European Temperature Extremes: Mechanisms and Responses to Climate Change

PhD Thesis

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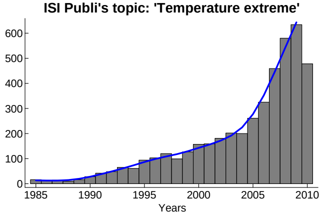
Extremes? Why?

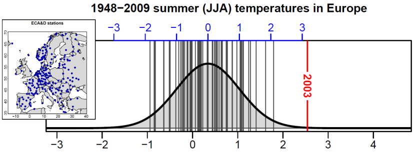
Summer 2003: public & scientific awareness.

- highest impacts on societies & ecosystems.
- numerous recent examples: signature of climate change?



Understanding the summer 2003. . .

- +2.5°C (+3.2σ) (e.g., Beniston, 2004; Trigo et al., 2005).
- soil–atmosphere feedback (e.g., Fischer et al., 2007; Seneviratne et al., 2006; Vautard et al., 2007).
- future amplification of summer heat-waves (e.g., Fischer and Schär, 2009).

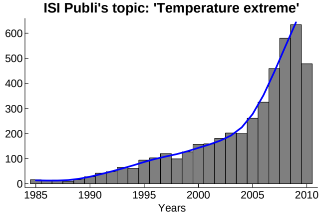


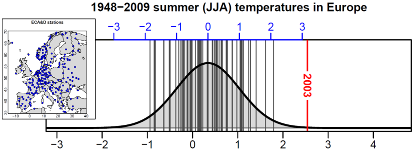
ECA&D stations (Klein-Tank et al., 2002). Anomalies *wrt.* 1961–1990.

Extremes? Why?

My PhD...

- Recent & future extremes in European seasonal temperatures, for all seasons.
- Role of the internal variability? Feedbacks?





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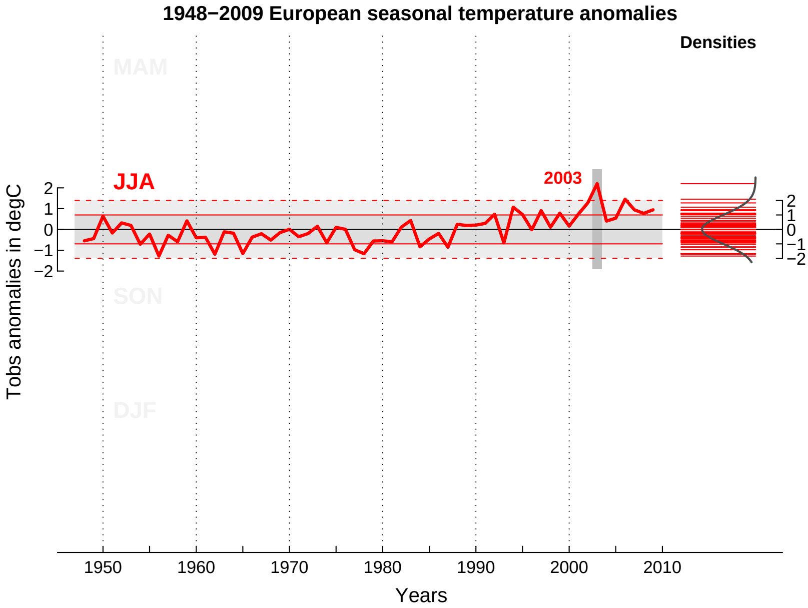
A *burning* issue. . .



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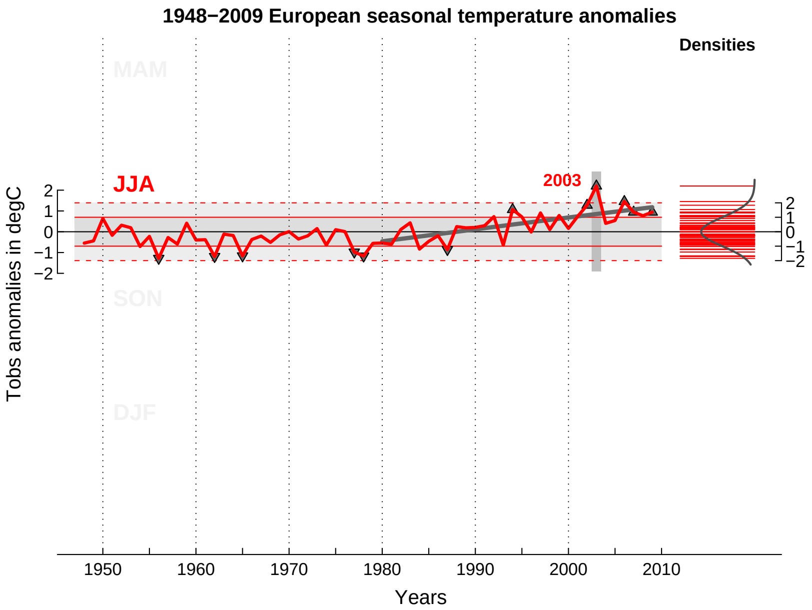

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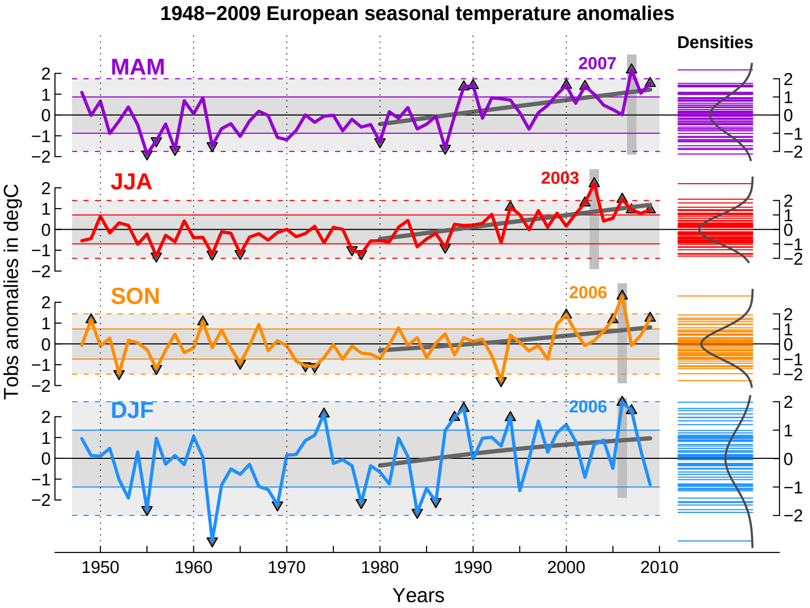
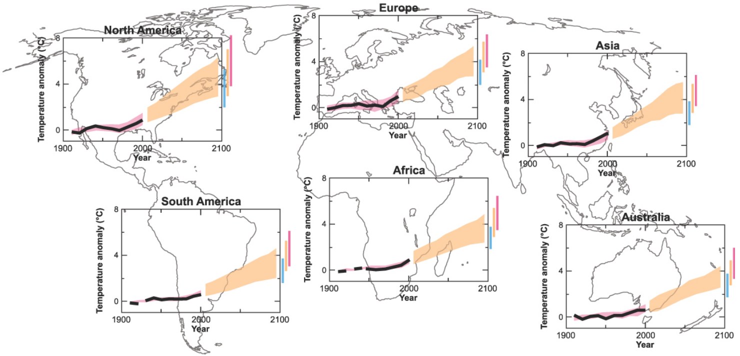


A concern for future years



IPCC, 2007.

Fate of extremely warm/cold seasons in the 21st century?

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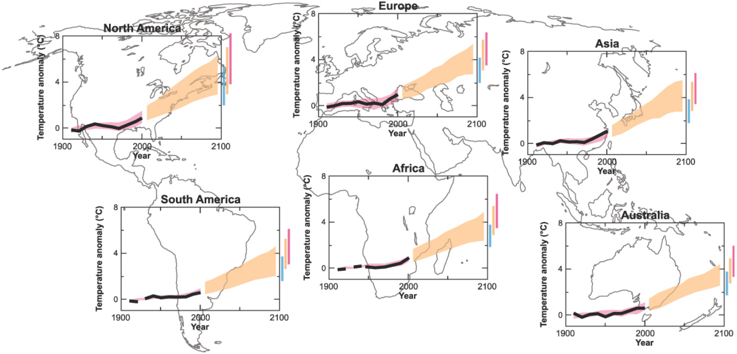

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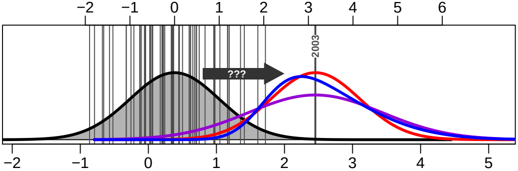
Future changes in European summer temperatures



Fate of extremely warm/cold seasons in the 21st century?

Main questions

Question 1

What are the main drivers of recent extremes & trends observed in European seasonal temperatures?

physical & dynamical mechanisms

Question 2

Does climate change affect the natural variability in the North-Atlantic – European (NAE) area? How does it contribute to the European warming?

responses to climate change

Outline

1. Drivers of recent extremes & trends

- Introduction: NAE dynamics as the main driver of European climate
- Case study of the exceptionally warm autumn of 2006
  J. Cattiaux et al. (2009), Origins of the extremely warm European fall of 2006, *Geophysical Research Letters*, *36* (6), pp. L06713. DOI: `10.1029/2009GL037339`
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2. Role of the natural variability in future European warming

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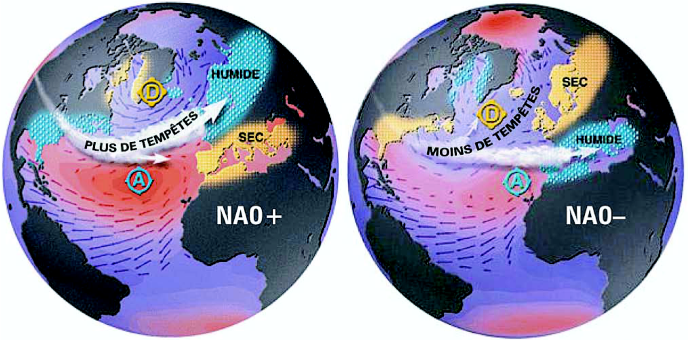
European temperatures & NAE dynamics

Introduction

- Europe is under the influence of the disturbances in the *mid-latitudes jet stream* (strongest in winter).
- First mode of variability: the *North Atlantic Oscillation* (NAO).
- NAO influence: NAO+ (NAO−) ↔ warm (cold) weather.



European temperatures & NAE dynamics

Recent winter warming: increase in NAO+?

- NAO influence: NAO+ (NAO−) ↔ warm (cold) weather.
- 1980, early 1990s: high frequency of NAO+ winters → "*European warming is driven by changes in the NAE dynamics*" (e.g., Corti et al., 1999; Gillett et al., 2003; Hsu and Zwiers, 2001; Palmer, 1999).
- since 1995: high frequency of NAO− winters, while temperatures still increase (e.g., 2006/07) → "inconsistency".

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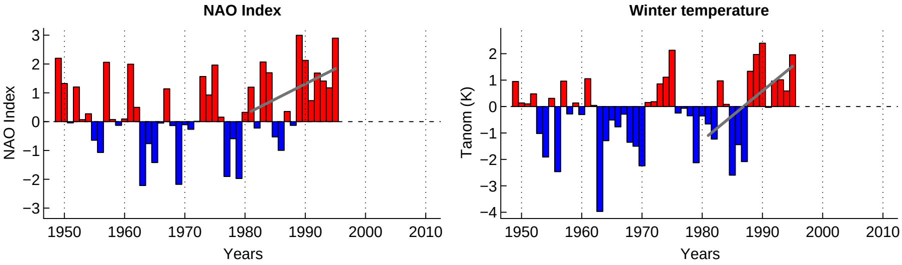

$r = 0.75$

NAO index: Jones et al. (1998). Temperatures: ECA&D stations (Klein-Tank et al., 2002).

European temperatures & NAE dynamics

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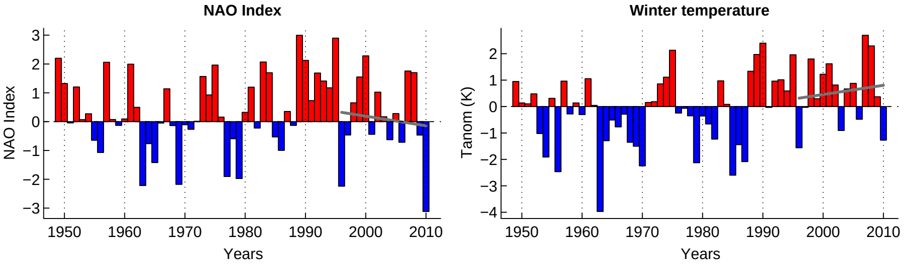


$r = 0.70$

NAO index: Jones et al. (1998). Temperatures: ECA&D stations (Klein-Tank et al., 2002).

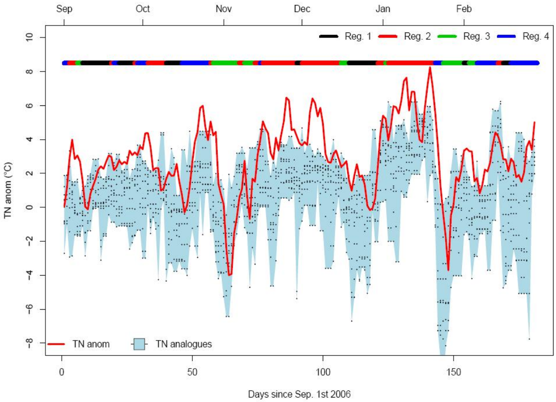
Inconsistency NAE dynamics / European temperatures

The example of autumn–winter 2006/07

Flow-analogues

Estimating the temperature of a given day by looking at temperatures associated with similar atmospheric circulations in the past (Lorenz, 1969).

Observed & analog temperatures of SONDJF 2006/07

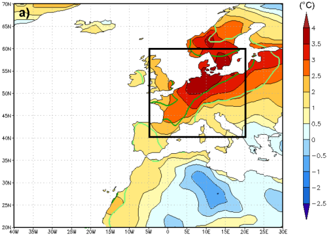


Yiou et al. (2007).

Temperatures: ECA&D stations (Tmin) (Klein-Tank et al., 2002).
Z500: NCEP/NCAR reanalysis (Kistler et al., 2001).

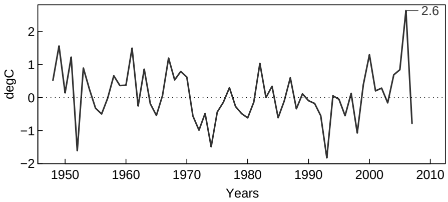
Contribution of NAE dynamics to the mild autumn of 2006

T2m



V500

T2m anomaly SON



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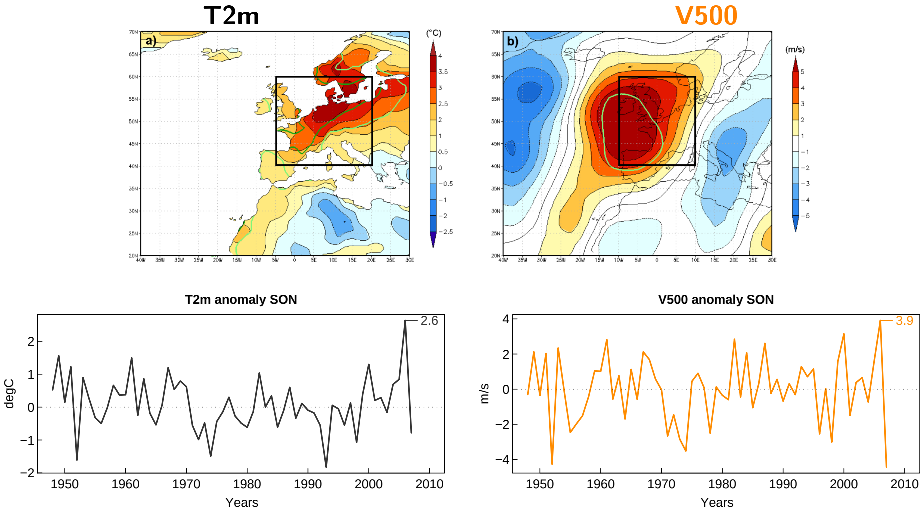

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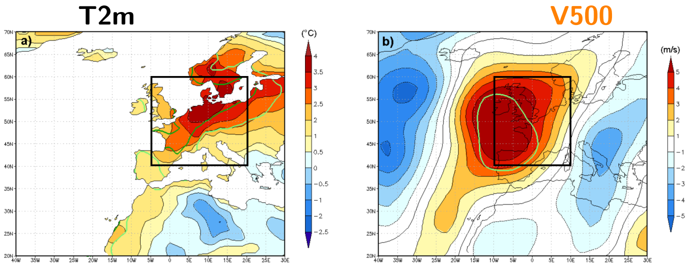

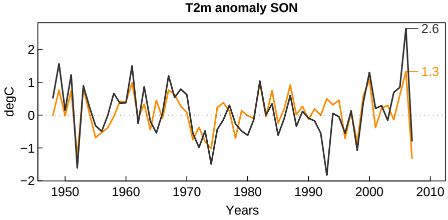

Linear regression model

- **T2m** and **V500** highly correlated ($r = 0.7$).
- **V500**: no trend in recent years, while European **T2m** increase.

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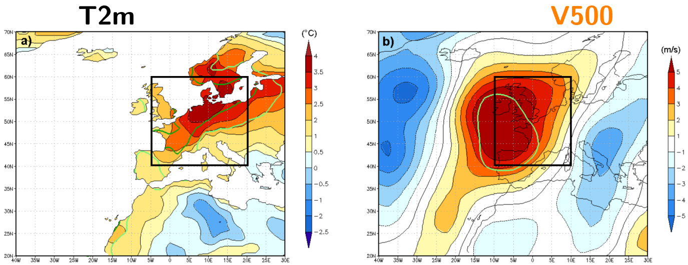

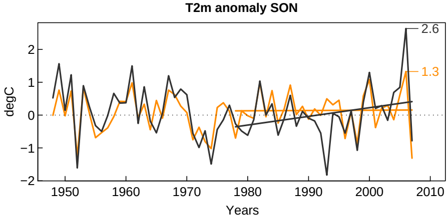

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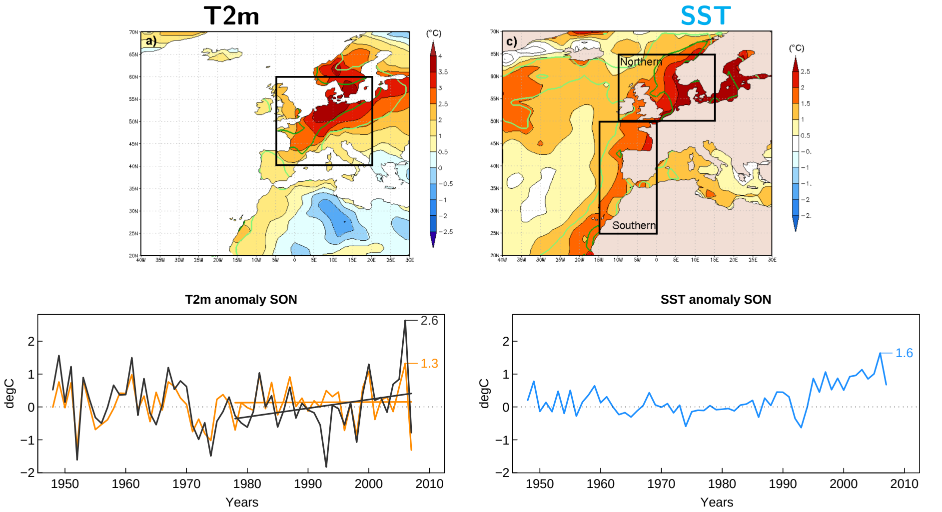

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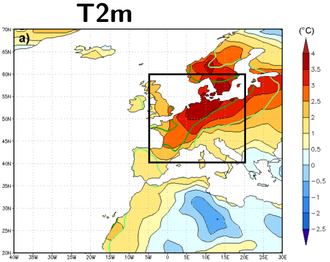
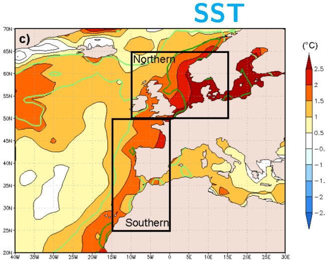
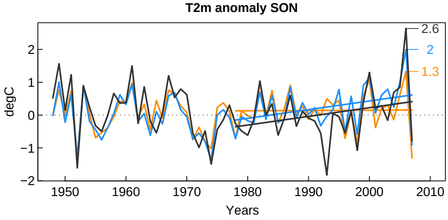






Linear regression model

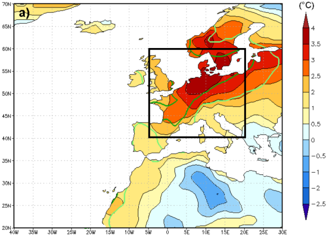
- Adding **SST** improves the fit ($r = 0.8$).
- The increasing trend in **T2m** is reproduced by the **SST** warming.

Cattiaux et al. (2009).

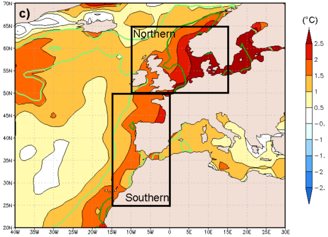
T2m, **V500** & **SST**: NCEP/NCAR reanalysis (Kistler et al., 2001).

Contribution of NAE SST to the mild autumn of 2006

T2m



SST



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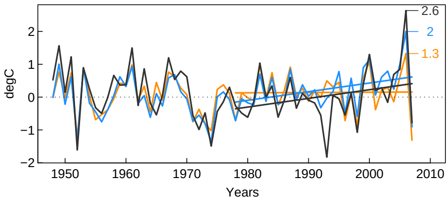


Linear regression model: limits

- No evidence for any causality.
- Dynamics & SST are not independent.

Cattiaux et al. (2009).

T2m, **V500** & **SST**: NCEP/NCAR reanalysis (Kistler et al., 2001).

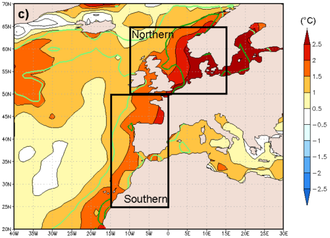
Contribution of NAE SST to the mild autumn of 2006

MM5 sensitivity experiment

MM5: regional climate model developed at PSU/NCAR.

Experimental set-up: 2 wind-nudged simulations of SON 2006, only differing by SST forcing such as **ΔSST** $\equiv$ observed anomaly. Resolution $0.5 \times 0.5°$, temperature & humidity not nudged.

ΔSST forcing



ΔT2m response

ΔT2m response $= 0.8°C$, consistent with statistical estimate.

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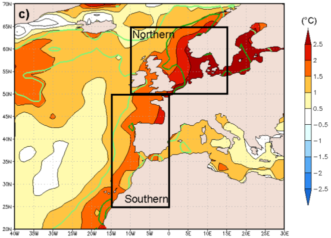

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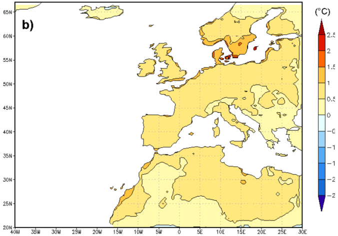

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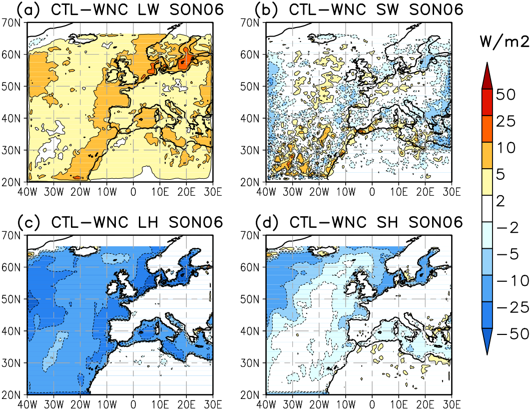
Physical mechanisms

$$\Delta_{\downarrow} E = \Delta_{\downarrow} LW' + \Delta_{\downarrow} SW' + LH'_{\downarrow} + SH'_{\downarrow}$$



ΔSST advection

- sensible heat.
- water vapor, enhancing local greenhouse effect.

Limits

Difficulty to interpret sea–air fluxes in SST-forced experiments (Barsugli and Battisti, 1998).

See also: M.E. Shongwe et al. (2009), Energy budget of the extreme Autumn 2006 in Europe, *Climate Dynamics*, pp. 1–12. DOI: 10.1007/s00382-009-0689-2

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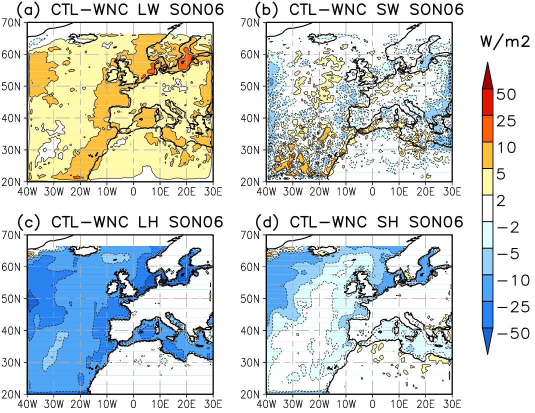

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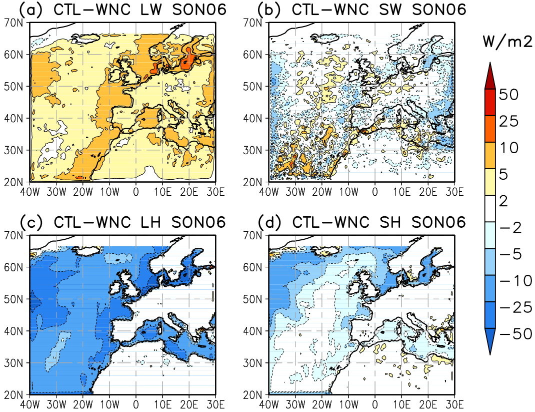

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Mild autumn 2006 in Europe: summary

- An extremely warm event comparable in seasonal amplitude to the summer 2003.
- Record-breaking southly flow: $\sim$50% of the temperature anomaly.
- Record-breaking warm NAE SST: $\sim$30% more, through the advection of both water vapor and sensible heat by the westerlies.
- $\sim$20% unexplained: non-linearities? Feedbacks (soil moisture, clouds, aerosols)?

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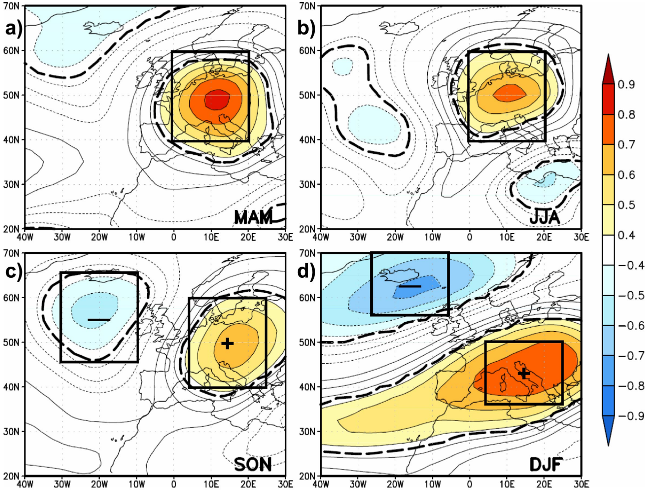

Cattiaux et al. (2010b): **SDI** based on **Z500–T2m** correlation patterns.

Tobs: E-OBS (ECA&D), **Z500**: NCEP/NCAR reanalysis.

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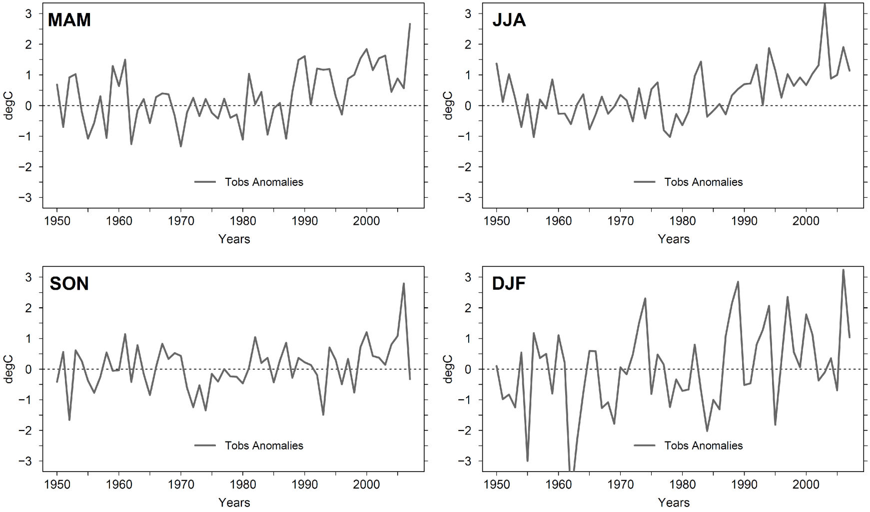

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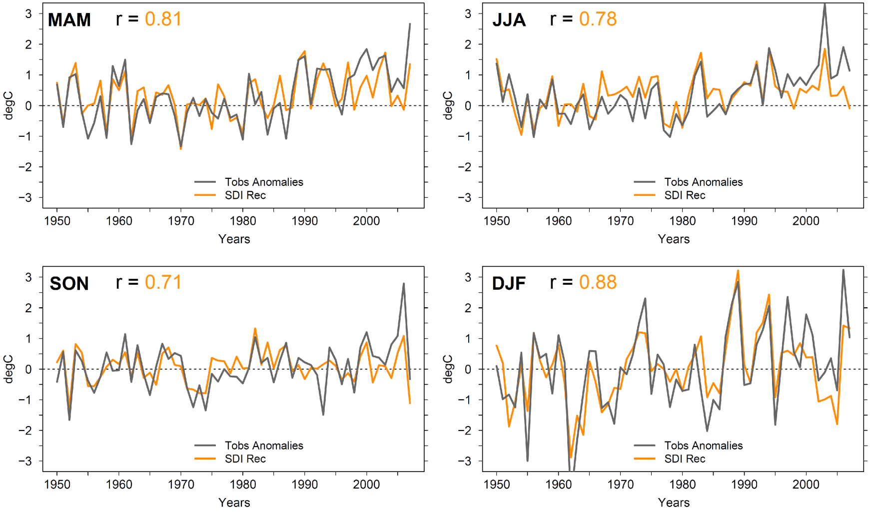

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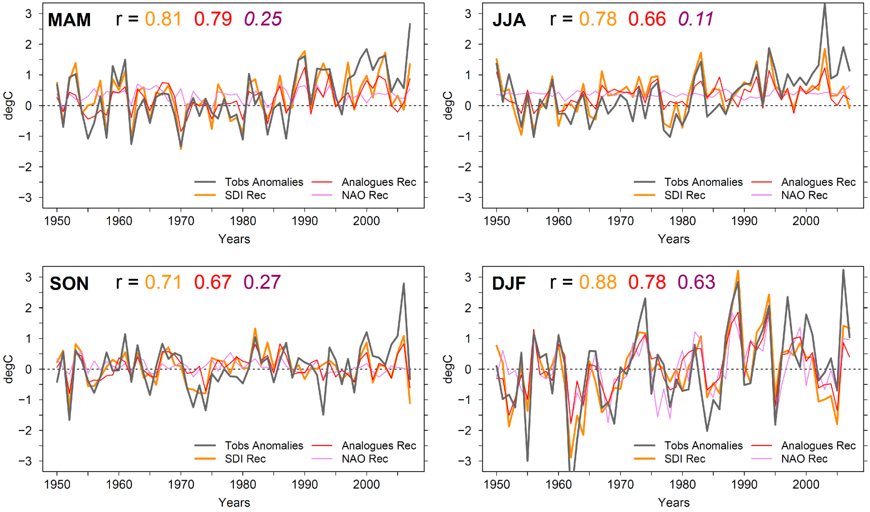

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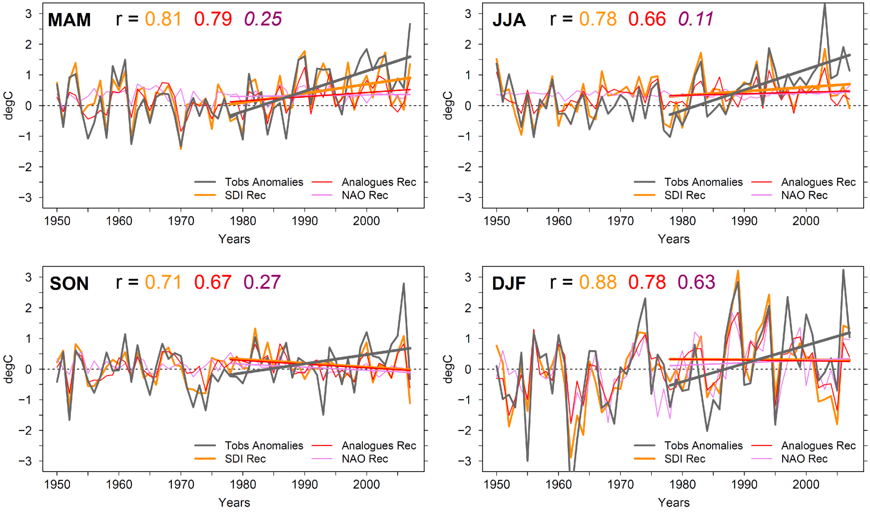

Cattiaux et al. (2010b): **SDI** based on **Z500–T2m** correlation patterns.

Tobs: E-OBS (ECA&D), **Z500**: NCEP/NCAR reanalysis.

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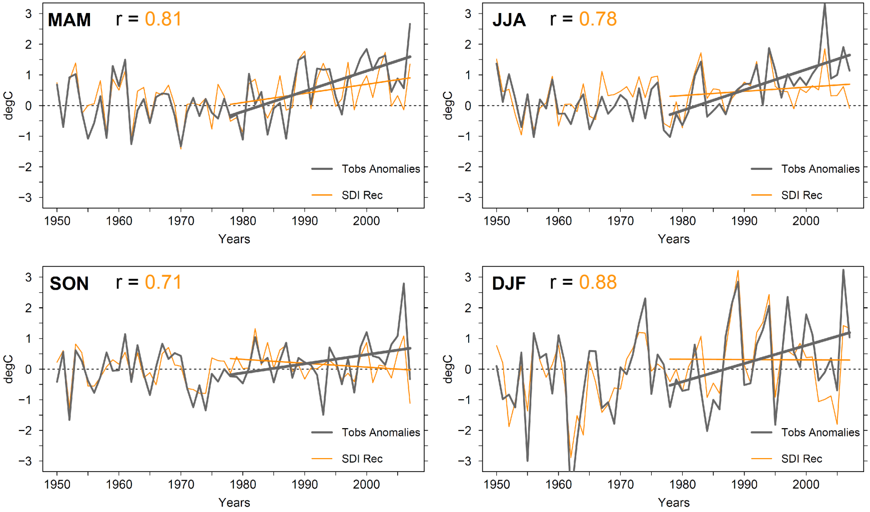

Cattiaux et al. (2010b).

Tobs: E-OBS (ECA&D), **Z500**: NCEP/NCAR reanalysis.

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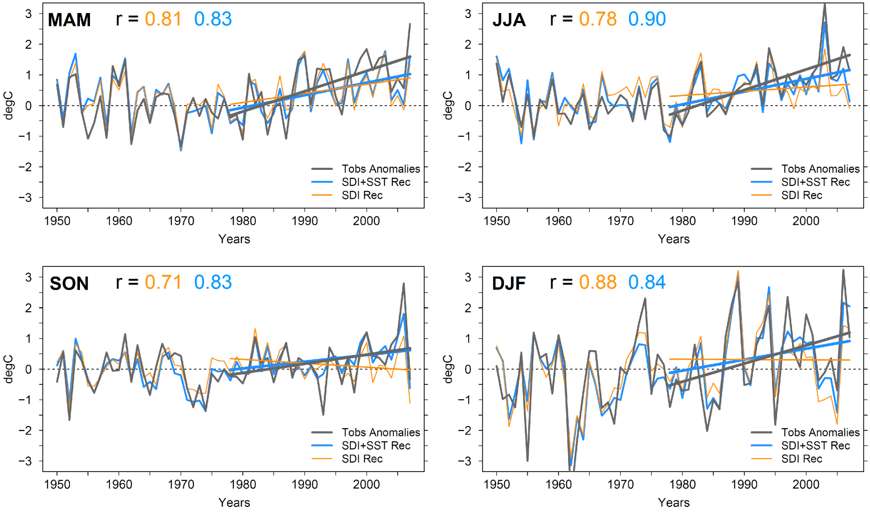

Cattiaux et al. (2010b).

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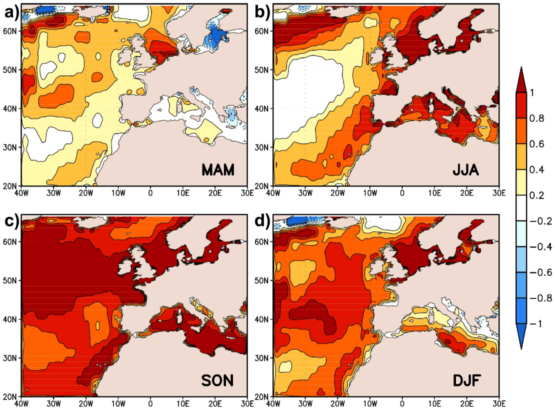
MM5 sensitivity experiments over 2003–2007

ΔSST forcings ΔT2m responses



Seasonality

- highest (lowest) SST trend in autumn (spring).
- westerlies advection more (less) efficient in autumn–winter (spring–summer).
- spring–summer: other feedbacks (e.g., soil moisture[1], aerosols[2], clouds[3]).

Cattiaux et al. (2010b).

[1] Seneviratne et al. (2006), [2] Ruckstuhl et al. (2008), [3] Vautard et al. (2009).

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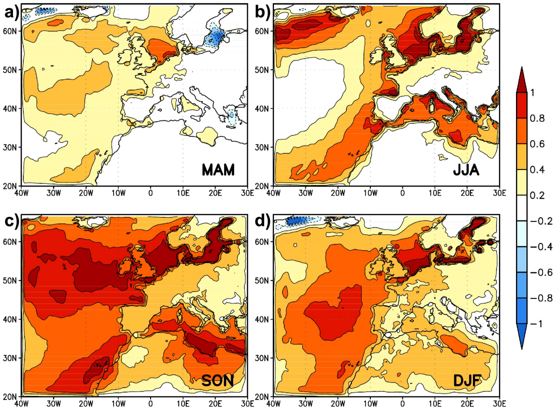

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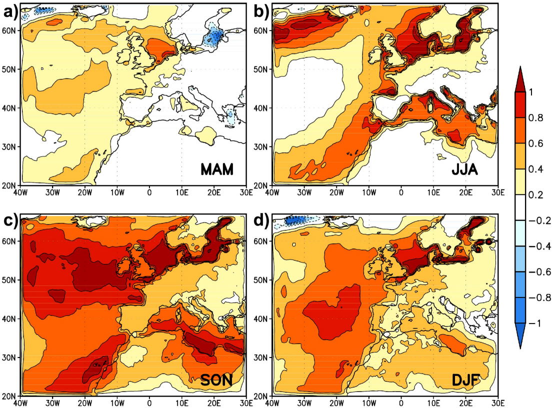

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Recent European temperature extremes and trends: summary

- All seasonal warm records have been broken since 2003, which acts in the recent long-term increase in European temperatures.
- The NAE atmospheric dynamics is the main driver of the temperatures' interannual variability, but does not explain upward trends.
- The simultaneous warming of the NAE SST contributes to the European warming, through the advection of both water vapor and sensible heat by the westerlies.
- The SST contribution is higher (lower) in autumn–winter (spring–summer).
- Other feedbacks amplify European temperatures in spring–summer (e.g., deficit in soil moisture, clouds, aerosols).
- Main limit: how to identify causality, since both dynamics and SST are coupled.

Back to outline II. . .

1. Drivers of recent extremes & trends

- Introduction: NAE dynamics as the main driver of European climate
- Case study of the exceptionally warm autumn of 2006
  J. Cattiaux et al. (2009), Origins of the extremely warm European fall of 2006, *Geophysical Research Letters*, *36* (6), pp. L06713. DOI: 10.1029/2009GL037339
- Generalization to other seasons
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2. Role of the natural variability in future European warming

- Analysis of future climate projections from IPCC-AR4 (2007)
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- Application: case study of the cold winter 2009/10
  J. Cattiaux et al. (2010c), Winter 2010 in Europe: A cold extreme in a warming climate, *Geophysical Research Letters*, *37*, pp. L20704. DOI: 10.1029/2010GL044613

In the future?

Questions:

Is the dynamics/temperature inconsistency expected to continue/amplify?

How to estimate the contribution of changes in internal variability to the temperature increase?

What are the atmospheric circulations associated with projected extremes?

Methodology:

- Multi-model analysis from 13 CMIP3 GCMs: T2m & SLP.
- Periods 1961–2000 (20c3m) 2046–2065 & 2081–2100, in SRES A2.
- Technique: flow-analogues & weather regimes (not shown today).
- Selection of "best" models: skillful model-ensembles per season.

Cattiaux et al. (2010a), submitted.

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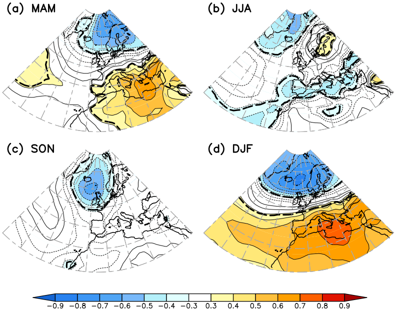
Models selection per season

Criterion: ability to reproduce *observed* **SLP**–**T2m** correlation patterns.

ERA-40



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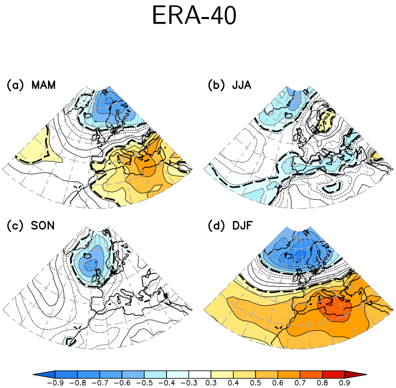

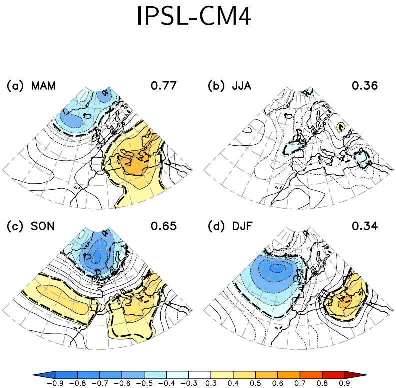

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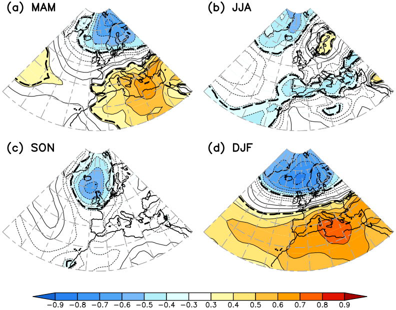

"Best models"

	MAM	JJA
1	CCC47	MIR32
2	GFDL21	GFDL21
3	GISSer	ECH5
4	MRI232	CCC47
5	ECHOg	ECH4

	SON	DJF
1	ECHOg	CCC47
2	CNRM3	GFDL20
3	GFDL21	CNRM3
4	CSI30	MRI232
5	IPSL4	ECH4

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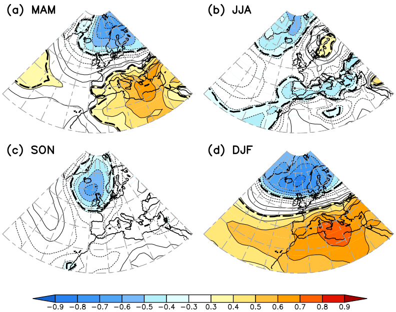
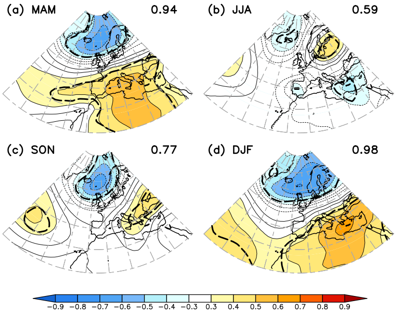


Model-ensembles

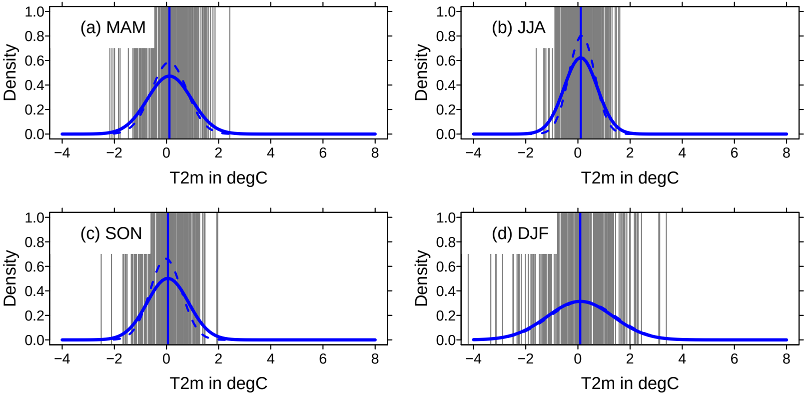


Cattiaux et al. (2010a), submitted.

Projected changes in European temperatures

From seasonal model-ensembles

20c3m 2046–2065 2081–2100



Increase in mean. Increase (decrease) in variability in summer (winter).

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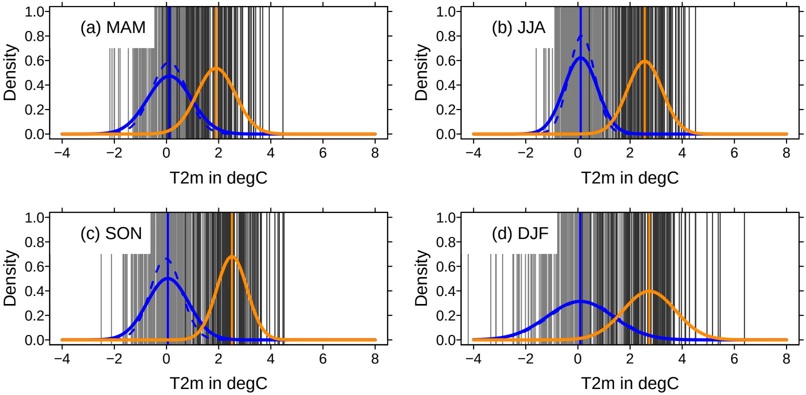

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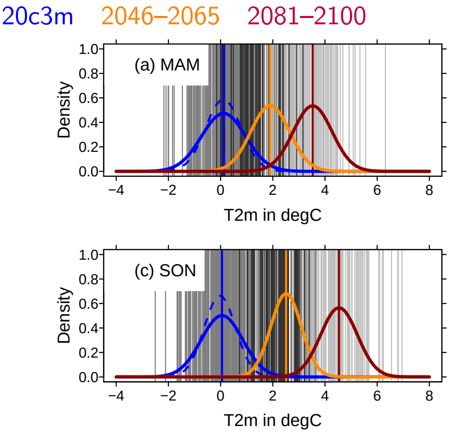

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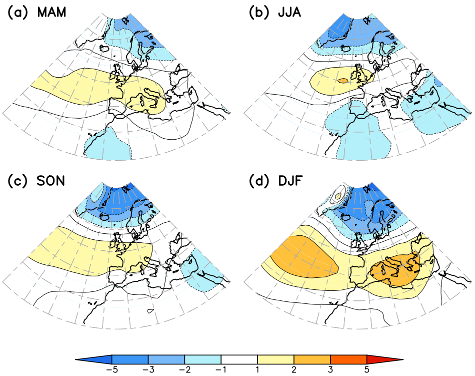
Projected changes in NAE dynamics

From seasonal model-ensembles

Difference 2081–2100 & 1961–2000

SLP (hPa): Mean Variance



Cattiaux et al. (2010a), submitted.

- Strengthening and northward shift of the jet stream → increase in NAO+ conditions (e.g., Terray et al., 2004).
- Generalized decrease in interannual variability.

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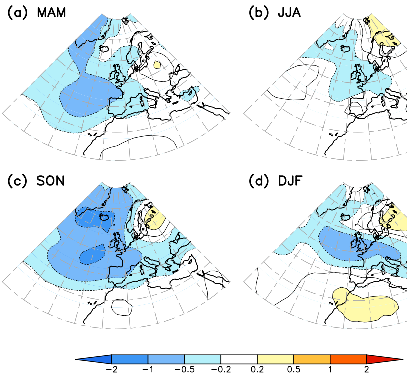

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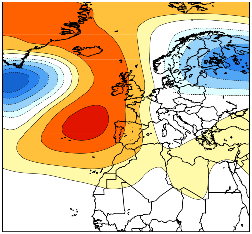
NAE dynamics & future temperature increase

Flow-analogues: method

SLP Dec 22, 2060 (CNRM-CM3)



Flow-analogues in 1961–2000

⇒

⇓

"Reference" temperature.

⇔ ??

⇓

N "analog" temperatures.

Limit?

Is a 40-year sampling period sufficient?

Cattiaux et al. (2010a), submitted.

NAE dynamics & future temperature increase

Flow-analogues: method

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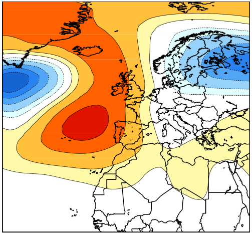
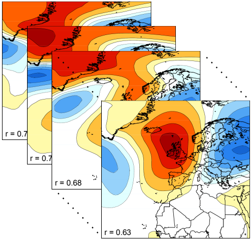


$\Rightarrow$

Flow-analogues in 1961–2000



$\Downarrow$ $\Downarrow$

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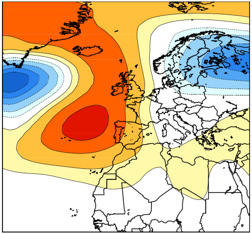

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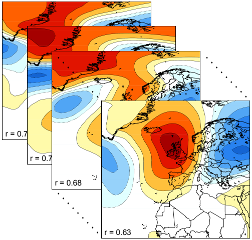

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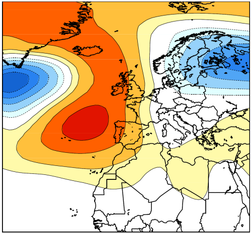

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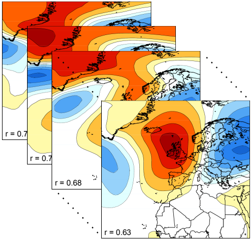

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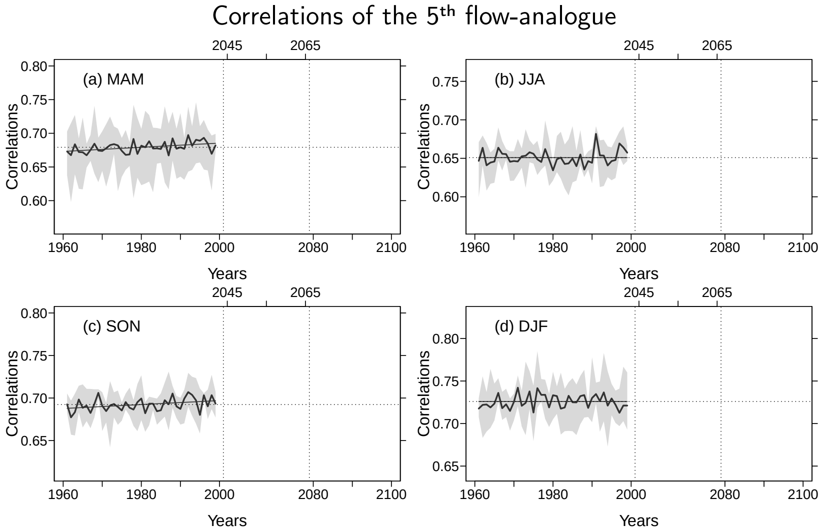
NAE dynamics & future temperature increase

Flow-analogues: correlations



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NAE dynamics & future temperature increase

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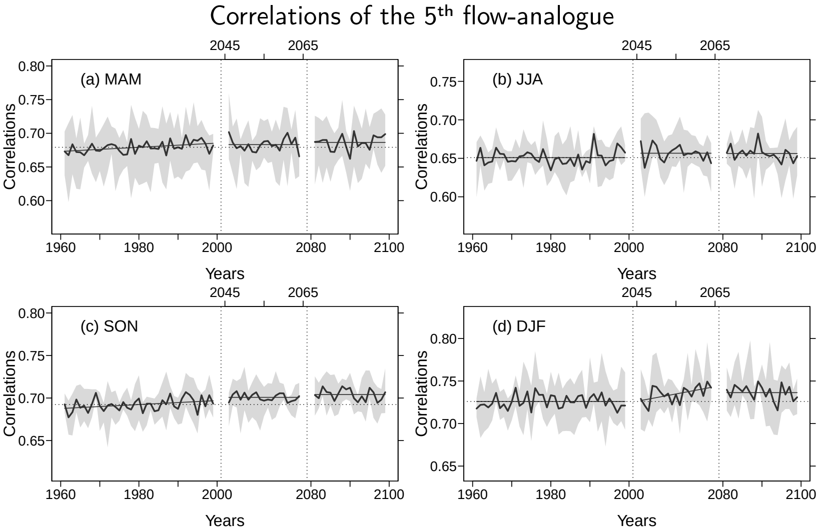
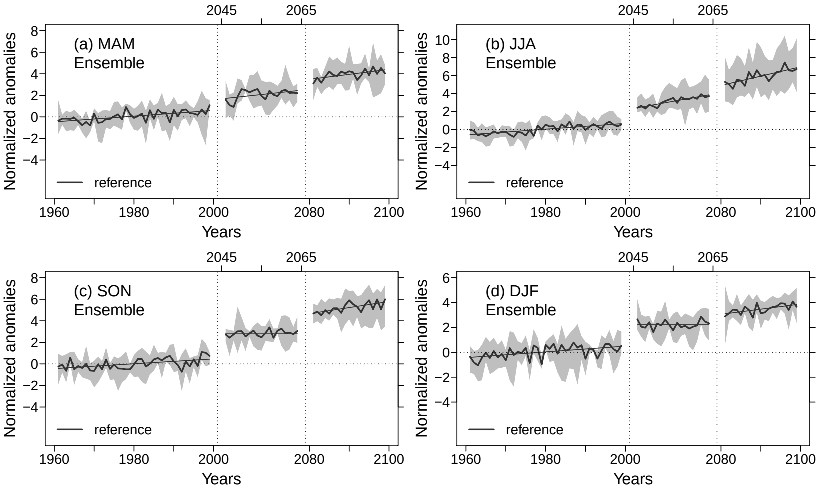


Cattiaux et al. (2010a), submitted.

NAE dynamics & future temperature increase

Flow-analogues: temperatures

Reference temperatures Analog temperatures



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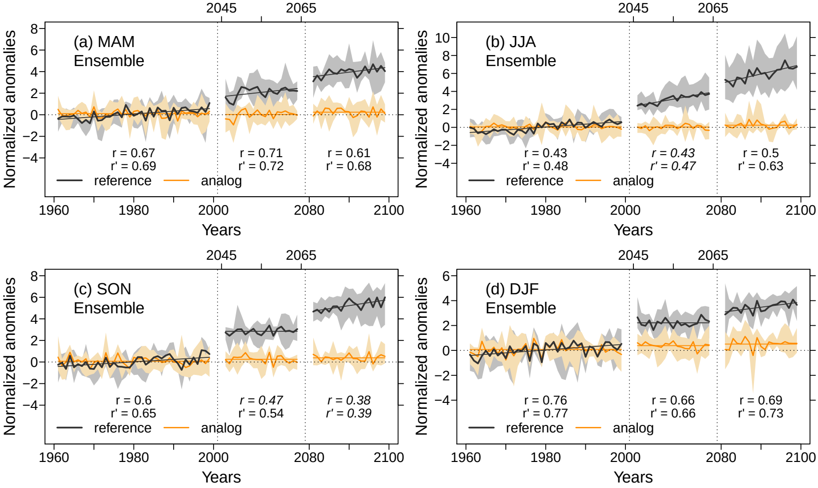

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Focus on extremely warm/cold seasons

Exceeding $\pm 1\sigma$ of detrended temperature distributions.

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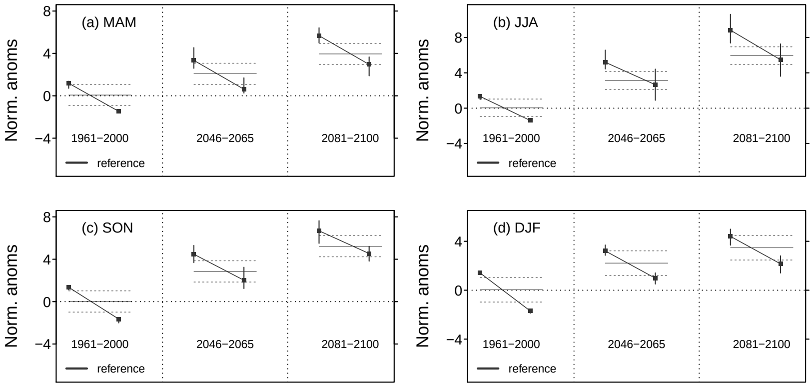

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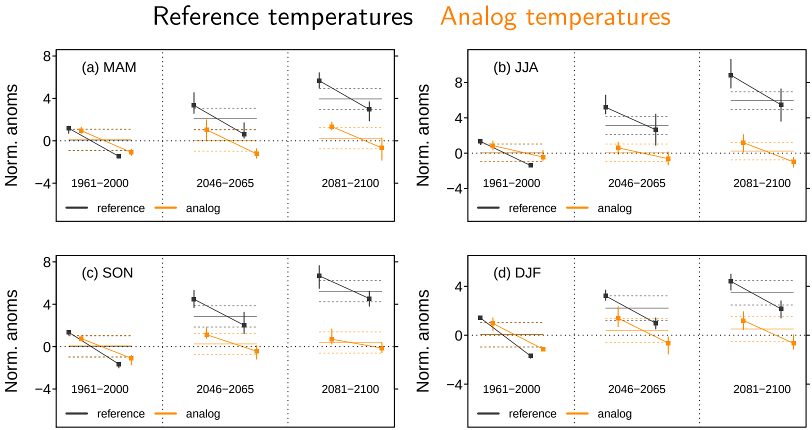

Cattiaux et al. (2010a), submitted.

NAE dynamics & future temperature increase: summary

- CMIP3 models generally perform well in reproducing NAE dynamics/temperature relationships.
- Changes in temperatures: increase in the mean. Widening (tightening) of summer (winter) distribution (see also Christensen et al., 2007; Fischer and Schär, 2009).
- Changes in dynamics: northward shift of the jet stream & decrease in the variability $\rightarrow$ increase in NAO+ (see also Terray et al., 2004).
- NAE dynamics is and remains the main driver of European temperatures variability, but only a minor part of long-term warming can be attributed to circulation changes (confirmed by weather-regime approach, not shown).
- Circulations associated with warm/cold seasons do not change. But feedbacks may change (e.g., amplify summer extremes (Fischer and Schär, 2009)).
- Main limit: are flow-analogues able to capture any trend?

Back to outline III. . .

1. Drivers of recent extremes & trends

- Introduction: NAE dynamics as the main driver of European climate
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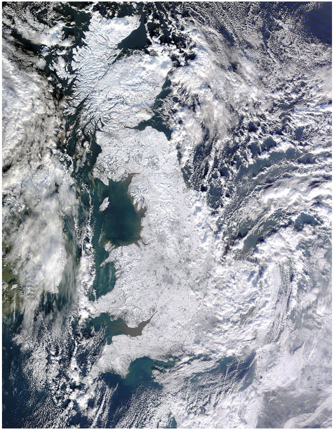
Winter 2009/10: what happened?

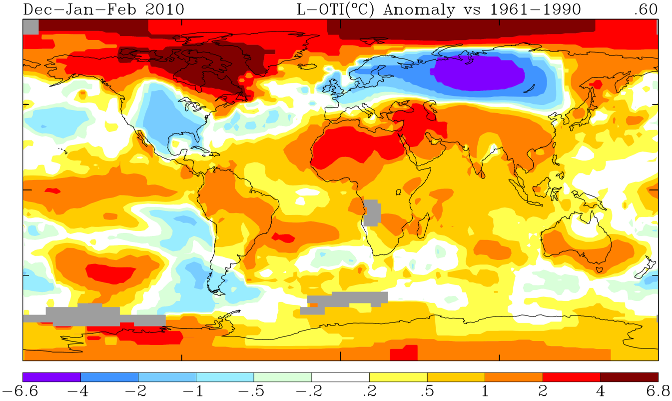
January 7, 2010 (NASA).



Are European cold spells of winter 2009/10 incompatible with global warming?

Winter 2009/10: locally cold, globally warm

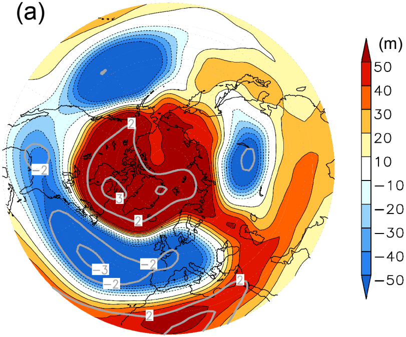
GISS-temp (http://data.giss.nasa.gov/cgi-bin/gistemp/).



5th warmest DJF on record since 1880 (NOAA, see Cohen et al. (2010)).

Winter 2009/10: an extreme persistence of NAO−

(a)



Cattiaux et al. (2010c).

Z500: NCEP/NCAR reanalysis. NAO index: Jones et al. (1998).

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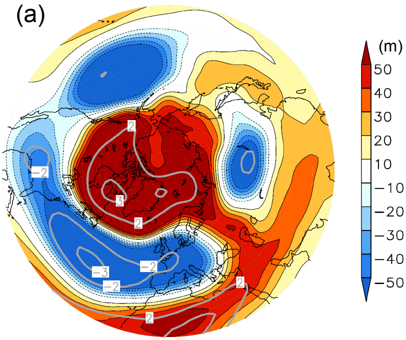

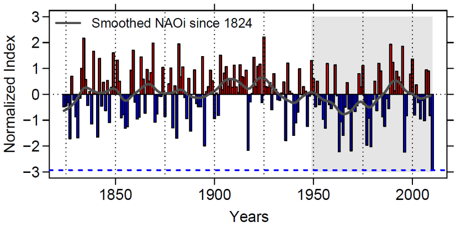

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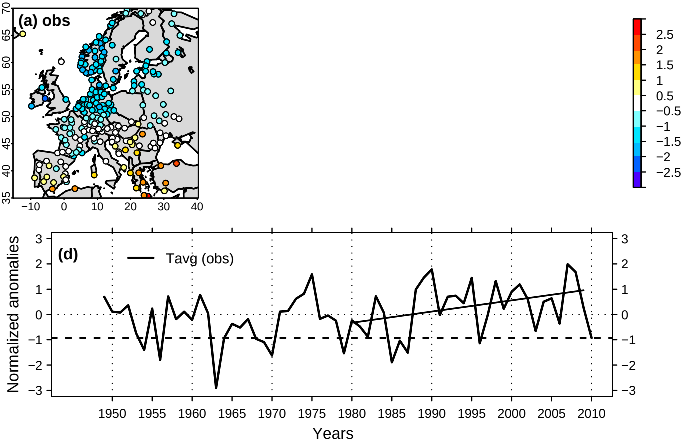
Winter 2009/10 in Europe

Cold, but not extreme

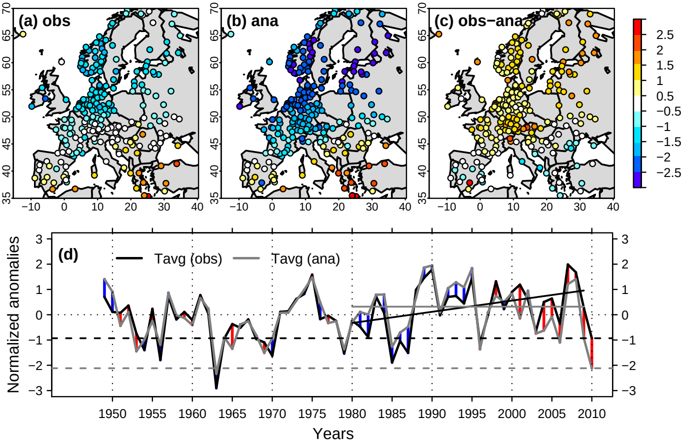


Cattiaux et al. (2010c).

Tobs: E-OBS (ECA&D).

Winter 2009/10 in Europe

Warmer than flow-analogues

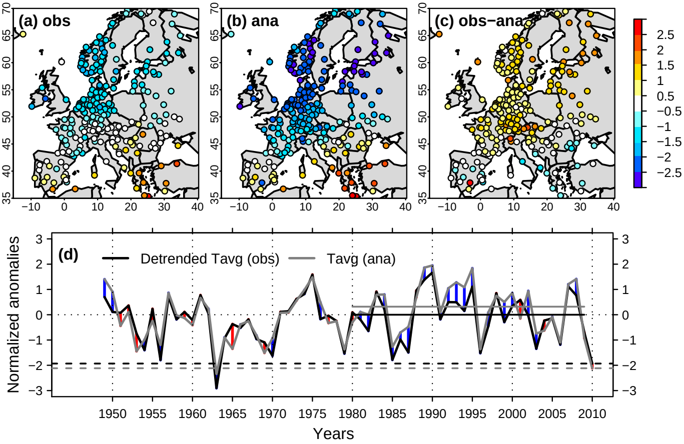


Cattiaux et al. (2010c).

Tobs: E-OBS (ECA&D), Flow-analogues from NCEP/NCAR Z500.

Winter 2009/10 in Europe

Warmer than flow-analogues

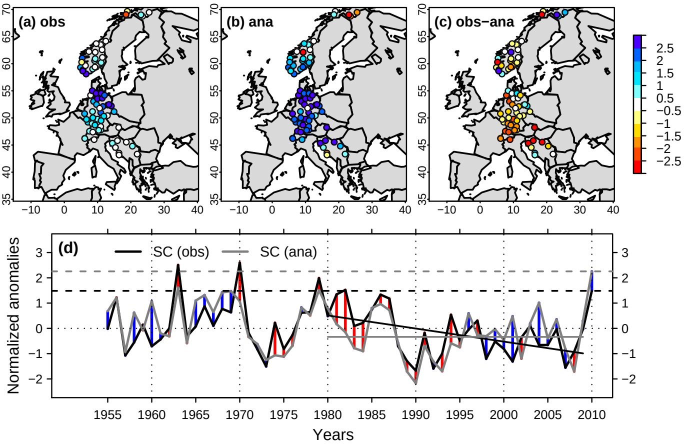


Cattiaux et al. (2010c).

Tobs: E-OBS (ECA&D), Flow-analogues from NCEP/NCAR Z500.

Winter 2009/10 in Europe

Less snowy than flow-analogues



...

Snow cover: E-OBS (ECA&D), Flow-analogues from NCEP/NCAR Z500.

Cold winter 2009/2010 in Europe: summary

- Regionally cold and snowy, globally warm (Cohen et al., 2010).
- Caused by an exceptional persistence of negative NAO conditions.
- In Europe, winter 2010 was cold (especially *Tmax*), but not extreme ...
- ...and warmer than expected from flow-analogues estimates.
- "Observed−analog" difference consistent with the 1980–2009 long-term observed trend.

Main conclusions

- Recent trends & extremes in European seasonal temperatures are not explained by the NAE atmospheric dynamics.
- Seasonality in the amplifying mechanisms: local feedbacks in spring–summer, heat & water vapor advection from Atlantic in autumn–winter.
- Projected changes in NAE circulations (enhanced NAO+) only have a minor contribution to projected temperature increase.
- Future warm/cold extremes are associated with similar circulations as recent warm/cold extremes.
- Recent wintertime cold spells in Europe are all but incompatible with global warming.

Main conclusions

- Recent trends & extremes in European seasonal temperatures are not explained by the NAE atmospheric dynamics.
- Seasonality in the amplifying mechanisms: local feedbacks in spring–summer, heat & water vapor advection from Atlantic in autumn–winter.
- Projected changes in NAE circulations (enhanced NAO+) only have a minor contribution to projected temperature increase.
- Future warm/cold extremes are associated with similar circulations as recent warm/cold extremes.
- Recent wintertime cold spells in Europe are all but incompatible with global warming.

Limits

- Difficulty to isolate individual signatures in coupled systems:
  - Linear regression model? No evidence for causality.
  - Sensitivity experiments? Physics must be broken somewhere.
- Flow-analogues method: could analog temperatures show up any trend, given that flow-analogues days are sampled in a quite stationary climate?
- Simplistic hypothesis in multi-model approach:
  - Selection of "best" models: arbitrary.
  - Equi-probability of models in combining future climate projections.
  - Using multi-model range as an estimate for uncertainties.

Prospects

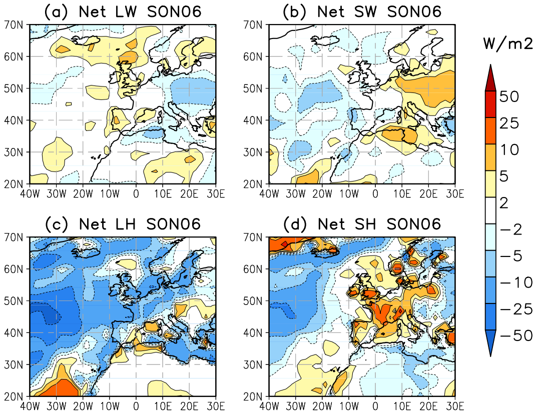
- Methodology, statistical & modeling tools could be applied to:
  - CMIP5 models (IPCC-AR5) → Post-doc at CNRM.
  - other regions → Arctic (with V. Masson-Delmotte), Asia (P. Yiou).
  - other variables (snow, rainfall (Vautard and Yiou, 2009)).
  - other periods (last millenium, volcanic eruptions (T. Salameh)).
  - model development → IPSL-CM4/5 analysis (with LMD people).
- Need for going to higher time & spatial scales (downscaling):
  - sub-seasonal scale: persistance/intensity of heat-waves & cold spells (PhD B. Quesada), weather-regime approach (with M. Vrac).
  - more local scale: regional climate projections (projects DRIAS, CORDEX, SALUTAIR).
- Towards prediction of temperature extreme events?
  - operational: looking for precursors (e.g., spring soil moisture, autumn arctic sea ice). Not shown today: discussion about different forcings of the NAO (case study of winter 2009/10).
  - statistical: probabilistic methods for weighted combinations of multi-model projections, wrt. individual model skills.

Thanks for your attention.
Questions?

Energy budget of the mild autumn of 2006

Physical mechanisms

$$\Delta_{\downarrow}E = \Delta_{\downarrow}LW' + \Delta_{\downarrow}SW' + LH'_{\downarrow} + SH'_{\downarrow}$$



- increased solar flux caused by the anticyclonic circulation.
- water vapor from warm SST, enhancing local greenhouse effect.
- sensible heat advected from warm SST.

See also: Shongwe et al. (2009) & Philipona et al. (2005).

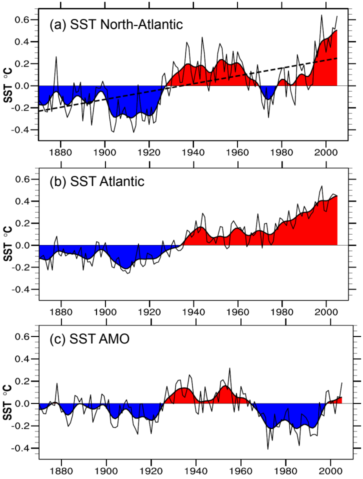
Warming of North Atlantic ocean

Natural or anthropogenic?

North-Atlantic SST trend

- natural multi-decadal oscillation (60 years): the AMO (Kerr, 2000).
- global warming, very likely due to human activities (IPCC-AR4).

→ Great debate in recent years! Knight et al. (2005) *vs.*
Trenberth and Shea (2006) or Ting et al. (2009).

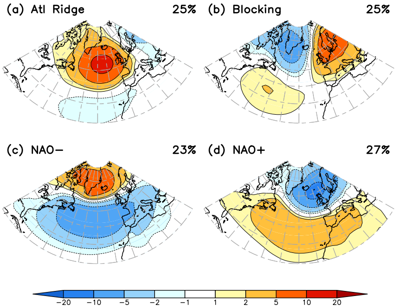


Trenberth and Shea (2006).

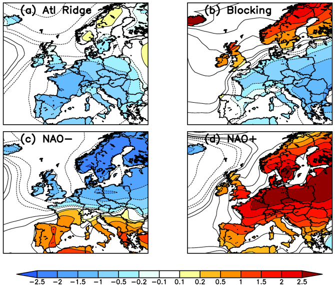
European temperatures & NAE dynamics

Winter weather regimes

- Preferential states of the NAE daily atmospheric circulation.
- Clustering algorithms → 4 winter regimes.
- Associated temperatures: composites.



Sea-Level Pressure (SLP), ERA-40
NDJFM 1961–2000.



2m-temperature (T2m), ERA-40
NDJFM 1961–2000.

European temperatures & NAE dynamics

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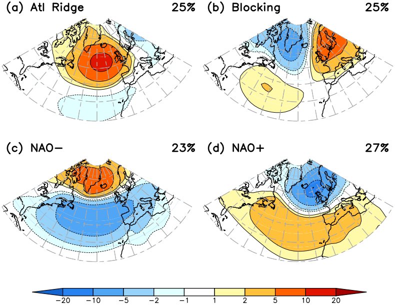
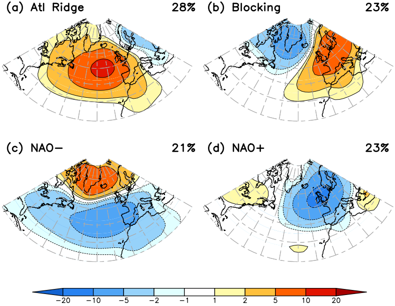


Sea-Level Pressure (SLP), ERA-40
NDJFM 1961–2000.



Sea-Level Pressure (SLP), IPSL-CM4
NDJFM 1961–2000.

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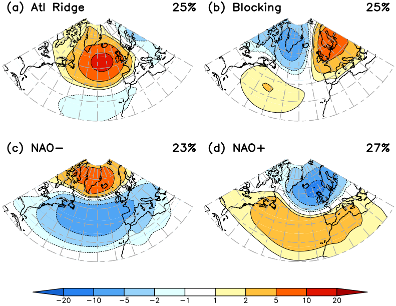

Sea-Level Pressure (SLP), ERA-40
NDJFM 1961–2000.

	Summer	Winter
1	ECHOg	CCC47
2	MRI232	GFDL21
3	IPSL4	CSI35
4	CSI35	ECHOg
5	ECH5	IPSL4

European temperatures & NAE dynamics

Winter weather regimes

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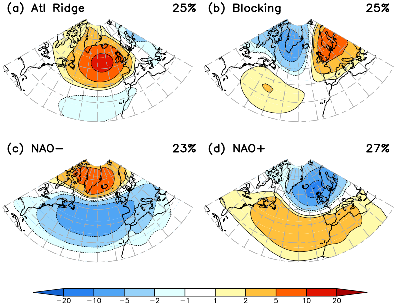
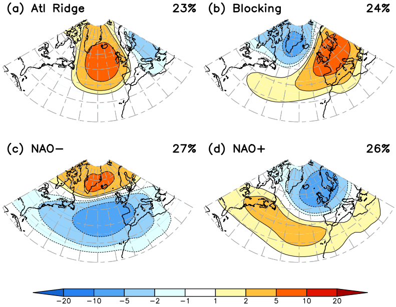
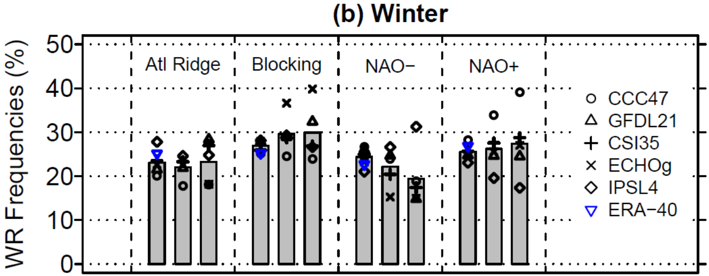


Sea-Level Pressure (SLP), ERA-40
NDJFM 1961–2000.



Sea-Level Pressure (SLP), Ensemble
NDJFM 1961–2000.

Temperature increase: changes in WR occurrences?



$$\Delta X = \underbrace{\sum_{i=1}^{N}\left(\Delta f_i \cdot x_i^P\right)}_{Inter} + \underbrace{\overline{\Delta x}}_{Intra-com} + \underbrace{\sum_{i=1}^{N}\left(f_i^P \cdot \Delta x_i'\right)}_{Intra-spe} + \underbrace{\sum_{i=1}^{N}(\Delta f_i \cdot \Delta x_i)}_{Residu}$$

Temperature increase: changes in WR occurrences?

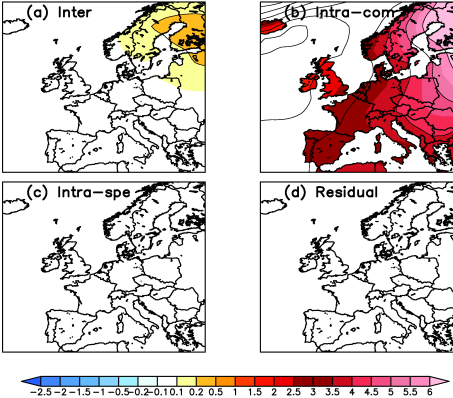
$$\Delta X = X^F - X^P = \sum_{i=1}^{N} \left(f_i^F x_i^F - f_i^P x_i^P \right)$$

$$\begin{aligned}
\Delta X &= \sum_{i=1}^{N} \left[\left(f_i^F - f_i^P \right) x_i^F + f_i^P x_i^F - f_i^P x_i^P \right] \\
&= \sum_{i=1}^{N} \left[\left(f_i^F - f_i^P \right) \left(x_i^P - x_i^P + x_i^F \right) + f_i^P \left(x_i^F - x_i^P \right) \right] \\
&= \sum_{i=1}^{N} \left[\left(f_i^F - f_i^P \right) x_i^P + f_i^P \left(x_i^F - x_i^P \right) + \left(f_i^F - f_i^P \right) \left(x_i^F - x_i^P \right) \right]
\end{aligned} \quad (1)$$

$$\Delta X = \underbrace{\sum_{i=1}^{N} \left(\Delta f_i \cdot x_i^P \right)}_{Inter} + \underbrace{\sum_{i=1}^{N} \left(f_i^P \cdot \Delta x_i \right)}_{Intra} + \underbrace{\sum_{i=1}^{N} \left(\Delta f_i \cdot \Delta x_i \right)}_{Residu}$$

$$\Delta X = \underbrace{\sum_{i=1}^{N} \left(\Delta f_i \cdot x_i^P \right)}_{Inter} + \underbrace{\overline{\Delta x}}_{Intra-com} + \underbrace{\sum_{i=1}^{N} \left(f_i^P \cdot \Delta x_i' \right)}_{Intra-spe} + \underbrace{\sum_{i=1}^{N} \left(\Delta f_i \cdot \Delta x_i \right)}_{Residu}$$

Temperature increase: changes in WR occurrences?



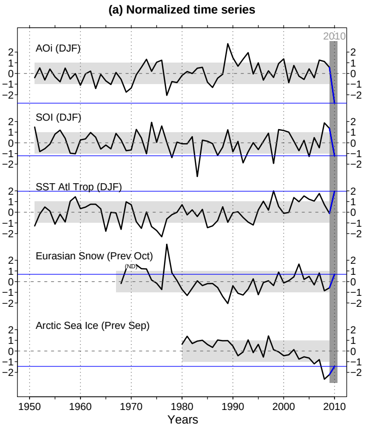
$$\Delta X = \underbrace{\sum_{i=1}^{N}\left(\Delta f_i \cdot x_i^P\right)}_{Inter} + \underbrace{\overline{\Delta x}}_{Intra-com} + \underbrace{\sum_{i=1}^{N}\left(f_i^P \cdot \Delta x_i'\right)}_{Intra-spe} + \underbrace{\sum_{i=1}^{N}(\Delta f_i \cdot \Delta x_i)}_{Residu}$$

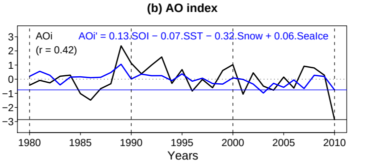
Winter 2009/10: why such an NAO−?

Forcings

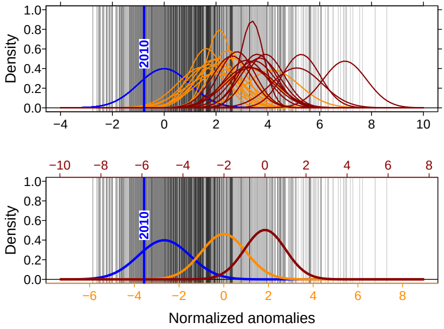
- ENSO (Cassou, 2001).
- Tropical-Atlantic SST (Cassou et al., 2004).
- Eurasian snow over in October (Cohen et al., 2010).
- Late-summer Arctic sea-ice extent (Francis et al., 2009).

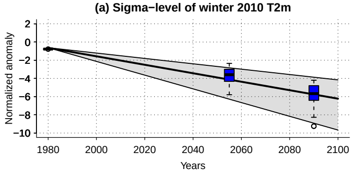
/!\ Not systematic!

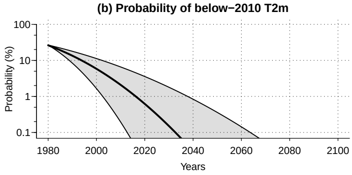




Winter 2009/10: a unbreakable record for future years?







Probability of below-2010 T2m

$$\Pr\left(\widetilde{T_y} \leq \widetilde{T_{2010}}\right) \begin{cases} = 0.21 & \text{si} \quad y \in 20c3m \\ \leq 0.01 & \text{si} \quad 2046 \leq y \leq 2065 \\ \ll 0.001 & \text{si} \quad 2081 \leq y \leq 2100 \end{cases}$$

Hypothesis

- Gaussian distributions.
- equi-probable models.
- models range as uncertainties.