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UNIVERSITÉ TOULOUSE III PAUL SABATIER Université de Toulouse

Present climate characterization and future changes in Clear-Air Turbulence (CAT) over the northern hemisphere

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Objectives

- CAT **recent trends**
- CAT **future changes**

Data

Daily fields			Period
Reanalysis	ERA5 (ECMWF)		1979 – 2020
Climate models	CNRM-CM6-1 (CNRM-CERFACS)	26 historical members	1979 – 2009
		20 ssp585 members	2015 – 2100
	IPSL-CM6A-LR (IPSL)	32 historical members	1979 – 2014
		6 ssp585 members	2015 – 2054

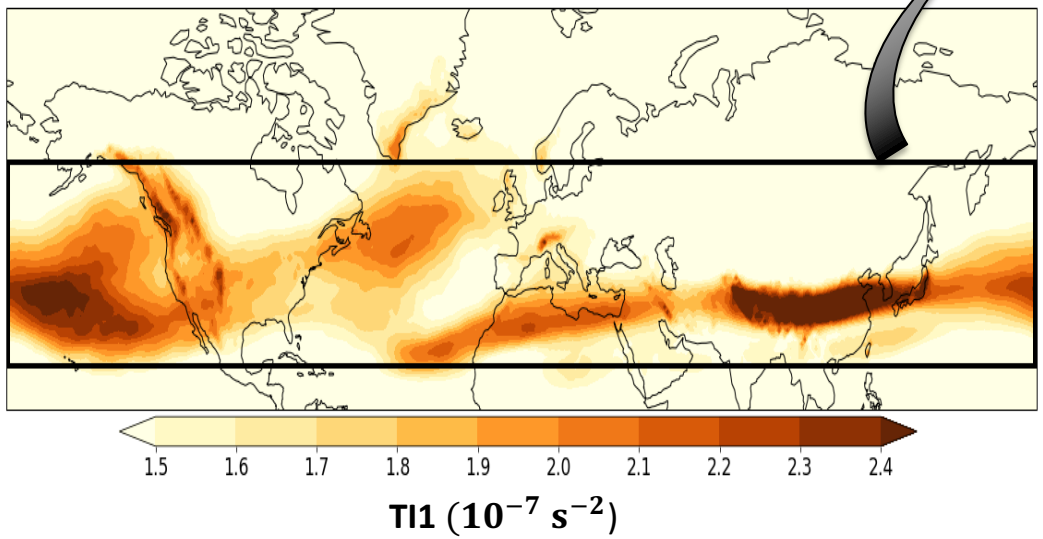
Methodology

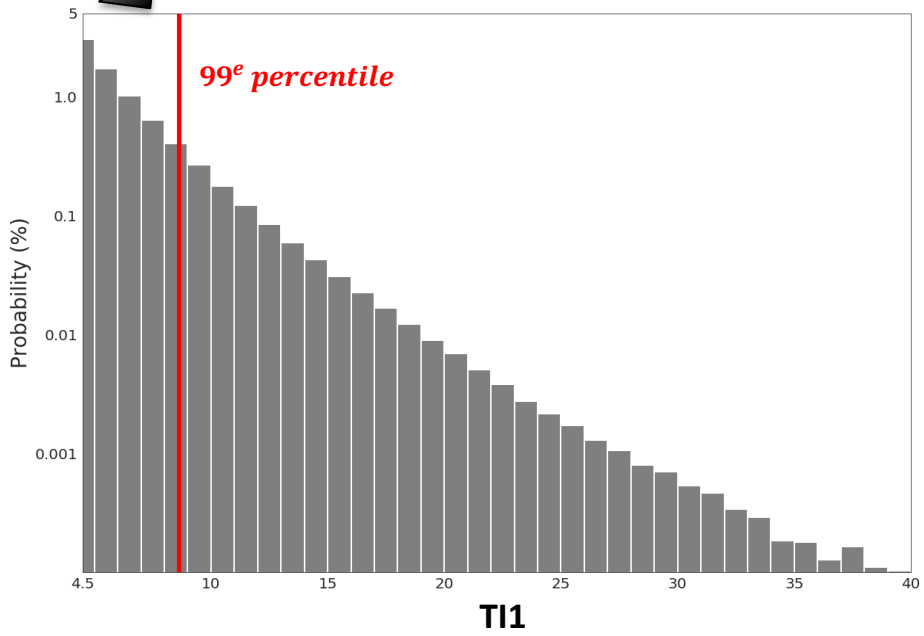
- **Turbulence index 1 (TI1)**

$$TI1 = Vertical\ Wind\ Shear \times flow\ deformation$$

- **Atmospheric layer :** 200 – 250hPa
- **Season and period for Moderate-Or-Greater CAT threshold :** winter (DJF), 1981-2010

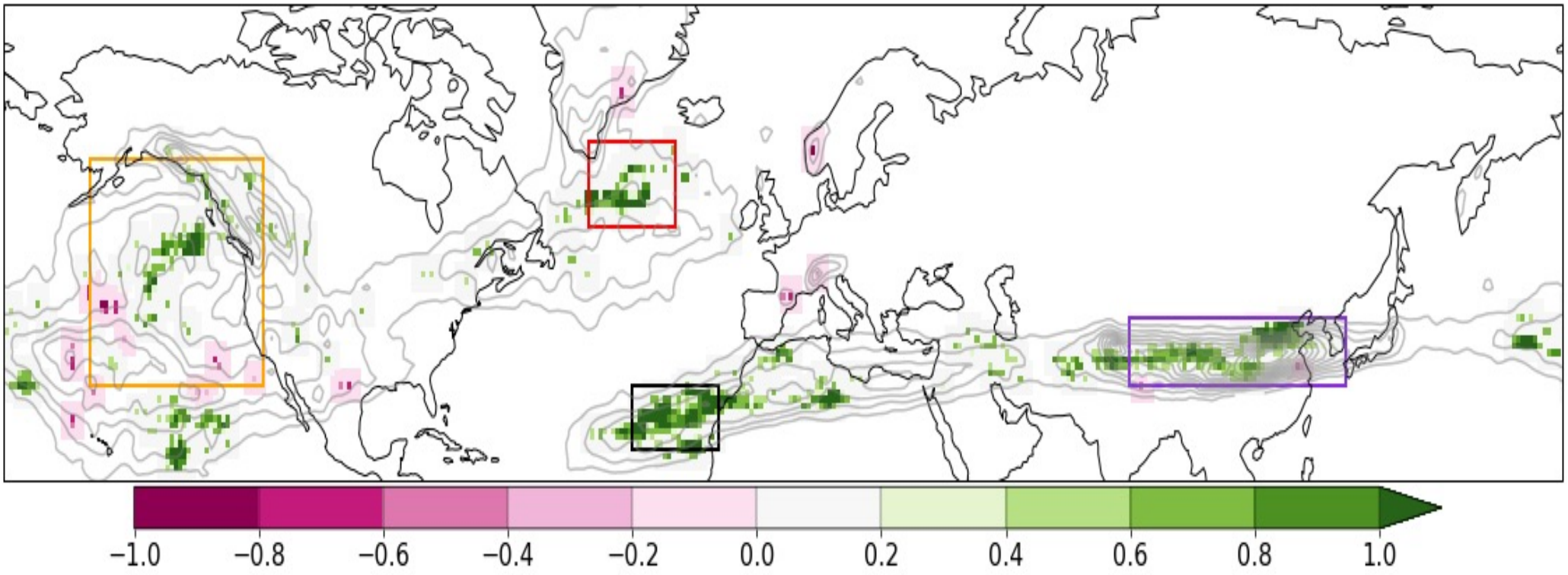
TI1 daily values





Are there significant CAT **trends** between 1979-2020 ?

$$\frac{trend}{interannual\ variability}$$



gray contours shows CAT climatology

Northeast Pacific

North NA *

South NA *

East Asia *

** indicates 5%-level statistical significance*

→ **internal variability**

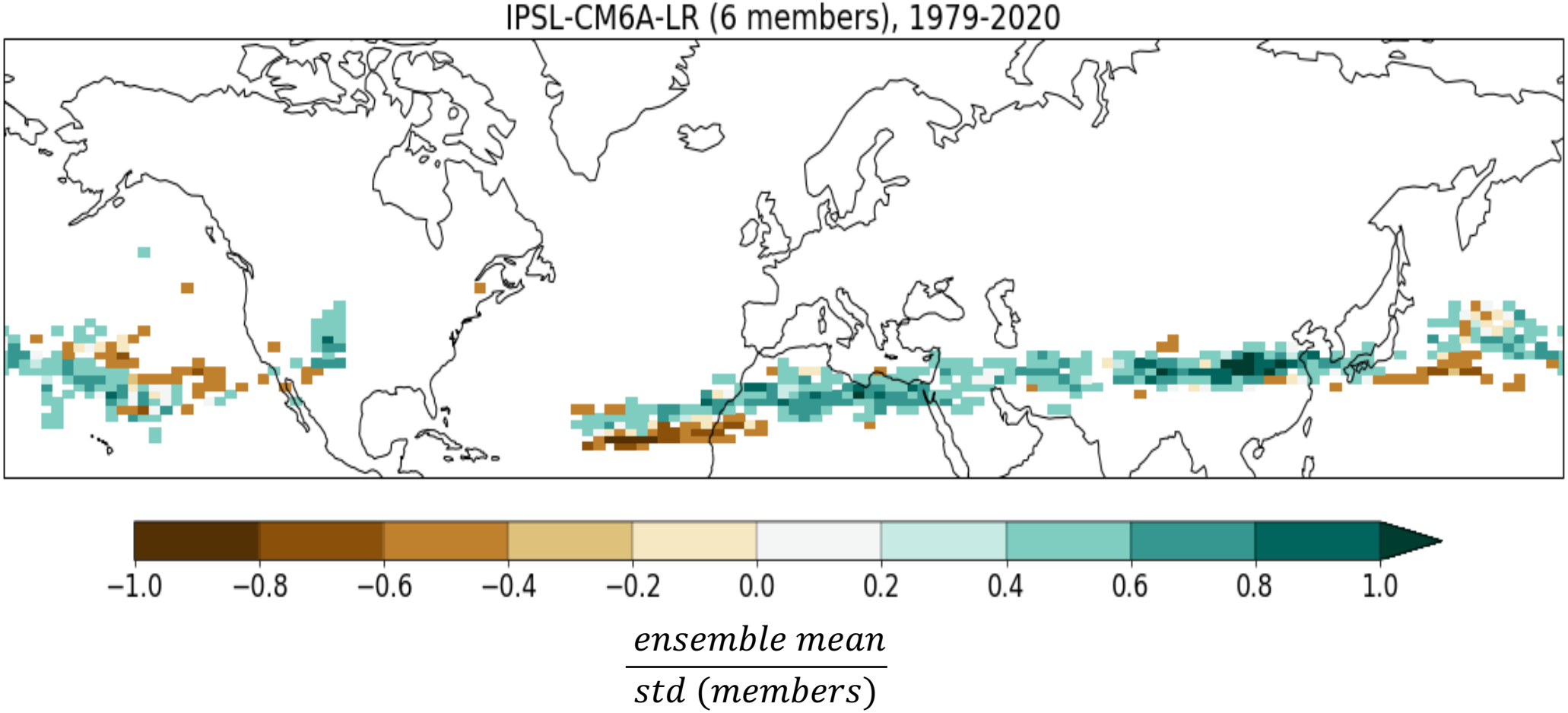
→ **external forcing**

- IPSL-CM6A-LR : 6 members

$$\frac{forced\ response}{internal\ variability} \sim \frac{ensemble\ mean}{std\ (members)} \sim \frac{signal}{noise}$$

Attribution of CAT trends

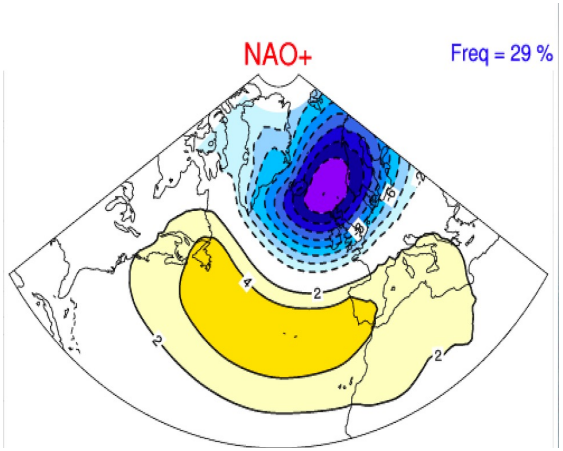
Separating the internal and forced signals of CAT trends



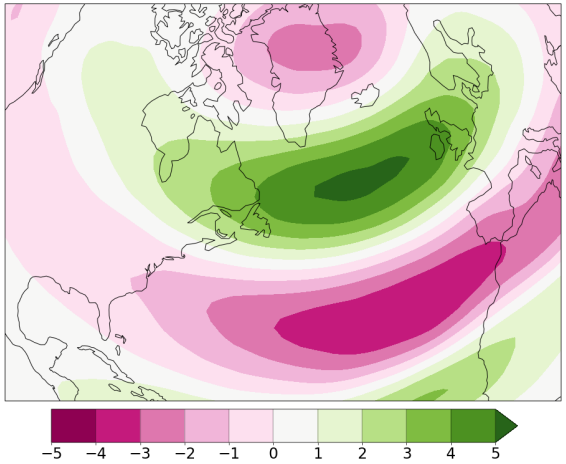
$$\frac{ensemble\ mean}{std\ (members)}$$

Links between CAT and The North Atlantic Oscillation (NAO+)

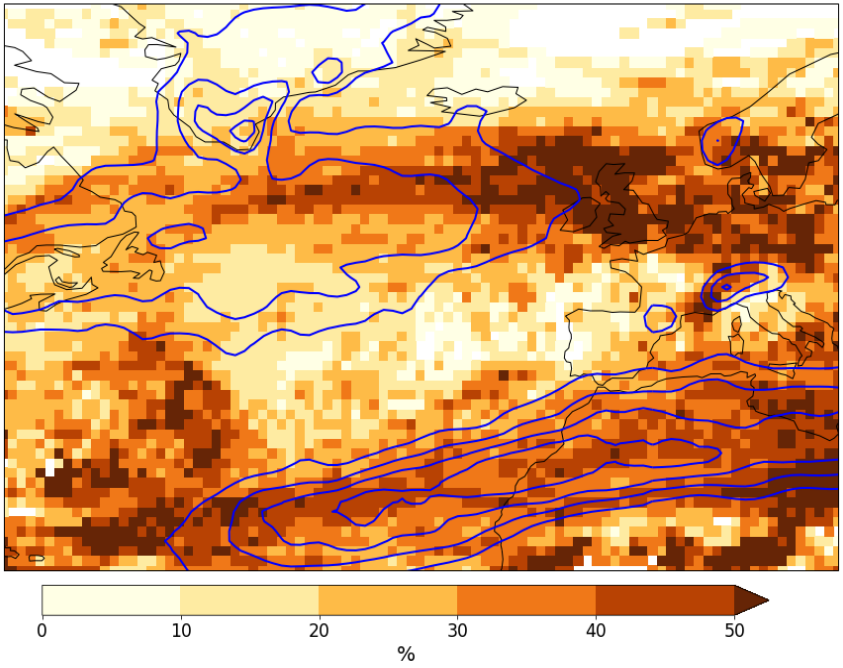
SLP anomalies



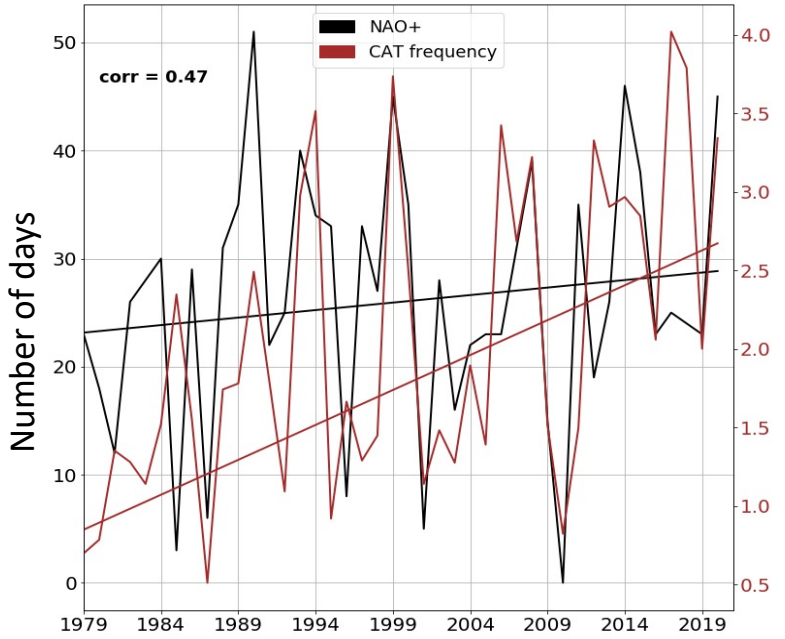
Zonal wind anomalies at 250hPa



Percentage of CAT frequency related to NAO+ regime. CAT climatology (Blue contours)

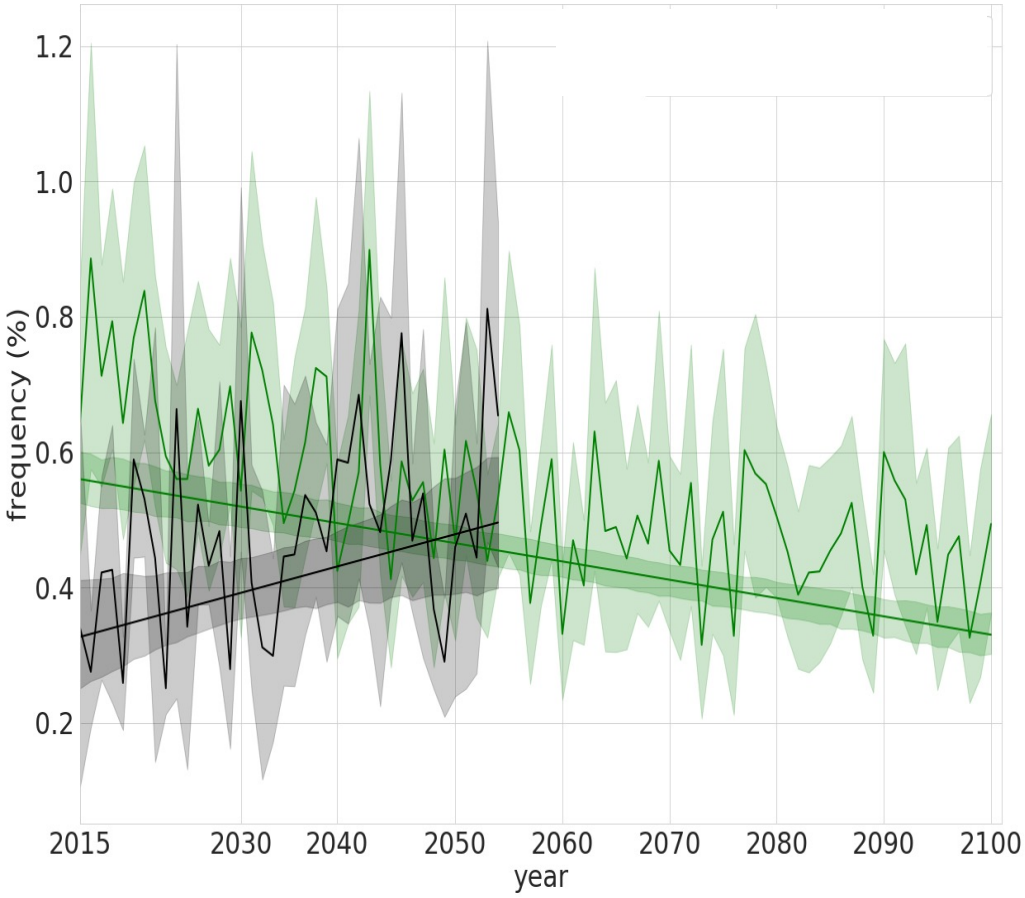


CAT Frequency time serie and linear trend (red lines), days number of NAO+ time serie and linear trend (black lines).

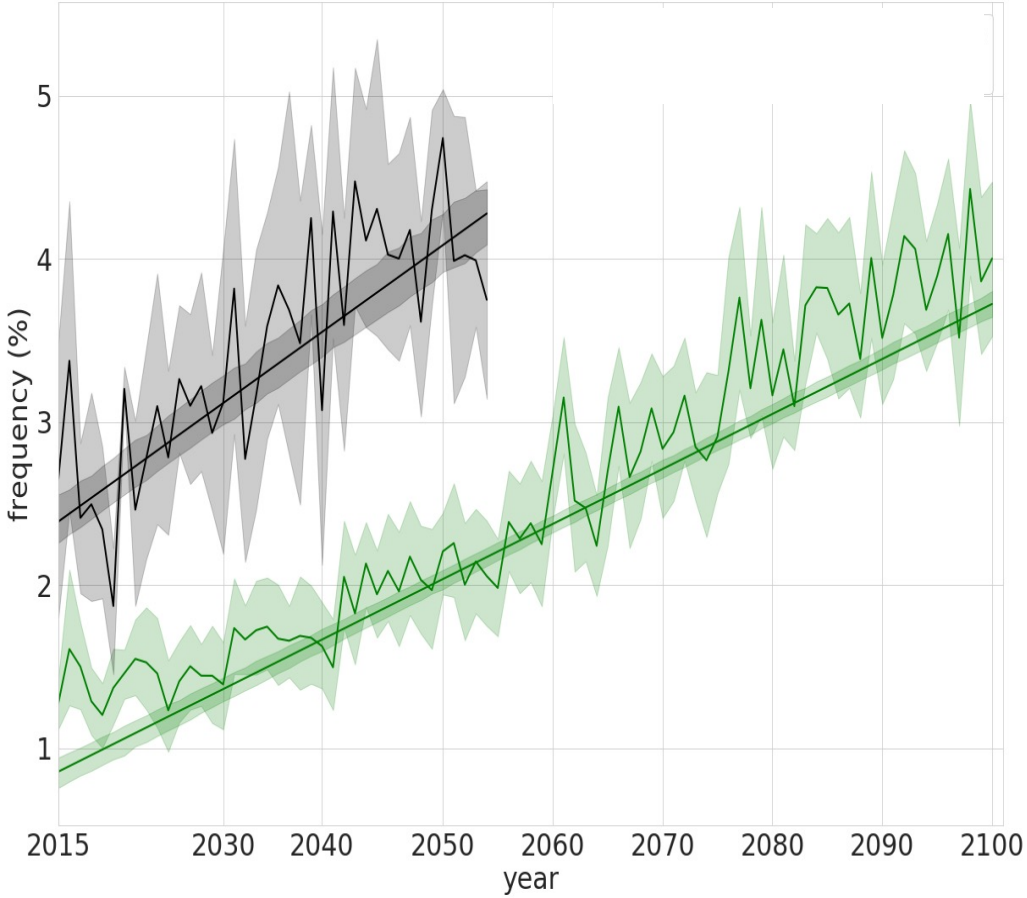


CAT future changes

Northern part of North Atlantic



East Asia



CNRM-CM6-1 (20 members)

IPSL-CM6A-LL (6 members)

Conclusions

- Significant positive CAT trends in recent decades were found over North Atlantic and East Asia between 1979 and 2020
- The positive trends are mostly related to internal variability but an emerging signal to external forcing is found over East Asia.
- We find that positive CAT trend frequency over East Asia is enhanced in response to global warming within the scenario ssp585
- The positive CAT trend over North Atlantic is related to positive trend on NAO+ regime
- Two climate models indicates opposite future CAT trends over the northern part of North Atlantic

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additional materials

CAT diagnostics computed

1. Vertical wind shear (SV)
2. Flow deformation (DEF)
3. Horizontal divergence (DIV)
4. Ellrod 1 (SV × DEF)
5. Ellrod 2 (SV × (DEF – DIV))
6. Dutton (horizontal + vertical shear of wind)
7. Brown (absolute vorticity + DEF)
8. Wind speed × DEF
9. Wind speed × directional shear
10. Horizontal temperature gradient
11. Frontogenesis function
12. Negative absolute vorticity advection
13. Relative vorticity advection
14. Richardson number
15. Colson-Panofsky index
16. NCSU1 index
17. Brunt-Väisälä frequency
18. Wind speed

correlation between CAT diagnostics

CAT diagnostics selected

- Ellrod1 et these two components (flow deformation, vertical wind shear)
- Frontogenesis function
- Horizontal temperature gradient
- North Carolina State University index 1

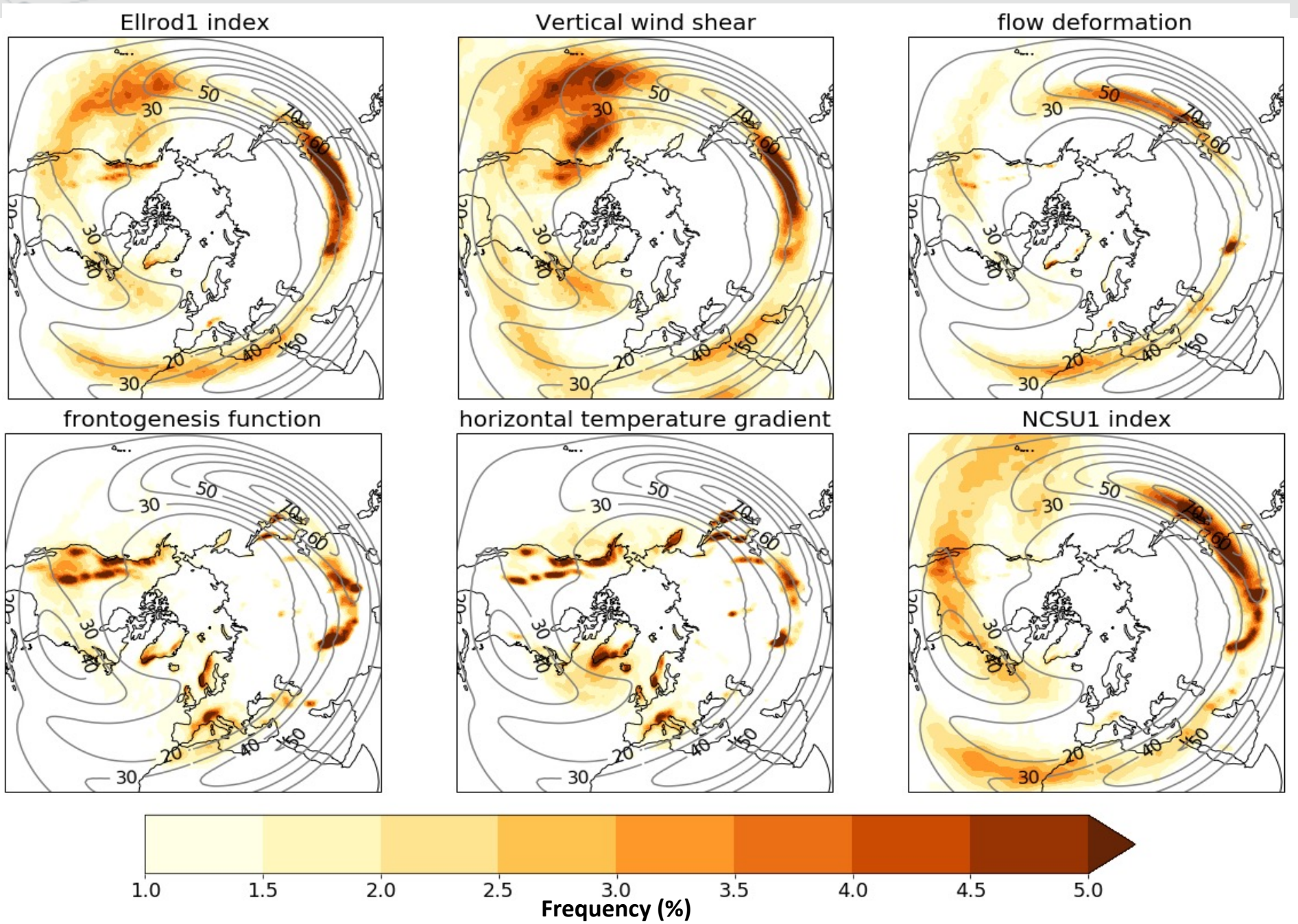
Data

Daily fields				Resolution	
				Horizontal	Levels
Reanalysis	ERA5 (ECMWF)	(1979 – 2020)		0,25°	37
	ERAI (ECMWF)	(1979 – 2018)		1,5°	37
	NCEP (NOAA)	(1948 – 2020)		2,5°	17
	20CR V2C (NOAA)	(1948 – 2014)		2°	24
	20CR V3 (NOAA)	(1979 – 2015)		1°	28
Climate models	CNRM-CM6-1 (CNRM-CERFACS)	26 historical members	(1979 – 2009)	1,4° (Atmosphère)	19
		20 ssp585 members	(2015 – 2100)		
	IPSL-CM6A-LR (IPSL)	32 historical members	(1979 – 2014)	2,5° × 1,3° (Atmosphère)	19
		6 ssp585 members	(2015 – 2054)		

For each member, the initial conditions are varied

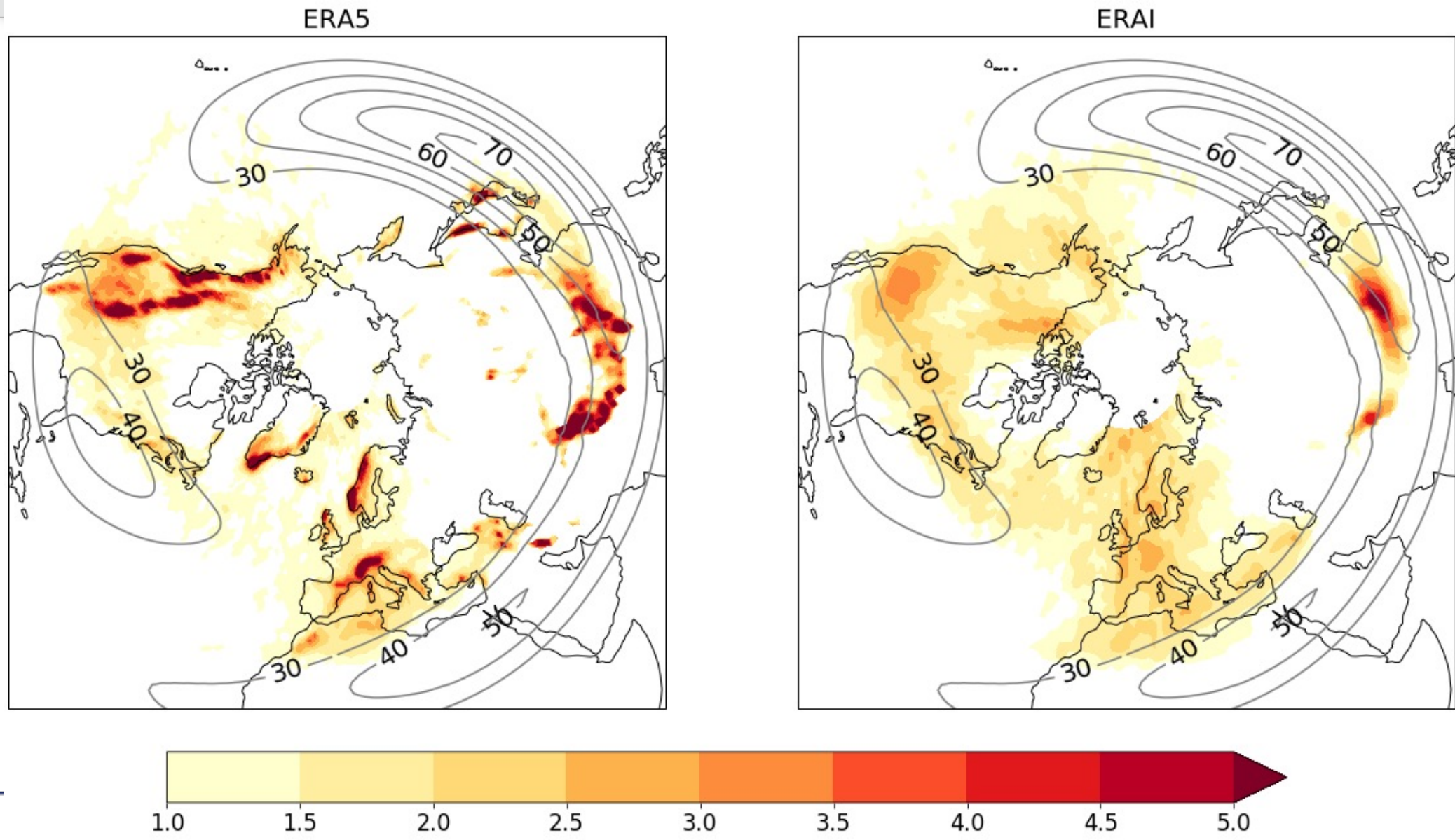
Performed for **CMIP6**

CAT climatology (DJF, 1981-2010)



Impact of spatial resolution on CAT diagnostics

frontogenesis



CAT Recent trends

Period : 1979 – 2020, ERA5 reanalysis

	Ellrod1	SV	DEF	Frontogenesis	∇T	NCSU1
North Atlantic	**p = 0.002** ** 0,48%	**p = 0.035** * 0,40%	**p = 0.02** * 0,34%	**p = 0.14** 0,11%	**p = 0.65** 0,05%	**p = 0.14** 0,19%
Northeast Pacific	**p = 0.12** 0,36%	**p = 0.28** 0,37%	**p = 0.4** 0,11%	**p = 0.38** 0,13%	**p = 0.42** 0,09%	**p = 0.13** 0,24%
East Asia	**p = 0.03** * 0,59%	**p = 0.02** * 0,50%	**p = 0.008** ** 0,3%	**p = 0.09** 0,32%	**p = 0.32** 0,15%	**p = 0.005** ** 0,6%

$p_{value} < \alpha = 0.01$**

$p_{value} < \alpha = 0.05$*

CAT Recent trends

Period : 1979 – 2014, different reanalysis

	North Atlantic				Northeast Pacific				East Asia			
	Ellrod1	SV	DEF	NCSU1	Ellrod1	SV	DEF	NCSU1	Ellrod1	SV	DEF	NCSU1
ERA5	p = 0.051	p = 0.016 *	p = 0.31	p = 0.89	p = 0.29	p = 0.49	p = 0.42	p = 0.29	p = 0,0008 **	p = 0,003 **	p = 0.011 *	p = 0.002 **
	0,41%	0,65%	0,18%	- 0,02%	0,41%	0,35%	0,13%	0,22%	1,10%	0,98%	0,38 %	0,92%
ERAI	p = 0.004 **	p = 1×10^{-5} **	p = 0.08	p = 0.11	p = 0.07	p = 0.07	p = 0.13	p = 0.04 *	p = 0.001 **	p = 0,0004 **	p = 0.06	p = 0.0003 **
	0,72%	1,24%	0,33%	0,36%	0,67%	0,79%	0,25%	0,50%	1,23%	1,53%	0,32%	1,79%
NOAA-V2C	p = 0.32	p = 0.19	p = 0.88	p = 0.54	p = 0.80	p = 0.71	p = 0.56	p = 0.67	p = 0.25	p = 0.06	p = 0.87	p = 0.22
	0,30%	0,24%	- 0,07%	- 0,22%	0,07%	0,11%	0,17%	0,12%	1,09%	2,26%	- 0,02%	1,04%
NOAA-V3	p = 0.33	p = 0.19	p = 0.7	p = 0.09	p = 0.36	p = 0.75	p = 0.88	p = 0.33	p = 0.11	p = 0.058	p = 0.06	p = 0.03 *
	- 0,31%	- 0,36%	- 0,12%	- 0,45%	0,29%	0,16%	0,05%	0,29%	1,07%	1,92%	0,28%	1,66%
NCEP	p = 5×10^{-5} **	p = 6×10^{-9} **	p = 0.02 *	p = 5×10^{-5} **	p = 6×10^{-5} **	p = 2×10^{-7} **	p = 0.07	p = 4×10^{-7} **	p = 5×10^{-7} **	p = 3×10^{-8} **	p = 0.003 **	p = 3×10^{-8} **
	1,60%	2,26%	0,65%	1,60 %	1,13%	2,73 %	0,52%	1,48 %	2,82%	4,62 %	0,37%	3,05 %

$p_{value} < \alpha = 0.01$**

$p_{value} < \alpha = 0.05$*

CAT Recent trends

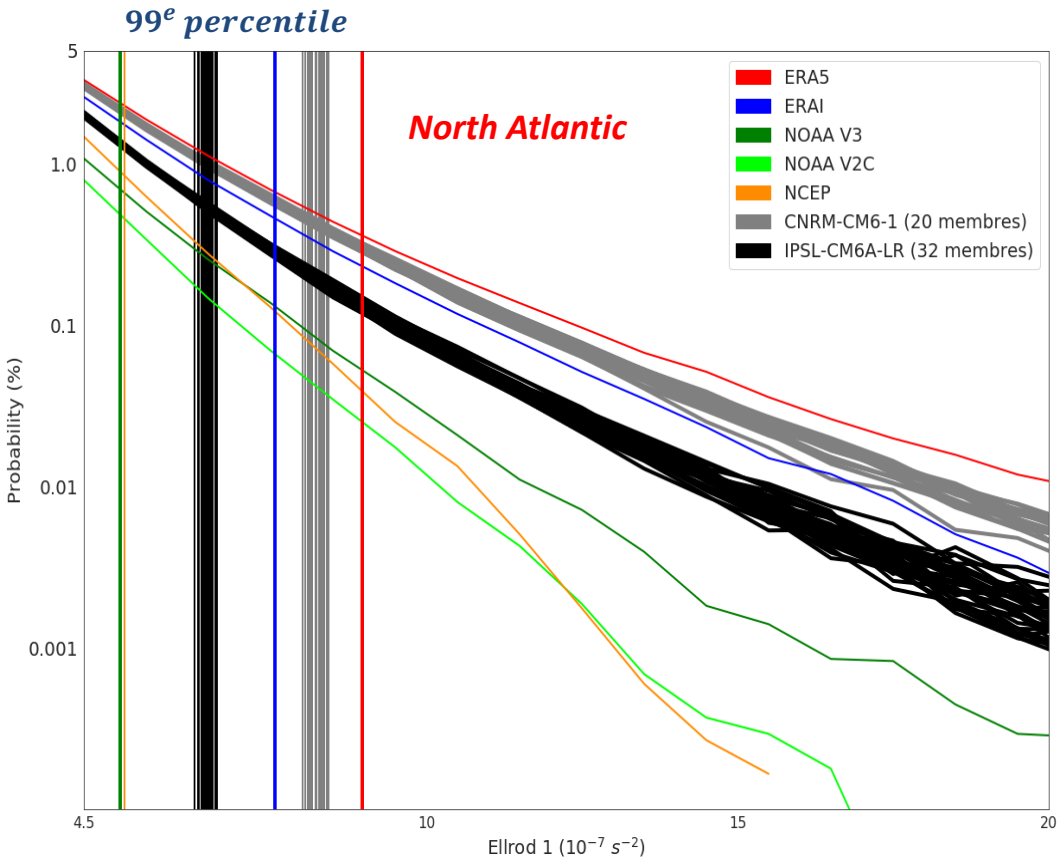
different atmospheric layers, TI1 index

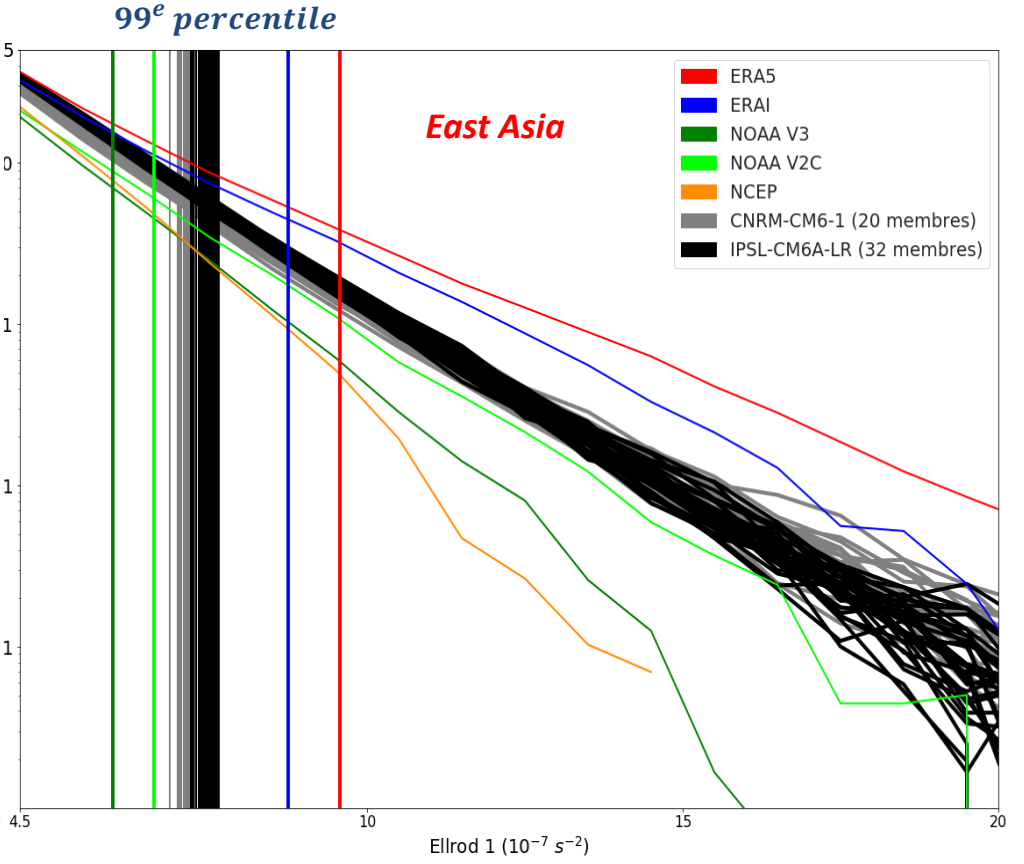
	North Atlantic			Northeast Pacific			East Asia		
	150–200hPa	200–250hPa	250–300hPa	150–200hPa	200–250hPa	250–300hPa	150–200hPa	200–250hPa	250–300hPa
ERA5	p = 0.65 0,039%	p = 0.051 0,41%	p = 0.0006 ** 0,43%	p = 0.08 0,04%	p = 0.29 0,41%	p = 0.79 - 0,09%	p = 0,0104 * 0,28%	p = 0,0008 ** 1,10%	p = 0.006 ** 1,70%
ERAI	p = 0.07 0,62%	p = 0.004 ** 0,72%	$p = 3\times10^{-6}$ ** 1,71%	p = 0.006 ** 0,81%	p = 0.07 0,67%	p = 0.68 0,10%	p = 0.011 * 0,29%	p = 0.001 ** 1,23%	p = 0.007 ** 1,90%
NOAA-V2C	p = 0.69 -0,22%	p = 0.32 0,30%	p = 0.41 0,21%	p = 0.71 0,16%	p = 0.80 0,07%	p = 0.25 - 0,41%	p = 0.55 -0,12%	p = 0.25 1,09%	p = 0.64 0,49%
NOAA-V3	p = 0.37 -0,42%	p = 0.33 - 0,31%	p = 0.33 0,17%	p = 0.20 0,47%	p = 0.36 0,29%	p = 0.61 - 0,20%	p = 0.60 0,03%	p = 0.11 1,07%	p = 0.34 0,63%
NCEP	p = 0.001 ** 1,24%	$p = 5\times10^{-5}$ ** 1,60 %	$p = 6\times10^{-9}$ ** 1,34%	p = 0.0002 ** 1,16%	$p = 6\times10^{-5}$ ** 1,13 %	p = 0.004 ** 1,08%	p = 0.005 ** 0,32%	$p = 5\times10^{-7}$ ** 2,82 %	$p = 3\times10^{-5}$ ** 3,55%

$p_{value} < \alpha = 0.01$**

$p_{value} < \alpha = 0.05$*

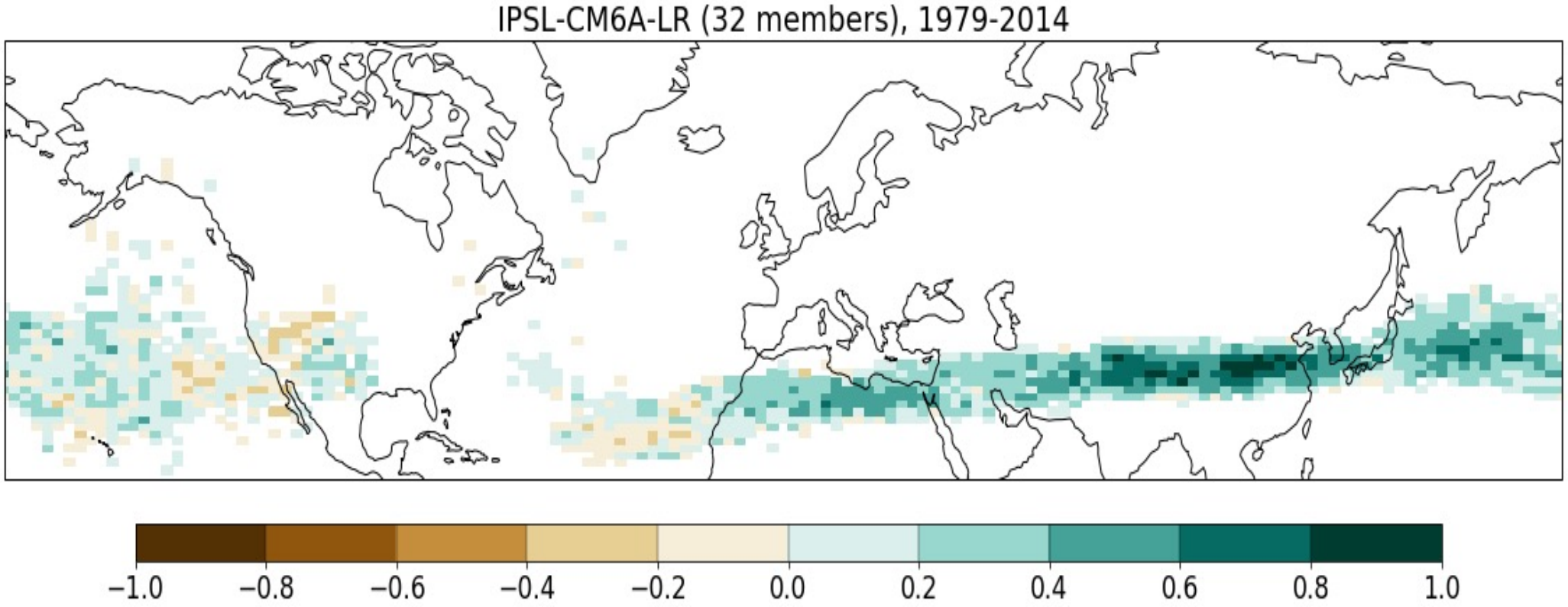
Climate models evaluation

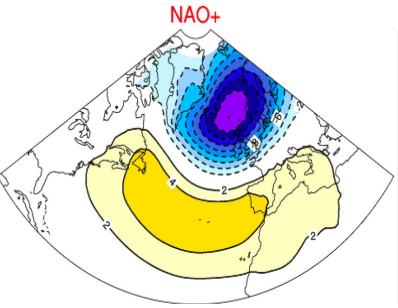




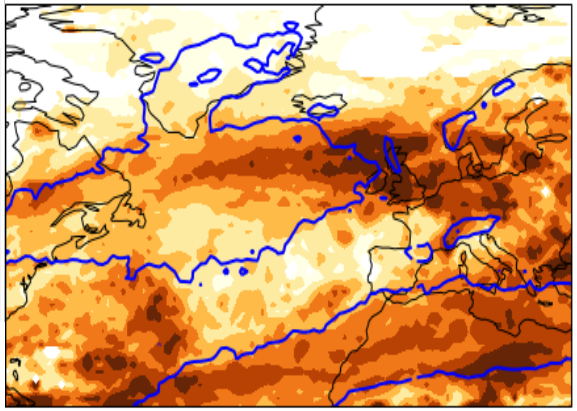
Attribution of CAT trends

Separating the internal and forced signals of CAT trends

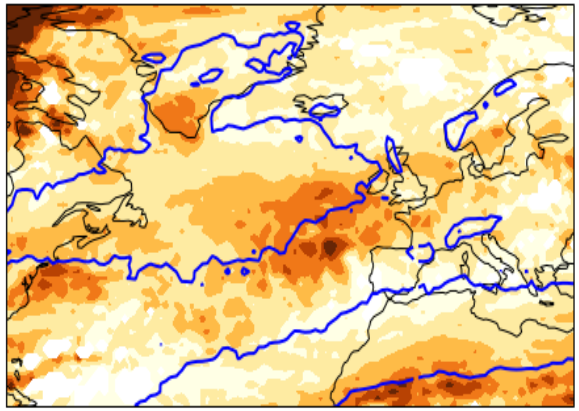


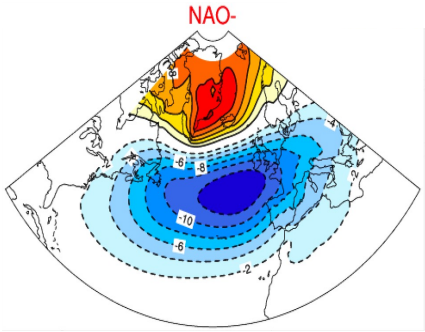


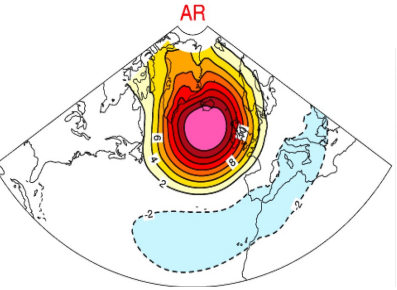
NAO+



NAO-







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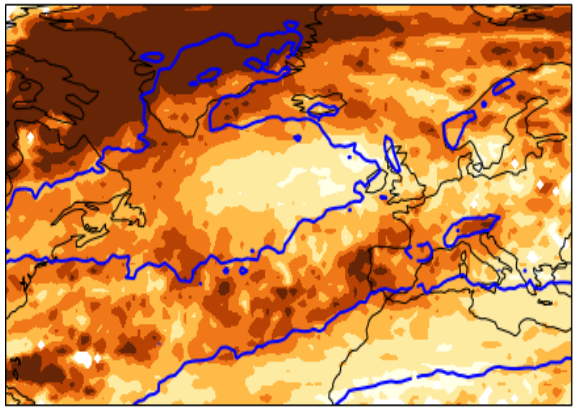

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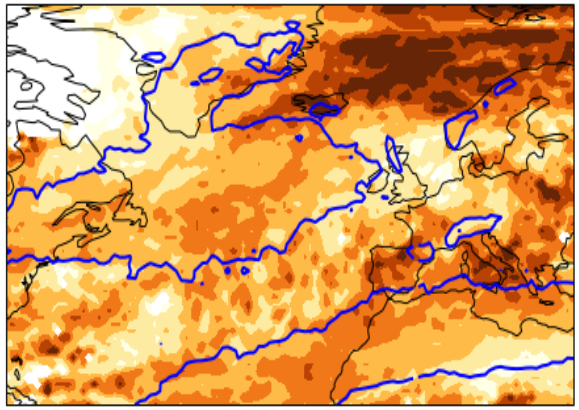
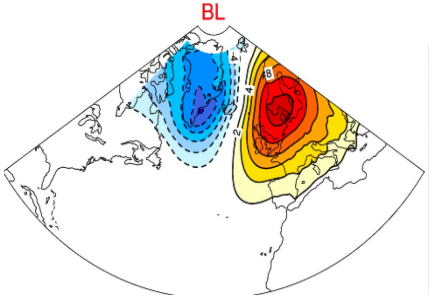
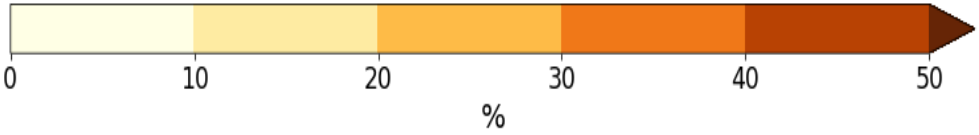
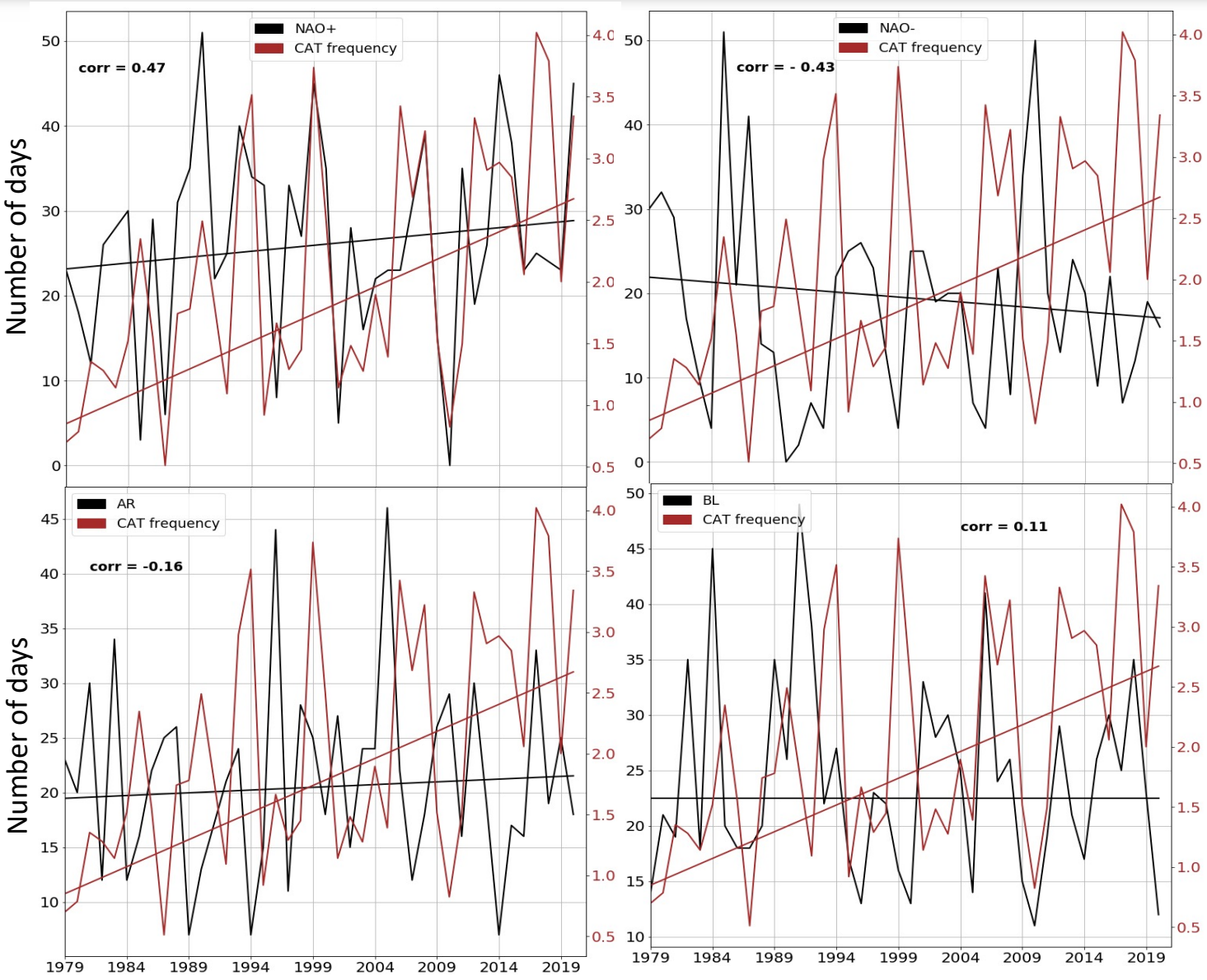




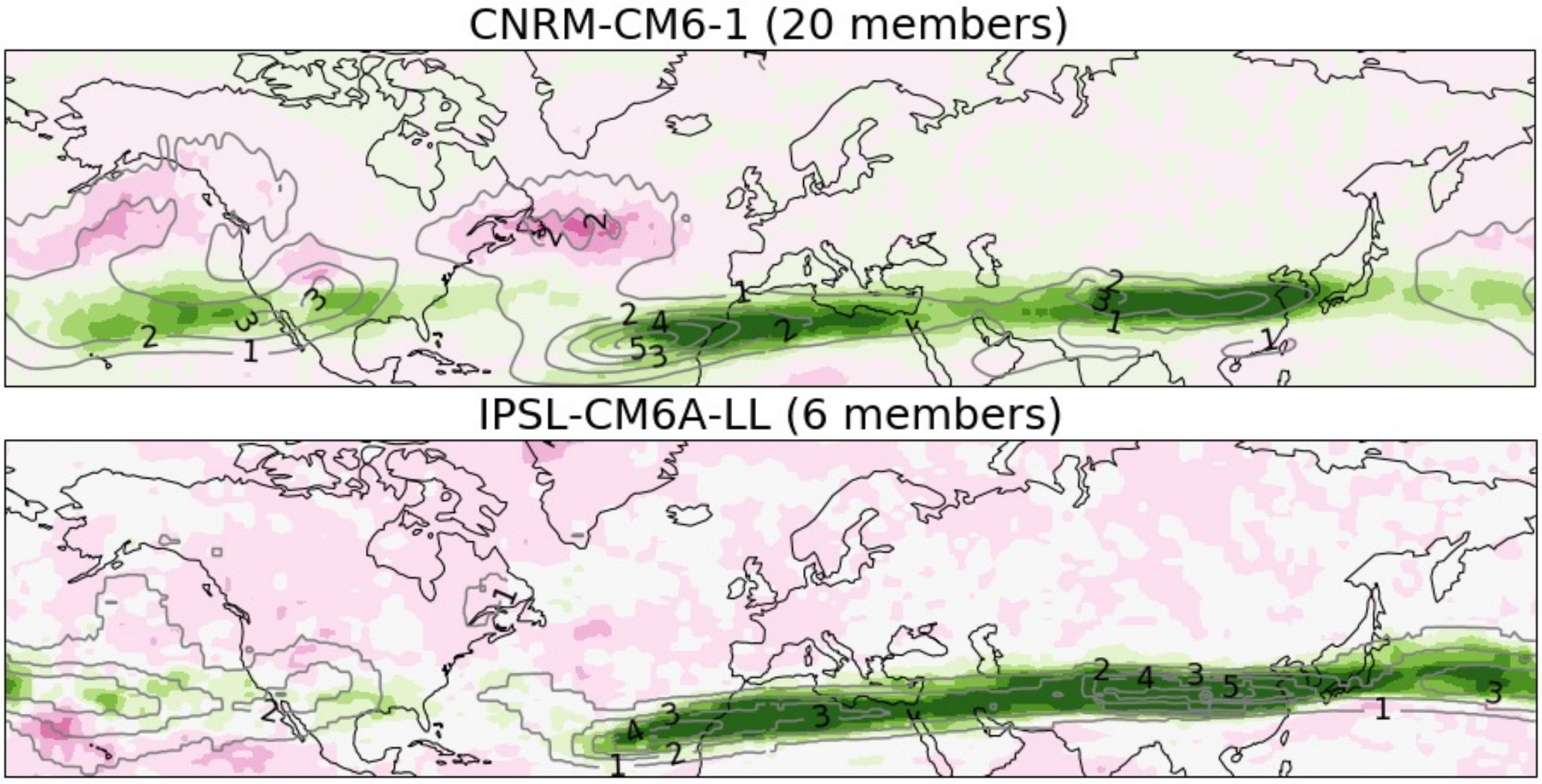


Recent CAT trends

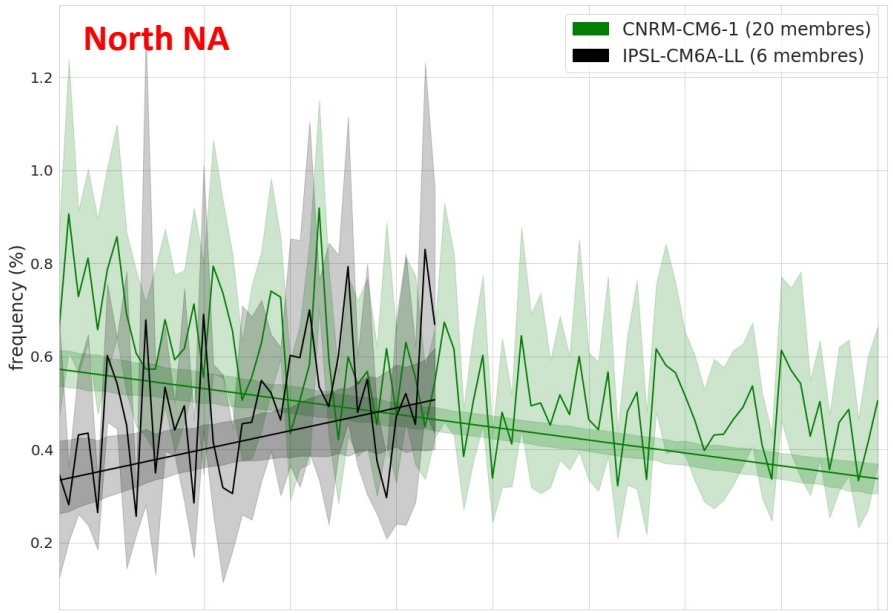
Links between CAT and large scale circulation patterns

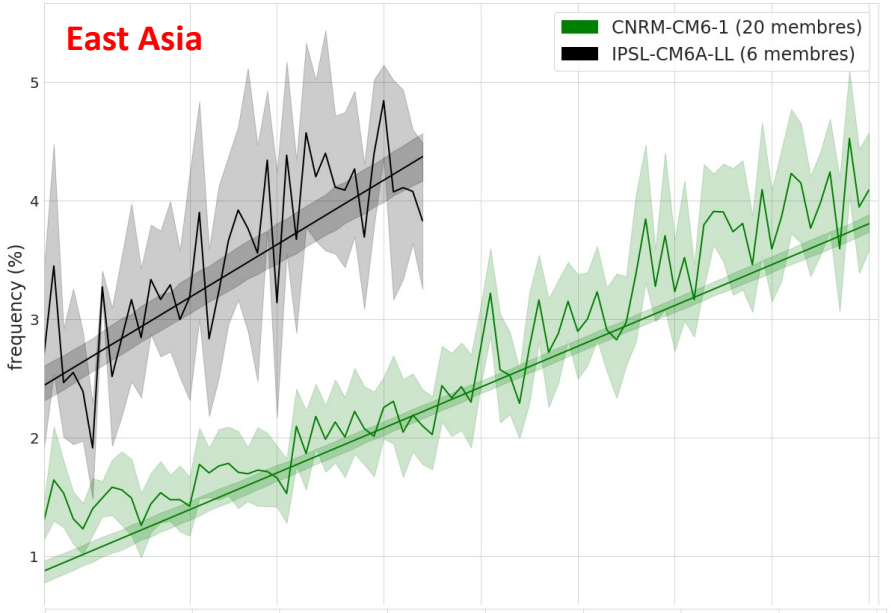


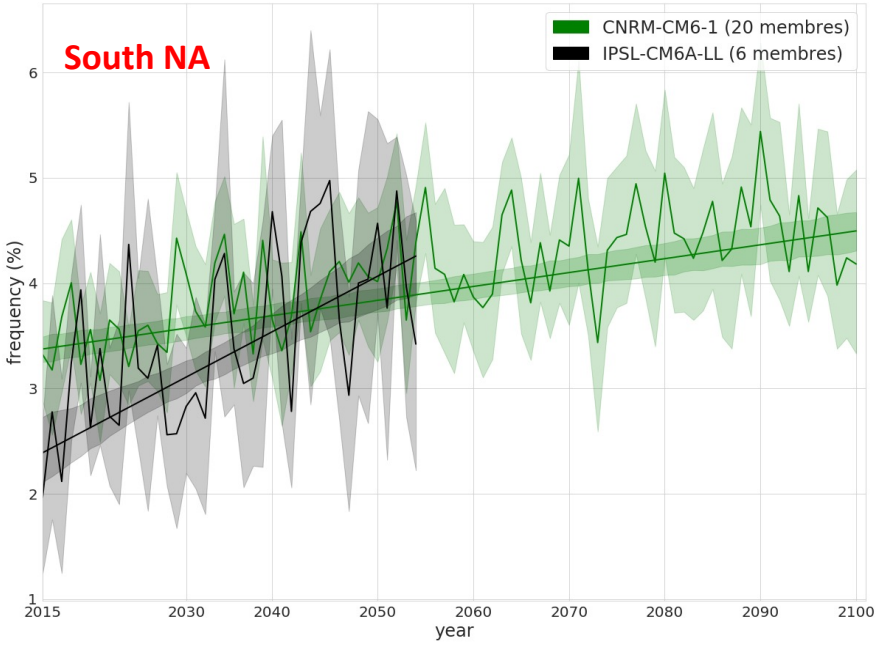
CAT future changes (2020-2050) - (1979-2009)

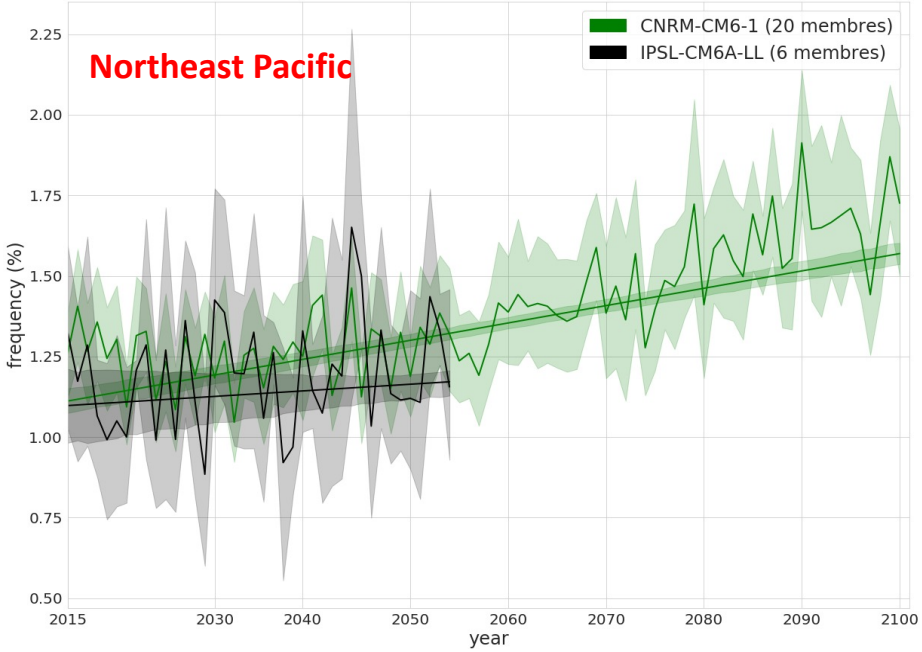


CAT future changes





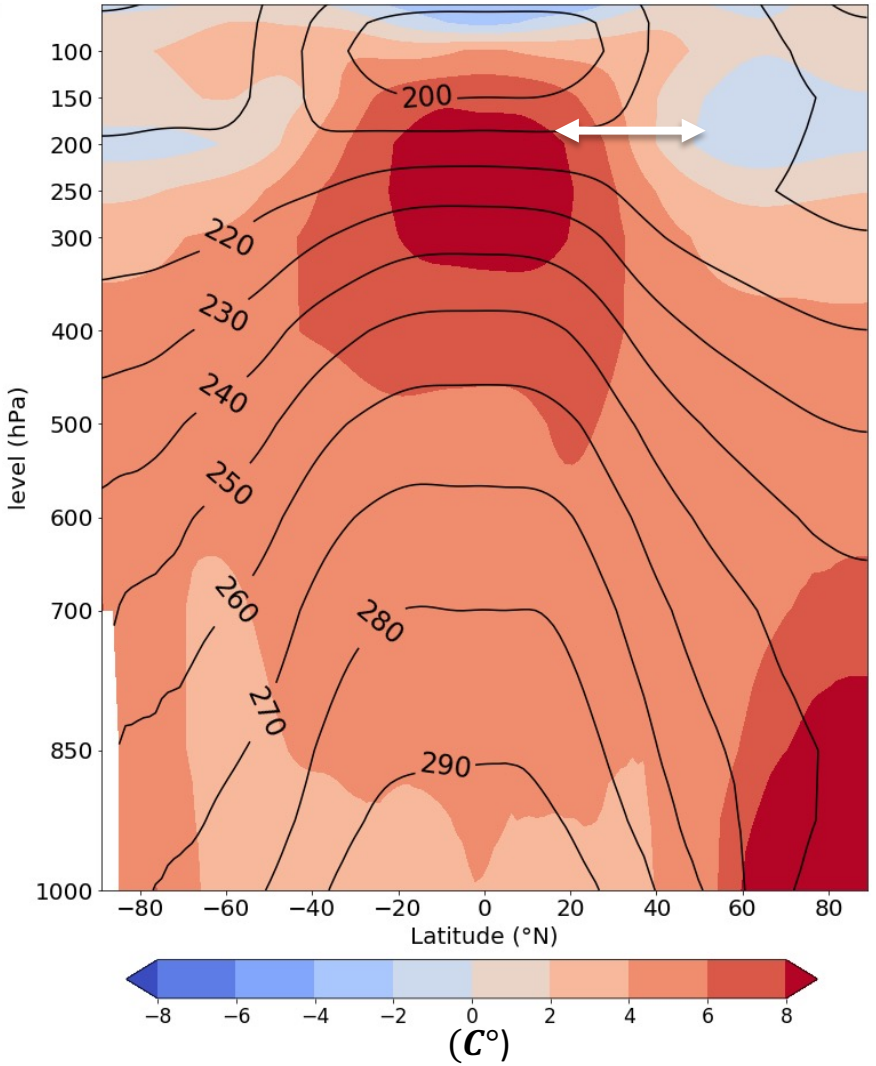




CAT future changes

Changes in zonal-mean temperature

ssp585 (2070-2100) – historical (1979-2009)



Amplification of the North-to-south Temperature gradient At high altitudes (~200 - 100hPa)

$$\frac{\partial u}{\partial z} \propto \frac{\partial T}{\partial y}$$

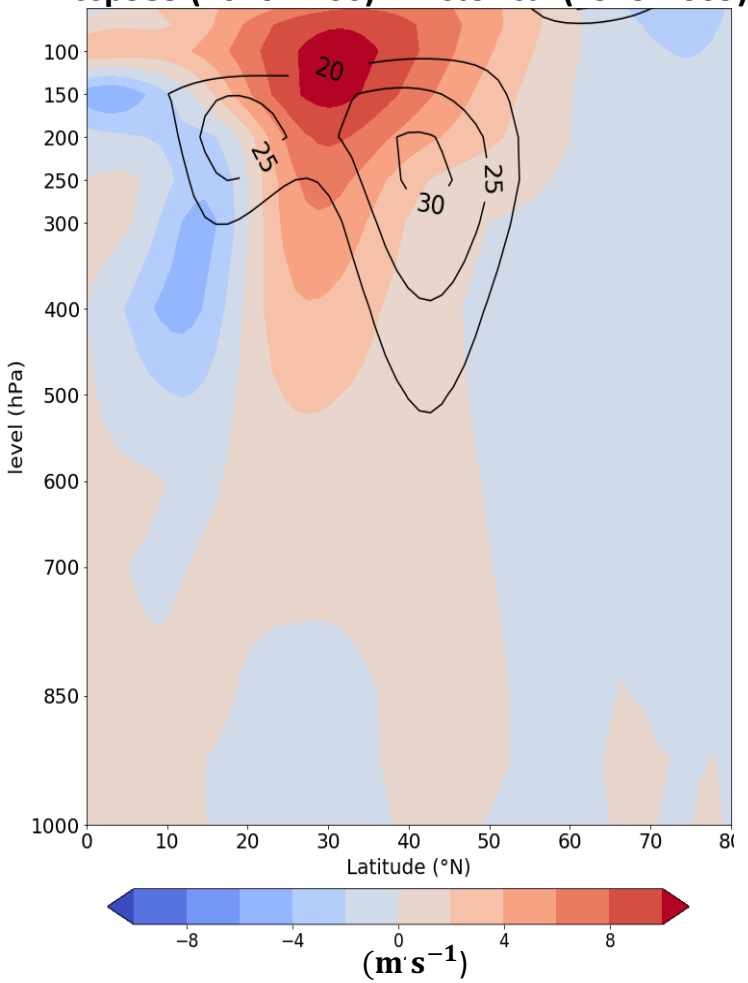
*Differences in zonal-mean temperature (T) between the **ssp585** scenario (**2070-2100)** and **historical period (1979 to 2009)** season DJF, by using **20 members** of **CNRM-CM6-1** model. **I**n contours the climatology of T in historical period*

CAT future changes

Changes in zonal-mean winds

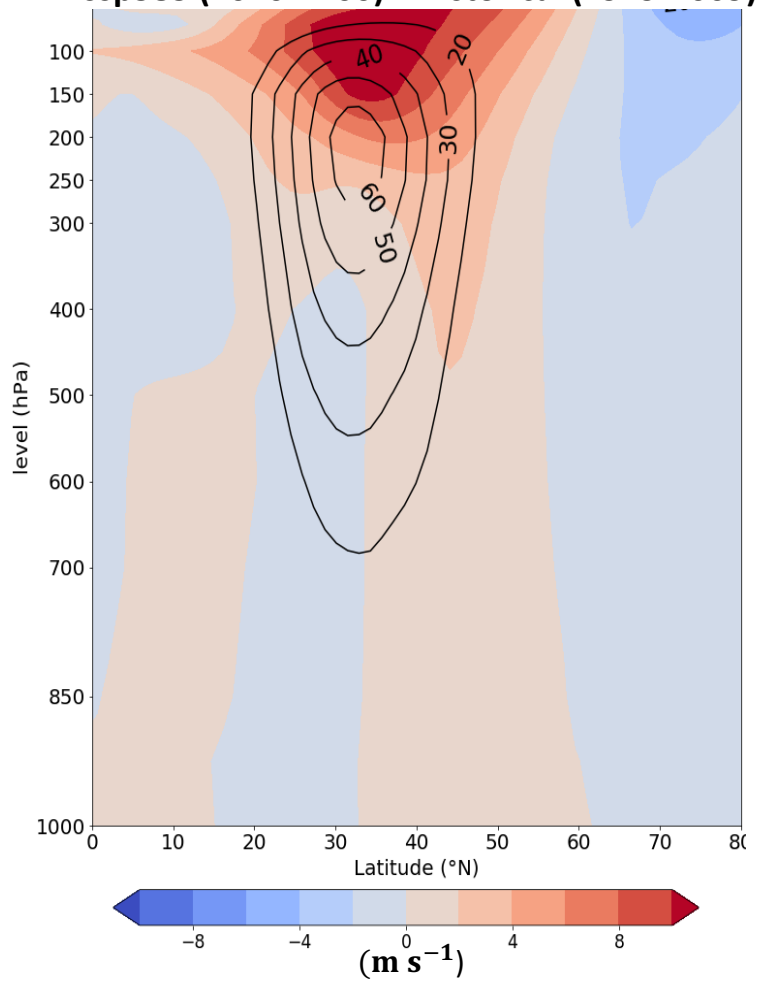
North Atlantic

ssp585 (2070-2100) – historical (1979-2009)



Northwest Pacific

ssp585 (2070-2100) – historical (1979-2009)



The Jet stream core shifts to upper levels in both regions.
In the North Atlantic, there is a southward displacement of the jet.

*Differences in zonal-mean winds (U) between the **ssp585** scenario (**2070-2100**) and **historical period (1979 to 2009)** season DJF, by using **20 members** of **CNRM-CM6-1** model. **I**n contours the climatology of U in historical period*