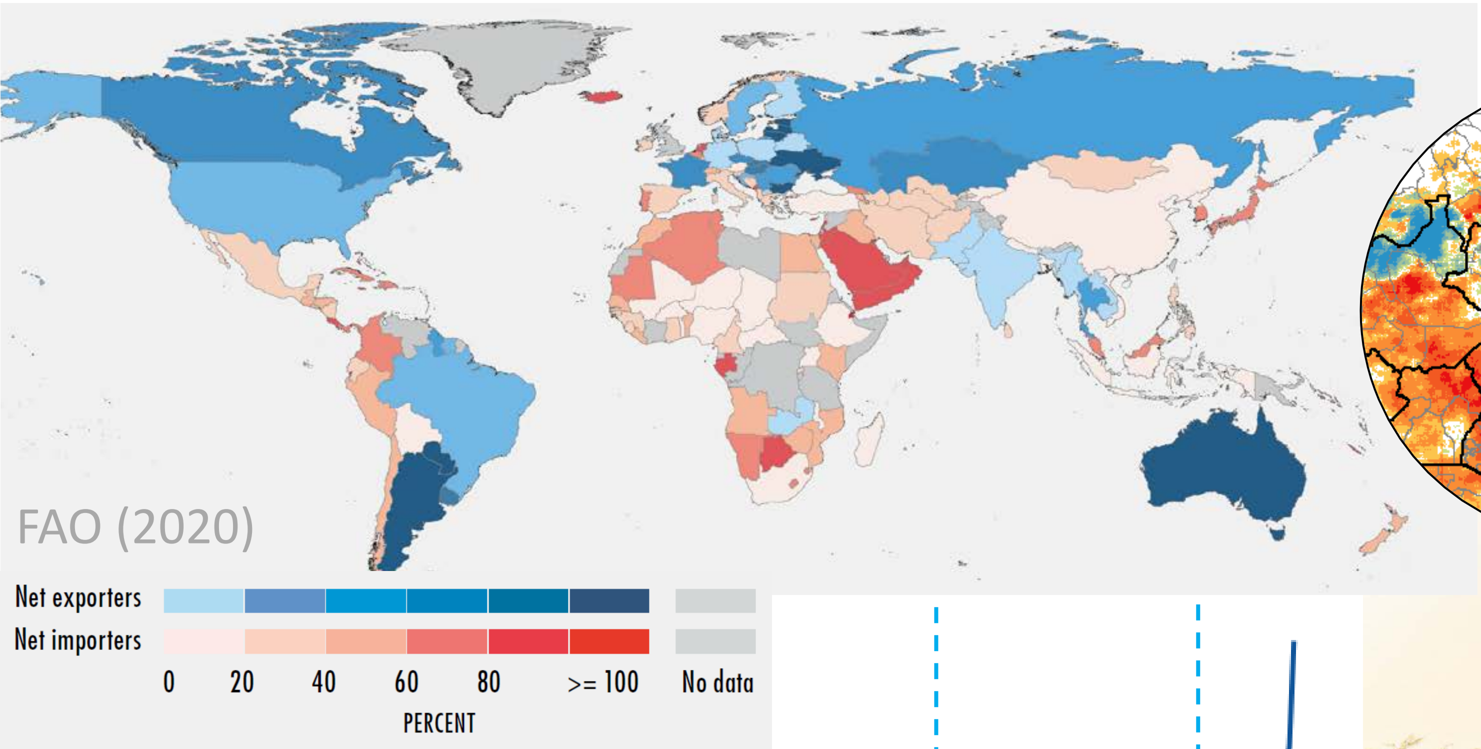

**Complex processes** operating on different timescales

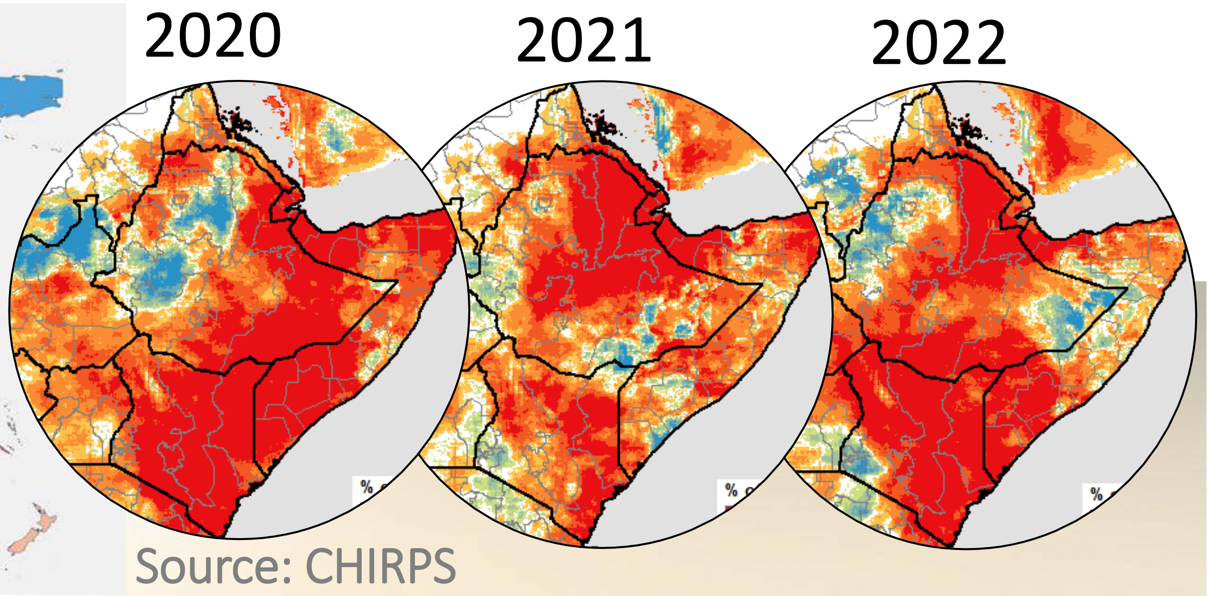
**Climate change** acts on all of these processes

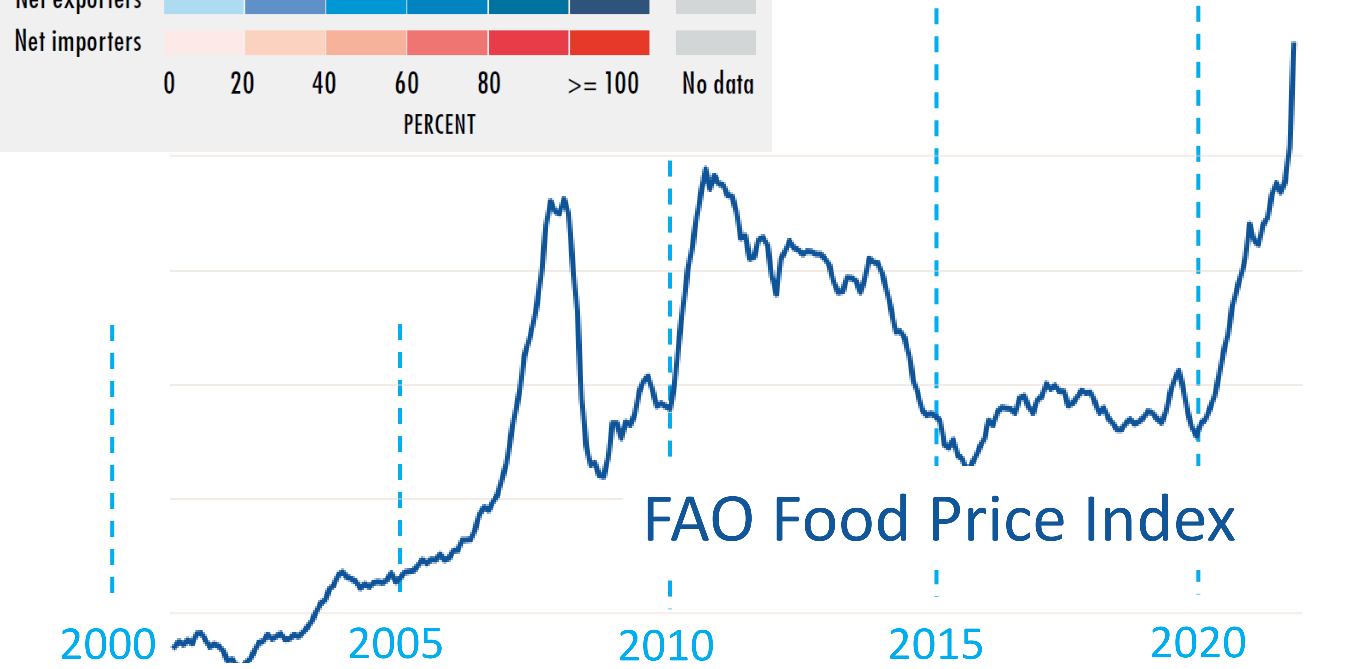
**How to disentangle cause and effect?**

# 2022 Food prices

# Continuing drought in E-Africa



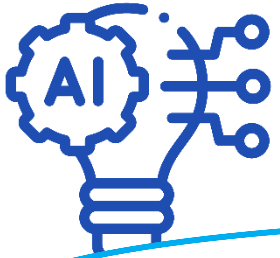




Record prices impact vulnerable importing nations

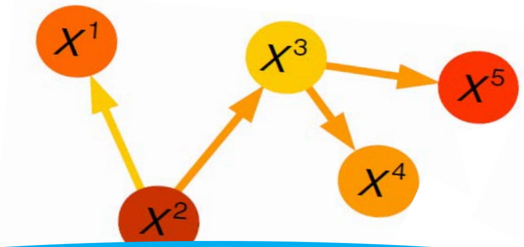
# How to harvest knowledge from big data?

**Data Sciences**

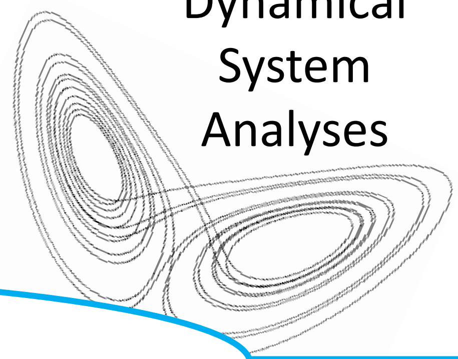
Explainable AI



Causal Discovery




Dynamical System Analyses

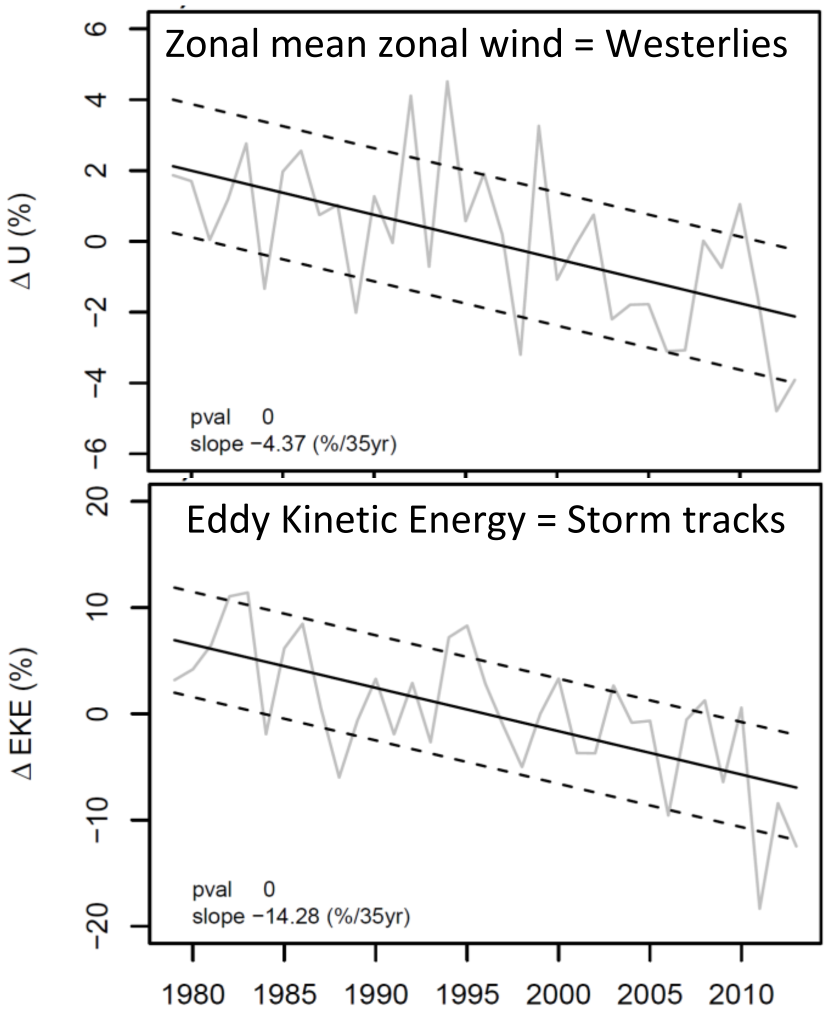


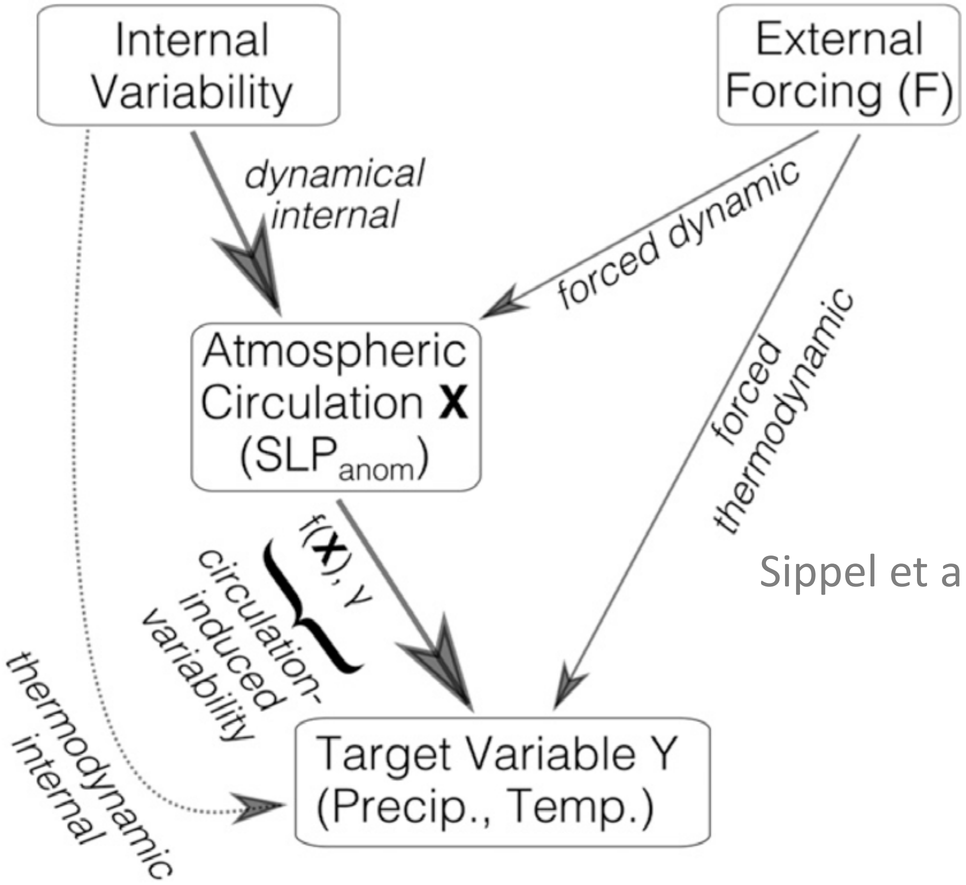
Process Understanding
Teleconnections & Extremes

**Goals**

1. Regional projections of extremes & Societal risks
2. (Sub) seasonal forecasting & impact-based forecasting
3. Attribution of (impacts from) extremes

# Is climate change affecting boreal summer circulation?

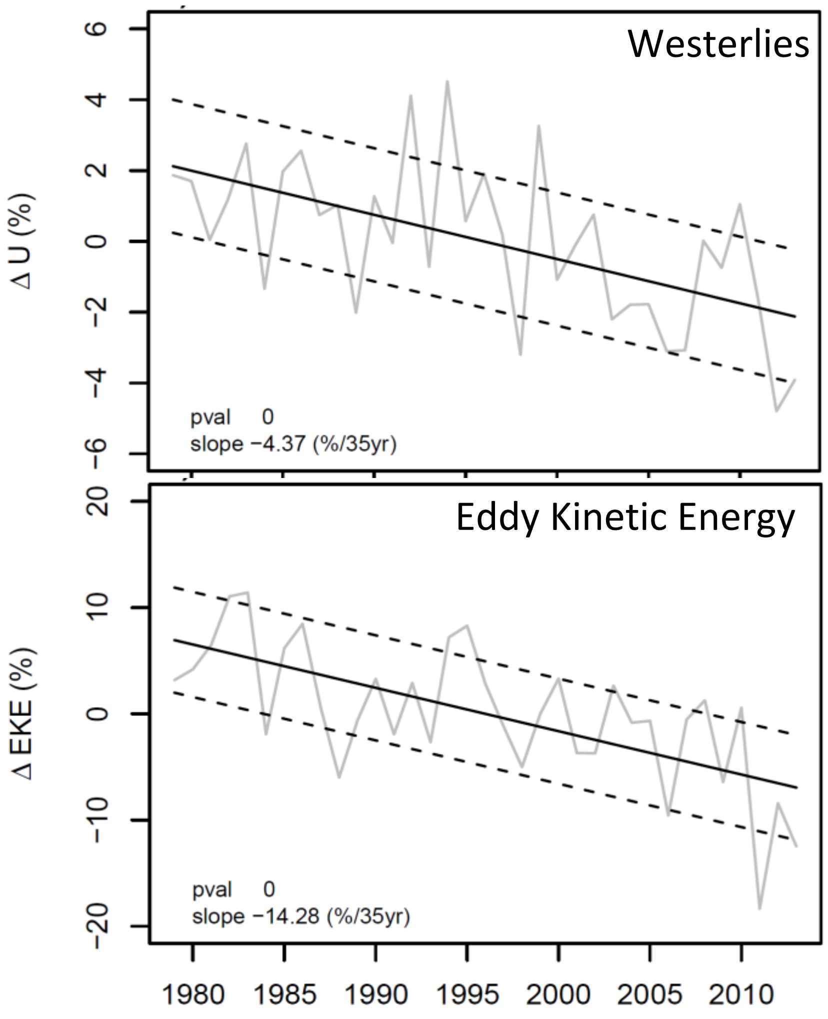


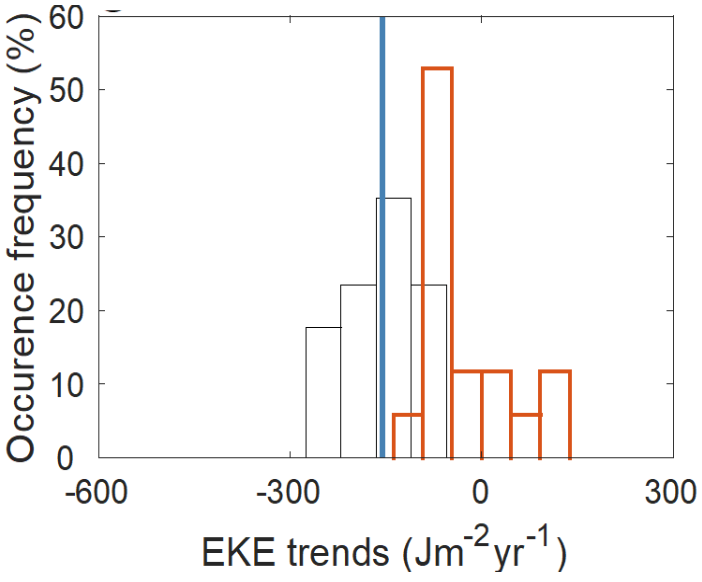



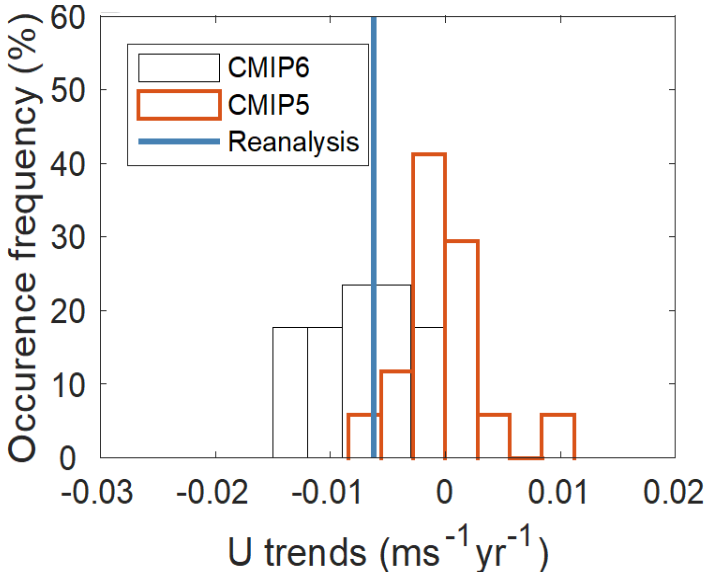

Sippel et al (2019)

Both westerlies & storm tracks have been weakening since 1979. Internal variability or forced?

# Is climate change affecting boreal summer circulation?



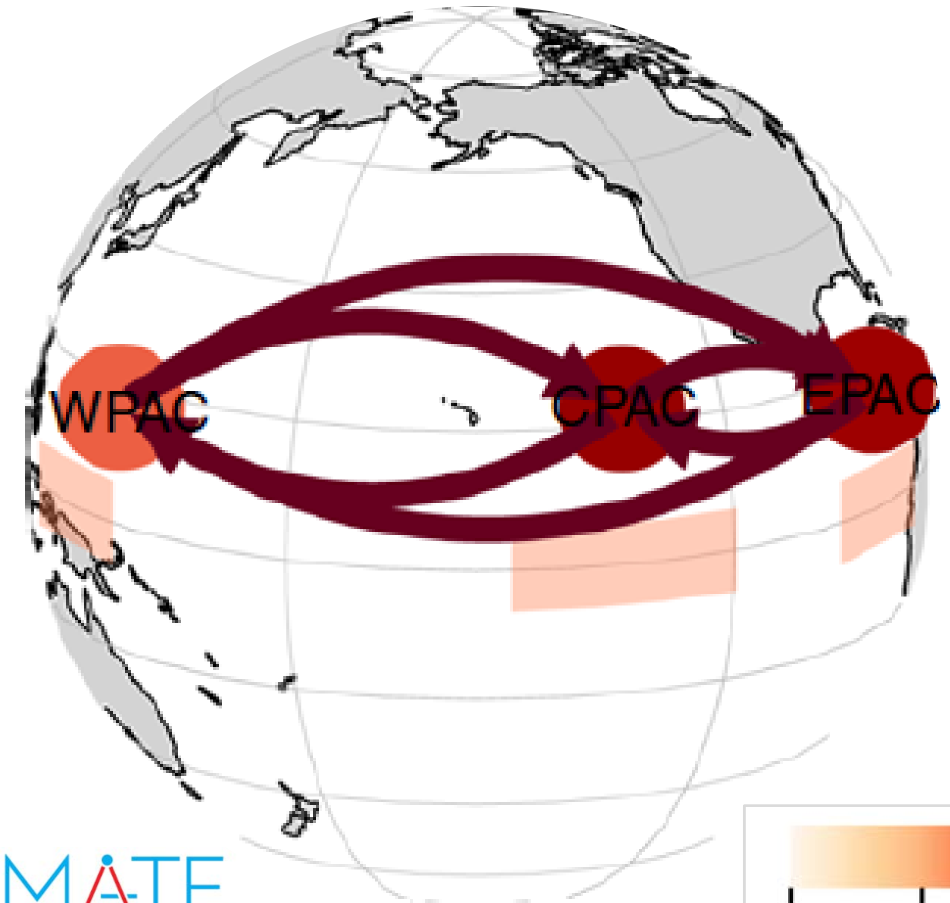

Both westerlies & storm tracks have been weakening since 1979

CMIP6 models capture this downward trend but CMIP5 models do not

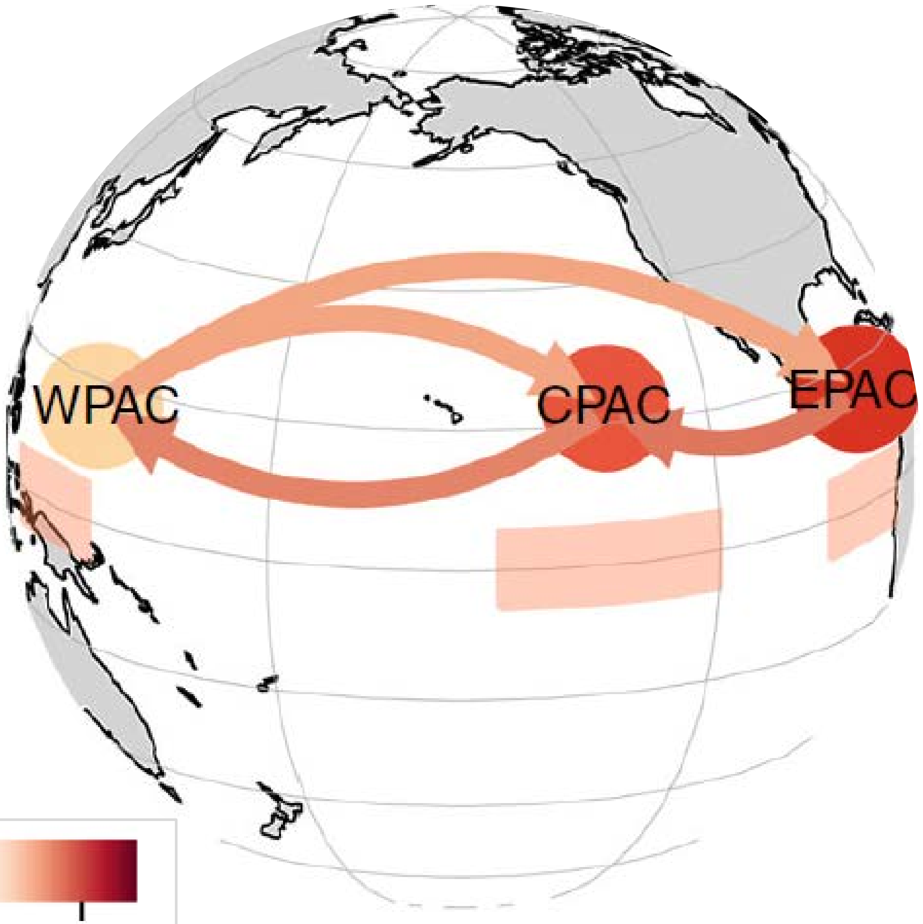
CLIMATE EXTREMES Coumou et al (2015); Chemke & Coumou (in review)

# Simple case: Dynamical Links over the Pacific Ocean

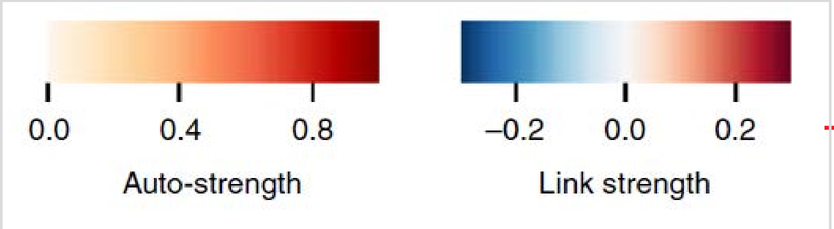
Correlation Network




Causal Effect Network



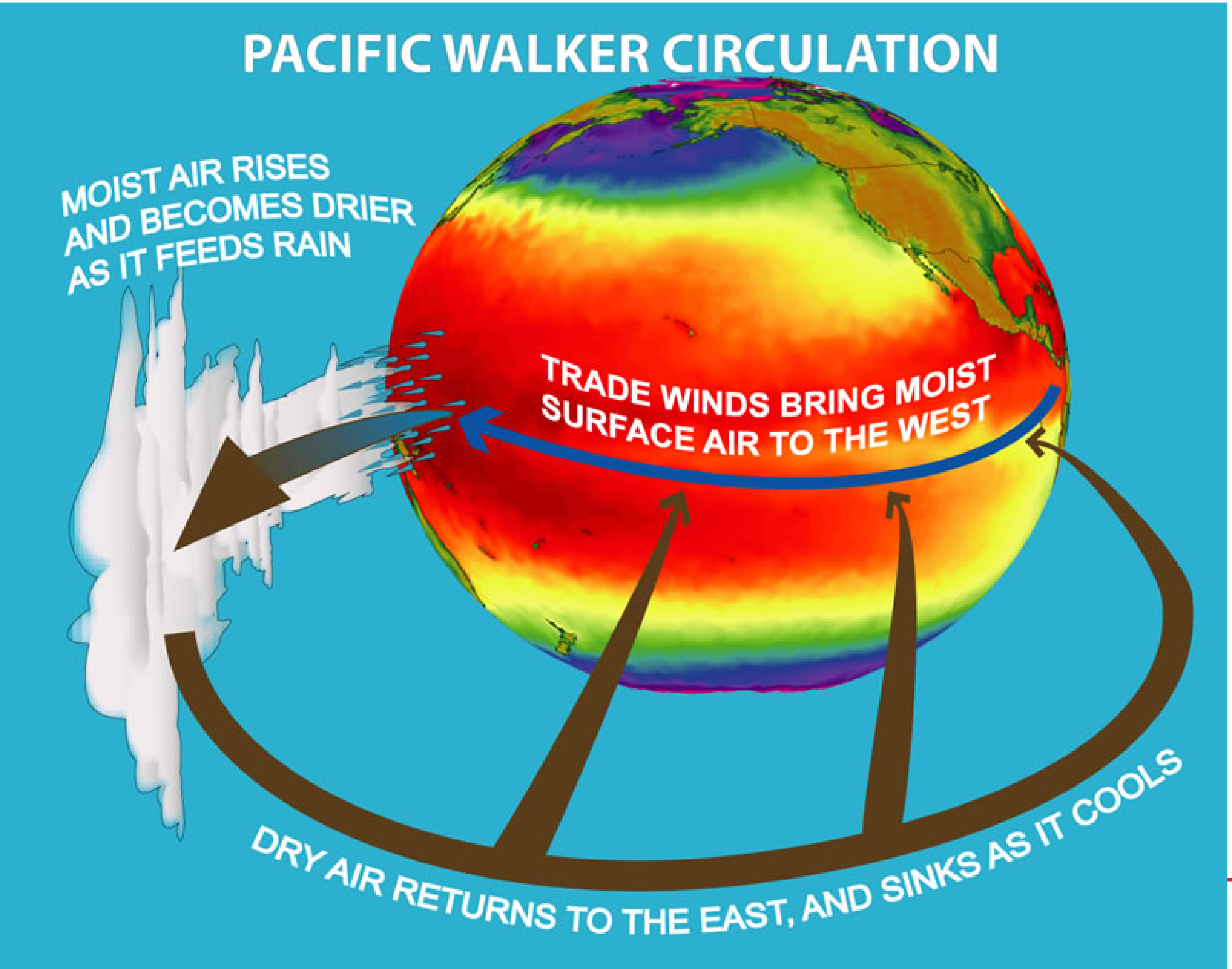

Monthly SLP anomalies



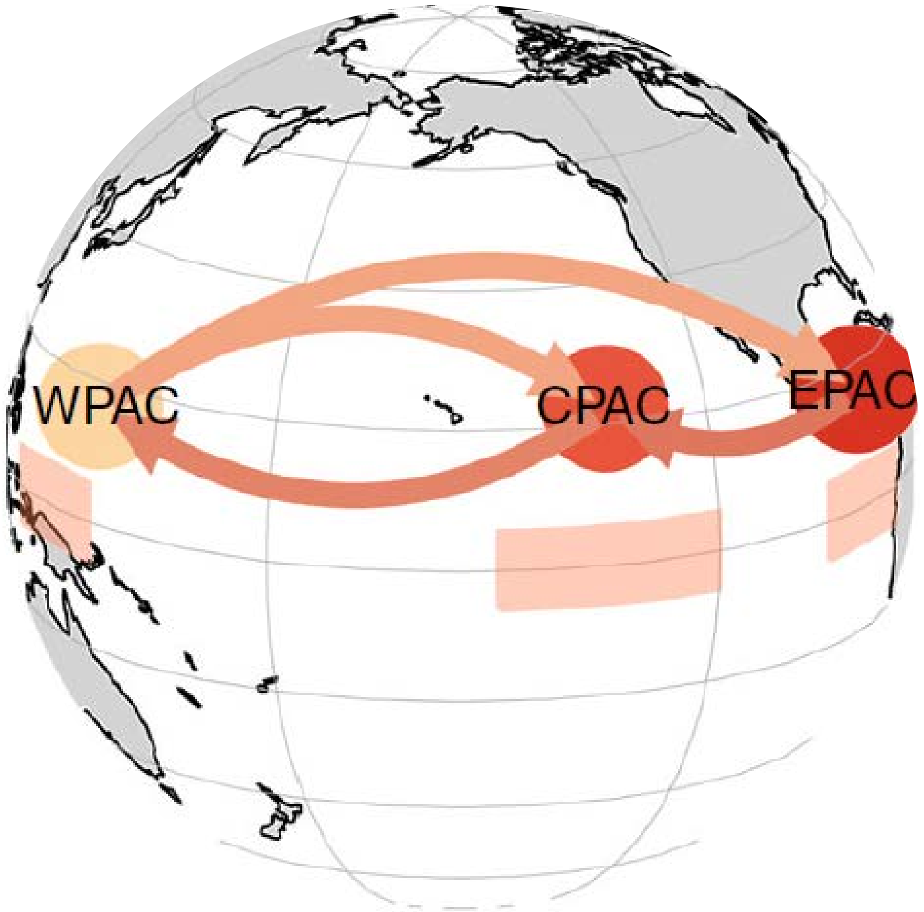

CLIMATE EXTREMES

Runge et al, *Nature Comm* (2019)

# Simple case: Dynamical Links over the Pacific Ocean




Causal Effect Network

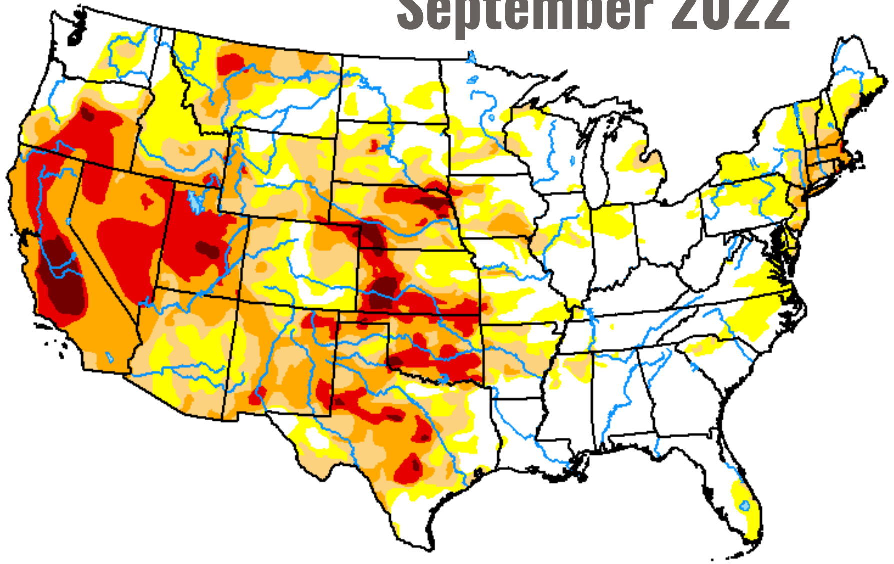


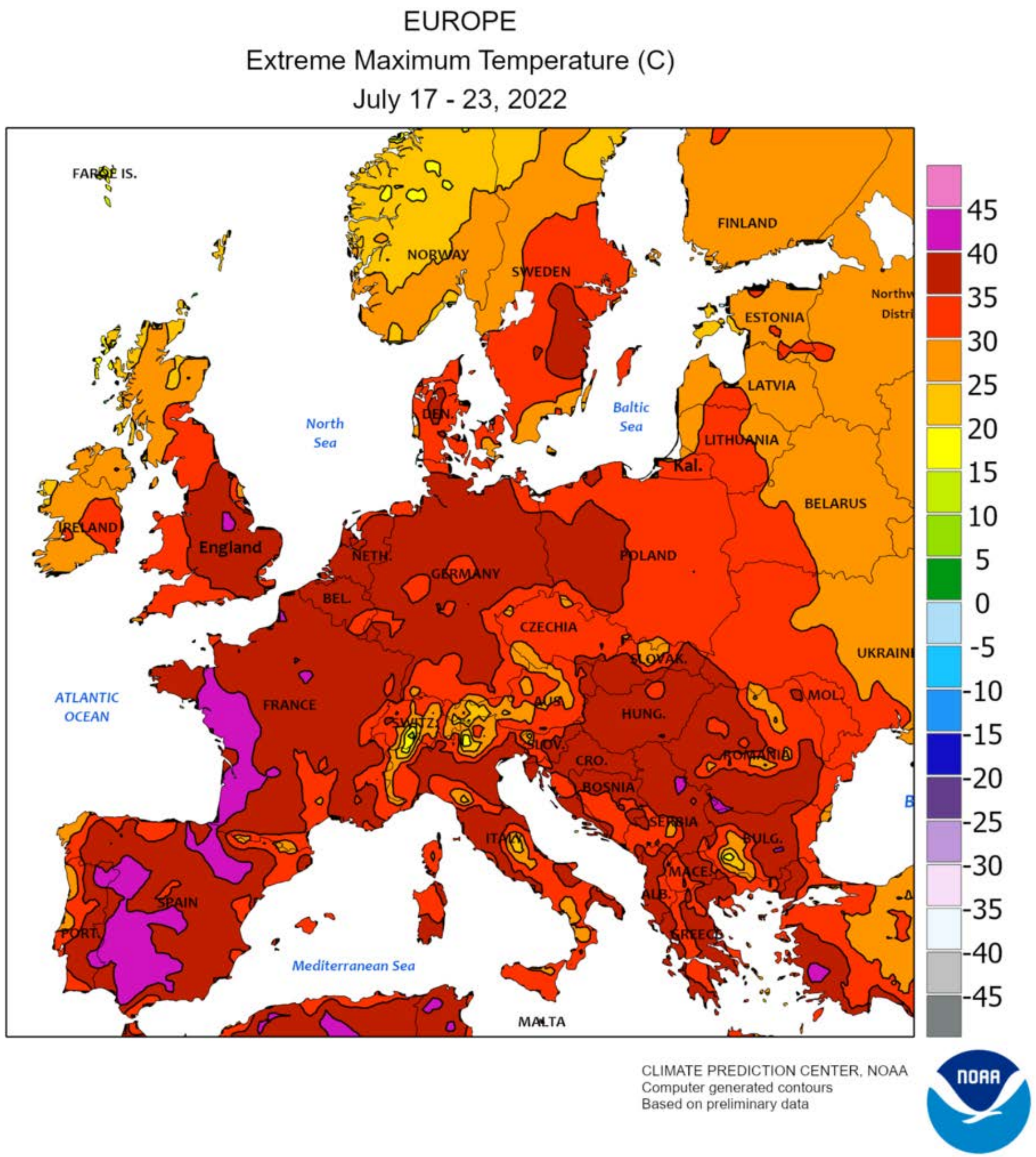

Runge et al, *Nature Comm* (2019)

# What are the implications for recent summer heat/drought?

- New work from Robert V suggests that climate models do not capture trend in dynamical states relevant for heat waves
- Are weakening storm tracks favoring summer droughts over Europe & potentially also western US?
- Sabbatical work…

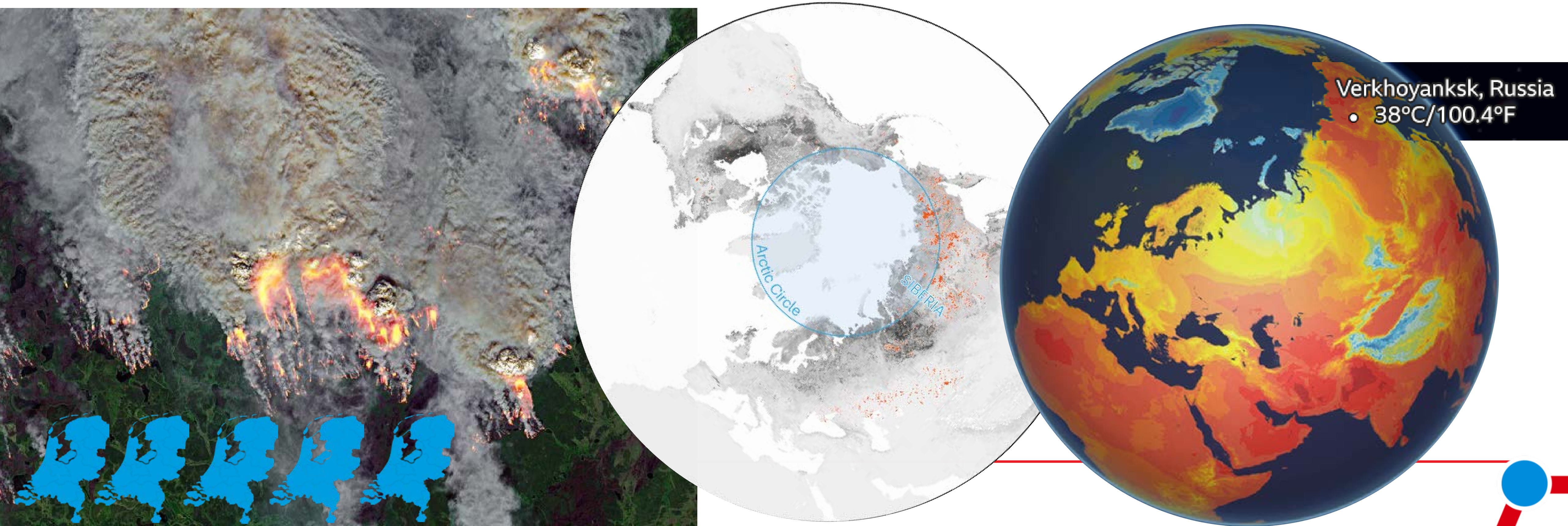
September 2022





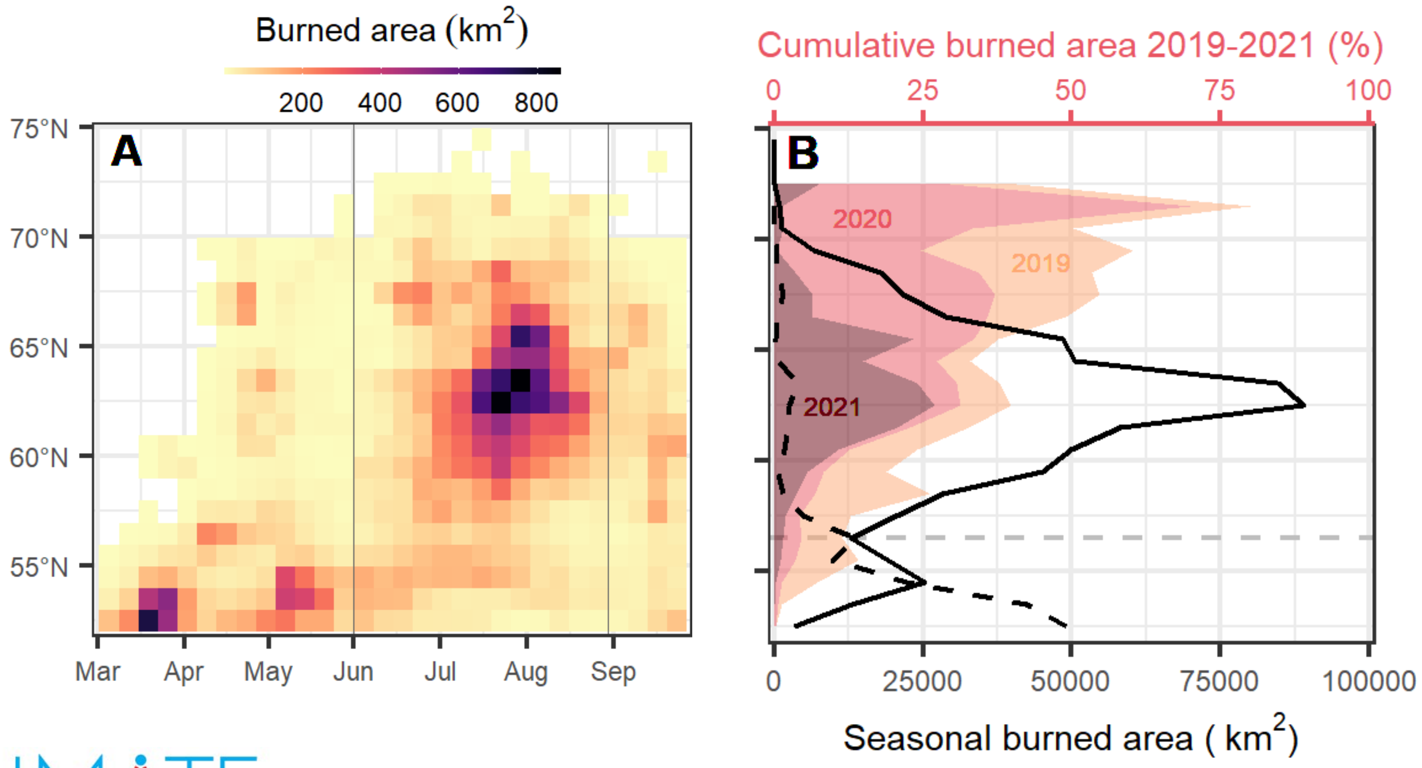
# Double jet also important for high-latitude extremes

Summers of 2019 and 2020 experienced extreme fire activity in northeastern Siberia that were driven by record-high spring and summer temperatures

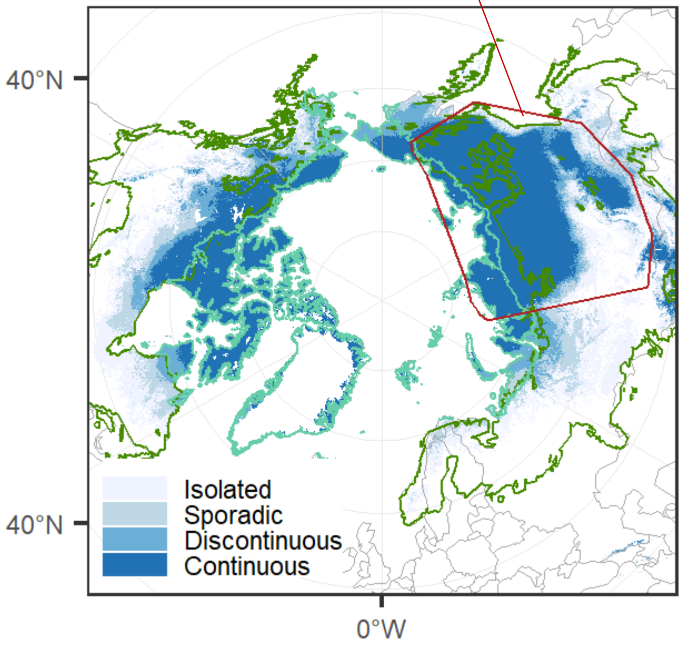


# Double jet also important for high-latitude extremes

- Fires in high-latitudes occur during July/Aug
- 2019/2020 exceptional, especially > 65N



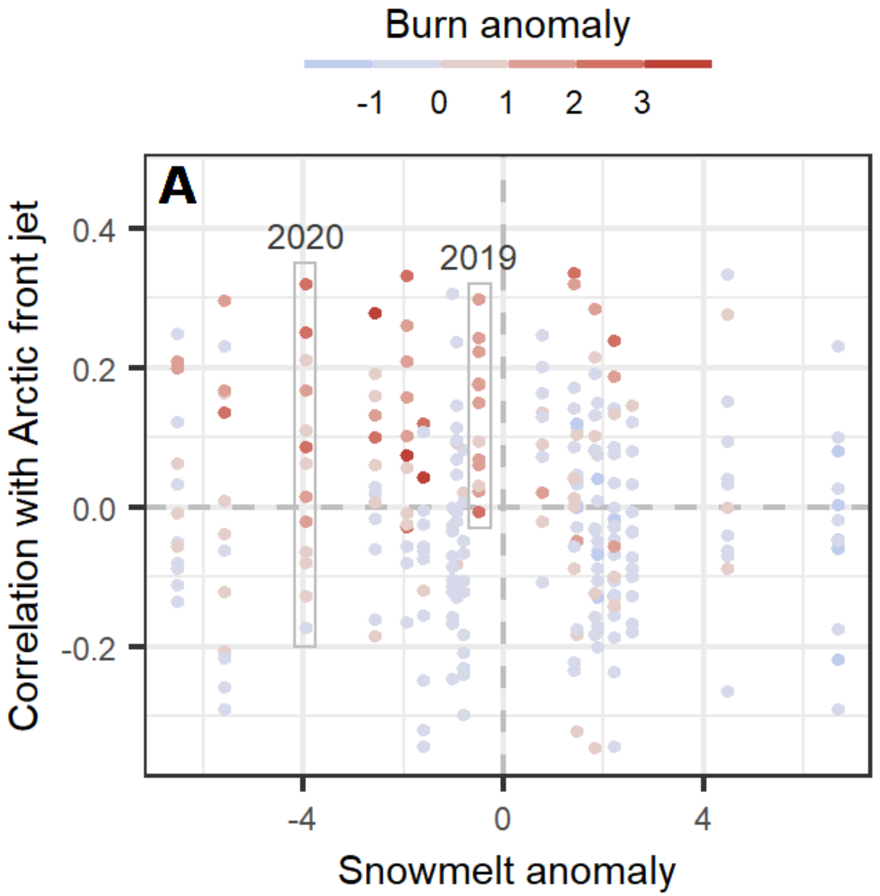

Study area:
Eastern Siberian larch forests and northern tundra



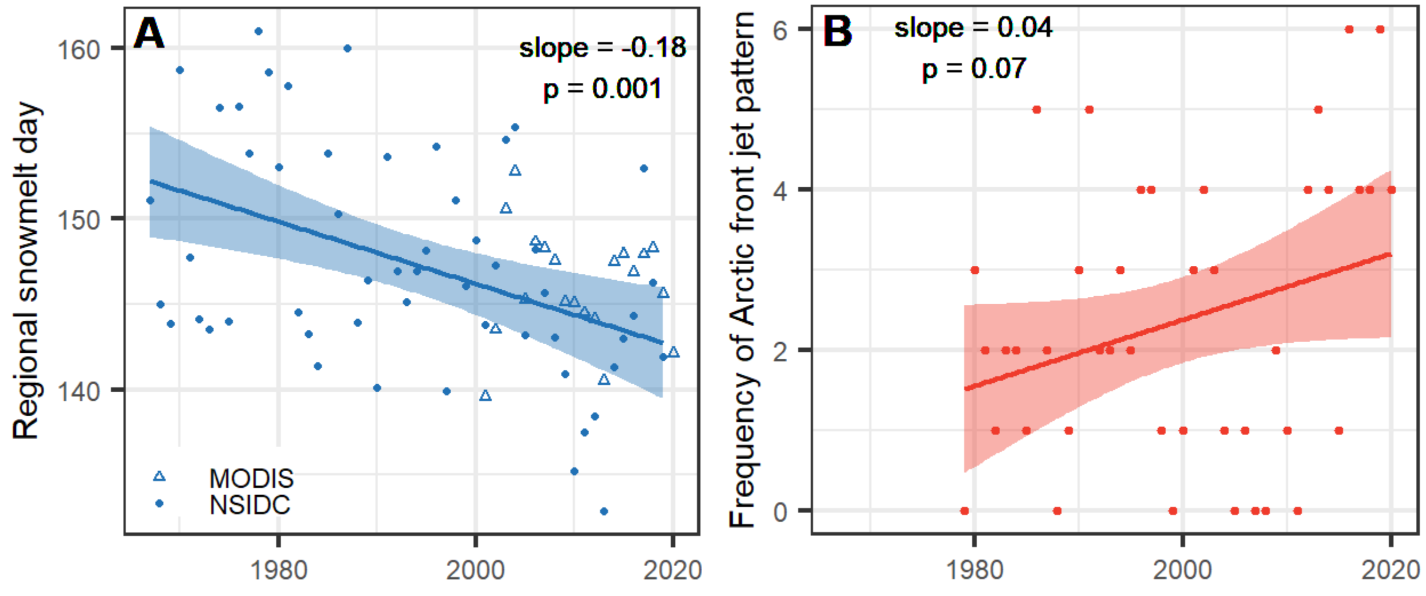

Scholten *et al.* (in review.)

# Double jet also important for high-latitude extremes

- Compound effects: Combined effect of early snow melt and Arctic front jets drives fires
- Long-term trends: Earlier snow melt & more frequent Arctic jets (=double jet states as in Rousi et al)

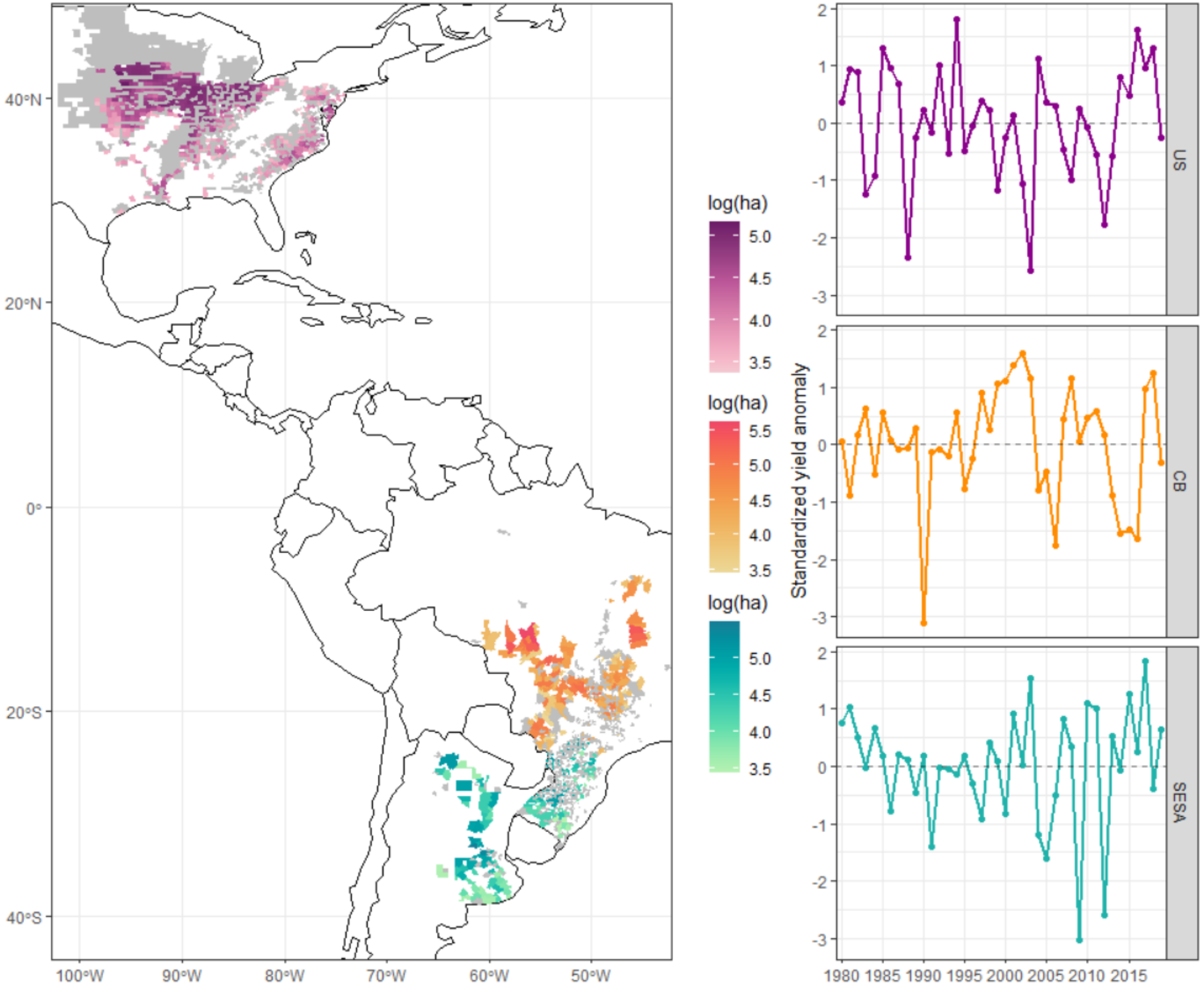



Long-term trends promote extreme fire activity




Scholten *et al.* (in review.)

# Soybean particularly sensitive to joint breadbasket failure



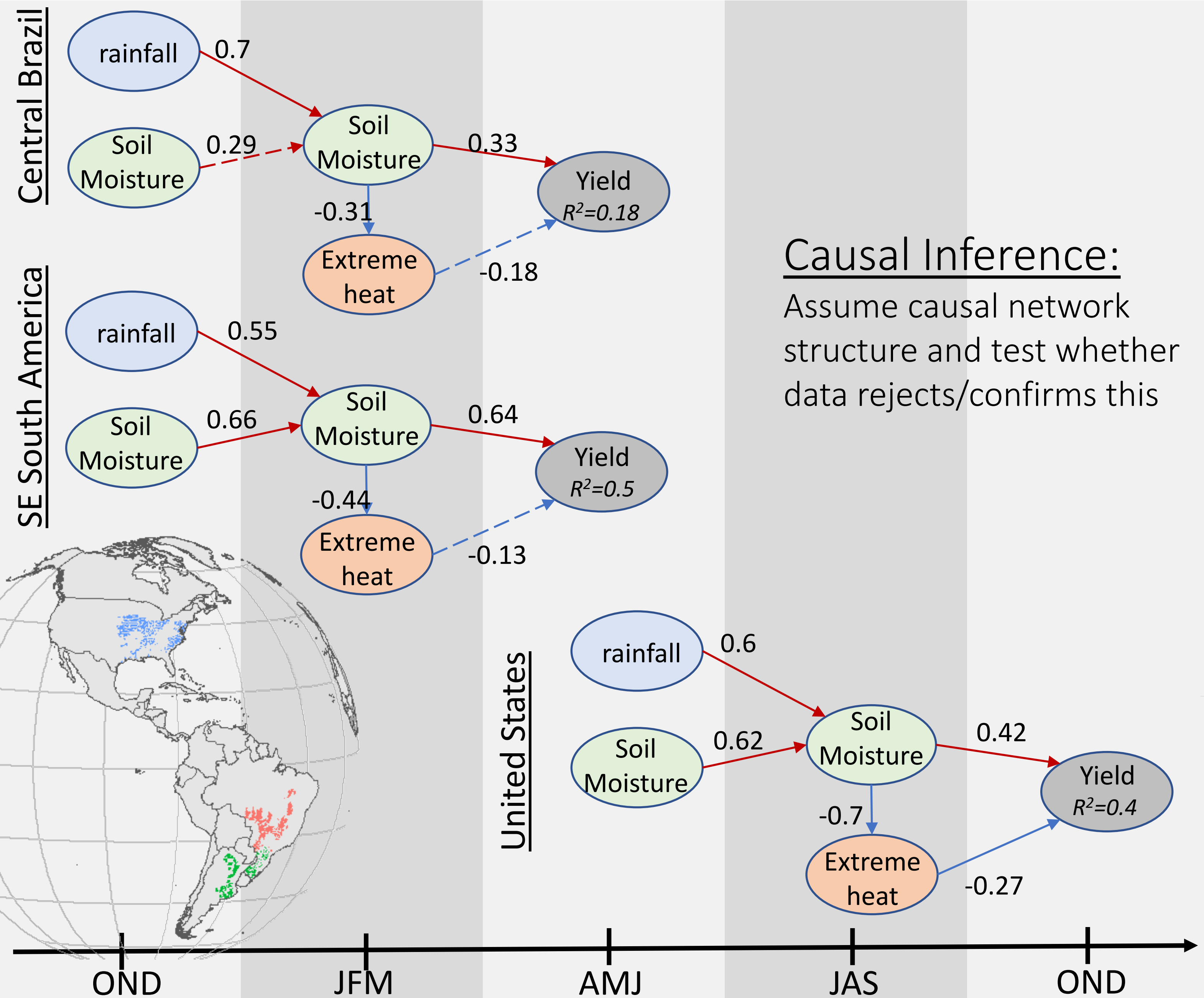

80% of global market supply comes from the three regions only:

- Eastern United States
- Central Brazil
- Northern Argentina

Are there teleconnection states that negatively impact soybean in all regions?

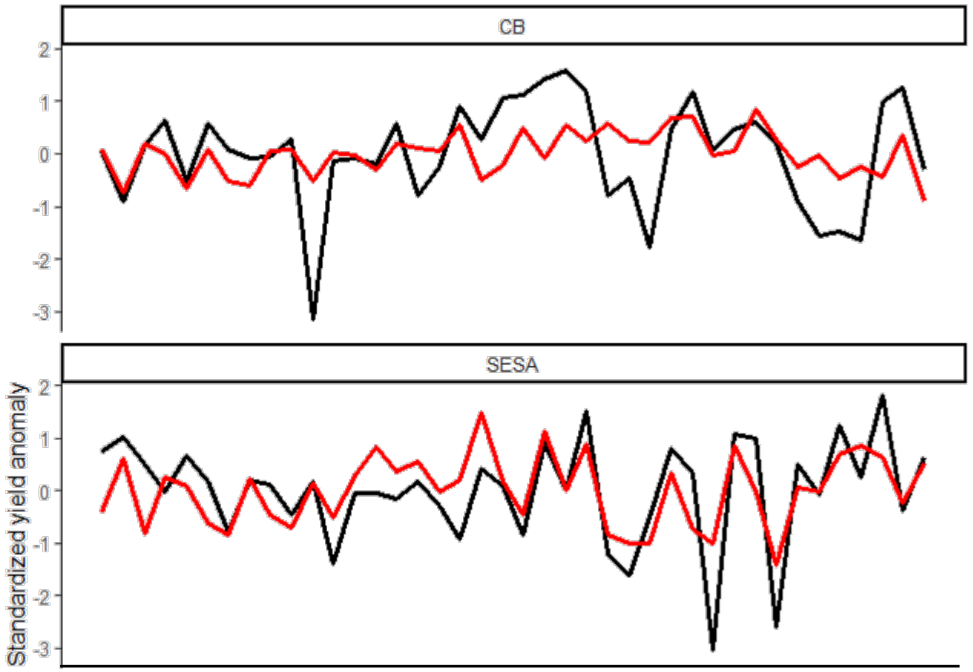
Hamed et al, *in prep*

# Local causal models: central role of soil-moisture memory

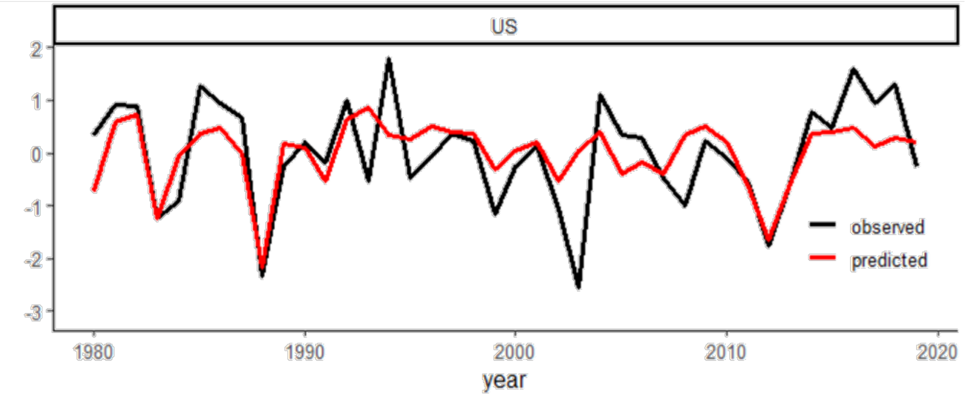



<u>Causal Inference:</u>

Assume causal network structure and test whether data rejects/confirms this

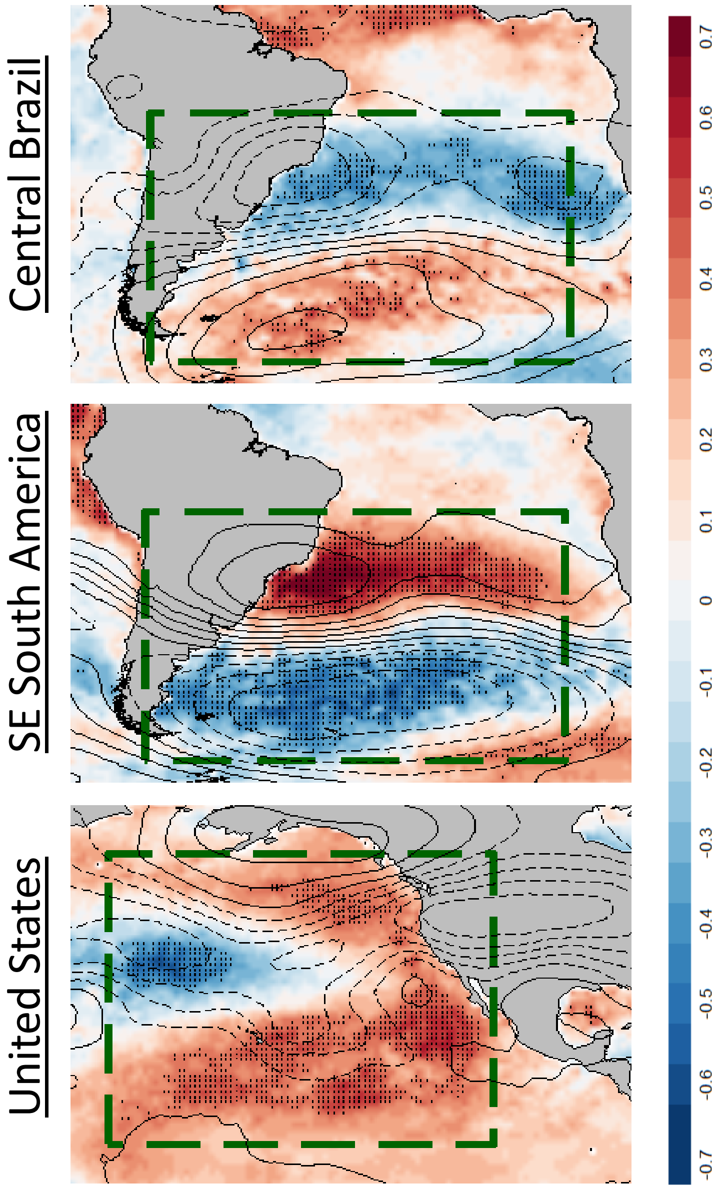



Hamed et al, *in prep*

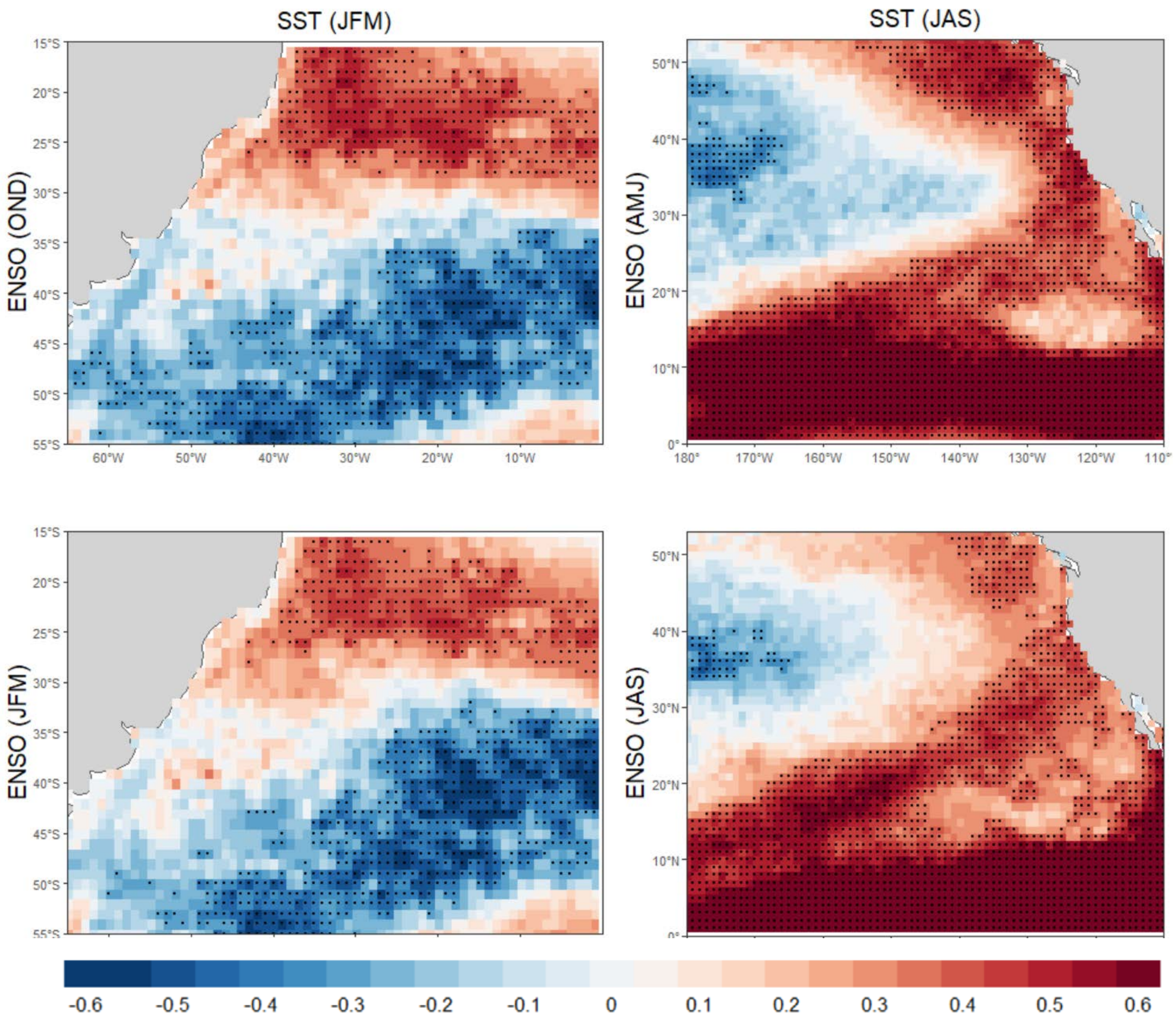


# Teleconnections: central role of ENSO

Correlation maps of soil-moisture with regional SST and Z500




Those regional SST patterns are strongly linked to ENSO

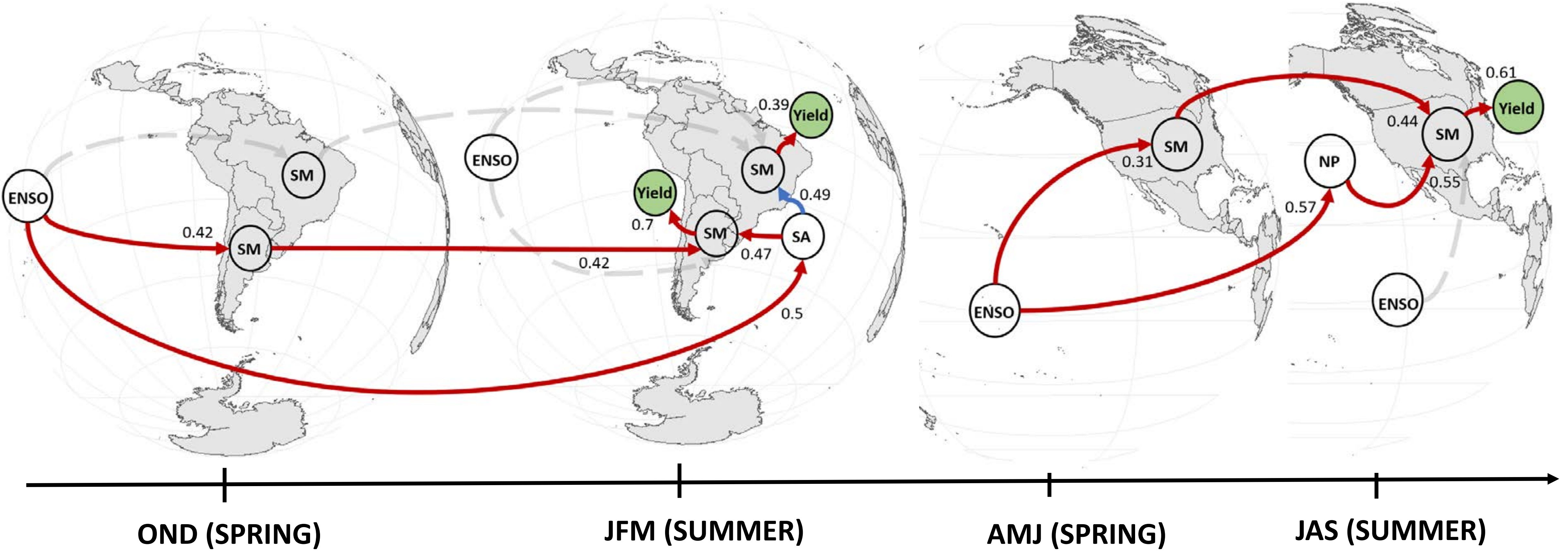



Hamed et al, *in prep*

# Global causal networks for Soybean production

Hamed et al, *in prep*

- ENSO influences soil-moisture in early growing season directly + indirectly via regional SSTs
- Multi-year La Niña most detrimental for global food production
- Such causal graphs can form basis of storyline analyses



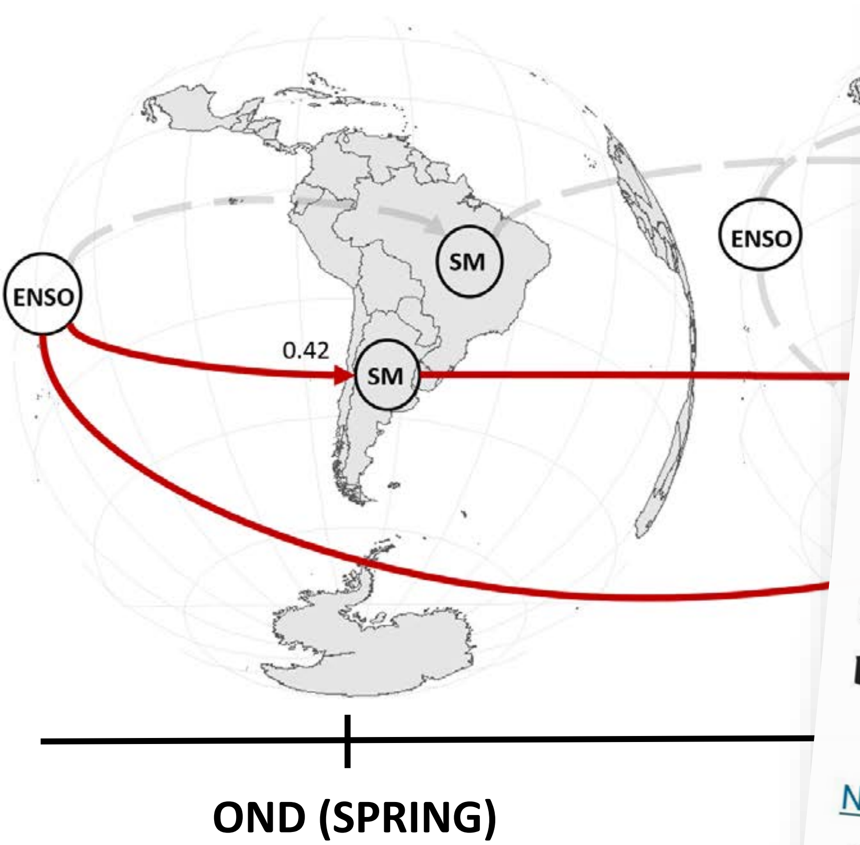

Southern Hemisphere growing season

Northern Hemisphere growing season

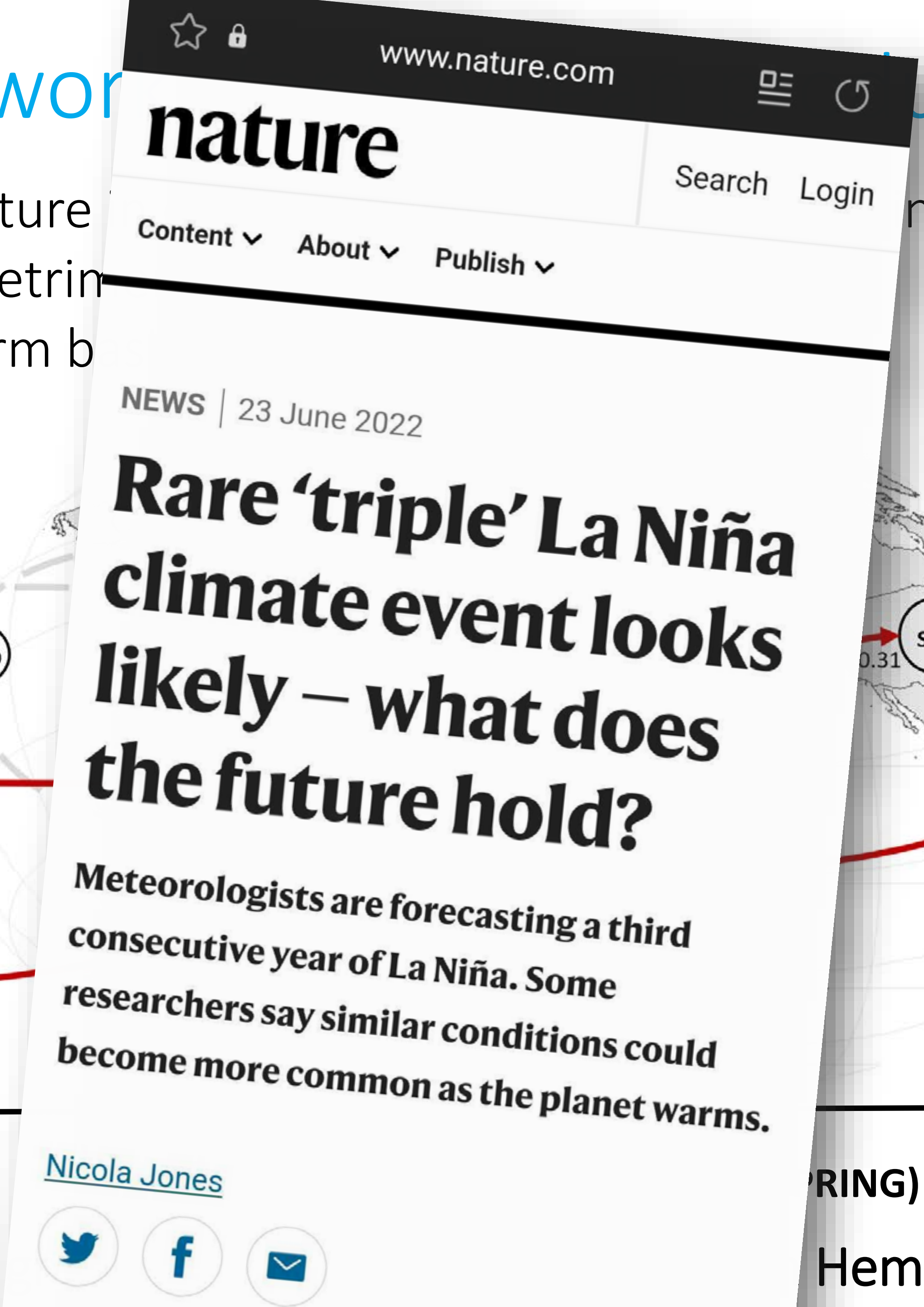
Hamed et al,
*in prep*

# Global causal networ… …uction

- ENSO influences soil-moisture … …ndirectly via regional SSTs
- Multi-year La Niña most detrim…
- Such causal graphs can form b…




Southern Hemisphere



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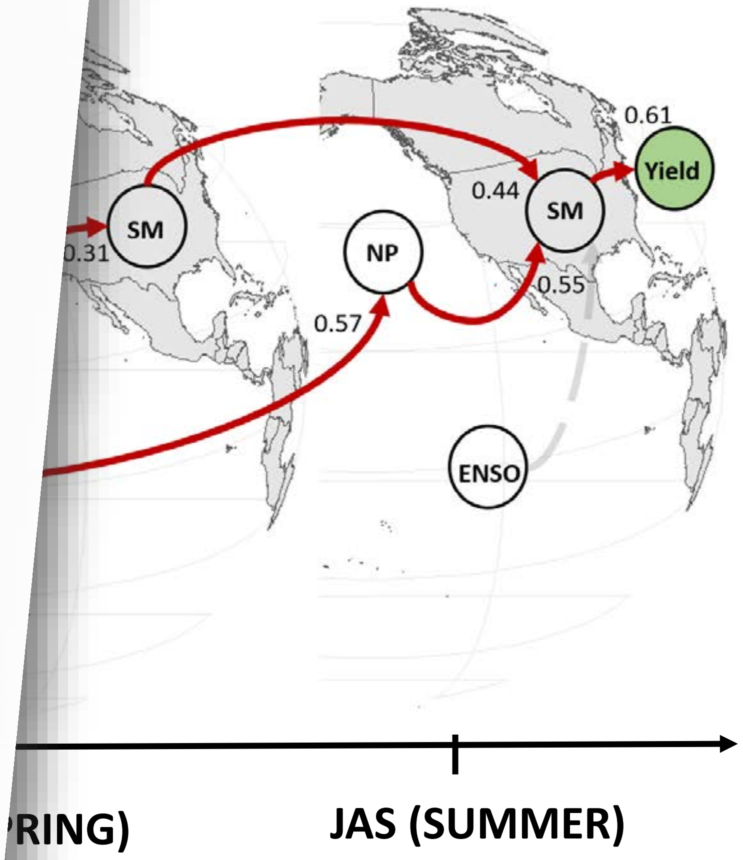
NEWS | 23 June 2022

**Rare 'triple' La Niña climate event looks likely – what does the future hold?**

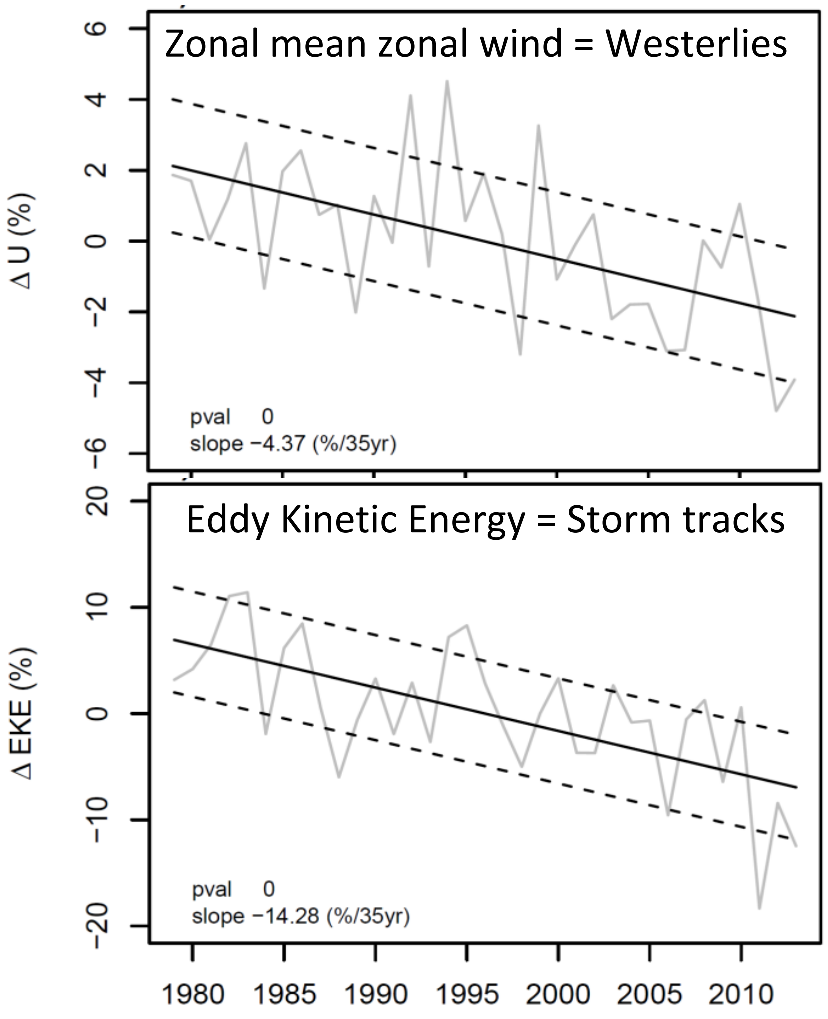
**Meteorologists are forecasting a third consecutive year of La Niña. Some researchers say similar conditions could become more common as the planet warms.**

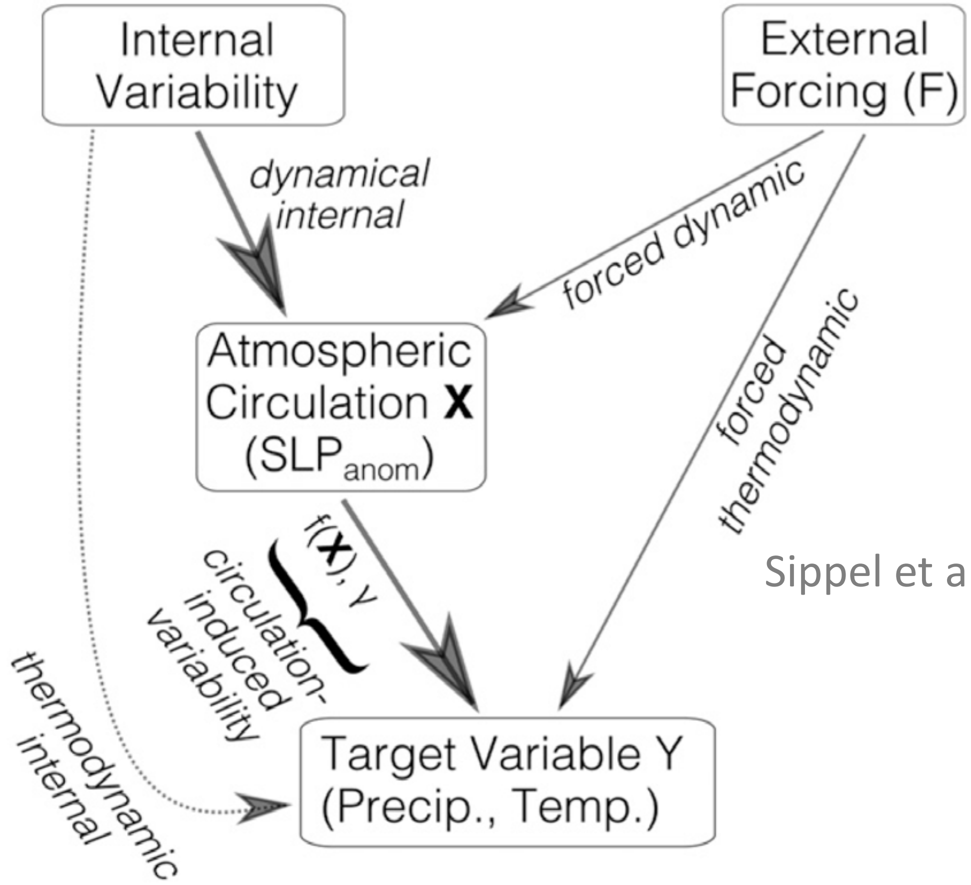
Nicola Jones




…Hemisphere growing season

# Is climate change affecting boreal summer circulation?



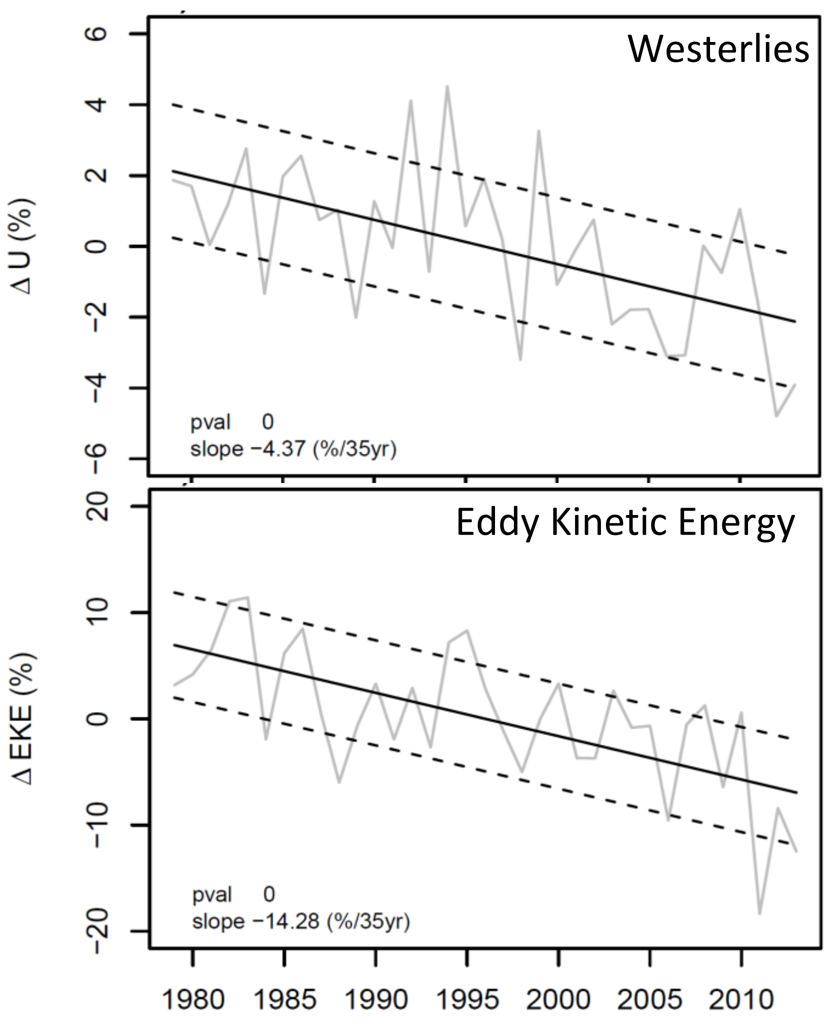



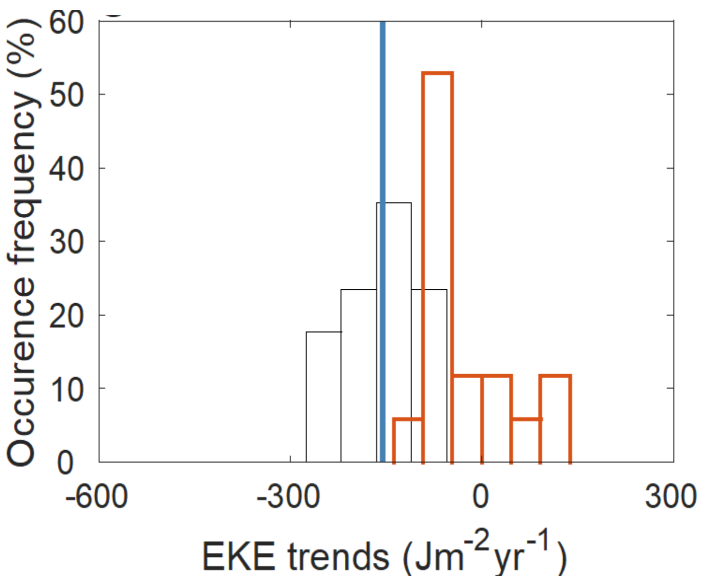

Sippel et al (2019)

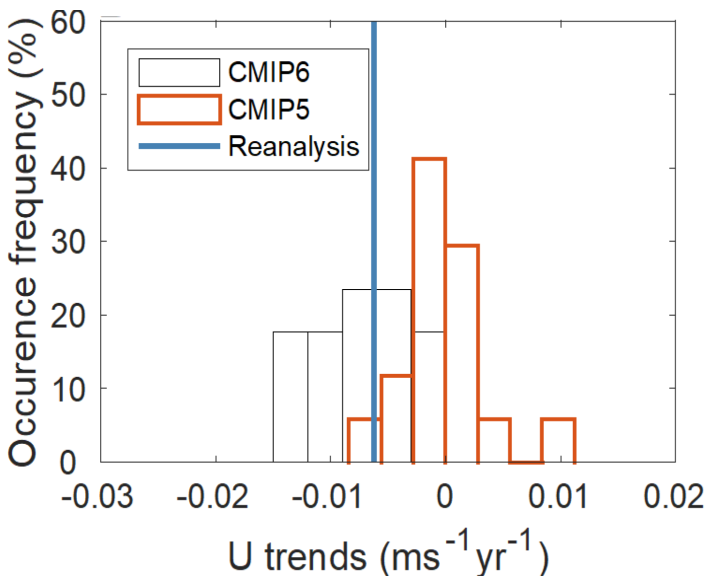
Both westerlies & storm tracks have been weakening since 1979. Internal variability or forced?

Coumou et al *Science* (2015);

# Is climate change affecting boreal summer circulation?



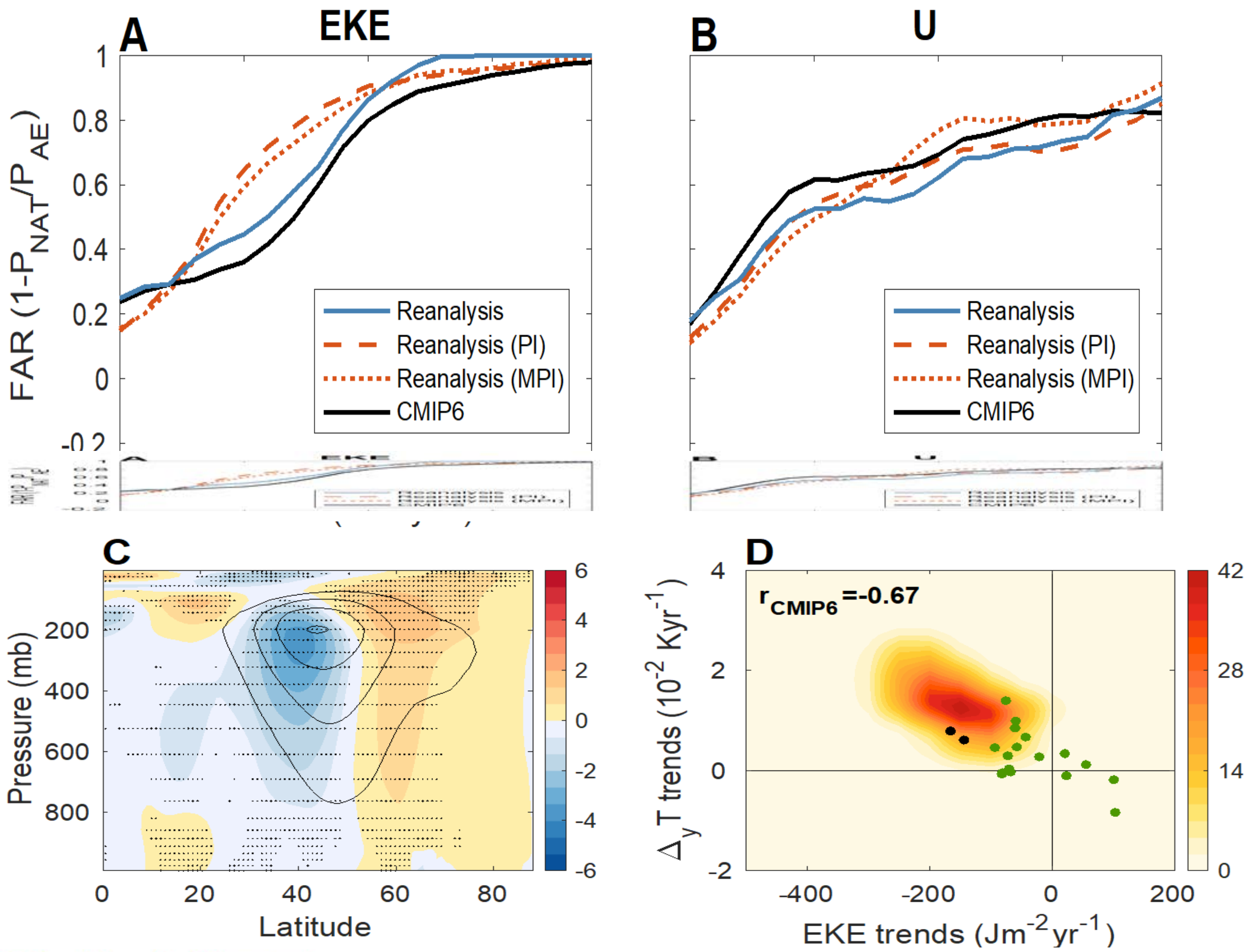




Both westerlies & storm tracks have been weakening since 1979

CMIP6 models capture this downward trend but CMIP5 models do not

# Weakening is attributable to anthropogenic emissions




Fractional Attributable Risk:

**FAR $= 1 - P_{NAT} / P_{AE}$**

P = probability of trend with natural forcing only (NAT) or with natural + anthropogenic emissions (AE)

Strong weakening at jet core, reduction in vertical shear

CMIP5 models underestimate trends in equator-to-pole temperature gradient (i.e. Arctic Amplification).

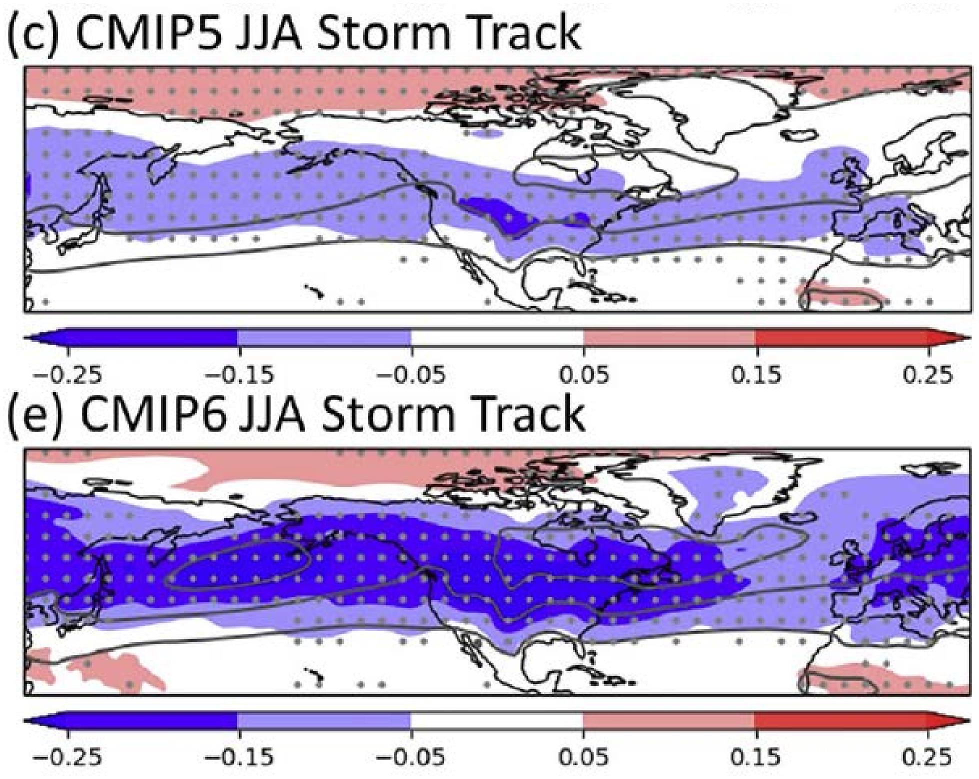
CLIMATE EXTREMES

Chemke & Coumou (in review)

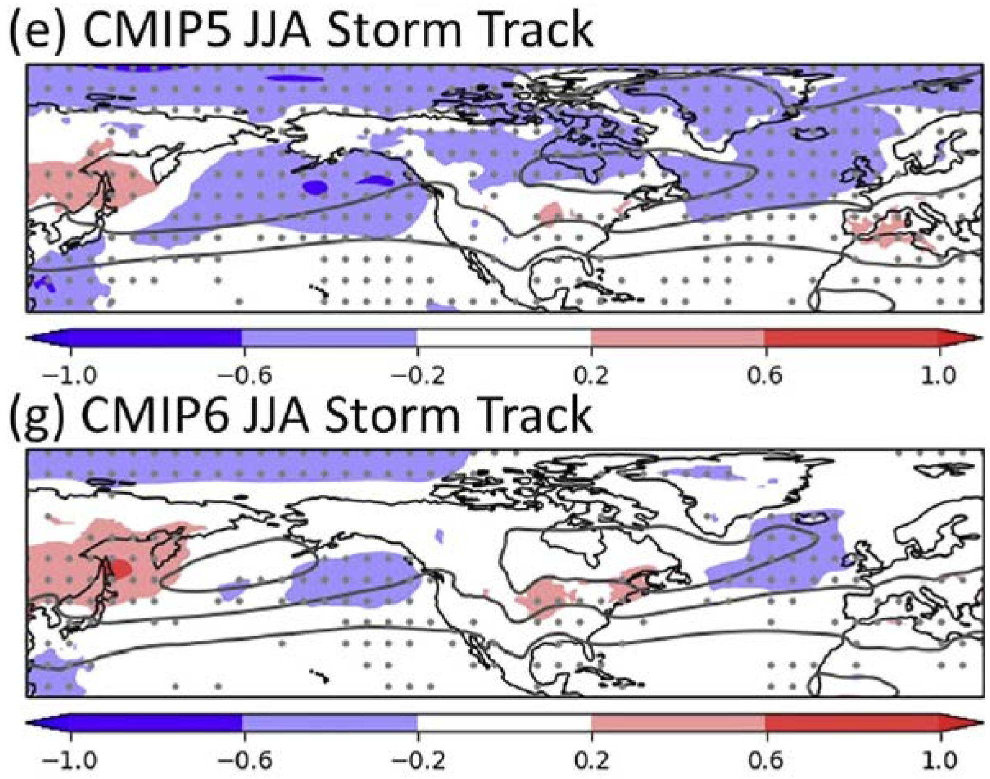
# Weakening of summer circulation: CMIP5 vs CMIP6

Climate models project same storm track weakening under future emissions

CMIP6: Improved storm track representation & stronger climate signal



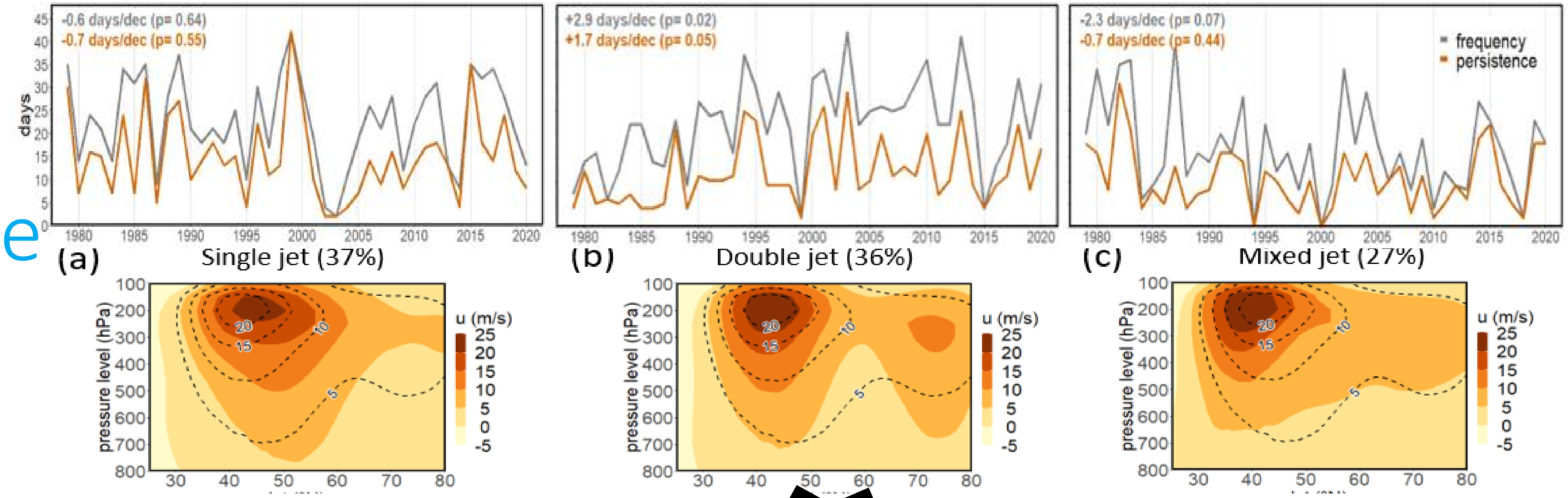

<u>FORCED RESPONSE</u>: JJA multimodel mean future minus present (RCP4.5)




<u>MODEL BIAS</u>: JJA multimodel mean present minus ERA5

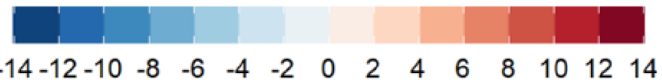
Harvey et al, JGR (2020)

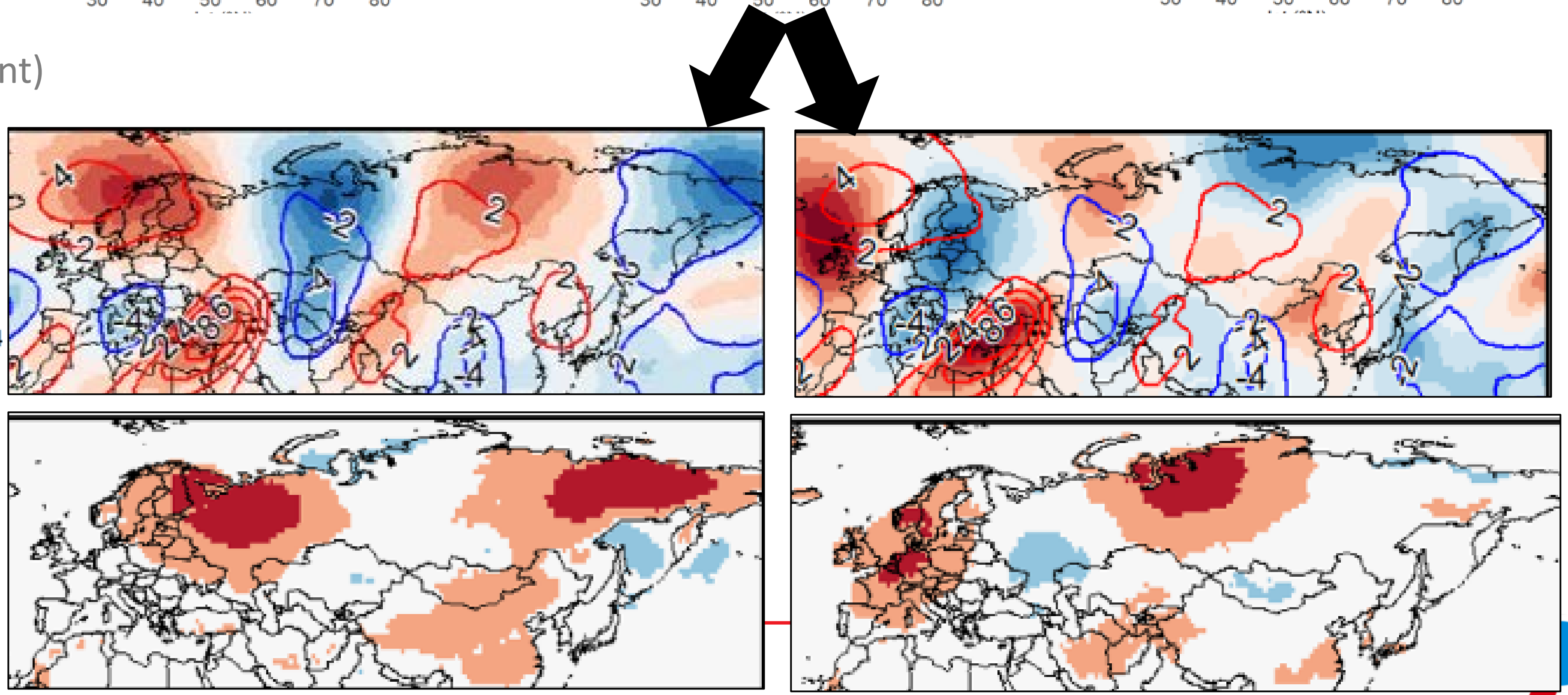
# ‘Double jet states’ have become more persistent over Eurasia




Rousi et al, *Nature Comm* (in print)

v at 250mb (anomaly)



T2m (anomaly)

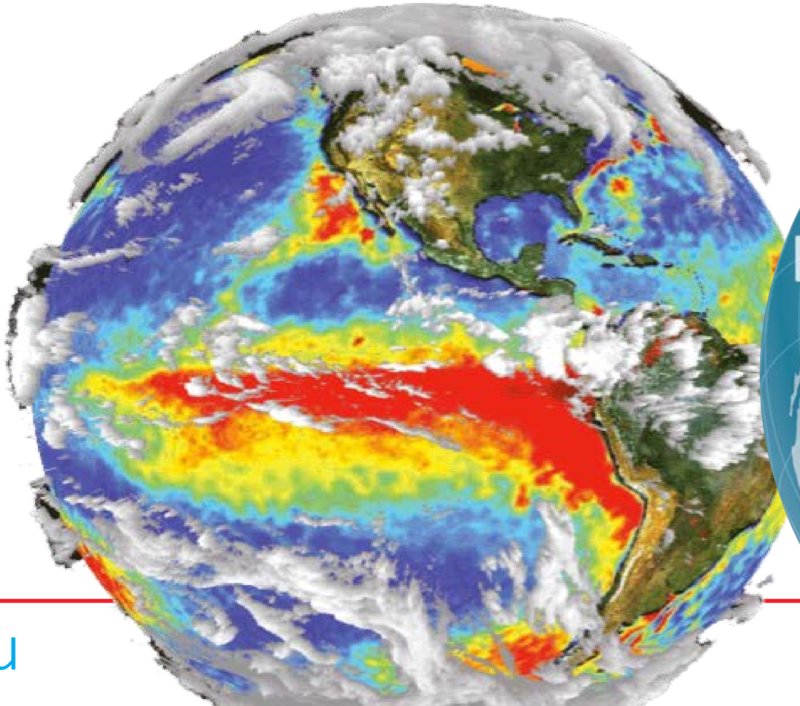

EXTREMES

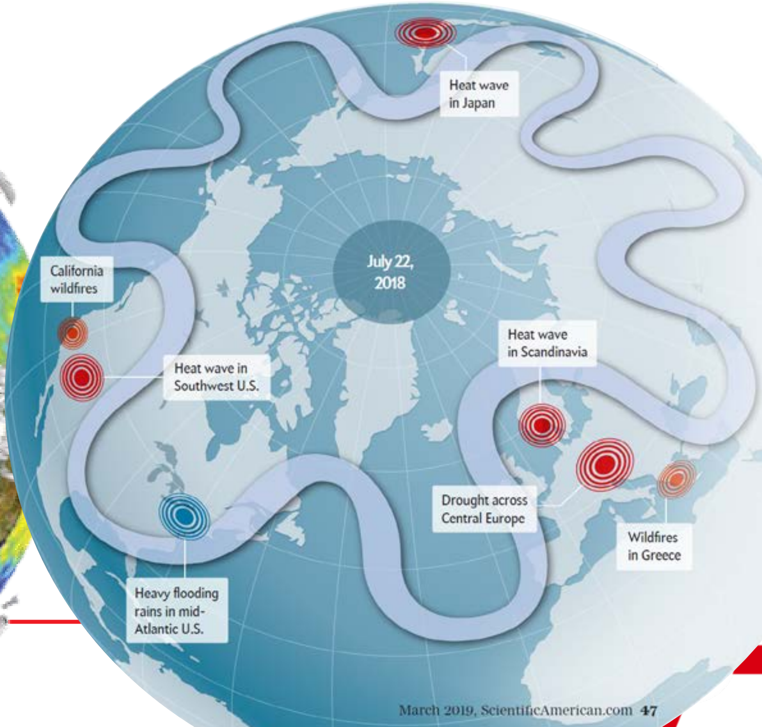
# Spatially compounding summer extremes

- Teleconnections can generate joint breadbasket failures affecting global food prices
- Northern hemisphere: Circum-global waves cause simultaneous hot-dry extremes
- Boreal summer circulation has been weakening and this is attributable to GHG forcing
- Global soybean production mostly from 3 regions that are influenced by ENSO dynamics. Multi-year La Niña causes strongest soybean losses
- Causal inference & Causal discovery algorithms provide insights into the processes

XAIDA

Grant Number 101003469

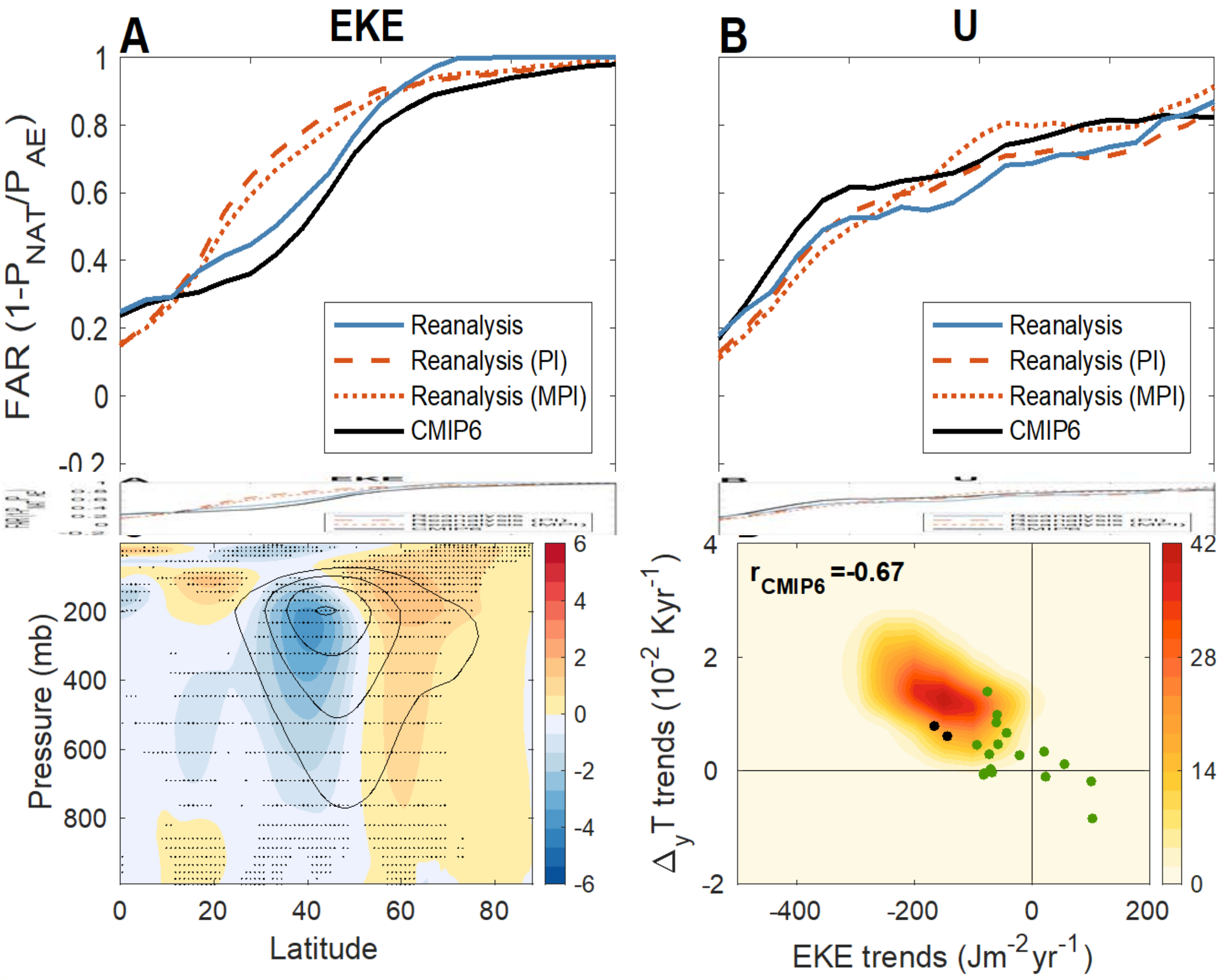





CLIMATE EXTREMES

@DimCoumou

# Weakening is attributable to anthropogenic emissions

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Strong weakening at jet core, reduction in vertical shear

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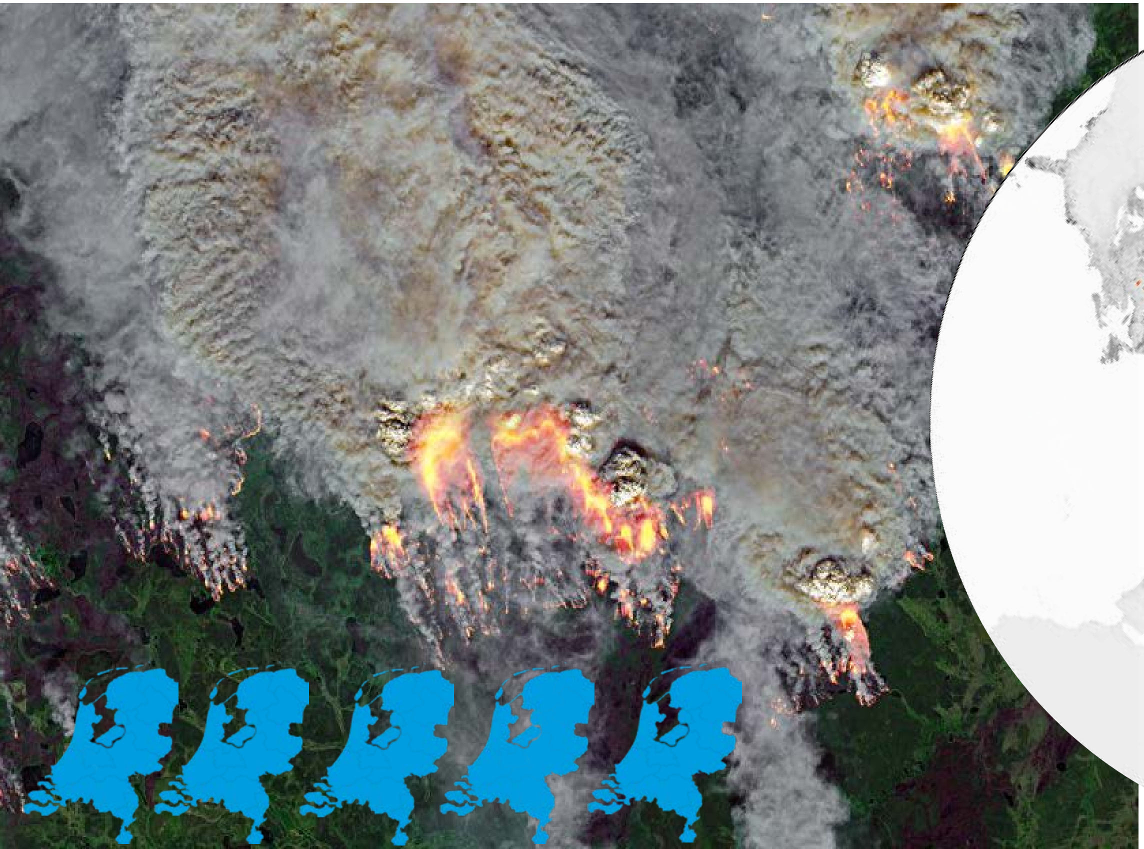
CLIMATE EXTREMES

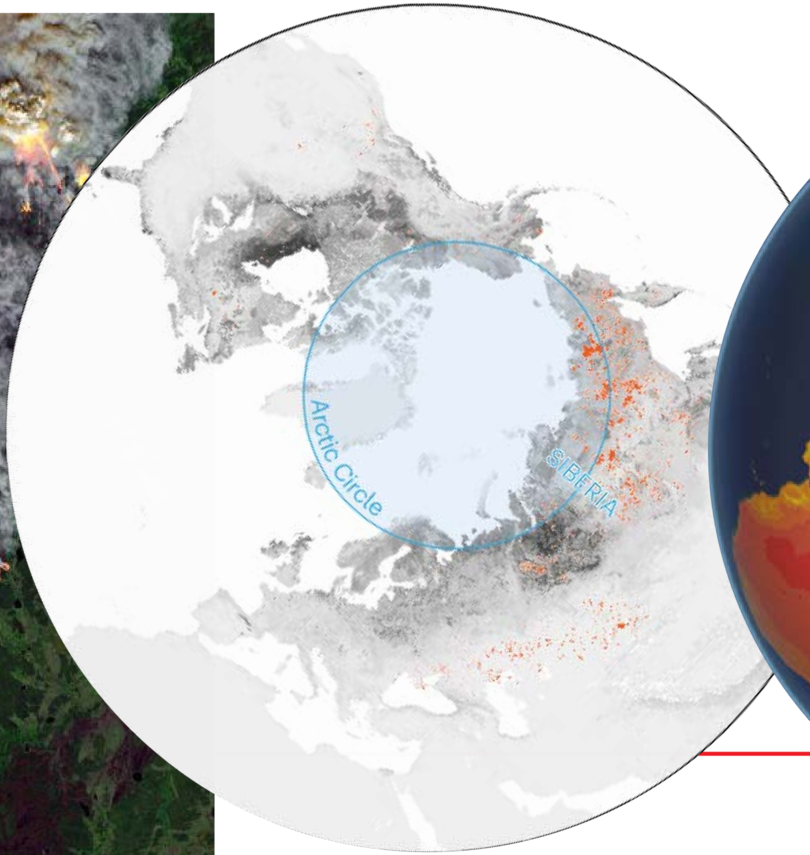
Chemke & Coumou (in review)

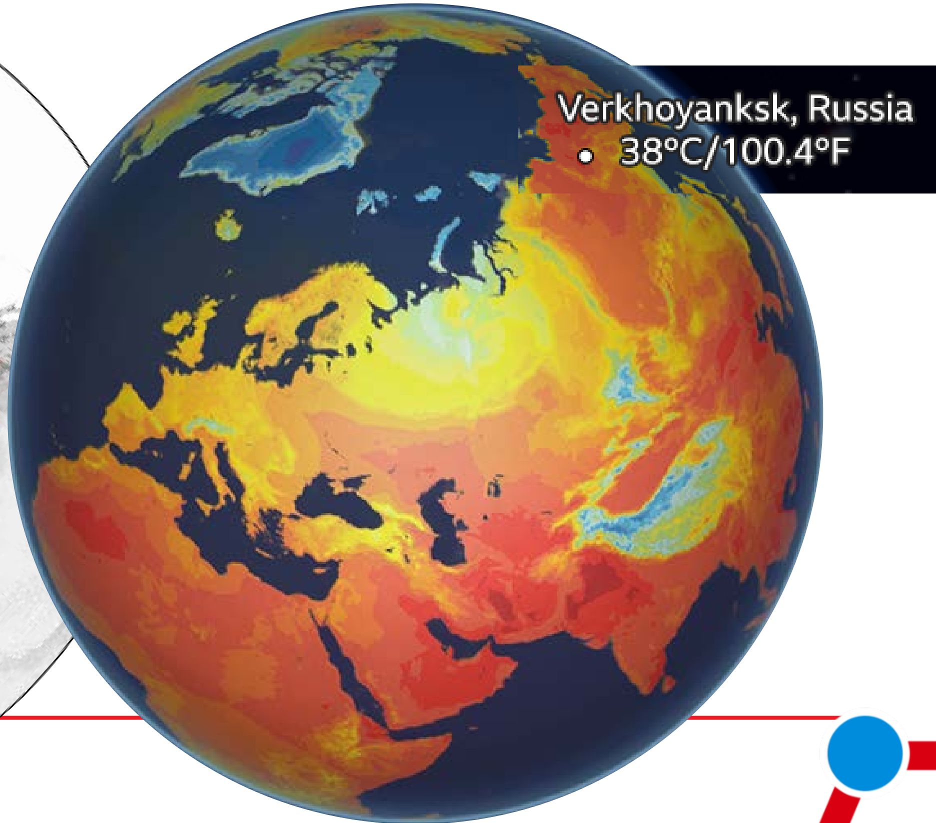
# Global trade:
# Efficient but vulnerable


# Double jet also important for high-latitude extremes

Summers of 2019 and 2020 experienced extreme fire activity in northeastern Siberia that were driven by record-high spring and summer temperatures

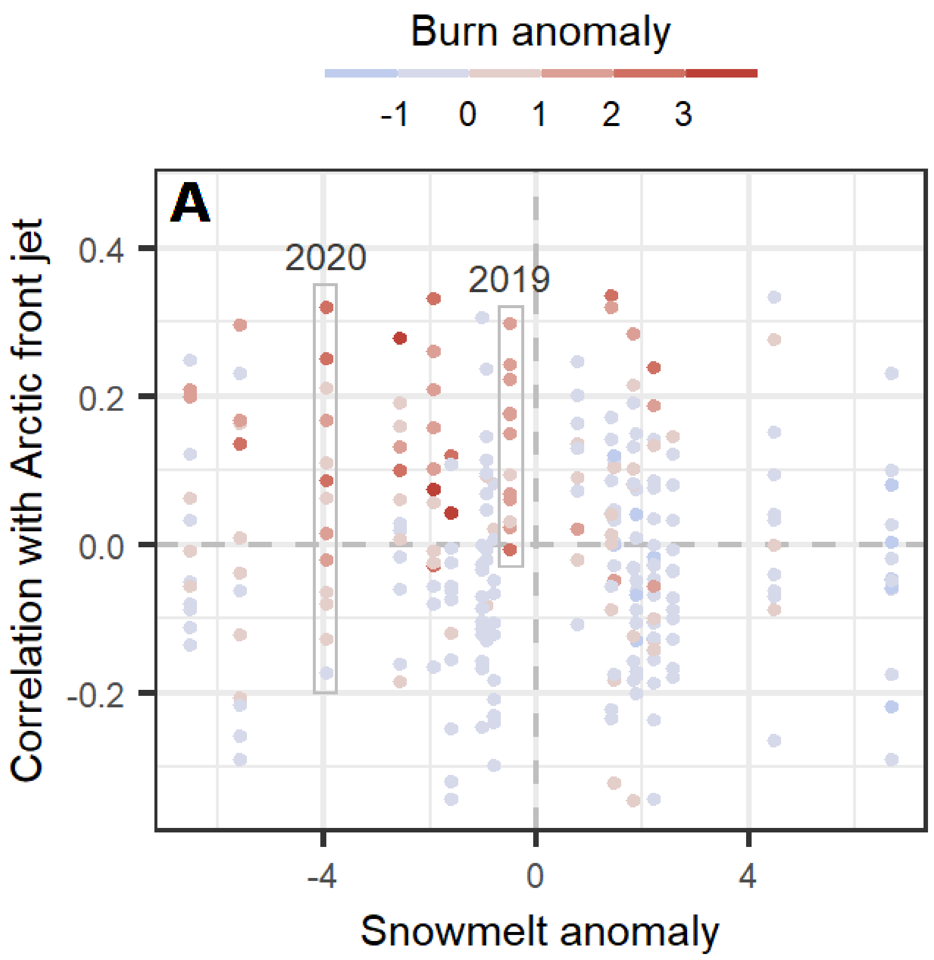




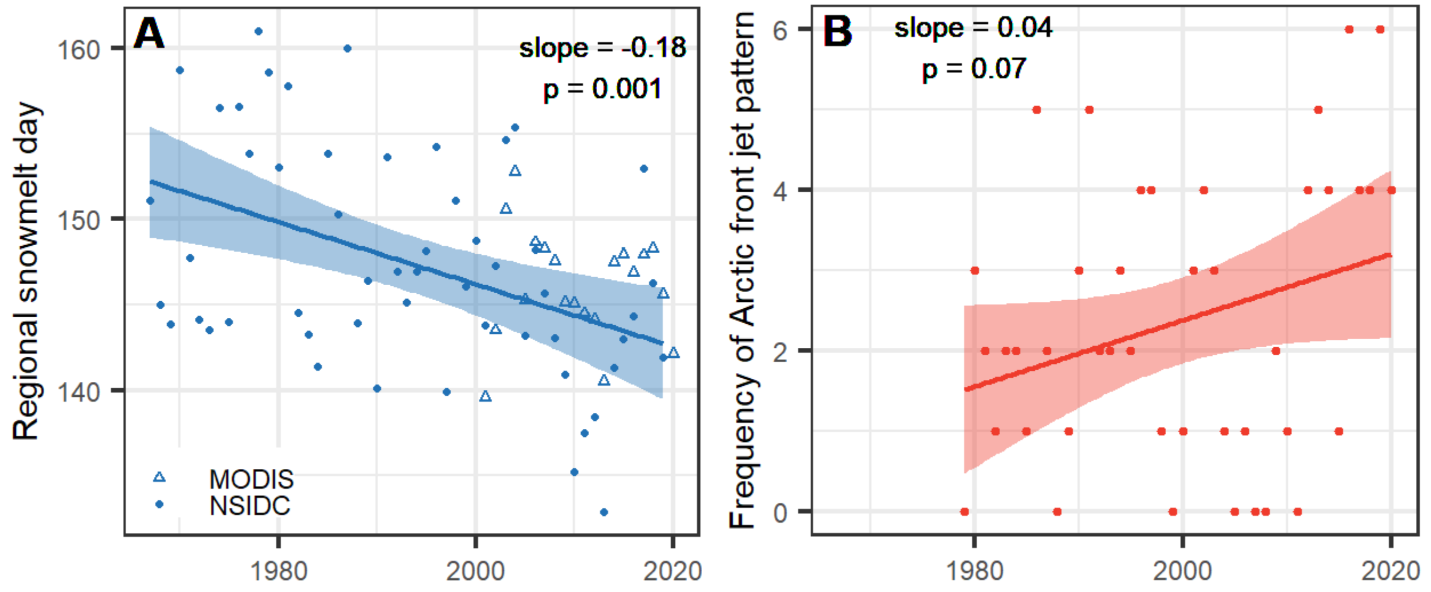



# Double jet also important for high-latitude extremes

Combined effect of early snow melt and Arctic front jets drive Siberian wildfires



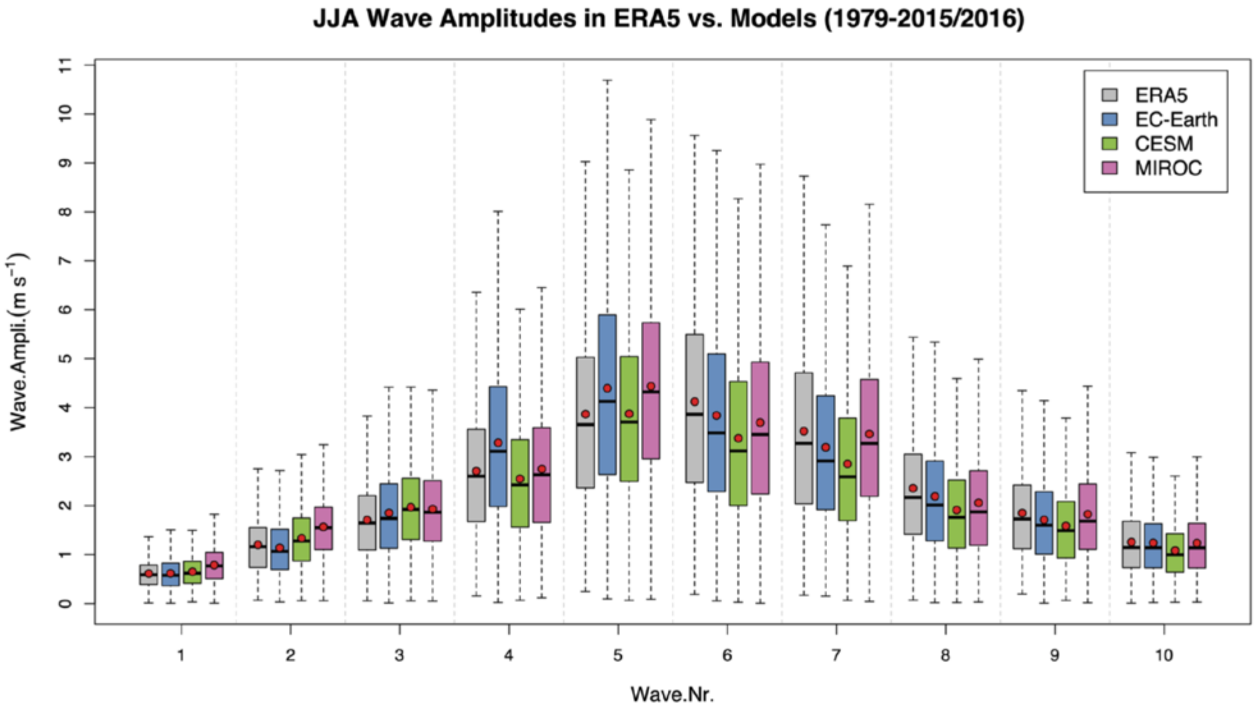

Long-term trends promote extreme fire activity

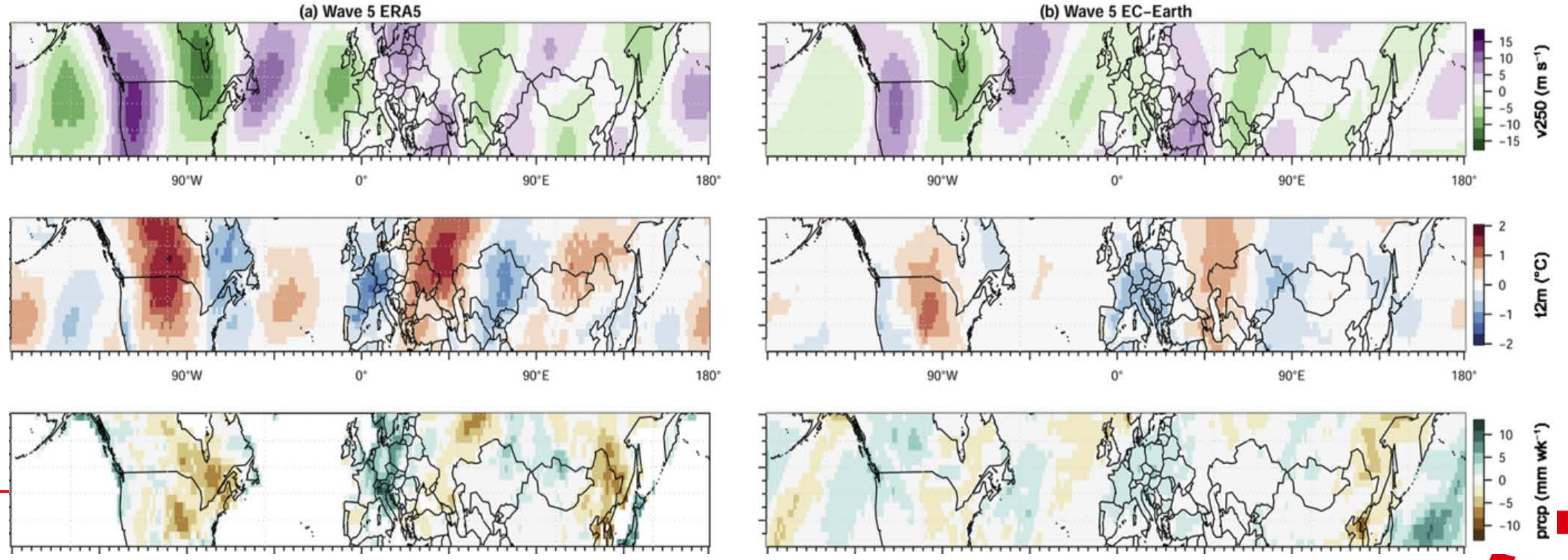



Scholten *et al.* (in review.)

# CGWT in climate models

- Fair wave spectrum (FFT, weekly data)
- Phase-locked position of wave-5 and wave-7 well-captured
- Surface temperature & precipitation imprint underestimated in models
- Seen across models

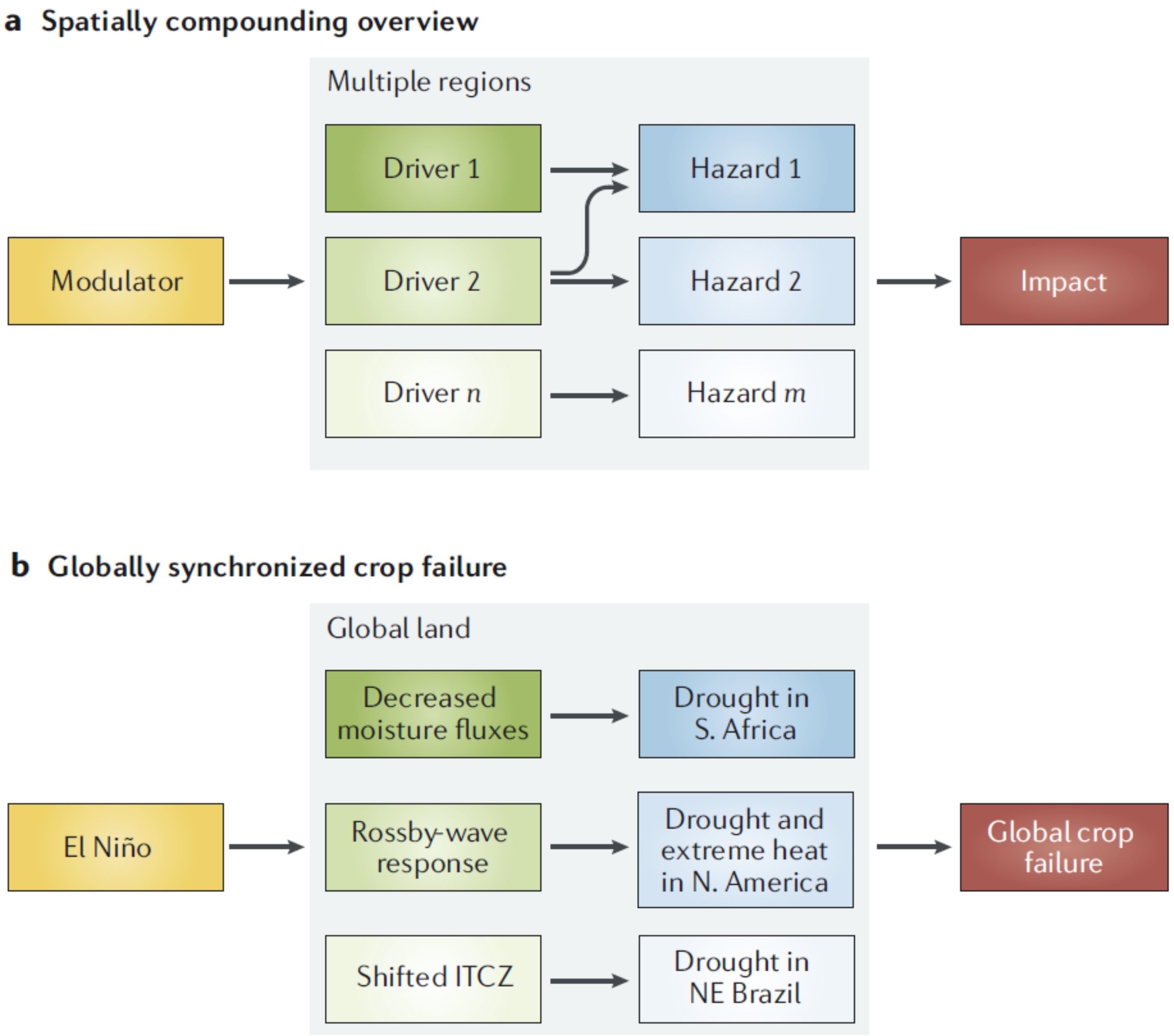



Luo et al, *WCD* (2022)

CLIMATE EXTREMES

# Outline: Spatially compounding summer extremes

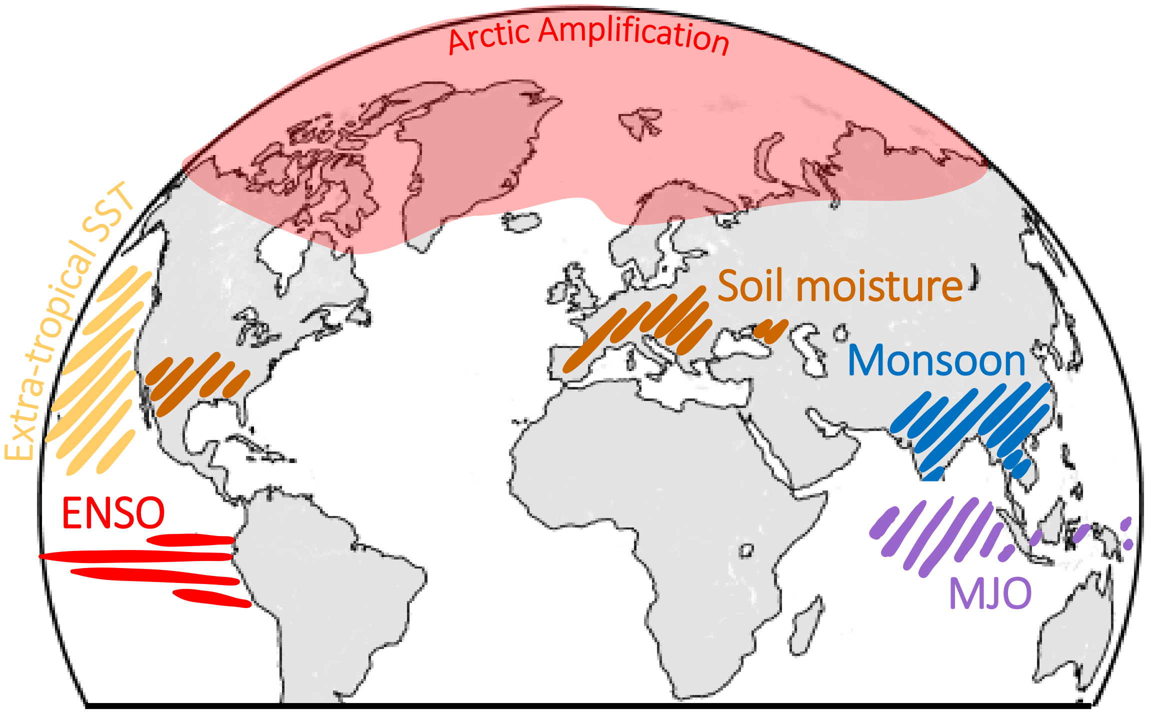



1. Drivers of circumglobal waves
2. Multi-year La Nina & Soybean production

...with applications of causal discovery / inference

Zscheischler et al, *NCC* (2018)

# Conclusions

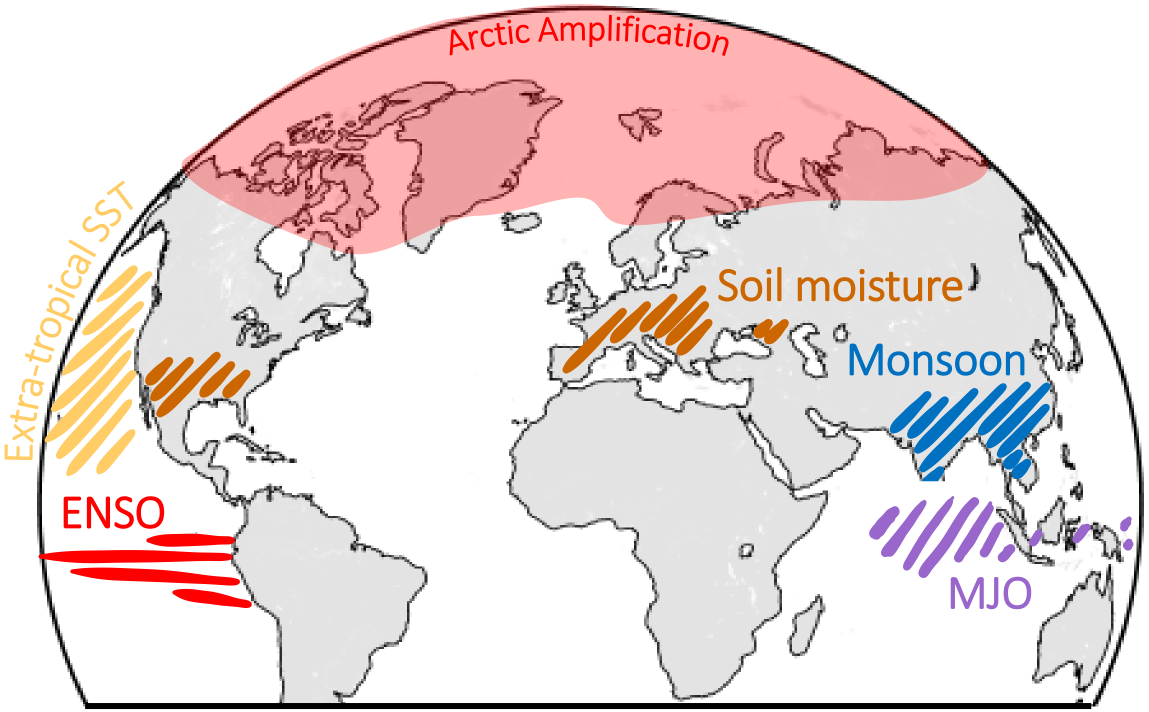


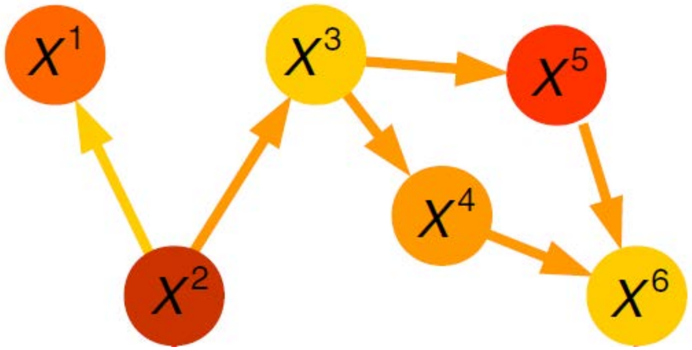

## Drivers of quasi-stat waves (summer):

- Tropical SSTs & monsoon activity important drivers of quasi-stat waves
- Extra-tropical SSTs & local soil-moisture patterns can cause 2-way feedback and thereby strengthen quasi-stat waves

These drivers are important sources of predictability at S2S timescales

# Conclusions

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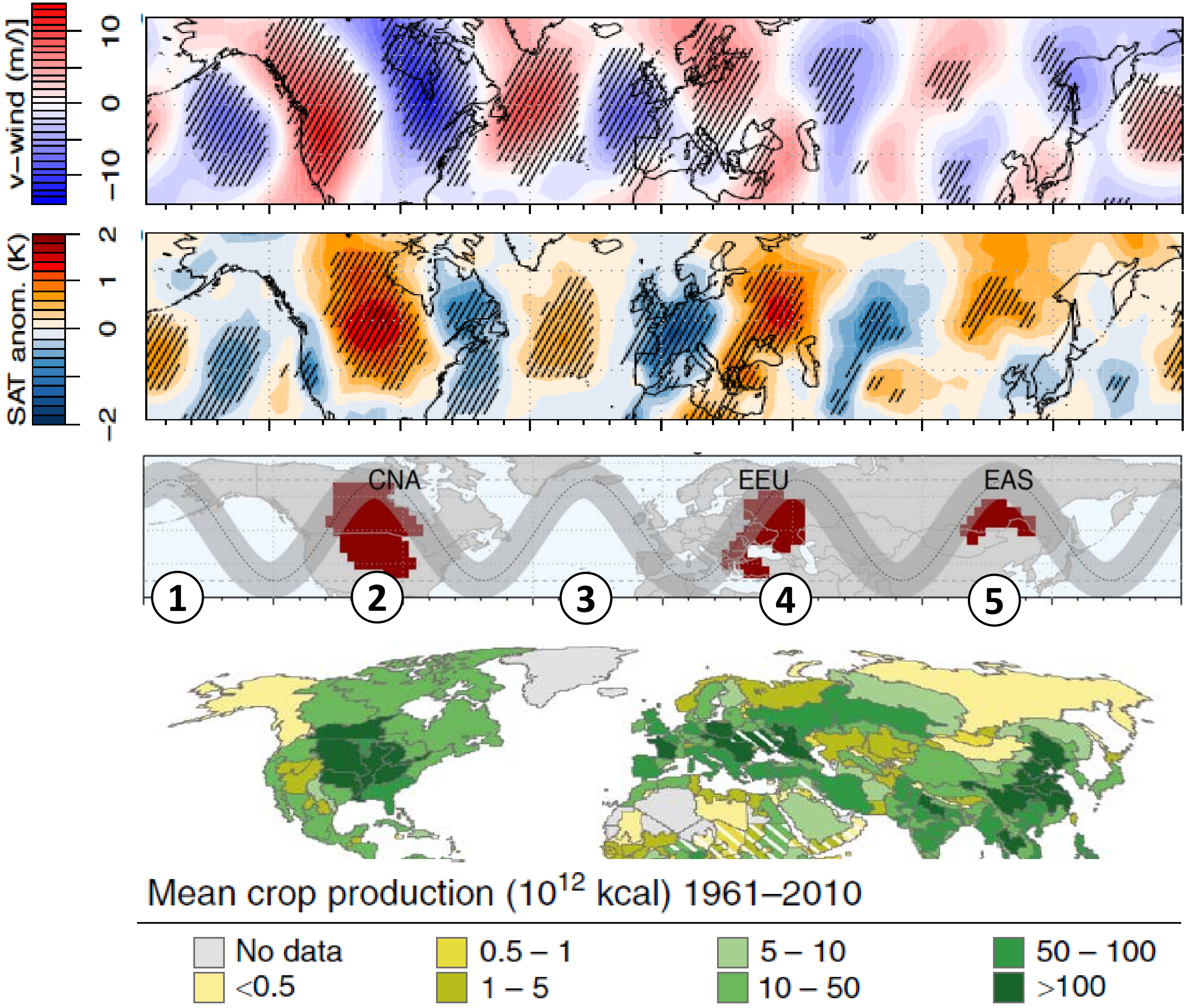
## Methods

- Causal Discovery & XAI can shed light on drivers, feedbacks & sources of predictability
- Models represent quasi stat waves well, but teleconnections are too weak especially in terms of surface imprint (= extremes)

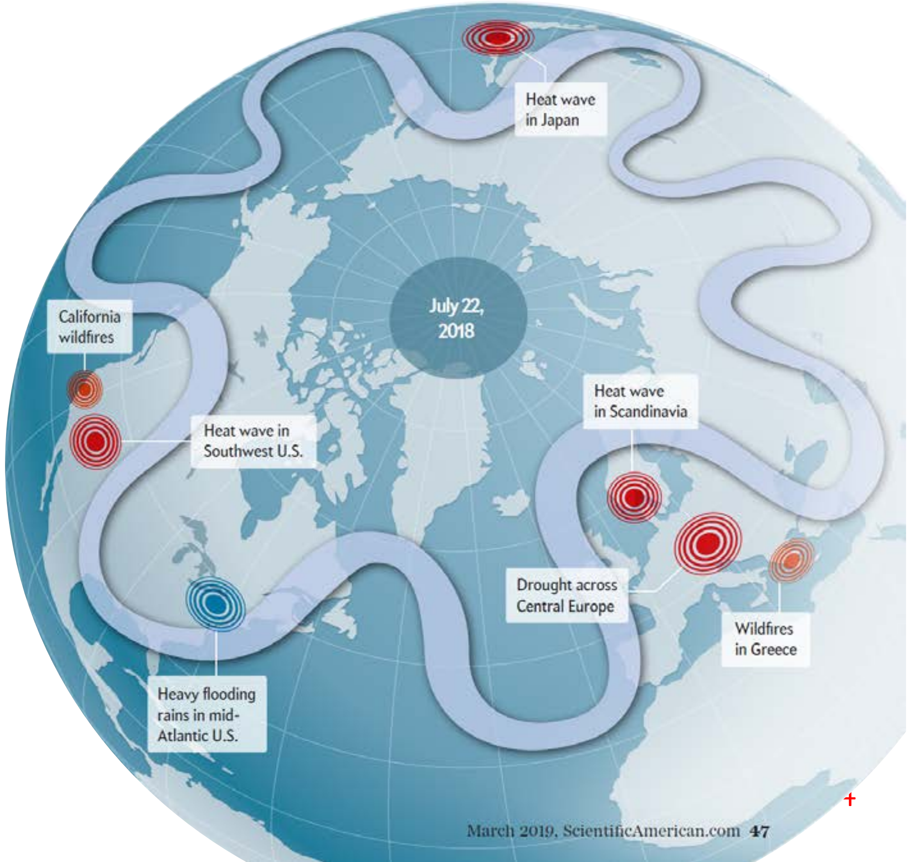
CLIMATE EXTREMES

# Quasi-stationary waves in summer: Compound extremes

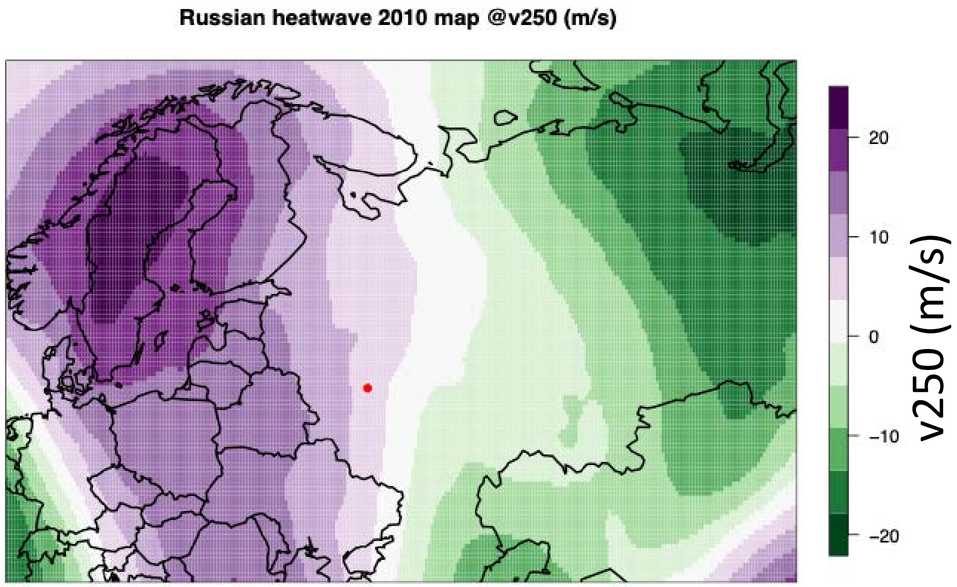


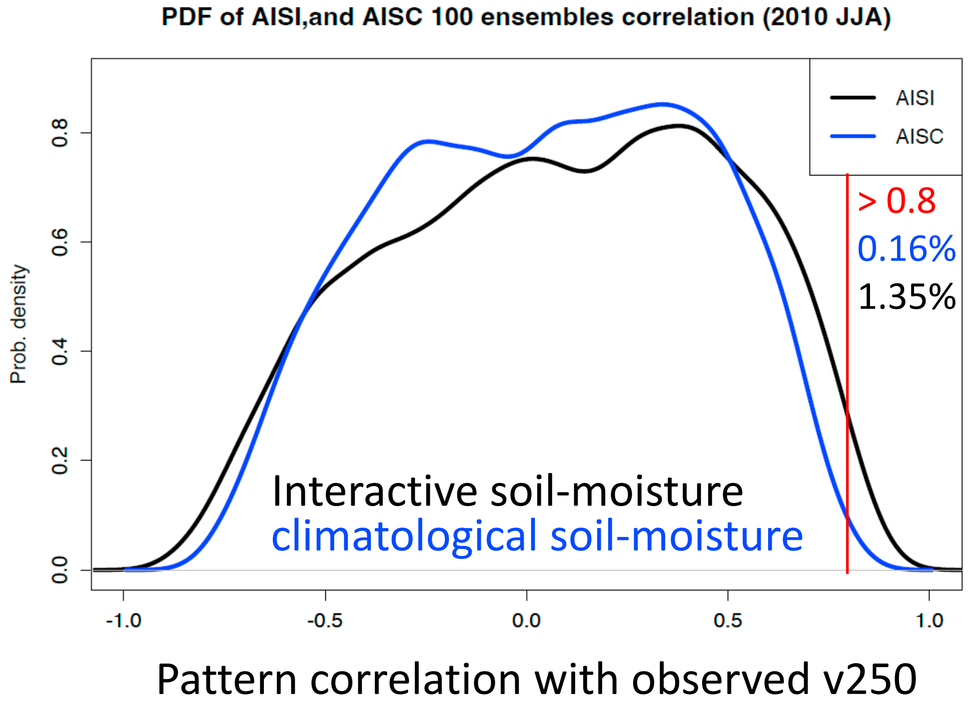

Persistent waves in the Jetstream can cause simultaneous hot-dry extremes in important breadbasket regions

Kornhuber et al, *NCC* (2020)



# ExtremeX, summer 2010



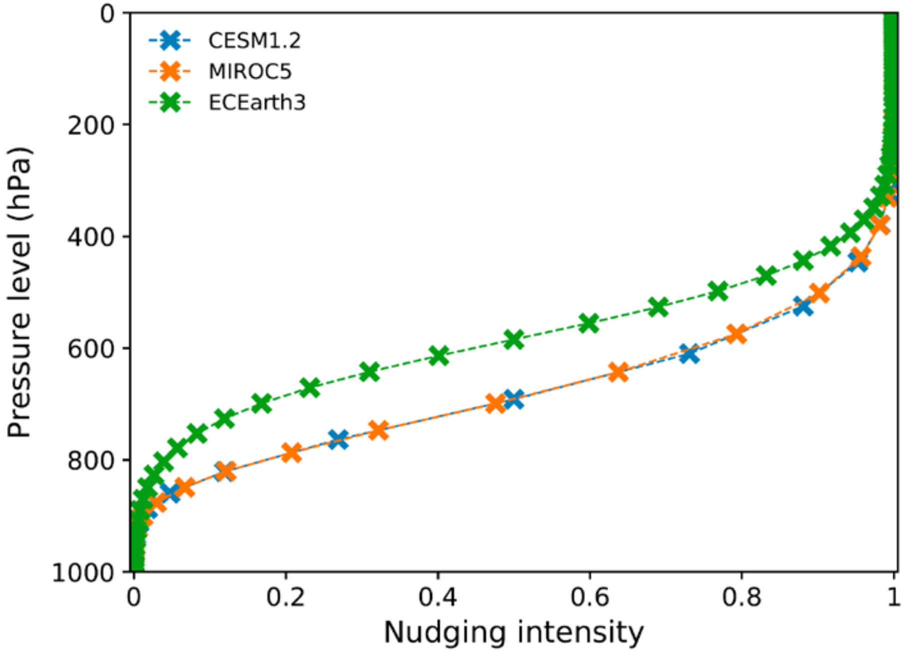




<u>Preliminary findings</u>:

- Interactive soil-moisture favors strongly positively correlating patterns.
- Suggests positive feedbacks between wave-pattern and soil-moisture

Luo et al, *in prep*

# ExtremeX:



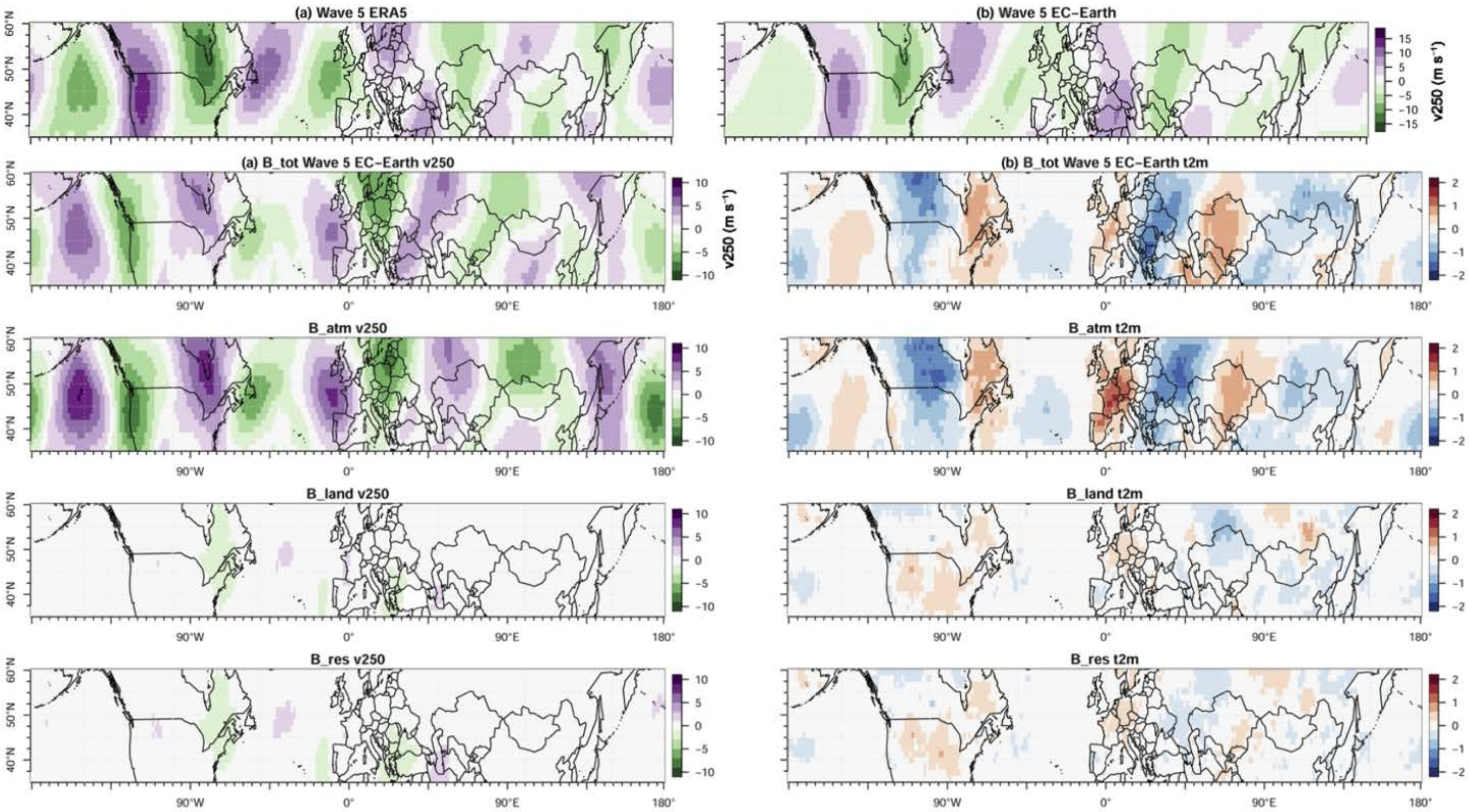

Earth System Dynamics
Discussions

**The ExtremeX global climate model experiment: Investigating thermodynamic and dynamic processes contributing to weather and climate extremes**

Kathrin Wehrli[1], Fei Luo[2,3], Mathias Hauser[1], Hideo Shiogama[4], Daisuke Tokuda[5], Hyungjun Kim[5], Dim Coumou[2,3], Wilhelm May[6], Philippe Le Sager[3], Frank Selten[3], Olivia Martius[7,8,9], Robert Vautard[10], and Sonia I. Seneviratne[1]

| Name | Acronym | Atmosphere | Soil Moisture | Ocean | # 1979–2008 | # 2009–2015/2016 |
|---|---|---|---|---|---|---|
| Control | AI_SI | interactive | interactive | forced | 5 | 100 |
| Soil moisture experiment | AI_SF | interactive | forced | forced | 5 | 100 |
| Nudging experiment | AF_SI | forced | interactive | forced | 1 / 5† | 1 / 5† |
| Fully constrained | AF_SF | forced | forced | forced | 1 / 5† | 1 / 5† |
| Soil moisture climatology | AF_SC | forced | forced* | forced | 1 / 5† | 1 / 5† |

Disentangle role of soil-moisture versus atmosphere dynamics for summer extremes using nudged model experiments (CESM, EC-Earth, MIROC)




B_tot = AISI – ERA5

When prescribing soil moisture in A
acting upon near-surface variables re

B_atm = AISF – ERA5

In contrast, when nudging the uppe
thus the bias arises from land-atmosp

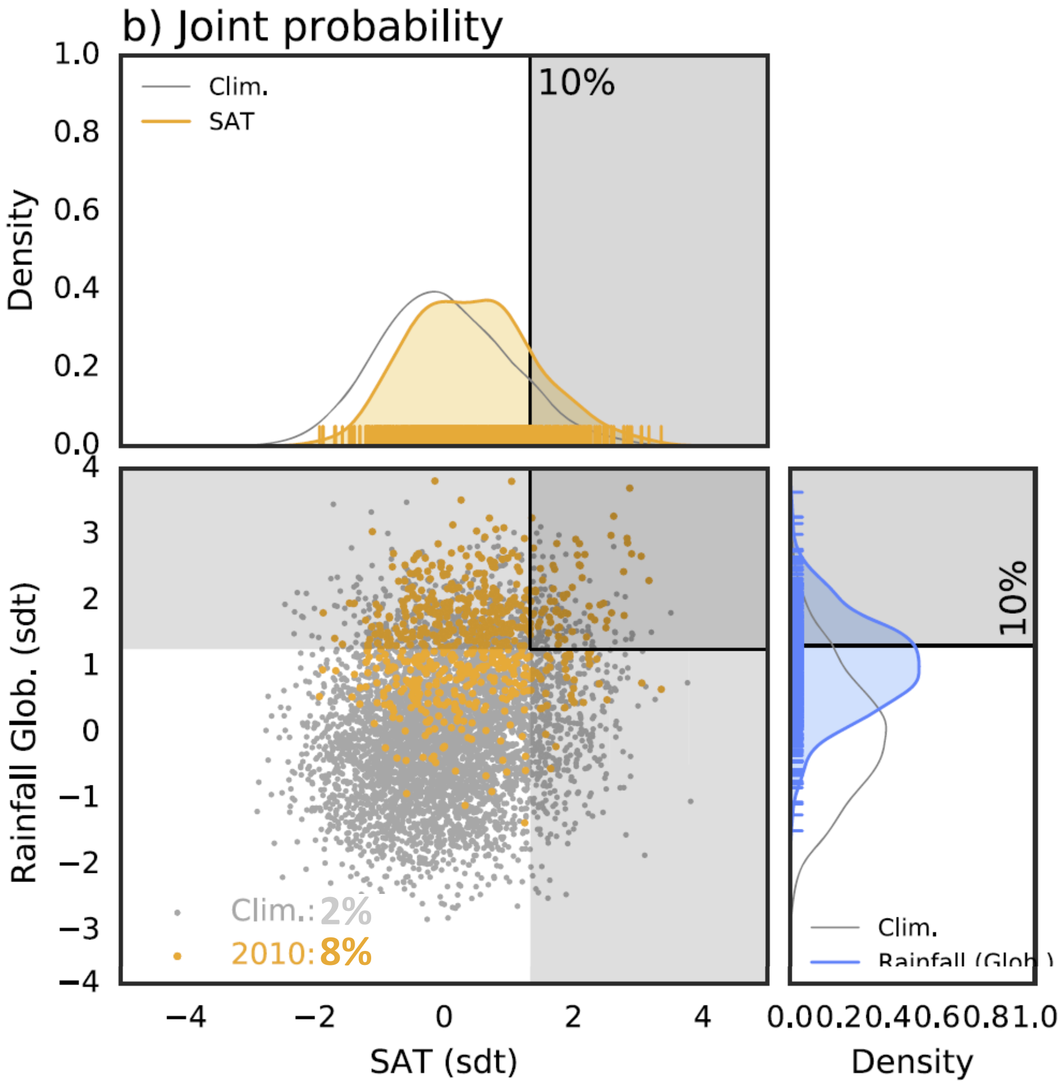
B_land = AFSI – ERA5

# Drivers of 2010 extremes: Russian Heatwave & Pakistan Flooding

<u>Compound Risks</u>:

- 2010 SSTs increase probability of wave train by factor 2-to-4.
- June soil moisture deficit in Russia and AA further favour occurrence/persistence of wave-train

| | ☀ | 🌧 | ☀🌧 |
|---|---|---|---|
| Climatology: | 10% | 10% (10%) | 2% (-) |
| 2010 SSTs: | 17% | 34% (43%) | 8% (9%) |
| 2010 SSTs \| SM: | 25% | 44% (48%) | 11% (13%) |
| 2010 SSTs \| AA: | 26% | 49% (54%) | 12% (11%) |

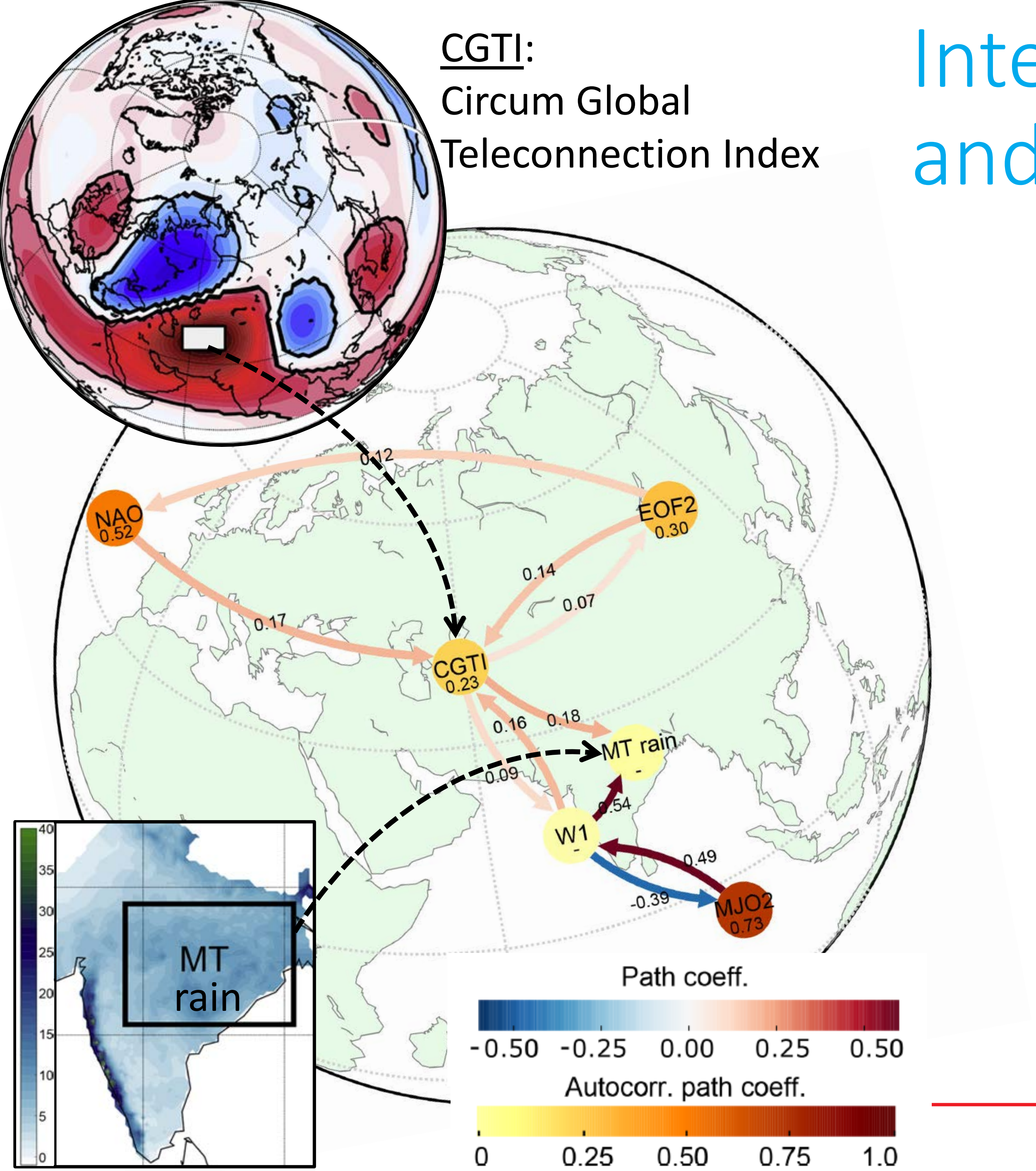



CLIMATE EXTREMES

Di Capua et al, *npj* (2021)

# Interactions between **wavetrains** and the Indian **monsoon**

(Ding & Wang, 2005)




**Causal Effect Network:**

- 2-way causal interaction between wavetrain (CGTI) and monsoon (MT)
- Wavetrain modulates monsoon rainfall, and monsoon activity strengthens the wave again
- MJO at least as important as mid-lat wavetrain for monsoon variability

Di Capua et al, *ESD* (2019)

IVM Institute for Environmental Studies

VU

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

# Anticipating Surprises

## Climate extremes in the next decade

Inaugural lecture | Chair in Climate Extremes & Societal Risk


Dim Coumou


CLIMATE EXTREMES

climateextremes.eu

@DimCoumou

"it is time to stop waffling so much and say that the evidence is pretty strong that the greenhouse effect is here" (Jim Hansen, 1988)


The New York Times

NEW YORK, FRIDAY, JUNE 24, 1988

# Global Warming Has Begun, Expert Tells Senate



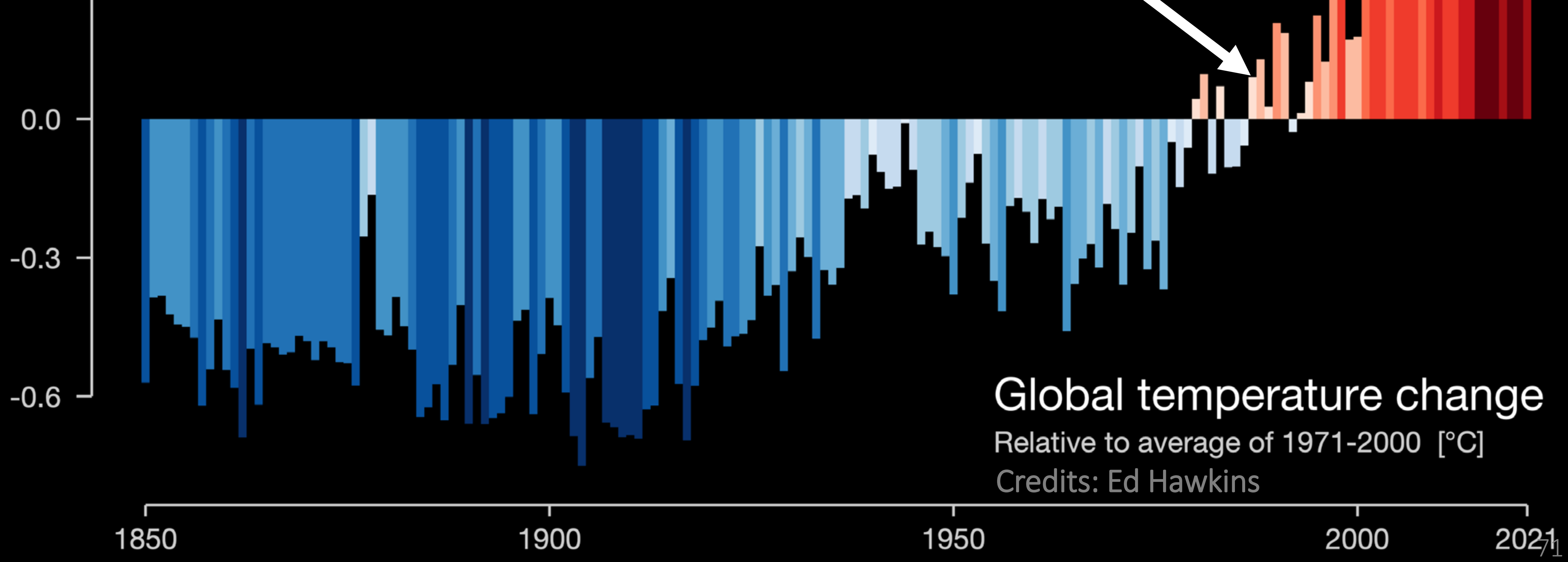
## Sharp Cut in Burning of Fossil Fuels Is Urged to Battle Shift in Climate

By PHIL

WASHINGTO

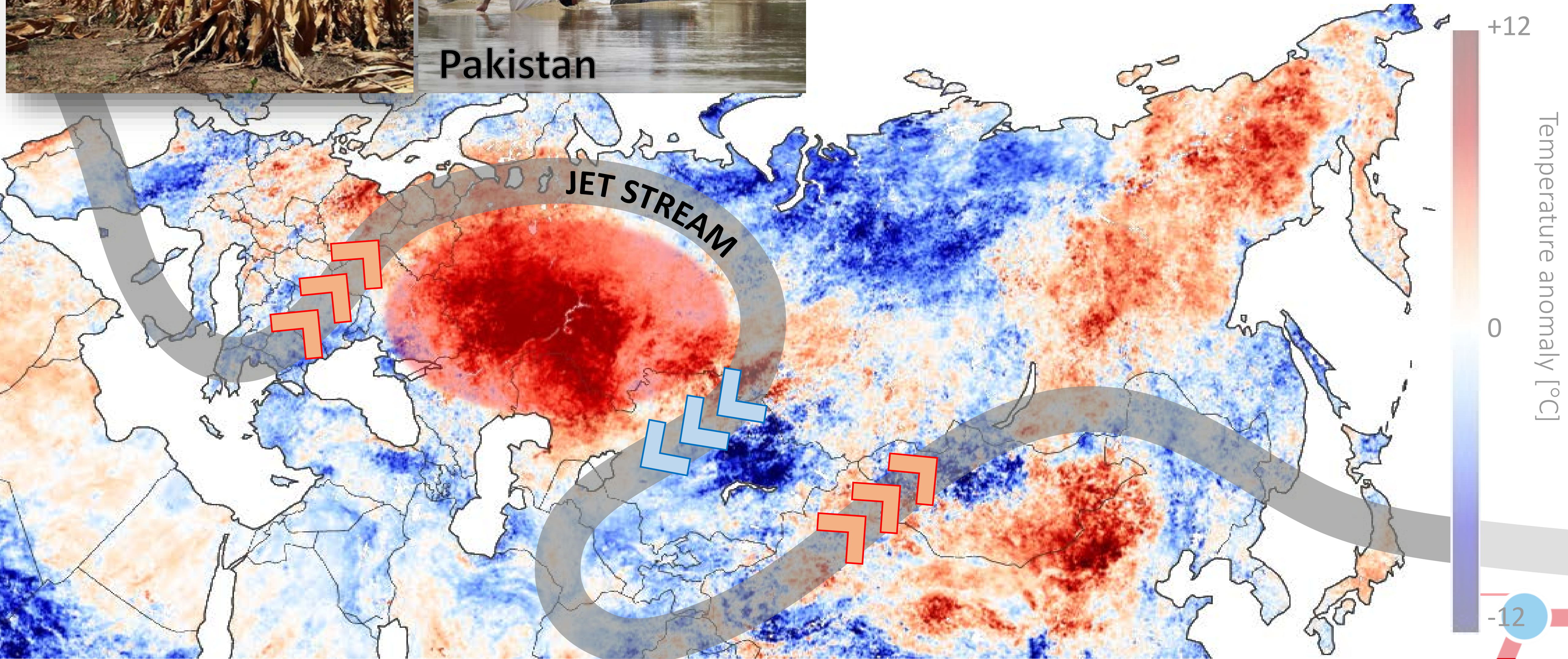
has been war

months of this



# Summer 2010: A wake up call for climate scientists





# Summer 2010: A wake up call for climate scientists



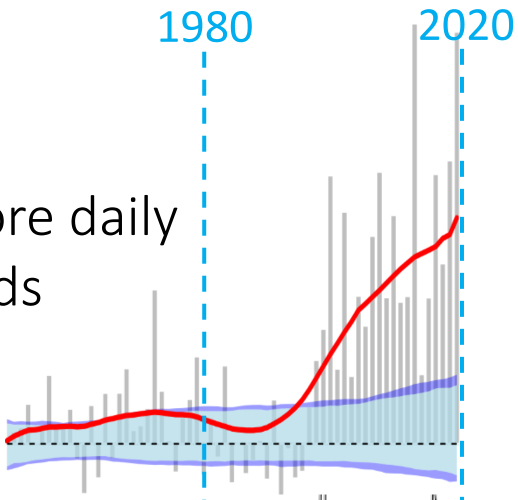

nature climate change
PERSPECTIVE
PUBLISHED ONLINE: 25 MARCH 2012 | DOI: 10.1038/NCLIMATE1452

## A decade of weather extremes

Dim Coumou and Stefan Rahmstorf*

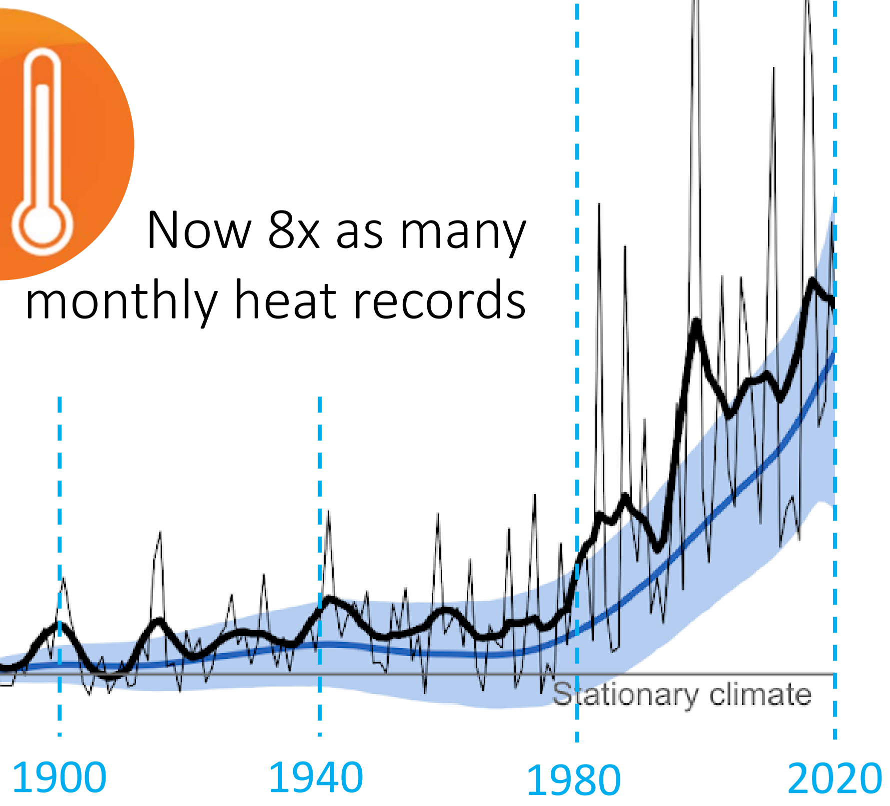
"it is time to stop waffling so much and say that the evidence is pretty strong [...] that anthropogenic, unprecedented heat and rainfall extremes are here"

# Globally extreme weather is on the rise




Now 30% more daily rainfall records

Now 8x as many monthly heat records




Lehmann et al (2015), Coumou et al (2013), Robinson et al (2021)

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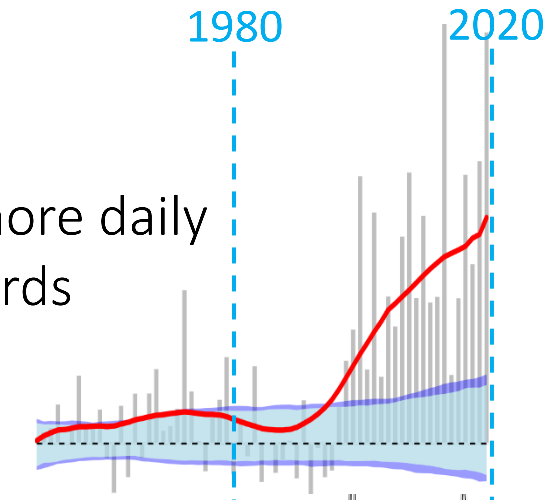


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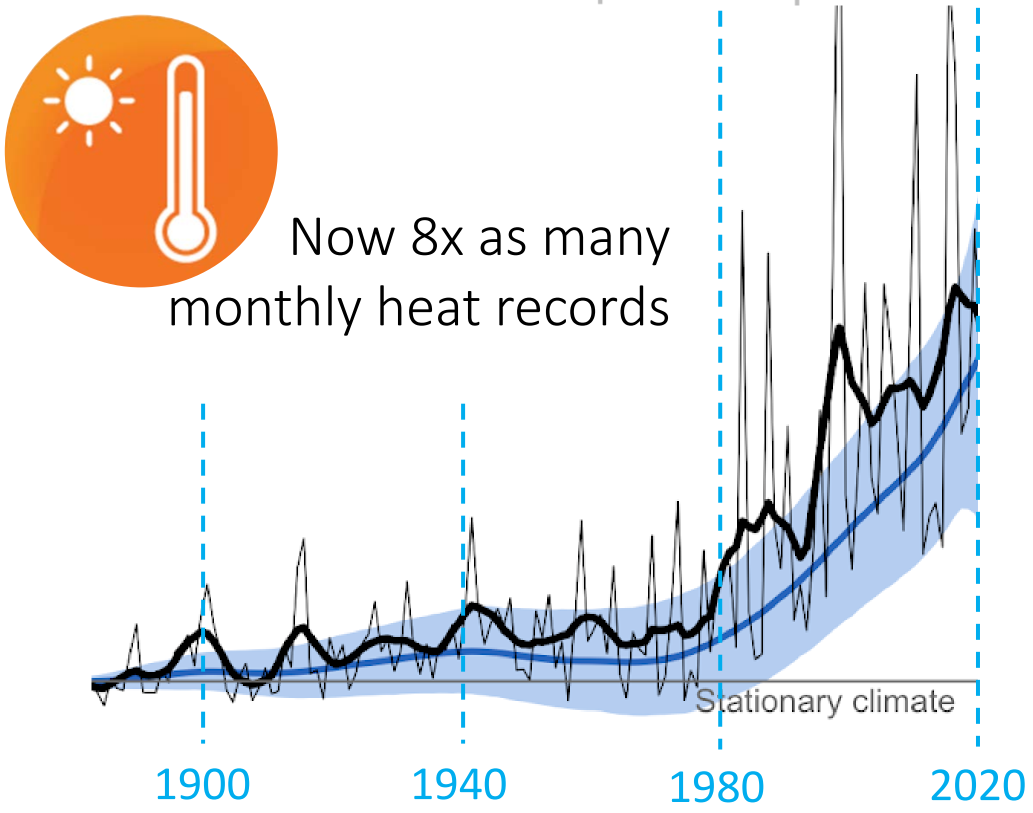
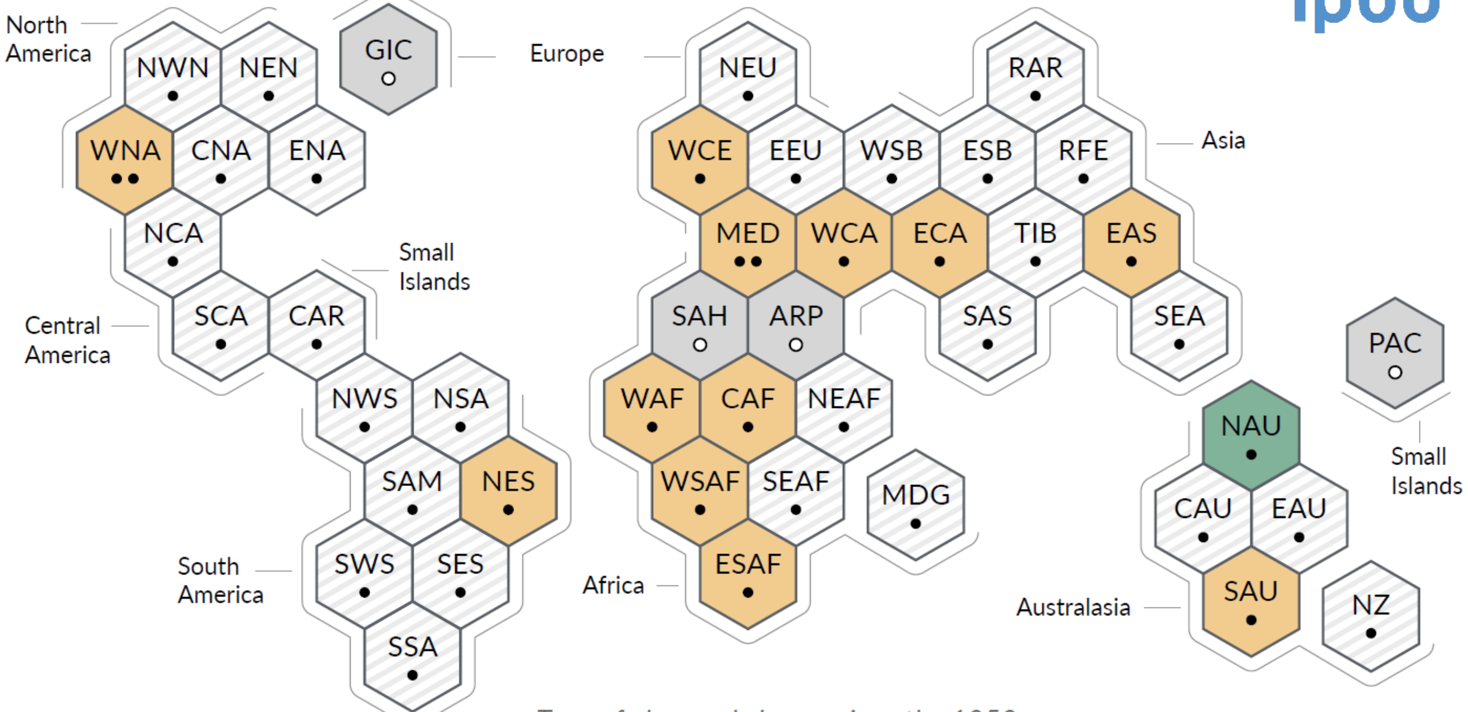



# Increase in drought in dry regions

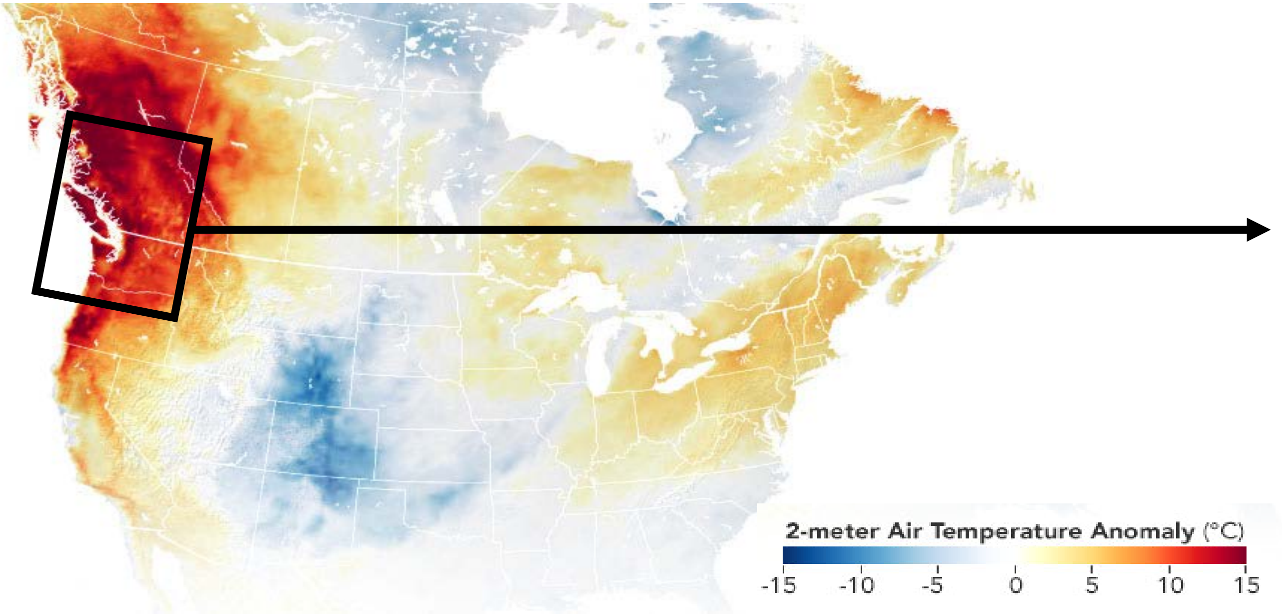
Increase Decrease

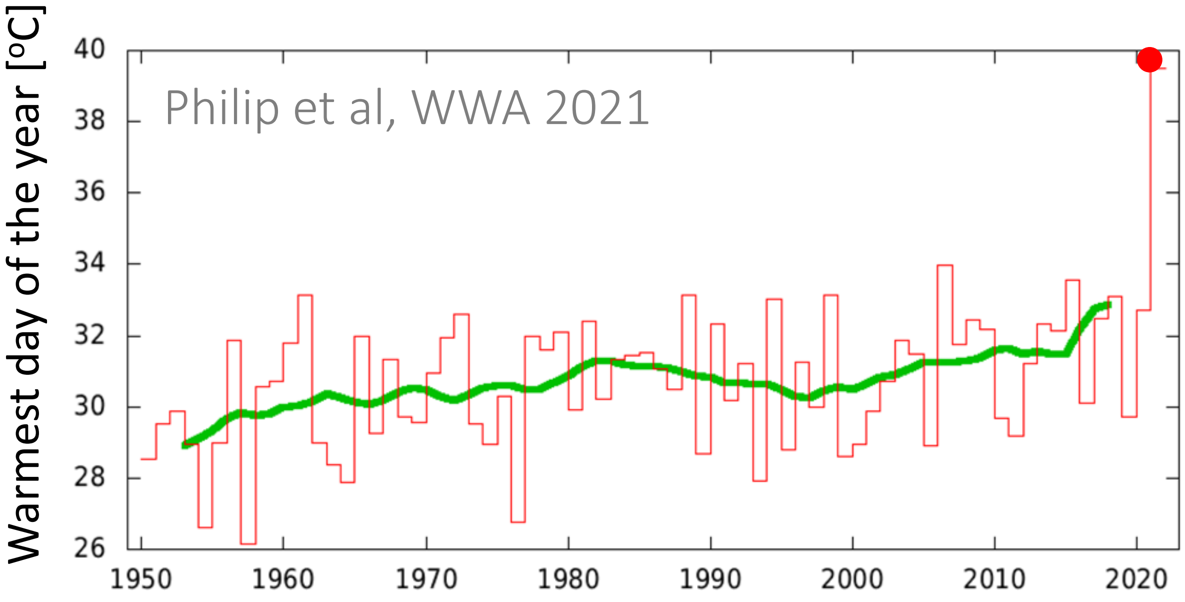
ipcc

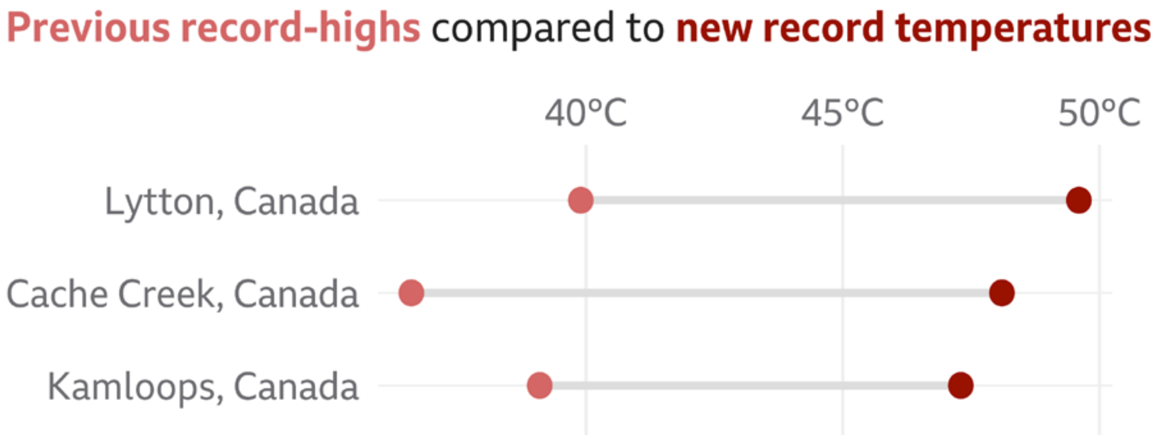



*Type of observed change since the 1950s*

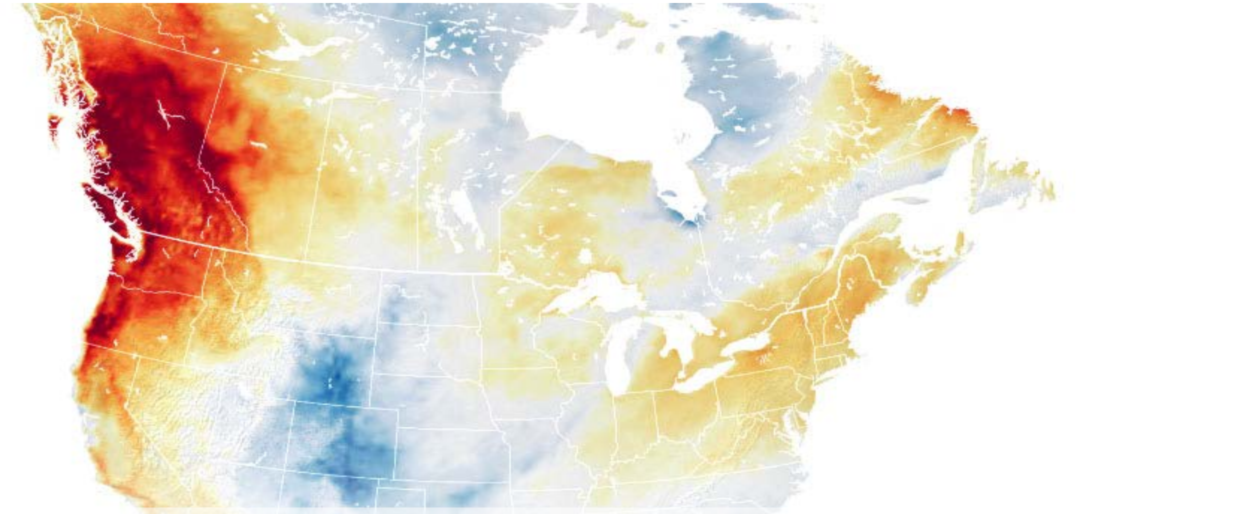
# 2021: A summer full of surprises - June Canadian heatwave

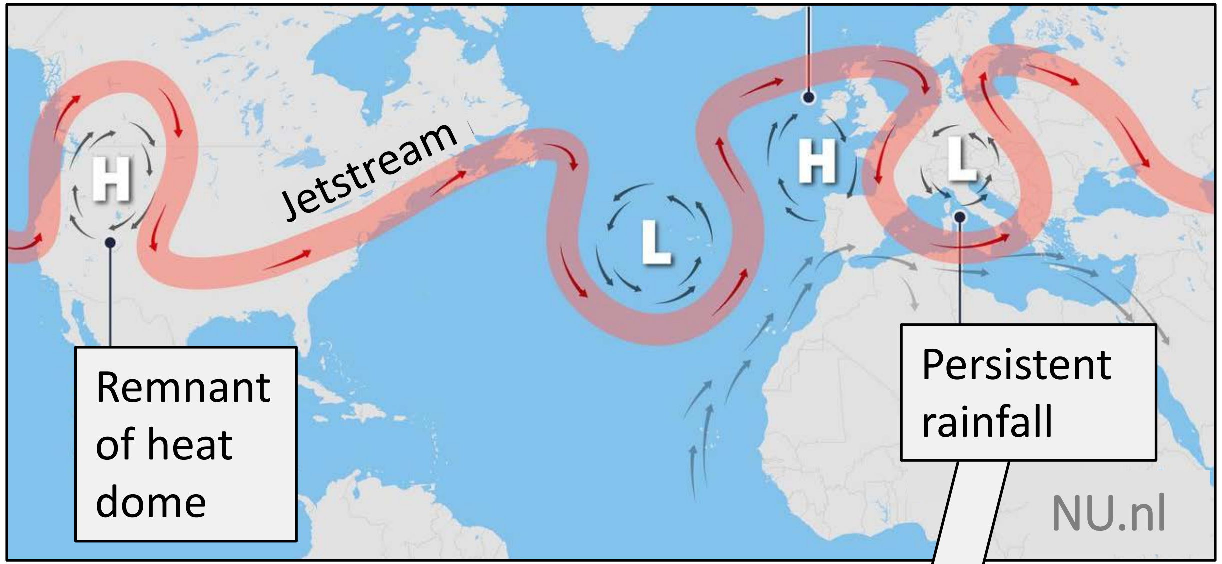


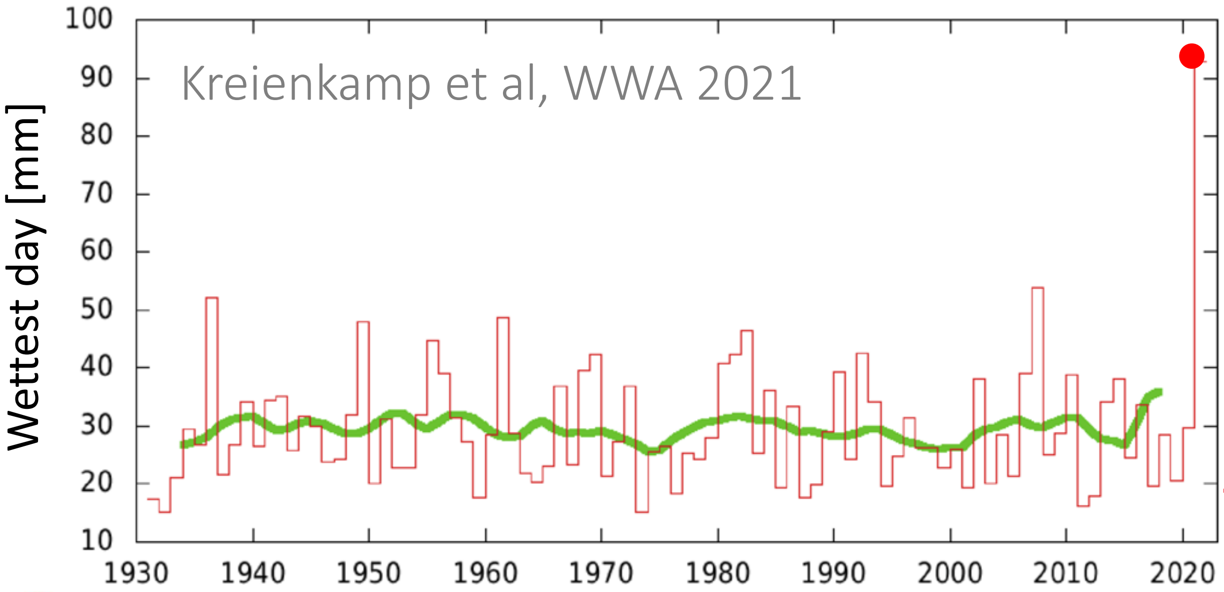



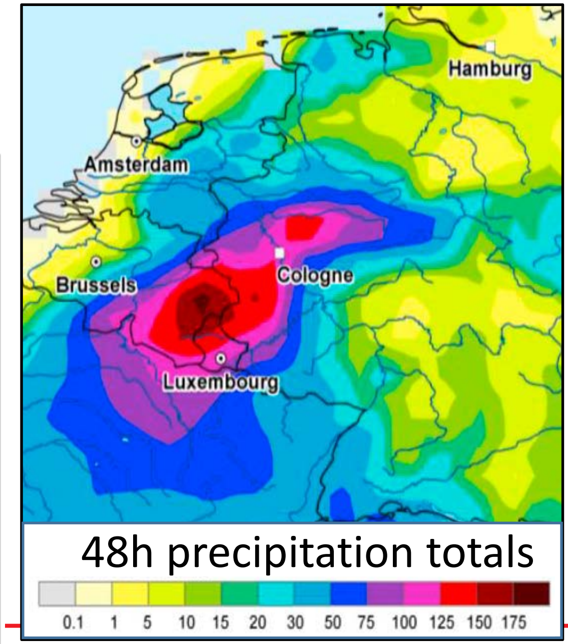
# 2021: A summer full of surprises – July European Flooding






Meandering Jetstream connecting far-away extreme weather events

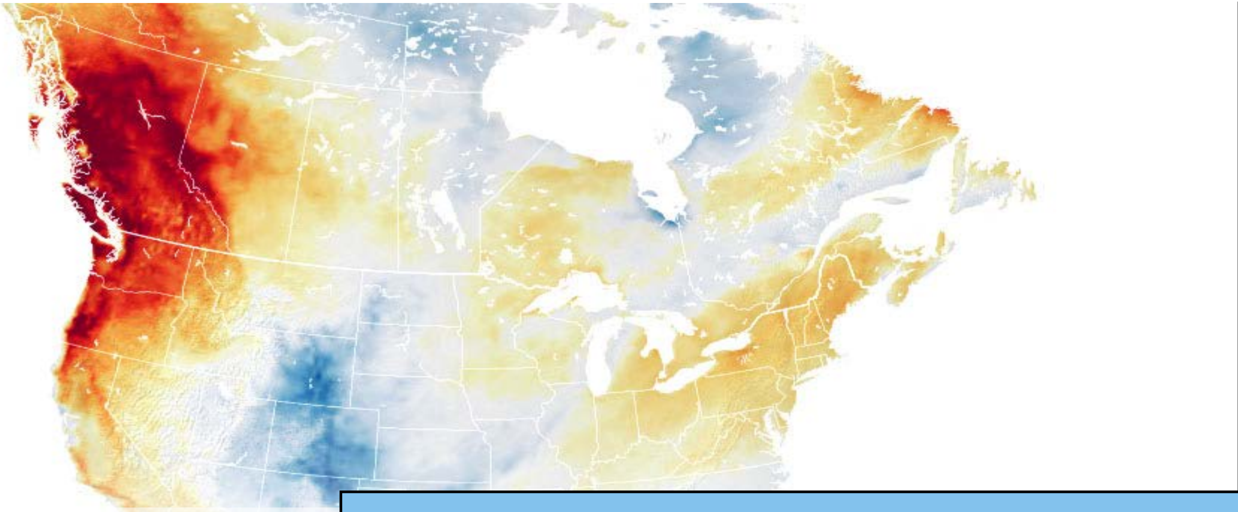


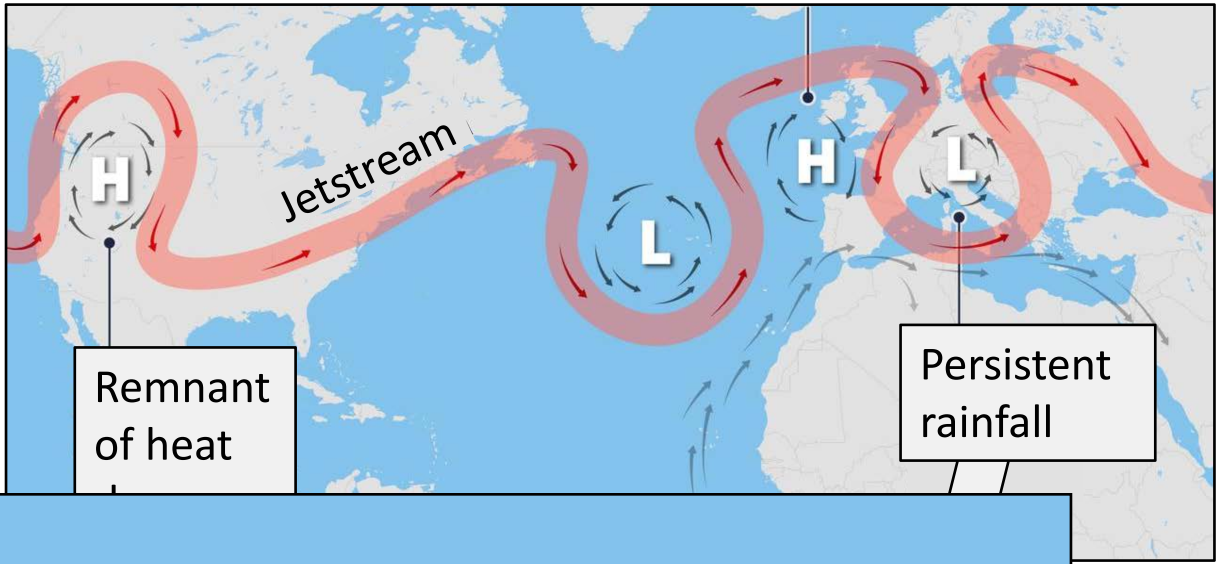



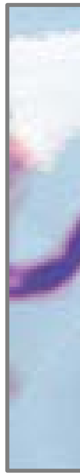


Damage $43B, costliest European weather disaster ever

# 2021: A summer full of surprises – July Chinese Flooding

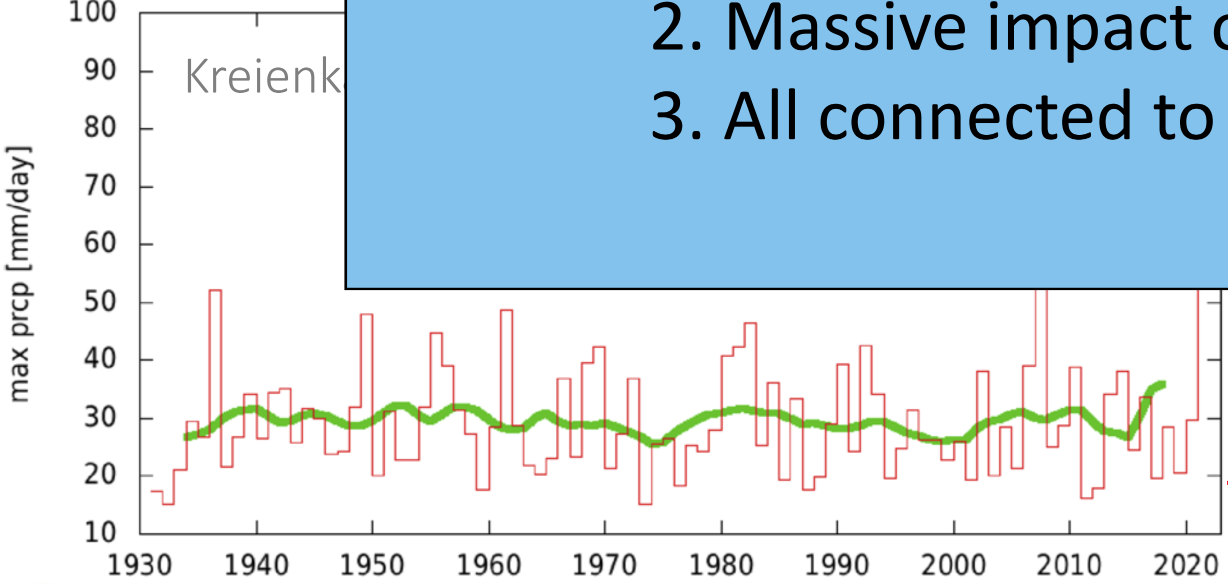




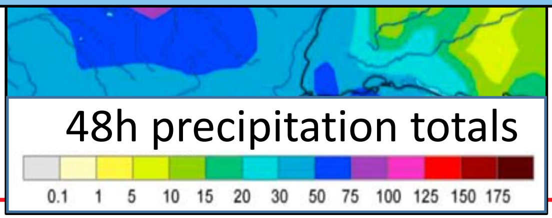



Meand

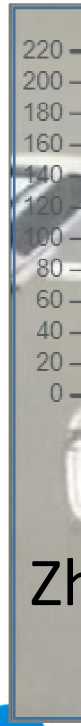
far-awa




1. Broke previous records by very large margins
2. Massive impact on society
3. All connected to dynamics of the Jetstream

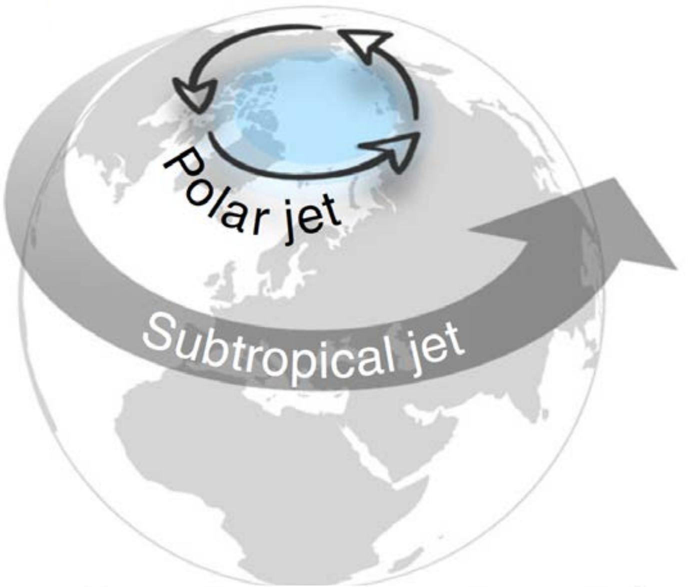


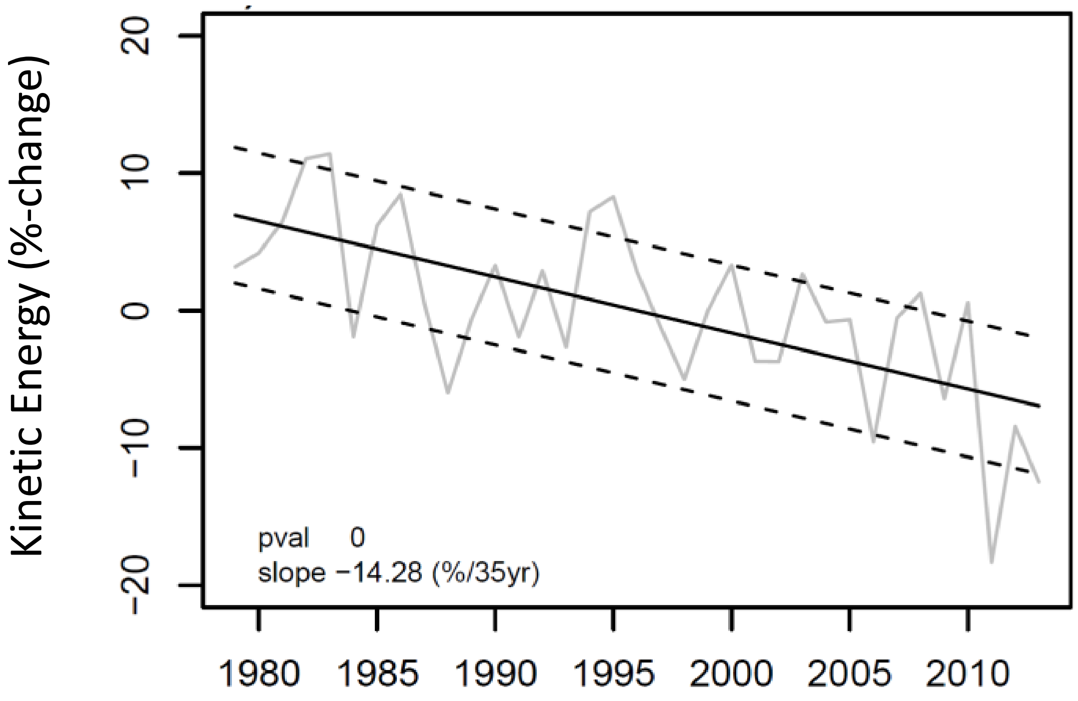

48h precipitation totals

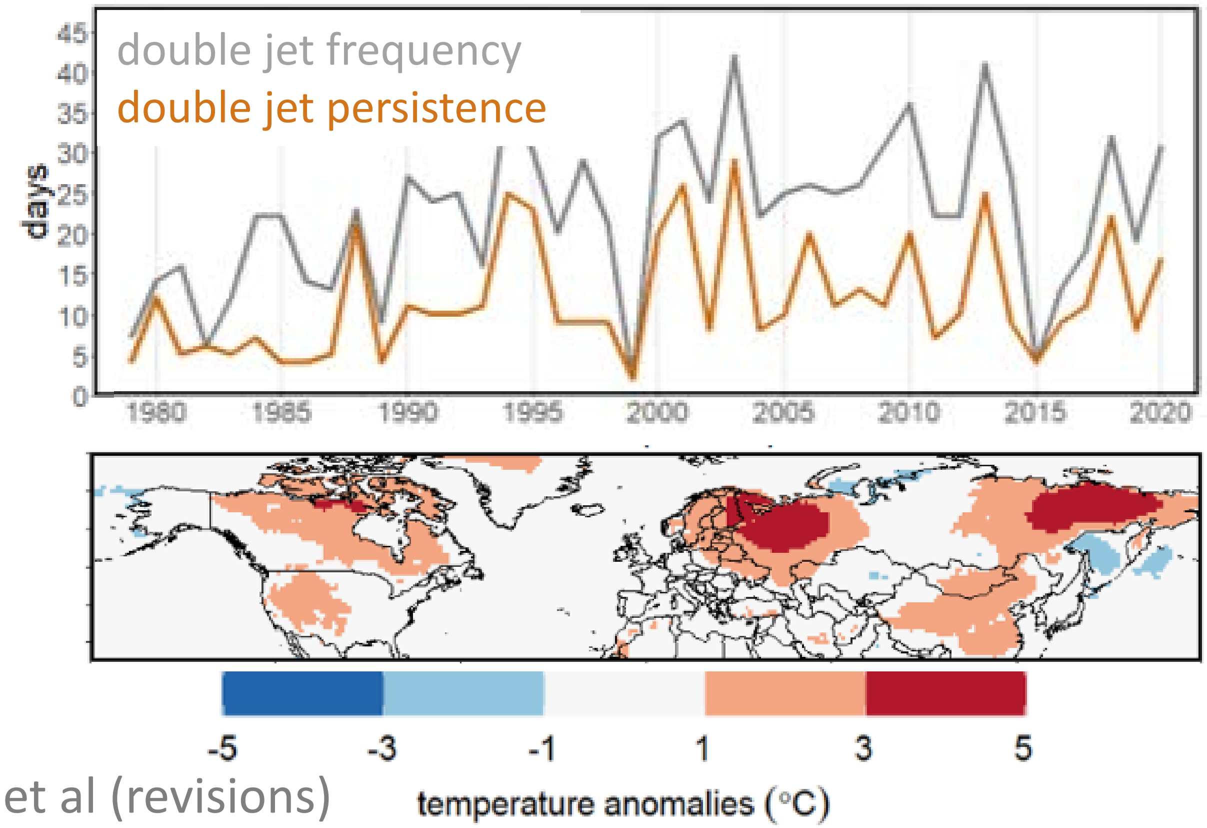


# Changes to the Jetstream in summer

- Weakening Jetstream & stormtracks, as predicted by climate models
- Increase in double-jet states



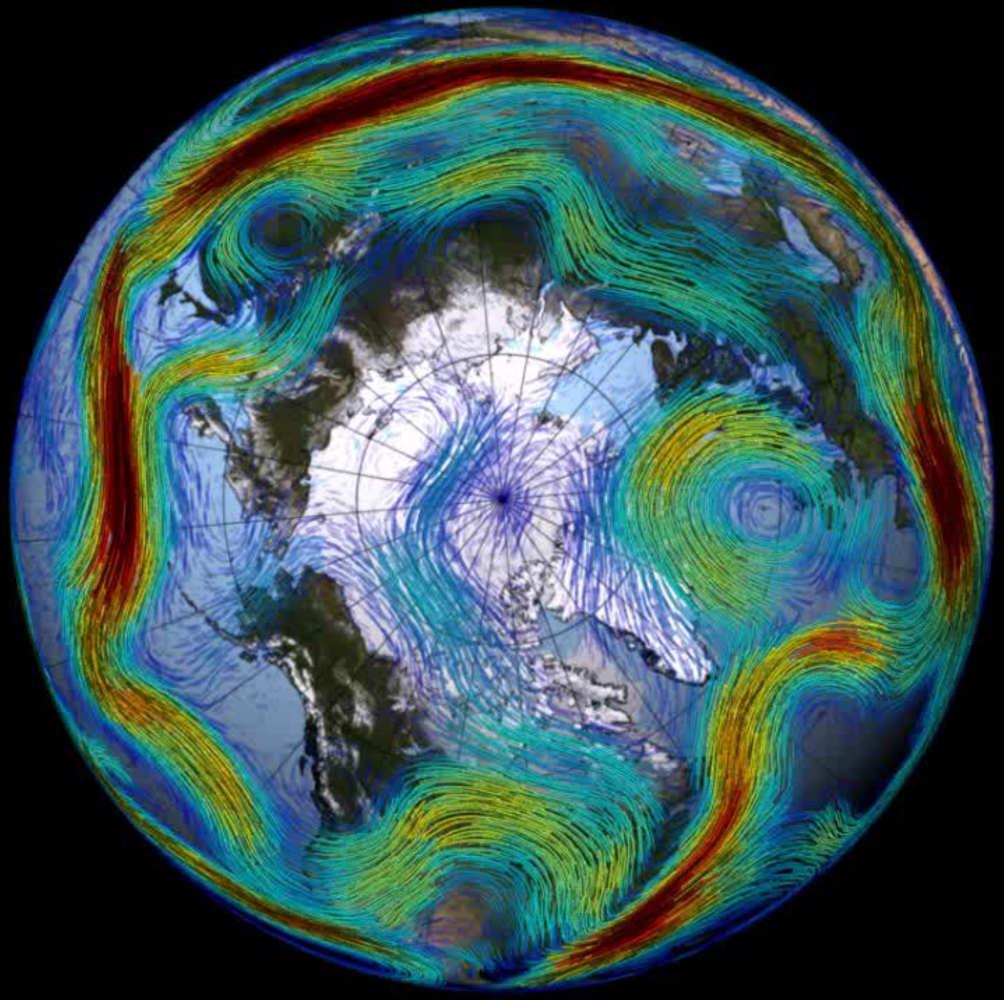




Coumou et al (2015, 2018); Rousi et al (revisions); Scholten et al (revisions)

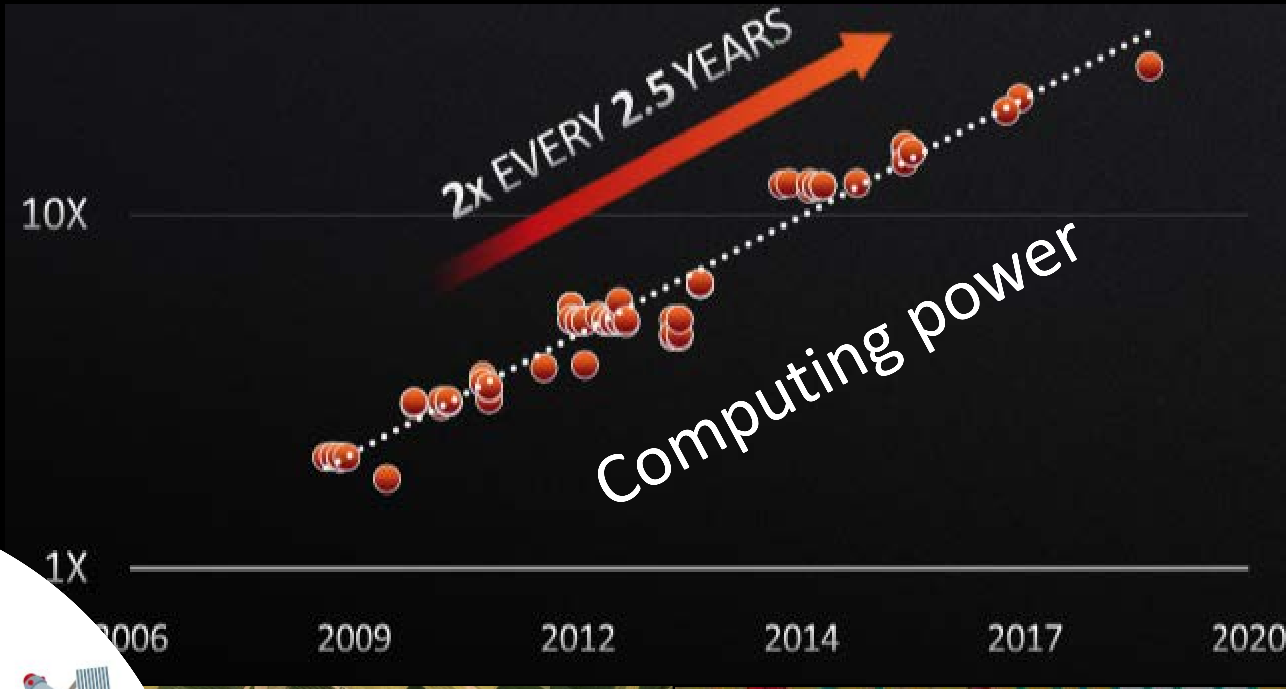
# Chair in Climate Extremes & Societal Risk

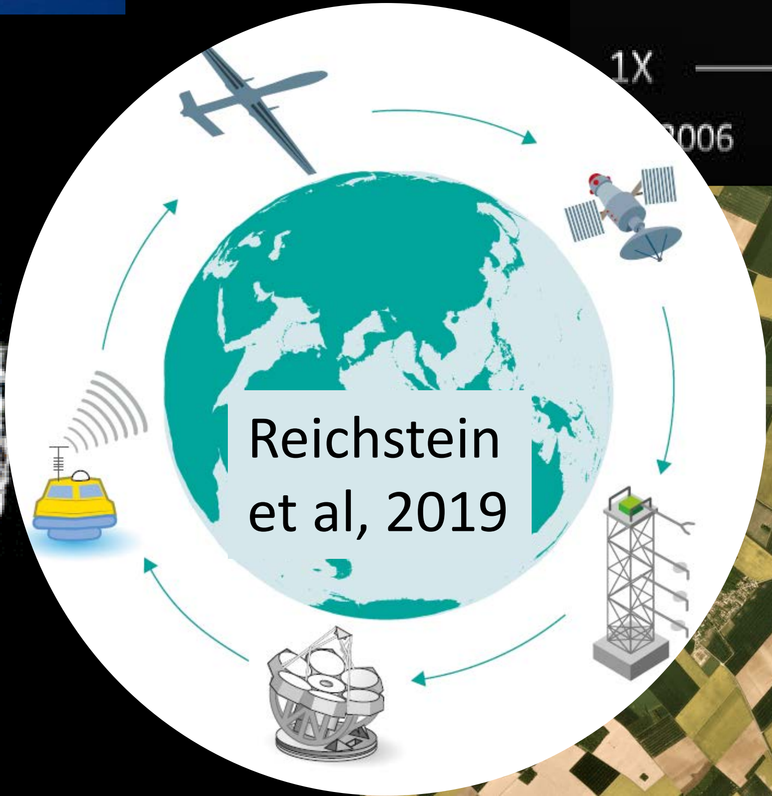
1. How does global warming affect atmosphere dynamics?
2. What new type of extremes can we expect?
3. What are the key risks for society?
4. Can we develop early warning systems?

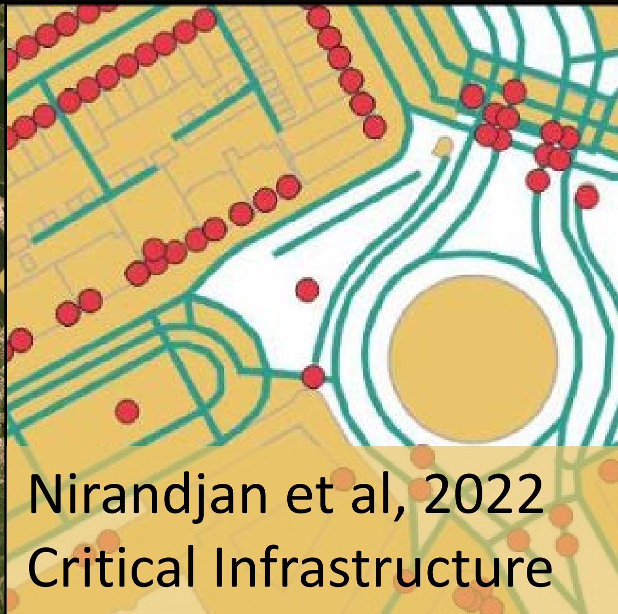


Credits: NASA

# Exascale computing & 100s of petabytes data



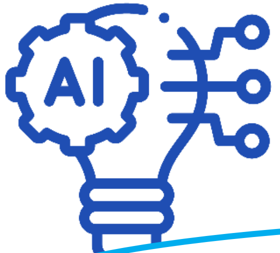



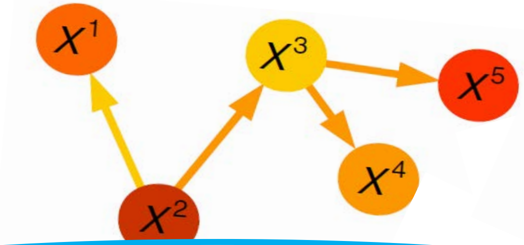
# How to harvest knowledge from big data?

Data Sciences

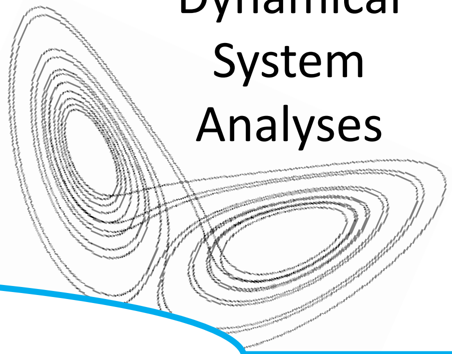
Explainable AI




Causal Discovery




Dynamical System Analyses



Process Understanding
Teleconnections & Extremes

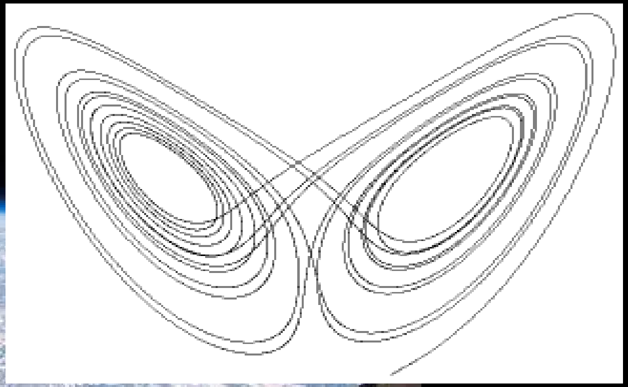
Goals

1. Regional projections of extremes & Societal risks
2. (Sub) seasonal forecasting & impact-based forecasting
3. Attribution of (impacts from) extremes

# European summer drought

## ISS, Aug 2018

Credits: A. Gerst



| | | | | |
|---|---|---|---|---|
| Di 26 mei | 8° / 22° | 3 | 9 | |
| Wo 27 mei | 11° / 19° | 4 | 9 | |
| Do 28 mei | 8° / 18° | 4 | 9 | |
| Vr 29 mei | 7° / 20° | 3 | 9 | |
| Za 30 mei | 10° / 22° | 3 | 9 | |
| Zo 31 mei | 11° / 22° | 4 | 9 | |
| Ma 1 juni | 12° / 22° | 4 | 9 | |
| Di 2 juni | 13° / 23° | 4 | 9 | |

# European summer drought

*Tellus* (1990), *42A*, 378–389

**Can chaos and intransitivity lead to interannual variability?**

By E. N. LORENZ, *Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

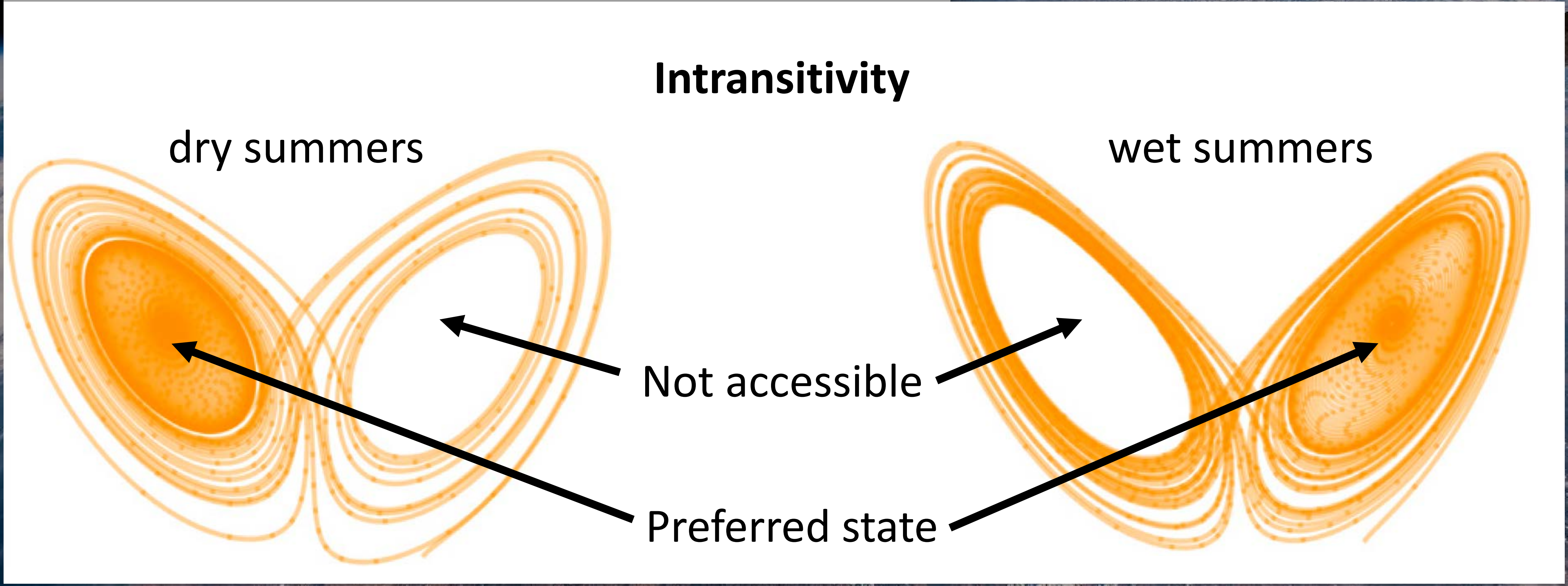
Attractor in phase-space of simplified chaotic system

(Edward Lorenz)

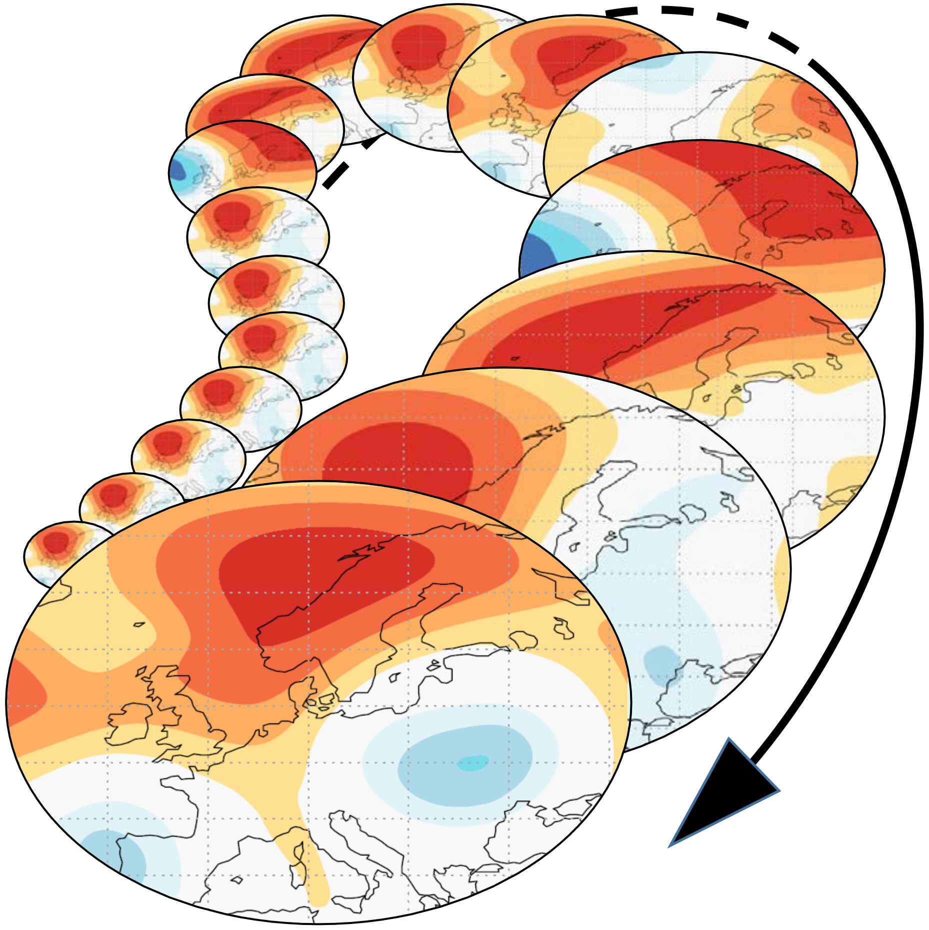
# European summer drought

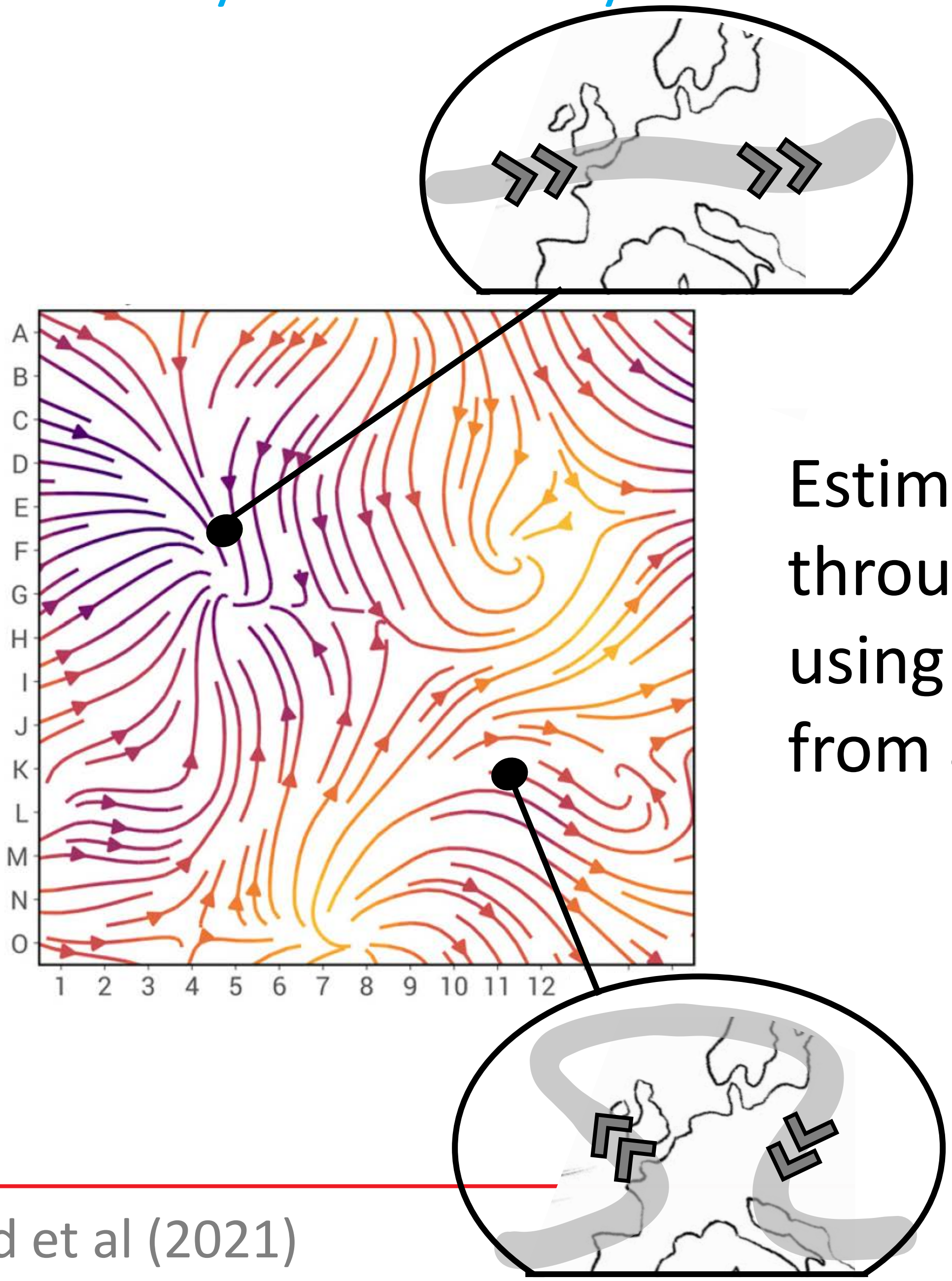
*Tellus* (1990), *42A*, 378–389

**Can chaos and intransitivity lead to interannual variability?**



# Mining knowledge from data: Dynamical System Analyses



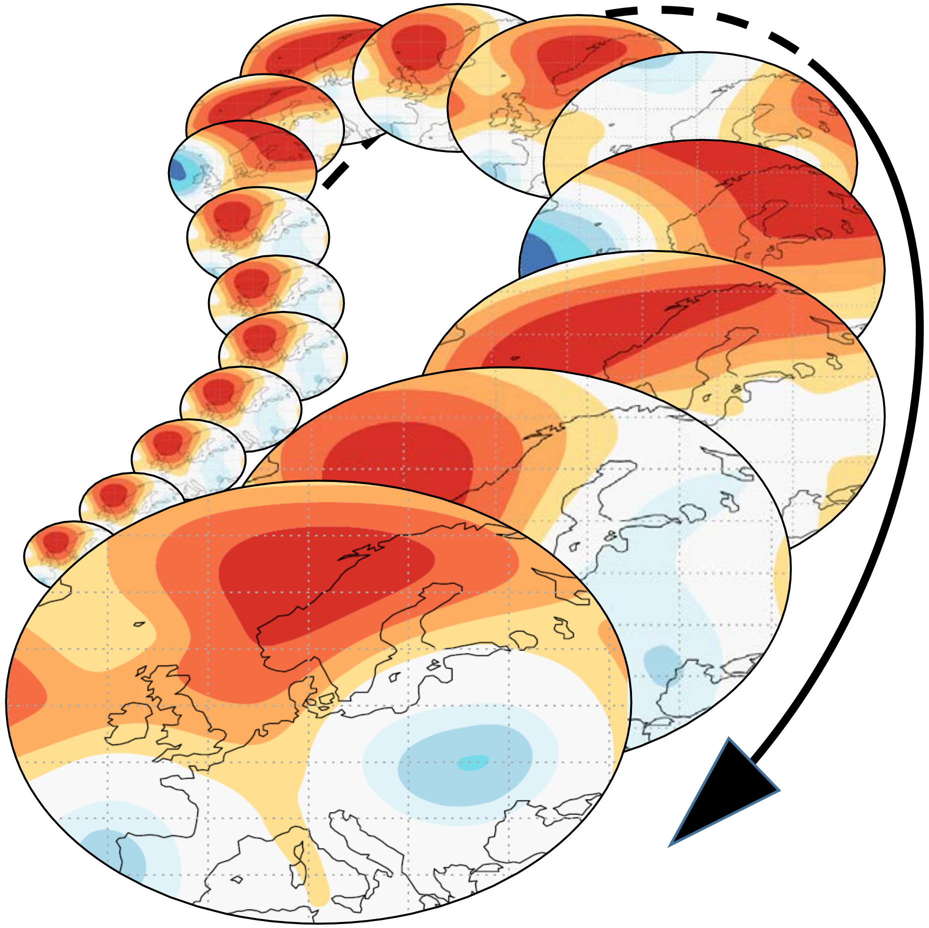


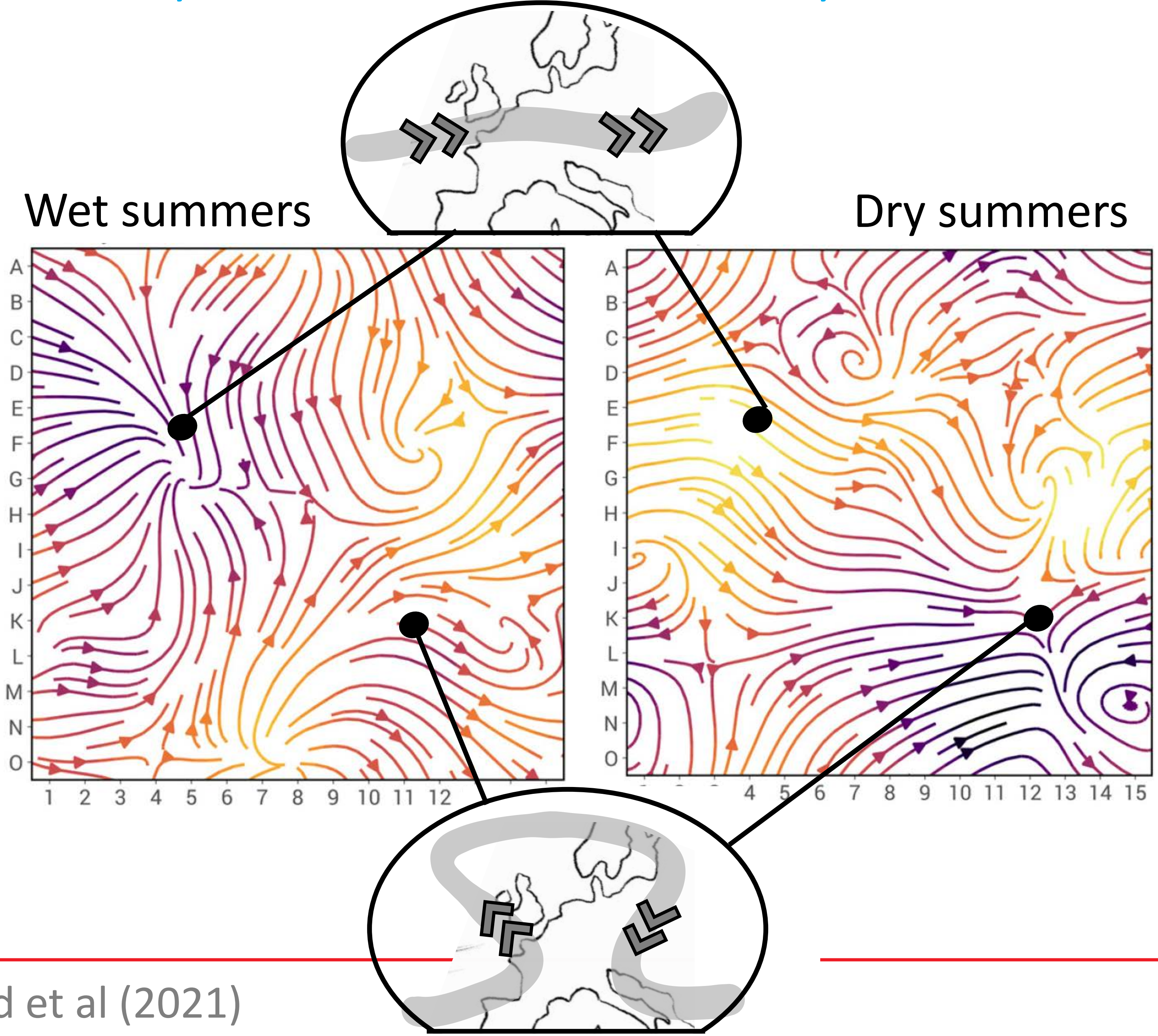

Estimate trajectories through phase space using 2000 summers from a climate model



Sperna Weiland et al (2021)

# Mining knowledge from data: Dynamical System Analyses



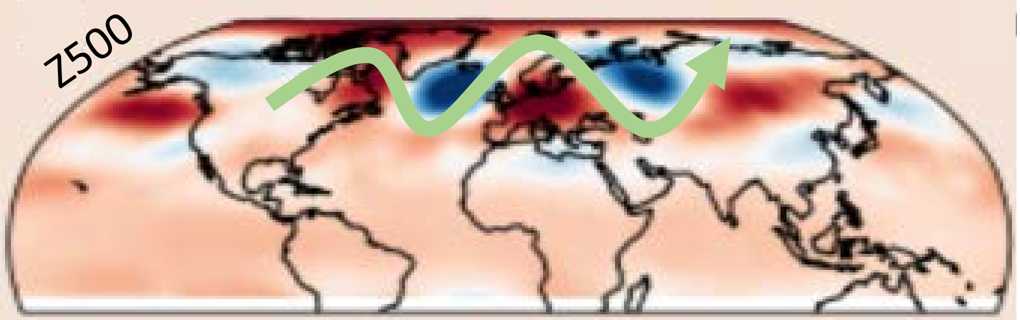


# Mining knowledge from data: Explainable AI

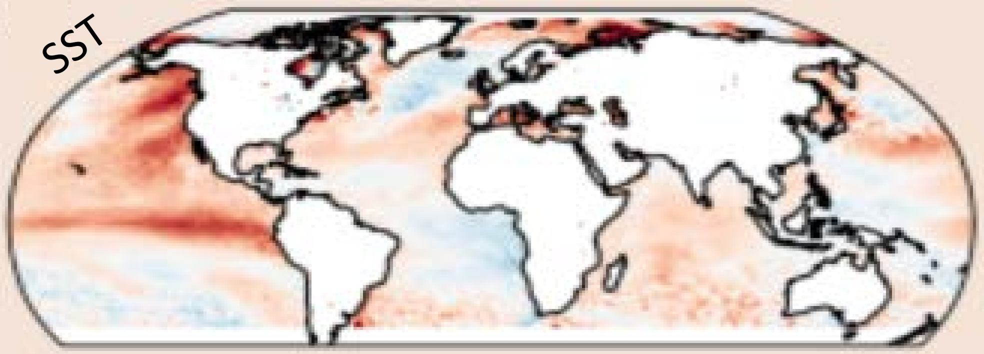
Forecasting summer temperature over Europe 1 month ahead

Train an AI to apply corrections to a seasonal forecast by a climate model

Upward correction needed

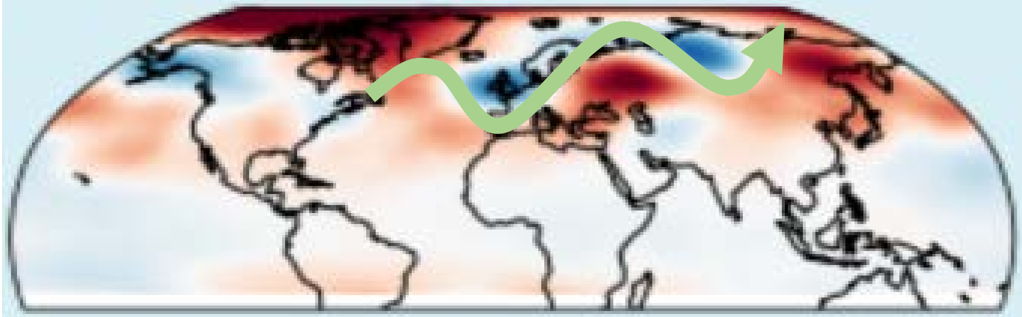



W-Europe hot & E-Europe cold

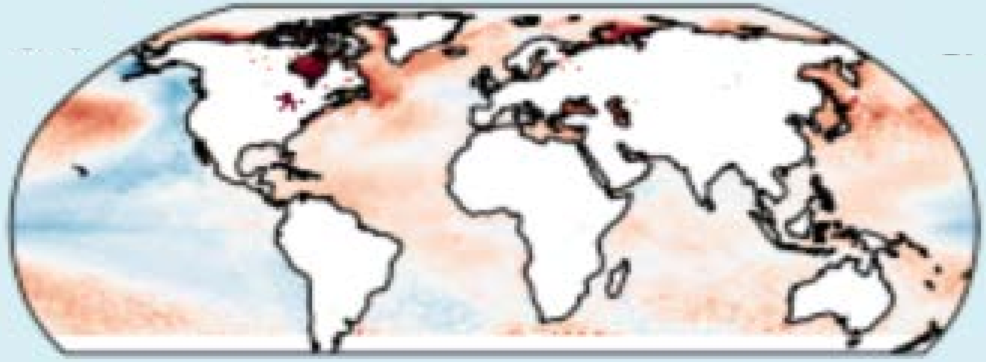



El Nino

Downward correction needed



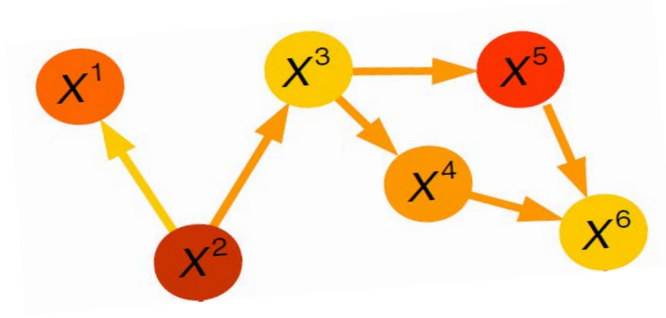
W-Europe cold & E-Europe hot

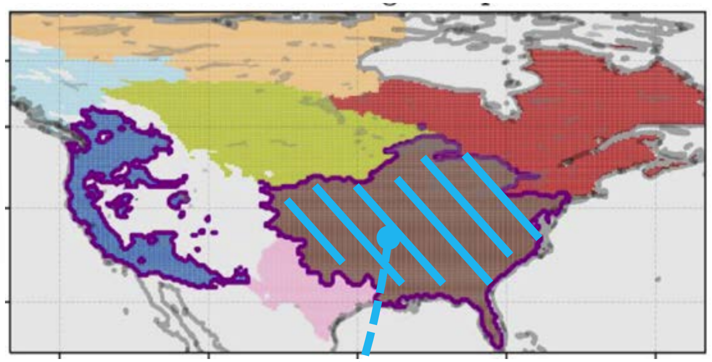


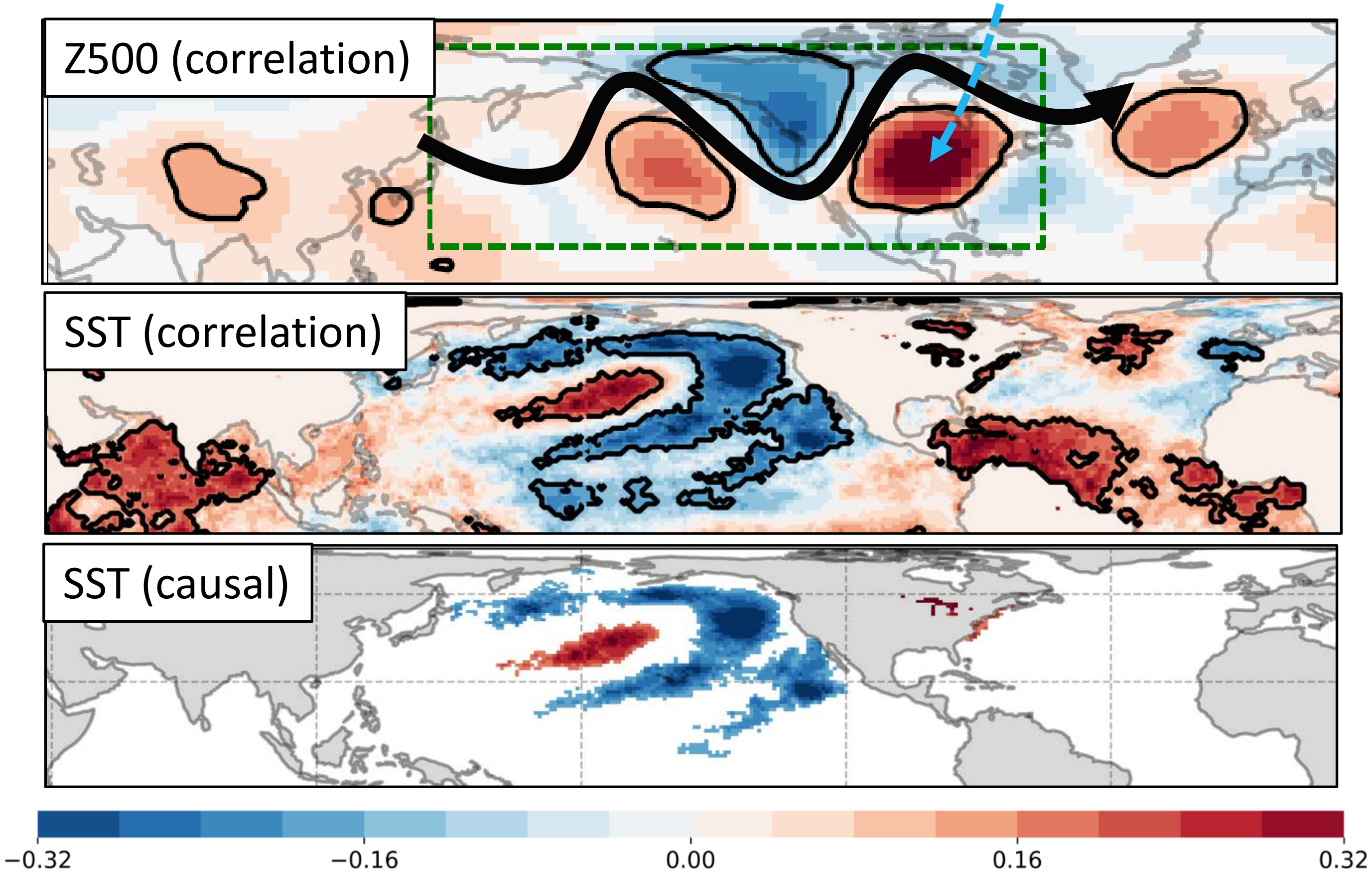
La Nina

Van Straaten et al (in prep.)

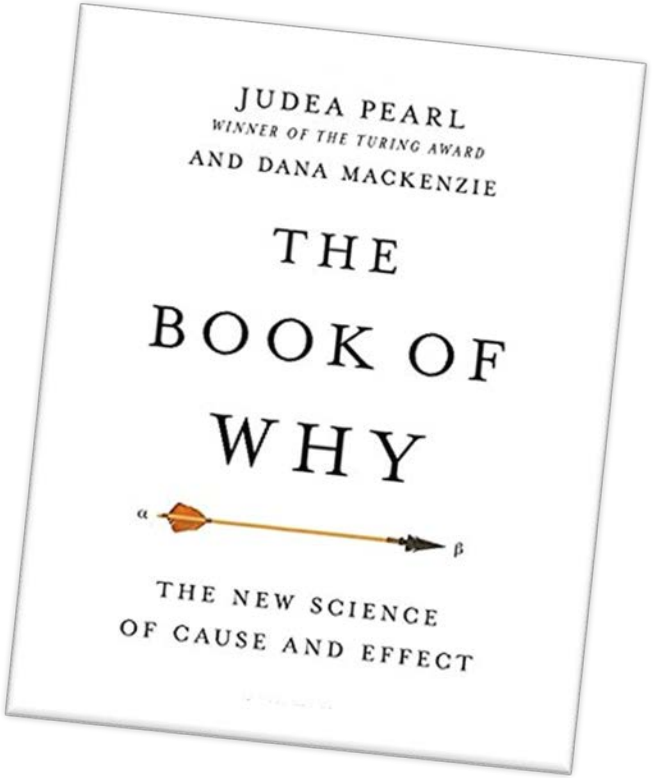
# Mining knowledge from data: Causal Discovery Algorithms






Causal sea surface temperature patterns over Pacific give predictability of eastern US heatwaves up to 60 days ahead



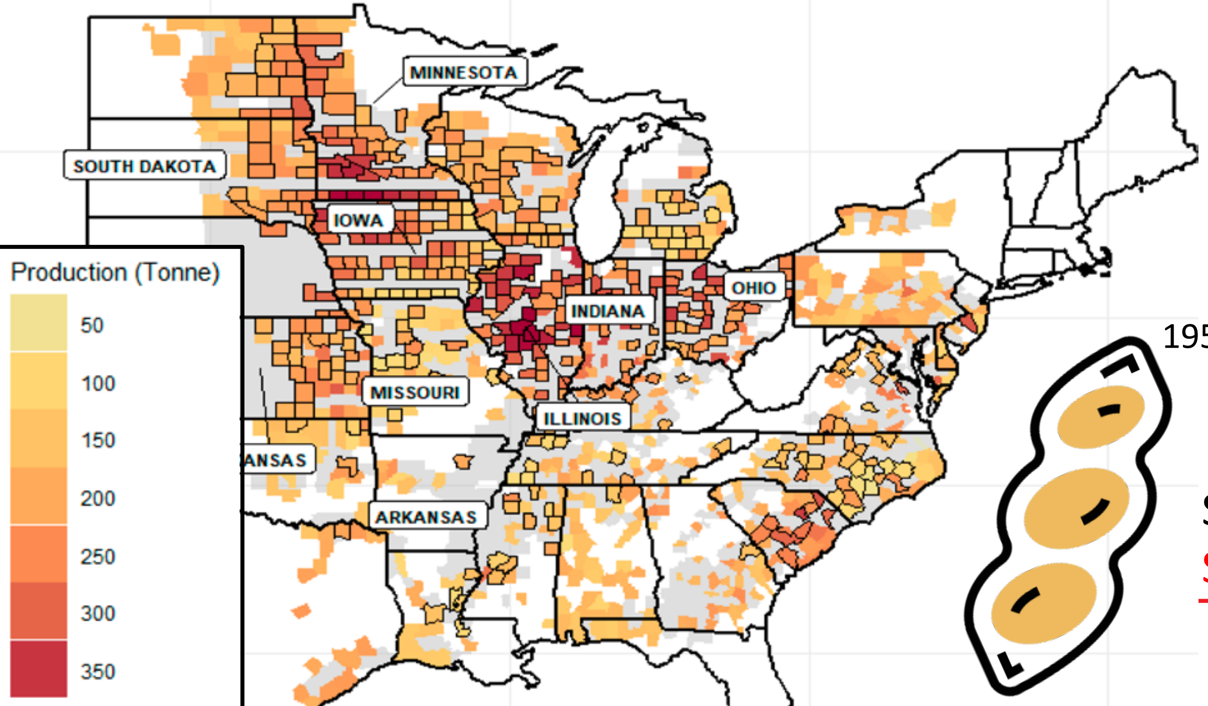

Vijverberg et al, 2020; Vijverberg & Coumou, 2022

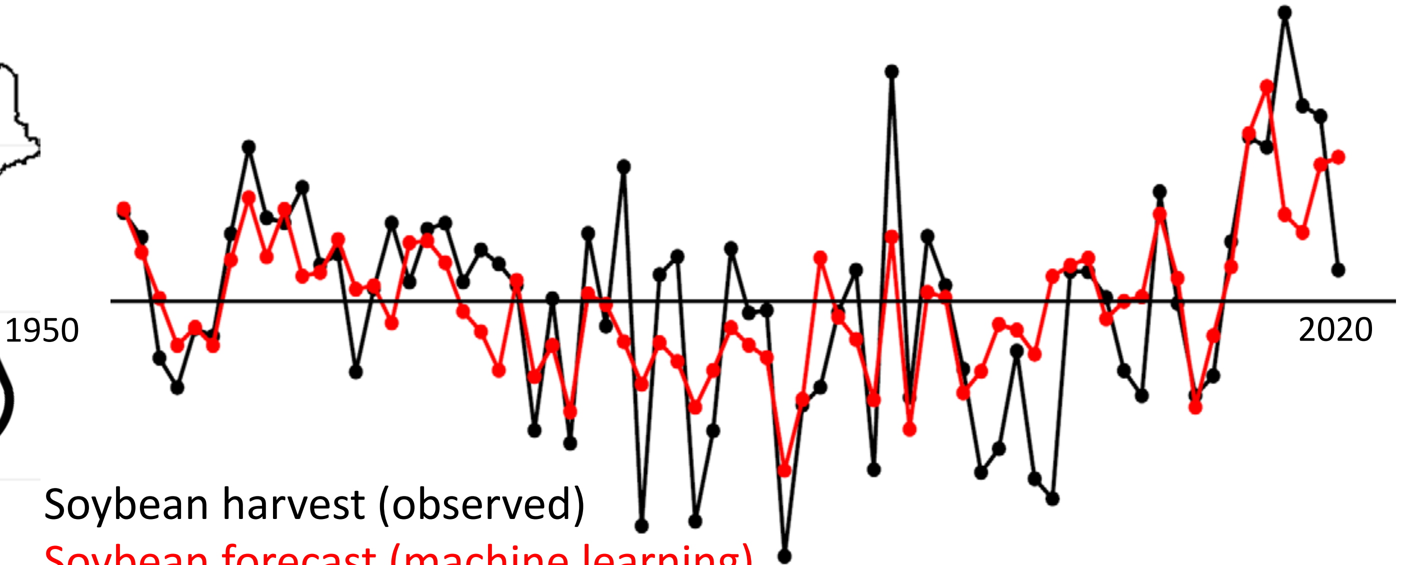
Kretschmer et al (2016, 2017); Di Capua et al (2020)

# AI-based impact forecasting

Eastern US Soybean harvest failures are predictable 3 months (!) before sowing

Sometimes the impact is better predictable than the weather



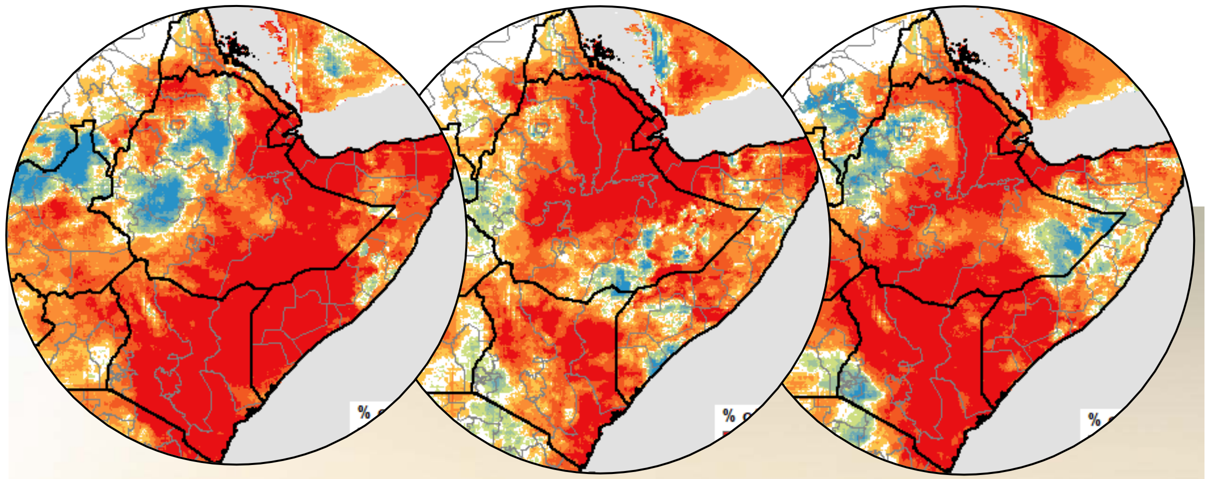




Hamed et al (2021); Vijverberg et al (revisions)

SEASONAL TO SUB-SEASONAL

ARTIFICIAL INTELLIGENCE

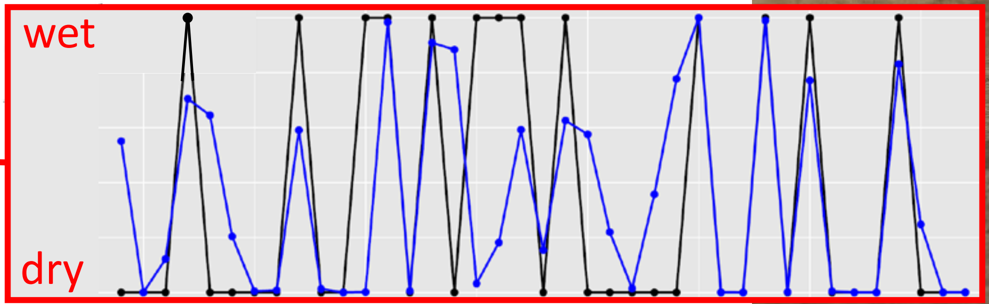
# Impact-based forecasting




Source: CHIRPS > 50% of normal rainfall

## Societal impact through entrepreneurship

WFP World Food Programme



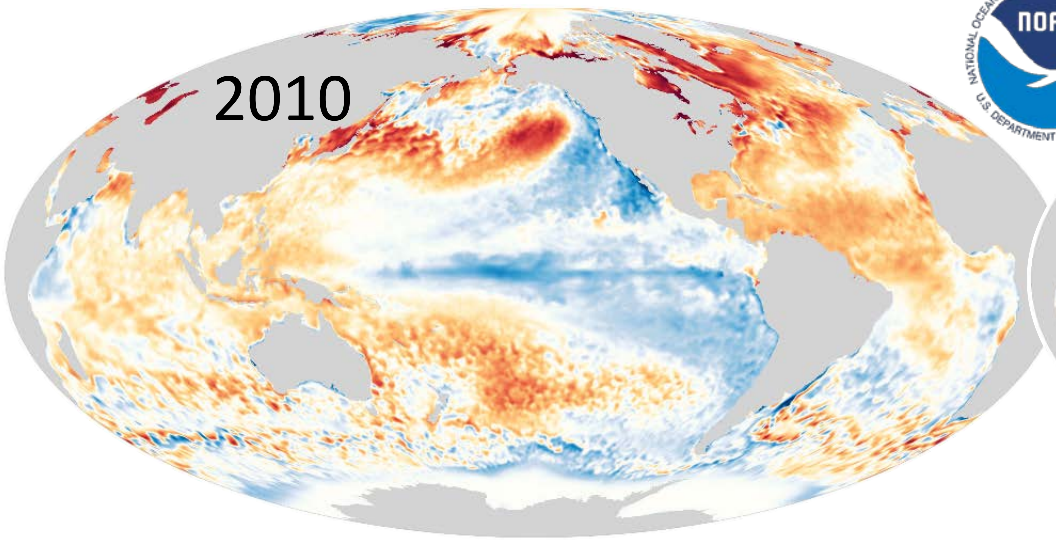

Observed rainy season

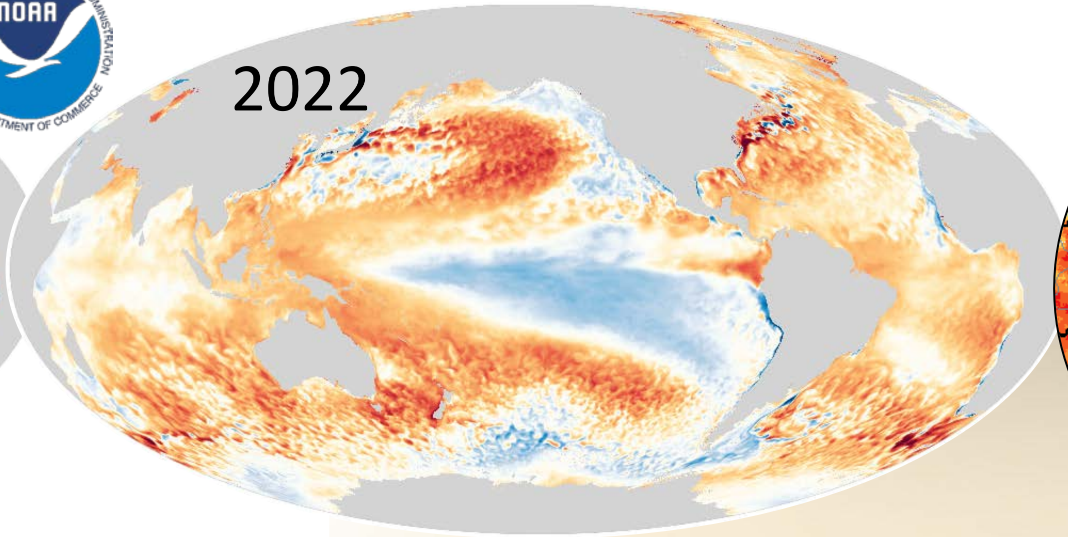
Forecasted rainy season

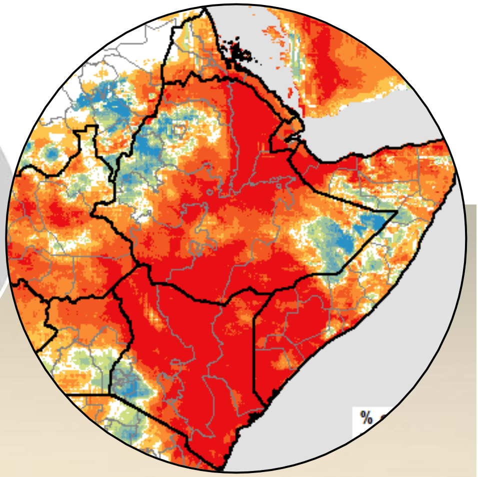
Grudnowska, Guimaraes-Nobre
Vijverberg, Van Ingen,
Vrubliauskas, Odonga, et al

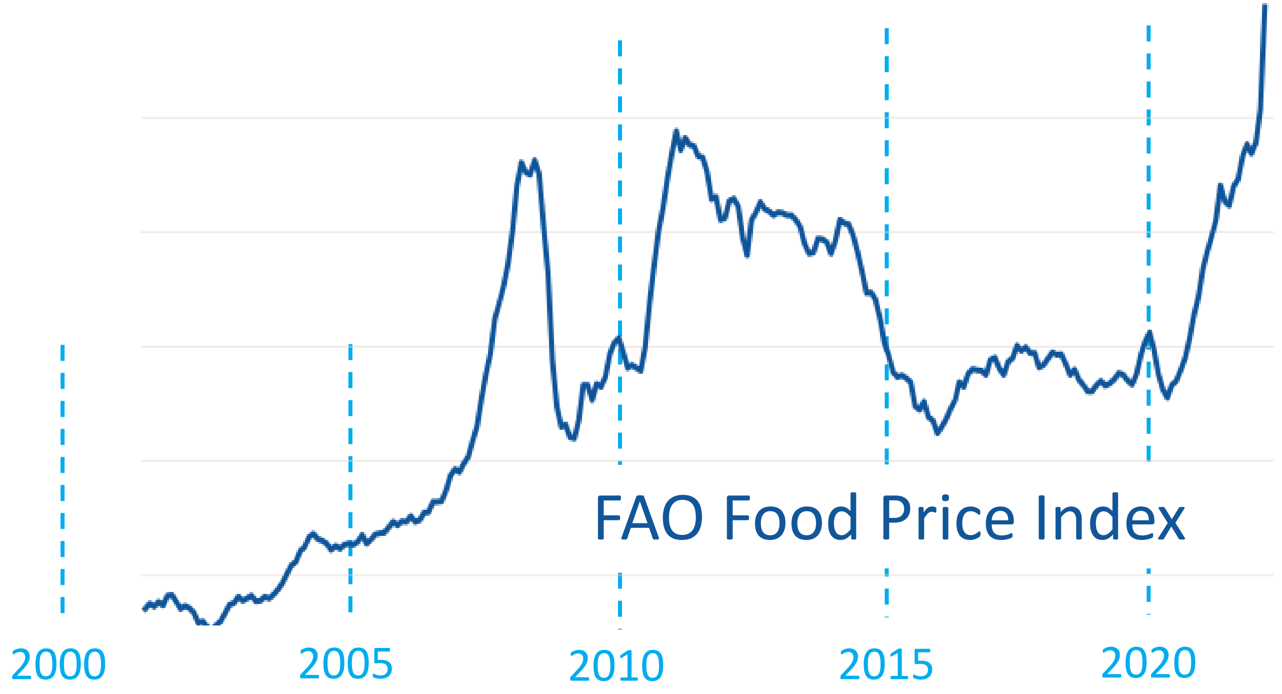
Di Capua et al (2021)
Luo et al (in prep)

# 2022: A perfect storm for food security?



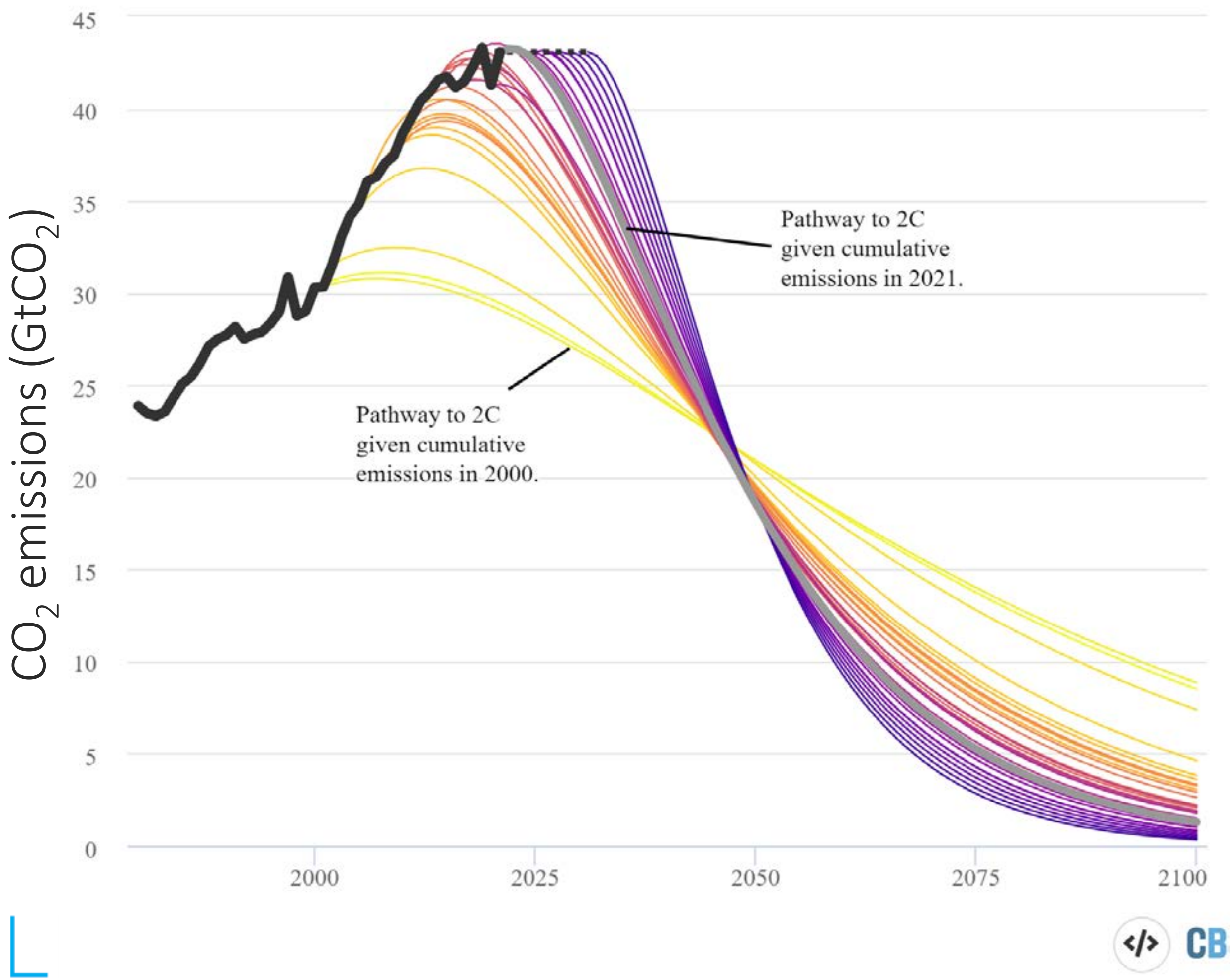



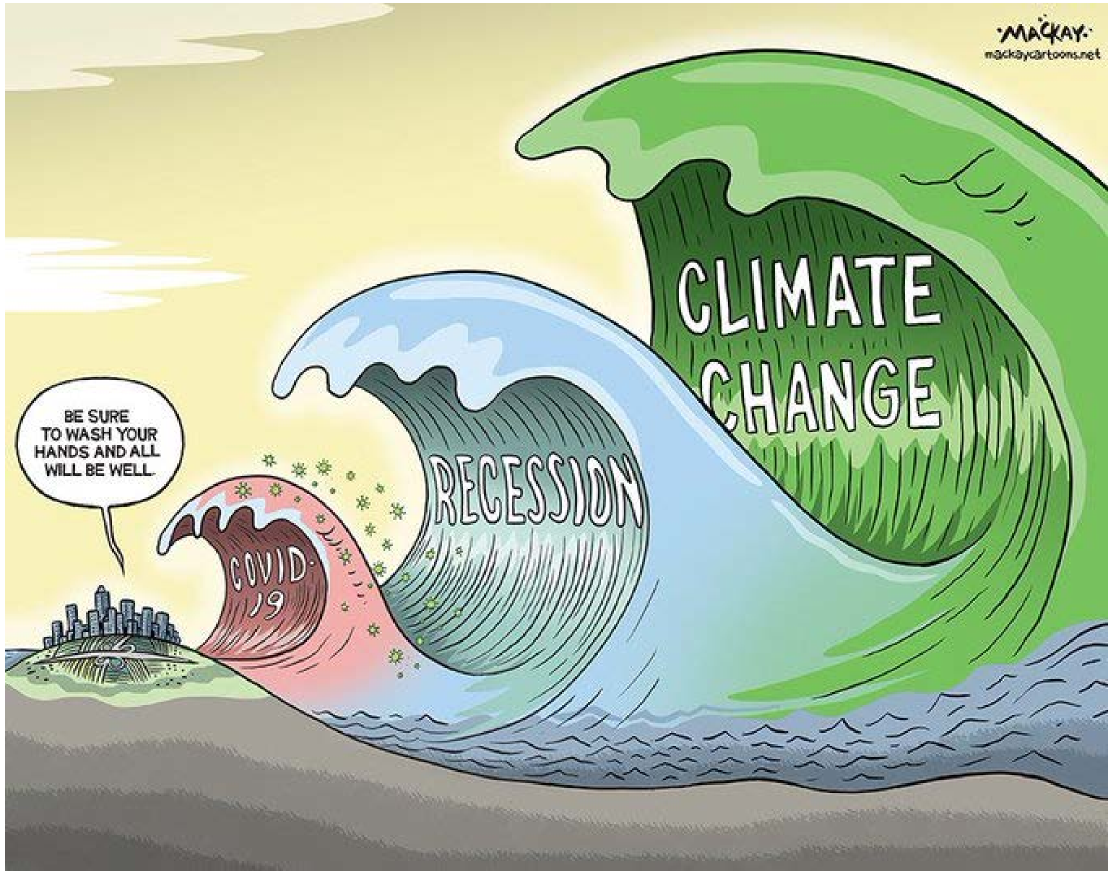




# The next 10 years are critical for 'Paris'

The later we peak, the faster we need to drop




CLI EXTREMES

# The human connection


POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH

IVM Institute for Environmental Studies

VU

Koninklijk Nederlands Meteorologisch Instituut
*Ministerie van Infrastructuur en Milieu*