European climate variability in a warming world

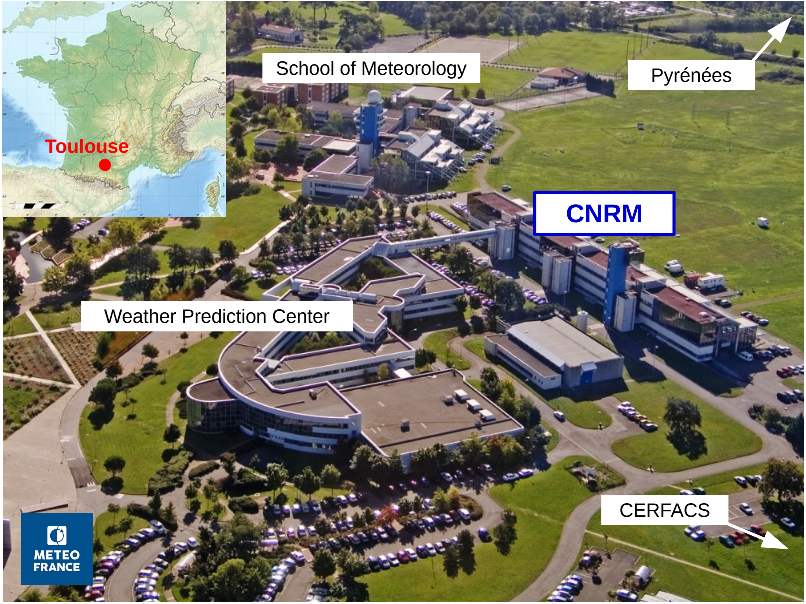
Julien Cattiaux[1]

with Christophe Cassou[2], Fabrice Chauvin[1], Jeanne Colin[1], Hervé Douville[1], Gudrun Magnusdottir[3], Thomas Oudar[2], Yannick Peings[1,3], Aurélien Ribes[1], David Saint-Martin[1], Robert Schoetter[1], Sophie Tyteca[1], Robert Vautard[4], Steve Vavrus[5], and Pascal Yiou[4].

1 – CNRM, UMR CNRS/Météo-France, Toulouse, France. 2 – CECI, UMR CNRS/CERFACS, Toulouse, France.
3 – University of California, Irvine, US. 4 – LSCE (IPSL), UMR CNRS/CEA/UVSQ, Gif-sur-Yvette, France.
5 – University of Wisconsin, Madison, US.

ETHZ Seminar | March 2017

Where?


Toulouse
School of Meteorology
Pyrénées
CNRM
Weather Prediction Center
CERFACS
METEO FRANCE

Who?

Centre **N**ational de **R**echerches **M**étéorologiques
Marc Pontaud, 300 people, 5 groups.

> Climate & Large-Scale Modelling Group
David Salas y Melia, 80 people, 7 teams.

> > Atmosphere & Climate Sensitivity Team
Hervé Douville, 12 people (Aurélien Ribes, Florent Brient. . .).

Related teams at CNRM:
Earth System Modelling (Bertrand Decharme, Jeanne Colin, Roland Séférian. . .),
Regional Modelling (Samuel Somot, Serge Planton. . .),
Predictability (Michel Déqué, Lauriane Batté. . .).

Related labs in France:
CERFACS (Laurent Terray, Christophe Cassou, Julien Boé. . .),
LSCE/IPSL (Robert Vautard, Pascal Yiou, Philippe Naveau. . .).

This talk

This talk

European
= geographical Europe (including Switzerland) (and UK).

Climate
= surface temperature and atmospheric circulation.

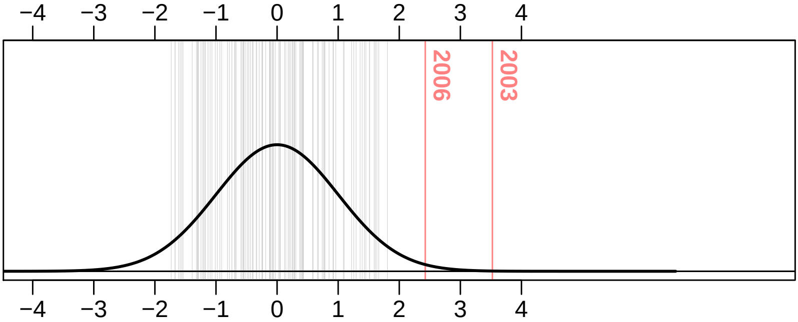
Variability
= intra-seasonal to inter-annual time scales.

In a warming world
= in CMIP5 future projections.

Variability in a warming world – Statistical point of view

- Beyond the mean warming (pdf location), changes in variability (pdf shape) modulate changes in extremes (pdf tails).

Illustration from European summer temperatures



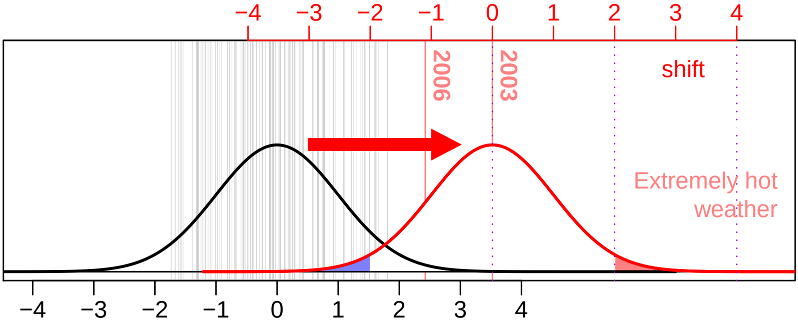
Plotted from E-OBS data over 1950–2012.

See also: Schär et al. 2004 (*Nature*).

Variability in a warming world – Statistical point of view

- Beyond the mean warming (pdf location), changes in variability (pdf shape) modulate changes in extremes (pdf tails).

Illustration from European summer temperatures



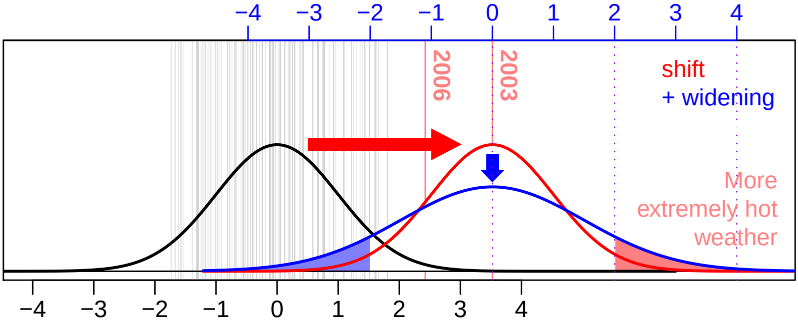
Plotted from E-OBS data over 1950–2012.

See also: Schär et al. 2004 (*Nature*).

Variability in a warming world – Statistical point of view

- Beyond the mean warming (pdf location), changes in variability (pdf shape) modulate changes in extremes (pdf tails).

Illustration from European summer temperatures



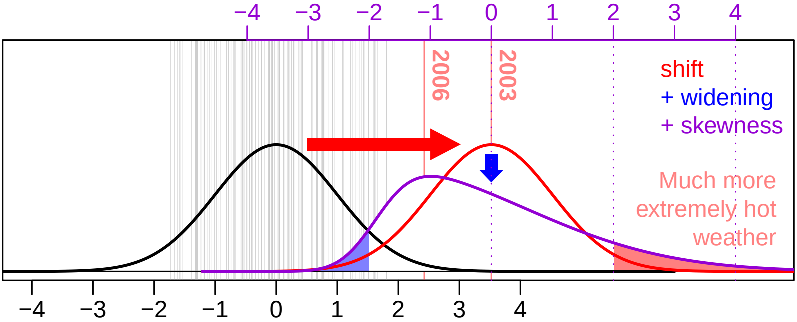
Plotted from E-OBS data over 1950–2012.

See also: Schär et al. 2004 (*Nature*).

Variability in a warming world – Statistical point of view

- Beyond the mean warming (pdf location), changes in variability (pdf shape) modulate changes in extremes (pdf tails).

Illustration from European summer temperatures



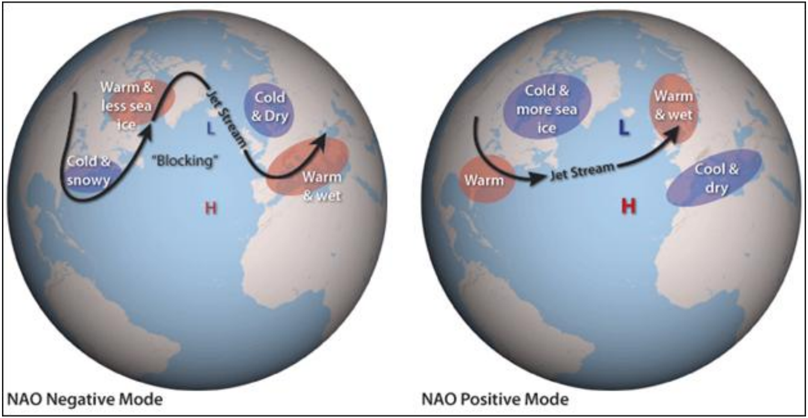
Plotted from E-OBS data over 1950–2012.

See also: Schär et al. 2004 (*Nature*).

Variability in a warming world – Physical point of view

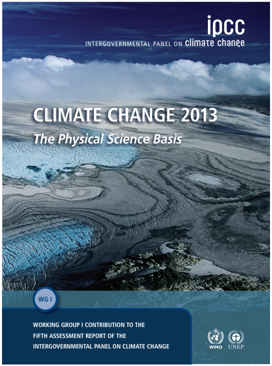
- Climate change might affect the modes of atmospheric variability that drives the European weather.

Example of the winter North Atlantic Oscillation



Source: climatology.co.uk

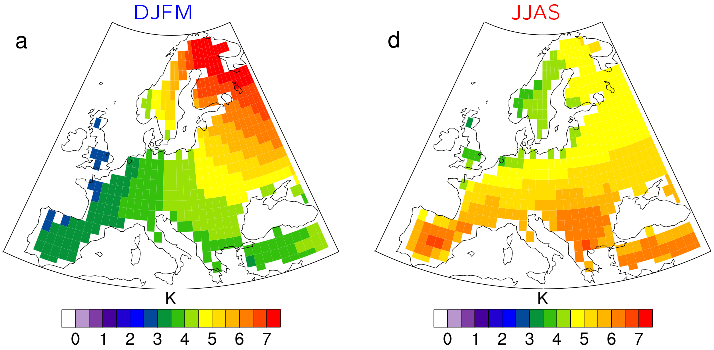
The projected warming in Europe – IPCC AR5



It is very likely that temperatures will continue to increase throughout the 21st century over all of Europe and the Mediterranean region. It is likely that winter mean temperature will rise more in NEU than in CEU or MED, whereas summer warming will likely be more intense in MED and CEU than in NEU.

The projected warming in Europe – CMIP5 ensemble

- $\Delta T \sim 5 \pm 1.5$ K by 2100 in the RCP8.5 scenario.
- Role of snow cover decline in winter, soil drying in summer.



CMIP5 ensemble-mean (34 models). 2070–2099 vs. 1979–2008 in RCP8.5.
© Cattiaux et al., 2013, *Clim. Dyn.*, Fig. 2.

See also: Kröner et al. 2016 (*Clim. Dyn.*).

Outline

Summer variability

Winter variability

Seasonal clock

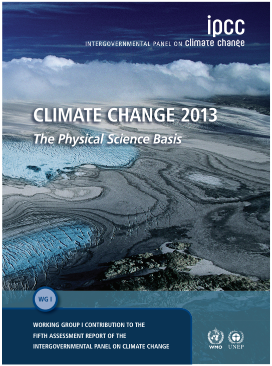
Outline

Summer variability

Winter variability

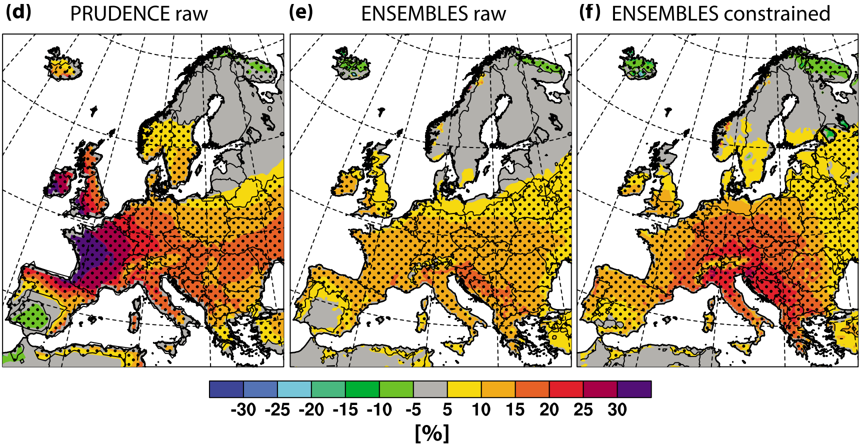
Seasonal clock

IPCC AR5



Recent studies have clearly identified a possible amplification of temperature extremes by changes in soil moisture (Jaeger and Seneviratne, 2010; Hirschi et al., 2011), acting as a mechanism that further magnifies the intensity and frequency of heat waves given the projected enhance of summer drying conditions.

Reported increase in day-to-day variability



JJA 2070–2099 vs. 1961–1990 in A2 (PRUDENCE) and 1970–1999 in A1B (ENSEMBLES).
© Fischer et al., 2012, *GRL*, Fig. 1.

See also: Fischer and Schär 2009 (*Clim. Dyn.*); Kjellström et al. 2007 (*Clim. Change*).

Measuring the day-to-day variability – 1/2

- Use a daily variance:

$$\sigma^2 = \frac{1}{N-1}\sum_{d=1}^{N}\left(T_d - \bar{T}\right)^2$$

- Use day-to-day variations:

$$\mathrm{ITV} = \frac{1}{N-1}\sum_{d=1}^{N-1}\left|T_{d+1} - T_d\right|$$

* ITV for Inter-diurnal Temperature Variability.

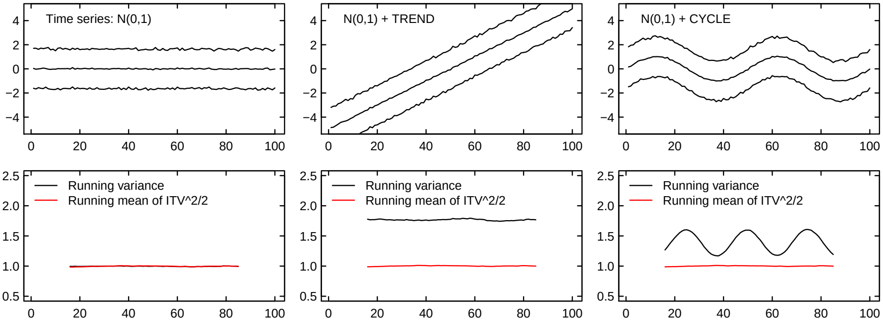
See also: Rosenthal 1960 (*J. Meteorol.*).

Measuring the day-to-day variability – 2/2

- Locally, day-to-day variations are linked to the daily variance:

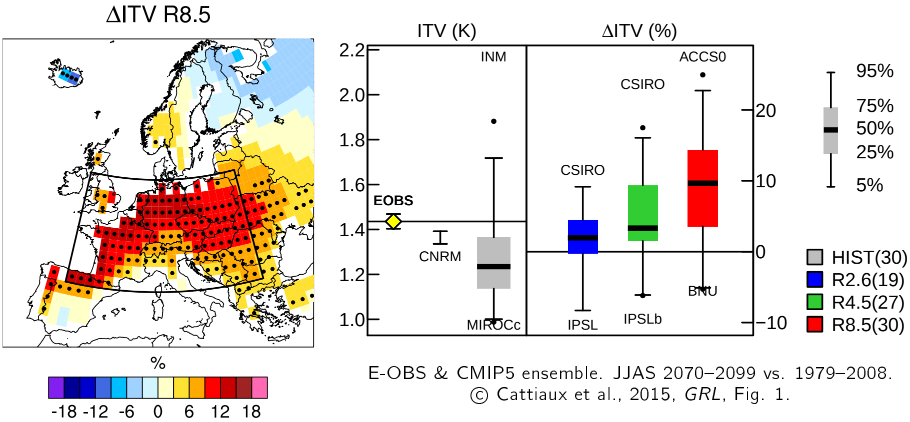
$$\mathrm{ITV}_d = |T_{d+1} - T_d| = \sqrt{2}\,\sigma(T_{[\![d,d+1]\!]})$$

- Contrarily to σ, ITV is not sensitive to long-term variations:



Based on 1000 random simulations of white noises.

Projected change in ITV



E-OBS & CMIP5 ensemble. JJAS 2070–2099 vs. 1979–2008.
© Cattiaux et al., 2015, *GRL*, Fig. 1.

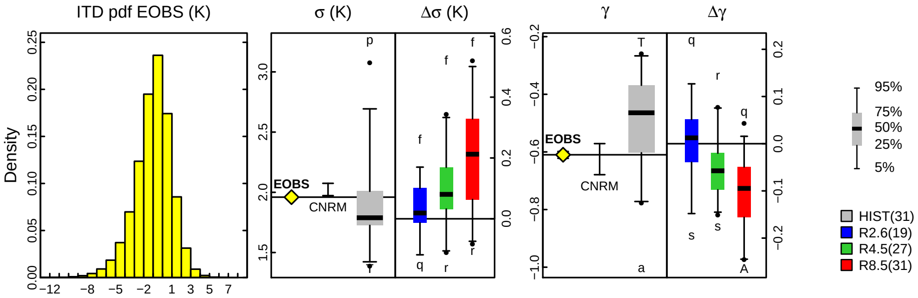
See also: Kim et al. 2013 (*Clim. Dyn.*).

A closer look at day-to-day variations

- Asymmetry of the ITV distribution towards negative values.

Easier to rapidly cool the surface (clouds, rain) than to produce hot increments.

- Widening of the distribution under climate change.

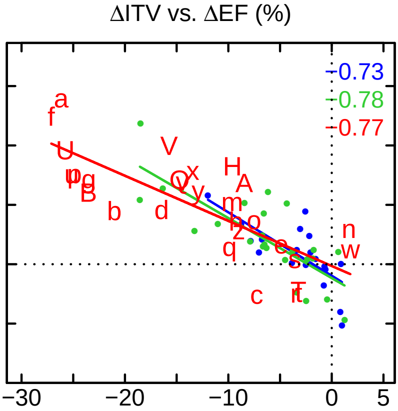


E-OBS & CMIP5 ensemble. JJAS 2070–2099 vs. 1979–2008.
© Cattiaux et al., 2015, *GRL*, Fig. 2.

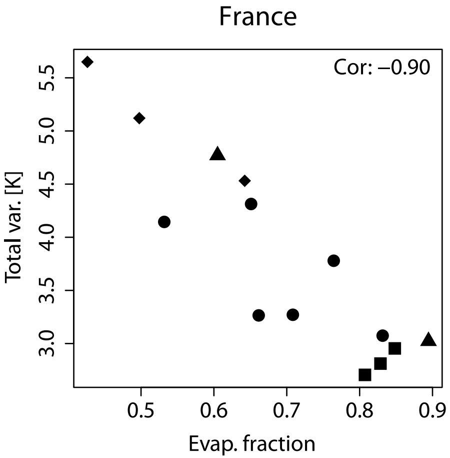
ITV increase linked to soil drying – Stats

- ITV anti-correlated to EF, and ΔITV anti-correlated to ΔEF.

EF = Evaporative Fraction = LH / (SH + LH)



RCP2.6, RCP4.5, RCP8.5. Y-axis incr. 10%.
© Cattiaux et al., 2015, *GRL*, Fig. 4.

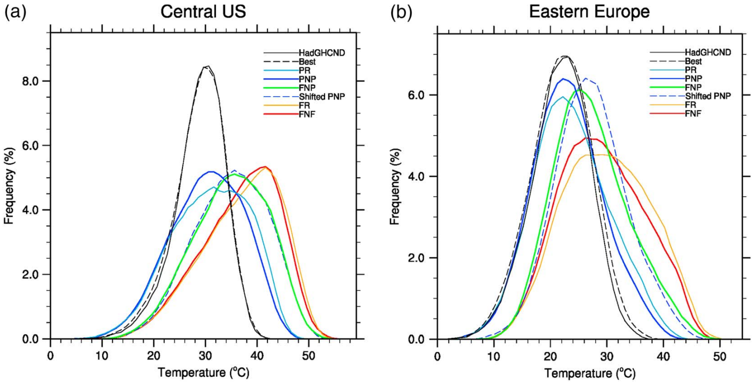


© Fischer et al., 2012, *GRL*, Fig. 3.

ITV increase linked to soil drying – Model exps

⟶ CNRM-CM nudged by PRE/FUT soil moisture in PRE/FUT GHG conditions.

- When the soil moisture feedback is off, the summer T pdf is shifted.
- When the SMF is on, the summer T pdf is re-shaped towards hot values.



PDF of JJA temperatures — © Douville et al., 2016, *GRL*, Fig. 2.

See also: GLACE-CMIP5 experiment, Seneviratne et al. 2013 (*GRL*).

Changes in heat waves – Methodology

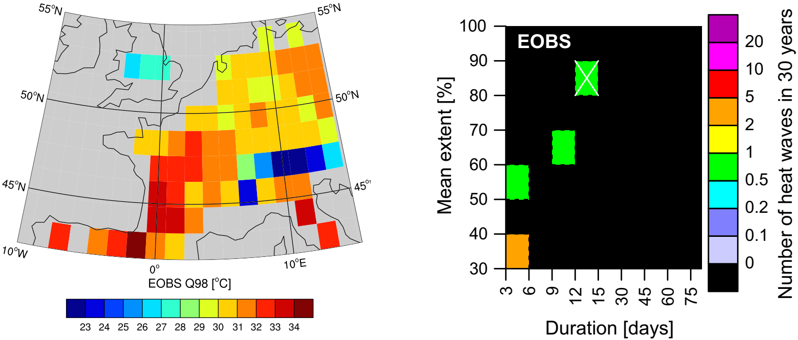
- Heat wave definition:

For each model, an event is at least 3 consecutive days with at least 30% of grid points where Tx exceeds the 98th percentile of the MJJASO 1979–2008 distribution.

- Heat wave characteristics:

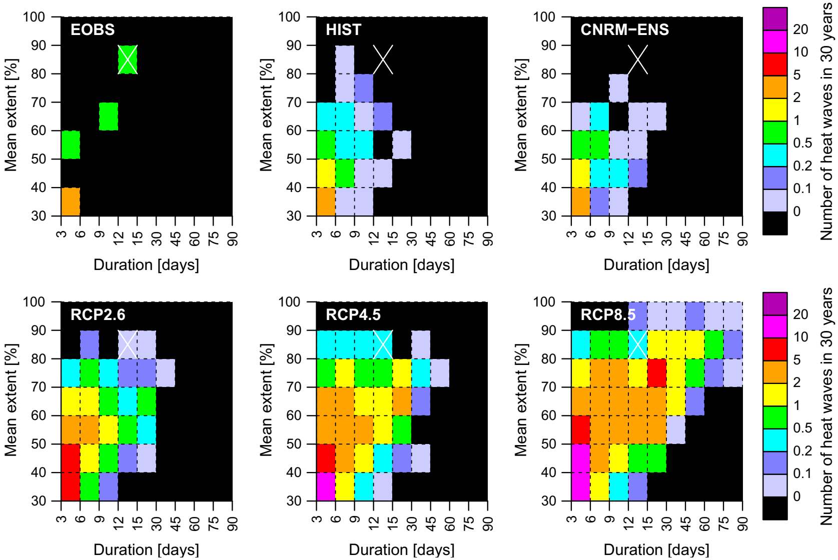
Number, duration (days), intensity (K), extent (%), and severity (product of all).

Tx threshold (left) + the 7 events in EOBS 1979–2008 (right, max = Aug 2003)



© Schoetter et al., 2015, *Clim. Dyn.*, Figs. 1 & 5.

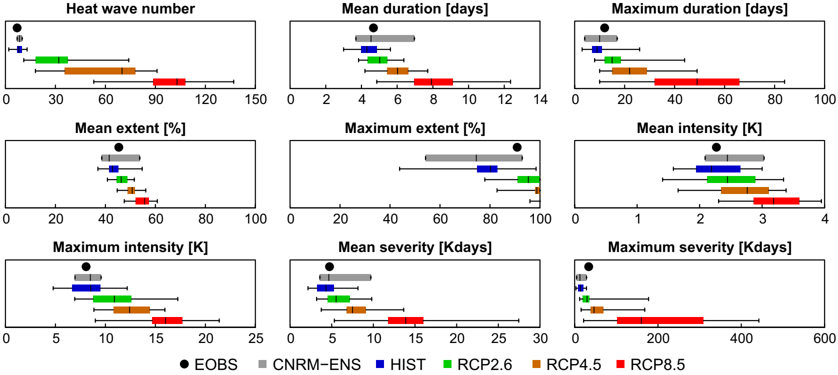
Changes in heat waves – Number of events



Based on 19 CMIP5 models and 2070–2099 vs. 1979–2008 periods.
© Schoetter et al., 2015, *Clim. Dyn.*, Fig. 5.

Changes in heat waves – Characteristics

- When using a fixed threshold (present-day Q98), increase in all characteristics (number, duration, extent, intensity, severity. . .)



© Schoetter et al., 2015, *Clim. Dyn.*, Fig. 3.

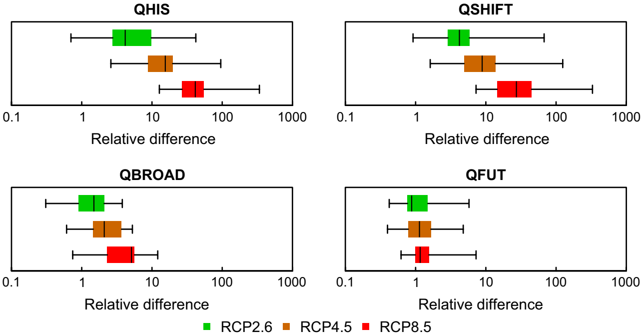
See also: Fischer and Schär 2010 (*Nature Geoscience*).

Contributions of mean and variability

Contribution of mean: threshold QSHIFT = $Q98_{\mathrm{FUT}} - \Delta Q50$.

Contribution of variability: threshold QBROAD = $Q98_{\mathrm{FUT}} - \Delta(Q98{-}Q50)$.

- The severity increase induced by the mean is about 5 times larger.



© Schoetter et al., 2015, *Clim. Dyn.*, Fig. 10.

See also: Lau and Nath 2014 (*J. Clim.*).

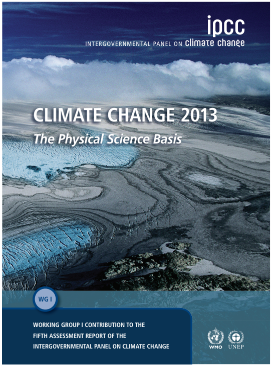
Outline

Summer variability

Winter variability

Seasonal clock

IPCC AR5

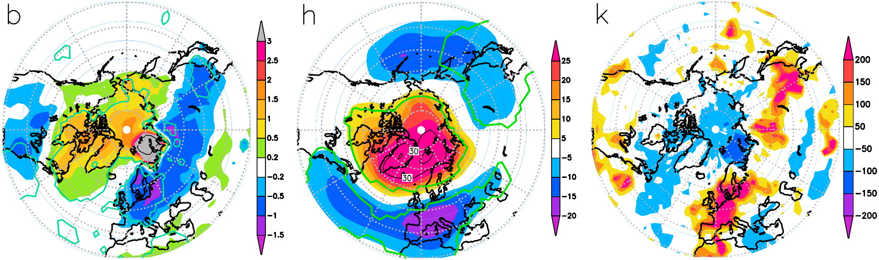


At the other end of the spectrum, studies indicate that European winter variability may be related to sea ice reductions in the Barents-Kara Sea (Petoukhov and Semenov, 2010) [. . .] Although the mechanism behind this relation remains unclear this suggests that cold winters in Europe will continue to occur in coming decades, despite an overall warming.

Arctic sea ice loss and European cold winters?

- **Hypothesis:** sea-ice loss > Arctic amplification > NAO− -like pattern > increased frequency of blockings > increased frequency of cold extremes.

Surface T (K), Z850 (m) and Prob$\{T < -1.5\sigma\}$ (%) responses to sea-ice loss



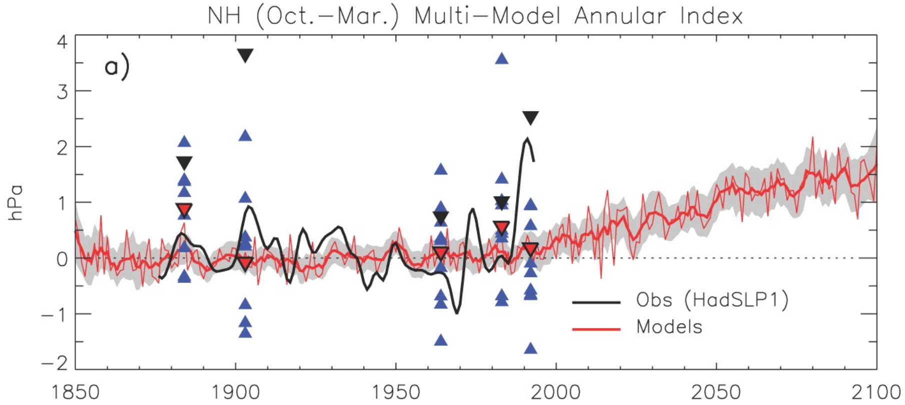
ECHAM5 simulations of a 80-to-40% decline in sea-ice extent, month of February.
© Petoukhov and Semenov, 2010, *JGR*, Fig. 3.

See other modelling studies: Deser et al. 2010, 2015; Screen et al. 2013; Peings and Magnusdottir 2014; Blackport and Kushner 2016 (all in *J. Clim.*).

\+ CNRM-CM exps: Oudar et al. 2017 (*Clim. Dyn.*).

The NAO in CMIP projections – 1/2

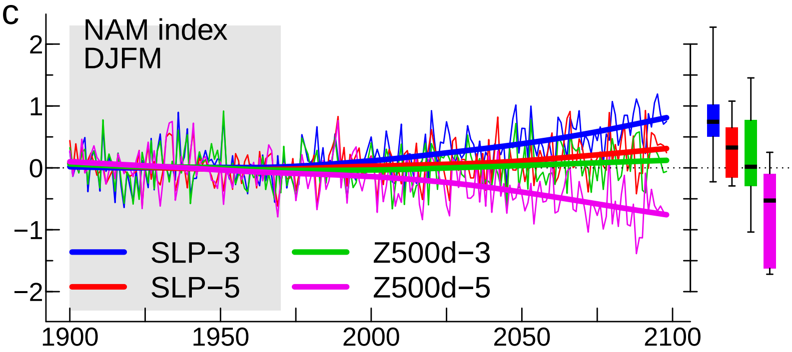
- IPCC-AR4: "it is likely that the NAM [NAO] index would not notably decrease in a future warmer climate (Miller et al. 2006)".



SLP PC-based index, CMIP3 ensemble, A1B, ONDJFM.
© Miller et al., 2006, *JGR*, Fig. 8.

The NAO in CMIP projections – 2/2

- Since Miller et al. 2006, baroclinicity (SLP vs. Z500) and shift towards NAM/NAO− (CMIP5 vs CMIP3), partly attributed to the Arctic sea ice loss.



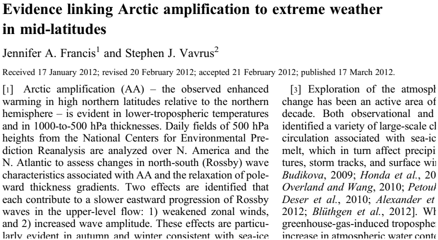
SLP + Z500 PC-based indices, CMIP3 + CMIP5 ensembles, A2/RCP8.5, DJFM.
© Cattiaux & Cassou, 2013, *GRL*, Fig. 1.

See also: Woollings 2008 (*GRL*); Barnes and Polvani 2015 (*J. Clim.*).

Is the flow becoming wavier?

Is the flow becoming wavier?

Francis and Vavrus 2012 (*GRL*)



Evidence linking Arctic amplification to extreme weather in mid-latitudes

Jennifer A. Francis[1] and Stephen J. Vavrus[2]

Received 17 January 2012; revised 20 February 2012; accepted 21 February 2012; published 17 March 2012.

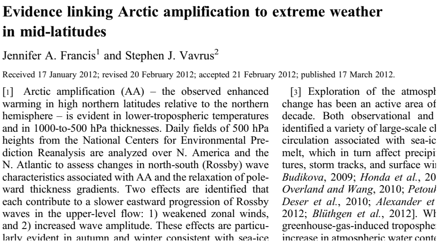
[1] Arctic amplification (AA) – the observed enhanced warming in high northern latitudes relative to the northern hemisphere – is evident in lower-tropospheric temperatures and in 1000-to-500 hPa thicknesses. Daily fields of 500 hPa heights from the National Centers for Environmental Prediction Reanalysis are analyzed over N. America and the N. Atlantic to assess changes in north-south (Rossby) wave characteristics associated with AA and the relaxation of poleward thickness gradients. Two effects are identified that each contribute to a slower eastward progression of Rossby waves in the upper-level flow: 1) weakened zonal winds, and 2) increased wave amplitude. These effects are particularly evident in autumn and winter consistent with sea-ice

[3] Exploration of the atmosph
change has been an active area of
decade. Both observational and
identified a variety of large-scale cl
circulation associated with sea-ic
melt, which in turn affect precipi
tures, storm tracks, and surface wi
Budikova, 2009; *Honda et al.*, 20
Overland and Wang, 2010; *Petouk*
Deser et al., 2010; *Alexander et*
2012; *Blüthgen et al.*, 2012]. Wh
greenhouse-gas-induced troposphe
increase in atmospheric water conte

weather patterns in mid-latitudes more persistent [. . .] increased probability of extreme weather events that result from prolonged conditions.

Is the flow becoming wavier?

Francis and Vavrus 2012 (*GRL*)



Evidence linking Arctic amplification to extreme weather in mid-latitudes

Jennifer A. Francis[1] and Stephen J. Vavrus[2]

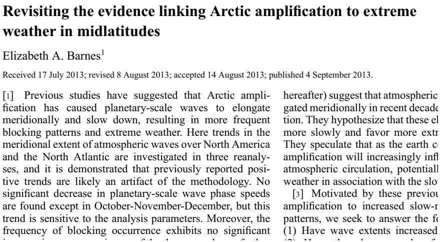
Received 17 January 2012; revised 20 February 2012; accepted 21 February 2012; published 17 March 2012.

[1] Arctic amplification (AA) – the observed enhanced warming in high northern latitudes relative to the northern hemisphere – is evident in lower-tropospheric temperatures and in 1000-to-500 hPa thicknesses. Daily fields of 500 hPa heights from the National Centers for Environmental Prediction Reanalysis are analyzed over N. America and the N. Atlantic to assess changes in north-south (Rossby) wave characteristics associated with AA and the relaxation of poleward thickness gradients. Two effects are identified that each contribute to a slower eastward progression of Rossby waves in the upper-level flow: 1) weakened zonal winds, and 2) increased wave amplitude. These effects are particularly evident in autumn and winter consistent with sea-ice

[3] Exploration of the atmosph
change has been an active area of
decade. Both observational and
identified a variety of large-scale cl
circulation associated with sea-ic
melt, which in turn affect precipi
tures, storm tracks, and surface wi
Budikova, 2009; *Honda et al.*, 20
Overland and Wang, 2010; *Petouk*
Deser et al., 2010; *Alexander et*
2012; *Blüthgen et al.*, 2012]. Wh
greenhouse-gas-induced tropospher
increase in atmospheric water conte

weather patterns in mid-latitudes more persistent [. . .] increased probability of extreme weather events that result from prolonged conditions.

Barnes, 2013 (*GRL*)



Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes

Elizabeth A. Barnes[1]

Received 17 July 2013; revised 8 August 2013; accepted 14 August 2013; published 4 September 2013.

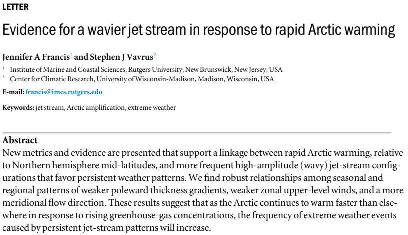
[1] Previous studies have suggested that Arctic amplification has caused planetary-scale waves to elongate meridionally and slow down, resulting in more frequent blocking patterns and extreme weather. Here trends in the meridional extent of atmospheric waves over North America and the North Atlantic are investigated in three reanalyses, and it is demonstrated that previously reported positive trends are likely an artifact of the methodology. No significant decrease in planetary-scale wave phase speeds are found except in October-November-December, but this trend is sensitive to the analysis parameters. Moreover, the frequency of blocking occurrence exhibits no significant

hereafter) suggest that atmospheric
gated meridionally in recent decade
tion. They hypothesize that these el
more slowly and favor more extr
They speculate that as the earth c
amplification will increasingly infl
atmospheric circulation, potentiall
weather in association with the slo
[3] Motivated by these previou
amplification to increased slow-r
patterns, we seek to answer the fo
(1) Have wave extents increased

previously reported trends are likely an artifact of the methodology [. . .] the frequency of blocking occurrence exhibits no significant increase.

Is the flow becoming wavier?

Francis and Vavrus 2015 (*ERL*)



LETTER

Evidence for a wavier jet stream in response to rapid Arctic warming

Jennifer A Francis[1] **and Stephen J Vavrus**[2]

[1] Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey, USA
[2] Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA

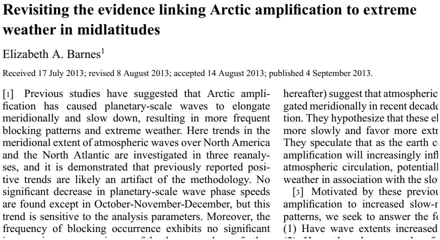
E-mail: francis@imcs.rutgers.edu

Keywords: jet stream, Arctic amplification, extreme weather

Abstract

New metrics and evidence are presented that support a linkage between rapid Arctic warming, relative to Northern hemisphere mid-latitudes, and more frequent high-amplitude (wavy) jet-stream configurations that favor persistent weather patterns. We find robust relationships among seasonal and regional patterns of weaker poleward thickness gradients, weaker zonal upper-level winds, and a more meridional flow direction. These results suggest that as the Arctic continues to warm faster than elsewhere in response to rising greenhouse-gas concentrations, the frequency of extreme weather events caused by persistent jet-stream patterns will increase.

Barnes, 2013 (*GRL*)



Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes

Elizabeth A. Barnes[1]

Received 17 July 2013; revised 8 August 2013; accepted 14 August 2013; published 4 September 2013.

[1] Previous studies have suggested that Arctic amplification has caused planetary-scale waves to elongate meridionally and slow down, resulting in more frequent blocking patterns and extreme weather. Here trends in the meridional extent of atmospheric waves over North America and the North Atlantic are investigated in three reanalyses, and it is demonstrated that previously reported positive trends are likely an artifact of the methodology. No significant decrease in planetary-scale wave phase speeds are found except in October-November-December, but this trend is sensitive to the analysis parameters. Moreover, the frequency of blocking occurrence exhibits no significant

hereafter) suggest that atmospheric
gated meridionally in recent decade
tion. They hypothesize that these el
more slowly and favor more extr
They speculate that as the earth c
amplification will increasingly infl
atmospheric circulation, potentiall
weather in association with the slo

[3] Motivated by these previou
amplification to increased slow-r
patterns, we seek to answer the fo
(1) Have wave extents increased

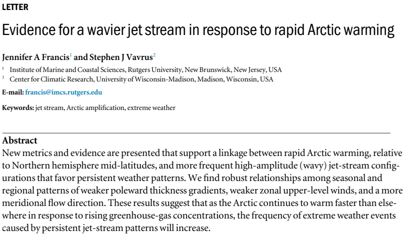
as the Arctic continues to warm faster than elsewhere [. . .] the frequency of extreme weather events caused by persistent jet-stream patterns will increase.

previously reported trends are likely an artifact of the methodology [. . .] the frequency of blocking occurrence exhibits no significant increase.

Is the flow becoming wavier?

Francis and Vavrus 2015 (*ERL*)

Barnes?



LETTER

Evidence for a wavier jet stream in response to rapid Arctic warming

Jennifer A Francis[1] **and Stephen J Vavrus**[2]

[1] Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey, USA
[2] Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA

E-mail: francis@imcs.rutgers.edu

Keywords: jet stream, Arctic amplification, extreme weather

Abstract

New metrics and evidence are presented that support a linkage between rapid Arctic warming, relative to Northern hemisphere mid-latitudes, and more frequent high-amplitude (wavy) jet-stream configurations that favor persistent weather patterns. We find robust relationships among seasonal and regional patterns of weaker poleward thickness gradients, weaker zonal upper-level winds, and a more meridional flow direction. These results suggest that as the Arctic continues to warm faster than elsewhere in response to rising greenhouse-gas concentrations, the frequency of extreme weather events caused by persistent jet-stream patterns will increase.

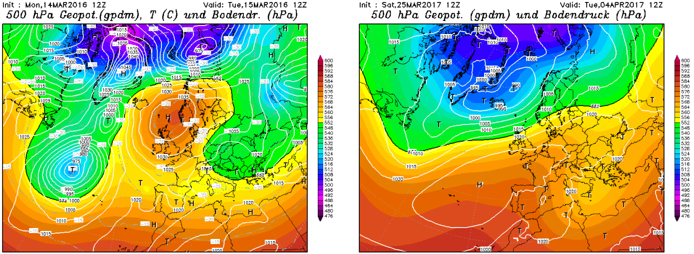
as the Arctic continues to warm faster than elsewhere [. . .] the frequency of extreme weather events caused by persistent jet-stream patterns will increase.

Measuring flow waviness through sinuosity – 1/2

- Sinuosity: length of a trajectory divided by length of the straight line.

Illustrations from Wikipedia.

- Use an iso-contour of Z500 (isohypse) to isolate the trajectory.

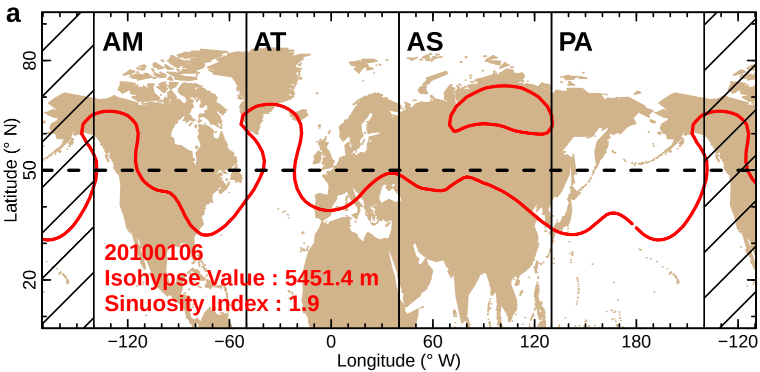


Examples of Z500 for March 15, 2016 and April 4, 2017, © Wetterzentrale.

Measuring flow waviness through sinuosity – 2/2

- Selected isohypse: for each day, the Z500 average over 30–70 °N.

Example of January 6, 2010 (ERAI Z500)

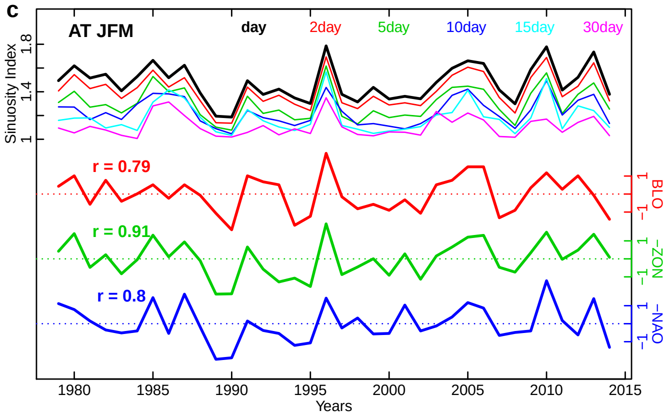


© Cattiaux et al., 2016, *GRL*, Fig. 1.

See also: Martin et al., in review (*J. Clim.*).

Link with more classical indices

- In the North-Atlantic in winter, the sinuosity is highly correlated with blocking[1], zonal[2] and NAO[3] indices at the inter-annual time scale.



© Cattiaux et al., 2016, *GRL*, Fig. 1.

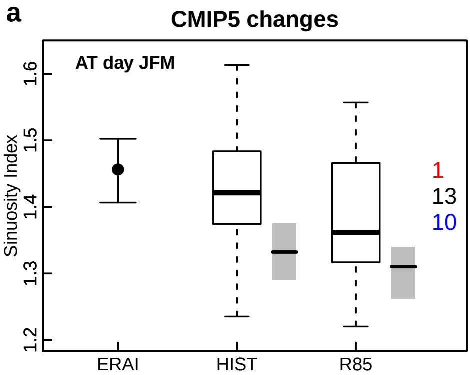
---

[1] Tibaldi and Molteni index computed on ERAI Z500 (link).

[2] ERAI Z500 difference between 20–50 °N and 60–90 °N (Woollings 2008).

[3] Station-based Hurrell index (link).

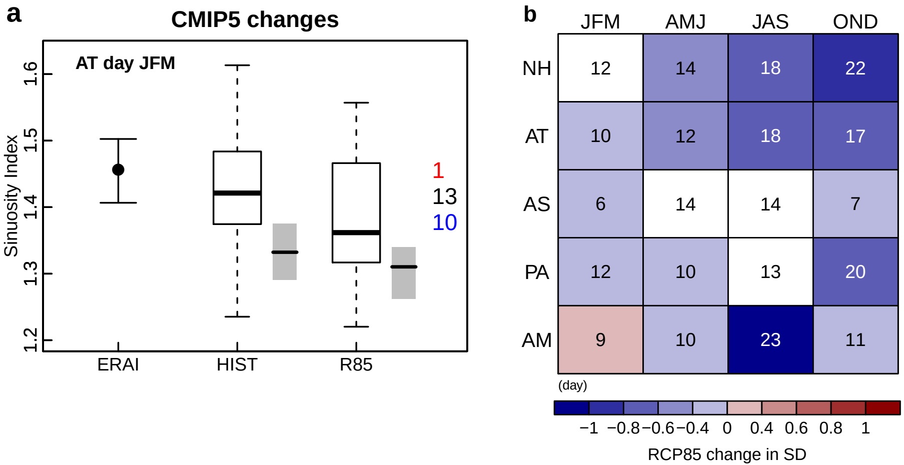
Projected changes in sinuosity



24 CMIP5 models. RCP85 2070–2099 vs HIST 1979–2008. Only 90%-level significant changes.
© Cattiaux et al., 2016, *GRL*, Fig. 3.

See also: Peings et al., in review (*J. Clim.*); Vavrus et al. 2017 (*J. Clim.*).

Projected changes in sinuosity



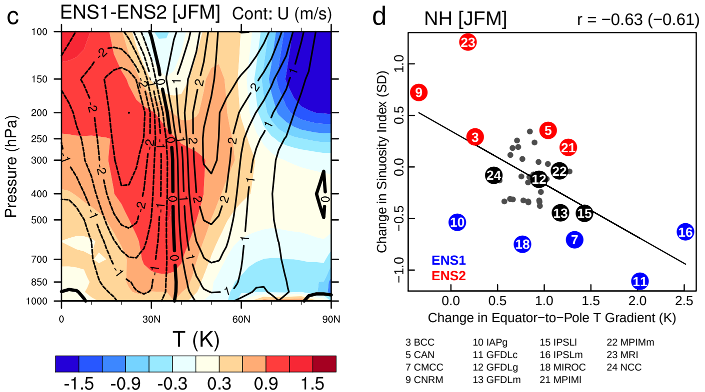
	JFM	AMJ	JAS	OND
NH	12	14	18	22
AT	10	12	18	17
AS	6	14	14	7
PA	12	10	13	20
AM	9	10	23	11

24 CMIP5 models. RCP85 2070–2099 vs HIST 1979–2008. Only 90%-level significant changes.
© Cattiaux et al., 2016, *GRL*, Fig. 3.

See also: Peings et al., in review (*J. Clim.*); Vavrus et al. 2017 (*J. Clim.*).

Why does the sinuosity decrease? – Stats

- Models with stronger sinuosity decrease (ENS1) have stronger tropical warming, stronger polar-stratospheric cooling and weaker Arctic Amplification, i.e. a stronger increase in the equator-to-pole T gradient.



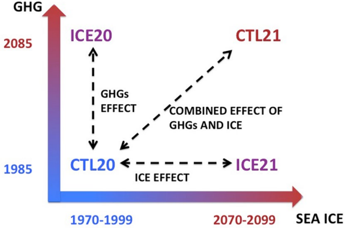
c Difference ENS1−ENS2 of ΔT (colors) and ΔU (contours). **d** Scatter plot ΔSIN vs. ΔGrad(T). Δ = RCP85 − HIST. Grad(T) = T[0–55N] − T[55–90N] (vertically averaged).

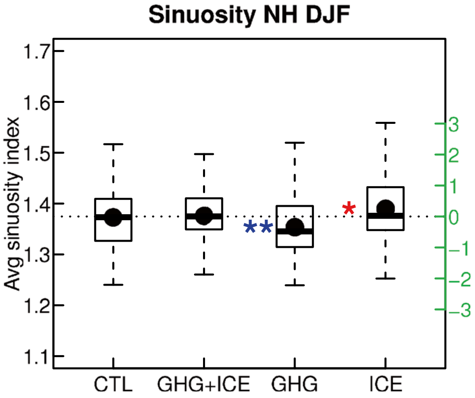
© Cattiaux et al., 2016, *GRL*, Fig.4.

Why does the sinuosity decrease? – Model exps

⟶ CNRM-CM coupled runs with PRE/FUT sea ice in PRE/FUT GHG conditions.

- Competing effects of GHG (tropical warming) and sea-ice (AA).



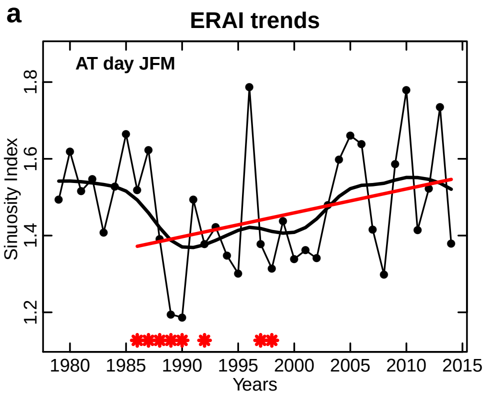


100-year (DJF) boxplots. 90% (∗) and 95% (∗∗) -level significant positive ou negative differences.
© Oudar et al., 2017, *Clim. Dyn.*, Figs 2 and 11.

Recent trends in sinuosity

- Slight increase in sinuosity since the mid-1980s.

Internal variability or different timings of the sinuosity forcings?

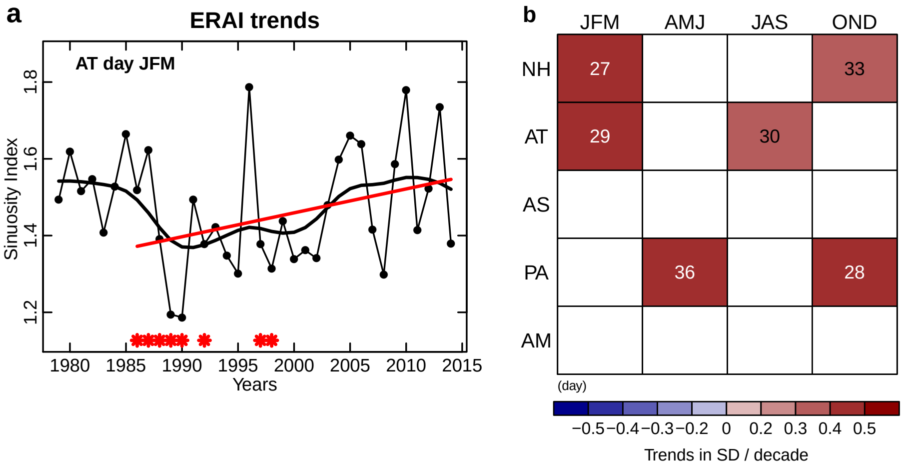


ERAI 1979–2014. Only >20yr & 90%-level significant trends.
© Cattiaux et al., 2016, *GRL*, Fig. 2.

Recent trends in sinuosity

- Slight increase in sinuosity since the mid-1980s.

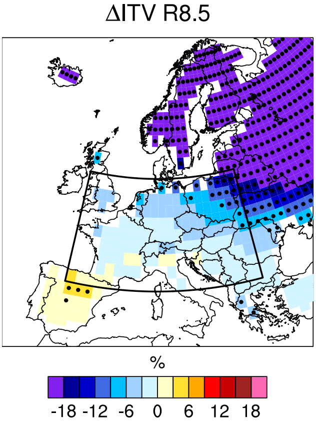
Internal variability or different timings of the sinuosity forcings?

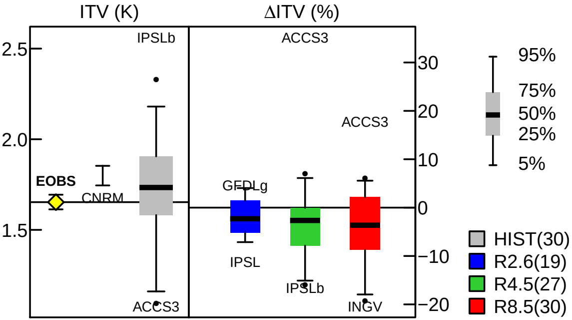


ERAI 1979–2014. Only >20yr & 90%-level significant trends.
© Cattiaux et al., 2016, *GRL*, Fig. 2.

Back to the European temperature variability

- Projected decrease in ITV, albeit no model agreement over WEU.
- Reduced efficiency of the advection from both westerlies (land/sea contrast) and easterlies (snow cover decline).



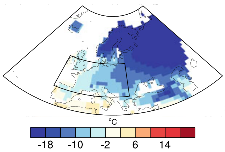


E-OBS & CMIP5 ensemble. JJAS 2070–2099 vs. 1979–2008.

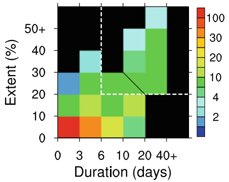
Consequence for cold spells

- When using a fixed threshold (present-day Q10), decrease in frequency.
- When using a relative threshold (future Q10), decrease in severity.

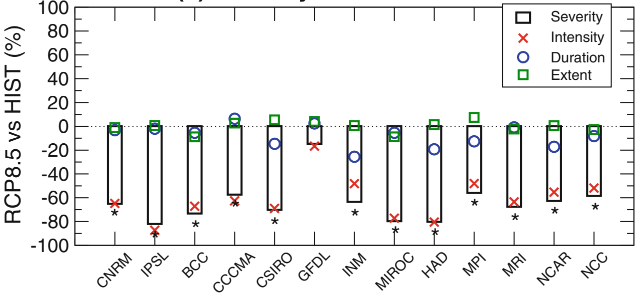
(a) QU10 in EOBS



(b) Coldevents in EOBS



(c) Severity in RCP8.5 w/ Q10F



Similar methodology as for heat waves.
© Peings et al., 2012, *Clim. Dyn.*, Figs 1 and 5.

See also: De Vries et al. 2012 (*GRL*).

Outline

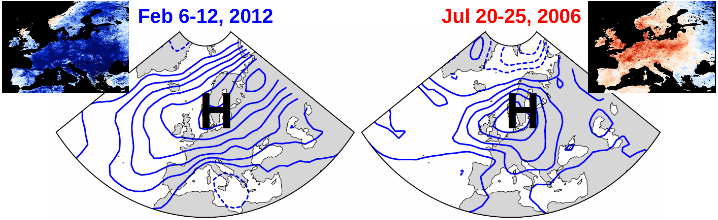
Summer variability

Winter variability

Seasonal clock

Context

- W-European T extremes are associated with persistent H systems (*blockings*).
  Cassou et al. 2005, Schneidereit et al. 2012, Sillmann et al. 2012...

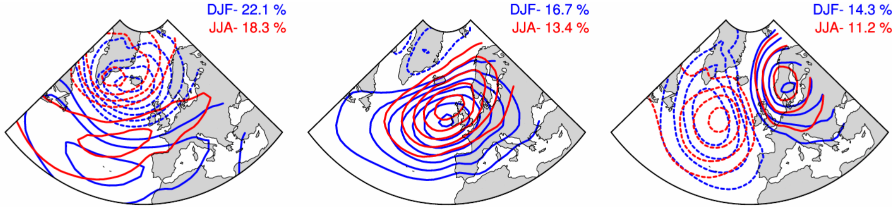


SLP anomaly of cold spell Feb 2012 & heat wave July 2006

© Cassou and Cattiaux, 2016, *Nature Climate Change*.

Context

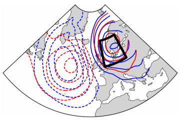
- W-European T extremes are associated with persistent H systems (*blockings*).
  Cassou et al. 2005, Schneidereit et al. 2012, Sillmann et al. 2012...
- The Scandinavian blocking is a recurrent pattern throughout the year (EOF 3).
  Barnston & Livezey 1987, Wettstein & Wallace 2010...

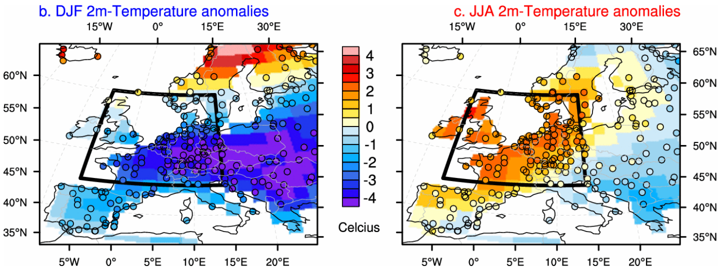


EOF 1, 2 & 3 of daily SLP anomalies | NCEP-NCAR reanalysis 1950–2012

Context

- W-European T extremes are associated with persistent H systems (*blockings*).
  Cassou et al. 2005, Schneidereit et al. 2012, Sillmann et al. 2012...
- The Scandinavian blocking is a recurrent pattern throughout the year (EOF 3).
  Barnston & Livezey 1987, Wettstein & Wallace 2010...
- It blocks the westerlies and induces cold episodes in winter / warm in summer.
  Rex 1950, Slonosky et al. 2001...



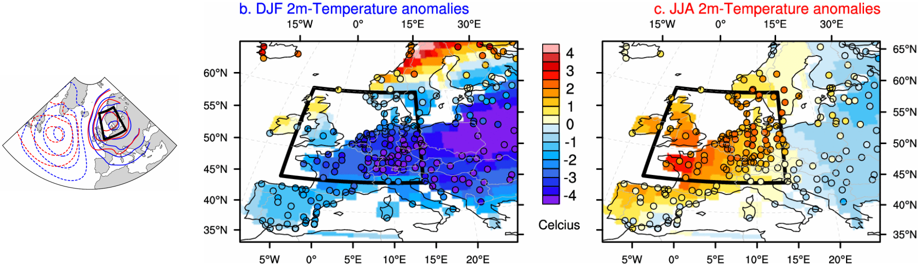


Composites of daily T anomalies over days with SLP index $> 1\sigma$
NCEP-NCAR reanalysis + ECA&D stations 1950–2012

© Cassou and Cattiaux, 2016, *Nature Climate Change*.

Context

- W-European T extremes are associated with persistent H systems (*blockings*).
  Cassou et al. 2005, Schneidereit et al. 2012, Sillmann et al. 2012...
- The Scandinavian blocking is a recurrent pattern throughout the year (EOF 3).
  Barnston & Livezey 1987, Wettstein & Wallace 2010...
- It blocks the westerlies and induces cold episodes in winter / warm in summer.
  Rex 1950, Slonosky et al. 2001...
- This season-dependent SLP-T relationship is well captured by climate models.

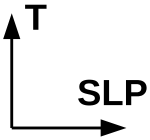


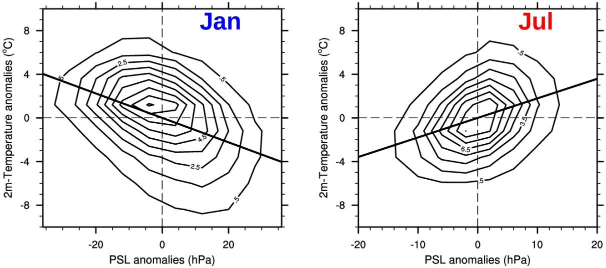
Composites of daily T anomalies over days with SLP index $> 1\sigma$
CNRM-CM5 historical simulation + ECA&D stations 1950–2012

© Cassou and Cattiaux, 2016, *Nature Climate Change*.

Context

- W-European T extremes are associated with persistent H systems (*blockings*).
  Cassou et al. 2005, Schneidereit et al. 2012, Sillmann et al. 2012...
- The Scandinavian blocking is a recurrent pattern throughout the year (EOF 3).
  Barnston & Livezey 1987, Wettstein & Wallace 2010...
- It blocks the westerlies and induces cold episodes in winter / warm in summer.
  Rex 1950, Slonosky et al. 2001...
- This season-dependent SLP-T relationship is well captured by climate models.
- The SLP-T regression is -1.4K/10hPa in January & 2.0K/10hPa in July.

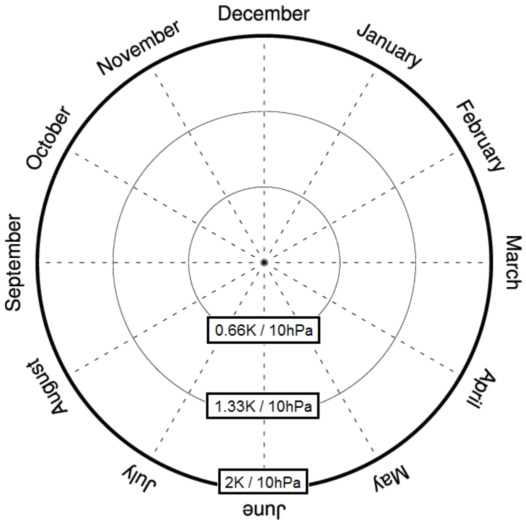


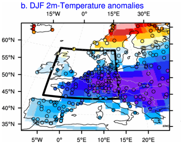


Daily T index vs. daily SLP index (illustrations)

© Cassou and Cattiaux, 2016, *Nature Climate Change*.

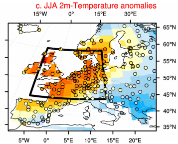
The European climate seasonal clock





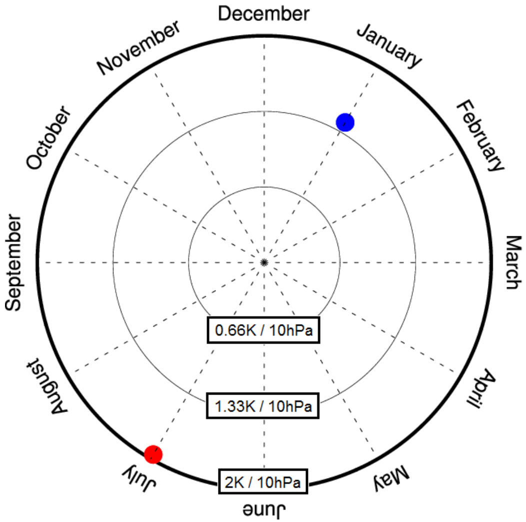
January
SLP-T regression:
−1.4K/10hPa

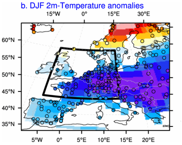
July
SLP-T regression:
2.0K/10hPa



© Cassou and Cattiaux, 2016, *Nature Climate Change*.

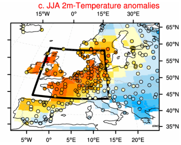
The European climate seasonal clock




b. DJF 2m-Temperature anomalies

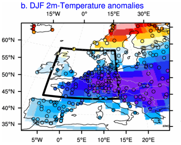
January
SLP-T regression:
-1.4K/10hPa

July
SLP-T regression:
2.0K/10hPa


c. JJA 2m-Temperature anomalies

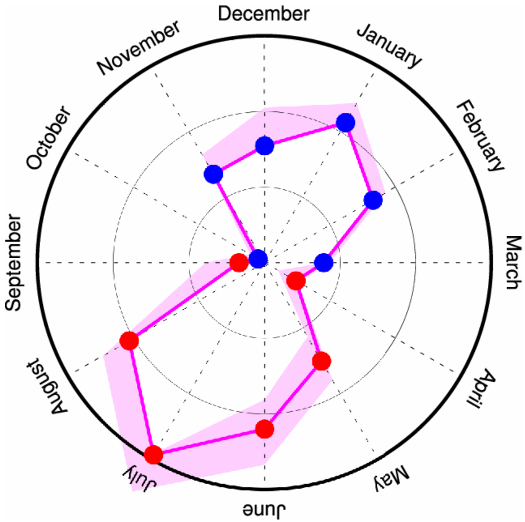
© Cassou and Cattiaux, 2016, *Nature Climate Change*.

The European climate seasonal clock

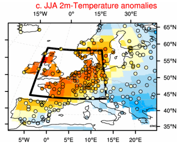


b. DJF 2m-Temperature anomalies

January
SLP-T regression:
-1.4K/10hPa



July
SLP-T regression:
2.0K/10hPa

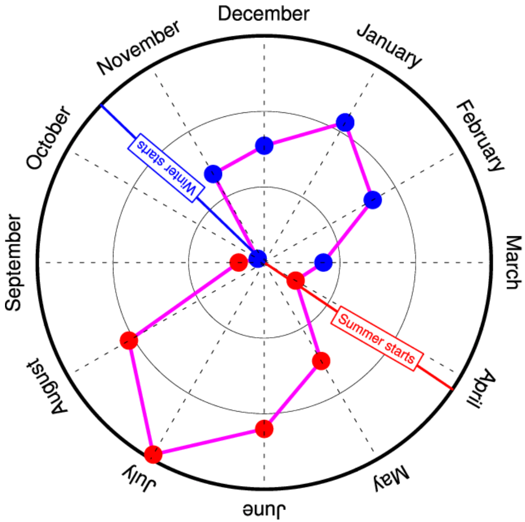


c. JJA 2m-Temperature anomalies

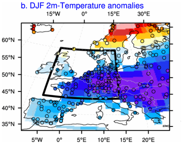
Obs. estimates (20CR/NCEP/ECA&D | 1950–2010)

© Cassou and Cattiaux, 2016, *Nature Climate Change*.

The European climate seasonal clock

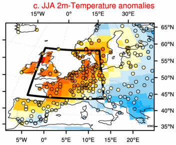


Obs. estimates (20CR/NCEP/ECA&D | 1950–2010)

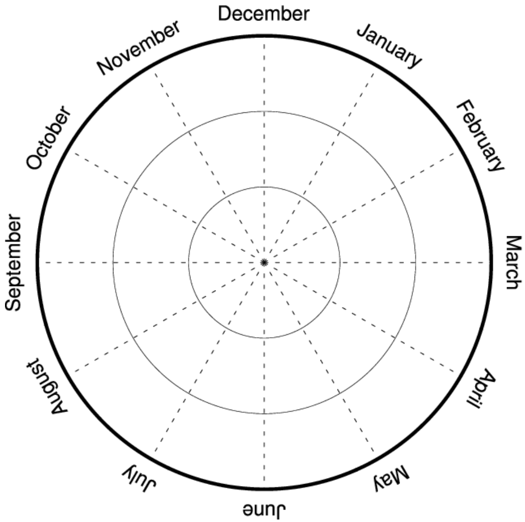


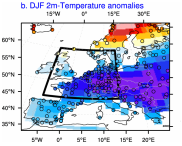
January
SLP-T regression:
−1.4K/10hPa

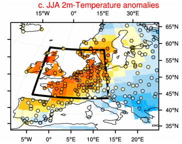
July
SLP-T regression:
2.0K/10hPa



The seasonal clock in a warmer world

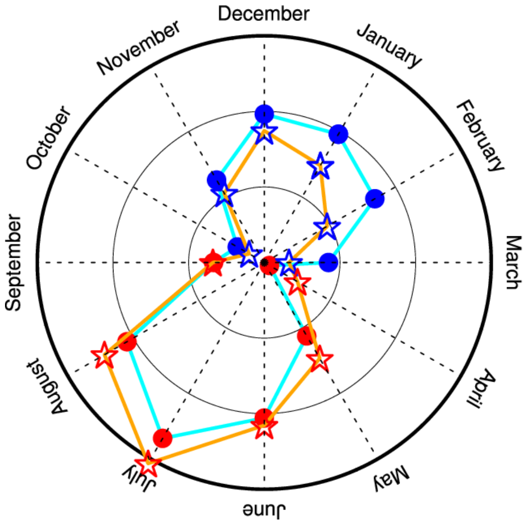



b. DJF 2m-Temperature anomalies


c. JJA 2m-Temperature anomalies

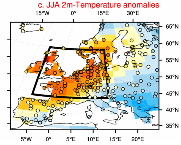
© Cassou and Cattiaux, 2016, *Nature Climate Change*.

The seasonal clock in a warmer world

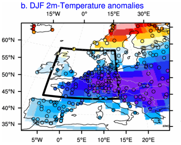


CNRM-CM5 piControl (1000 yrs)
CNRM-CM5 rcp85 (5 members 2070–2100)

The regression increases in summer ($\sigma \nearrow$).



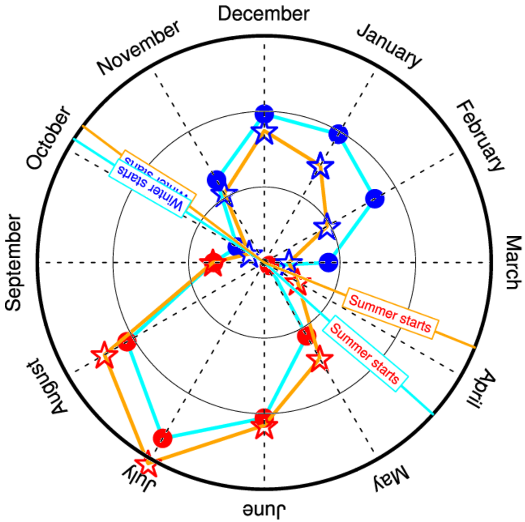
The regression decreases in winter ($\sigma \searrow$).



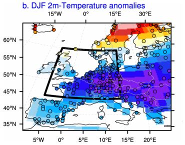
© Cassou and Cattiaux, 2016, *Nature Climate Change*.

The seasonal clock in a warmer world

The winter onset is slightly delayed.

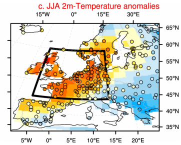


CNRM-CM5 piControl (1000 yrs)
CNRM-CM5 rcp85 (5 members 2070–2100)



The regression decreases in winter ($\sigma \searrow$).

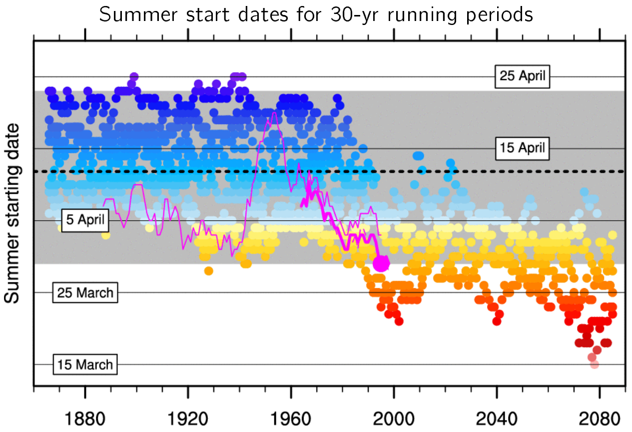
The regression increases in summer ($\sigma \nearrow$).



The summer starts ∼25 days earlier.

Earlier summertime weather conditions

- Detectable trend of ~ -2.5 days/decade since the 1960s.
- Attributed to NEU snow cover decline induced by ANT forcing (not shown).



Obs. estimates (NCEP 1948–2014 | 20CR 1870–2012)
CNRM-CM5 piControl 90%-level C.I from 1000 random 30-yr periods
CNRM-CM5 historical+rcp85 (10 members 1850–2005 | 5 members 2006–2100)

© Cassou and Cattiaux, 2016, *Nature Climate Change*.

Summary

So far.

Europe is projected to warm, with distinct summer/winter patterns.

Summer T variability is projected to increase in line with the soil drying.

Winter T variability is projected to decrease in line with the snow retreat.

Summertime conditions are projected to occur earlier in the year.

Projected changes in the atmospheric dynamics are uncertain, and recently observed trends might result from internal variability.

Next?

Reduce uncertainties in future projections through emergent constraints.

Generalize the day-to-day index both spatially (global scale) and temporally (week-to-week, month-to-month, year-to-year, etc.).

Investigate changes in the persistence of the mid-latitude flow, rather than in its trajectory (e.g. Yiou et al., in prep, using flow-analogues).

Non-exhaustive and highly-biased list of references

European warming

Cattiaux, J., H. Douville, and Y. Peings (2013), European temperatures in CMIP5 : origins of present-day biases and future uncertainties, *Climate Dynamics*, 41 (11-12), 2889-2907.

Summer variability

Cattiaux, J., H. Douville, R. Schoetter, S. Parey and P. Yiou (2015), Projected increase in diurnal and inter-diurnal variations of European summer temperatures, *Geophysical Research Letters*, 42(3), 899-907.

Douville, H., J. Colin, E. Krug, J. Cattiaux and S. Thao (2016), Mid-latitude daily summer temperatures reshaped by soil moisture under climate change, *Geophysical Research Letters*, 43(2), 812-818.

Schoetter, R., J. Cattiaux and H. Douville (2015), Changes of western European heat wave characteristics projected by the CMIP5 ensemble, *Climate Dynamics*, 45(5), 1601-1616.

Winter variability

Cattiaux, J., and C. Cassou (2013), Opposite CMIP3/5 trends in the Northern Annular Mode explained by combined local sea-ice and remote tropical influences, *Geophysical Research Letters*, 40 (14), 3682-3687.

Cattiaux, J., Y. Peings, D. Saint-Martin, N. Trou-Kechout and S.J. Vavrus (2016), Sinuosity of mid-latitude atmospheric flow in a warming world, *Geophysical Research Letters*, 43, 8259-8268.

Oudar, T., E. Sanchez-Gomez, F. Chauvin, J. Cattiaux, C. Cassou and L. Terray (2017), Respective effects of Arctic sea ice loss and GHGs increase on the Northern Hemisphere atmospheric circulation, *Climate Dynamics*, in press.

Peings, Y., J. Cattiaux and H. Douville (2013), Evaluation and response of cold spells over Western Europe in CMIP5 models, *Climate Dynamics*, 41 (11-12), 3025-3037.

Seasonal clock

Cassou, C. and J. Cattiaux (2016), Disruption of the European climate seasonal clock in a warming world, *Nature Climate Change*, 6, 589-594.