North-Atlantic atmospheric dynamics and climate change

Julien Cattiaux[1]

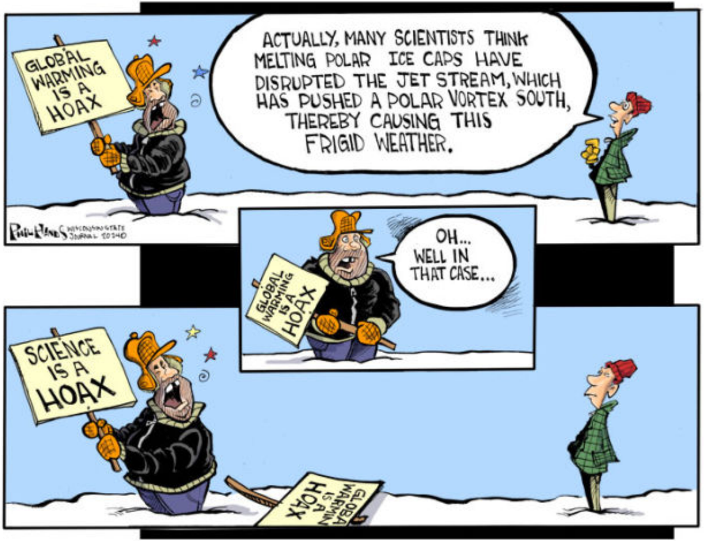
with Christophe Cassou[2], Francis Codron[3], Hervé Douville[1], Gaëlle Ouzeau[1], Yannick Peings[1,4], Aurélien Ribes[1], David Saint-Martin[1], Sophie Tyteca[1], Robert Vautard[5] and Pascal Yiou[5].

Thanks to Libby Barnes[6], Jennifer Francis[7], Steve Vavrus[8] and Fuyao Wang[8] for sharing slides.

1 – CNRM-GAME, UMR CNRS/Météo-France, Toulouse, France. 2 – CNRS/CERFACS, Toulouse, France. 3 – LMD (IPSL), UMR CNRS/ENS/UPMC/X, Paris, France. 4 – University of California, Irvine, US. 5 – LSCE (IPSL), UMR CNRS/CEA/UVSQ, Gif-sur-Yvette, France. 6 – Colorado State University, US. 7 – Institute of Coastal and Marine Sciences, Rutgers University, US. 8 – University of Wisconsin, Madison, US.

Ateliers de Modélisation de l'Atmosphère
Atelier LEFE-IMAGO
Toulouse, Jan 21, 2015

Midlatitude cold weather and global warming



Why would the climate change affect the dynamics?

- The midlatitude dynamics is driven by the equator-to-pole T gradient...

Why would the climate change affect the dynamics?

- The midlatitude dynamics is driven by the equator-to-pole T gradient. . .
- . . . which is modified by climate change, differently at surface and aloft.

Why would the climate change affect the dynamics?

- The midlatitude dynamics is driven by the equator-to-pole T gradient...
- ... which is modified by climate change, differently at surface and aloft.

$\longrightarrow$ So how does the midlatitude dynamics respond?

Why would the climate change affect the dynamics?

- The midlatitude dynamics is driven by the equator-to-pole T gradient…
- … which is modified by climate change, differently at surface and aloft.

⟶ So how does the midlatitude dynamics respond?

Large-Scale Dynamics and Global Warming

Isaac M. Held
Geophysical Fluid Dynamics Laboratory/ NOAA, Princeton University, Princeton, New Jersey

Abstract

Predictions of future climate change raise a variety of issues in large-scale atmospheric and oceanic dynamics. Several of these are reviewed in this essay, including the sensitivity of the circulation of the Atlantic Ocean to increasing freshwater input at high latitudes; the possibility of greenhouse cooling in the southern oceans; the sensitivity of monsoonal circulations to differential warming of the two hemispheres; the response of midlatitude storms to changing temperature gradients and increasing water vapor in the atmosphere; and the possible importance of positive feedback between the mean winds and eddy-induced heating in the polar stratosphere.

Held, 1993, *BAMS*.

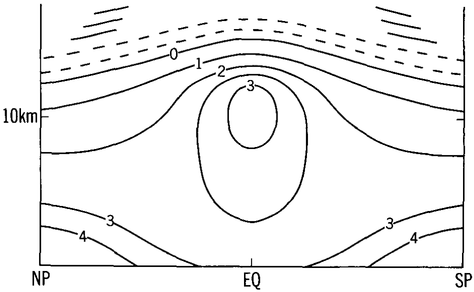


FIG. 6. A schematic of the equilibrium annual mean temperature response to a doubling of CO_2, as typically predicted by GCMs, emphasizing the maxima at upper-tropospheric levels in the tropics and at low levels in the polar regions. Polar amplification is present only in winter.

Why would the climate change affect the dynamics?

- The midlatitude dynamics is driven by the equator-to-pole T gradient. . .
- . . . which is modified by climate change, differently at surface and aloft.

$\longrightarrow$ So how does the midlatitude dynamics respond?

Large-Scale Dynamics and Global Warming

Isaac M. Held
Geophysical Fluid Dynamics Laboratory/ NOAA, Princeton University, Princeton, New Jersey

Abstract

Predictions of future climate change raise a variety of issues in large-scale atmospheric and oceanic dynamics. Several of these are reviewed in this essay, including the sensitivity of the circulation of the Atlantic Ocean to increasing freshwater input at high latitudes; the possibility of greenhouse cooling in the southern oceans; the sensitivity of monsoonal circulations to differential warming of the two hemispheres; the response of midlatitude storms to changing temperature gradients and increasing water vapor in the atmosphere; and the possible importance of positive feedback between the mean winds and eddy-induced heating in the polar stratosphere.

The dominant wintertime baroclinic eddies are coherent through the depth of the troposphere in midlatitudes. As a result, it is unclear whether the eddies would respond primarily to the decrease in lower-tropospheric temperature gradient or the increase in the upper-tropospheric gradient. (In the

Held, 1993, *BAMS*.

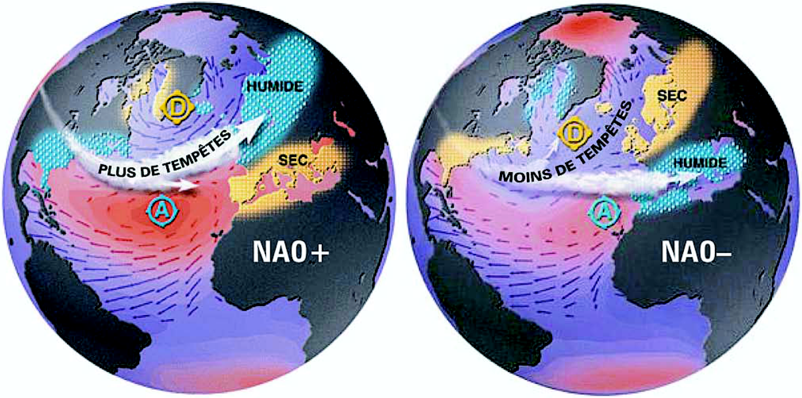
Contents

Contents

The North Atlantic Oscillation (NAO)

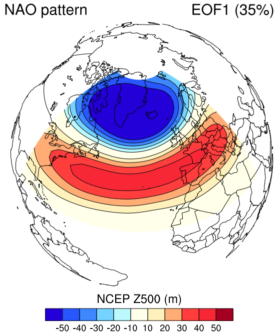
- First mode of variability, linked to fluctuations in the jet stream.

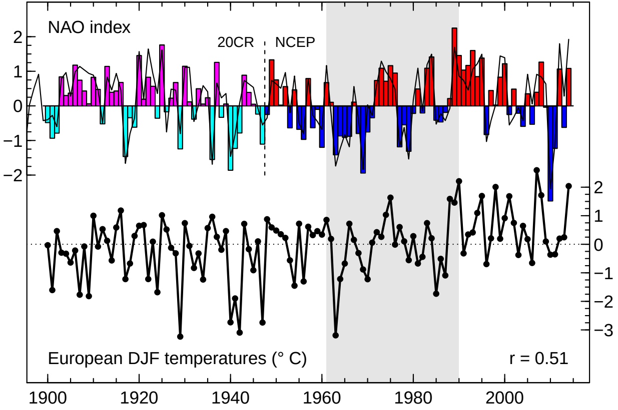
Van Loon & Rogers (1978), Jones et al. (1998), Hurrell (2003), Osborn (2005), among others.



NAO indices and European temperatures

- Indices based on stations or PCA of circulation variables (here Z500).
- Explains ~25 % of variance of European DJF temperatures.





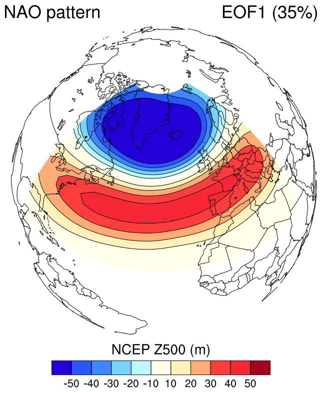
Z500 20CR & NCEP (EOF 1979–2008) + T HadCRUT4.

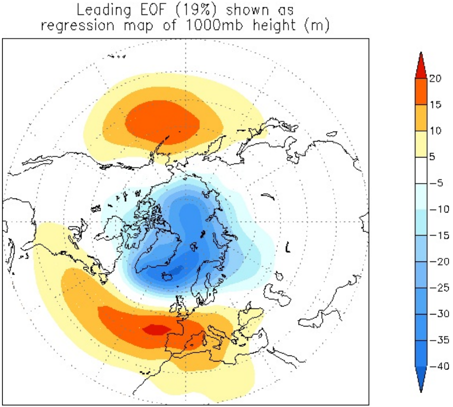
An endless debate

- Is the NAO the regional signature of the NAM/AO...

  ... or is the NAM/AO an hemispheric artefact of the NAO?

  e.g. Ambaum et al. (2001).



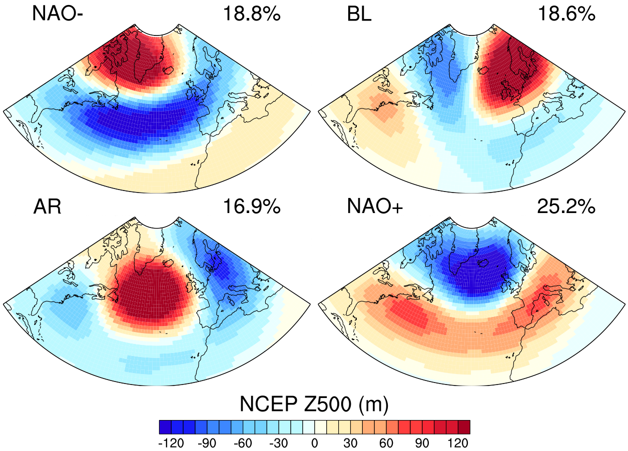


Left: Z500 NCEP 1979–2008 | Right: NCEP website.

Beyond the NAO: the weather regimes

- Recurrent patterns derived from Z500 clustering (here *k-means*).

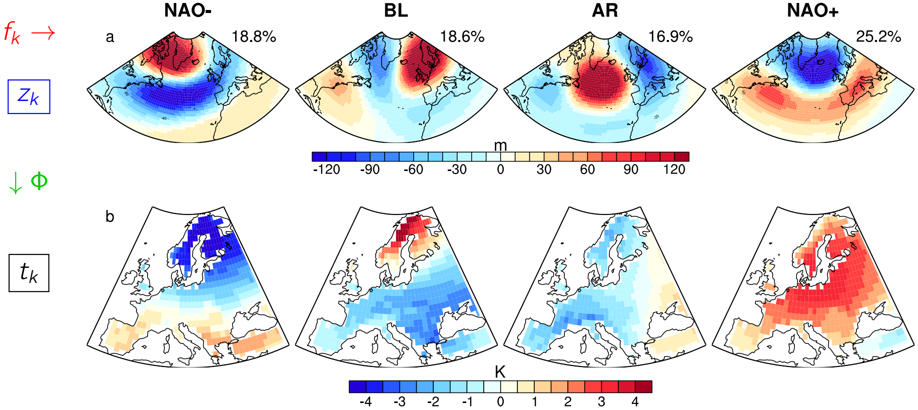
Legras & Ghil (1985), Vautard (1990), Michelangeli et al. (1995), Cassou (2008).



Z500 NCEP2 (DJFM 1979–2008) | Cattiaux et al., 2013a, *Clim. Dyn.*

WRs and European temperatures 1/2

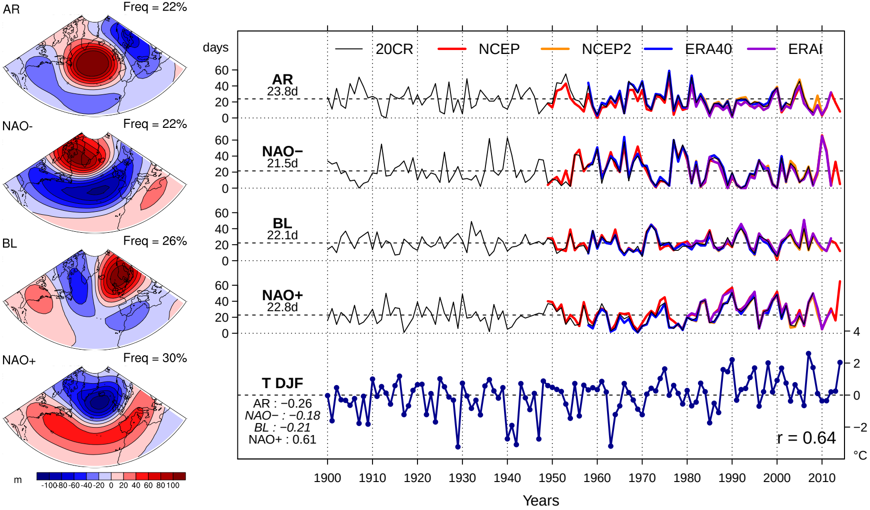
- Temperature composites: $\overline{T} = \sum_k f_k \cdot t_k = \sum_k f_k \cdot \Phi(z_k)$.



Z500 NCEP2 & T EOBS (DJFM 1979–2008) | Cattiaux et al., 2013, *Clim. Dyn.*

WRs and European temperatures 2/2

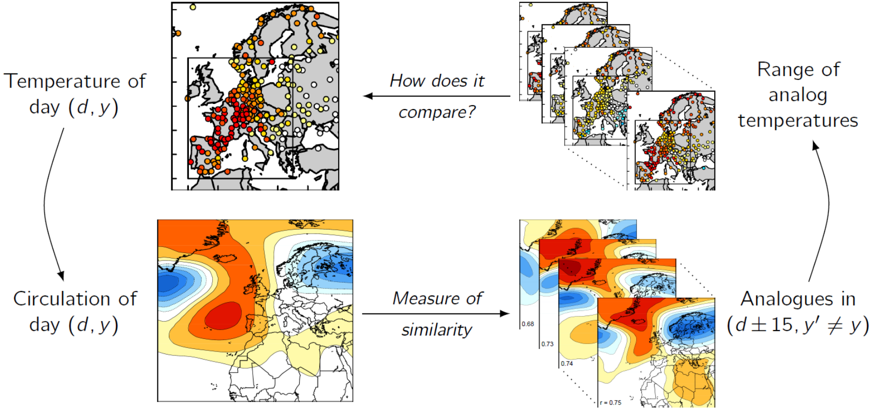
- Explain ∼40 % of variance of European DJF temperatures.



Z500 (5 reanalyses) & T HadCRUT4 | Updated from Ouzeau et al., 2012, *GRL*.

Flow-analogues: the concept

- Search for analog synoptic situations in other years (e.g., the past).
- Possibly look at an associated variable (here European temperatures).



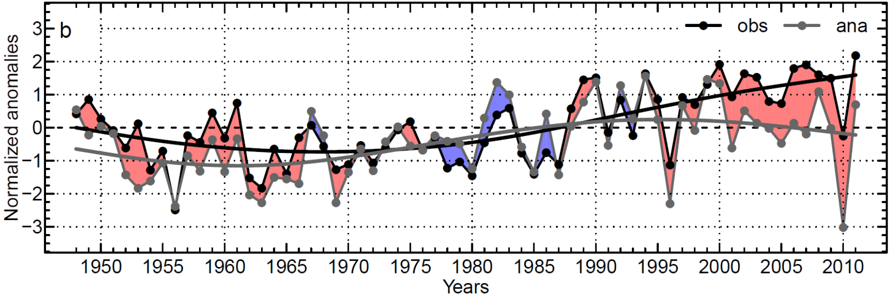
Method from Lorenz, 1969, *J. Atm. Sci.*

Flow-analogues and European temperatures

- Explain ∼70 % of variance of European DJF temperatures.

See also Cattiaux et al. (2010), Vautard & Yiou (2009), among others.

Yearly temperature anomalies over Europe ($r = 0.75$) ($r = 0.85$ for DJF).



Z500 NCEP & T ECA&D | Cattiaux and Yiou, 2012, *BAMS*.

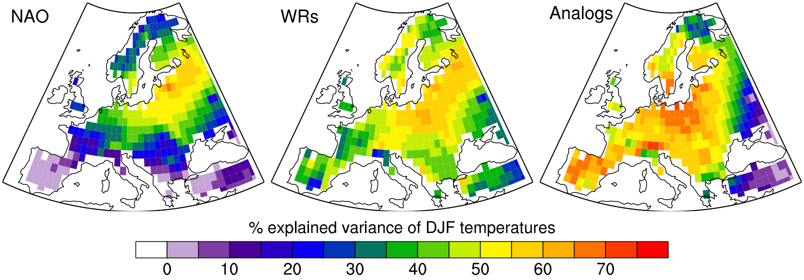
Methods: summary

- Different ways to describe the NA atmospheric dynamics in climate studies.

NAO/NAM indices, weather regimes, flow-analogues.
But also blocking metrics, jet stream metrics, storm tracks metrics, self-organizing maps etc.

- Description depends on the focus.

Example of the link with European temperatures.



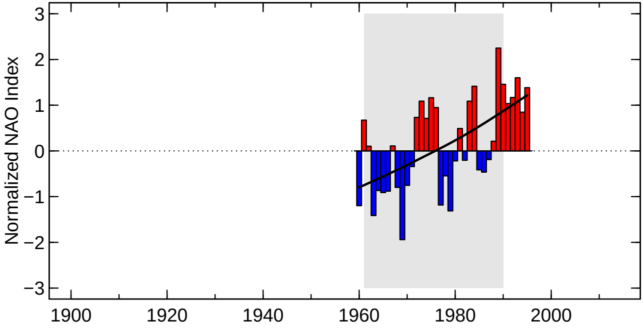
Z500 NCEP & T EOBS – Estimated over 1979–2008.

Contents

Observed trends in the NAM/NAO

- 2000s: climate change projects onto NAO+.

Corti et al. (1999), Gillett et al. (2003), Hsu & Zwiers (2001), Palmer (1999).



Z500 NCEP 1960–1995.

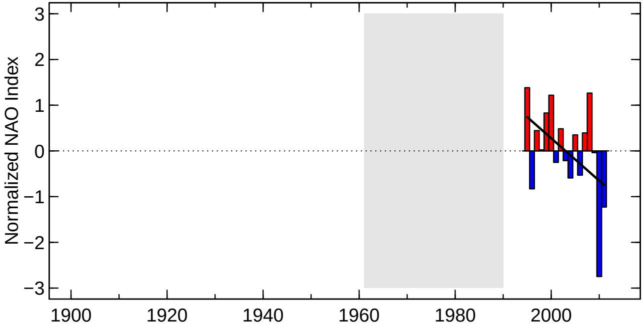
Observed trends in the NAM/NAO

- 2000s: climate change projects onto NAO+.

Corti et al. (1999), Gillett et al. (2003), Hsu & Zwiers (2001), Palmer (1999).

- 2010s: Arctic amplification forces NAM−.

Cohen et al. (2012), Francis & Vavrus (2012), Overland et al. (2011). See review by Cohen et al. (2014).



Z500 NCEP 1995–2011.

Observed trends in the NAM/NAO

- 2000s: climate change projects onto NAO+.

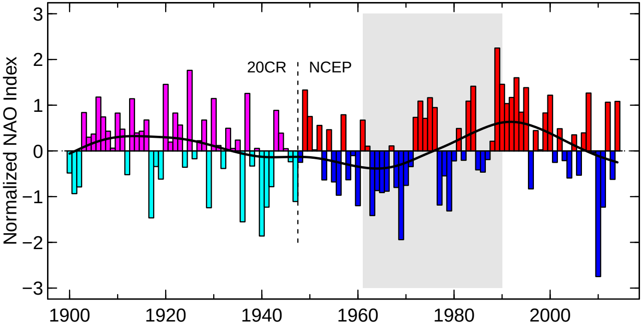
Corti et al. (1999), Gillett et al. (2003), Hsu & Zwiers (2001), Palmer (1999).

- 2010s: Arctic amplification forces NAM−.

Cohen et al. (2012), Francis & Vavrus (2012), Overland et al. (2011). See review by Cohen et al. (2014).

- Well, could it just be decadal internal variability?

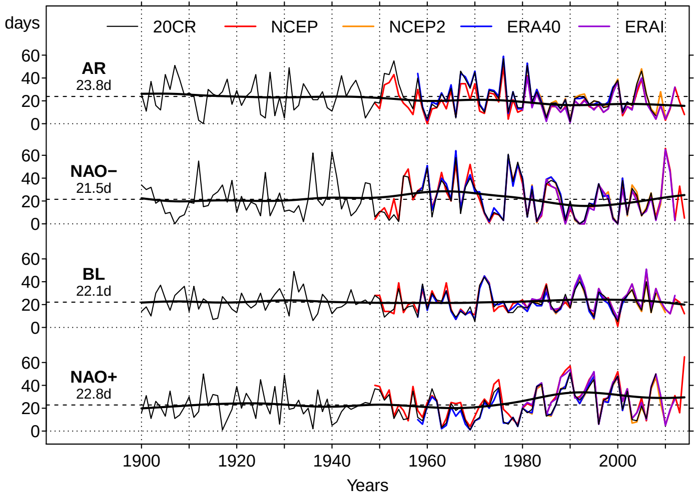
Barnes et al. (2013), Screen and Simmonds (2013), Woollings et al. (2014).



Z500 NCEP + 20CR 1900–2014.

Trends in the frequencies of the WRs

- 1900–2014: decrease in AR & increase in NAO+ (∼1 day/decade, p-value∼1%).
- 1975–2014 (satellite era): nothing significant.



Z500 (5 reanalyses). Updated from Ouzeau et al., 2012, *GRL*.

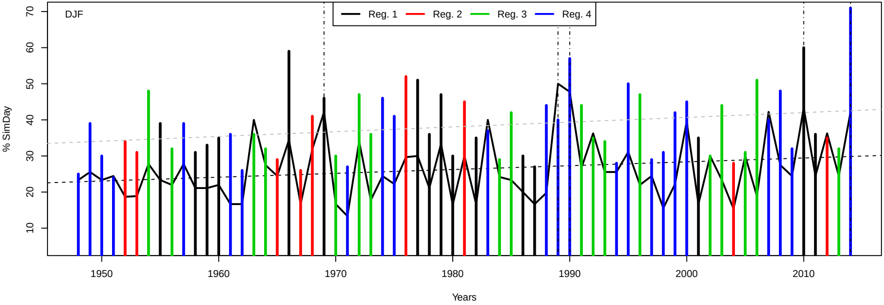
Trends in the recurrence of weather patterns?

- Increase in the recurrence of the dominant WR.

Vertical bars: NAO+ NAO− BL or AR).

- Increase in the maximal number of *friends*.

Based on intra-seasonal flow-analogues, solid line.



SLP NCEP | EXTREMOSCOPE project | Figure by P. Yiou.

More persistent patterns? More blockings? The debate

Francis & 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; *Petoul* *Deser et al.*, 2010; *Alexander et* 2012; *Blüthgen et al.*, 2012]. Wh greenhouse-gas-induced tropospher increase in atmospheric water conte

"*weather patterns in midlatitudes more persistent [...] increased probability of extreme weather events that result from prolonged conditions.*"

More persistent patterns? More blockings? The debate

Francis & 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; *Petoul* *Deser et al.*, 2010; *Alexander et* 2012; *Blüthgen et al.*, 2012]. Wh greenhouse-gas-induced tropospher increase in atmospheric water conte

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

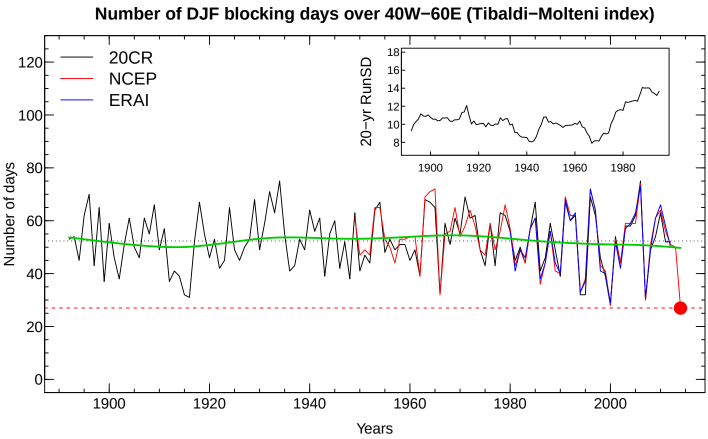
[3] Motivated by these previou amplification to increased slow-r patterns, we seek to answer the fo (1) Have wave extents increased

"*weather patterns in midlatitudes more persistent [. . .] increased probability of extreme weather events that result from prolonged conditions.*"

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

More persistent patterns? More blockings? A simple index

- No significant trend over the NA sector.
- Internal variability is large. See also Barnes et al. (2014), Perlwitz et al. (in review).



Z500 (3 reanalyses) | EXTREMOSCOPE project | Figure by J. Cattiaux.

More amplified patterns? A wavier jet stream?

- Francis & Vavrus, 2015, *ERL* (the return): new metrics.

Atmospheric thickness, meridional circulation index, high-amplitude patterns.

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 config-

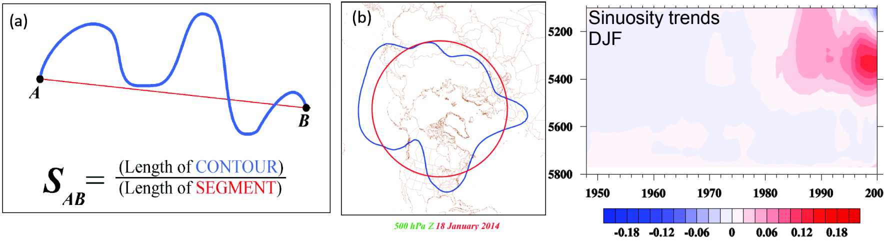
"*These results suggest that as the Arctic continues to warm faster than elsewhere in response to rising GHG concentrations, the frequency of extreme weather events caused by persistent jet-stream patterns will increase.*"

More amplified patterns? A wavier jet stream?

- Francis & Vavrus, 2015, *ERL* (the return): new metrics.

Atmospheric thickness, meridional circulation index, high-amplitude patterns.

- Wang et al. (in prep): increase in the *sinuosity* (Z500 contours).



Z500 NCEP | Figure by F. Wang and S. Vavrus.

Observed trends: summary

- Hard to find significant trends.

Classical statistical test issue.
Weak signal-to-noise ratio due to internal variability.
Short observational records.

- A significant trend is not necessarily a climate change signal.

Detection and attribution issue.
Internal variability also at decadal time scale.
Incomplete mechanistic understanding.

- Two different issues with two different null hypotheses.

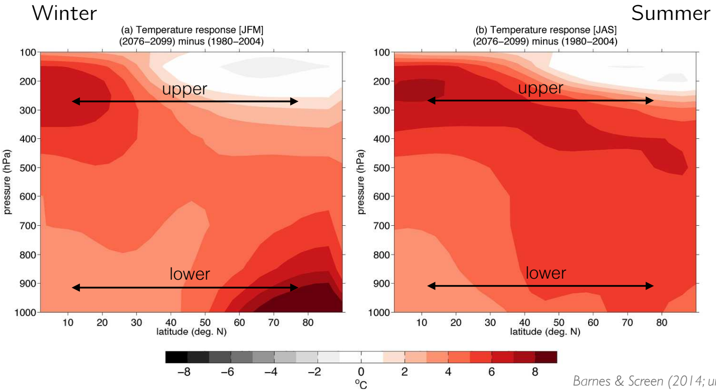
$\longrightarrow$ What signal are we looking for, by the way? What do models say?

Contents

What can we expect?

- Tropospheric warming: opposite surface/aloft effects on the T gradient.

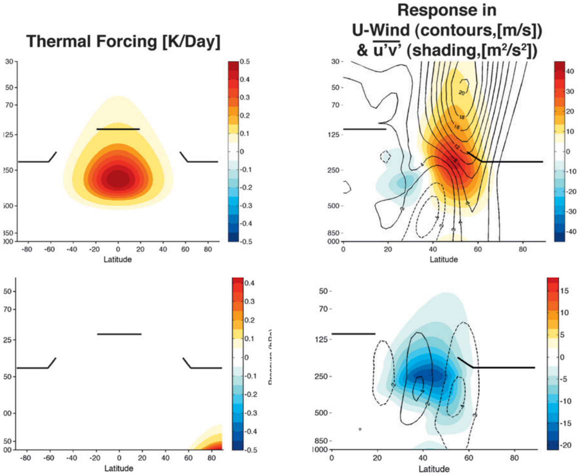
Example of CMIP5 RCP8.5



Barnes & Screen (2014; under review)

What can we expect?

- Tropospheric warming: opposite surface/aloft effects on the T gradient.
- Idealized GCM exps: opposite responses to tropical and polar forcings.



Here, tropics win.
⟶ But in CMIP?

Butler et al., 2010, *J. Clim.*

Can CMIP models represent the NA dynamics?

Can CMIP models represent the NA dynamics?

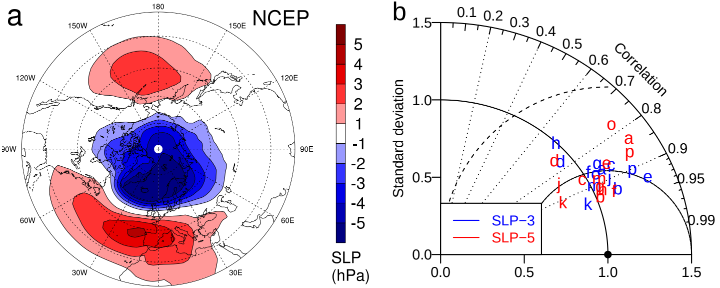
- Short answer: yes, remember they are GCMs!

Can CMIP models represent the NA dynamics?

- Short answer: yes, remember they are GCMs!

- Longer answer: they have well known biases (e.g., too zonal jets, blockings deficits) but simulate many of the relevant processes reasonably well.

Example of the NAM pattern:

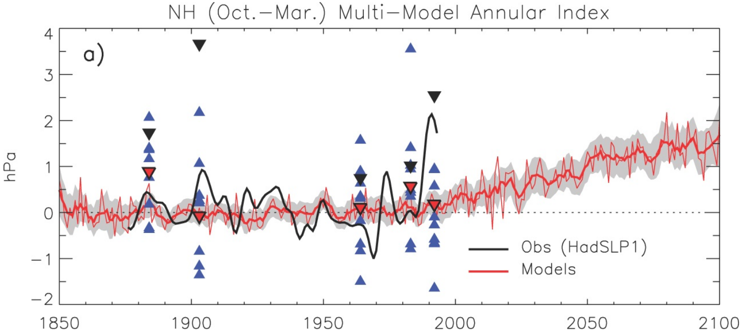


EOF1 SLP NCEP vs. CMIP3 & CMIP5 | Cattiaux & Cassou, 2013, *GRL*.

Previously in CMIP

CMIP3 projections (IPCC AR4, (2007))

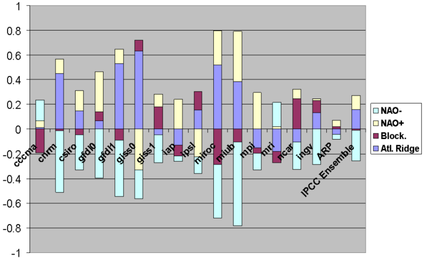
- Generalized positive trend in the NAM.
- Explained by the poleward expansion of the Hadley cells (tropics win!).



SLP index, 14 CMIP3 GCMs, SRES A1B, ONDJFM. | Miller et al., 2006, *JGR*.

NA weather regimes in CMIP

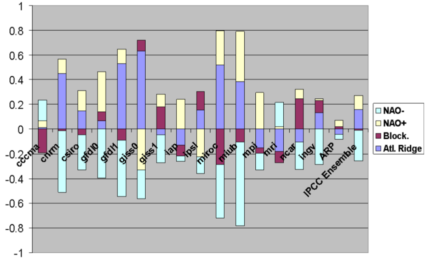
- CMIP3 SLP: increased frequency of NAO+. Consistent!

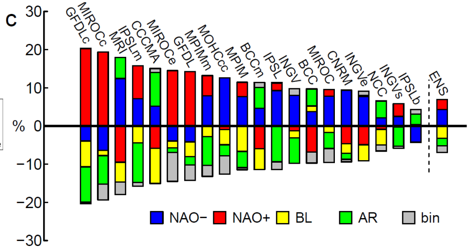


Left: Boé, 2007, *PhD* | CMIP3-A1B, SLP DJF.

NA weather regimes in CMIP

- CMIP3 SLP: increased frequency of NAO+. Consistent!
- CMIP5 Z500: increased frequency of NAO−. Hmm.



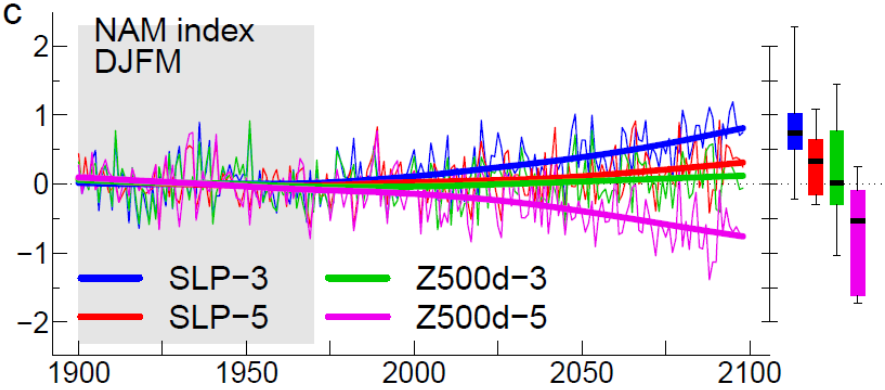


Left: Boé, 2007, *PhD* | CMIP3-A1B, SLP DJF.

Right: Cattiaux et al., 2013, *Clim. Dyn.* | CMIP5-RCP8.5, Z500 DJFM.

Baroclinicity + CMIP3/5 disagreement

- NAM: a barotropic mode but a baroclinic response. See also Woollings (2008).
- The whole response shifts towards NAM− in CMIP5.



Generalized from Miller et al. (2006) | Cattiaux & Cassou, 2013, *GRL*.

Seasonality of the response & the CMIP3/5 difference

- CMIP5: jet stream shifts poleward except in winter. E. Barnes (pers. comm.).

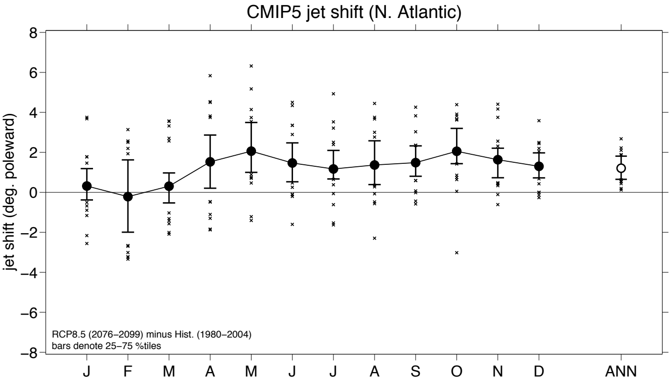
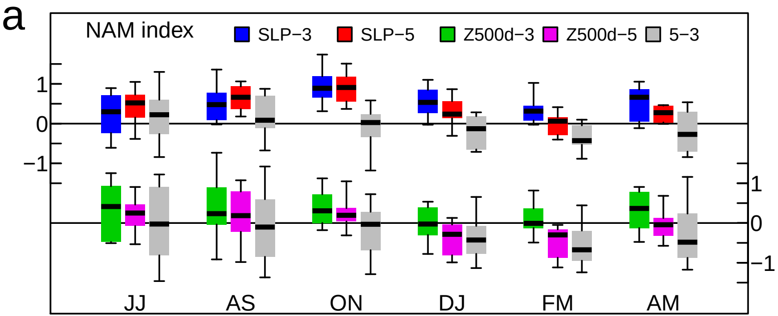


Figure by E. Barnes.

Seasonality of the response & the CMIP3/5 difference

- CMIP5: jet stream shifts poleward except in winter. E. Barnes (pers. comm.).
- CMIP3/5 disagree on the NAM response only in winter.

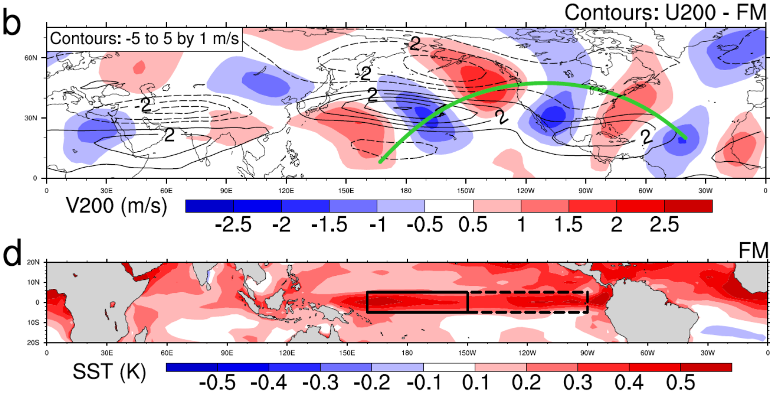


Cattiaux & Cassou, 2013, *GRL*.

⟶ Different interplay between tropical and polar forcings in CMIP5?

CMIP5: a stronger warming in the Tropical Pacific

- Rossby wave emerging from Western tropical Pacific (Niño 4 box).

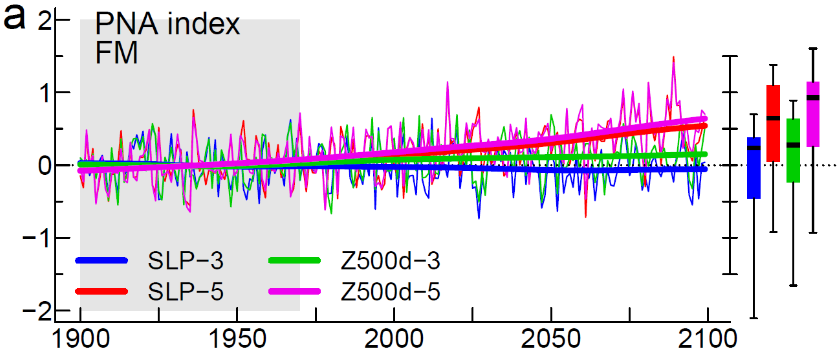


CMIP5−CMIP3 differences in the 21C−20C responses | Cattiaux & Cassou, 2013, GRL.

- Not the case in 1pctCO2 exps: due to scenarios or internal variability.

CMIP5: a stronger warming in the Tropical Pacific

- Rossby wave emerging from Western tropical Pacific (Niño 4 box).
- Barotropic PNA+ response in CMIP5, contributing to NAM−.



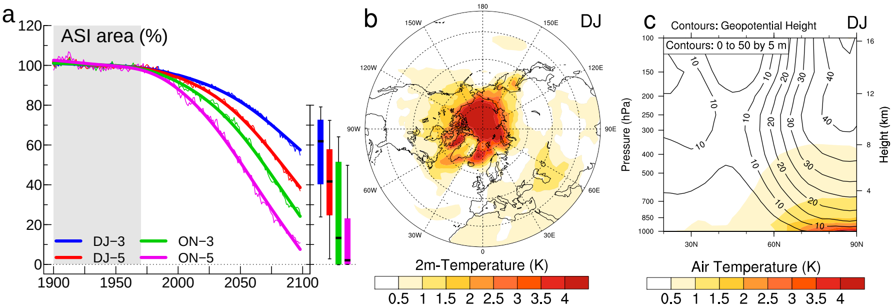
CMIP5−CMIP3 differences in the 21C−20C responses | Cattiaux & Cassou, 2013, GRL.

- Not the case in 1pctCO2 exps: due to scenarios or internal variability.

CMIP5: a stronger Arctic amplification

- Faster sea-ice decline and enhanced baroclinicity.
- Seasonal timing and vertical response consistent with sensitivity exps.

Deser et al. (2010), Peings and Magnusdottir (2012), among others.



CMIP5−CMIP3 differences in the 21C−20C responses | Cattiaux & Cassou, 2013, GRL.

- Also the case in 1pctCO2 exps: due to model characteristics.

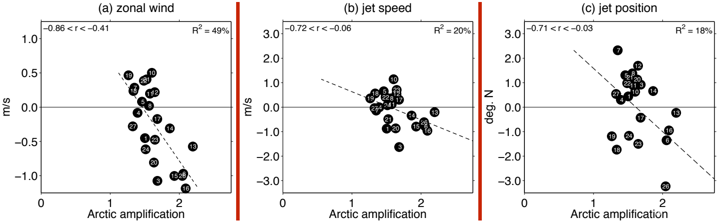
Projected changes: summary

- **In winter, competition between tropical and polar forcings.**

Baroclinicity of the response due to changes in the meridional T gradient.
Tropics won in CMIP3. Less clear in CMIP5.

- **Assess the individual contributions of forcings?**

Perform sensitivity experiments and/or use the CMIP ensemble.
Example of the modulation of the mean-flow response by the Arctic amplification:



CMIP5 changes – Each dot is a model – Barnes & Polvani (2014, under review).

- **Test other metrics (recurrence, sinuosity, etc.) in CMIP projections?**

Conclusions

Conclusions

Has the NA atmospheric dynamics recently changed?

Maybe. But internal variability.

Conclusions

Has the NA atmospheric dynamics recently changed?

Maybe. But internal variability.

Is the NA atmospheric dynamics projected to change? How?

Probably. But competitive mechanisms, and large uncertainties.

Conclusions

Has the NA atmospheric dynamics recently changed?

Maybe. But internal variability.

Is the NA atmospheric dynamics projected to change? How?

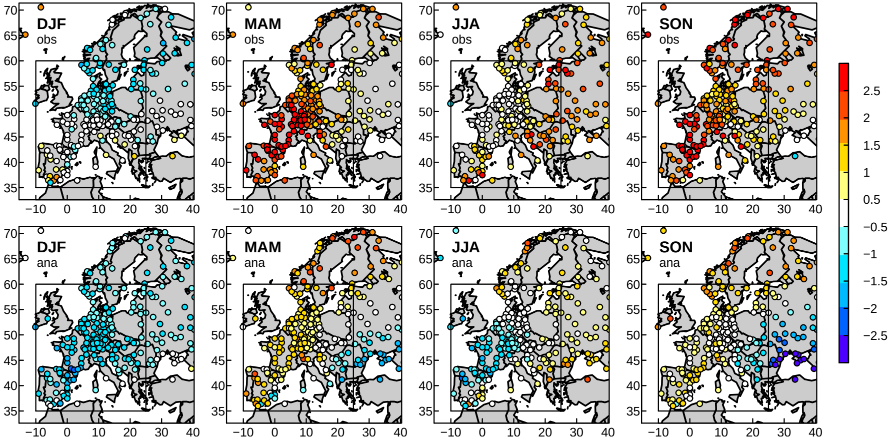
Probably. But competitive mechanisms, and large uncertainties.

In any case, already warmer in Europe for analog synoptic patterns.

...

Conclusions

Example of year 2011, warmest year on record (before 2014!) but 10th in analogues.



T ECA&D (stations) | Cattiaux & Yiou, 2012, *BAMS*.

Conclusions

Has the NA atmospheric dynamics recently changed?

Maybe. But internal variability.

Is the NA atmospheric dynamics projected to change? How?

Probably. But competitive mechanisms, and large uncertainties.

In any case, already warmer in Europe for analog synoptic patterns.

Conclusions

Has the NA atmospheric dynamics recently changed?

Maybe. But internal variability.

Is the NA atmospheric dynamics projected to change? How?

Probably. But competitive mechanisms, and large uncertainties.

In any case, already warmer in Europe for analog synoptic patterns.

Thanks.