Ocean a klimat:
wczoraj, dziś i jutro

Wykład 5 bis:

Zmienność klimatu w skali dekadalnej
(AMO, NAO, PDO)

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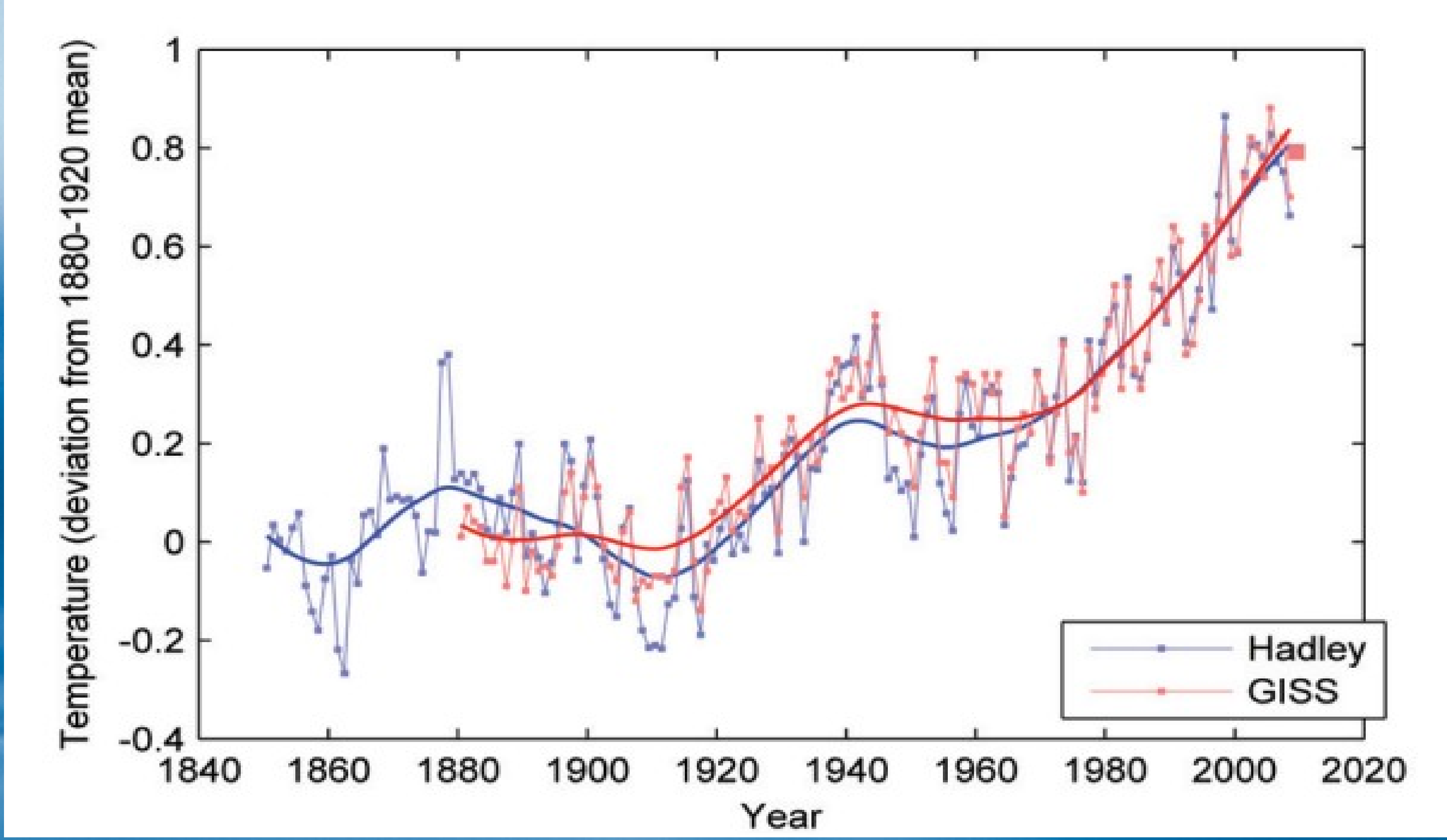
http://www.iopan.gda.pl/~piskozub/klimat/

Jacek Piskozub "Klimat a ocean: wczoraj, dziś i jutro",
kurs wykładów dla doktorantów 2016 / 2017

- Maszyna klimatyczna Ziemia (*zmienność w skali geologicznej*)
- Epoka lodowa w której żyjemy (*zmienność w skali astronomicznej*)
- Gwałtowne zmiany klimatu (*deglacjacja, zmienność "suborbitalna"*)
- Holocen: klimat, ocean a cywilizacja, (*stała słoneczna i wulkanizm*)
- Północny Atlantyk – kuźnia klimatu (*cyrkulacja termohalinowa)*
- Zmienność klimatu w skali dekadalnej (*AMO, NAO, PDO*)
- Tropiki a zmienność klimatu (*ENSO, huragany, monsuny*)
- Aerozol: wielka niewiadoma klimatyczna
- Gazy o znaczeniu klimatycznym (*cykl węgla, CO_2, metan, DMS*)
- Globalne ocieplenie a ocean (*zmienność antropogeniczna*)
- Zmiany klimatyczne w rejonach polarnych

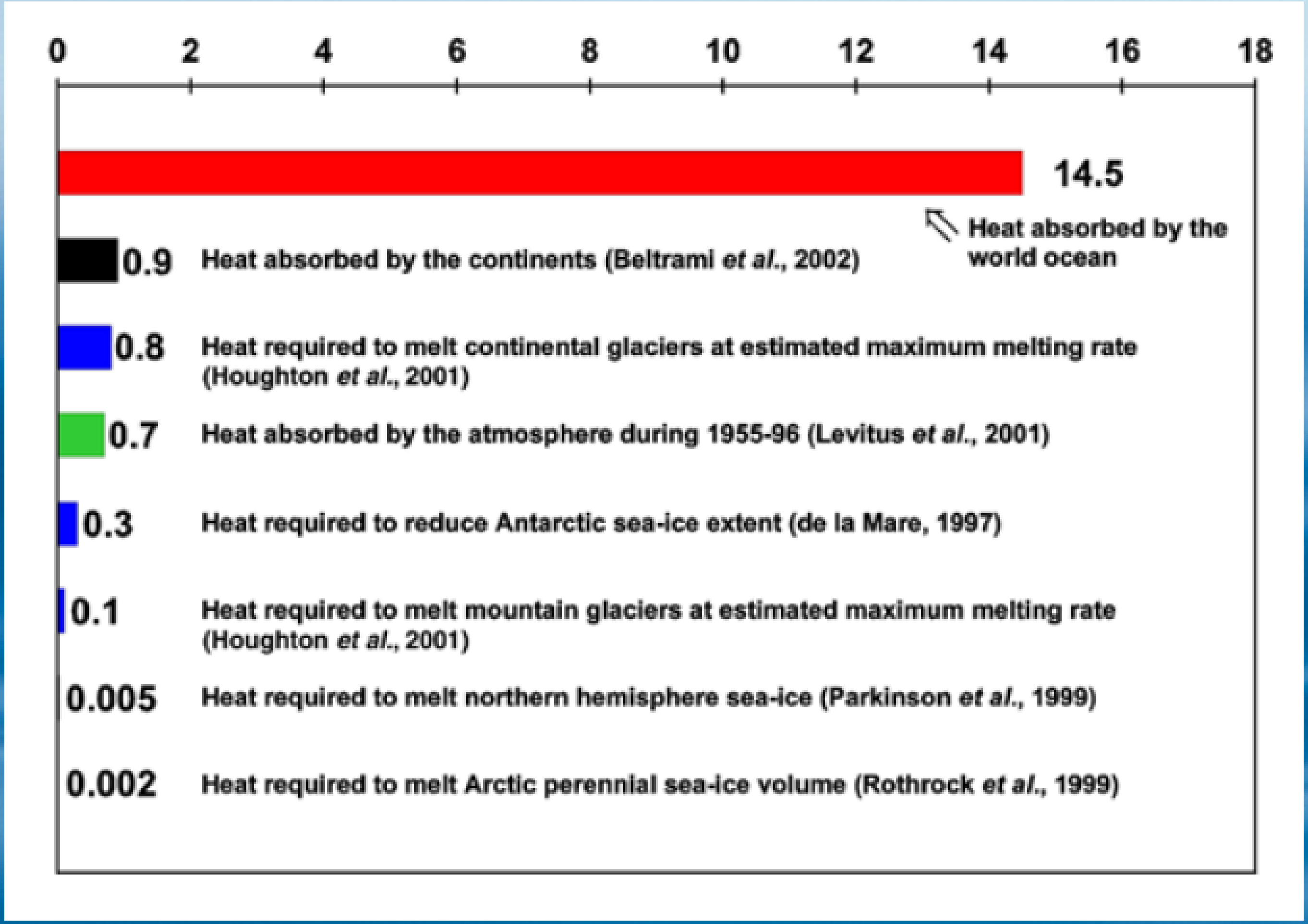
What causes the multidecadal variability of global temperature?



On top of the global warming trend, the instrumental temperature records show significant multidecadal variability. To better learn the actual climate sensitivity to greenhouse gases, we need to understand how much of it is caused by changing forcing (natural and anthropogenic) and how much by natural variability? And what this variability actually is?

The Copenhagen Diagnosis 2009

How can we explain any multiannual climate oscillations?



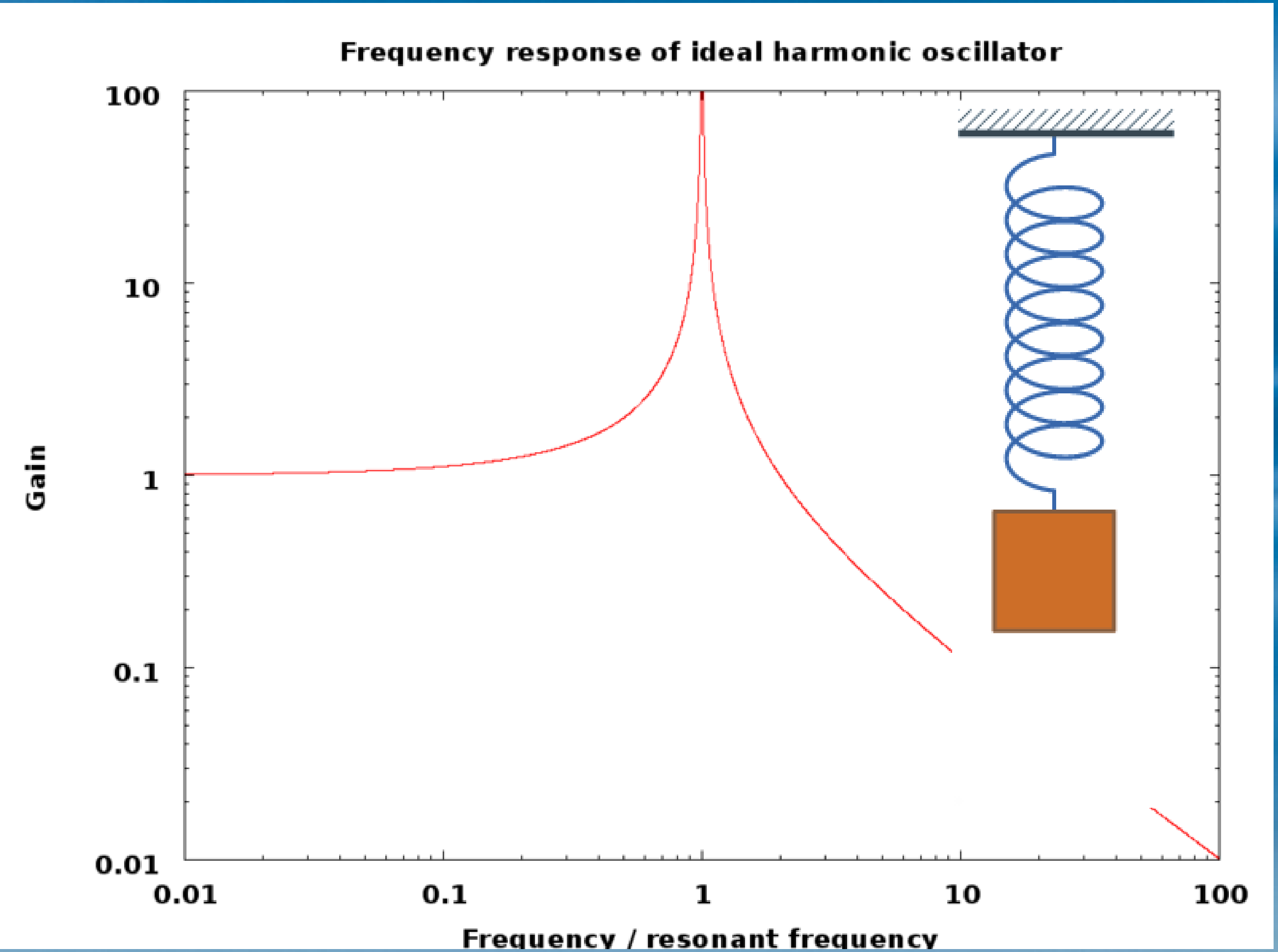
The absorbed amount of heat (in 10^{22} J) by various components of Earth climate machine: ocean absorbed 84%, land 4% and atmosphere 5%. The missing 7% is the latent heat of ice-sheets and sea ice. The actual heat content share of the ocean even bigger share of the pie as ocean has a long relaxation time for heat fluxes (hundreds of years) and has not yet adjusted to the present greenhouse forcing.

Levitus, Antono, Boyer 2005 (Geophysical Res. Letters)

There are many known or suspected multiannual climate oscillations (examples will be shown soon) but it is not possible to explain any of them without air-sea interaction because the heat content of land and atmosphere is too small for a multiannual climate "memory" (and continental moisture can barely explain biannual variability).

What are the possible mechanisms of interannual climate oscillations?

If we observe climate oscillations with a period of multiple years we can suspect either a forced (driven) oscillator, with a periodic forcing controlling its period, or a stochastically forced oscillator (possibly bistable) with a period close to its resonant period. In any case it is very hard to force oscillations when the resonance period is longer than the forcing period (low gain).



Frequency response of an ideal harmonic oscillator. Real climate system are neither harmonic (nonlinearities) nor ideal (they have damping) but the main conclusions are still true.

en.wikipedia.org

What need we to do?

To understand any interannual climate oscillation we need to identify either the person pushing the swing (external periodical forcing) or the way someone on the swing can keep it in motion (internal physics of the phenomenon).

Jean-Honore Fragonard: "The Swing"

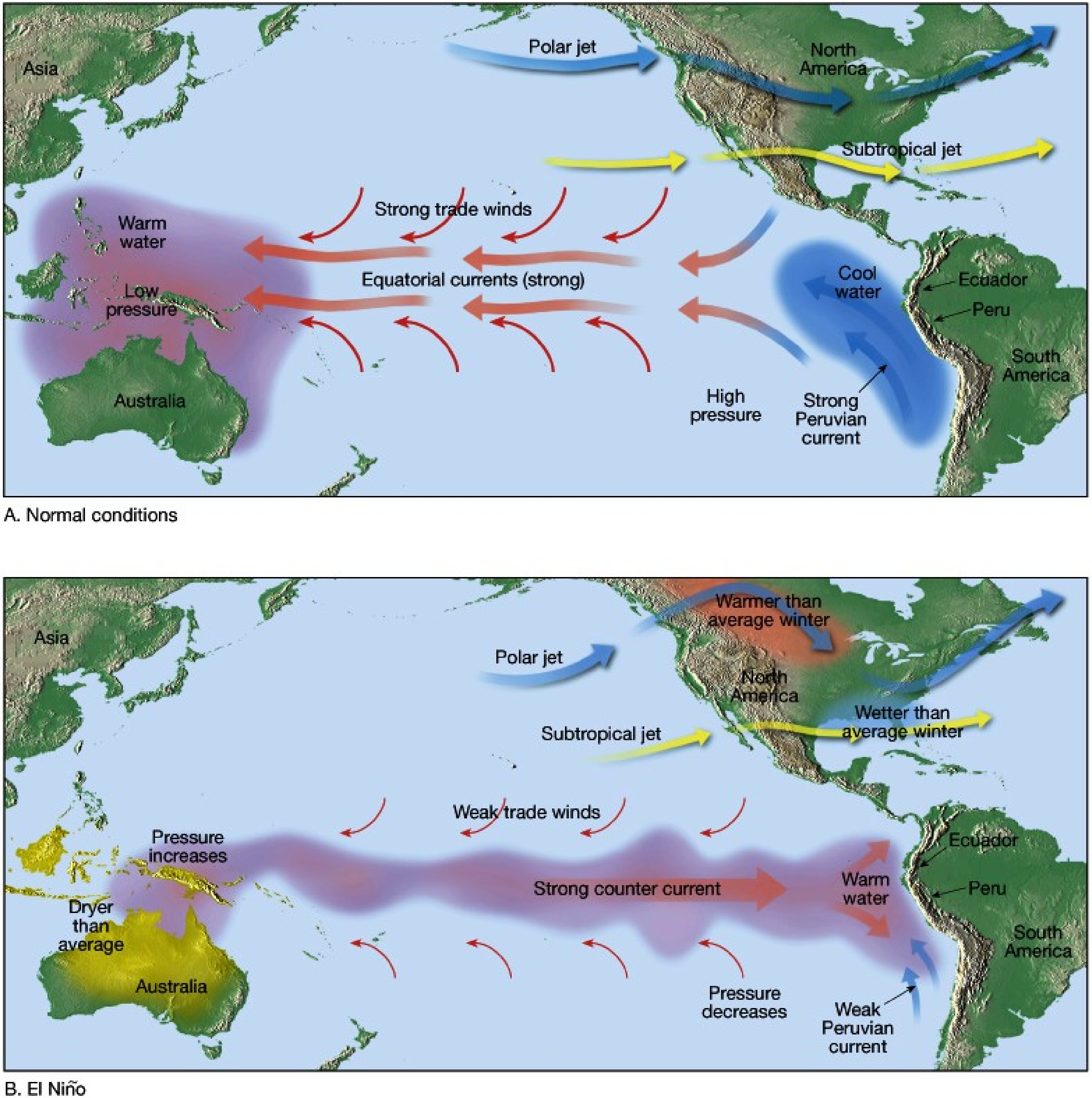
Two phases of ENSO

La Niña (top)

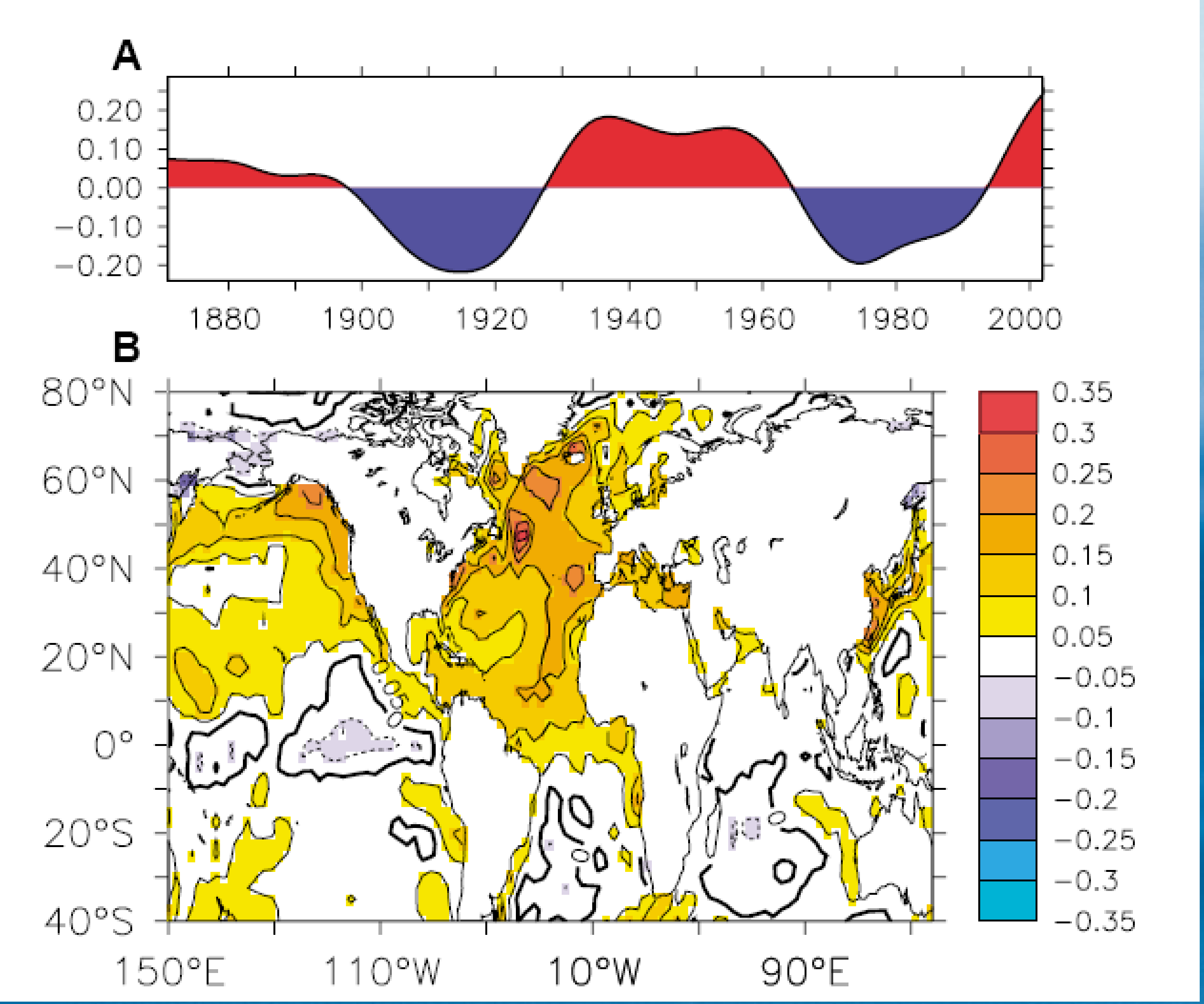
and

El Niño (bottom)

El Niño-Southern Oscillation (ENSO):
a quasi bistable ocean-atmospheric system of 3 to 7 year period with stochastic forcing?



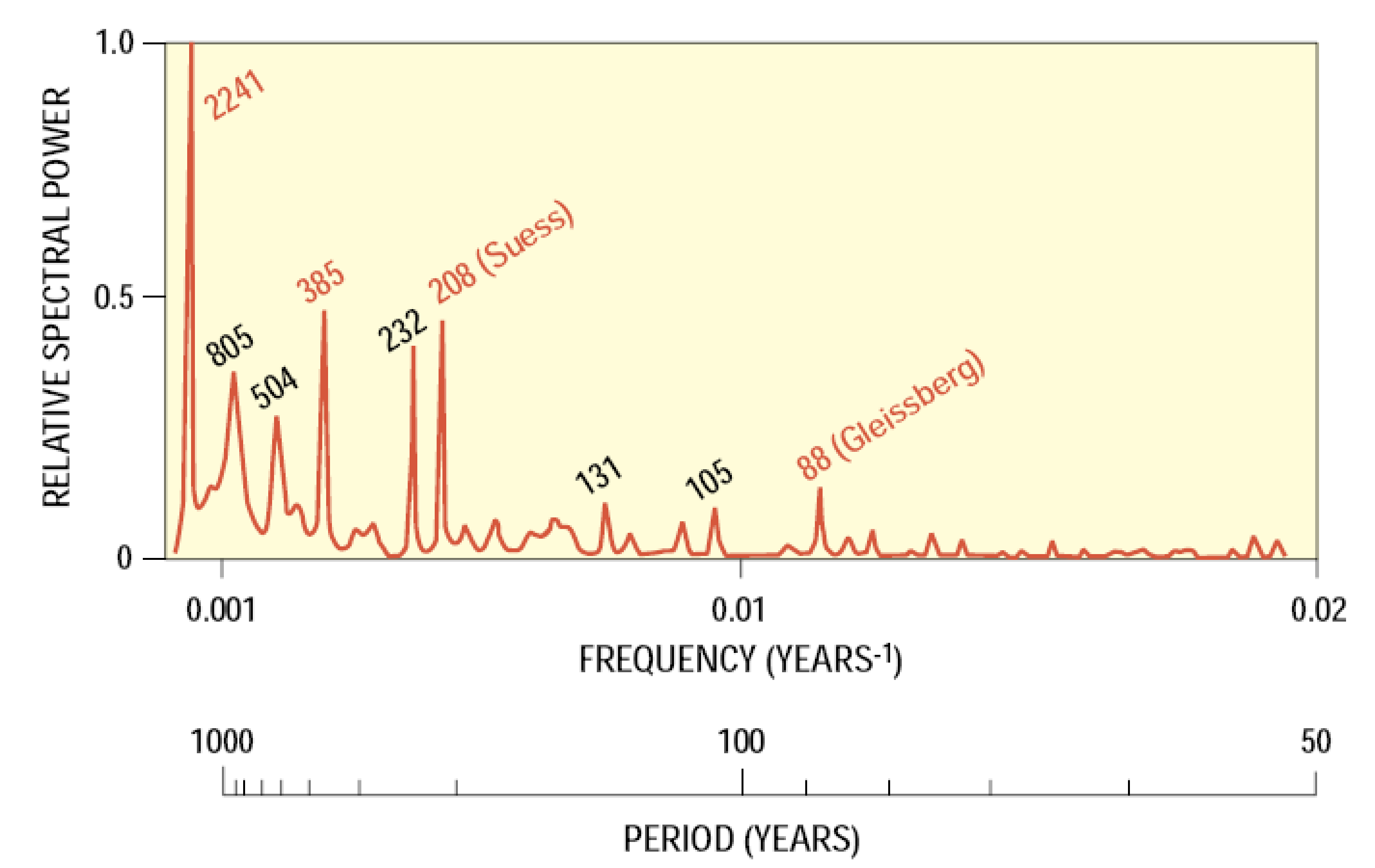
Atlantic Multidecadal Oscillation



Atlantic Multidecadal oscillation is a periodical (60-70 years) warming and cooling of North Atlantic. The temperature anomaly of North Atlantic (top) is used as the AMO index.

Sutton, Hodson 2005 (Science)

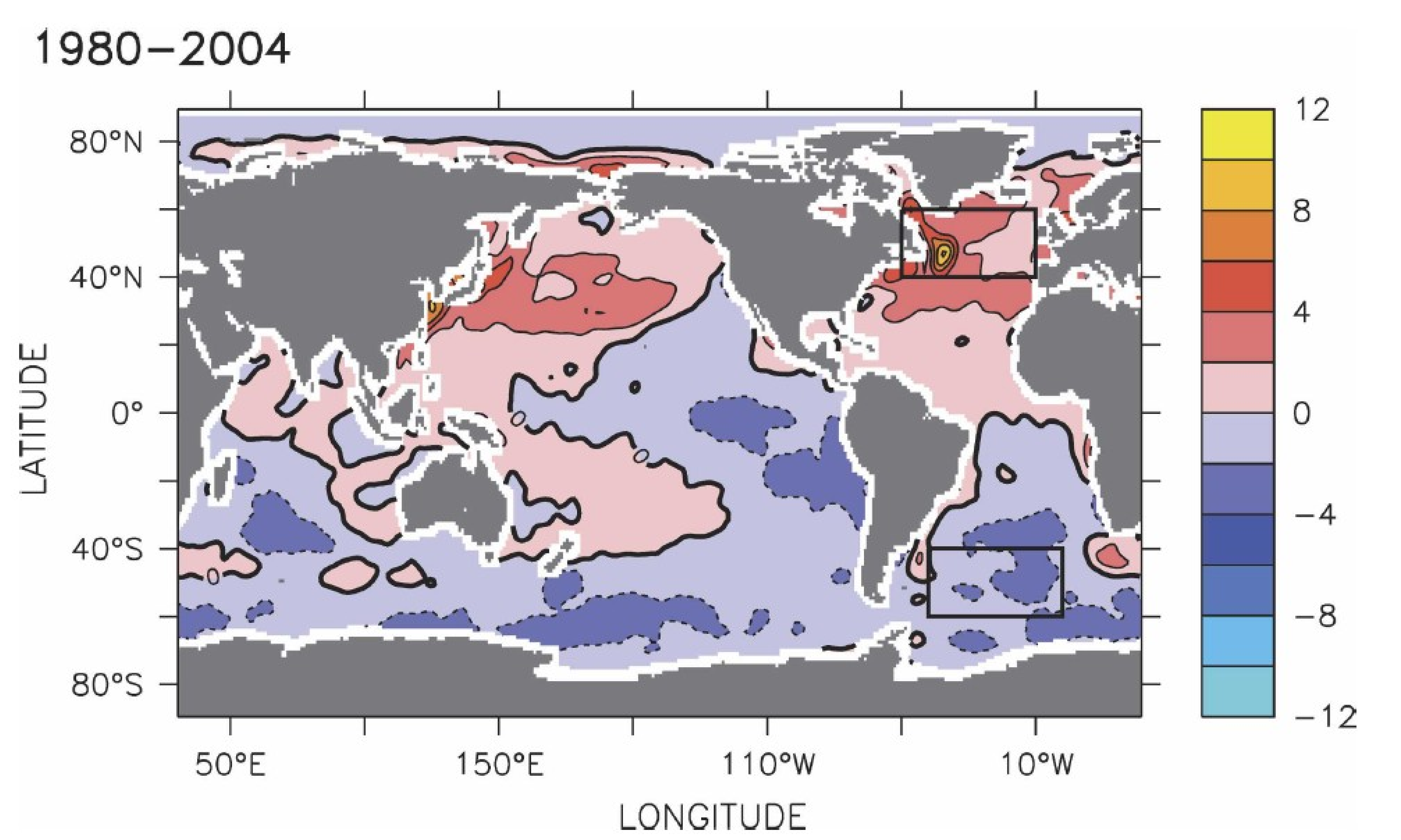
Solar forcing: sun activity spectrum from tree ring C^{14}



Solar activity from tree ring ^{14}C shows many cycles but the shorter important one is 88 year long. It is difficult to explain any multiannual or multidecadal variability of a shorter period by sun only. We also know of no other external decadal periodical forcings.

Dean 2000 (USGS)

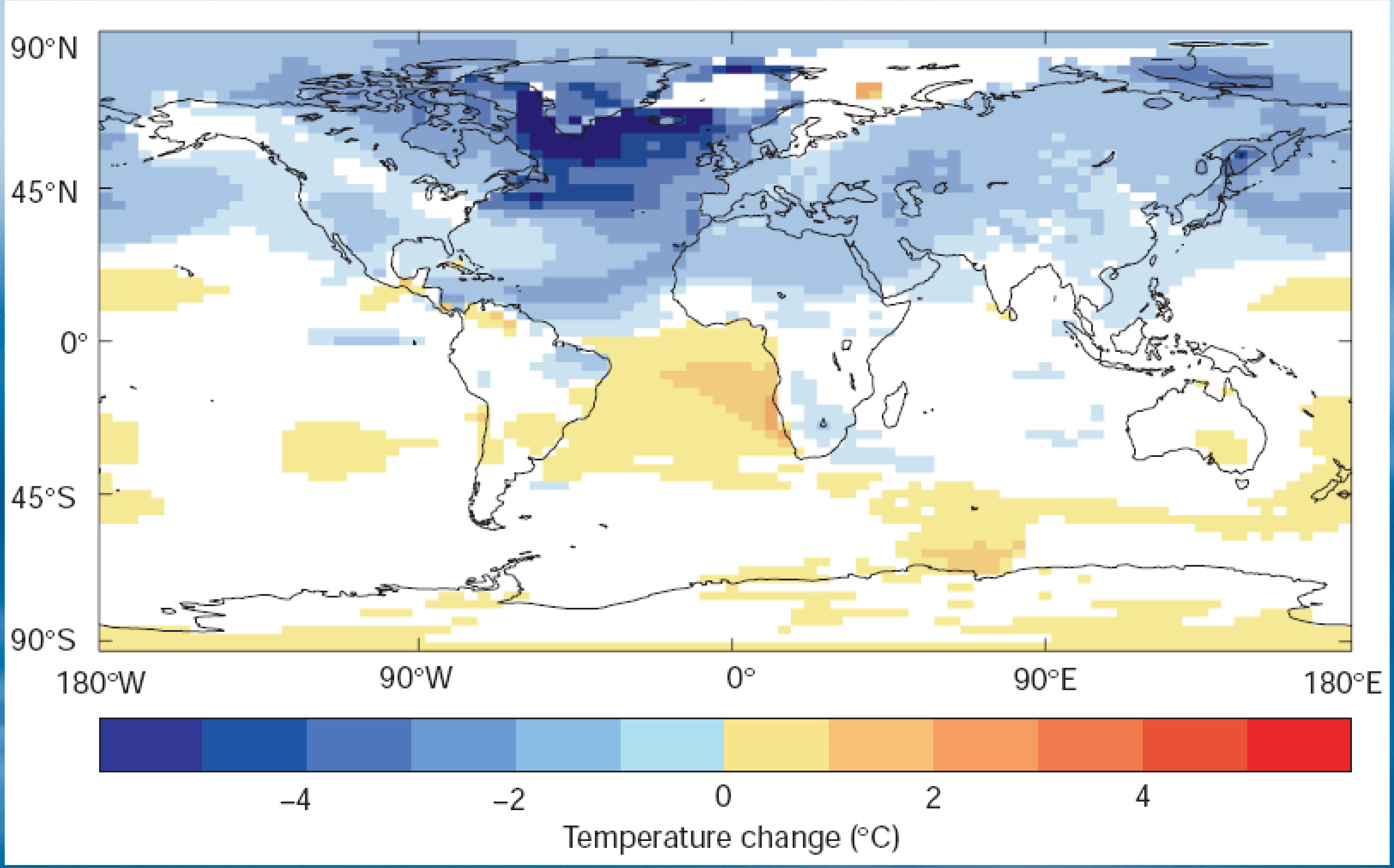
Observed AMO pattern



Linear SST trend (in ºC) between AMO low (1980) and high (2004) values, after subtracting global SST increase trend.

Latif et al. 2006 (Journal of Climate)

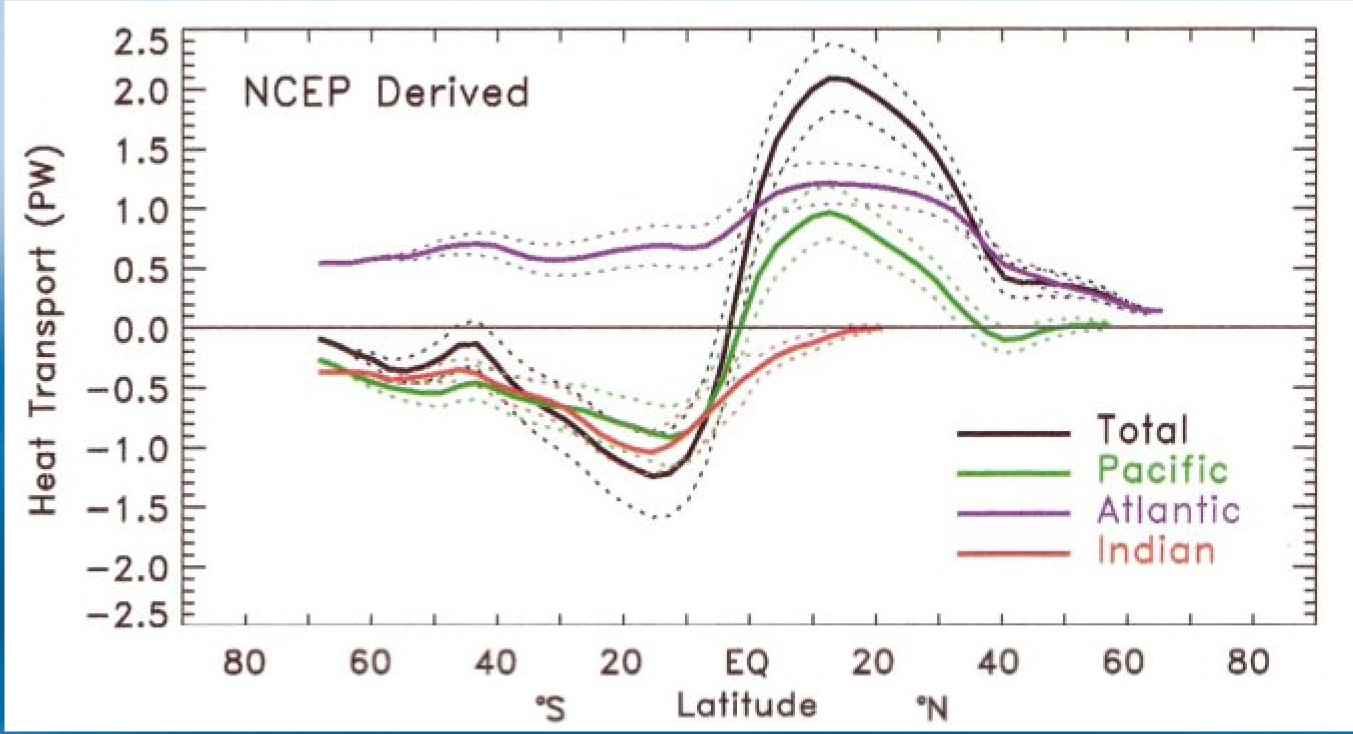
Meridional overturning climate effect



General circulation models (here HadCM3 model) show that stopping MOC would create a characteristic climate pattern of northern cooling (especially in North Atlantic) and southern warming (more diffuse). Strengthening MOC has an inverse effect.

Rahmstorf 2002

Meridional transport of heat: the Atlantic exception

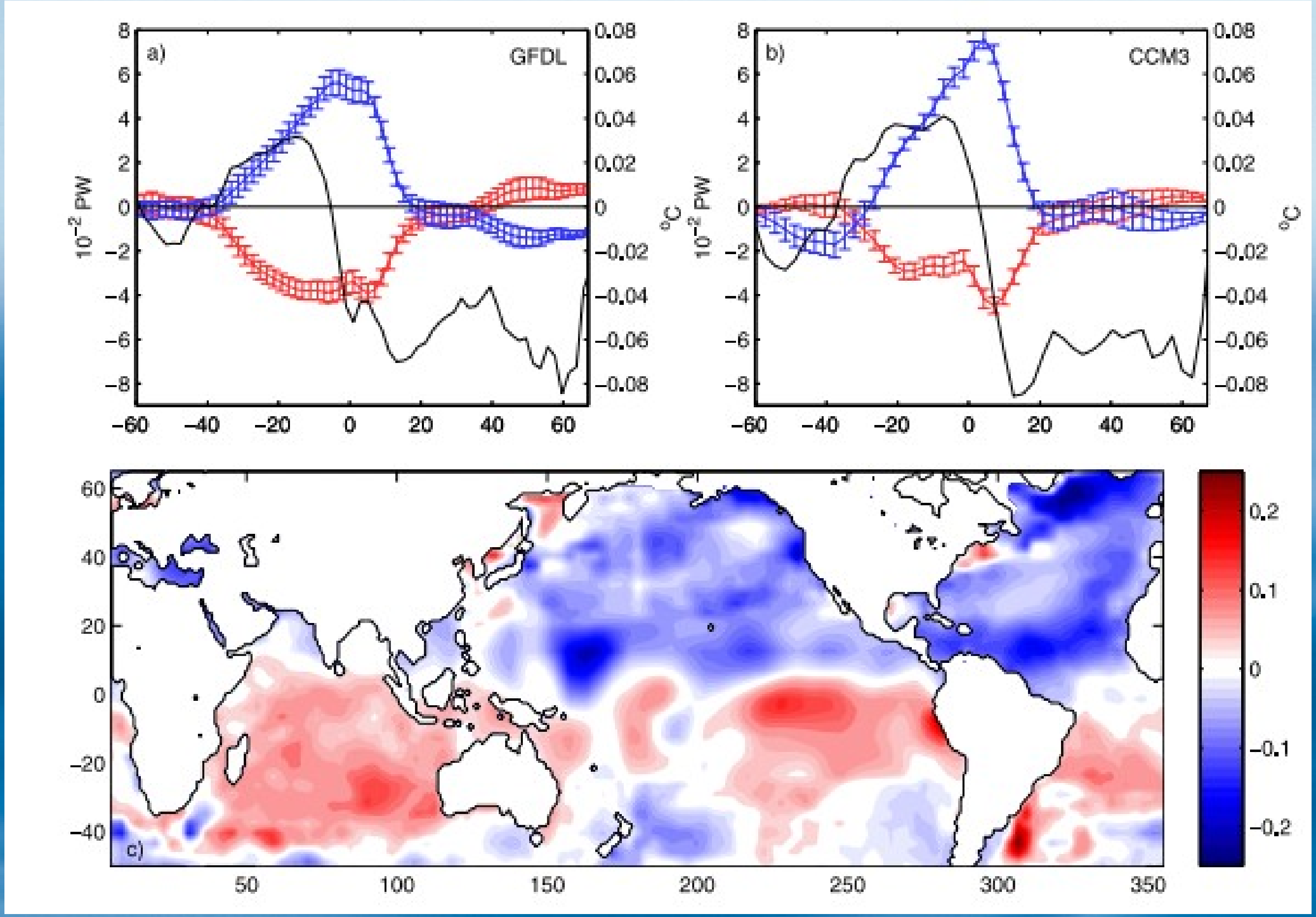


Ocean heat transport (positive means Northward, negative Southward)

The Atlantic is the only ocean where thanks to THC, the hear transport crosses the equator and reaches much further North than in the Pacific. With the exception of Indian Ocean monsoon (transporting heat southward), it is the only significant mechanism coupling the climate of Northern and Southern Hemispheres.

Trenberth & Caron, 2001 (Journal of Climate)

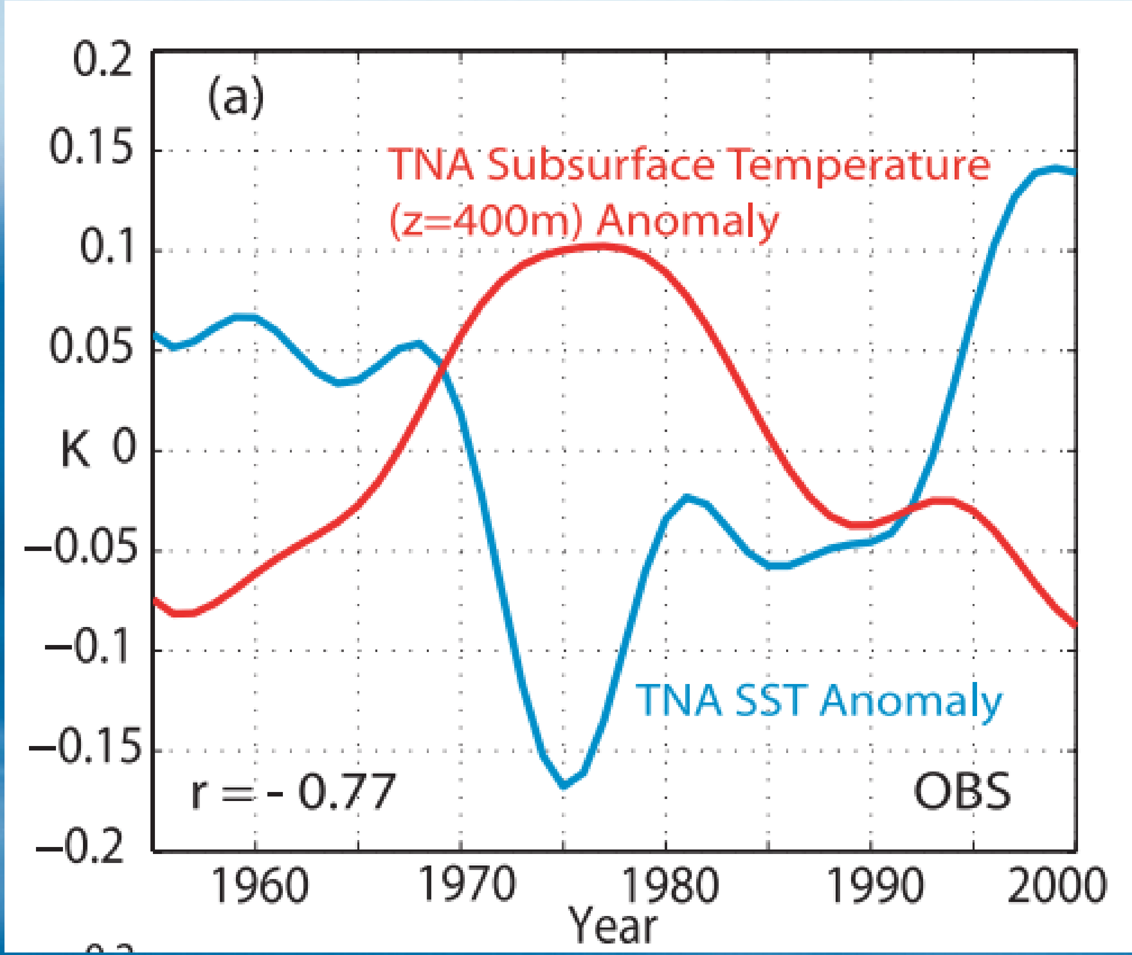
Ocean and atmospheric MOC heat transport variability



(a)–(b) Regressions of the anomalous heat transport for the ocean (red), atmosphere (blue), with one standard deviation ensemble member spread, and the zonal mean SST anomaly (black) on the normalized V-index. (c) Spatial distribution of the regression of the SST's on the normalized V-index (CCM3 model only). Results are multiplied with -1.

Mantsis & Clement. 2009 (GRL)

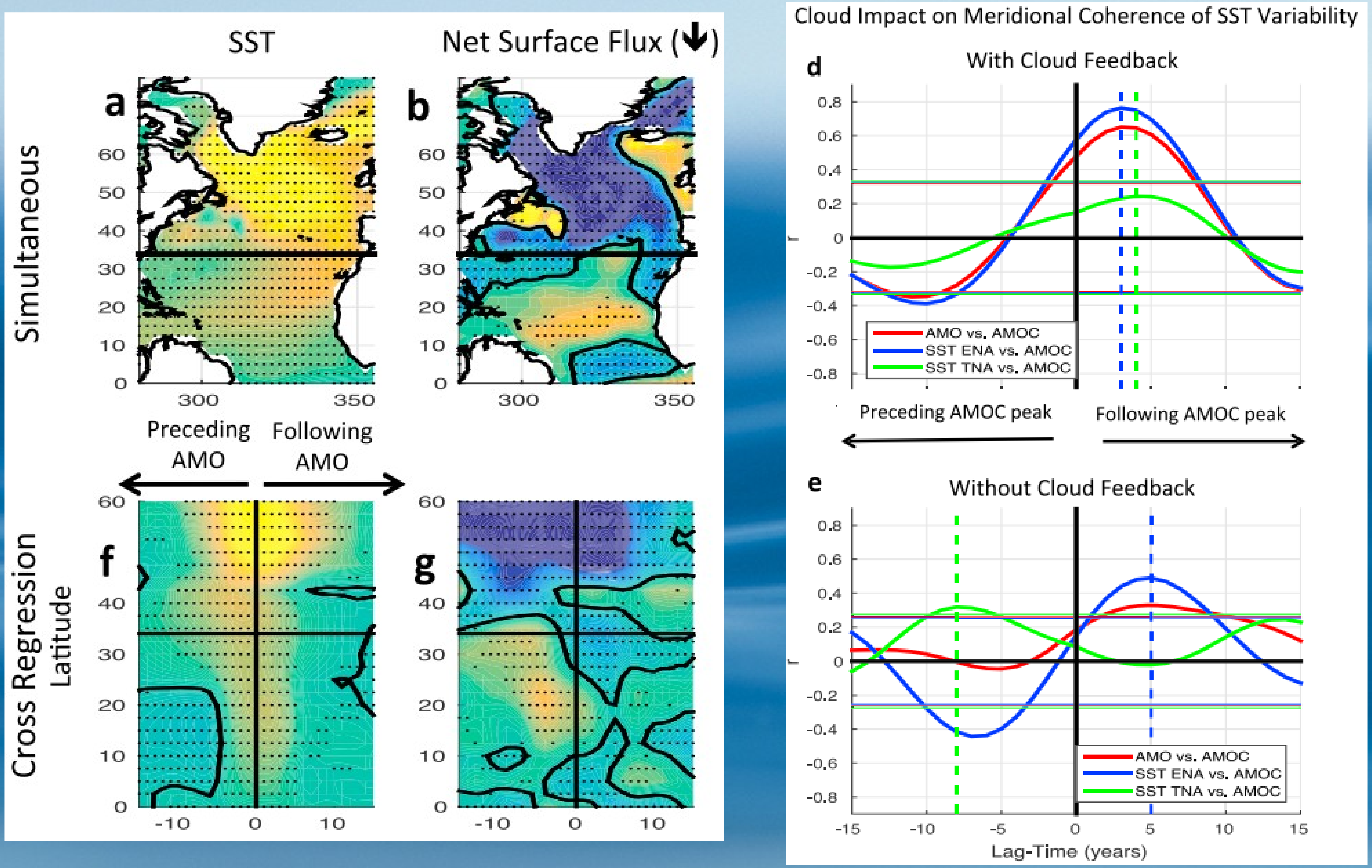
AMOC exchanges heat between ocean and the atmosphere on decadal scales



The temperature of subsurface tropical North Atlantic and surface waters are anticorrelated on decadal scales showing that AMOC exchanges heat not only between the hemispheres but also between the ocean and the atmosphere with an AMO-like timescale

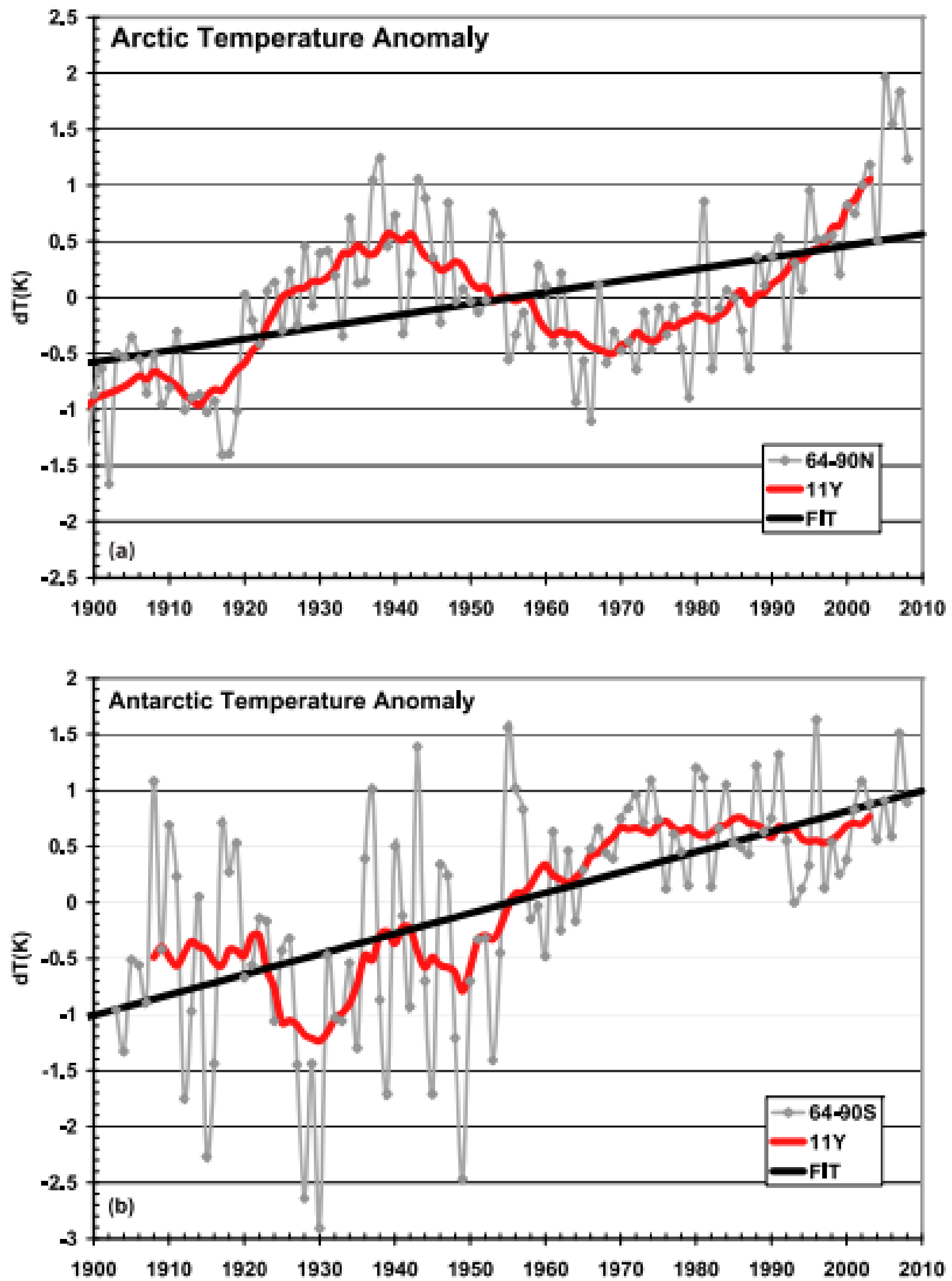
Zhang 2007 (GRL)

Cloud feedback helps kee the phase of AMO over the whole North Atlantic basin



Brown et al 2016 (GRL)

The bipolar see-saw was active also in the 20th century

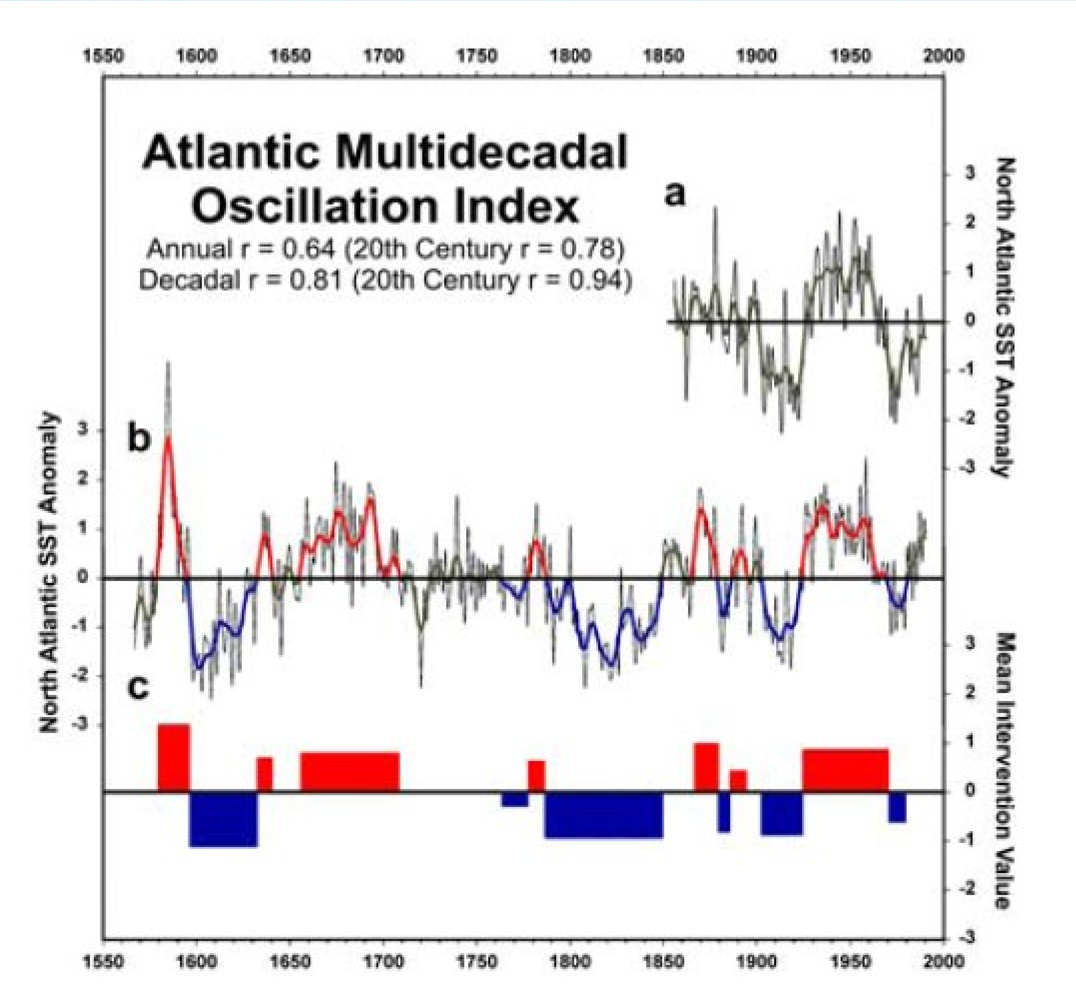


The bipolar "see-saw" first discovered in the glacial era paleodata was also active in the 20th century.

The Arctic and Antarctic temperature anomalies (from NASA GISS dataset) seem to have inverse phases strongly suggesting a MOC related interhemispherical heat transport. The linear trend is similar for both hemispheres and therefore related to global forcings (greenhouse gases and solar variability).

Chylek et al. 2010 (GRL)

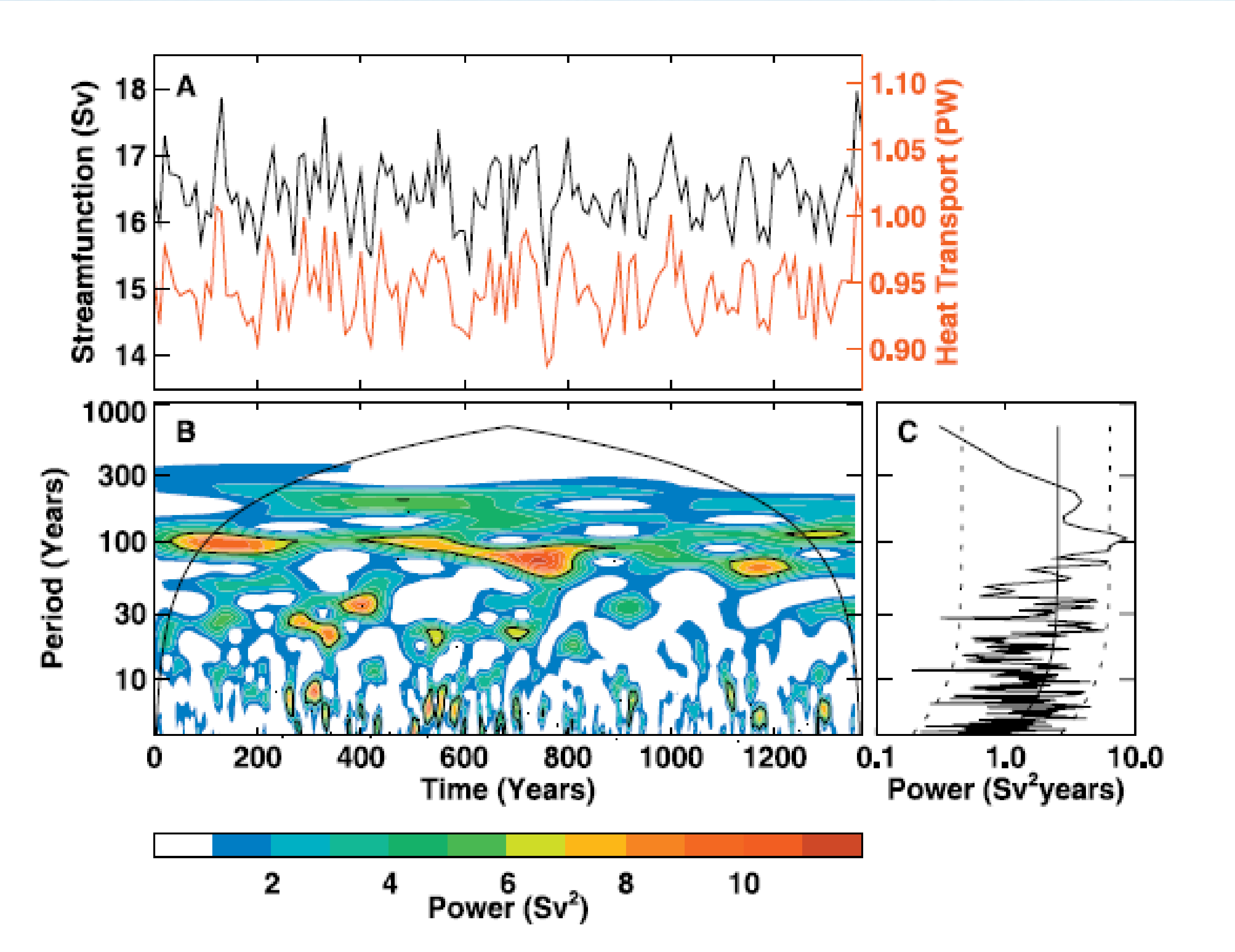
Observed and reconstructed values of AMO



Using tree-ring width it was possible to reconstruct AMO of past four centuries (caveat: or at least something that well correlates with AMO during the time we could observe it directly)

Gray et al. 2004 (Geophysical Research Letters)

Modeled AMO: wavelet analysis

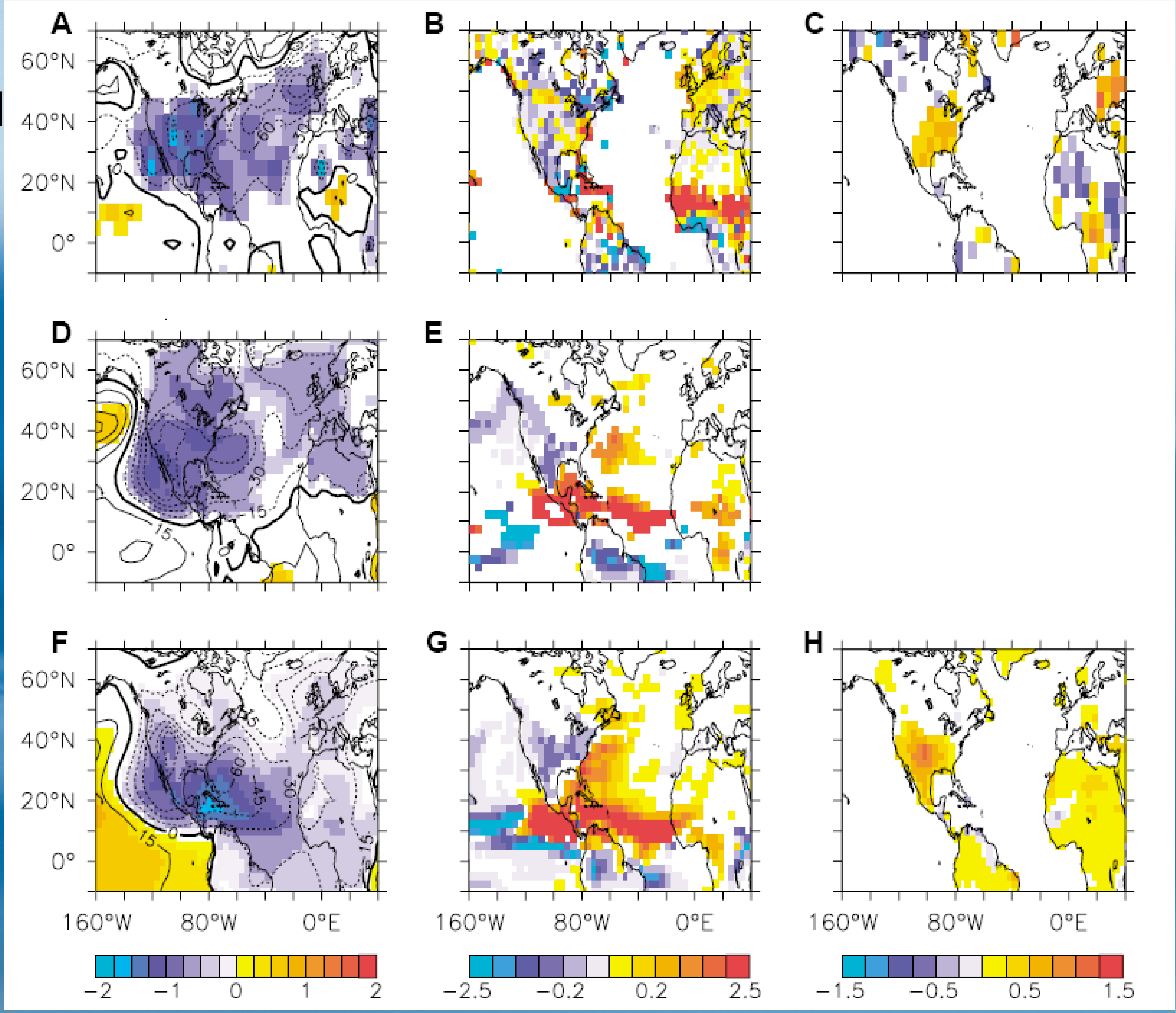


Wavelet analysis of modeled 1400 years of AMO (HadCM3 model) showing a 70-120 year period of AMO.

Knight et al. 2005 (Geophysical Research Letters)

Observed and modeled AMO climate effects

Observed (top) and modeled using as a forcing observed SST (middle) and ideal AMO SST values (bottom) decadal variability of air pressure (left), precipitation (center) and surface temperature (right). The plots should be interpreted as positive – negative phase of AMO values.

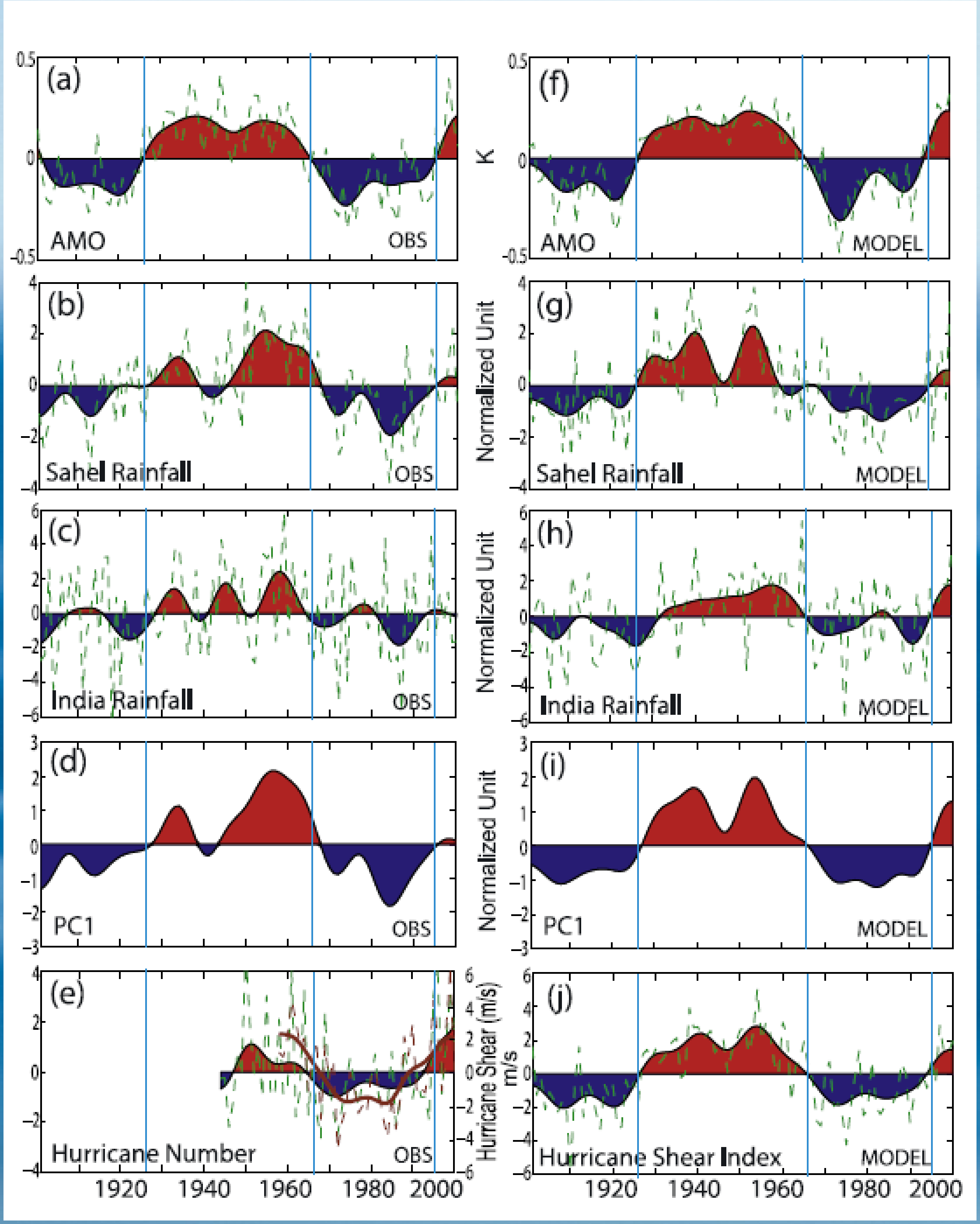


Sutton, Hodson 2005 (Science)

Observed and modeled AMO influences

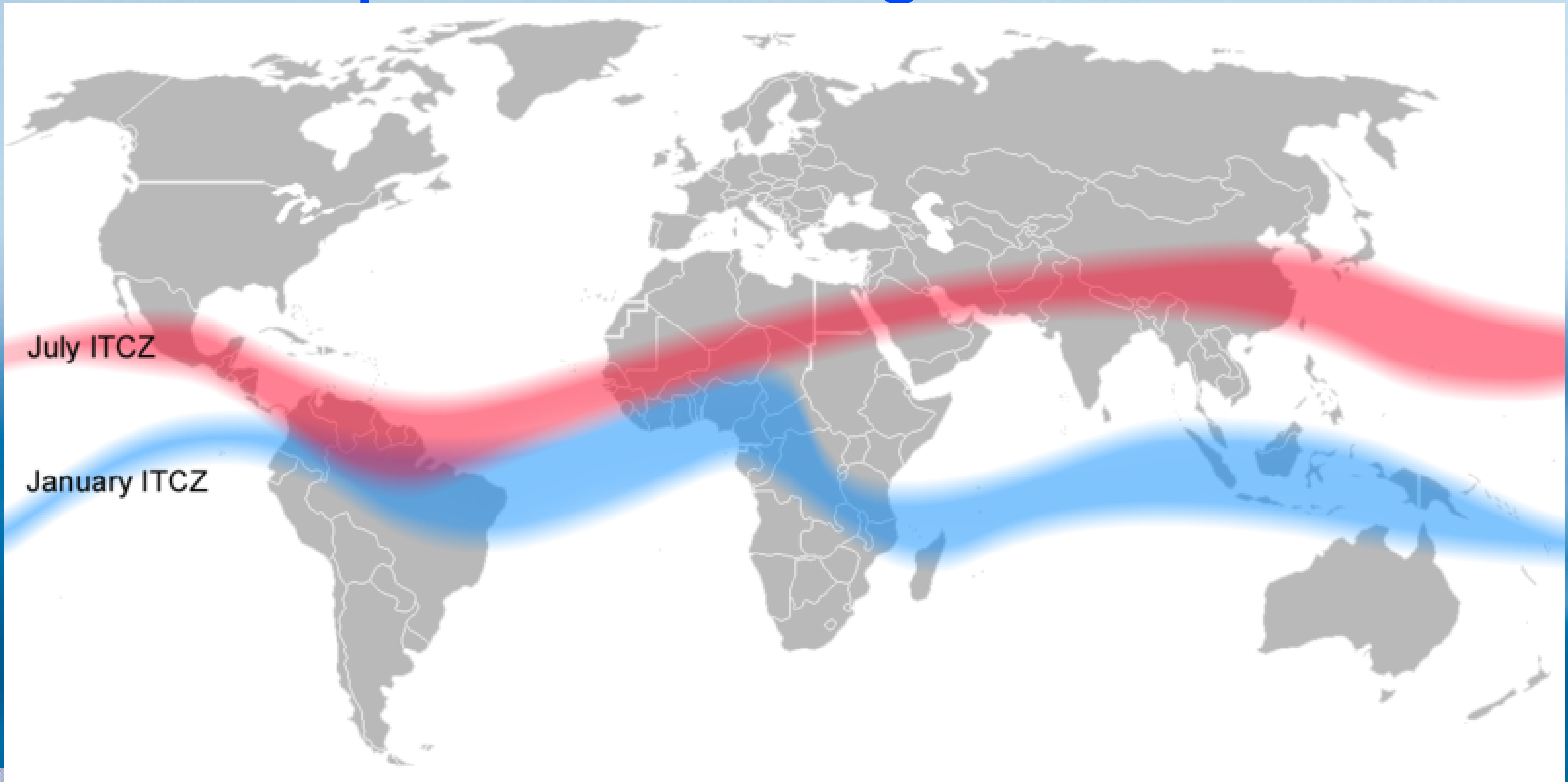
AMO correlates very well with summer Sahel and India rainfall (even better with its low-pass filtered first principal component) and with Atlantic hurricane numbers both for observations (left) and with model (right), for a general circulation model (GFDL CM2.1) forced with observed Atlantic heat fluxes .

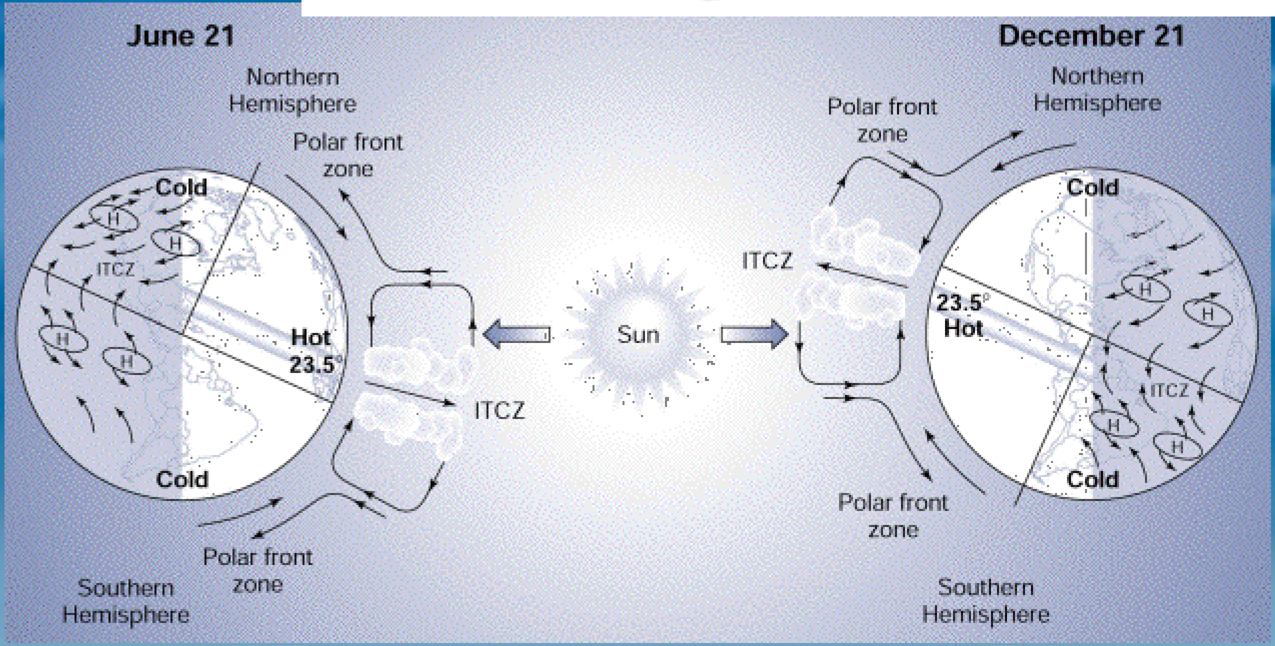
Is it easy to explain the relationships?



Zhang Delworth 2006 (Geophysical Research Letters)

Intertropical Convergence Zone





In the yearly cycle, ITCZ moves always to the hemisphere which receives more heat from the sun see lower panel).

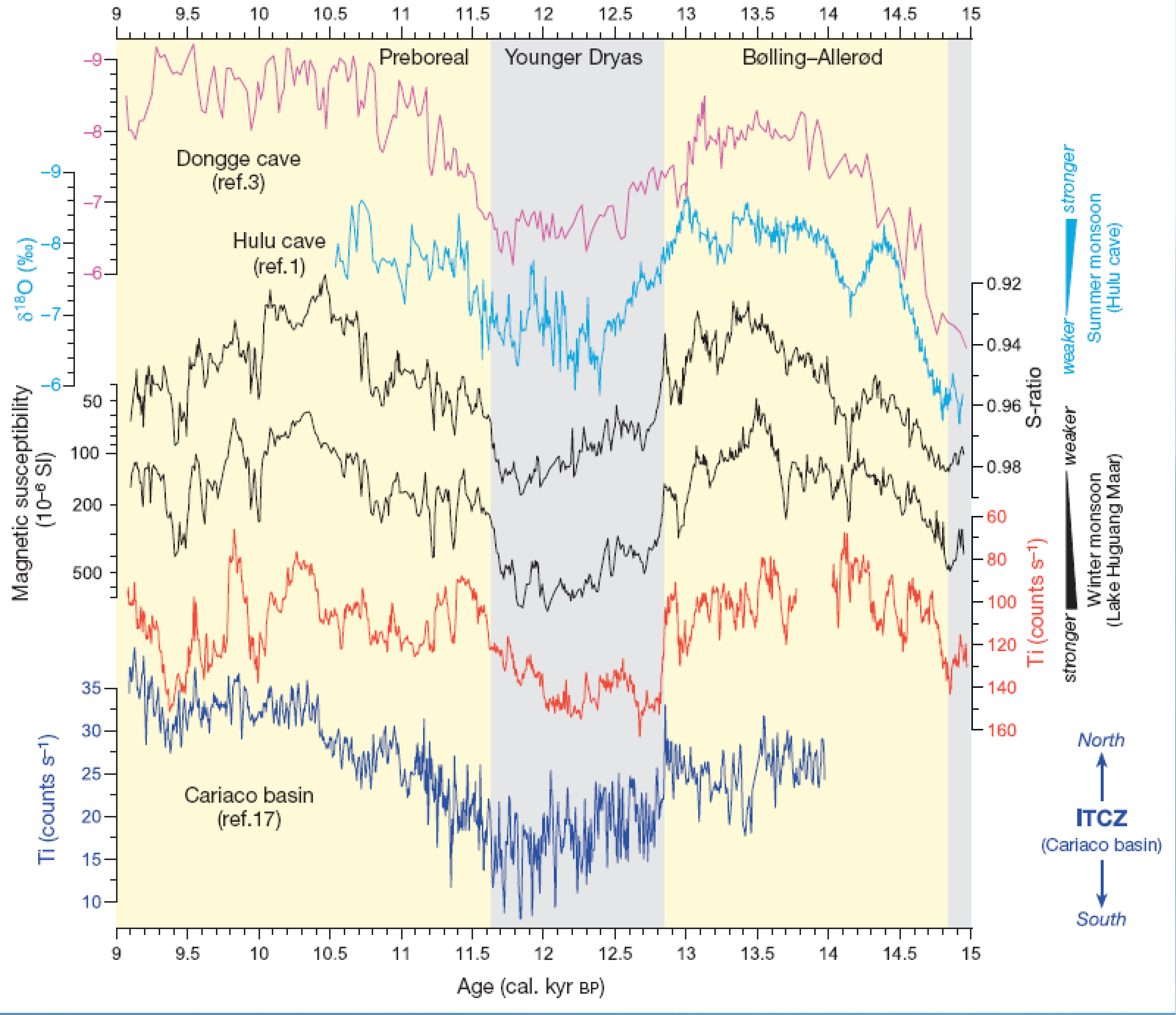
Kump et al. 2004

Variability of Asia monsoon and Caribbean precipitation

During the deglaciation (right) and glacial era (not shown), changes of the tropical climate were highly synchronous.

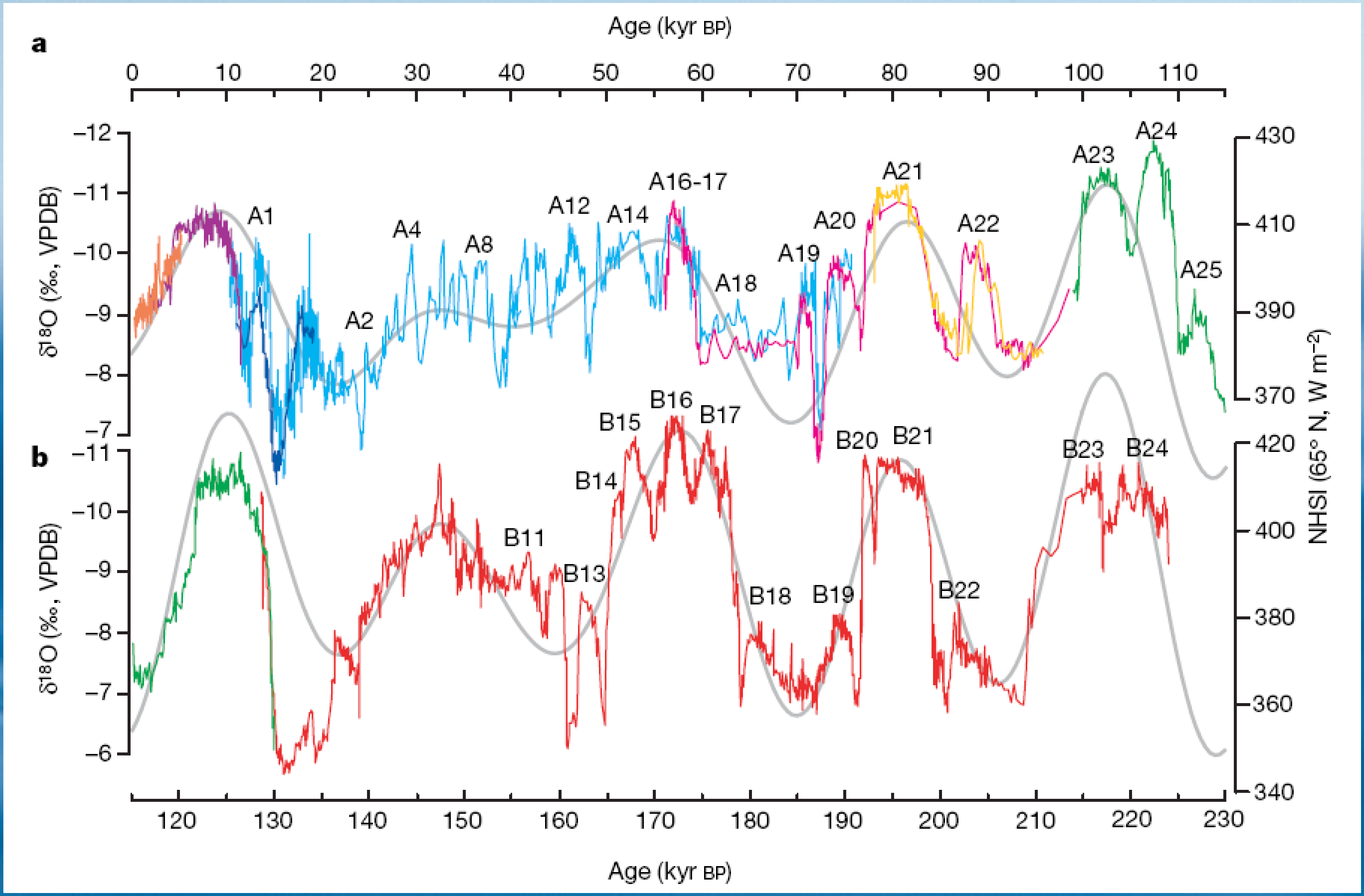
Common denominator?

THC regulated northward and southward movements of ITCZ.



Yancheva et al. 2007 (Nature)

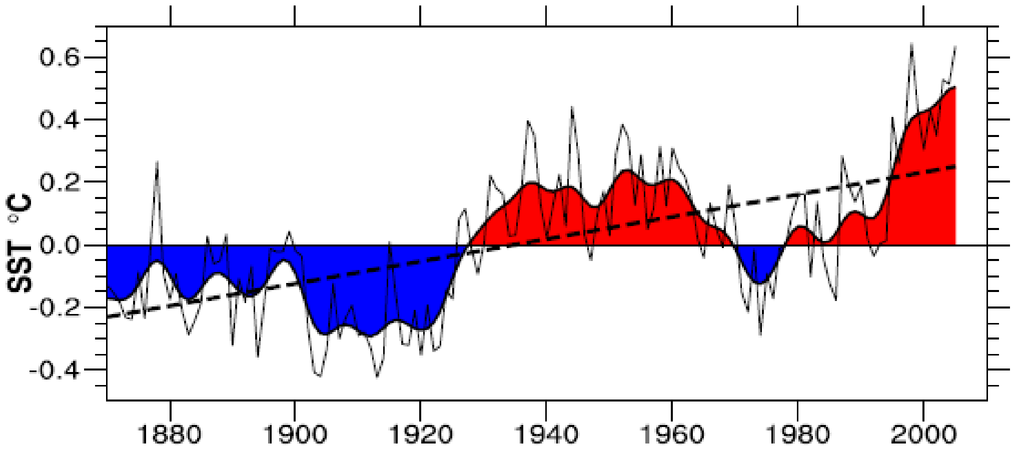
Long term monsoon variability controlled by NH insolation

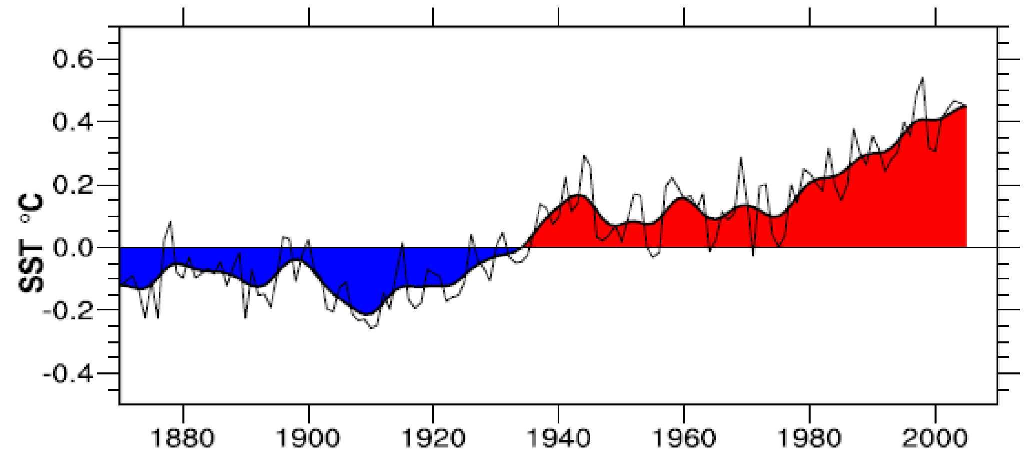


Monsoon intensity over last 230ka from south China stalagmites compared with summer insolation at 65º N. AI named “wiggles” correspondent to THC related North Atlantic events. It is clear that the ITCZ position is controlled by North-South temperature difference.

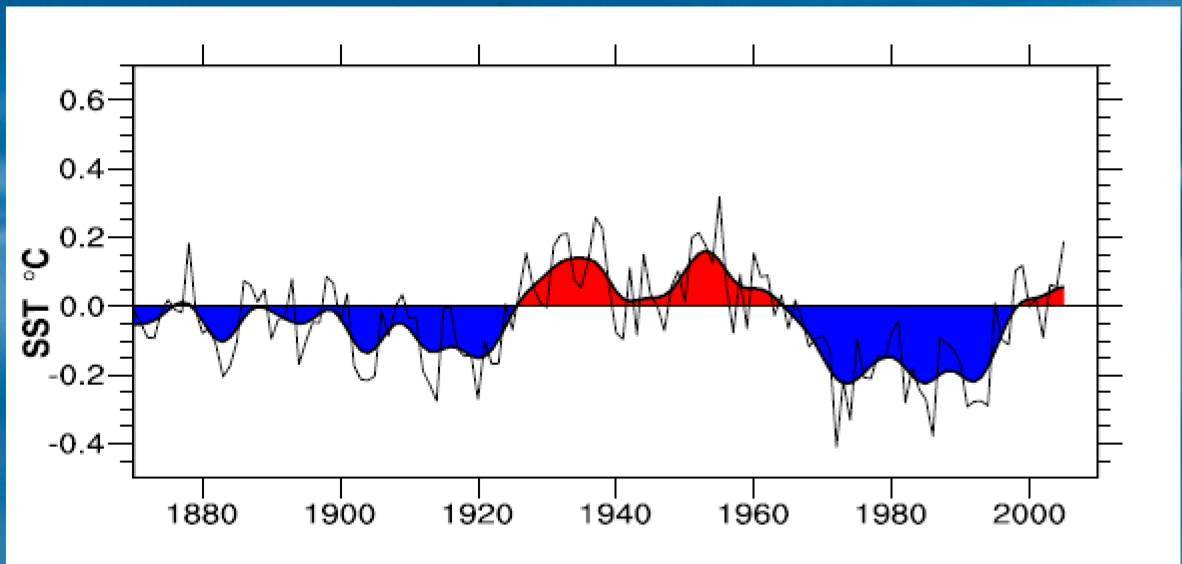
Wang et al. 2008 (Nature)

Is AMO another name for global warming?





SST changes of North Atlantic [0º to 60º N] (left) and global oceans [60º S to 60º N] (right) show similar temporal variability. Is one of them due to the other?



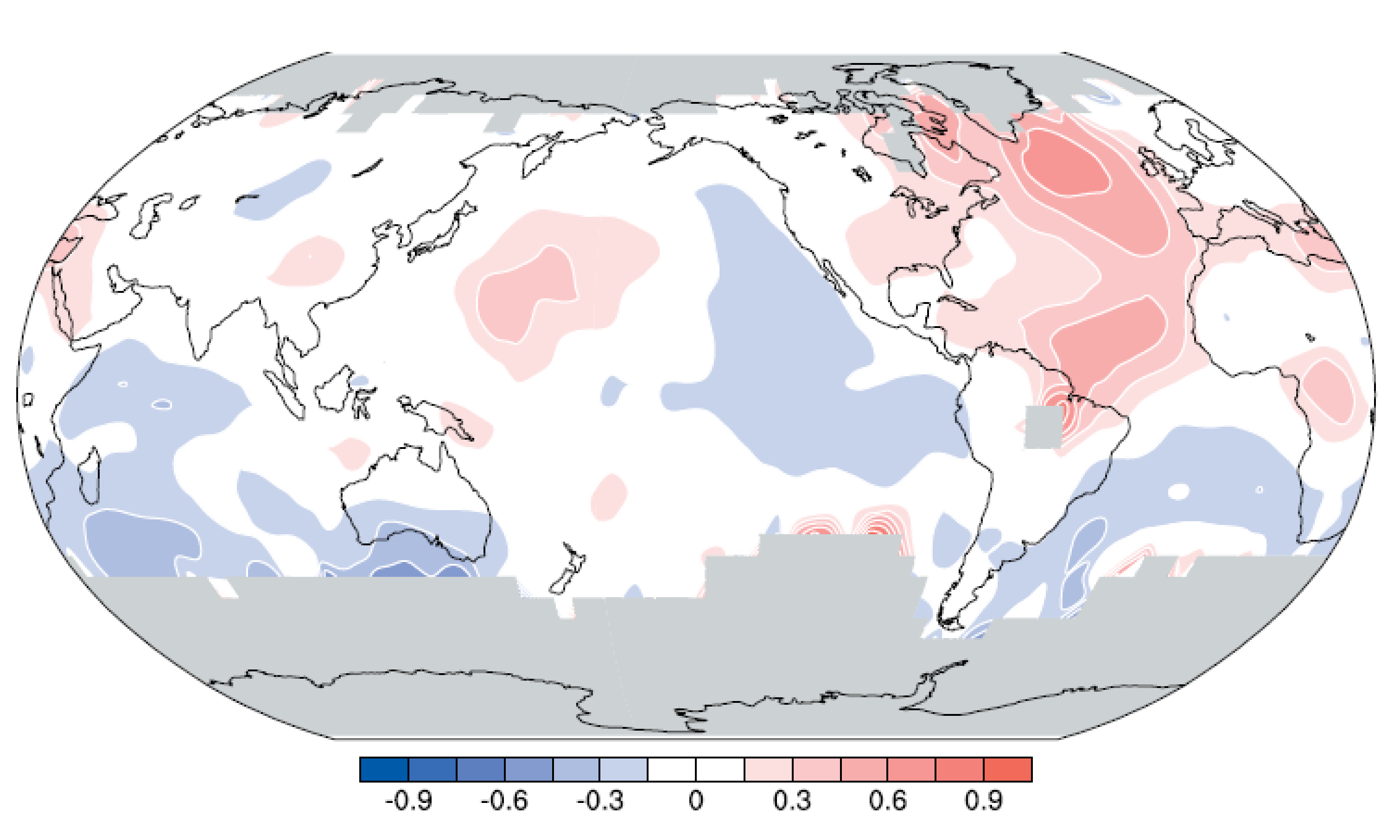
SST changes of North Atlantic with the global trend subtracted This can be treated as an improved AMO index.

Subtracting the global trend from North Atlantic SST time series shows the residual AMO. But isn't it strange that it is in phase with global temperature variability?

However it nicely explains the hurricane correlation if Vecci & Soden 2007 are right.

Trenberth Shea 2006 (Geophysical Research Letters)

Is AMO another name for global warming?
The spatial pattern.

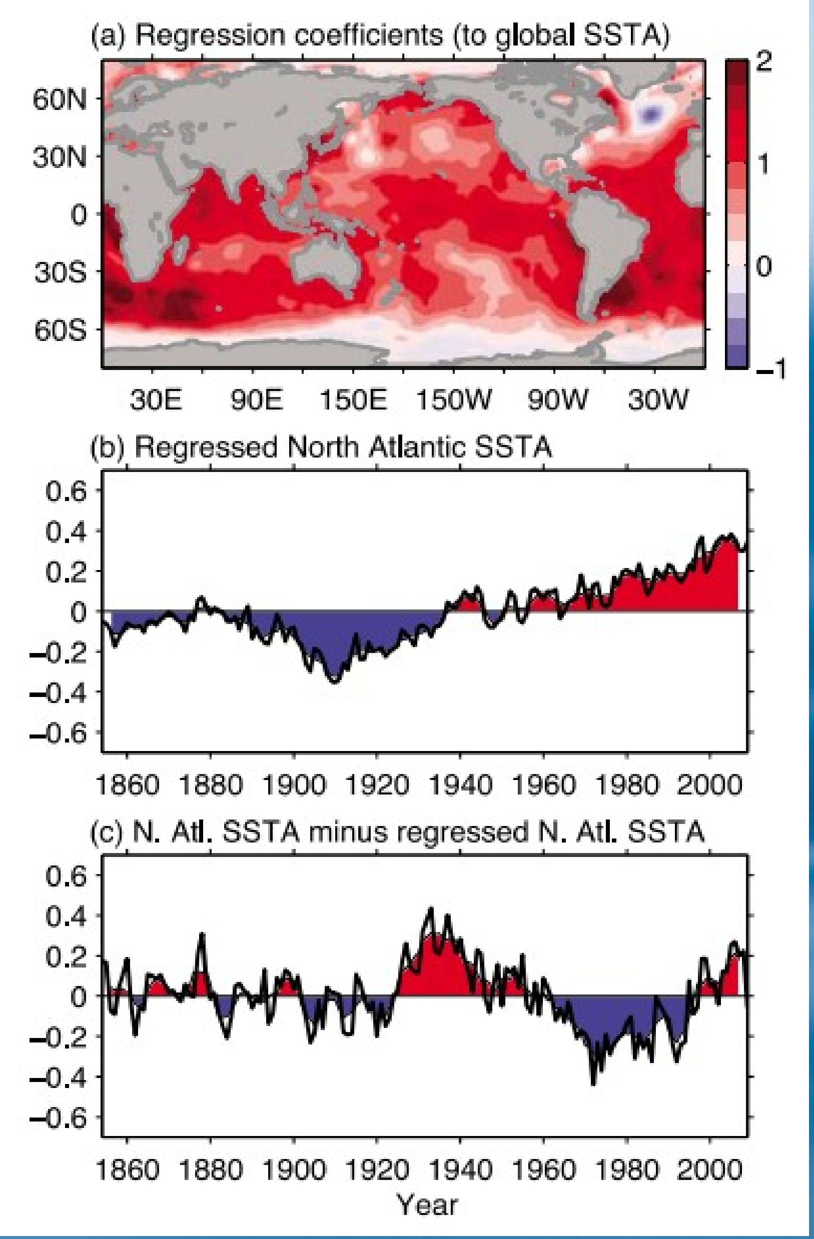


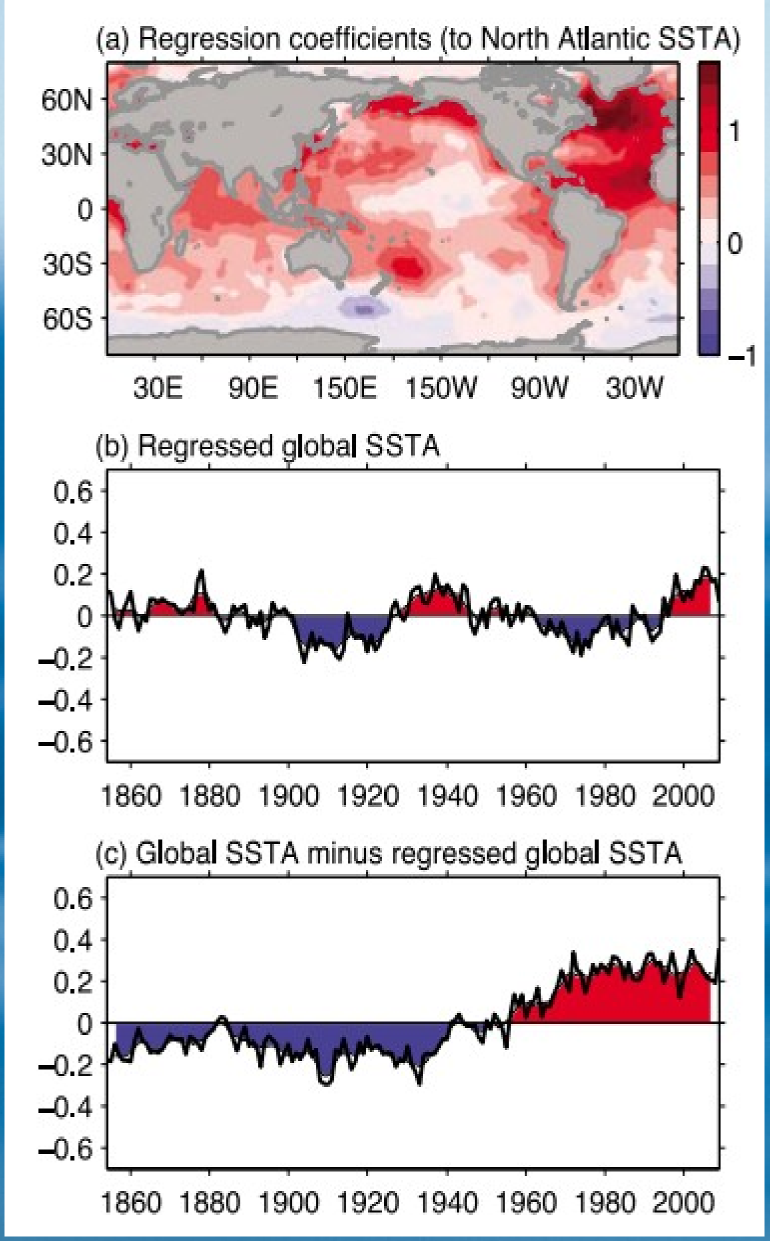
Correlation of the revised AMO index with global surface air temperatures for 1900 to 2004 based on annual values. Only values in the North Atlantic can be considered significant.

Is there a good reason for AMO to be in phase with global temperature?

Trenberth Shea 2006 (Geophysical Research Letters)

Global SST and AMO idices are not fully independent

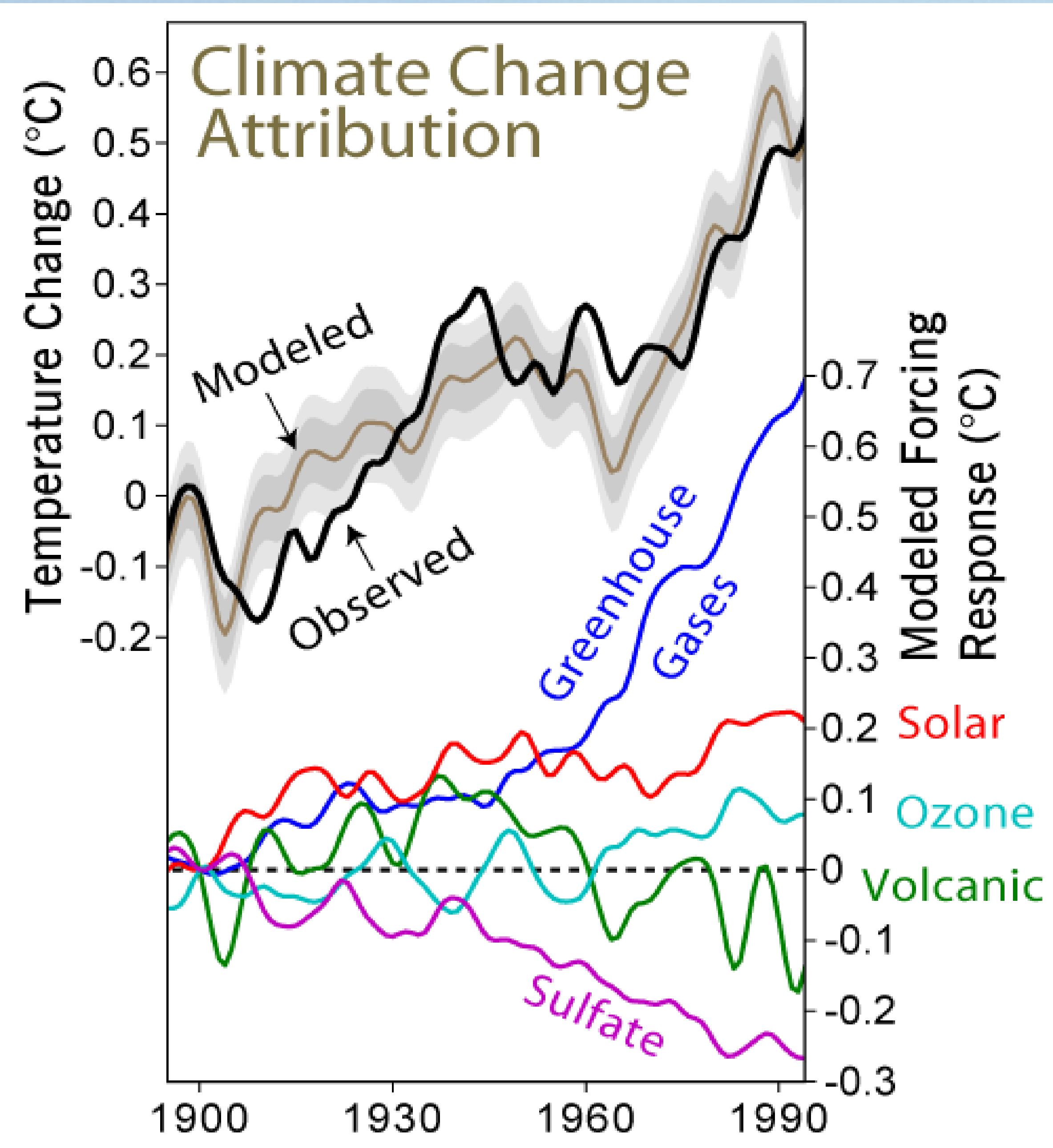




Influence of global SST on NA SSTs and the resulting “cleaned” AMO index (left) and the influence of AMO on world temperatures and the AMO-free global temperature data series.

Wang & Dong 2010 (GRL)

There is only one problem...



It seems we do not need THC to explain the average changes of Earth temperature.

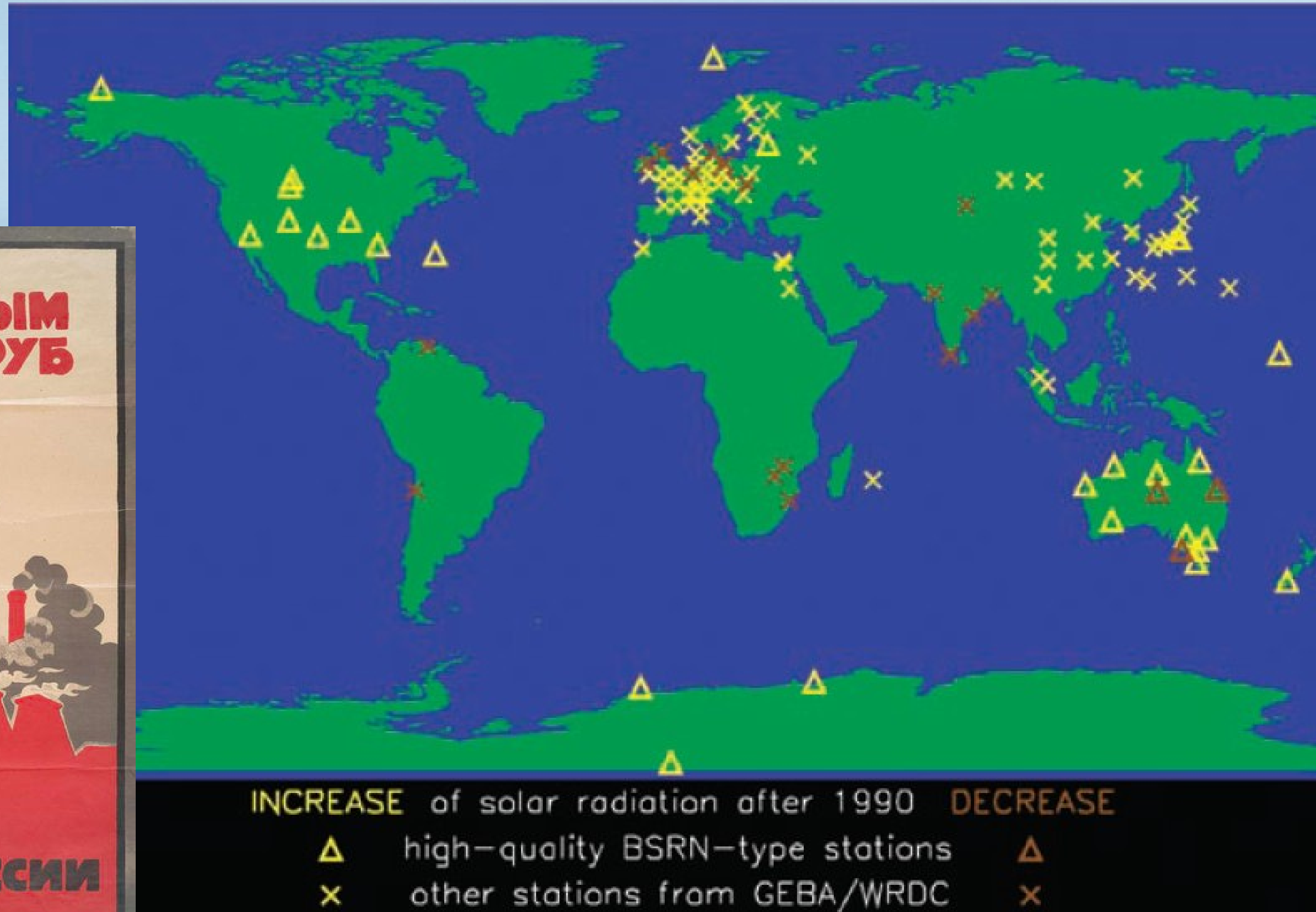
Warming of the 1920s and 1930s was caused by increasing solar activity and green house gases and a break in volcanism.

The cooling of 1950s and 1960s was due to more aerosol emission (industrial sulfur rich smoke) and increase of volcanism.

The last 30 years were dominated by greenhouse gases increase.

Meehl et al. 2003, 2004 (Journal of Climate)

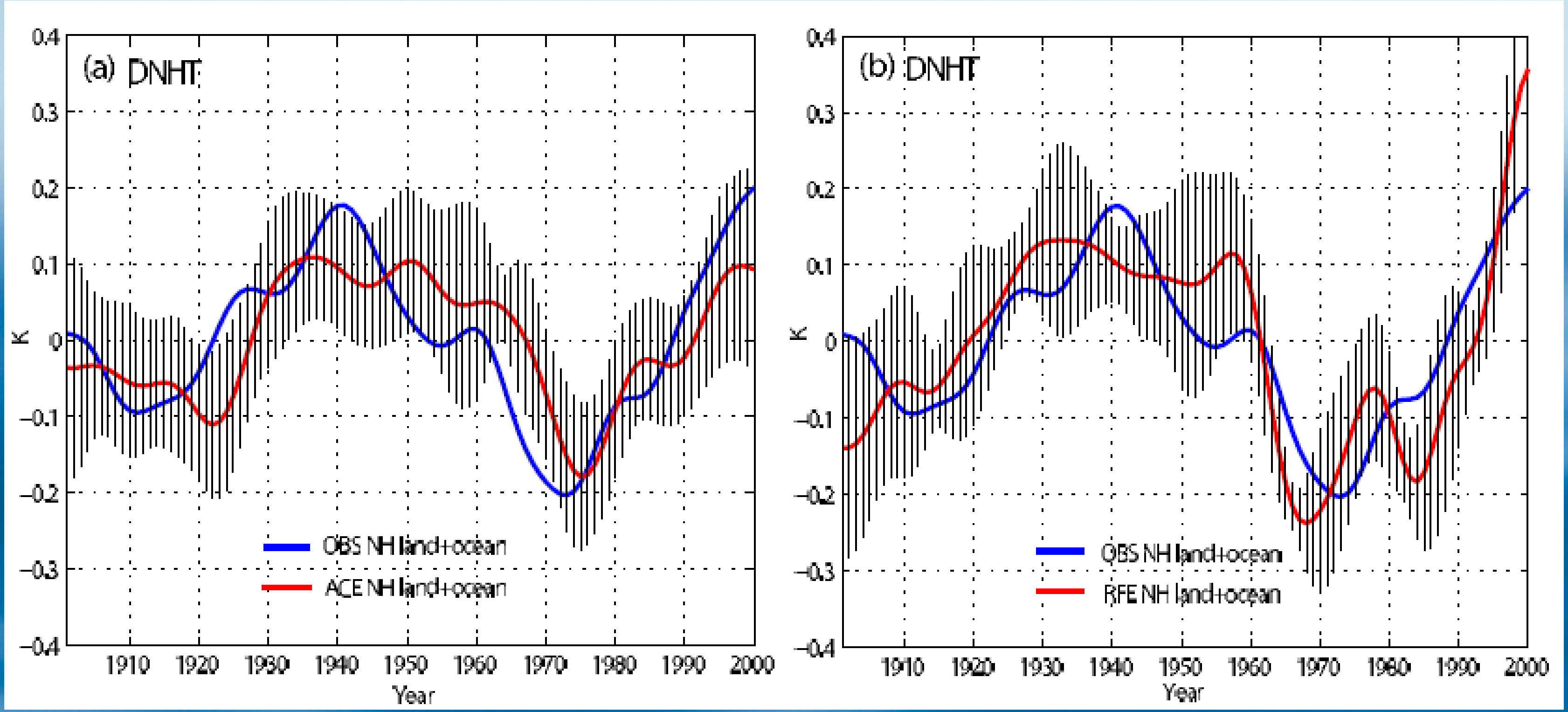
Brightening of Earth (since 1990)



Most stations measuring aerosol optical thickness note increasing irradiation (less aerosol) since 1990. Only tropical stations in India subcontinent, Africa and South America show decrease of irradiation. Especially the Northern Hemisphere became clearer since the fall of Soviet era heavy industry.

Wild et al. 2005 (Science)

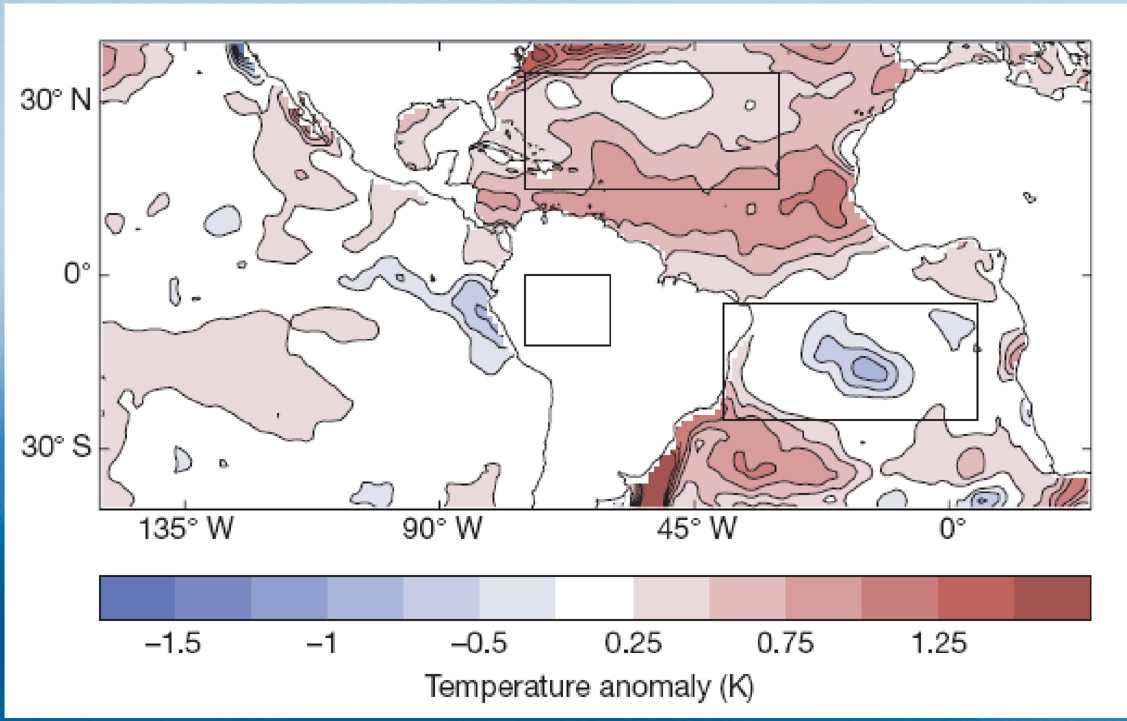
Again: why is AMO in phase with greenhouse and aerosol forced global warming?



Northern Hemisphere temperatures measured and modeled using AMO forced (left) and greenhouse gas forced (right) general circulation model. Both allegedly explain the observed variability. This looks too good to be true. Unless...

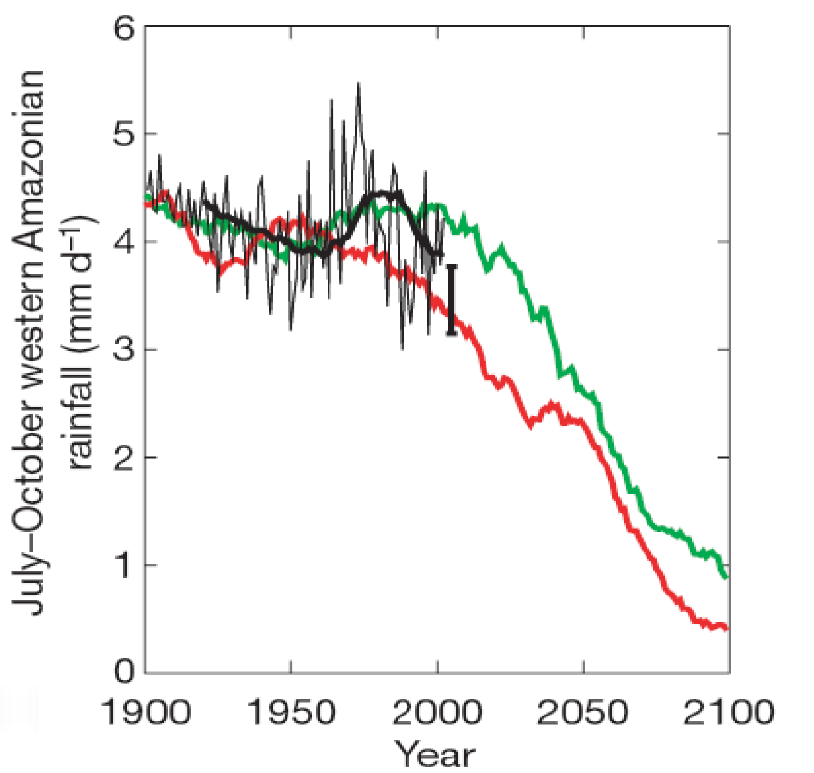
Zhang Delworth Held 2007 (GRL)

Apparently other people are thinking too...



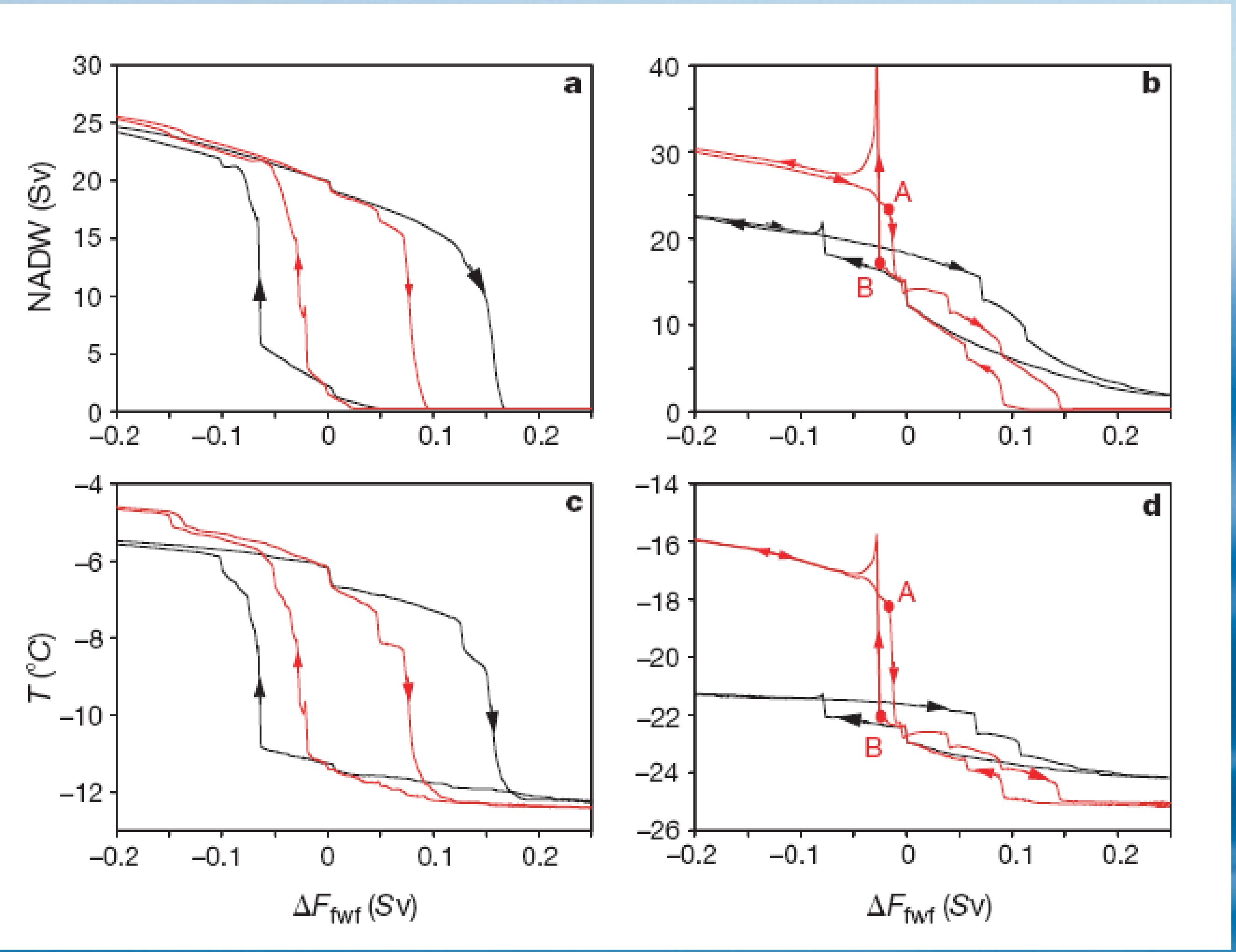
Met Office Hadley Centre has the only operating global model with interactive aerosol and carbon cycle: HadCM3LC. A recent study of droughts in the Amazonia (left: 2005 drought) links them to ITCZ shifts... caused by hemisphere differences in aerosol forcing.

Right: July-October western Amazonian rainfall (black) with 20 year average, results of HadCM3LC model runs with greenhouse gases only (red) and greenhouse gas + aerosol (green). The future part of the runs suggests dry western Amazon in the greenhouse world.



Cox et al. 2008 (Nature) *Published on April 29, 2008*

A reminder: THC volume depends on the inflow of fresh water to North Atlantic

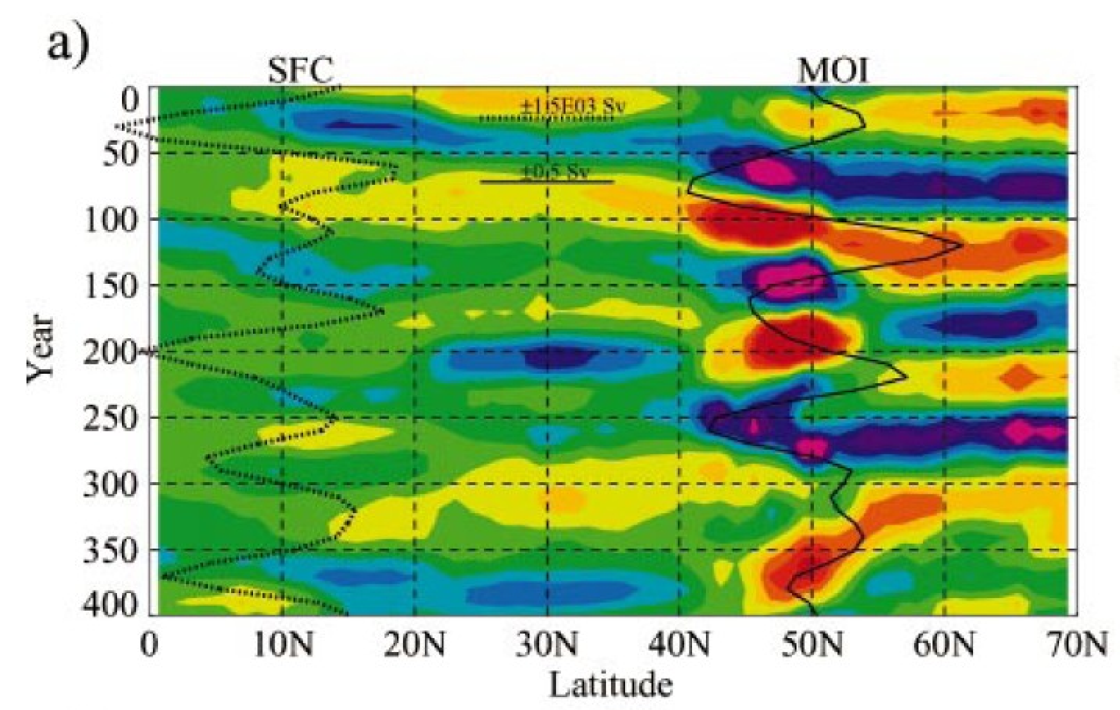


Model of NADW production (*top*) and SST (*bottom*) of present day North Atlantic (*left*) and glaciation era Atlantic (*right*) as a function of fresh water inflow flux into Subarctic (*red*) and Polar (*black*) Atlantic

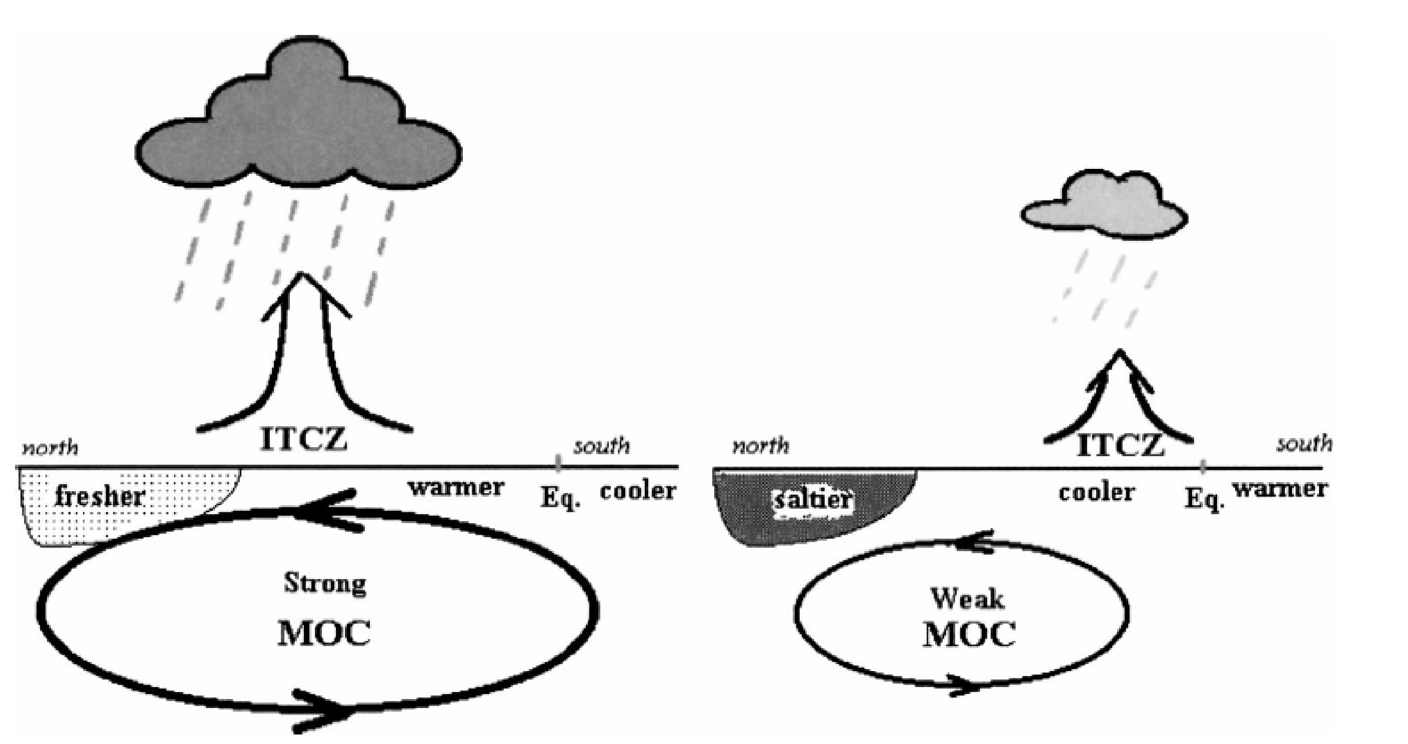
Climate models show that fresh water influences NADW production in non-linear way (with a hysteresis). In order to stop THC, nature needs more fresh water added far from the Arctic (in the Tropical Atlantic) or less added in the Subarctic. In the glacial times the hysteresis loop was narrower (due smaller NADW producing basins) which caused the climate to be unstable.

Ganopolski & Rahmstorf 2001 (Nature)

We have a mechanism for AMO



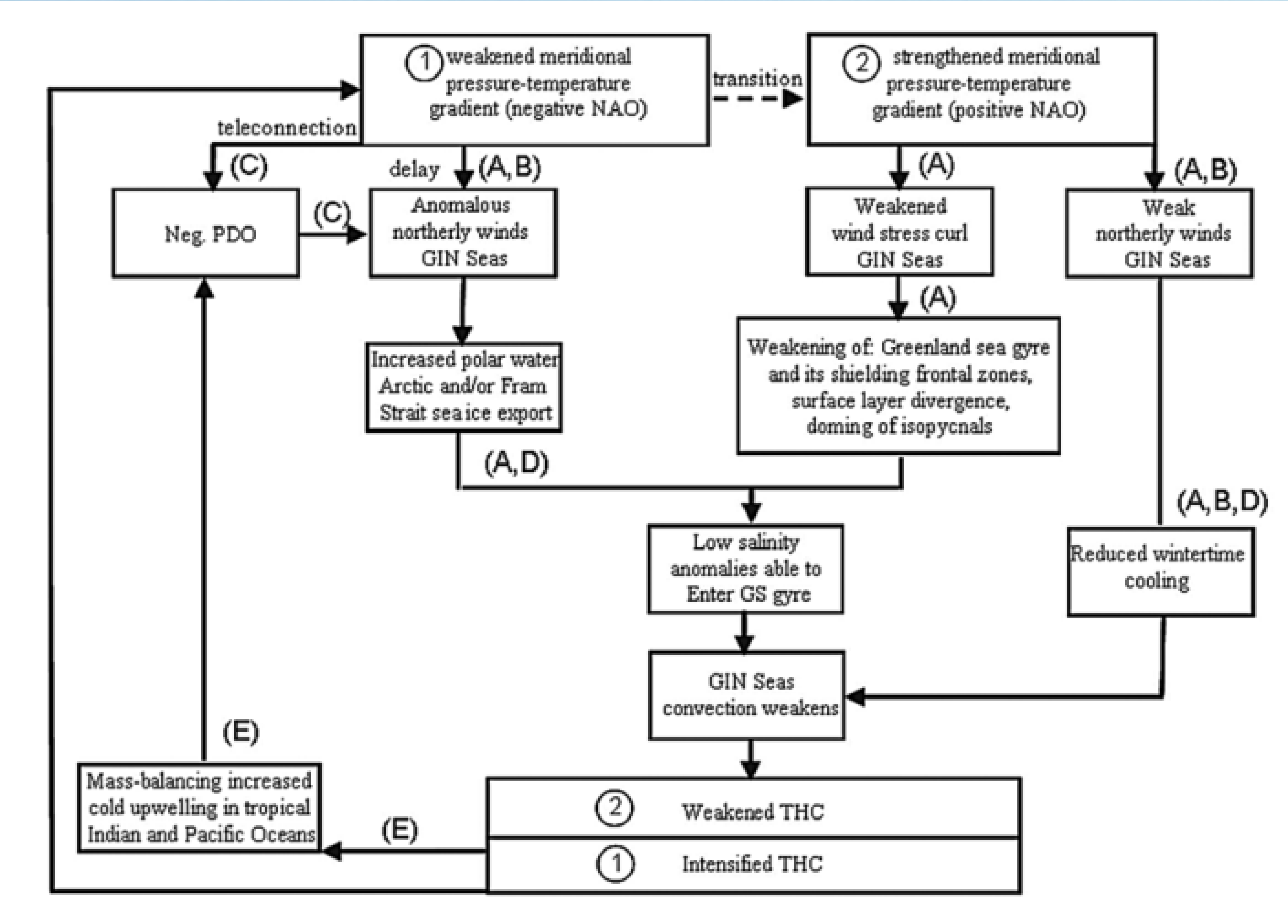
Unforced modeling with HadCM3 general circulation model shows a salinity pulse followed by freshwater pulse traveling from tropics northwards with a period of about 100 years.
The mechanism is as follows:



decreased THC →
south shifted ITCZ →
less rain in TAO →
salty impulse →
increased THC →
north shifted ITCZ →
more rain in TAO →
freshwater impulse →
decreased THC

Velliniga Wu 2004
(Journal of Climate)

We have even more than one possible mechanism



Dima and Lohmann proposed a more complicated mechanism involving NAO changes influencing freshwater inflows from the Arctic. The above graph is supposed to explain at least part of it.

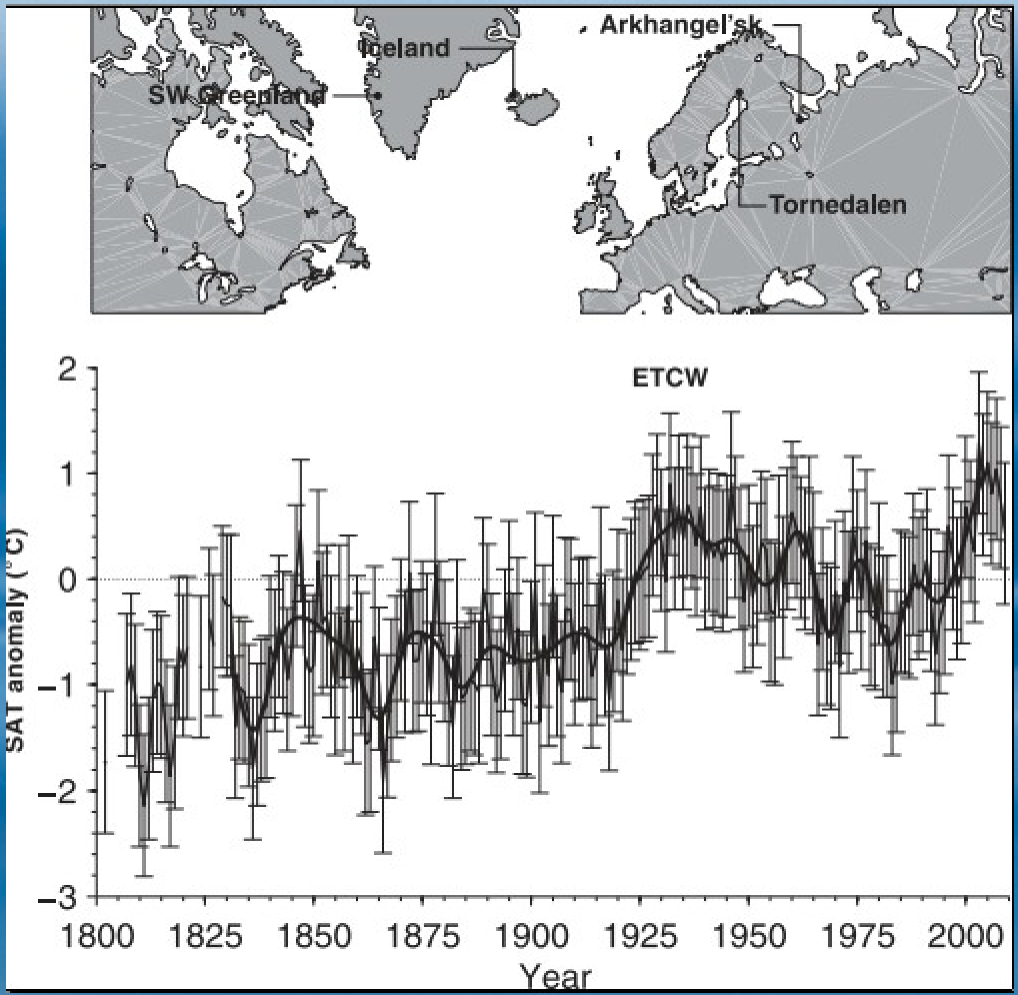
Grossmann & Klotzbach 2009 (JGR) explaining the mechanism proposed by Dima & Lohmann 2007 (or rather part of it)

So why is AMO in phase with “global warming”?

Because the anthropogenic forcings (especially aerosol related but also, to a lesser degree greenhouse gases) are stronger in the Northern Hemisphere, they create a inter-hemisphere temperature gradients. This moves ITCZ, influencing THC in similar manner as AMO itself. I believe it possible that we created a forced oscillator AMO pattern, forcing its phase to be in step with the sum anthropogenic forcings.

How could we possibly test the hypothesis? Only by using coupled general circulation models.

Some proof that AMO may be still a side-product of the 20th century anthropogenic forcings?



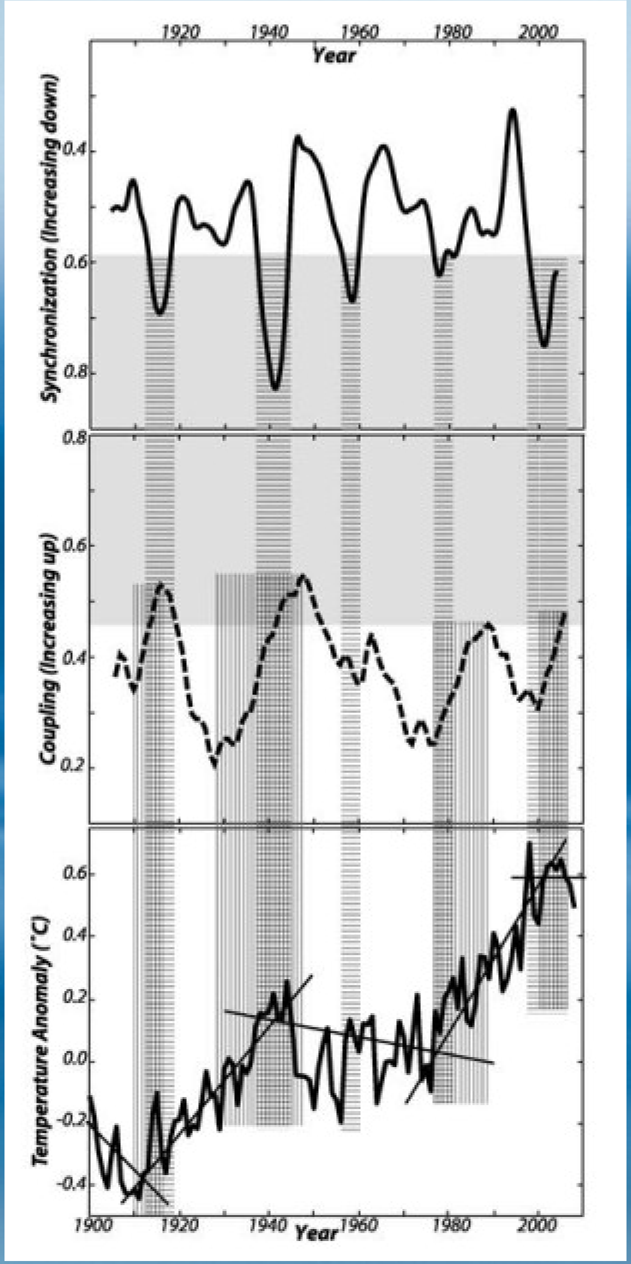
"Remember, no cycles!"
Jim Overland

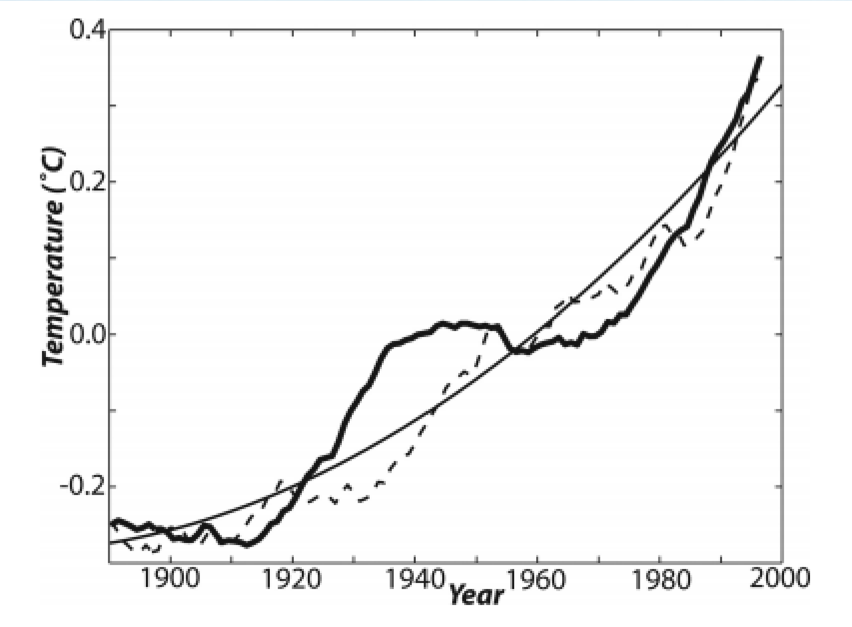
A new reconstruction of North Atlantic surface air temperatures from meteorological records going back to 1802 does not show a 60-70 year cycle before the beginning of the 20th century.

This leaves open the possibility that even as the cycle is a natural oscillation, it was put in motion only by anthropogenic forcing (most probably North Hemisphere aerosol load).

Wood, Overland, Jonsson & Smoliak 2010 (GRL – in press)

What it all means for our future
(*two different views by the same authors*)

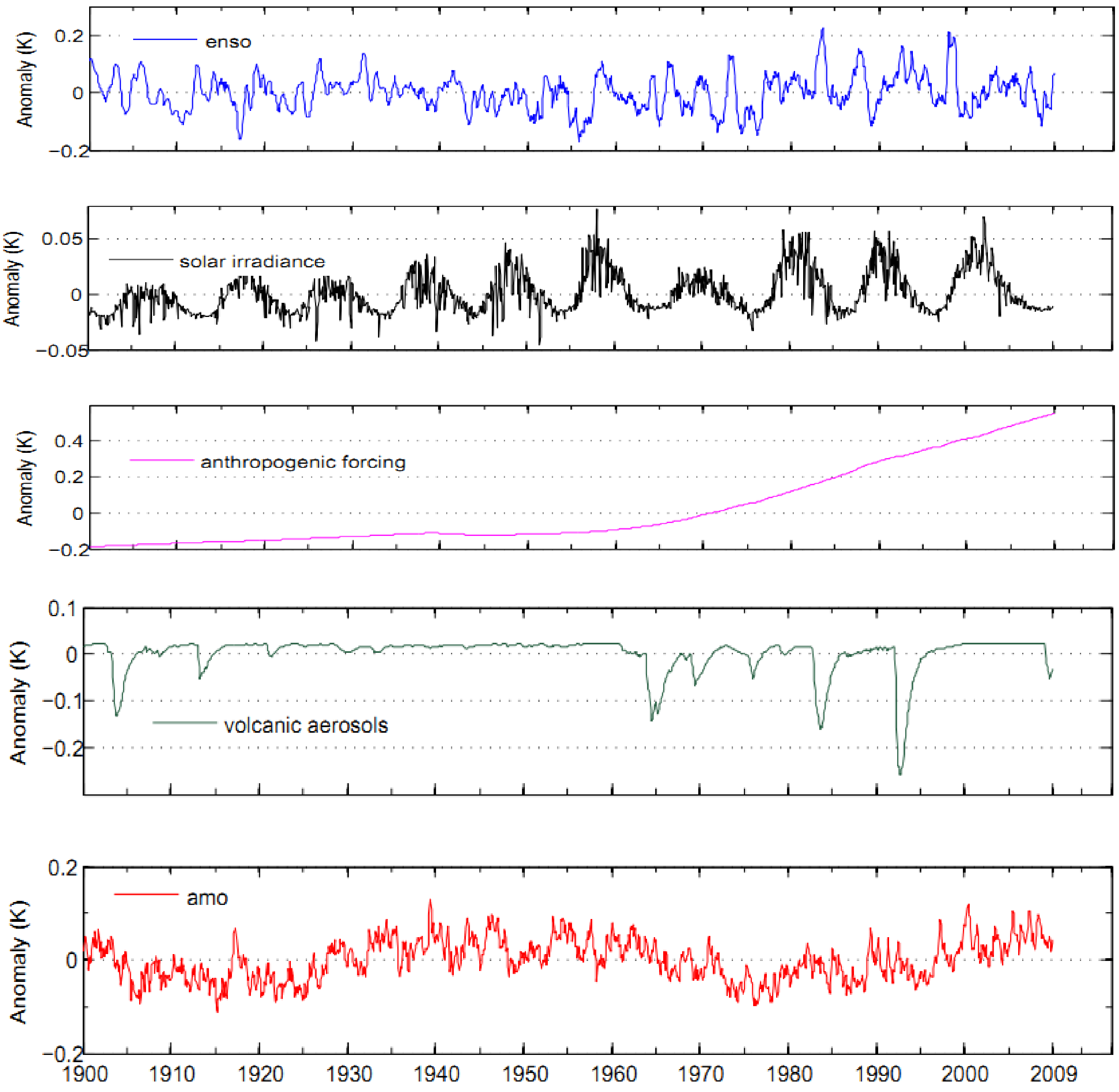




A statistical analysis of multiple climate indices (but not AMO) told Swanson and Tsonis that a a climate shift has recently happened. However adding one oceanographer to the team (and AMO) changed the story. Now the record (heavy solid) can be explained by AMO related variability and a greenhouse gases driven trend (dashed line – temperature with the variability is subtracted, thin solid – quadratic fit.

Swanson & Tsonis 2009 (GRL); Swanson, Sugihara & Tsonis 2009

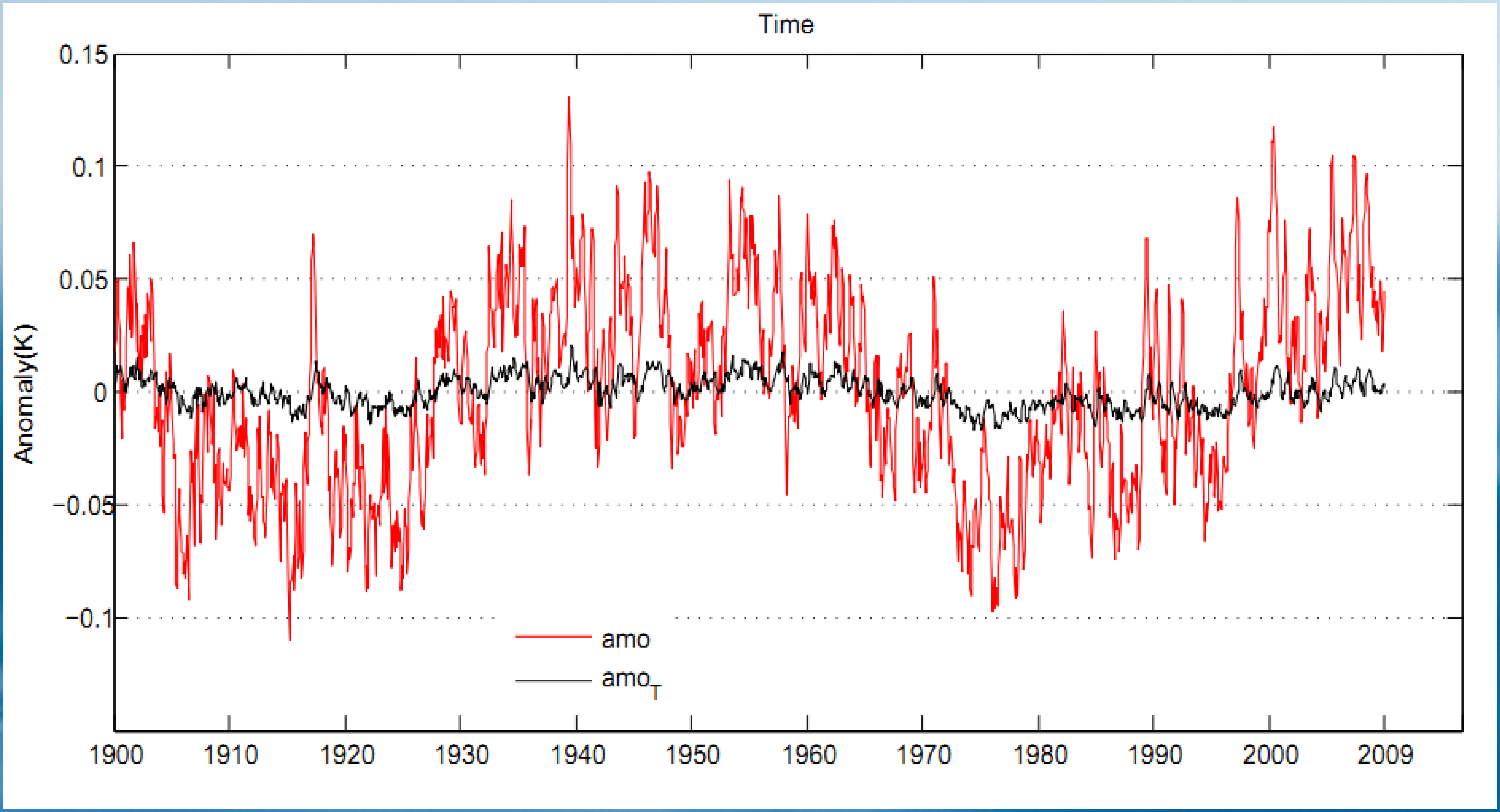
Attribution of global temperature anomalies



Attribution of 20th century global temperature variability to particulate natural and anthropogenic forcings (including AMO, added added as an additional forcing) from multiple regression analysis.

Piskozub & Gutowska 2011 (EGU 2011)

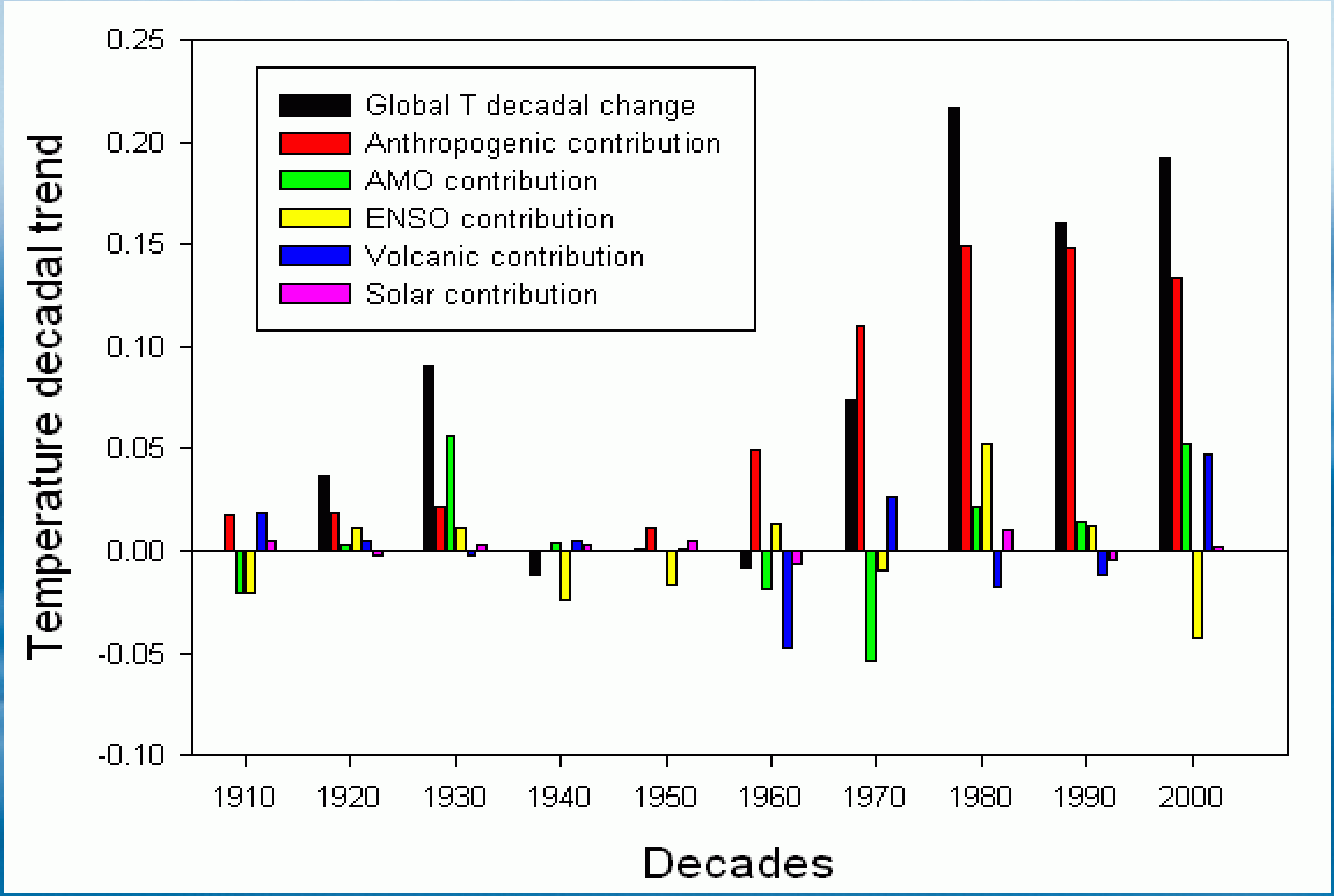
Constraining the AMO effect on global temperature



Attribution of AMO (red) and AMO_T (defined as AMO minus AMO regressed onto global temperature) (black) contribution into global temperature anomaly. The treat the former as an upper bound and the latter an the lower bound.

Piskozub & Gutowska 2011 (EGU 2011)

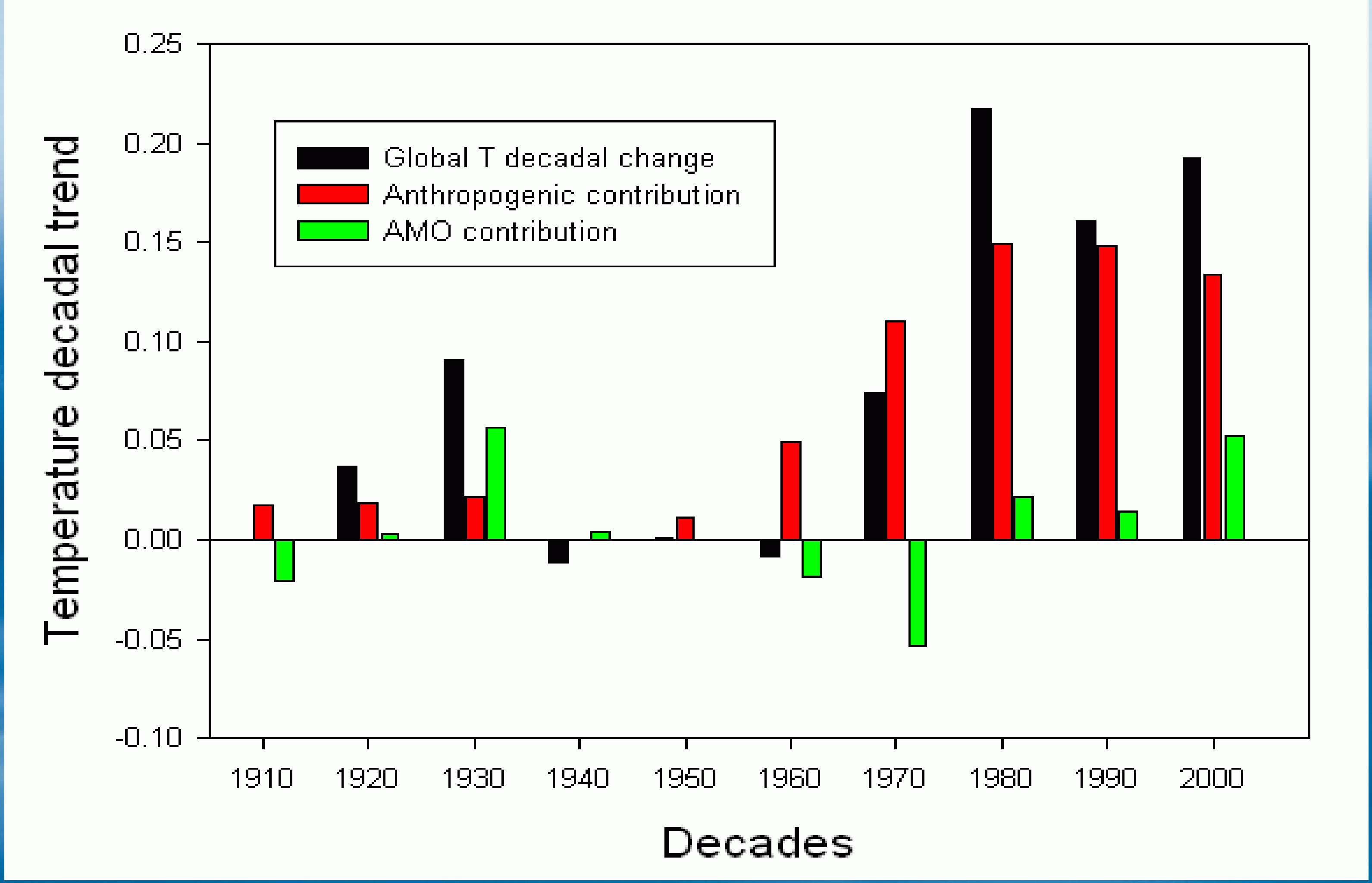
Attribution of global temperature anomalies



Decadal trends for each forcing component of global temperature anomalies, together with their sum (the reconstructed global temperature)

Piskozub & Gutowska 2011 (EGU 2011)

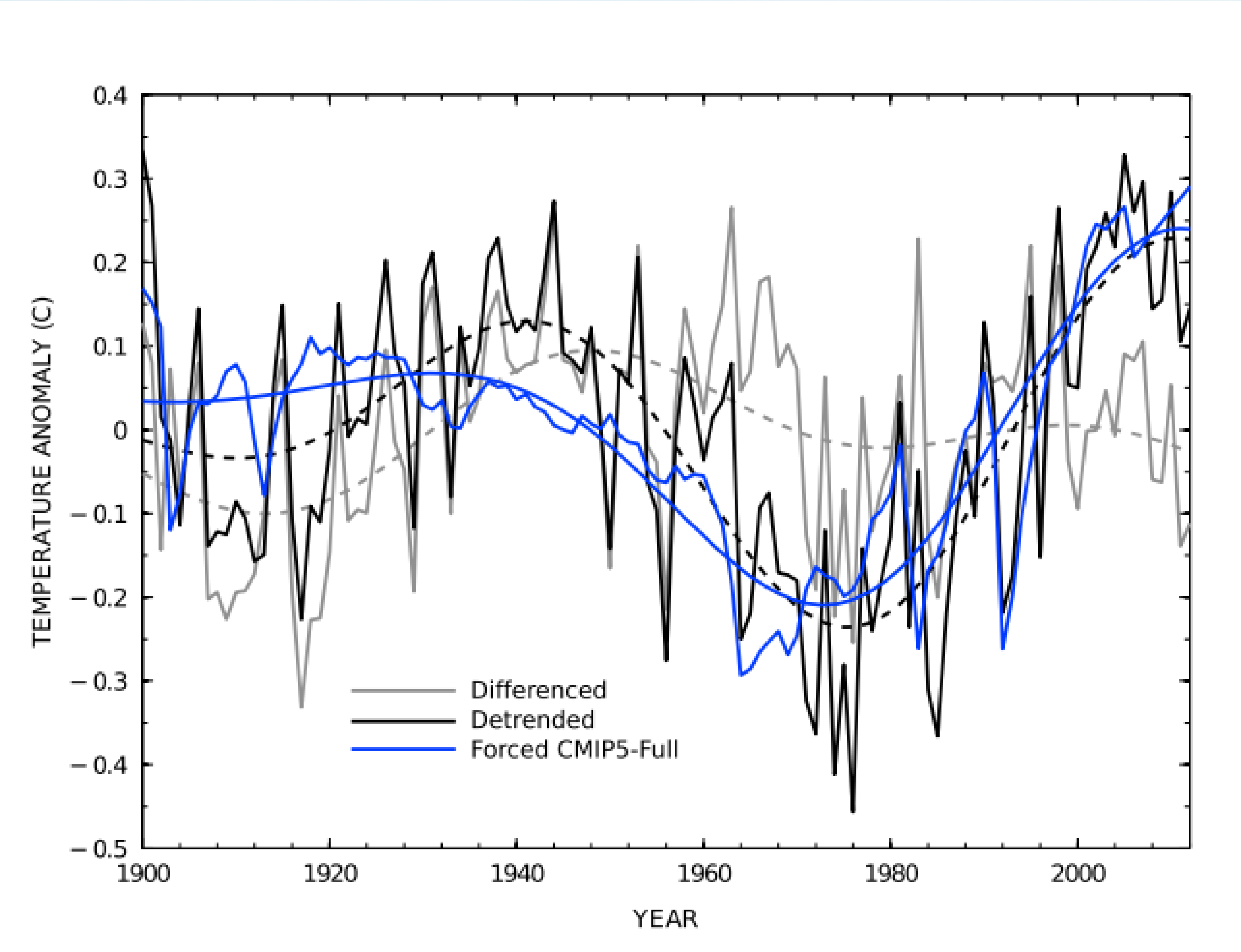
Anthropogenic and AMO related component of decadal temperature trends



Comparison of anthropogenic and AMO contributions to temperature change between subsequent decades. It is obvious that AMO may increase or decrease decadal trends by up to 1/3 of their values and that the next change will be rather down than up (assuming the 70 year period will continue)

Piskozub & Gutowska 2011 (EGU 2011)

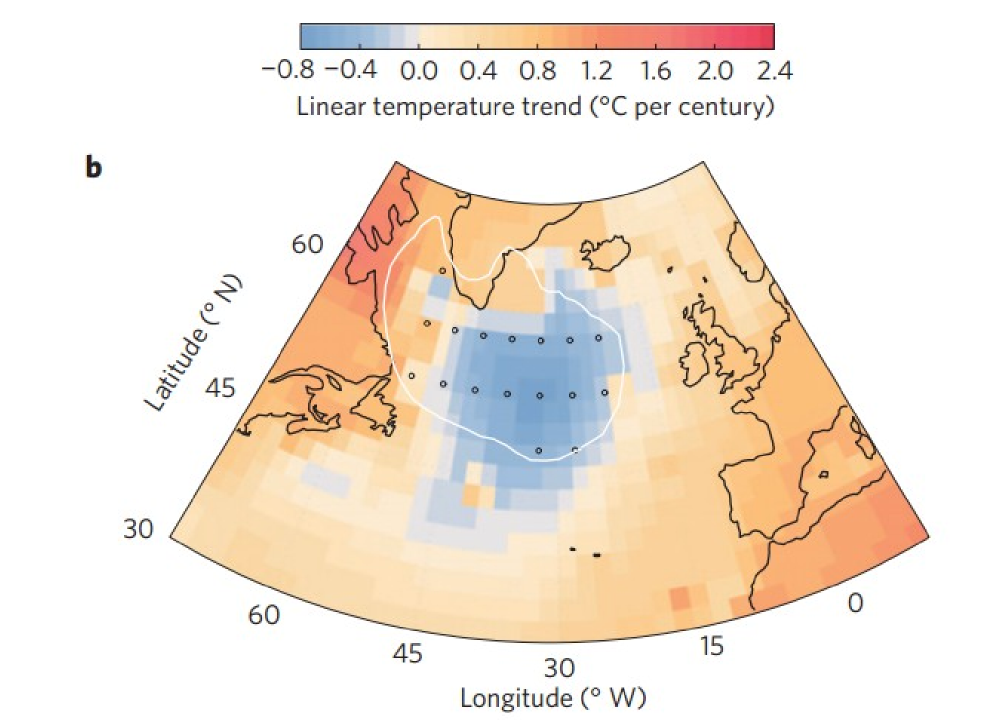
Is AMO definition wrong?

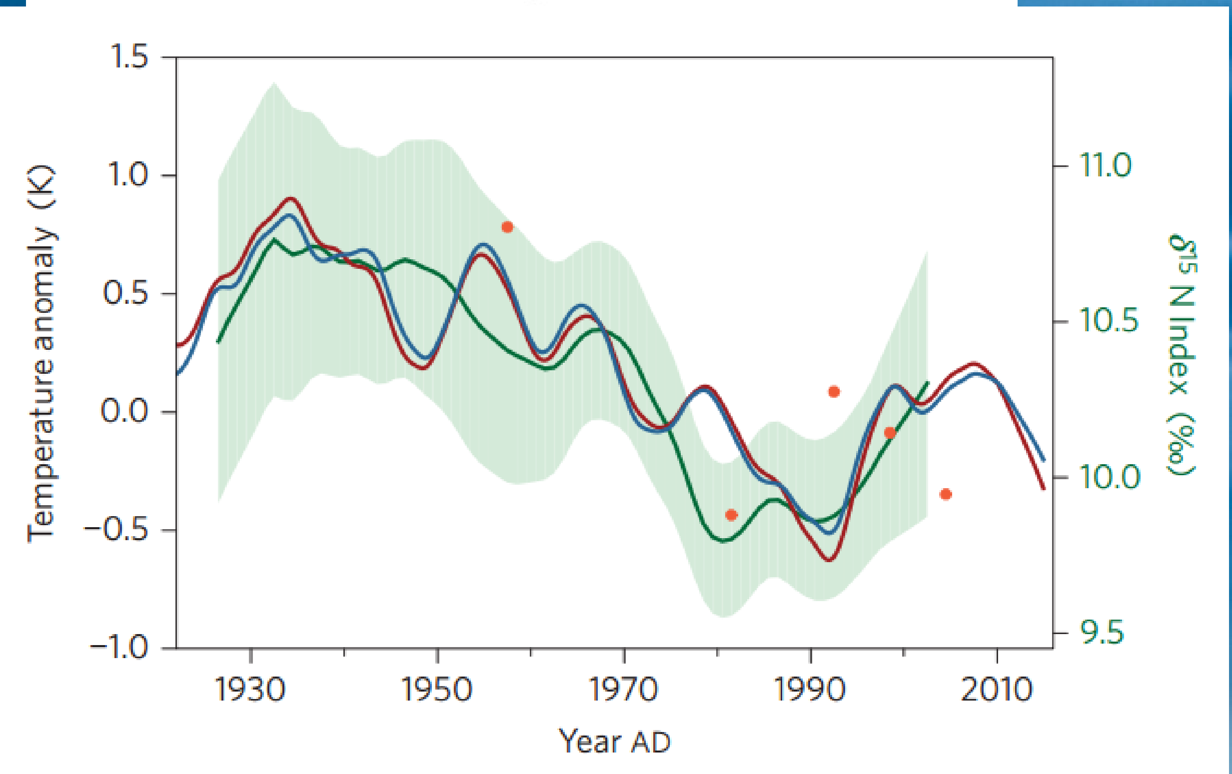


The authors propose to use instead of detrended AMO (black), a version which is subtracted from the effect of all known external forcings (blue), a "differenced AMO" (gray). If they were right, AMO would be much less pronounced and would not have a maximum since the 1940s.

Mann, Steinmann & Miller 2014 (GRL)

Was AMOC slowing down most of the 20th century?

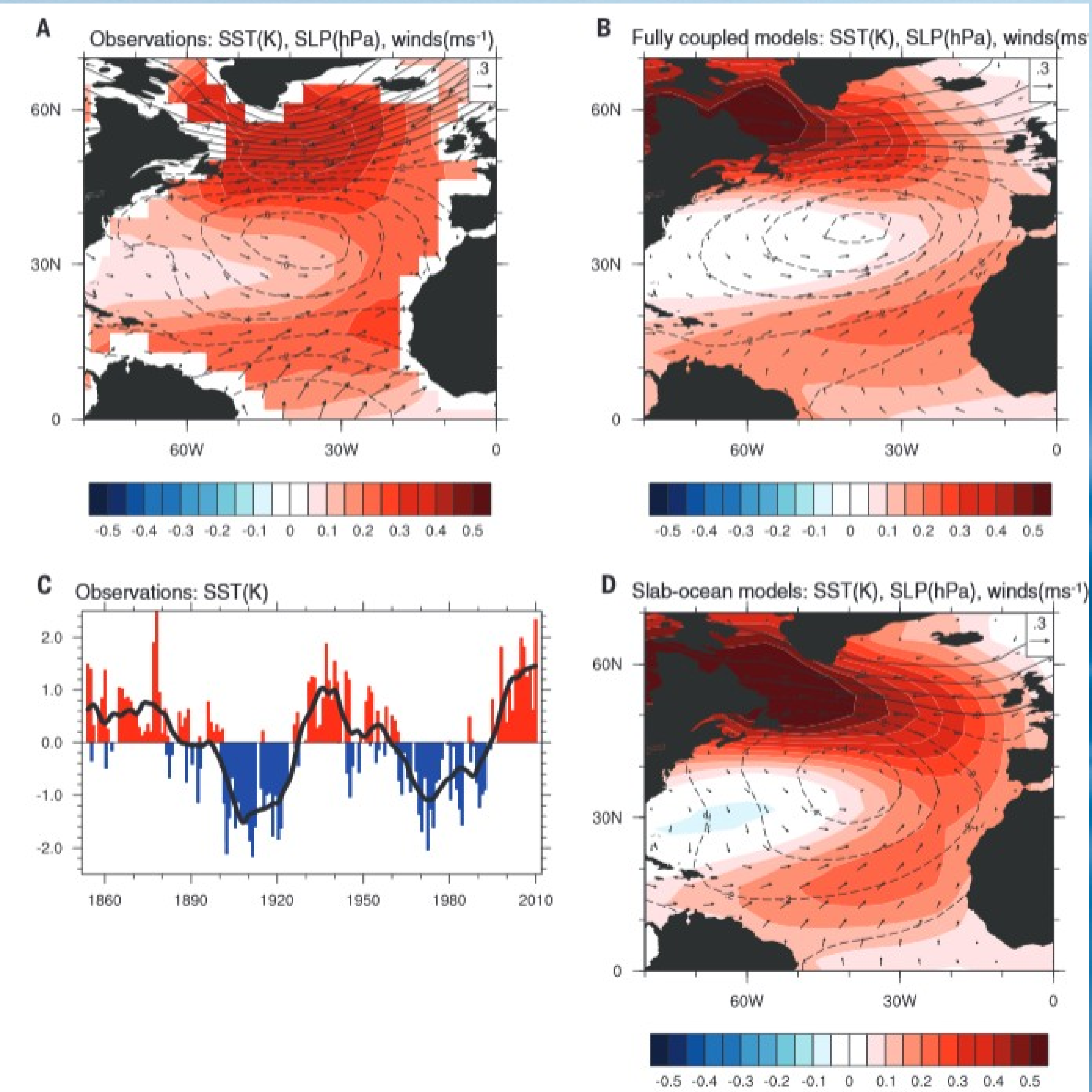




Rahmstorf et al 2015 used an idnex of AMOC based on the difference of temperature between the Subarctic Gyre and North Hemisphere. They claim to observe a weakening of AMOC between 1930 and 1990 using climate proxies (blue), GISTEMP (red) and a coral based proxy (green with uncertainty band). They aso compare it to 29 N AMOC measurements (red dots).

Rahmstorf et al 2015 (Nature Climate Change)

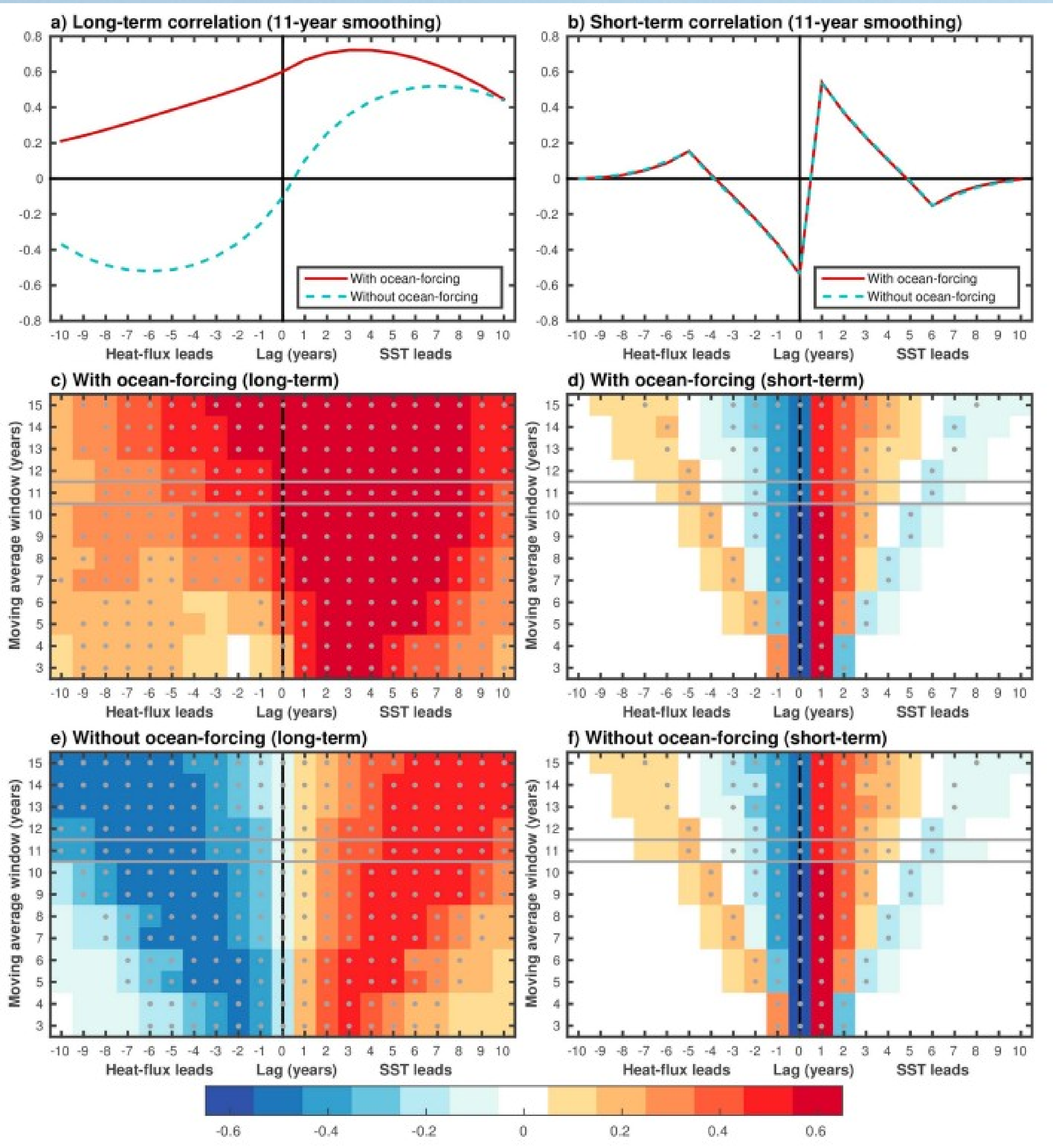
Or maybe there is no AMO at all?



Clement et al see the same SST (shaded), SLP (contours) and wind (arrows) anomalies regressed on AMO in observations (A), fully coupled (B) and slab ocean (D) models. However their models dis not have any cycle longer than 30 years.

Clement et al 2015 (Science)

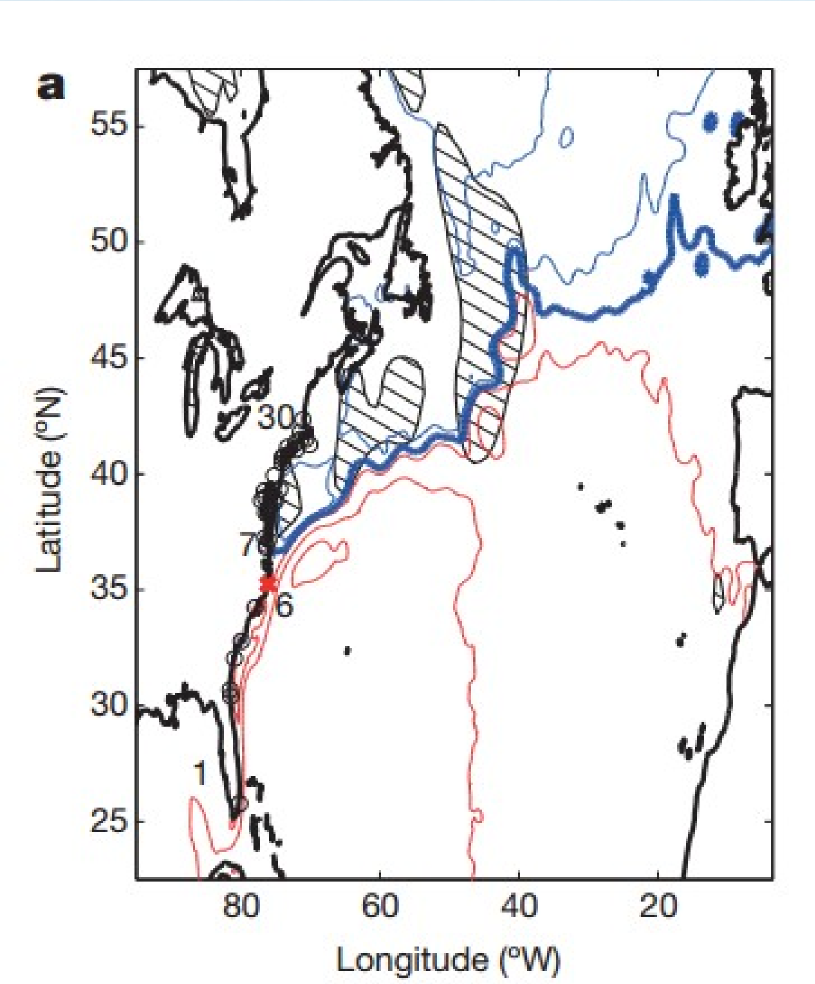
Yes there is. AMO is real.

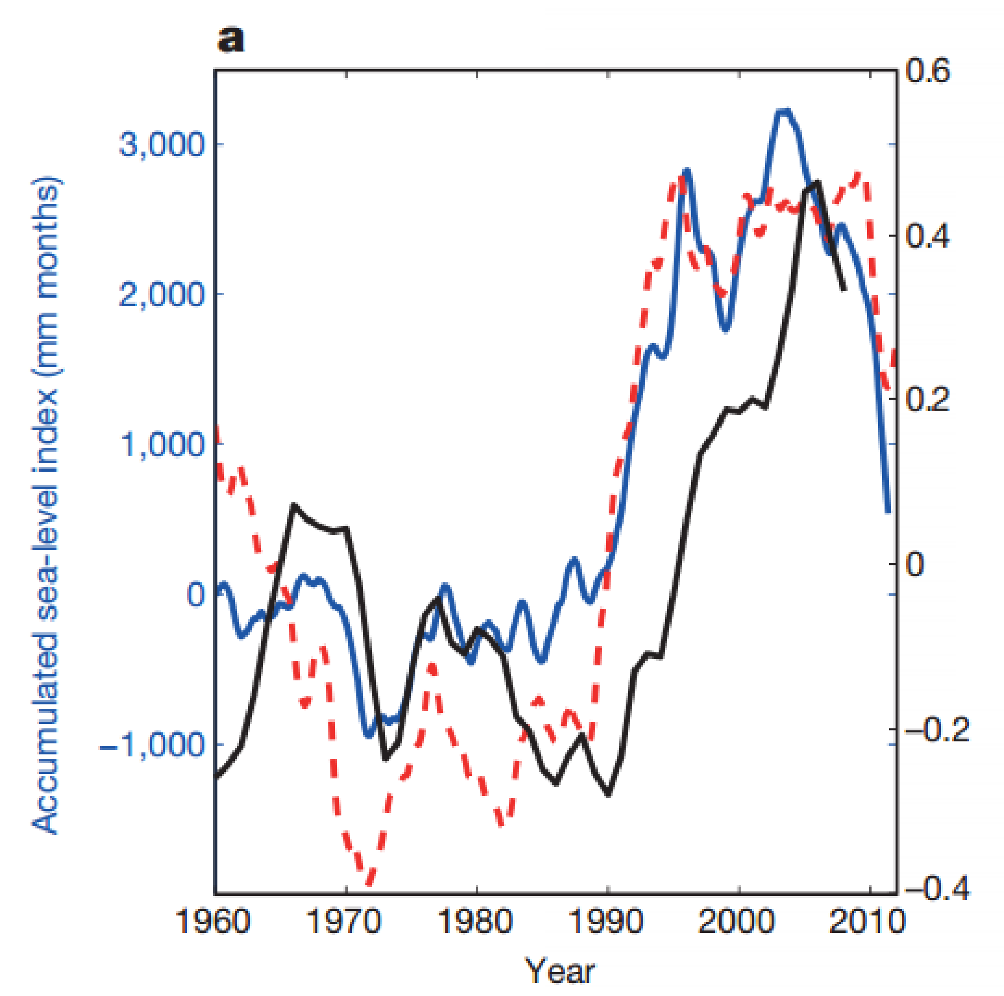


If AMO is divided into long and short-term variability Clement et al see the surface fluxes ave the same sign before and after an AMO maximum with ocean-forcing models (as in observations) but not with ocean-slab models (bottom). The short term variabiity is similar: heat fluxes to the ocean before and from after a SST increase.

O'Reilly et al 2016 (GRL)

First physical evidence for past AMO





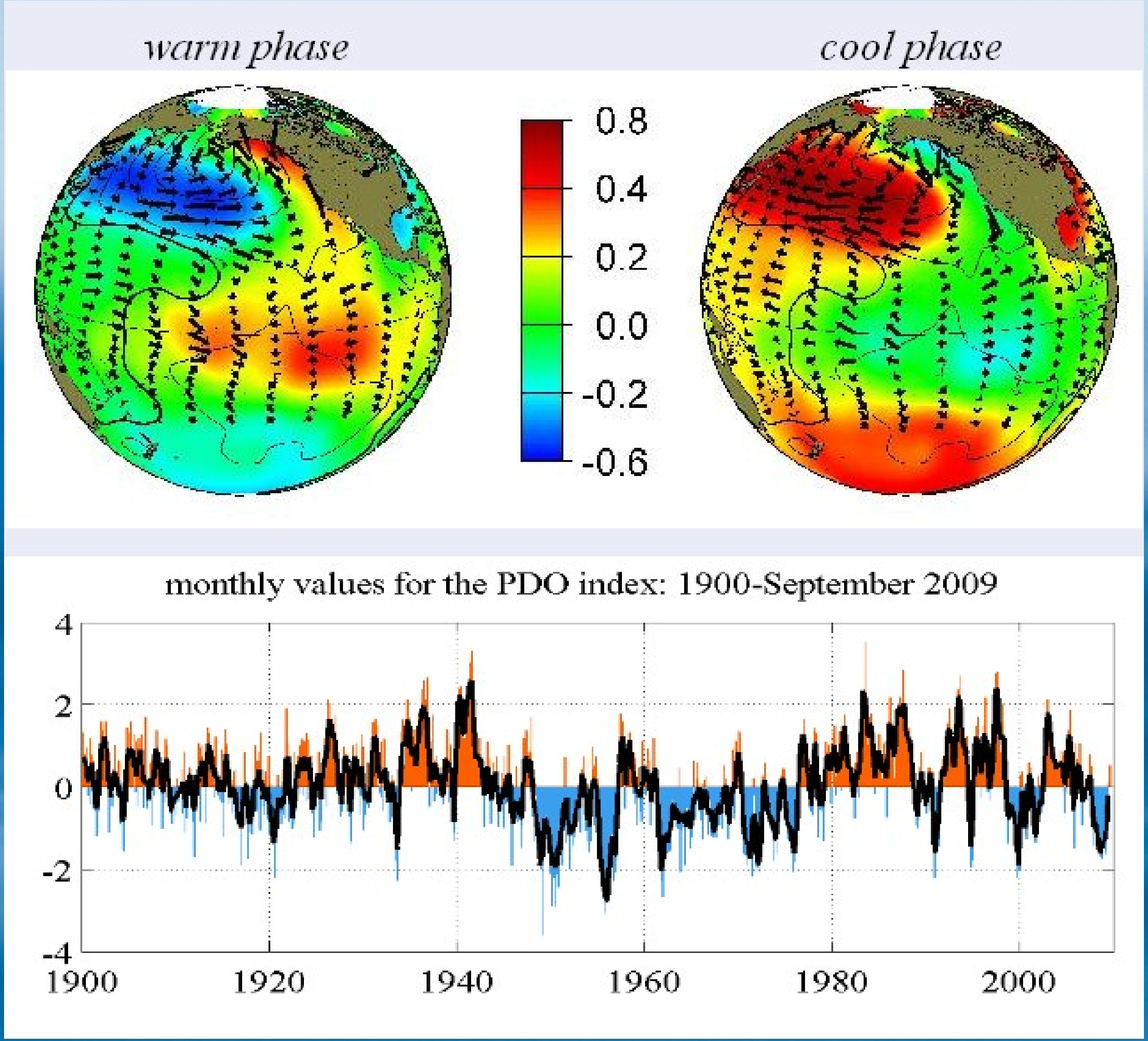
McCarthy et al. 2015 used sea surface data from North Atlantic coastal stations as a measure of AMOC (sea positive [red] and negative [blue] contours of regressed AMOC). The accumulated sea-level inndex (blue) looks very similar to AMO (black) and even more to accumulated (integrated) NAO.

McCarthy et al 2015 (Nature)

Podsumowanie 1/3

- Jednym z głównych elementów zmienności temperatury XX wieku jest cykl o okresie ok. 70 lat, związany z regionem wokół Północnego Atlantyku, zwany Atlantycka Oscylacją Multidekadową (AMO).
- Wzorzec przestrzenny AMO, a szczególnie odwrotna faza zmian w okolicy Arktyki i Antarktydy świadczy, że związany jest on ze zmian ami intensywności cyrkulacją termohalinowej
- Jesteśmy w stanie wytłumaczyć taki cykl zmianami opadów w rejonie tropikalnego Atlantyku Północnego wymuszonymi różnica temperatur obu półkuli i spowodowanymi tym zmianami zasolenia Atlantyku.
- Jednak podobne różnice temperatur między półkula północna i południową mogliśmy wywołać zadymiając tę pierwszą w pierwszej połowie XX wieku
- Czy zatem "rozkołysalismy" naturalny mod zmienności THC przy pomocy aerozolu? I czy ta zmienność będzie kontynuowana i czy oznacza to wolniejszy wzrost temperatury przez następne 30 lat?

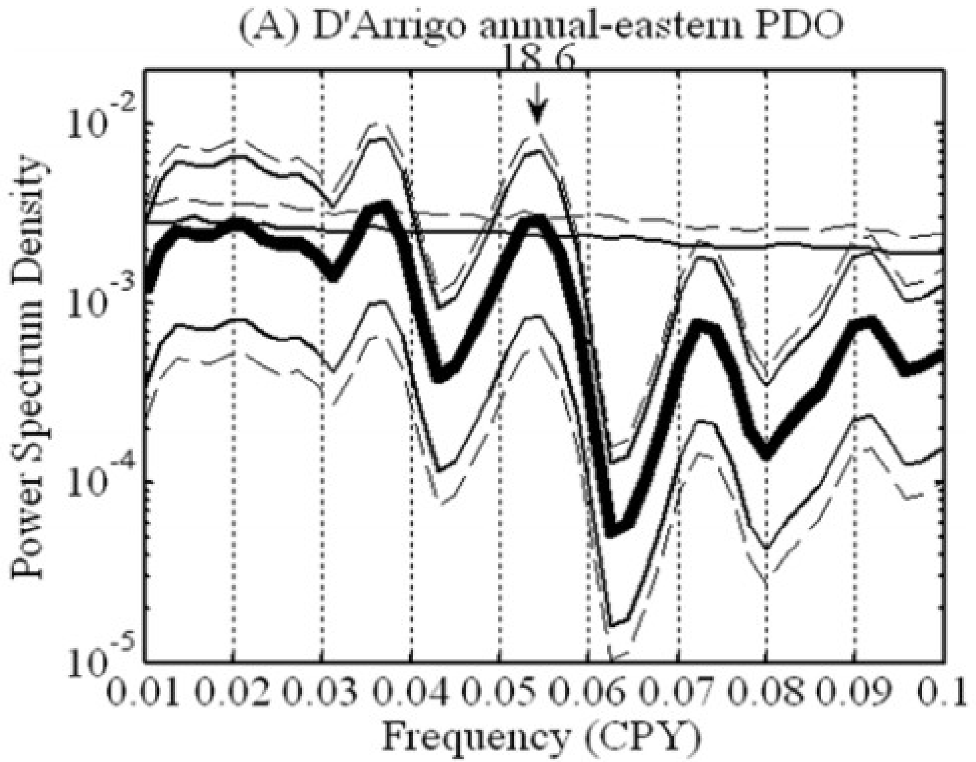
Pacific Decadal Oscillation (PDO)

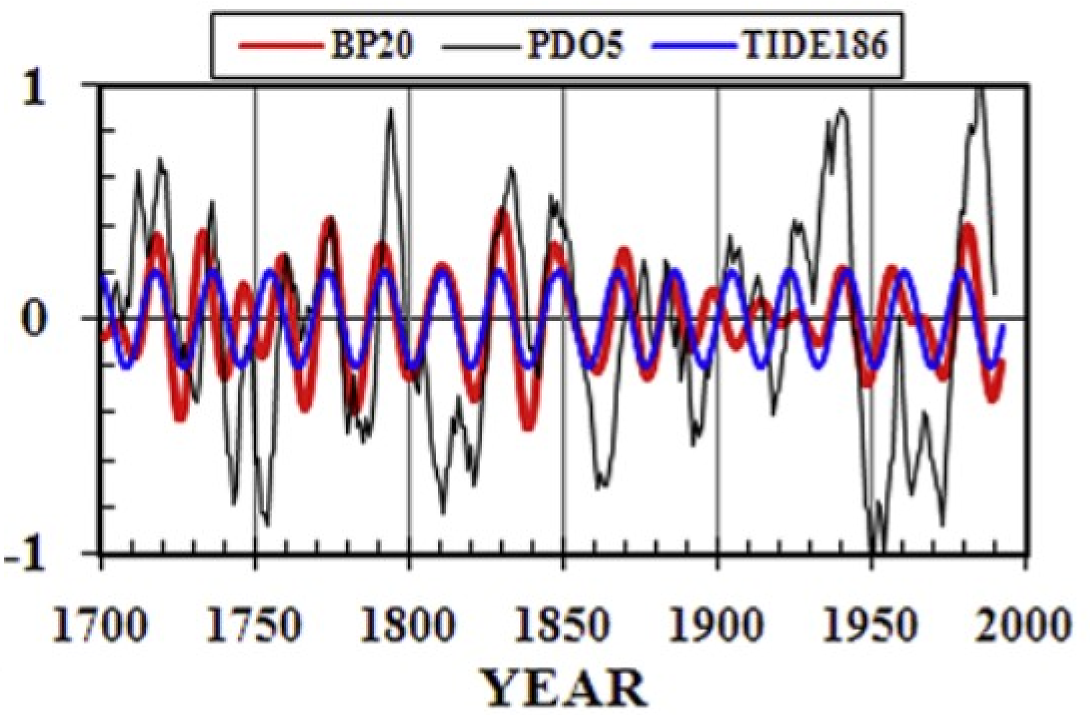


Odpowiednikiem AMO na Pacyfiku jest PDO, o okresie cyklu ok. 20 lat, zidentyfikowany przez Latifa i Barnetta (1994) i zdefiniowany jako pierwszy EOF zmienności temperatury Pn. Pacyfiku przez Mantuę i innych (1997).

http://jisao.washington.edu/pdo/

PDO is phase-locked to Lunar tidal cycle



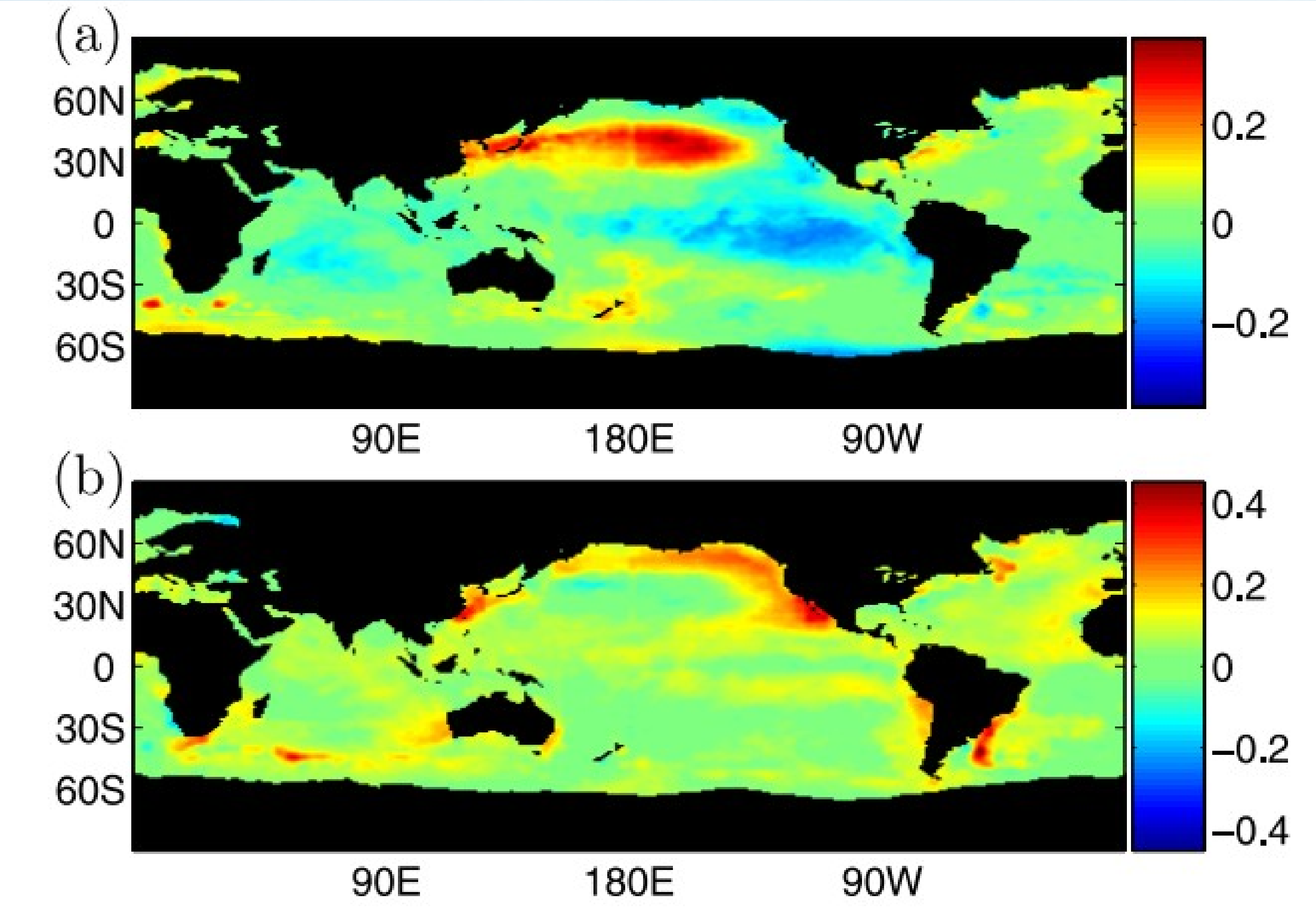


PDO FFT-spectrum shows a prominent 18.6 year maximum which is identical to the Lunar induced nodal tidal cycle (left). The right panel is time-series of 5-year running mean PDO (PDO5: thin black curve), bi-decadal (BP20: 15.5–23.3year) component of the PDO (red) and inverted-18.6-year period moon cycle (TIDE186: blue) where the maximum corresponds to the minimum diurnal tide.

The tidal cycle seems to weak to create PDO but it may be able to phase-lock a natural oscillation of North Pacific of roughly 20-year period.

Yasuda 2009 (GRL)

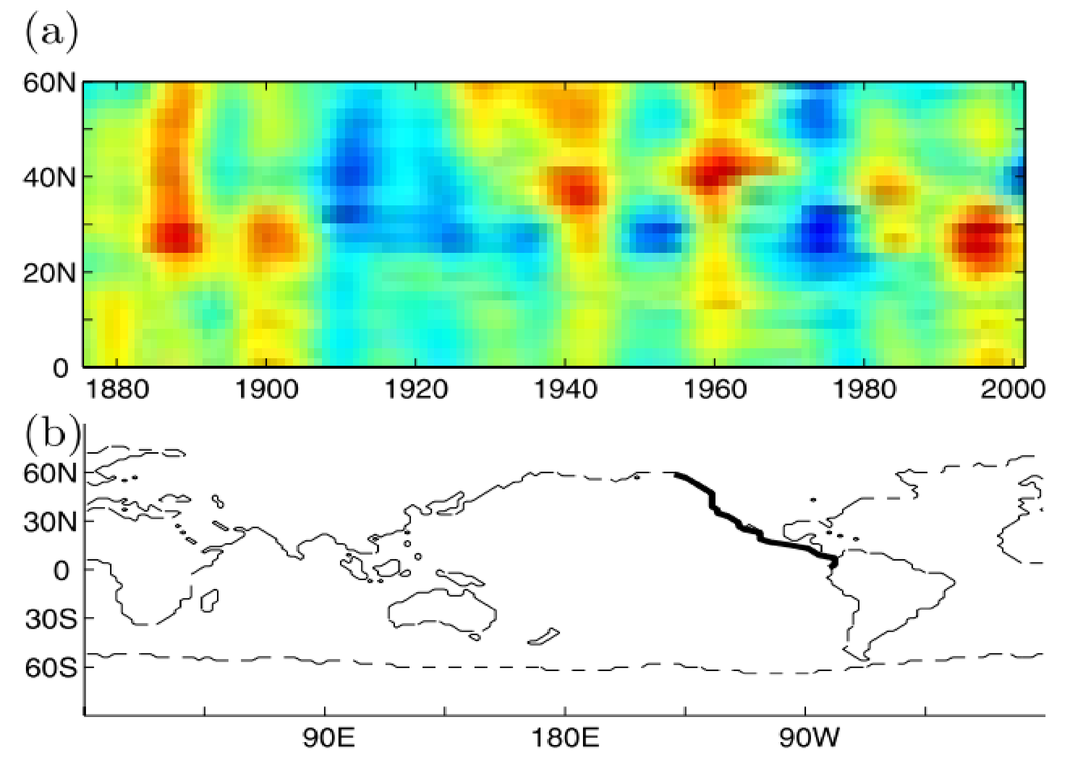
However PDO seems to have two independent components

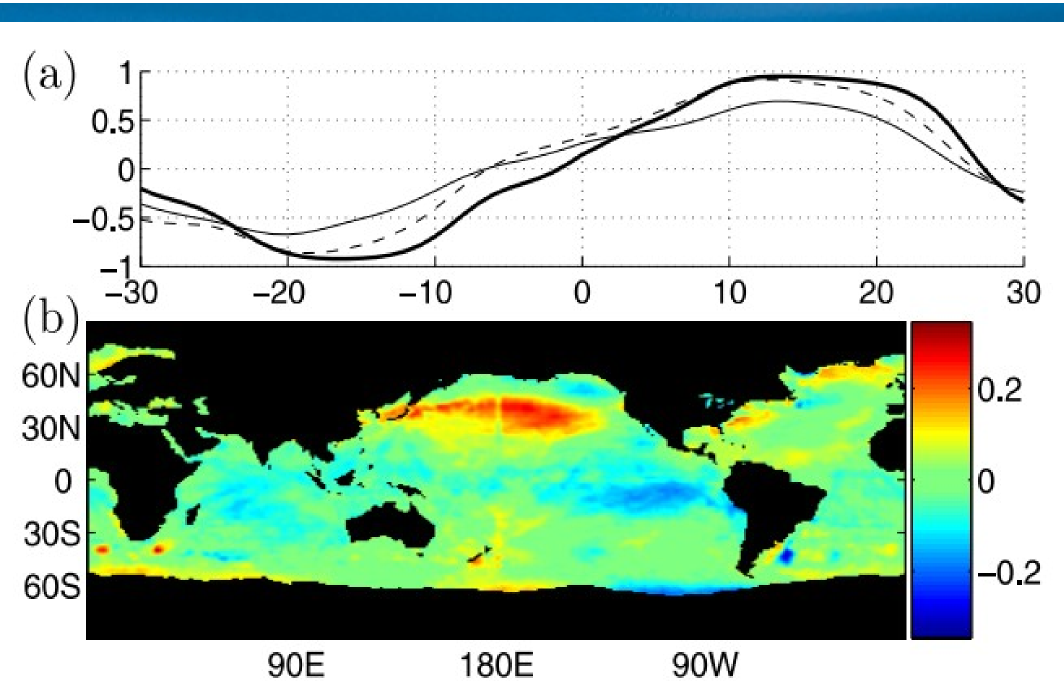


Two first EOFs of North Pacific SST variability since 1870.

D'Orgeville & Peltier 2007 (GRL)

However PDO seems to have two independent components



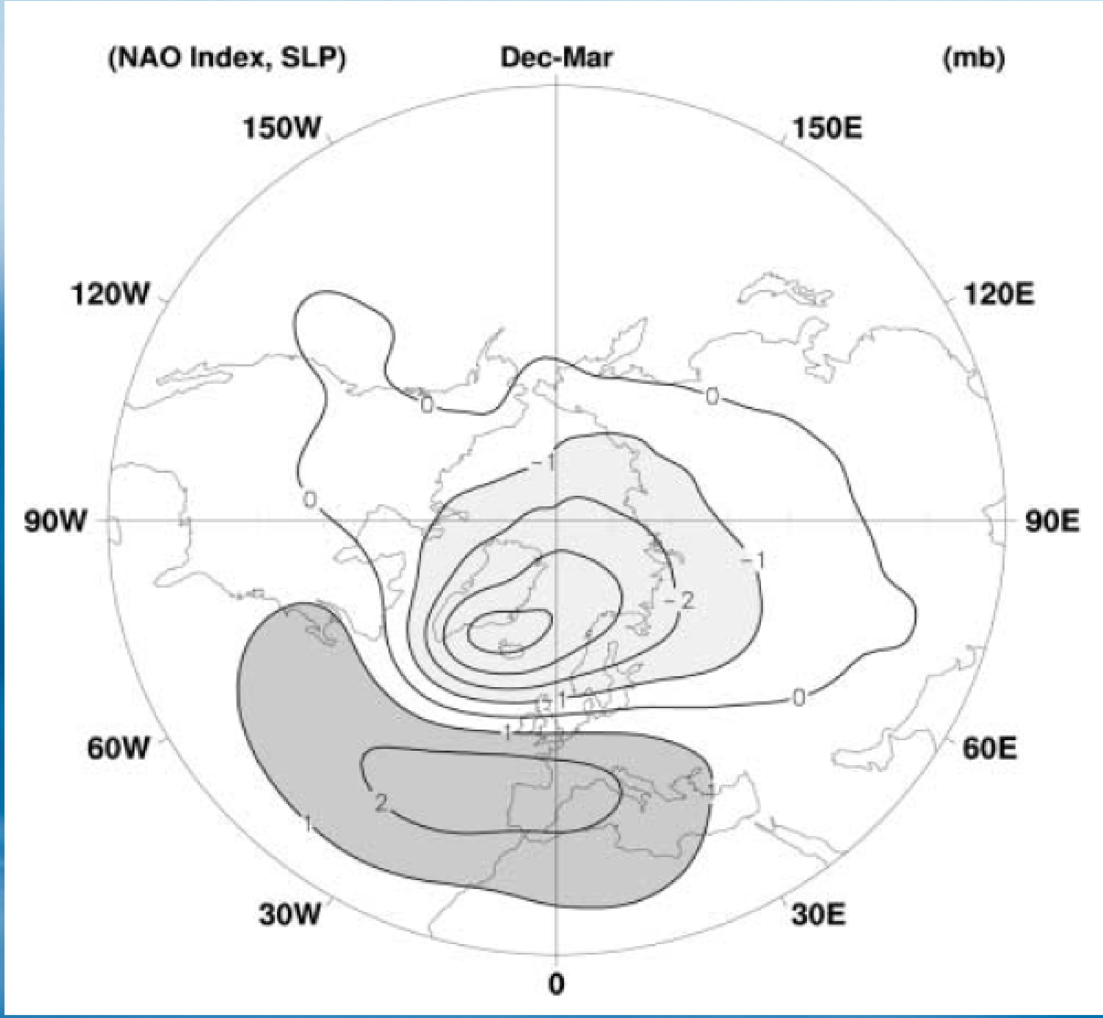


One of the EOFs seem related to Eastern boundary SST anomalies with the Lunar tidal cycle of 18.6 years (top).

The other (bottom) seems to be mirroring AMO with a 13 year time lag. The bottom figure consists of (a) Spatial correlation between the PDO and the time-lag regression on the AMO index. (b) Spatial structure of the time-lag correlation on the AMO index at lag of 13 years

D'Orgeville & Peltier 2007 (GRL)

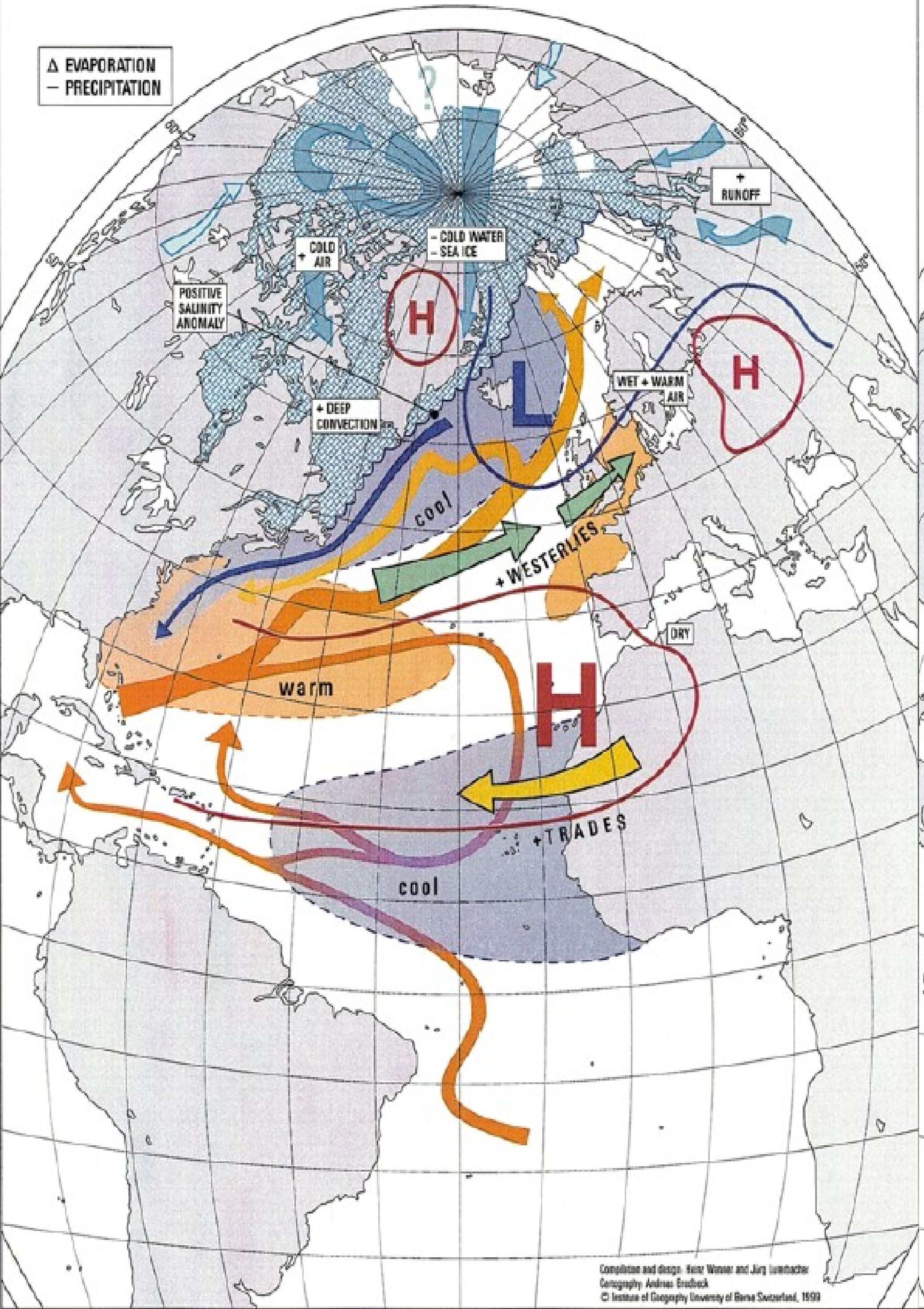
North Atlantic Oscillation (NAO)



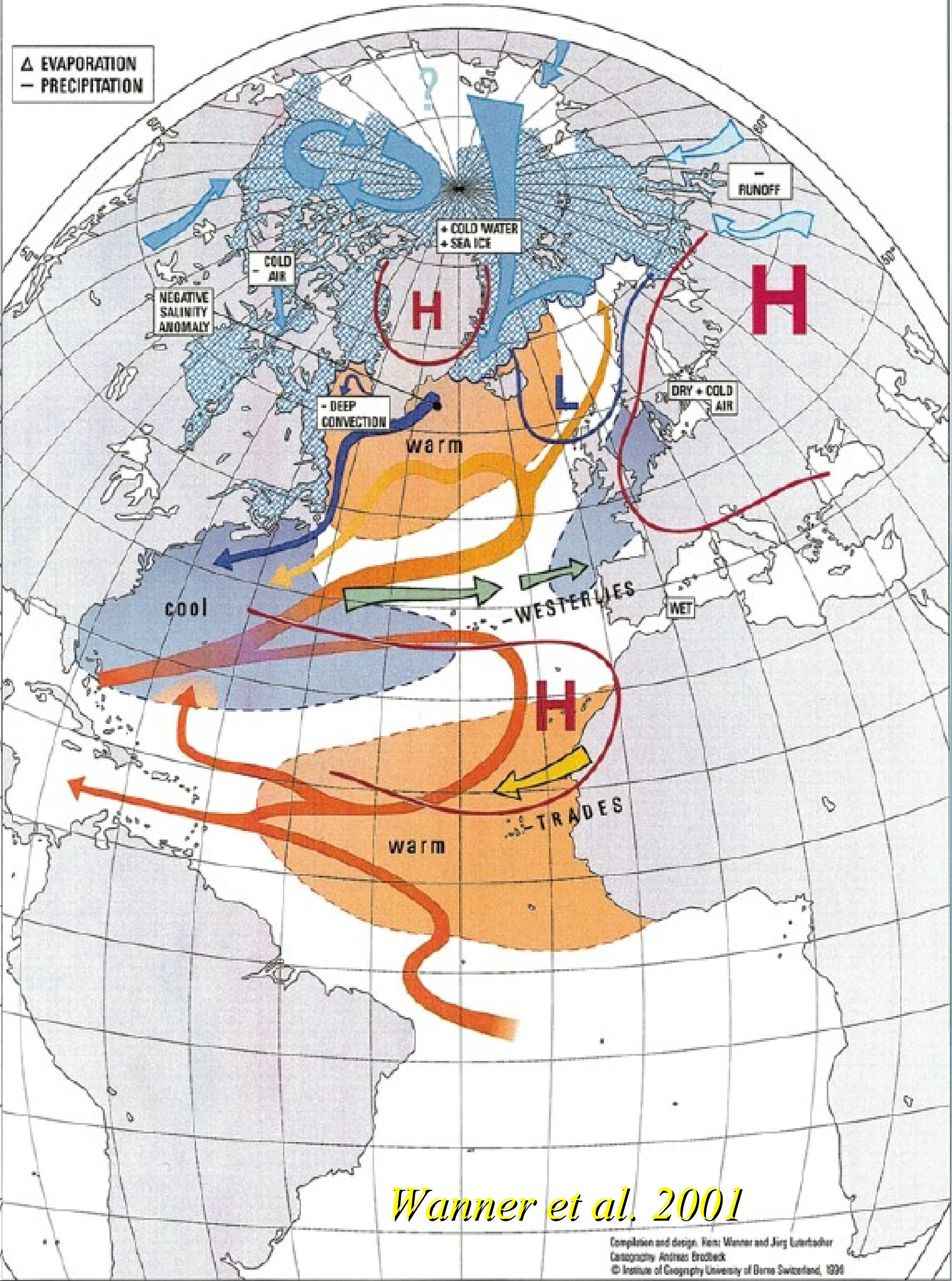
Indeks NAO, zidentyfikowany przez Walkera (1924), najczęściej definiowany jako różnica ciśnień między Lizboną a Reykjavikiem (na rysunku sytuacja dodatniego NAO). Indeks ten tłumaczy 31% zróżnicowania zimowych temperatur na północ od 20º N.

Greatbatch 2000

NAO +

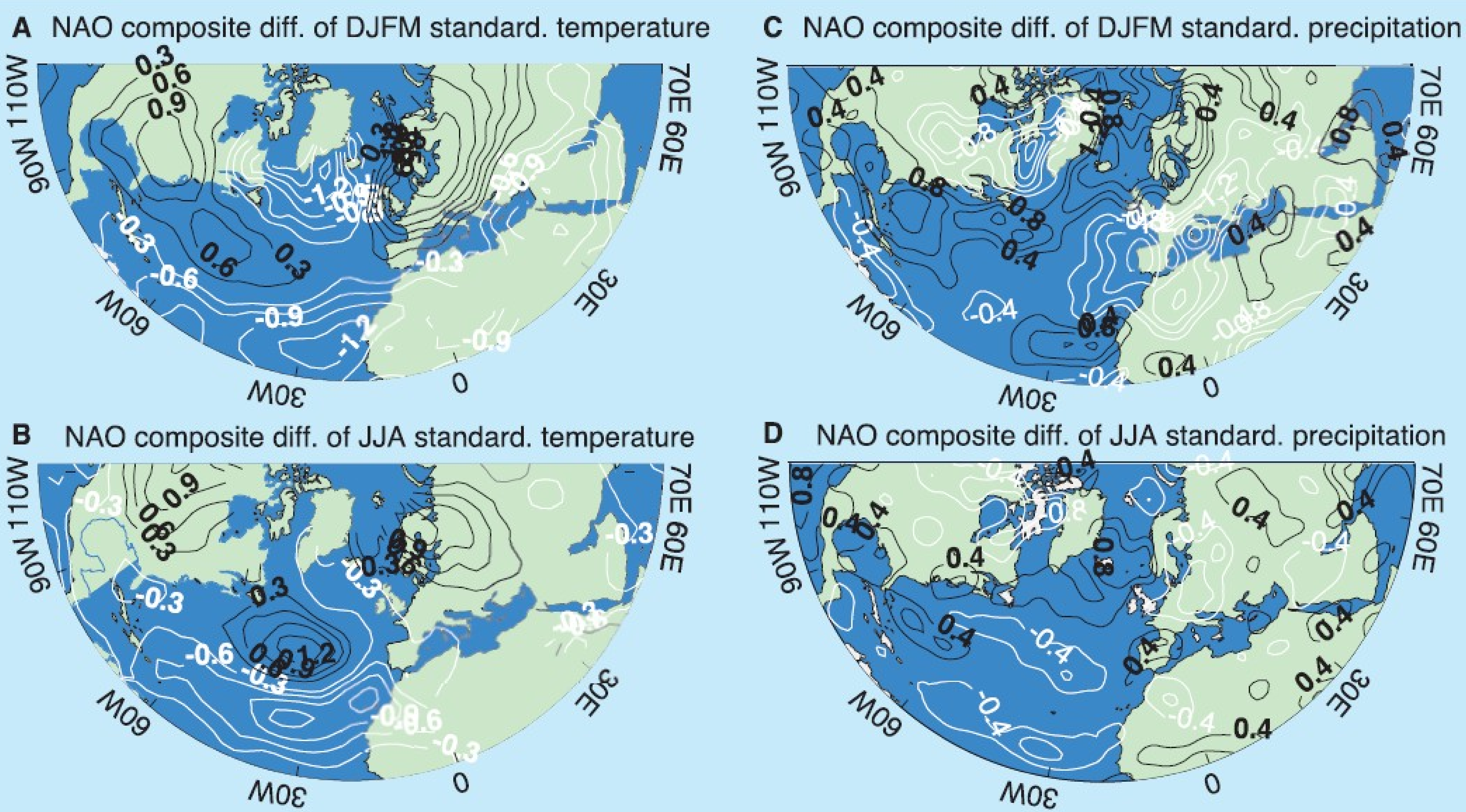


NAO -



Wanner et al. 2001

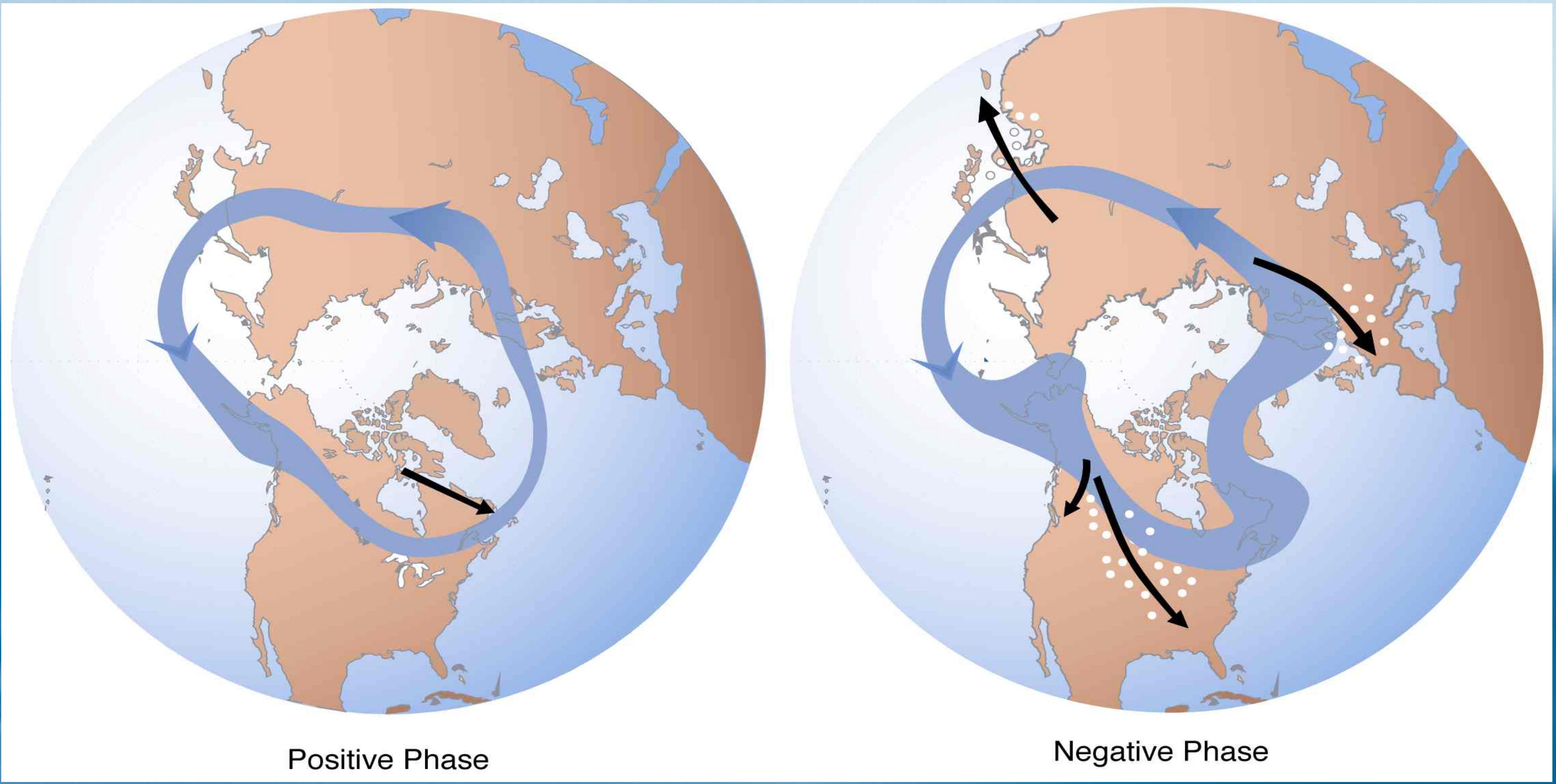
Jak NOA wpływa na pogodę wokół Atlantyku?



Odchylenie wartości temperatury (lewe panele) i opadów (prawe) w stosunku do średniej wielorocznej zimą (góra) i latem(dół) – różnica między dodatnimi i ujemnymi NAO.

Bradley et al., 2002

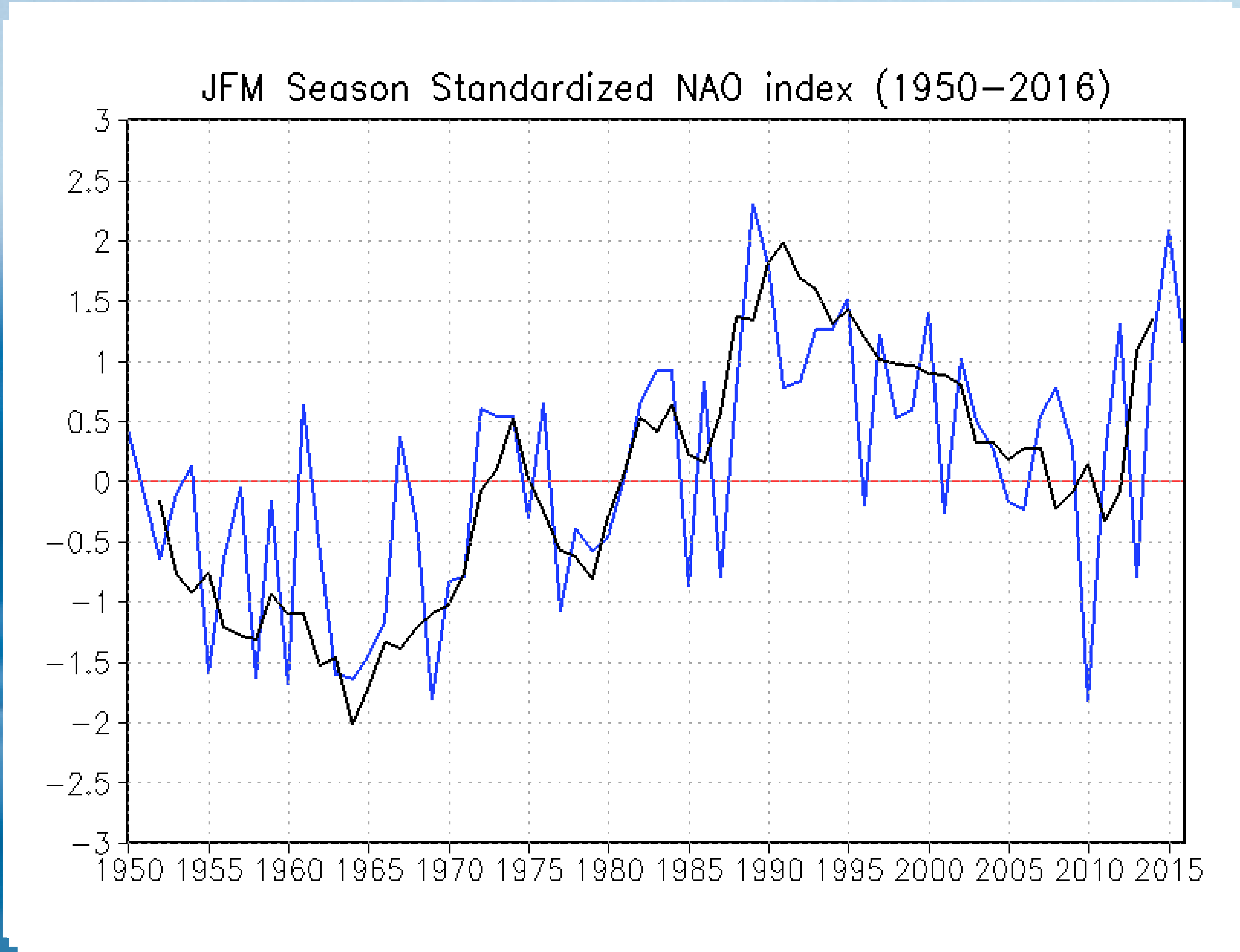
Wartość Arctic Oscillation (AO) i zasięg niżów



Innym indeksem wysoce skorelowanym z NAO jest Arctic Oscillation – różnica ciśnienia między szerokościami 37º-45º N a polarnymi, a zatem miara intensywności niżu polarnego. Przy ujemnych wartościach AO (czyli zazwyczaj i NAO) front polarny ("*jet stream*") odsuwa się od bieguna sprawiając, że trasy niżów, a zatem i strefy opadów przesuwają się na południe.

Ganopolski i Rahmstorf, 2002

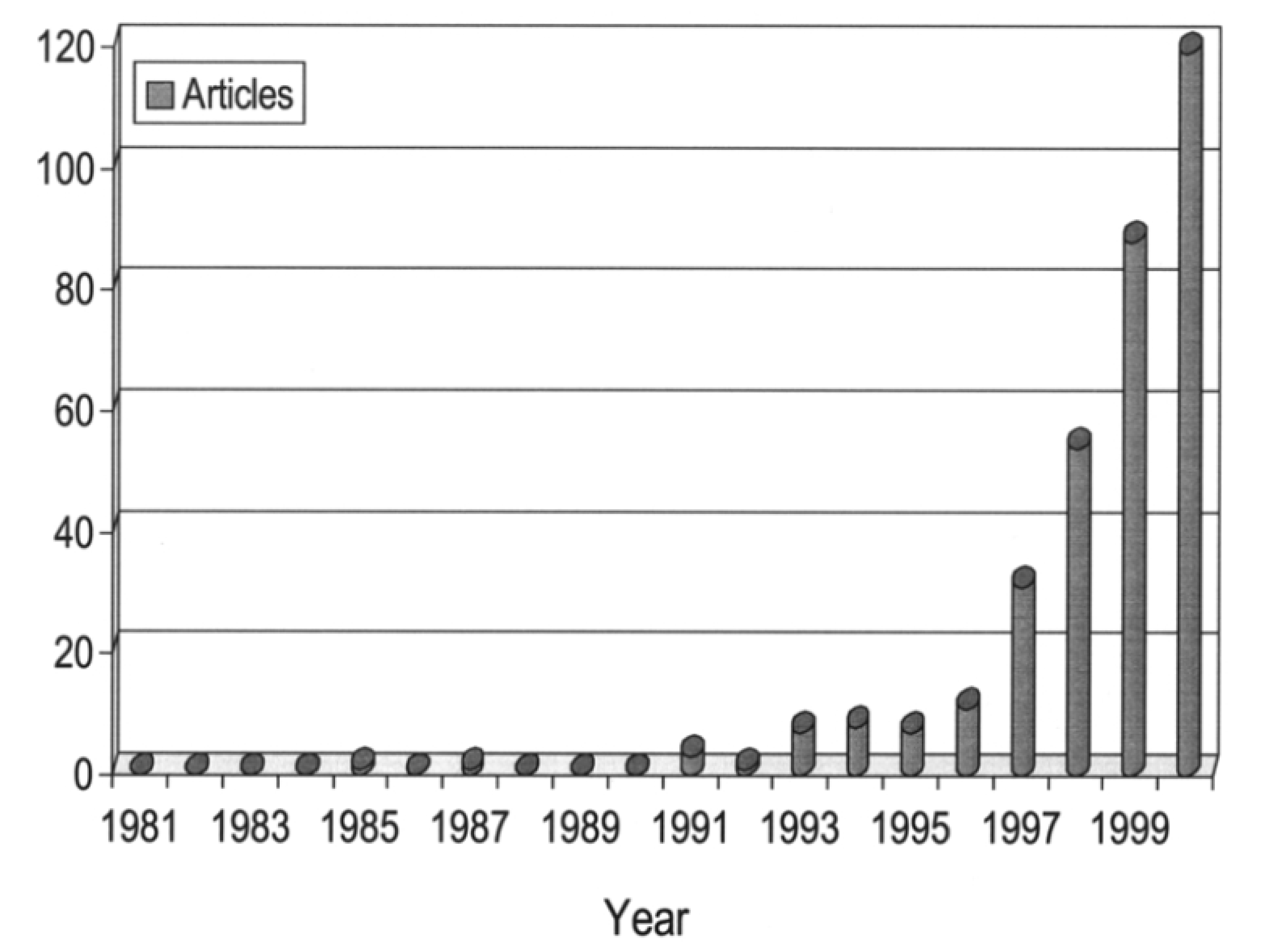
Zimowe wartości indeksu NAO od 1950



Zwraca uwagę okres niskich wartości w latach 60-tych i wysokich w 90-tych oraz malejąca wartość w ostatnich latach.

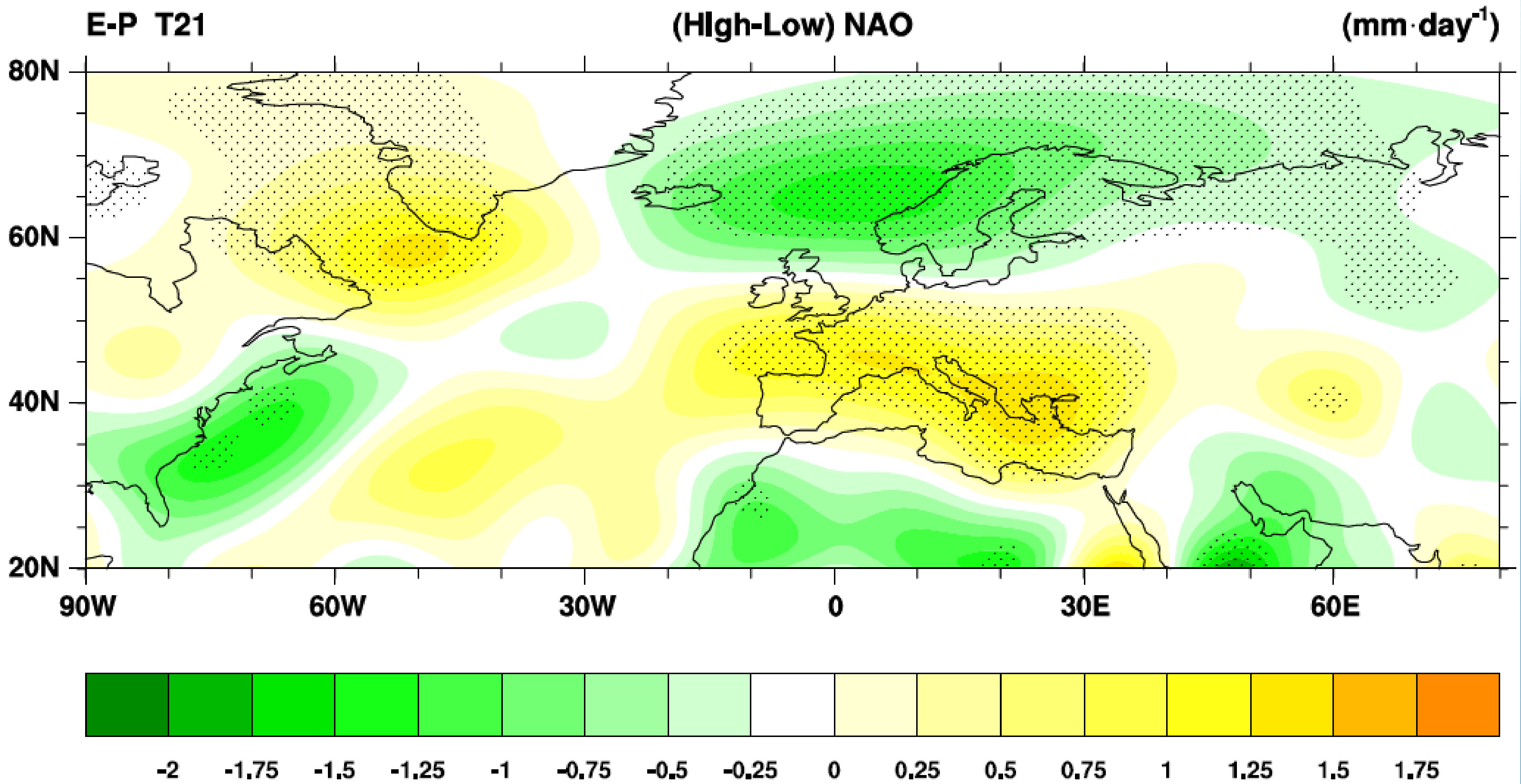
http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/season.JFM.nao.gif

Ilość artykułów naukowych na temat NAO



Wanner et al. 2001

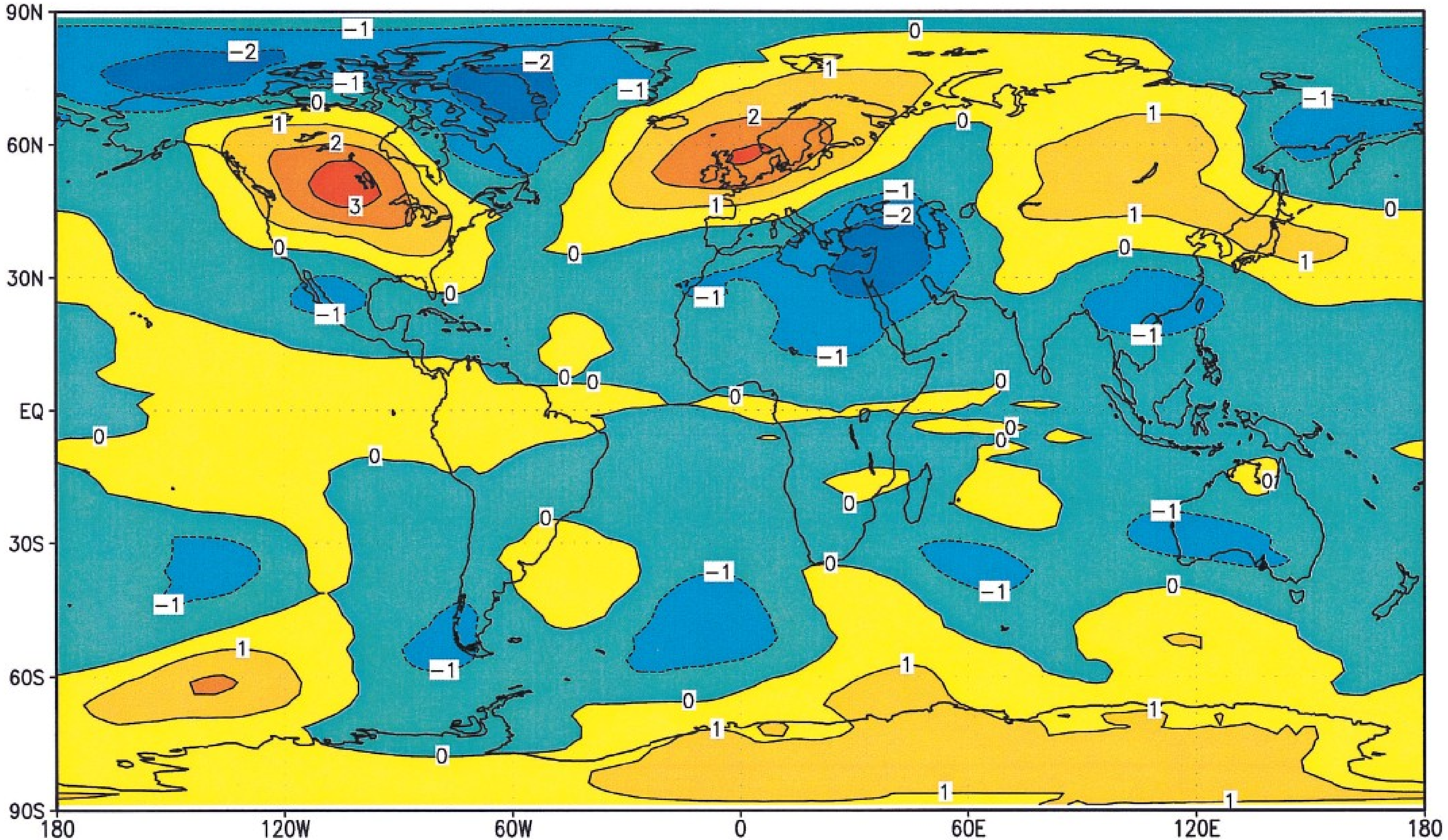
Wpływ NAO na opady



Anomalie opadów związane z zimowym indeksem NAO [mm/dzień]: średnia dla zim z dodatnim NAO minus średnia dla zim z ujemnym. Wygląd układu identyczny jak efekt wybuchu wulkanu na temperaturę zimą (*uwaga: znak przy skali na dole ewidentnie pomylony!*)

Za Hurell 1995 (Science)

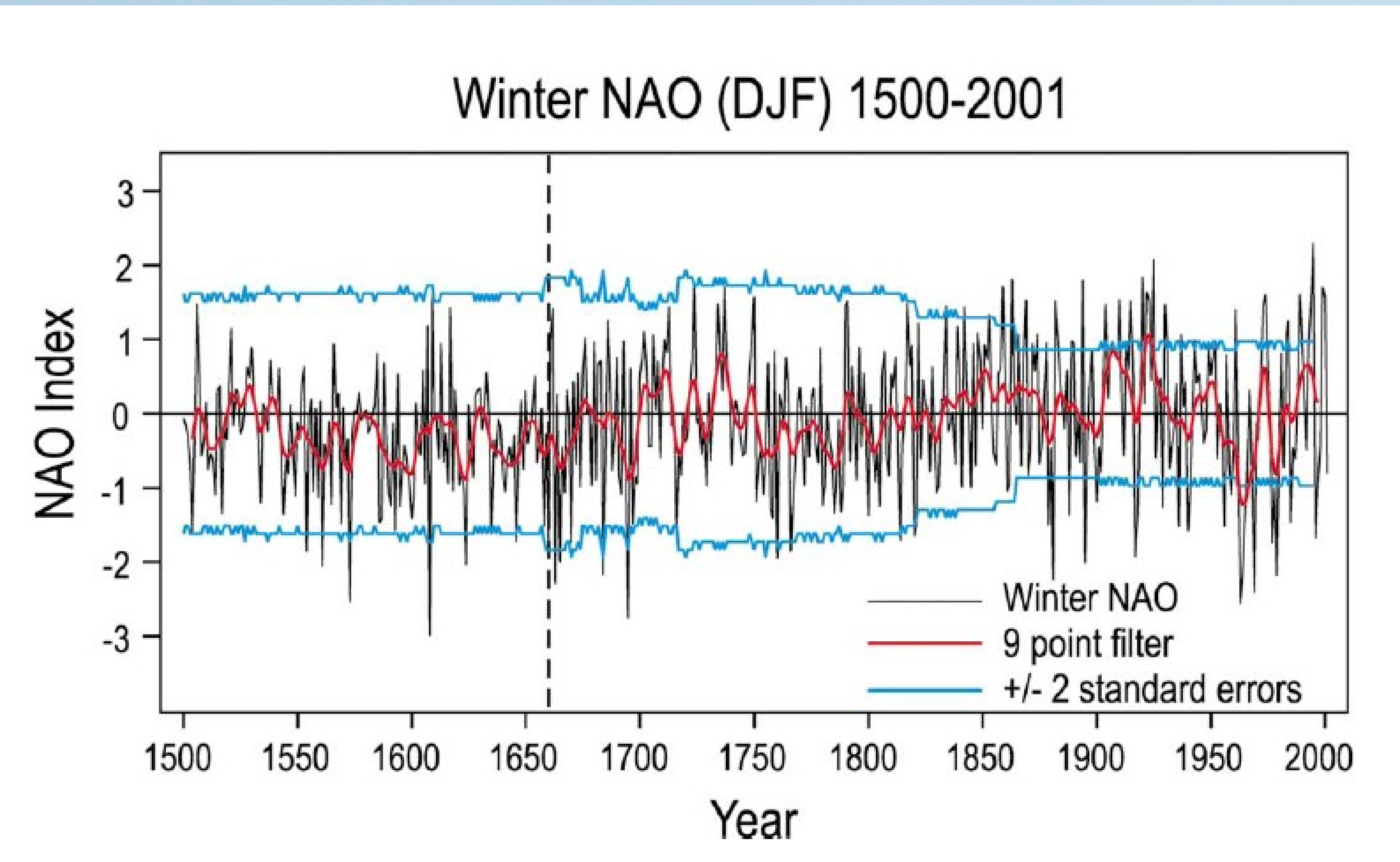
Przypomnienie: anomalie temperatury zimą po Pinatubo



Po wybuchu wulkanów tropikalnego pierwsza zima typowo jest ciepła m. in. w Pn. Europie a zimny na Bliskim Wschodzie.

Robock 2000

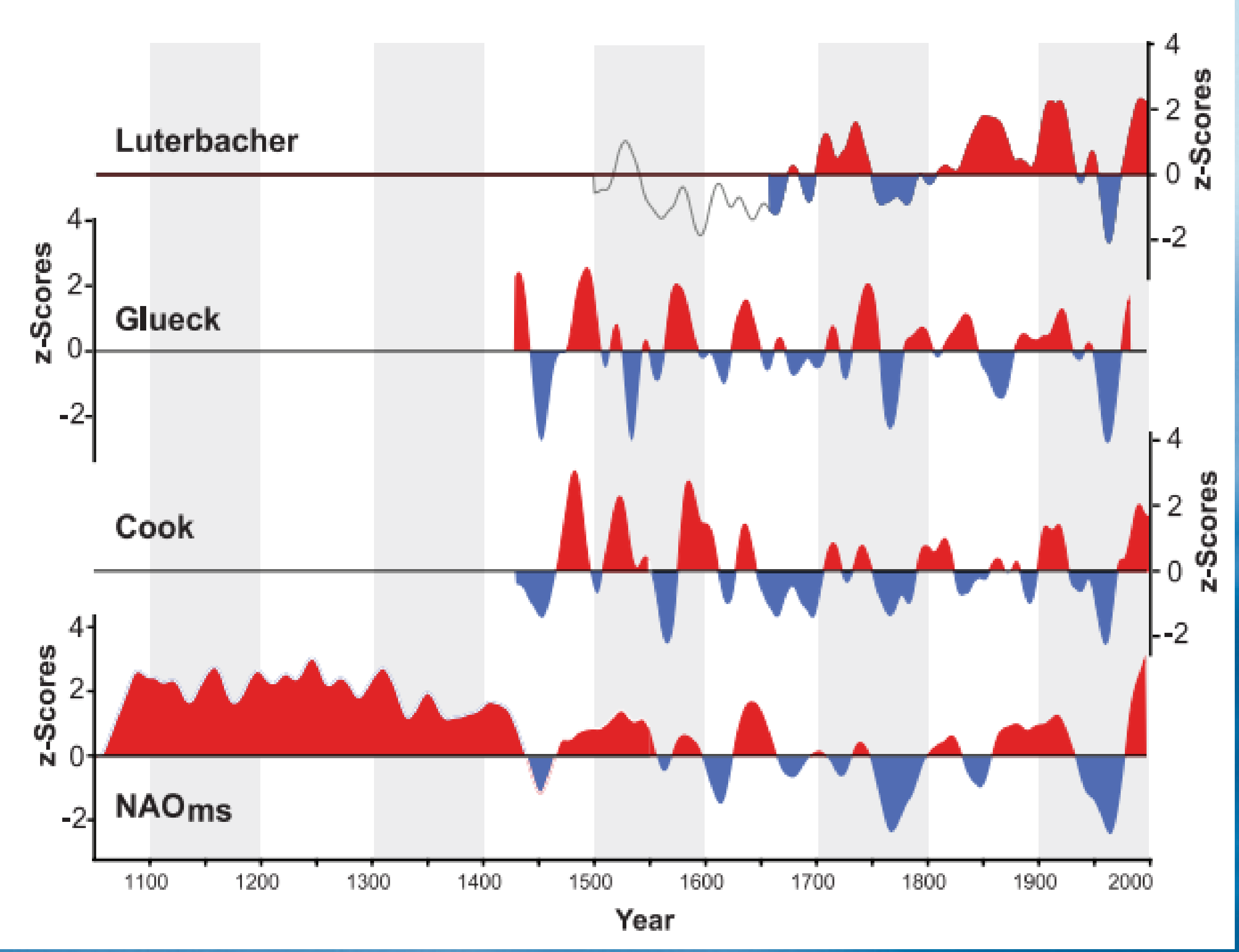
Przypomnienie: wartości NAO w ciągu ostatnich 500 lat



Indeks NAO jest wysoki gdy produkcja wód głębinowych (THC) jest wysoka (i odwrotnie). Co jest przyczyną? NAO, THC czy aktywność słońca.
Zatem dlaczego przez ostatnie kilkadziesiąt lat THC malała gdy NAO rósł?
Odpowiedź: malała tylko na Morzach Nordyckich.

Luterbacher et al. 2002

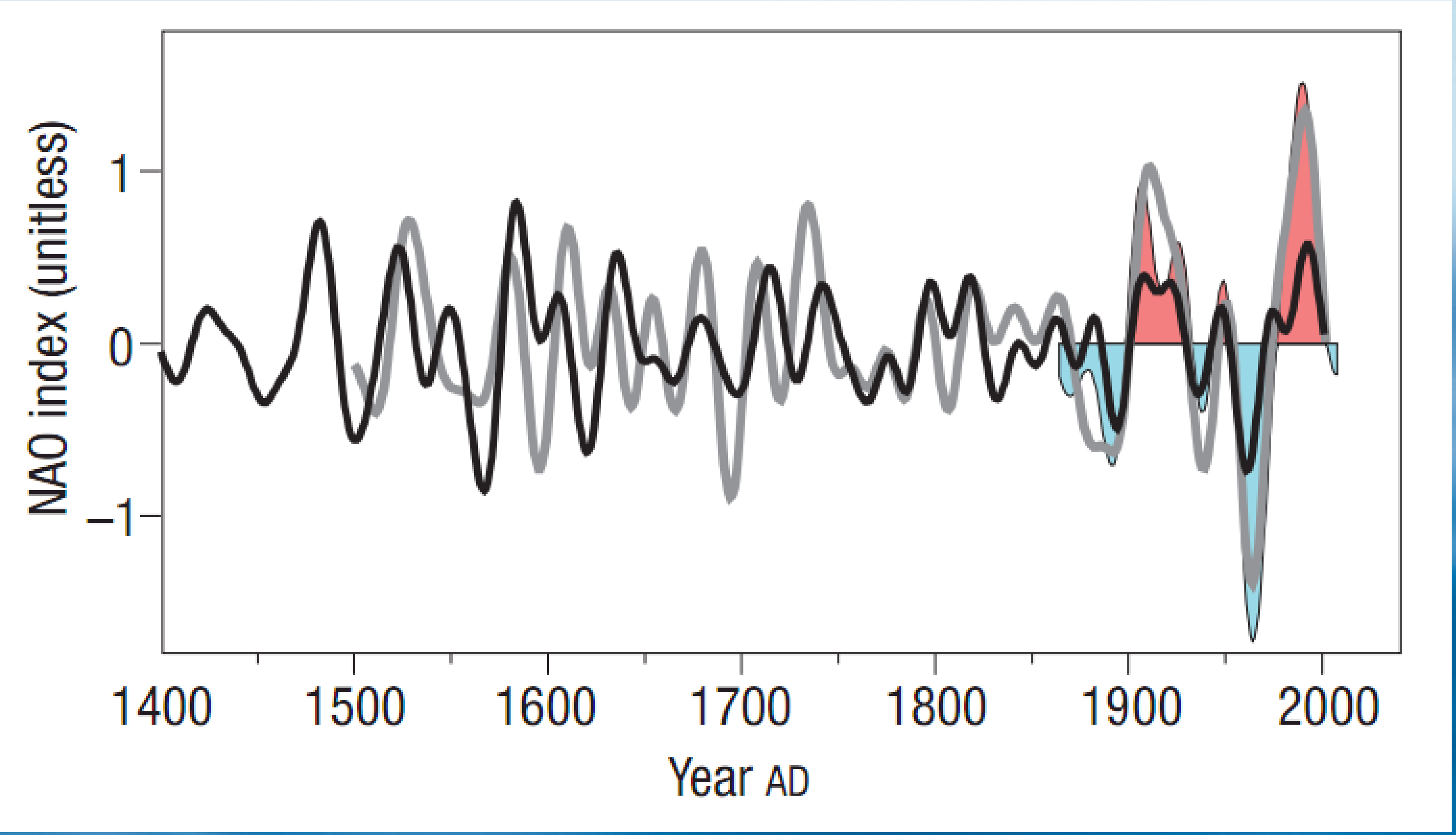
Nieustające dodatnie NAO w czasie „ciepłego średniowiecza”?



Rekonstrukcja indeksu NAO na podstawie wartości izotopowych stalaktytów ze Szkocji i słoi drzew z Maroka (czyli opadów w rejonach zależnych od znaku NAO) świadczy o istnieniu okresu około 300 lat (1100-1400 n.e.) z nieustająco dodatnim indeksem NAO.

Trouet et al 2009 (Science)

Zmienność NAO silniejsza w „okresie przemysłowym”?



Rekonstrukcja indeksu NAO na podstawie wartości izotopowych korali z Bermudów (jakkolwiek ryzykowna!) pokazuje zwiększoną amplitudę zmian NAO od późnego XIX wieku. Nawet jeśli autorzy mierzyli bardziej AMO niż NAO jest to ciekawy wynik.

Timm 2008 using data of Goodkin et al 2008 (Nature Geoscience)

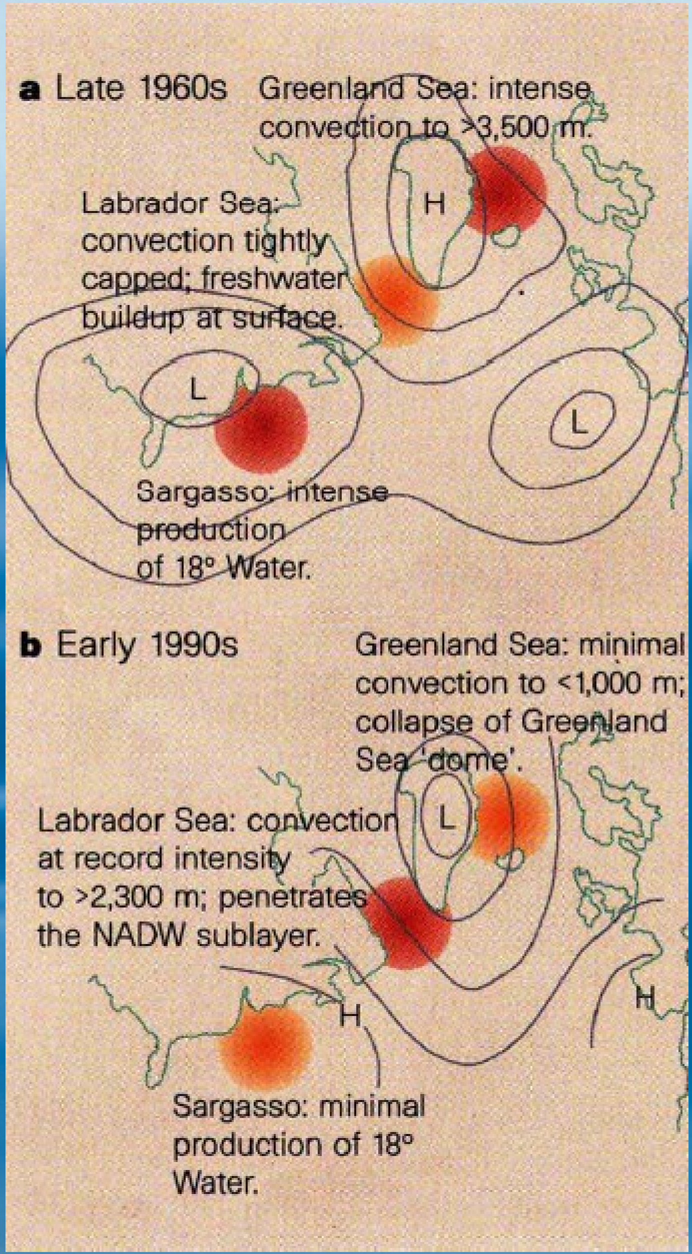
Zmiany w produkcji wód głębinowych

Zmienność NAO wpływa na miejsce (i zapewne ilość) produkowanych wód głębinowych.

Przy ujemnych wartościach NAO (lata 60-te) zmalała produkcja wód głębinowych na Morzu Labradorskim a zwiększyła się na Morzach Nordyckich.

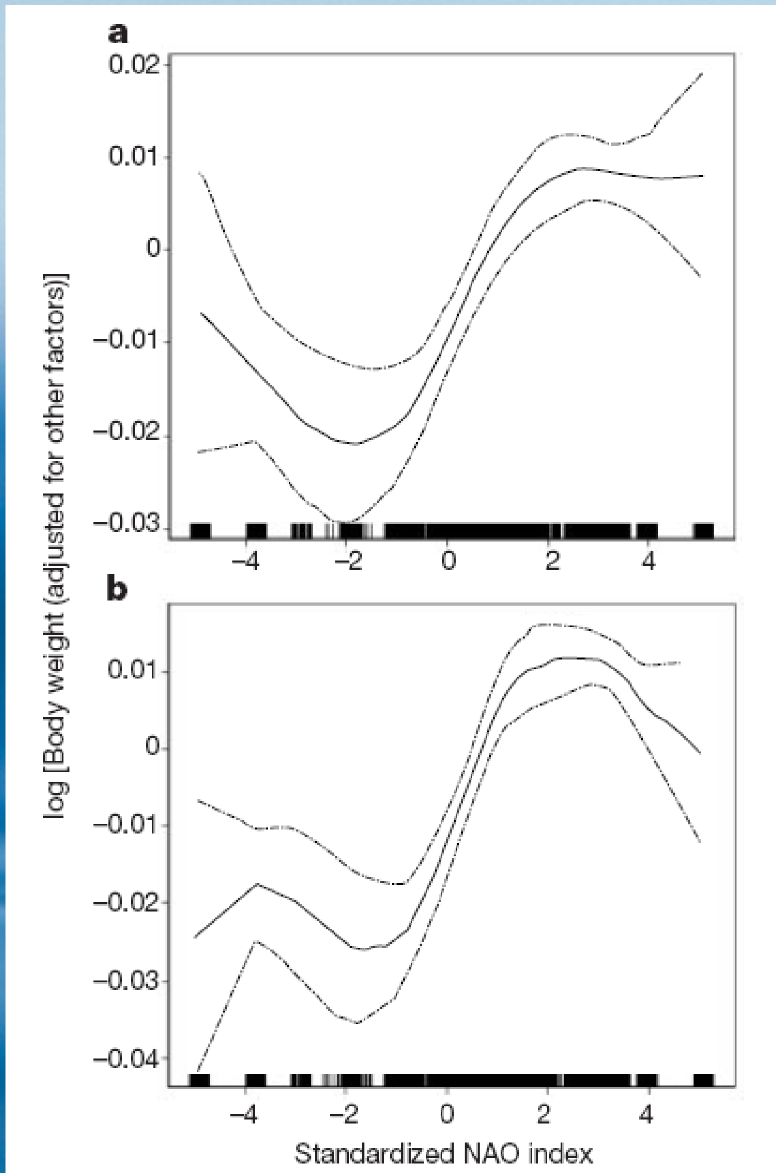
Przy dodatnim NAO (lata 90-te) zaszło zjawisko odwrotne.

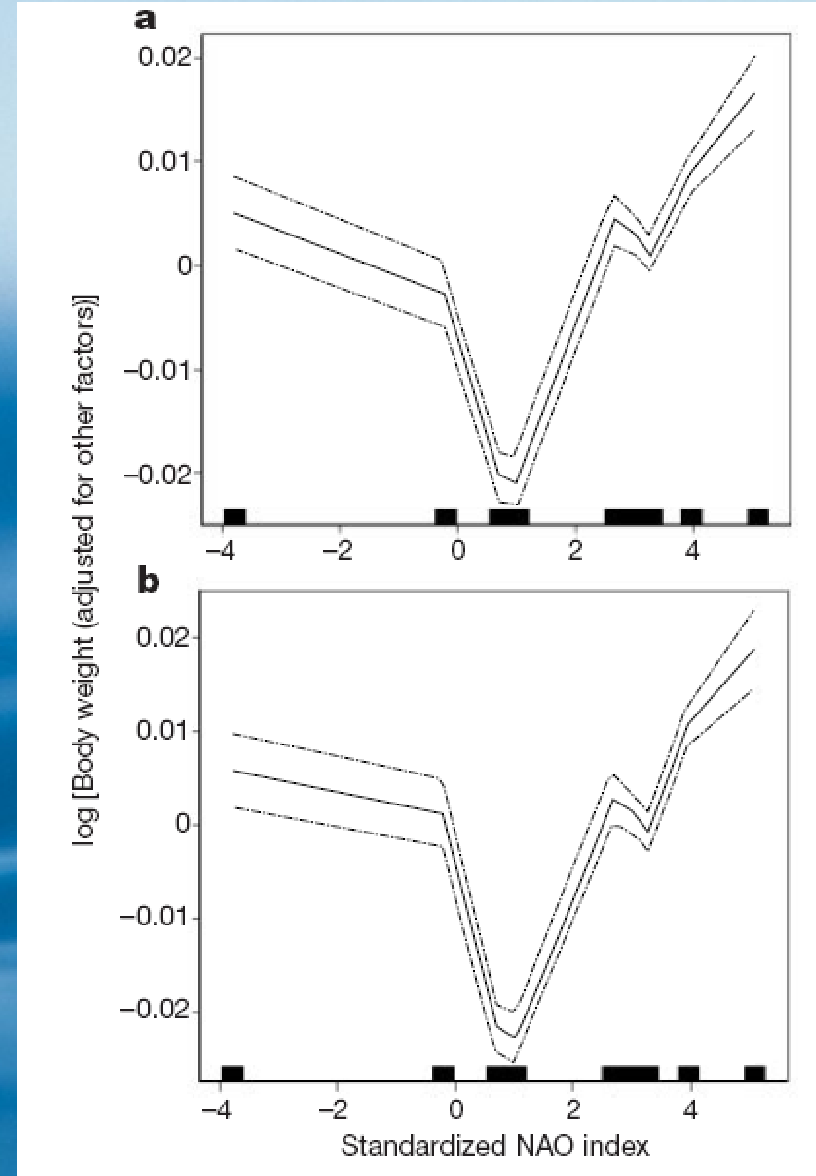
Zmiana ta tłumaczy zmniejszenie się przepływu wód głębinowych z Mórz Nordyckich do właściwego Atlantyku od lat 60-tych.



Dickson et al. 1997 (Nature)

Wpływ NAO na przyrodę Europy: przykład pierwszy

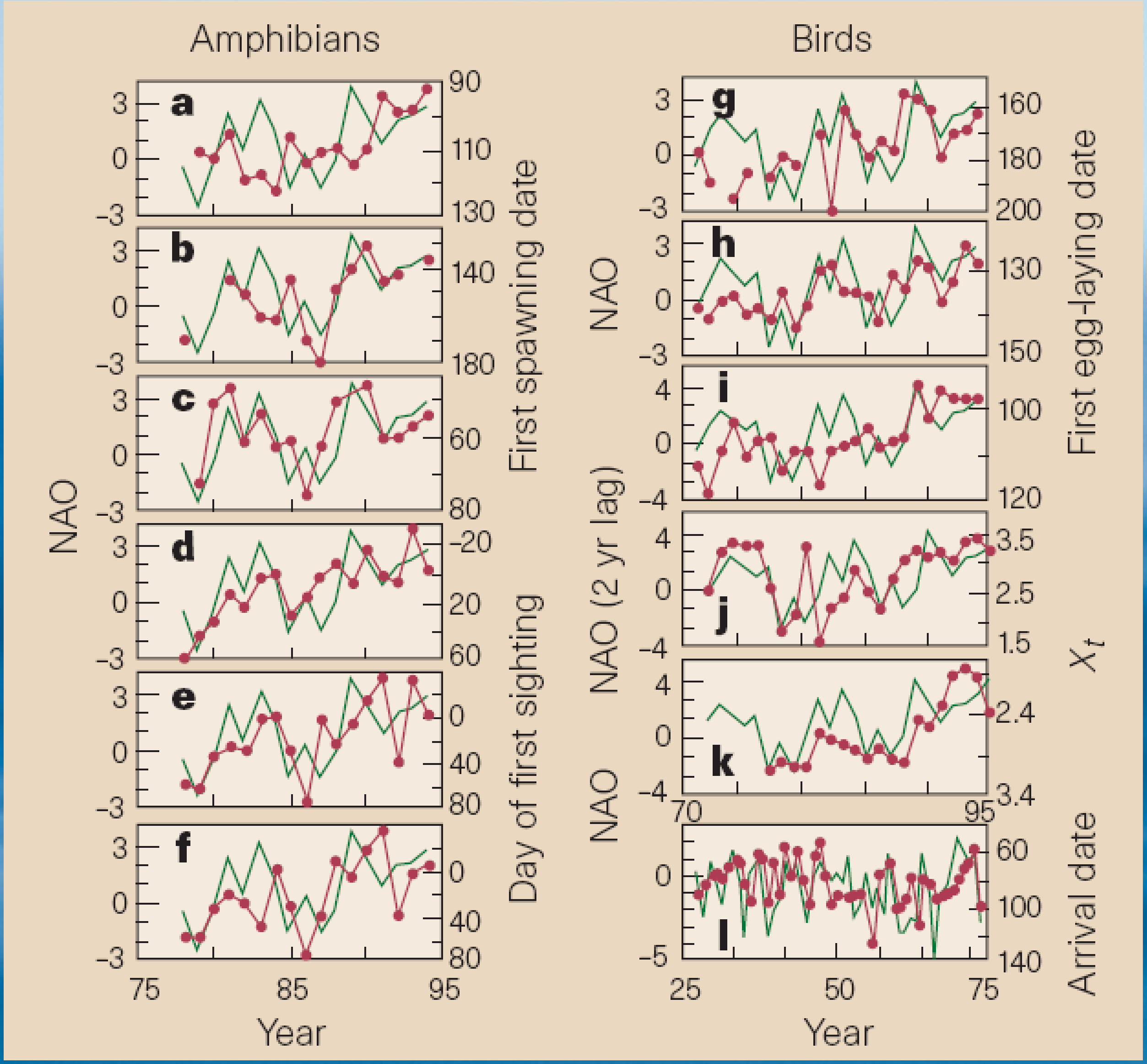




Wpływ wartości NAO na wagę samic (góra) i samców (dół) skandynawskich jeleni (lewe) i owiec (prawe).

Mysterud et al. 2001 (Nature)

Wpływ NAO na przyrodę Europy: przykład drugi

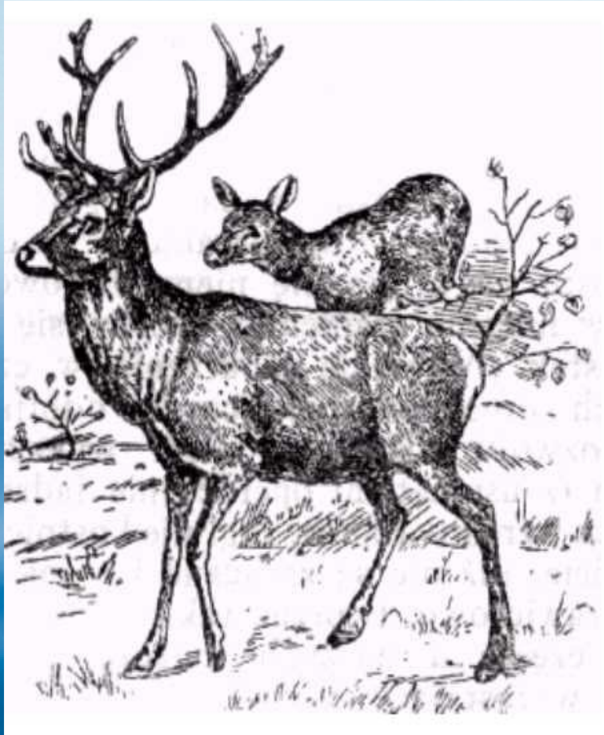


Wpływ wartości NAO na datę składania jaj przez płazy (lewe) i ptaki brytyjskie – *uwaga skala dni odwrócona*.

Forchhammer et al. 1998 (Nature)

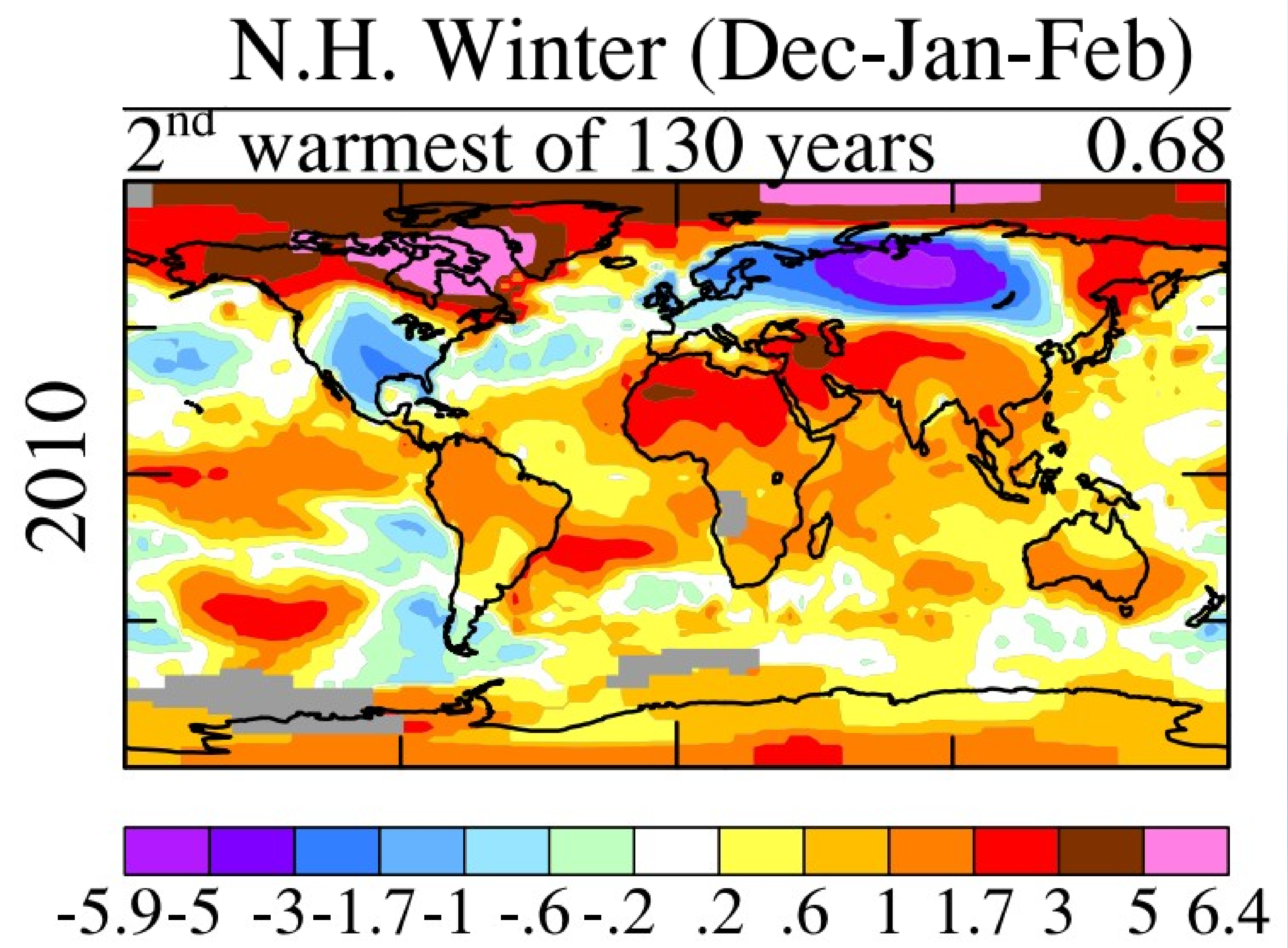
Podsumowanie 2/3

- Temperatura i opady zimą w Europie zdeterminowane są głównie wartością indeksu NAO. Dla całej półkuli północnej tłumaczy on ponad 30% zmienności klimatu.
- W czasie Małej Epoki Lodowej indeks ten był średnio ujemny. Czy w skutek małej objętości produkowanych wód głębinowych (THC)?
- Lata 90-te to okres dodatnich wartości NAO, 60-te ujemnych. W pierwszym tych okresów wody głębinowe produkowane były głównie na Morzu Labradorskim a w drugim na Morzach Nordyckich.

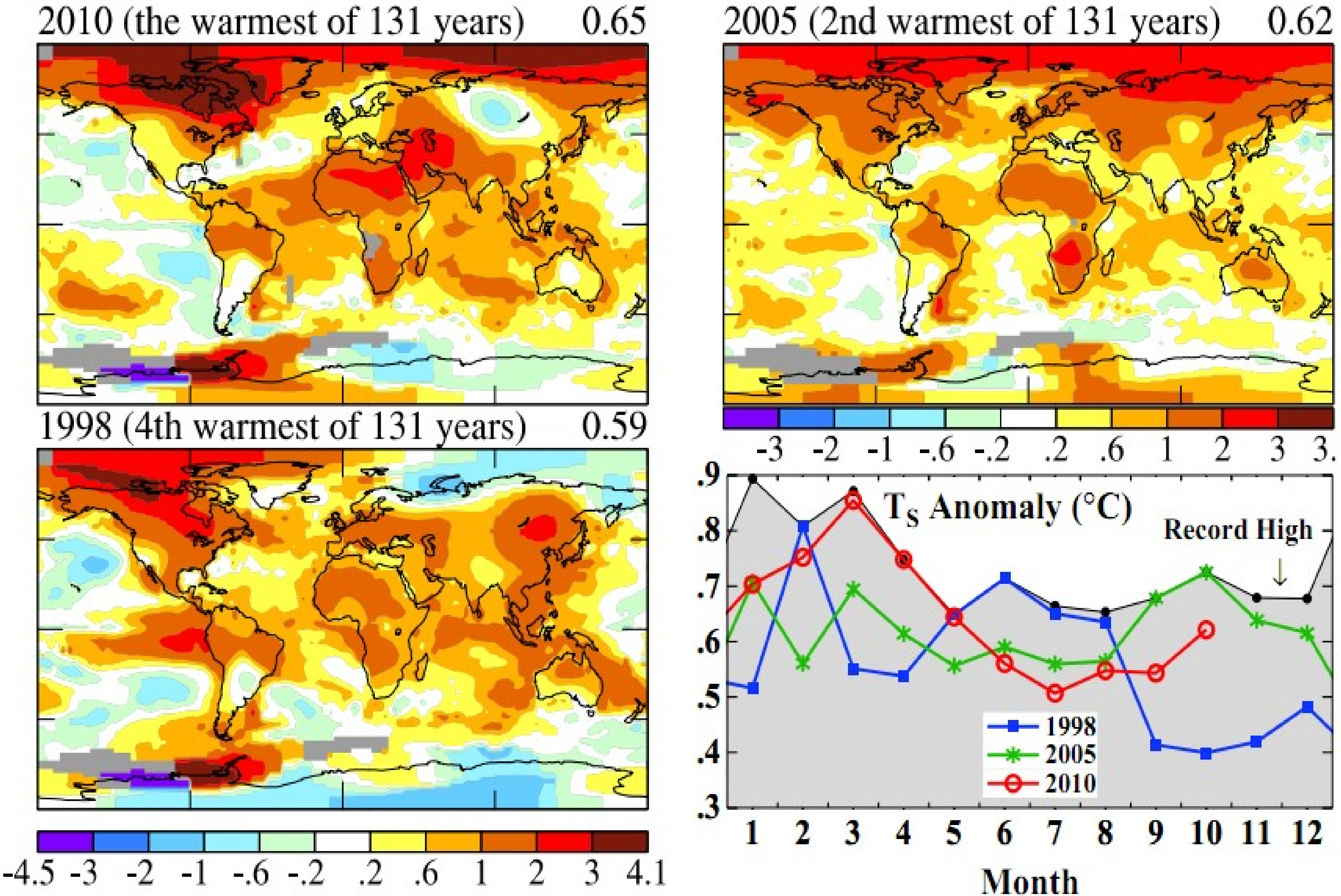


Jeleń szlachetny – jego jakość życia zależy od indeksu NAO?

- Wg. niektórych ujemne NAO spowodowało tzw. Wielką Anomalię Zasolenia. Jednak zasolenie północnego Atlantyku maleje od lat 60-ych ponad 30 lat (prawdopodobnie równolegle z napełnianiem Arktyki słonymi wodami Atlantyckimi).
- Tylko czy to nie bardziej AMO niż NAO?


N.H. Winter (Dec-Jan-Feb)
2nd warmest of 130 years
0.68
2010
-5.9
-5
-3
-1.7
-1
-.6
-.2
.2
.6
1
1.7
3
5
6.4

January-October Mean Surface Temperature Anomaly (°C)

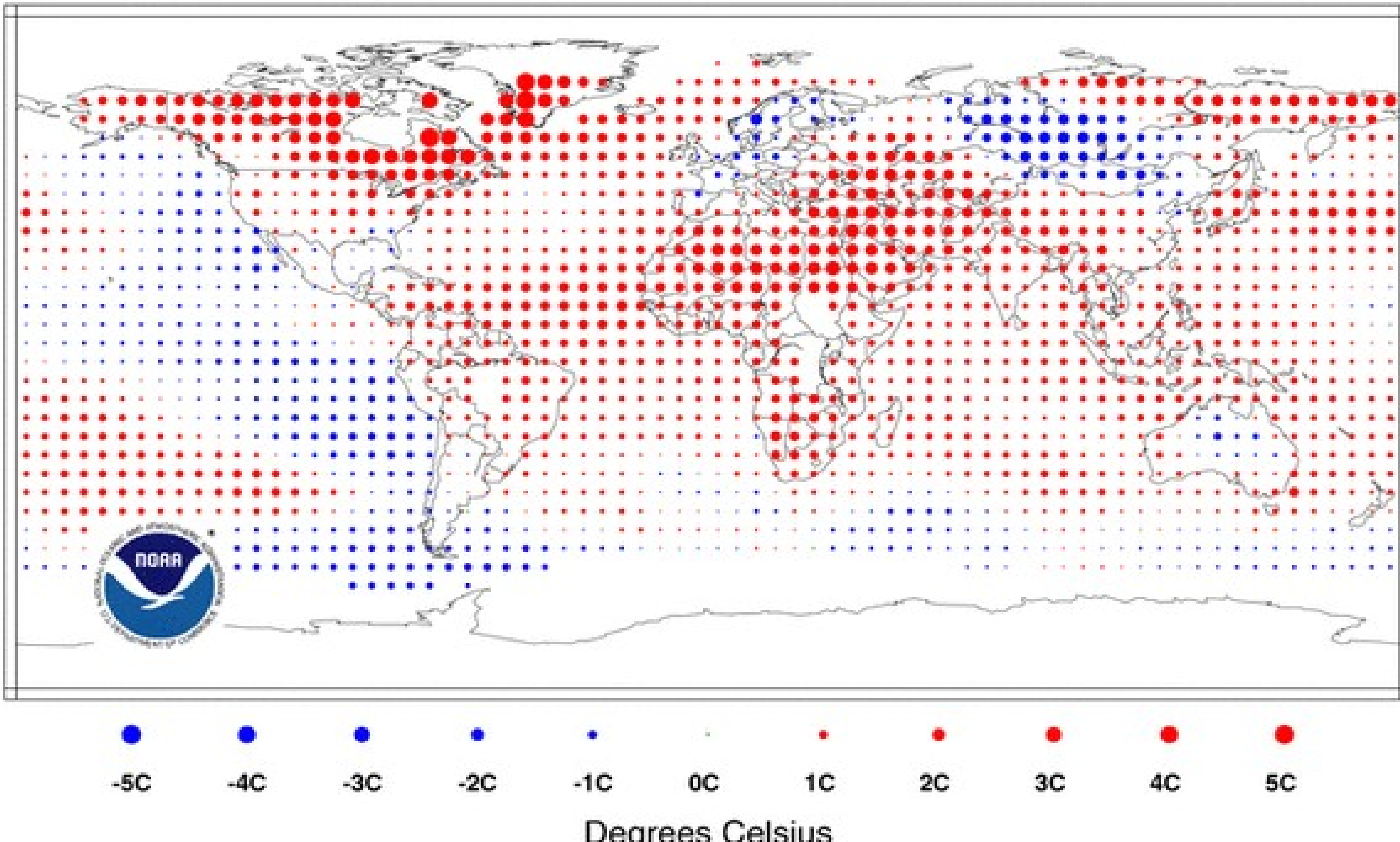


Base Period: 1951-1980

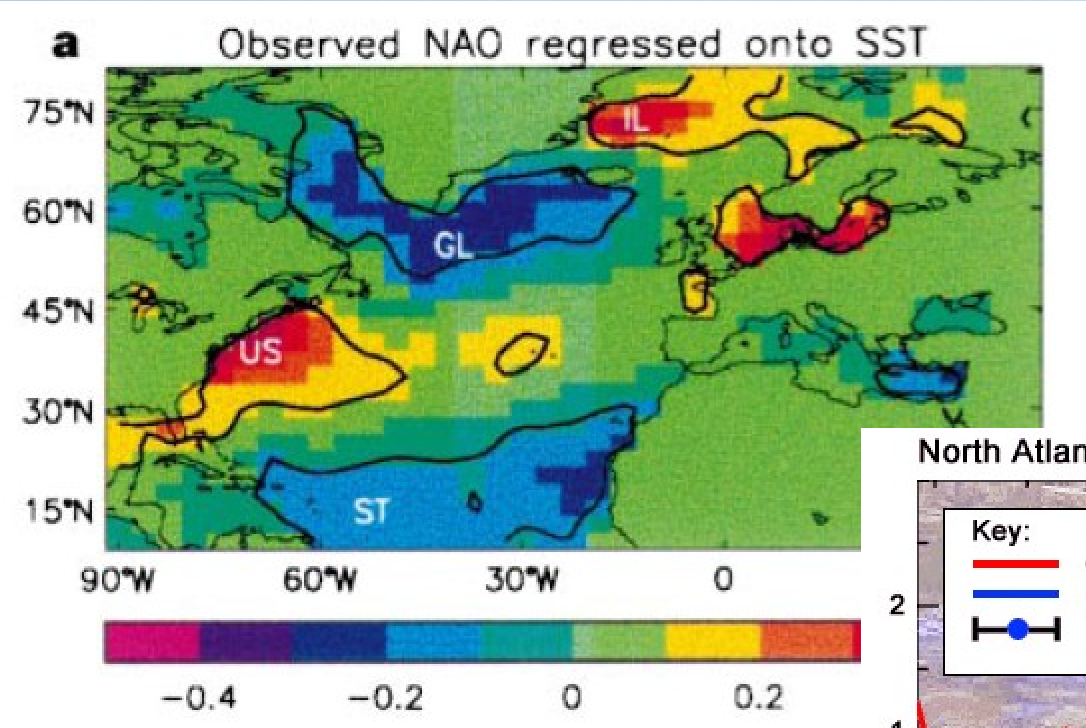
Temperature Anomalies Jan-Dec 2010

(with respect to a 1971-2000 base period)

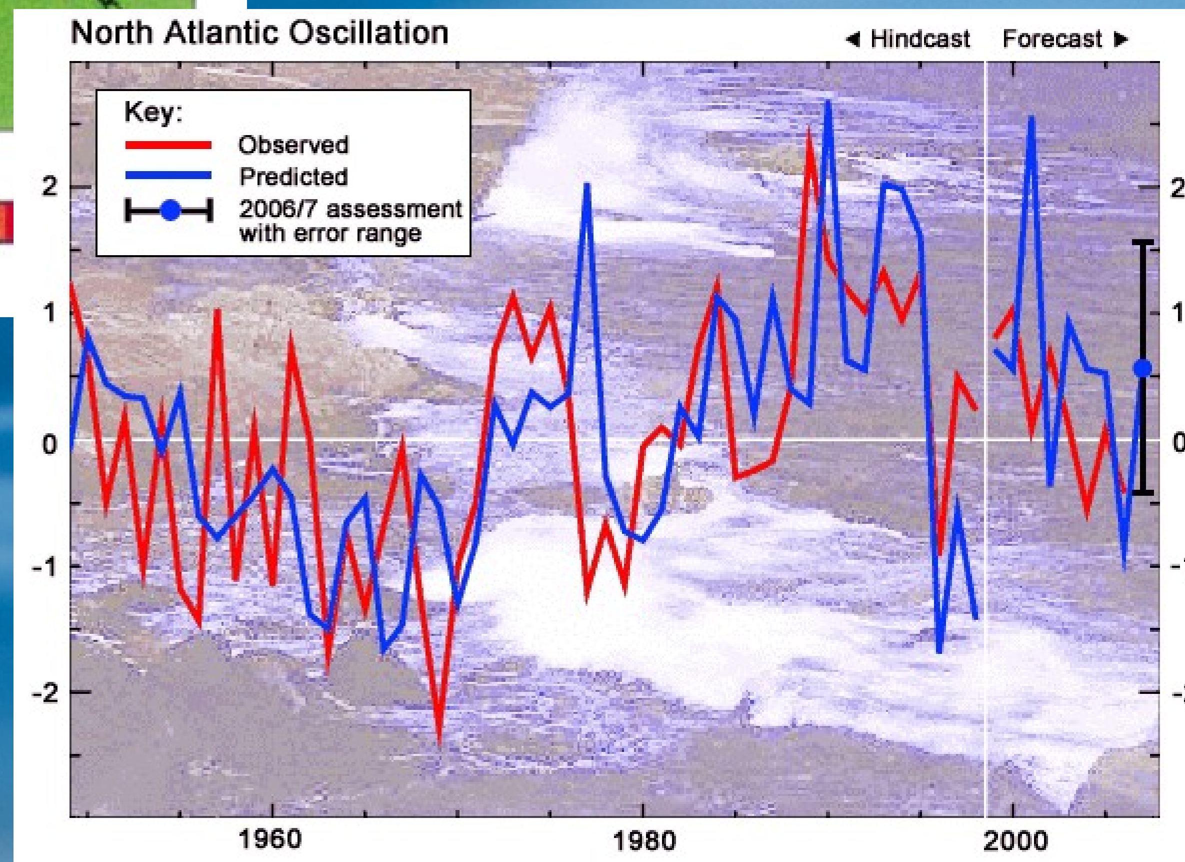
National Climatic Data Center/NESDIS/NOAA



Can we predict NAO values?



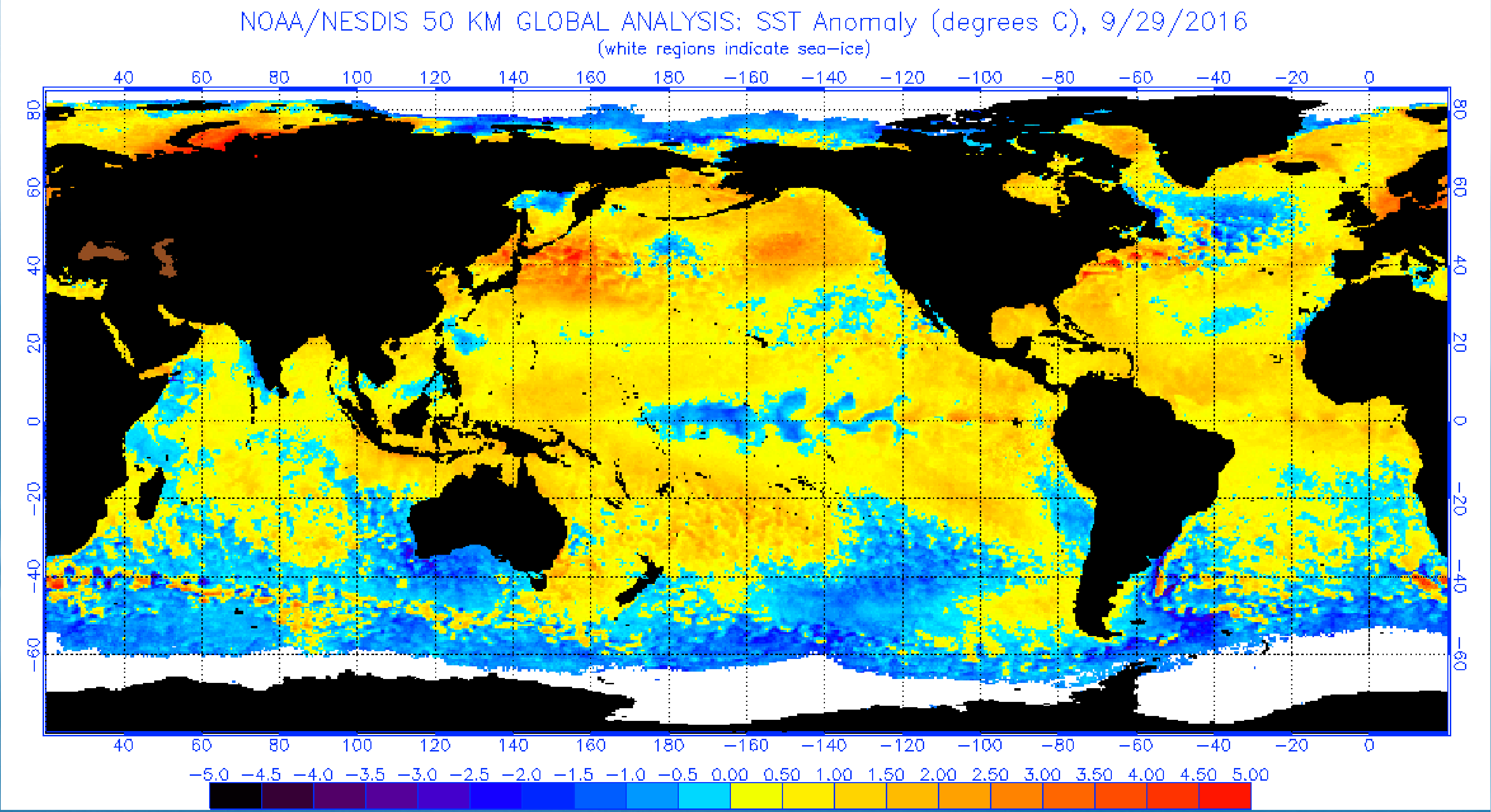
Correlations of summer ocean SST with NAO index of the following winter (Rodwell et al. 1999)



British Met Office has a hindcasting 2/3 successful prediction of winter NAO sign from North Atlantic SST of the previous summer.

Rodwell, Rowell & Folland 1999 (Nature) & www.metoffice.gov.uk

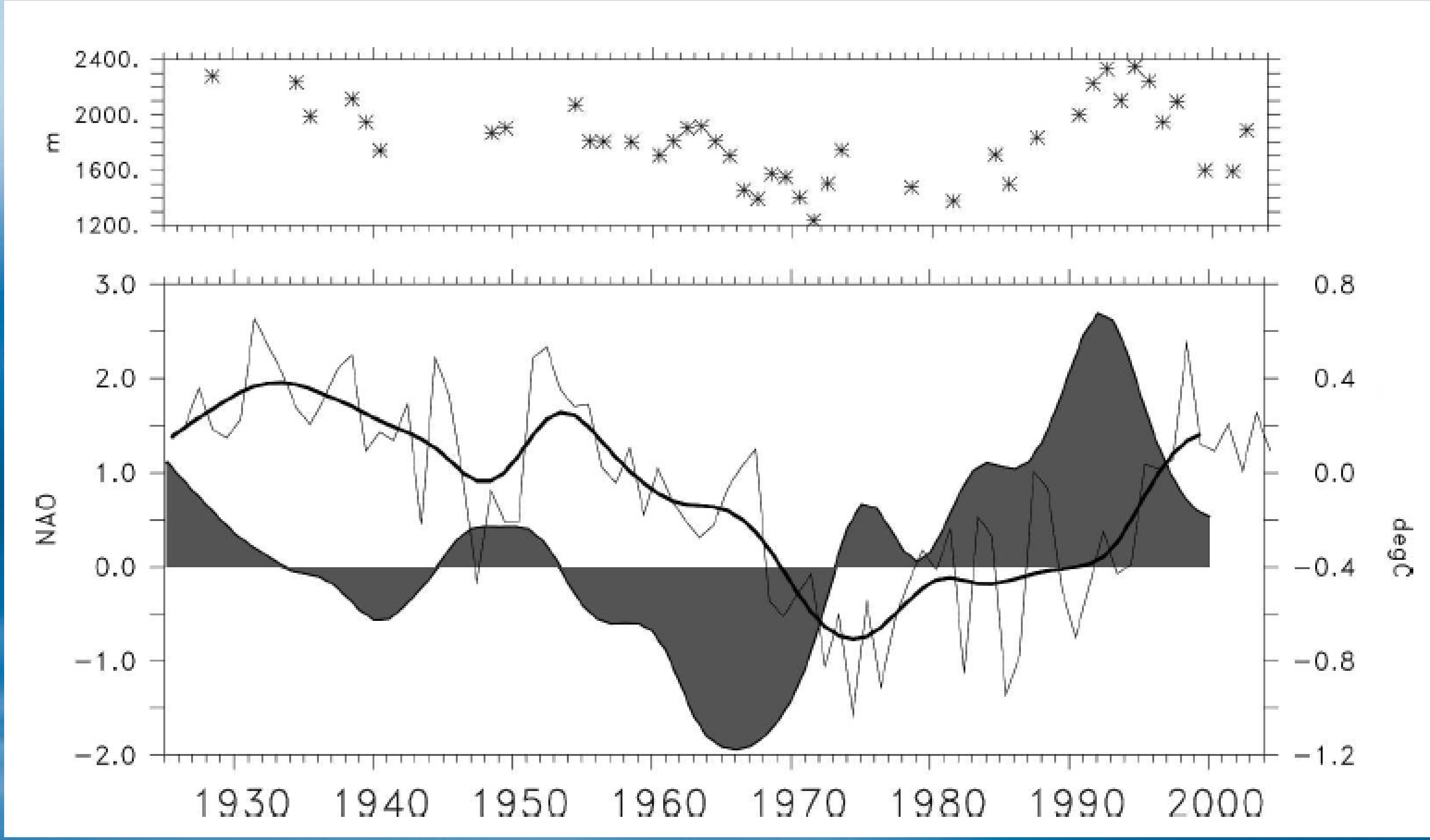
O czym świadczy Atlantyk w tym roku?



Ciepłe i zimne anomalie w okolicach Golfsztromu (jeśli odjąć globalne ocieplenie) dają sie naciągnąć jako przewidujące dodatnie NAO ;-)

http://www.ospo.noaa.gov/Products/ocean/sst/anomaly/index.html

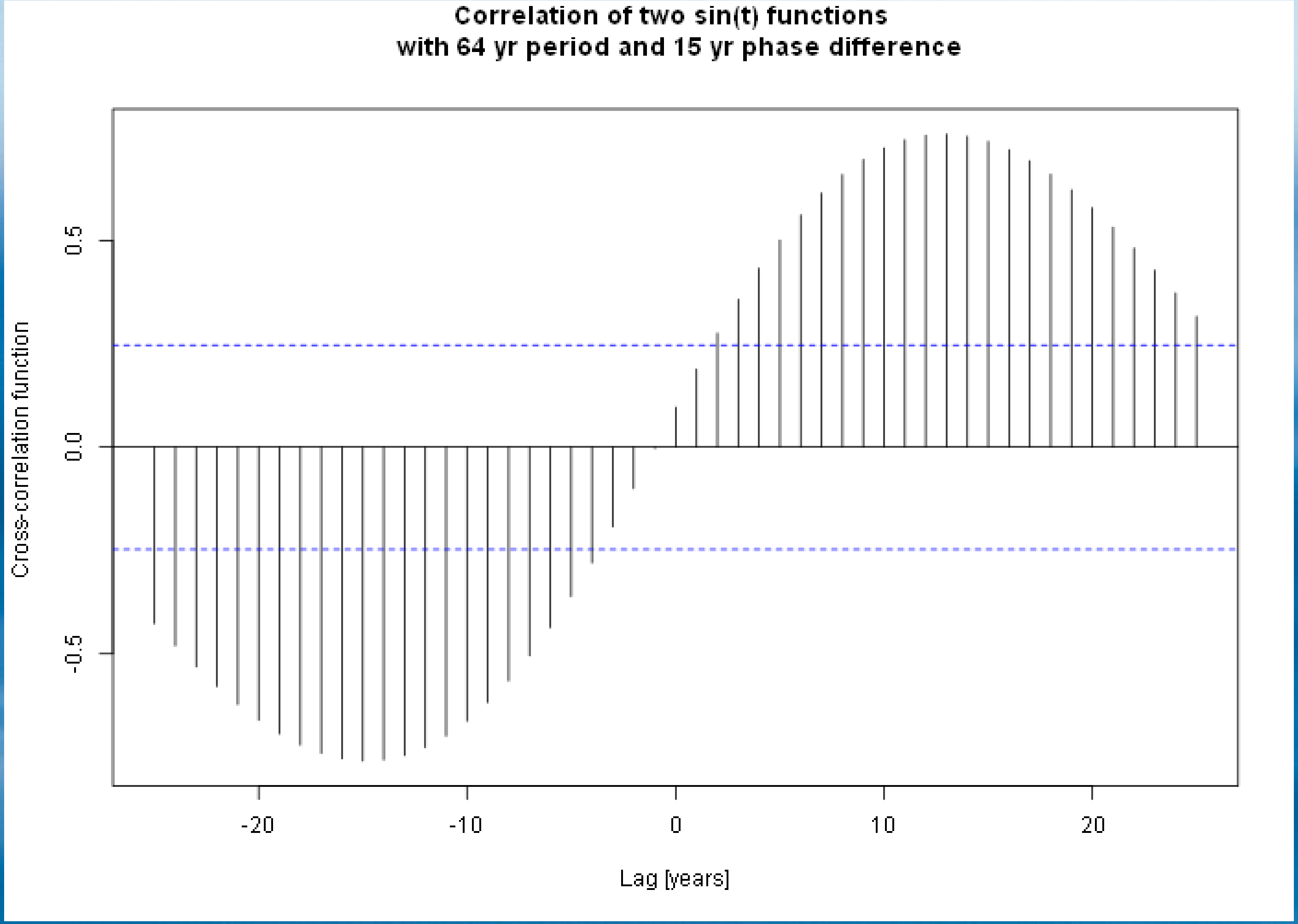
NAO leads THC by 10 years!



NAO index (shaded) seems to lead North Atlantic temperature (a simple measure of THC volume) by 10 years (thick line is a 11-year running mean). The mechanism explaining the phenomenon is supposed to be the NAO effect on Labrador Sea deep convection (top is Labrador Sea Water thickness in meters).

Latif et al. 2006 (Journal of Climate)

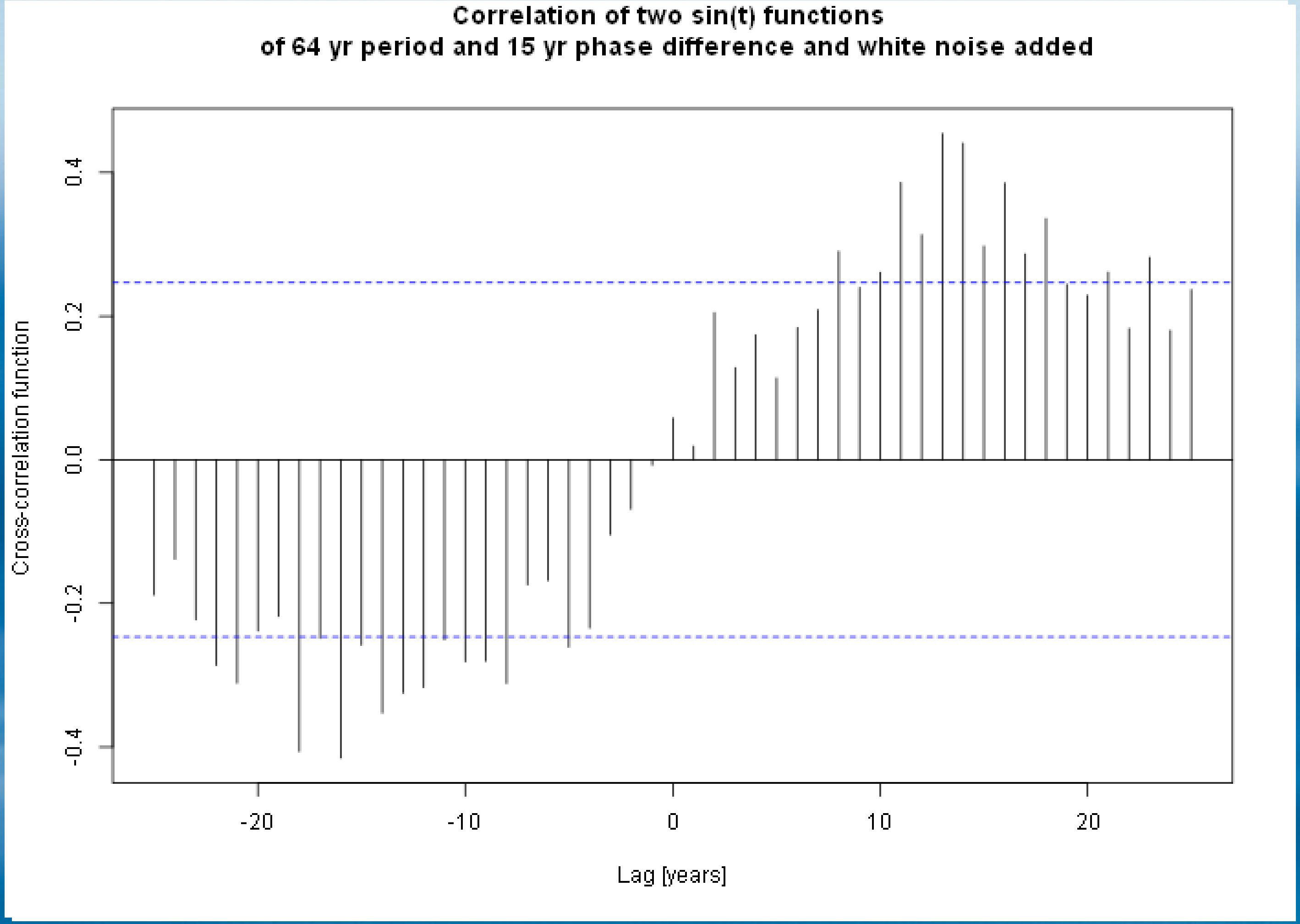
This is how two sine functions with a phase difference cross-correlate



The result of cross-correlation of the sine functions of 64 year period and a 15 year phase difference with **no** white noise added.

Piskozub 2013 (IAPSO)

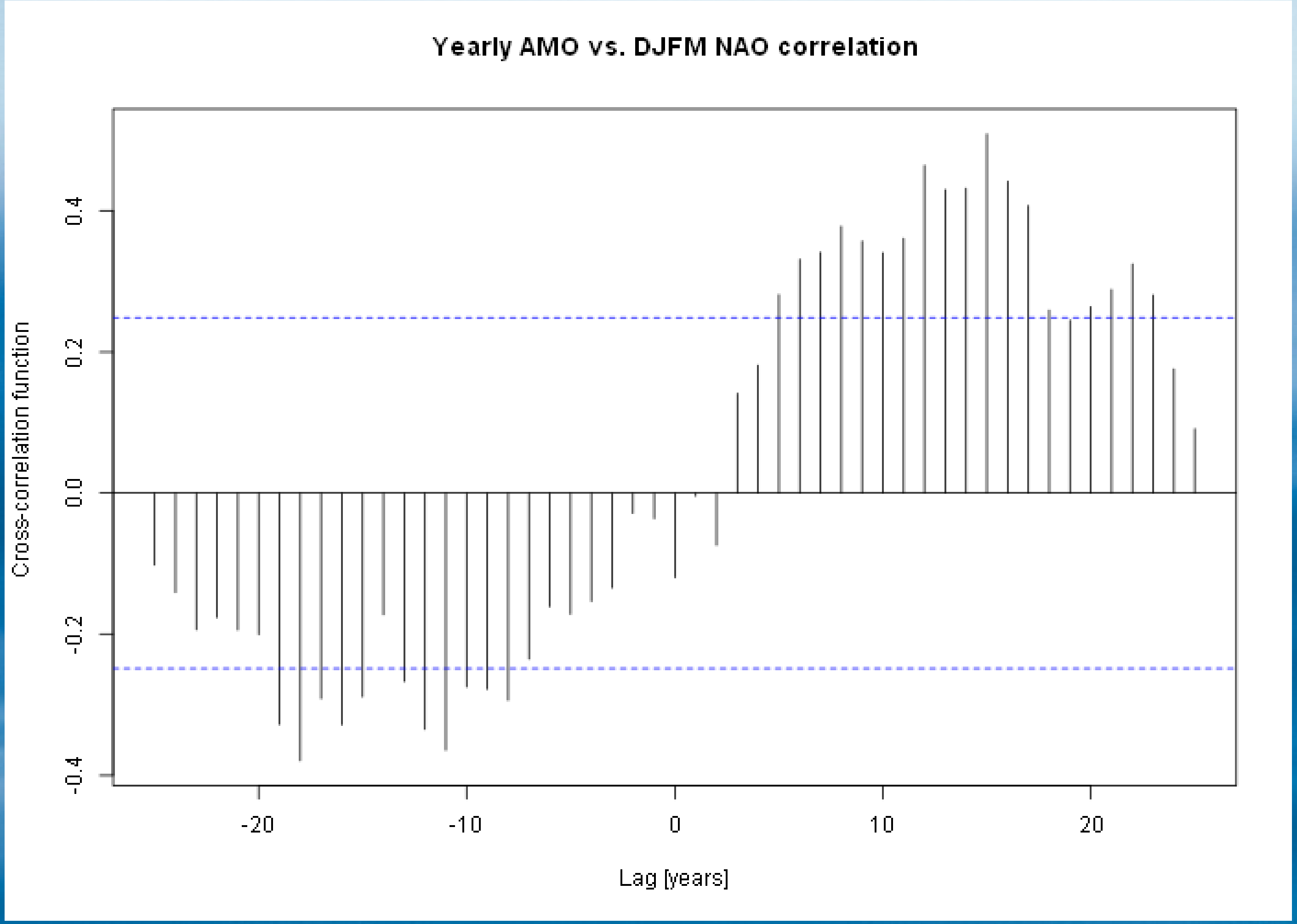
Same sine functions with some noise added



The result of cross-correlation of the sine functions of 64 year period and a 15 year phase difference with some white noise added.

Piskozub 2013 (IAPASO)

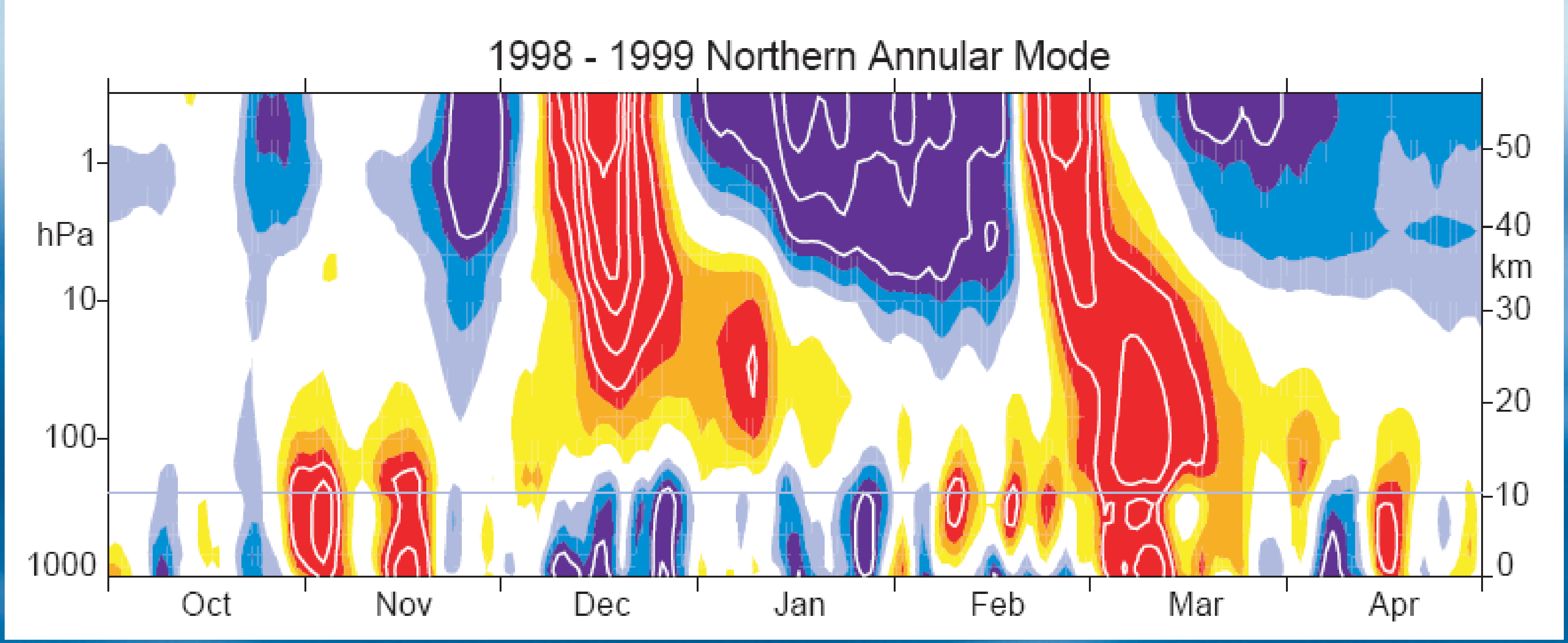
This is NAO cross-correlated with AMO



NAO index seems to lead AMO by about 15 years while AMO leads NAO 9with inverted sign) by another ca. 15 years. It looks almost exactly as if the two indices were the same approximately 60 year cycle but with different phases.

Piskozub 2013 (IAPSO)

But then, NAO starts in the stratosphere

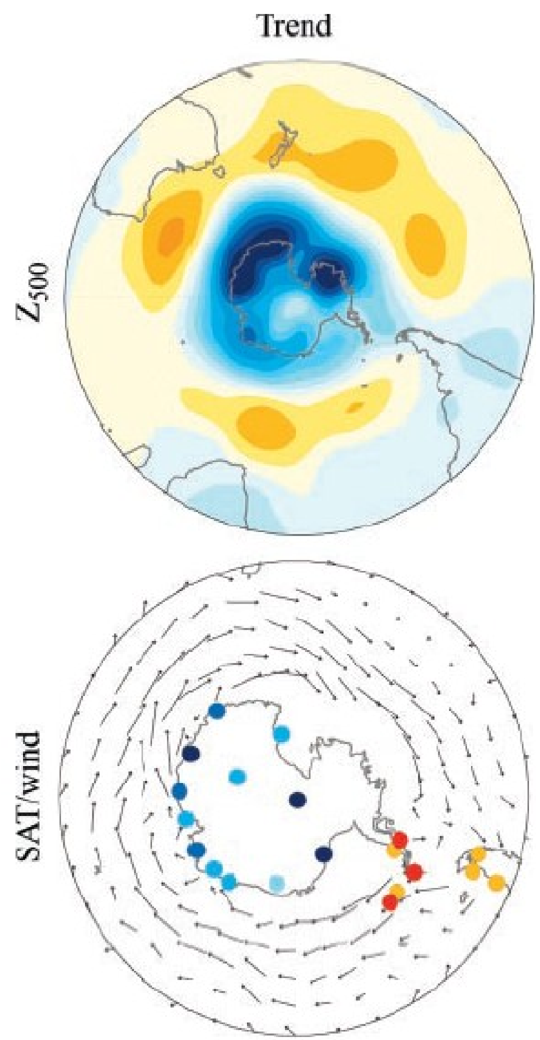


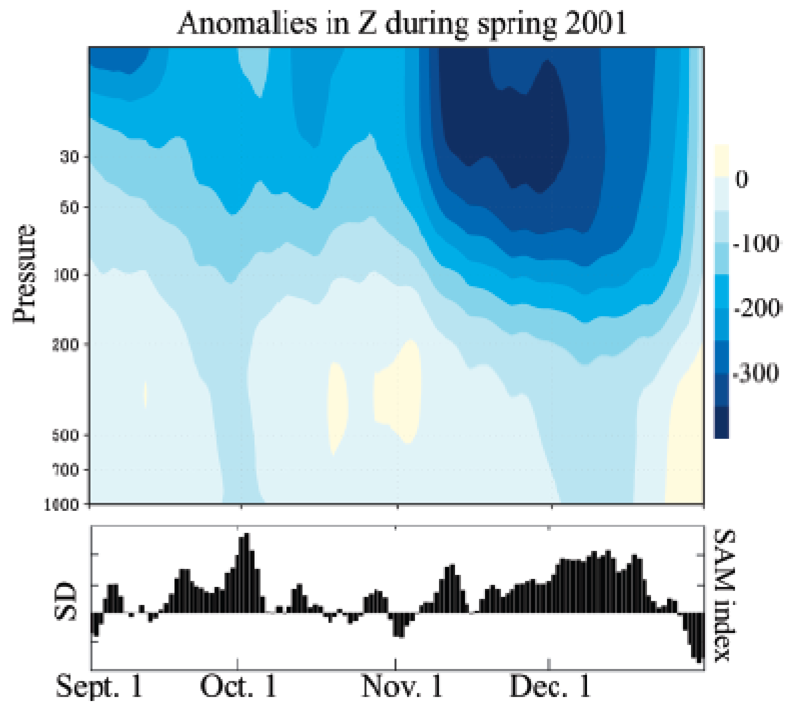
It seems NAO-like vortex circulation starts in the stratosphere and descends from the 50 km altitude within 60 days to the surface level.

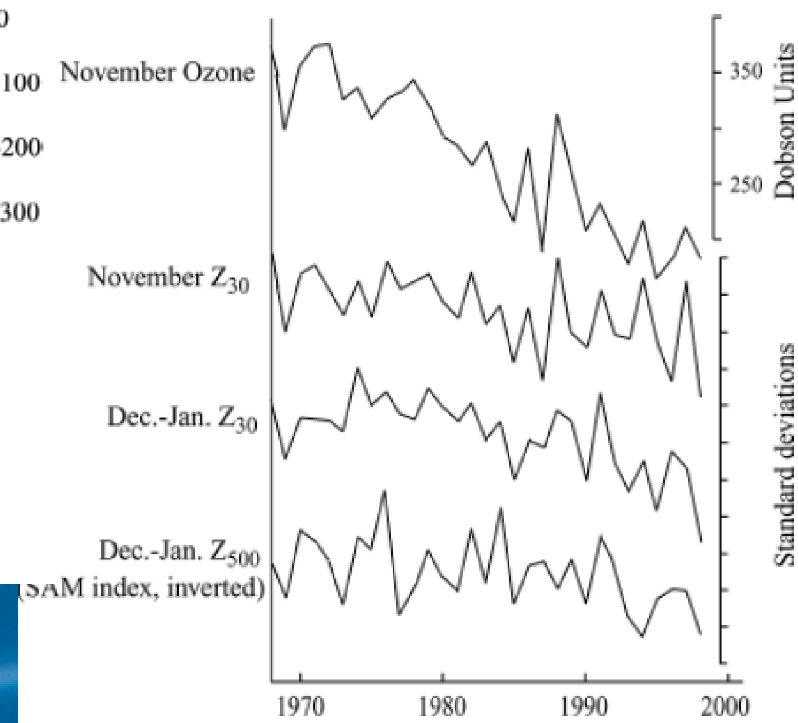
Northern Annular Mode is another name of NAO / AO
(compare *http://ao.atmos.colostate.edu/introduction.html*).

Baldwin & Dunkerton 2001 (Science)

Ozone controls SAM („southern NAO")?



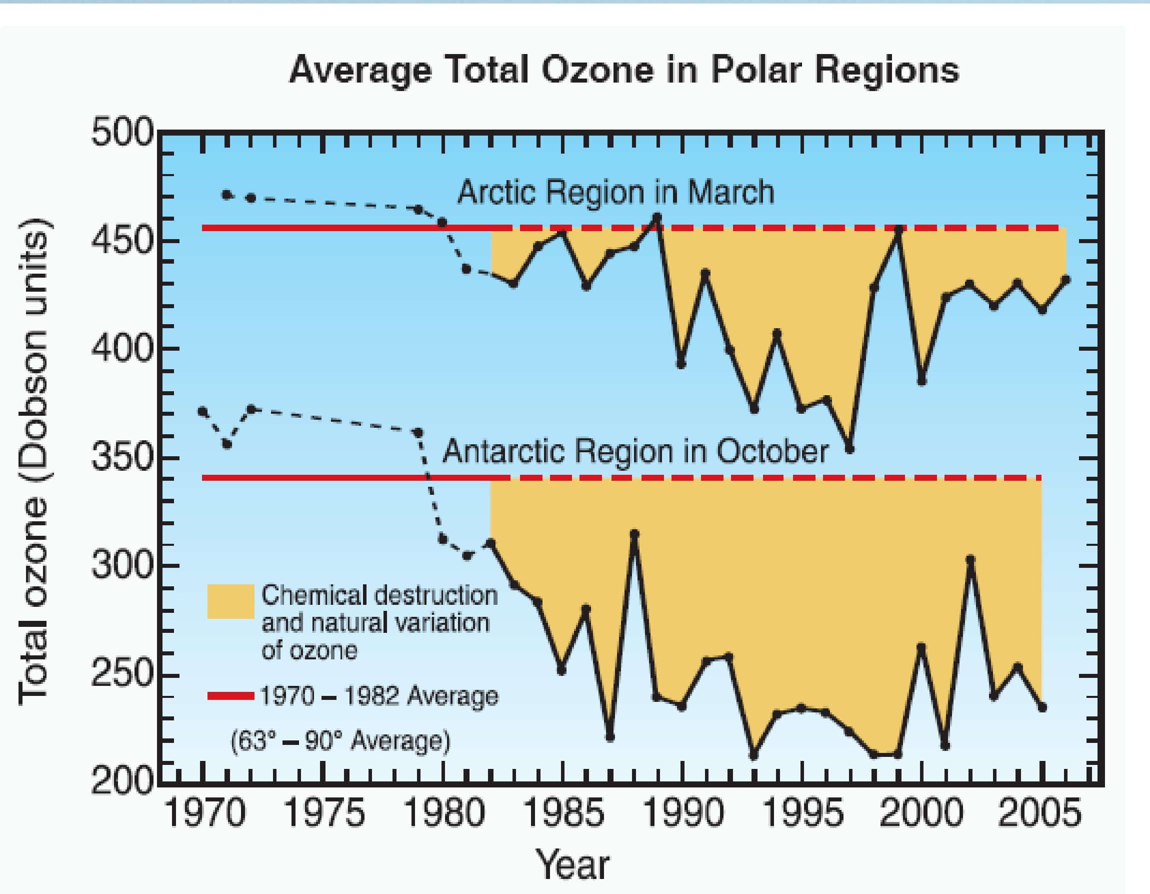


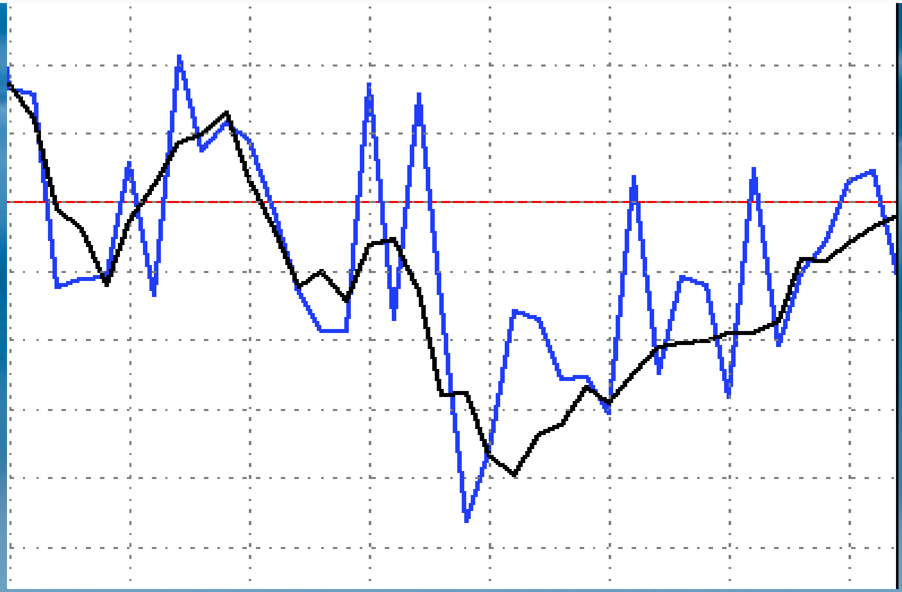


The trend (1979-2000) of deepening low pressure and the Antarctic vortex is consistent with observed increase of Southern Annual Mode (SAM – the southern counterpart of AO). This deepens the thermal isolation of the Antarctic. Anomalies of geopotential height (an inverted measure of AO) start from stratosphere which temperature is influenced by the presence of ozone. The isolation of the polar vortex deepens the ozone hole. The covariance of stratospheric ozone and SAM seem an established fact. But does it prove causality?

Thompson & Solomon 2002 (Science)

Ozone and NAO



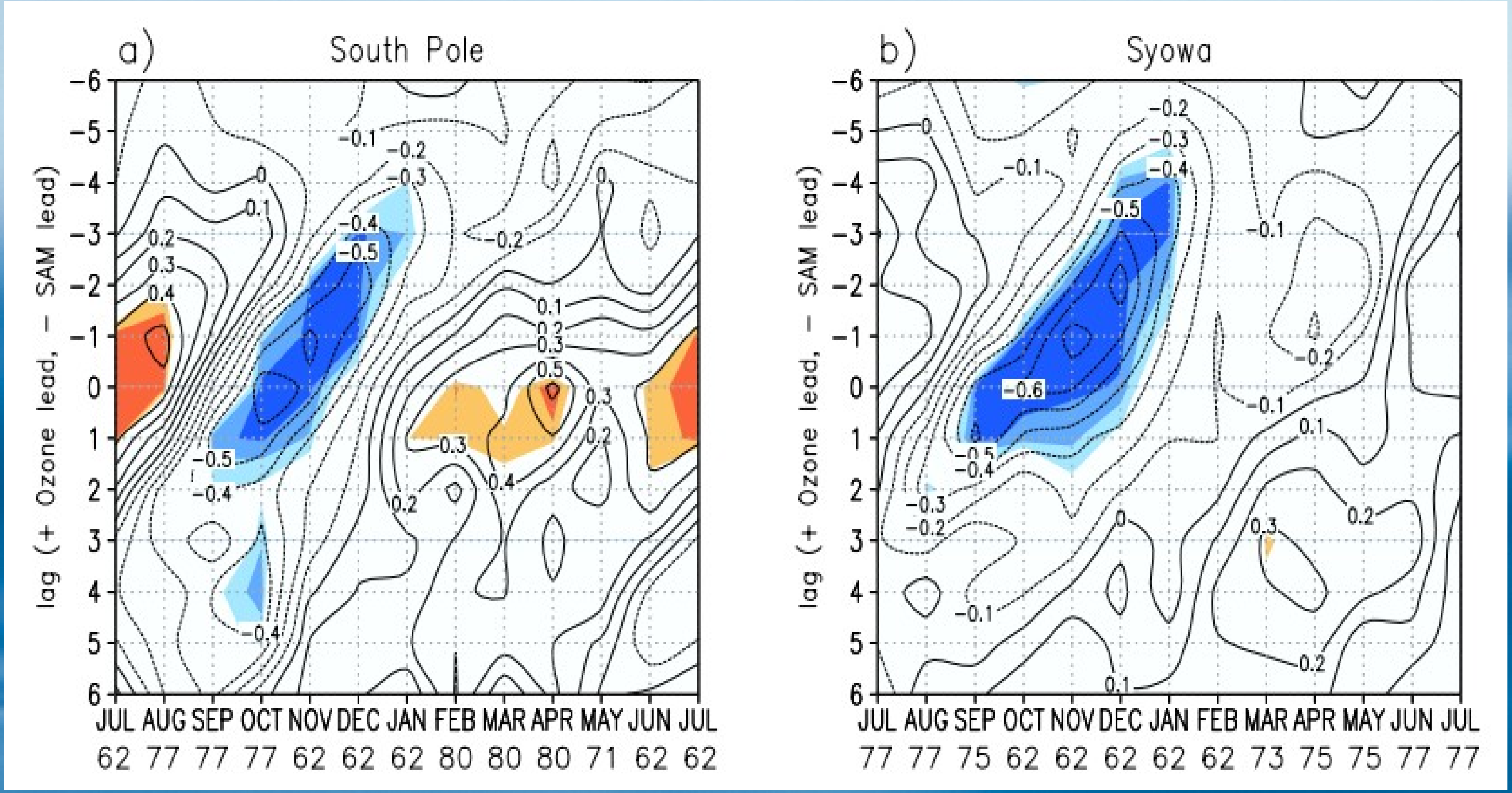


Polar stratospheric ozone for Northern and Southern 63º-90º polar areas (top) and inverted NAO index (bottom) – with the same time scale.

Is the covariance accidental? If not, which controls which? The effect can be "explained" qualitatively both ways. But which is true? Or maybe both?

World Meteorological Organization, "Scientific Assessment of Ozone Depletion: 2006"

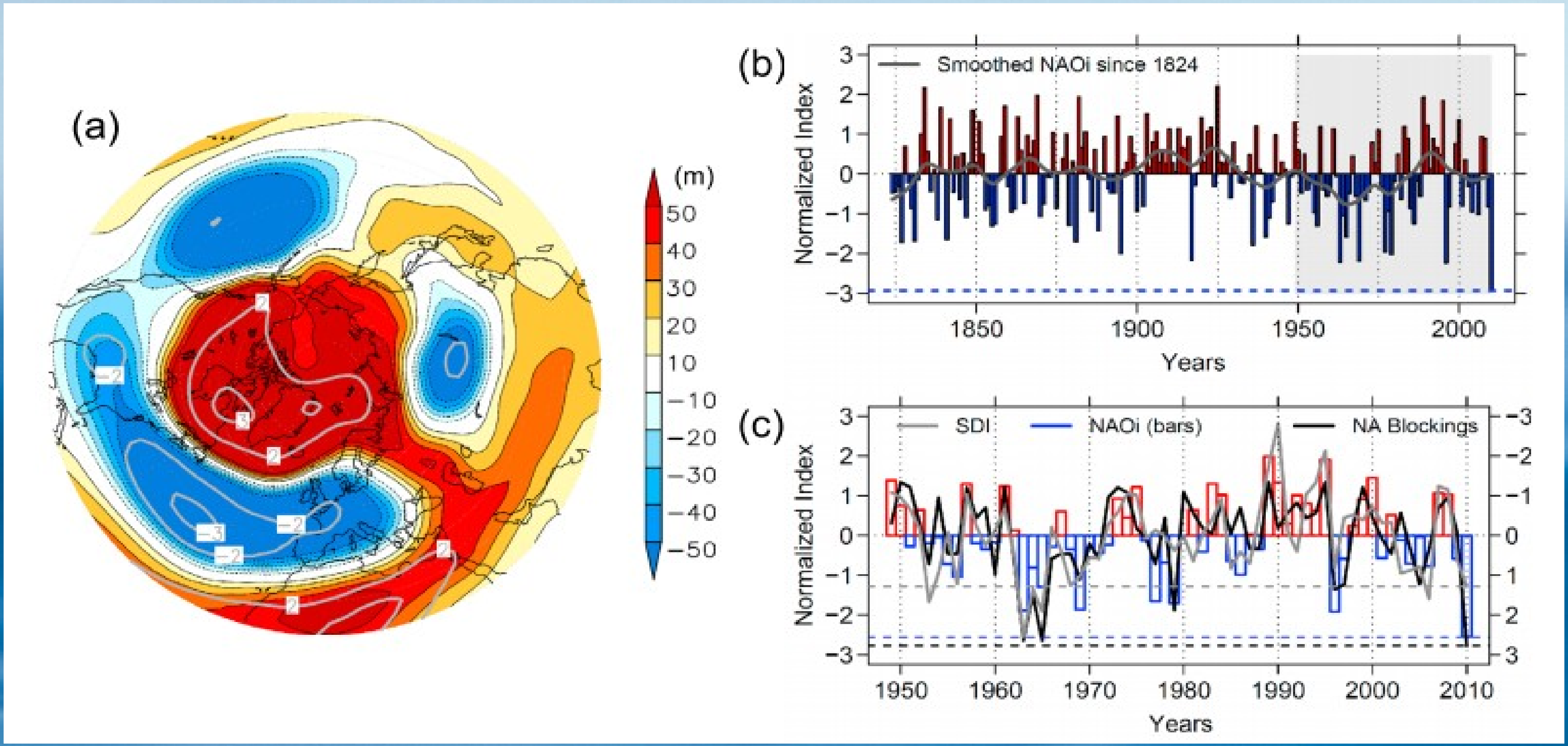
Ozone and SAM



Observations show that at least in short time time scale ozone anomalies over Antarctide precede the Southern Annual Mode by up to 4 months (in SH Spring). This does not prove causation but...

Fogt et al. 2009 (GRL)

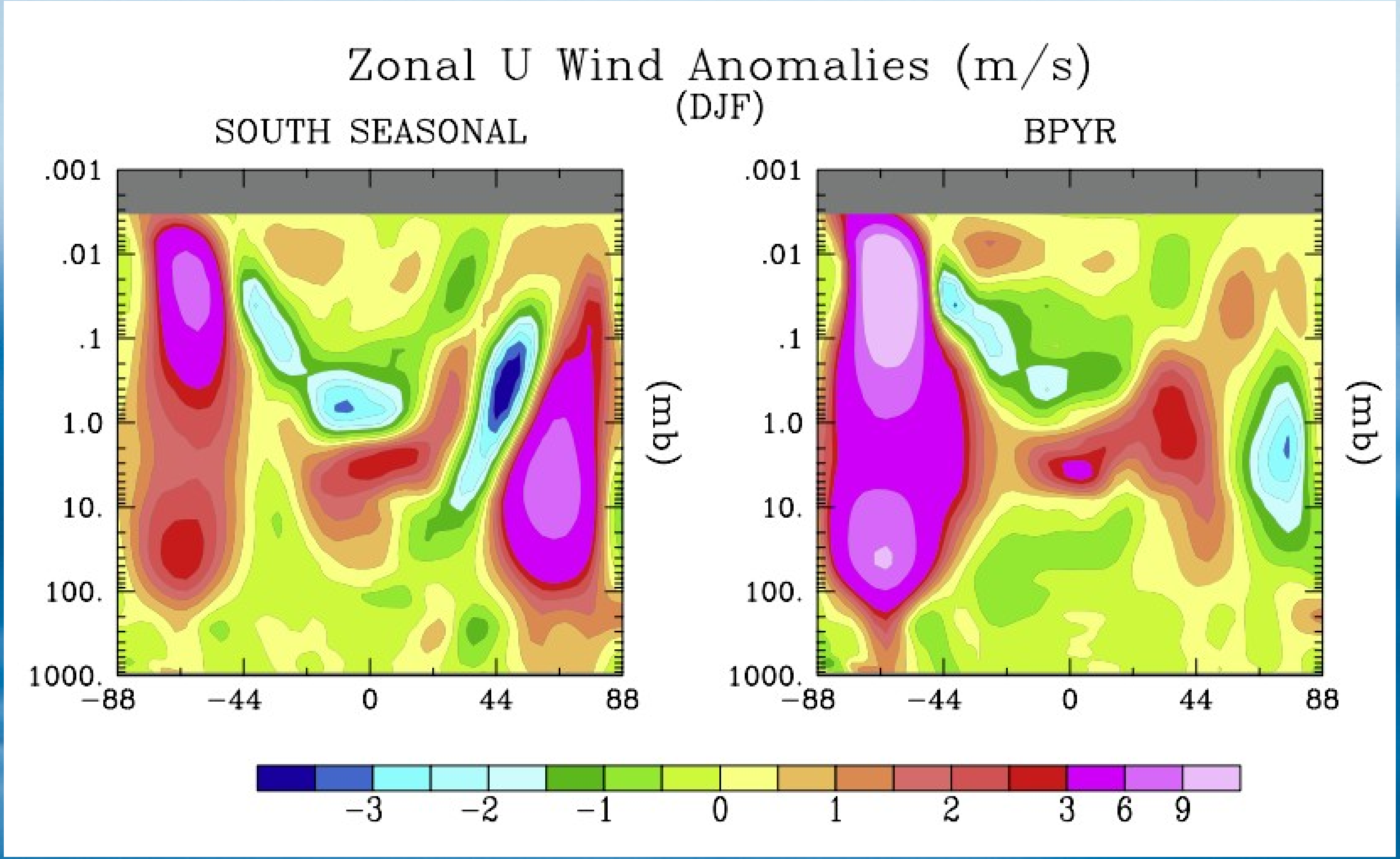
We had the winter with lowest NAO in history?



It seems we had not only the lowest winter NAO values since meteorology started but also the second longest blockings (see panel a) since 1949 (the longest were in 1963).

Cattiaux et al 2010 (GRL)
"Winter 2010 in Europe: A cold extreme in a warming climate" published on October 22

The WTF result: Antarctic ozone and NAO !?



Rind et al 2009 made modelling “experiments” of checking the atmospheric circulation effect of removing all ozone over the Antarctic in SH spring or on both hemispheres (BPYR = Both Poles Year Round). It seems northern ozone does not have much effect but removing the southern one makes both SAM and NAO (yes!) stronger. Hard to believe? Yes, but...

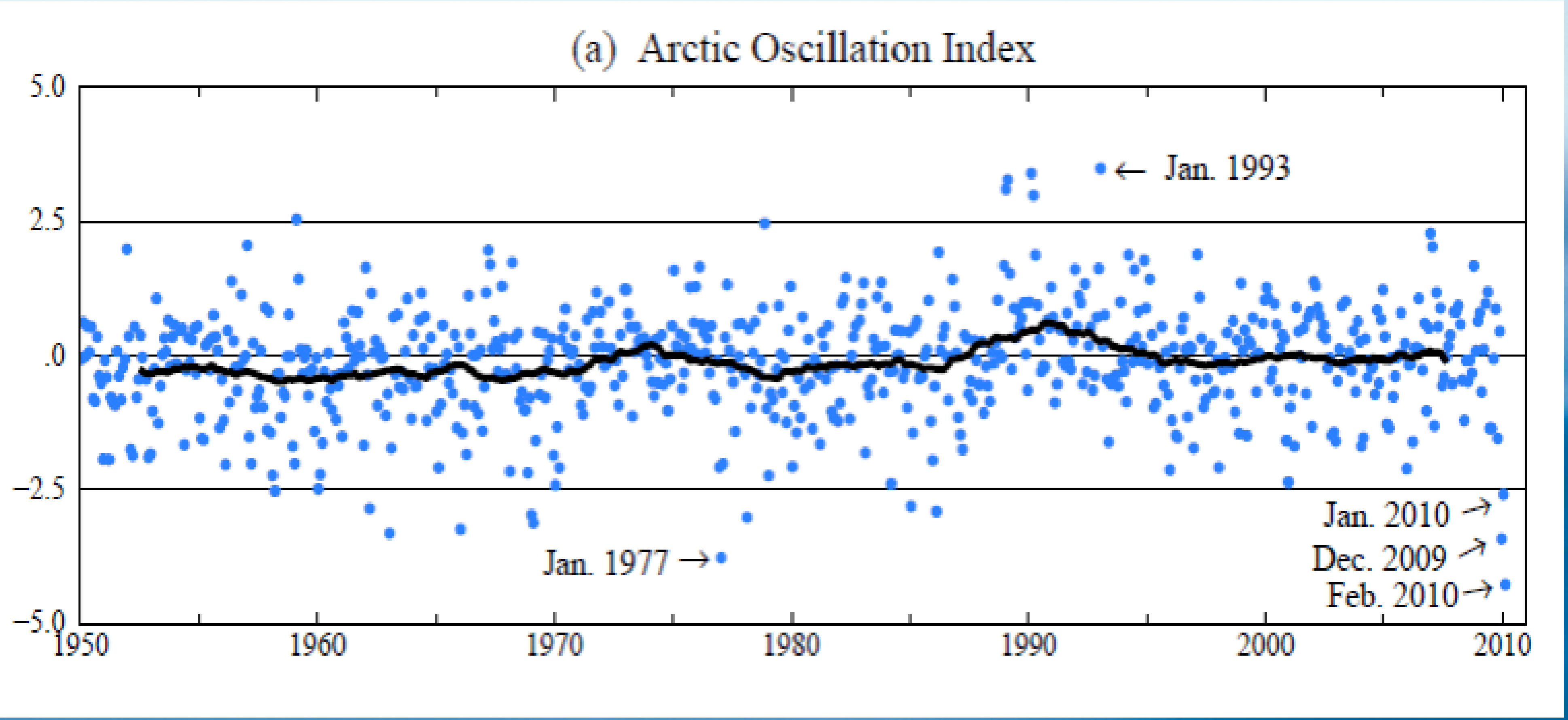
Rind et al. 2009 (GRL)

So what will be the weather of the next decades?

- Of course with increasing atmospheric CO_2, it will be generally warmer everywhere but especially in the Arctic (with positive feedback caused by sea-ice loss)
- We should expect more precipitation in North Europe (and less in the South), including more extreme precipitation (almost everywhere)
- The 60-70 AMO oscillation index seems to be decreasing implying decreasing Atlantic overturning circulation. This should slow down a little the warming around North Atlantic but not stop it.
- At the same time the NAO index went into negative values implying the possibility of several cold winters in North Europe.

So do we understand it all? Certainly not as well as we would like. There are many unknowns (including how much of AMO variability is actually anthropogenic). But it starts to make some sense.

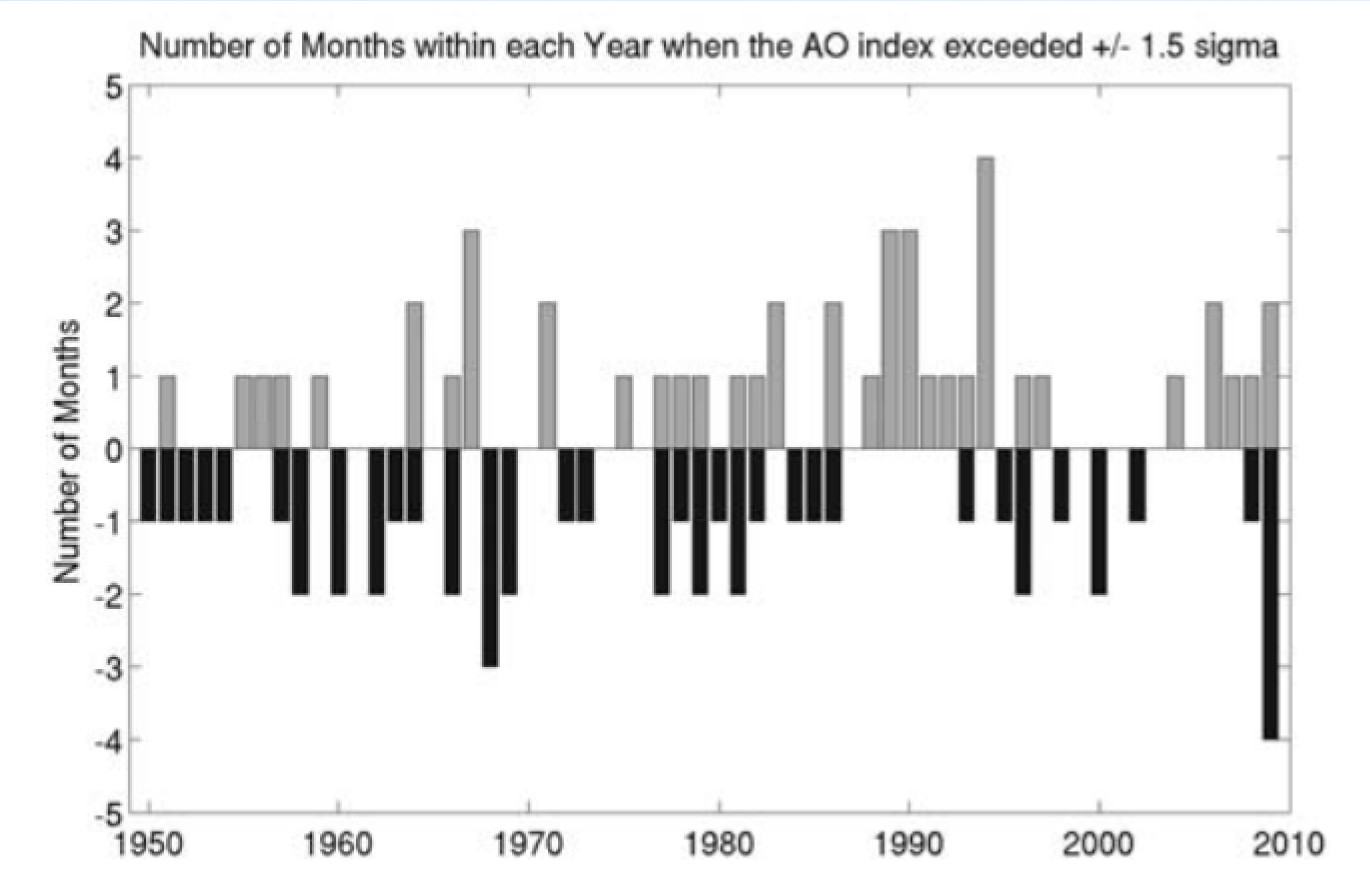
Why did we have such a cold winter?



The winter AO values of 2010 were the lowest since 1977. Blue dots are monthly means and black curve is the 60-month (5-year) running mean.

Hansen 2010 (unpublished)

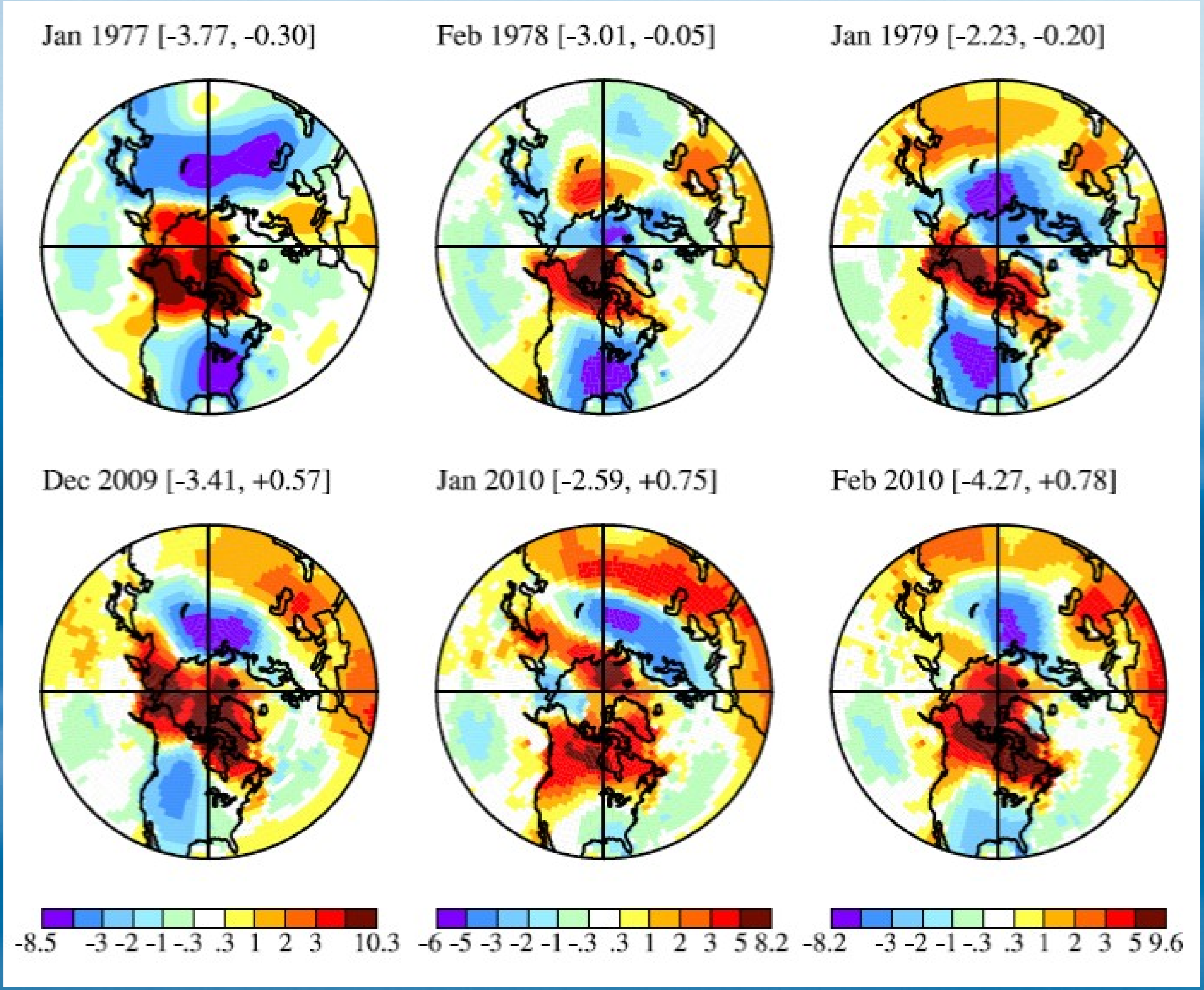
2009 had a record number of low NAO months



Even before the winter started, AO had three months of extremely low NAO values (June, July and October). December was the fourth (and as we know the next months continued the trend). The values itself were the lowest in 60 years. It may be noted that 2009 had also two months of very high NAO values (May and September).

L'Heureux et al 2010 (GRL)

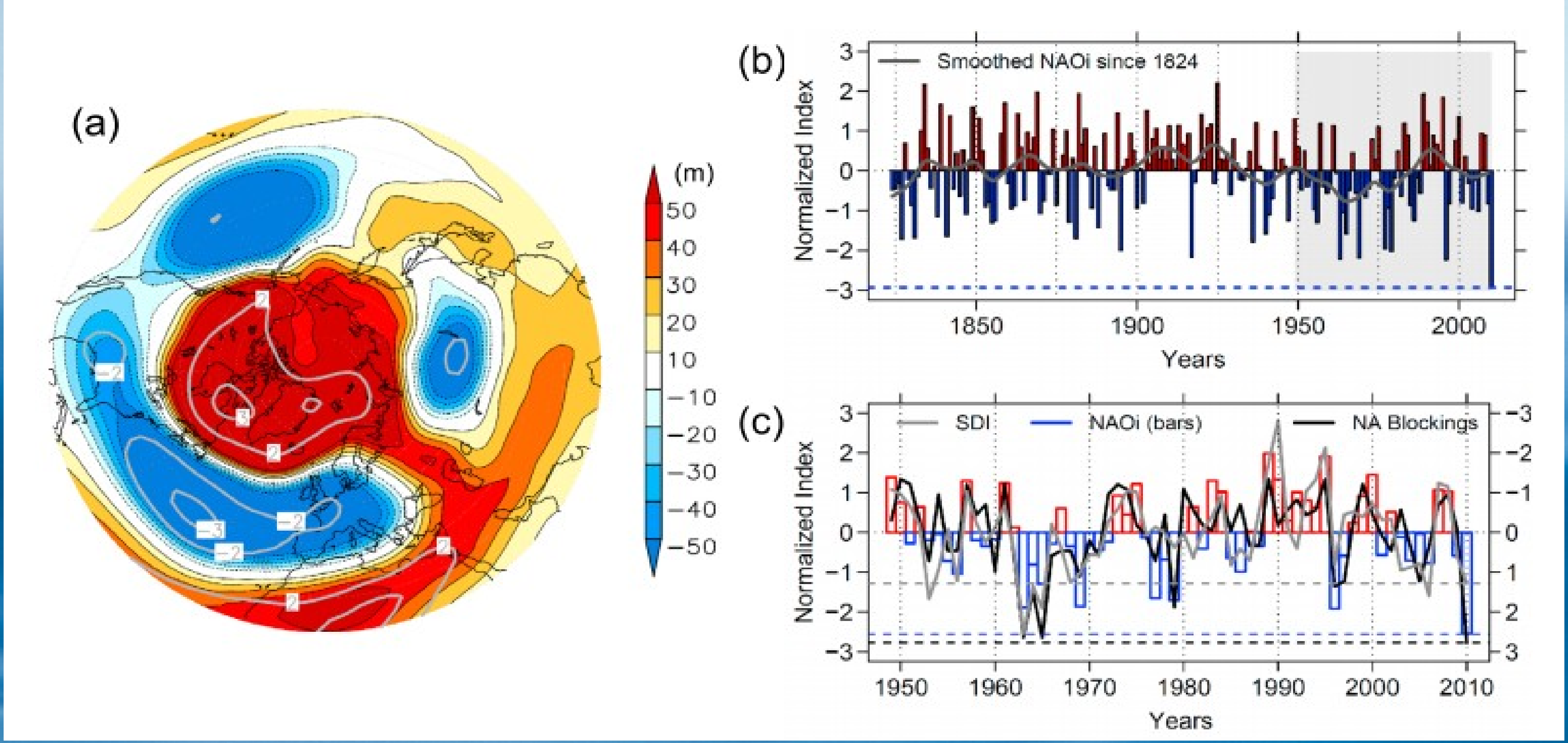
Low AO values lead to this kind of winters



90-24 N temperature anomaly for months with extremely negative AO Index

Hansen 2010 (unpublished)

We had the winter with lowest NAO in history?

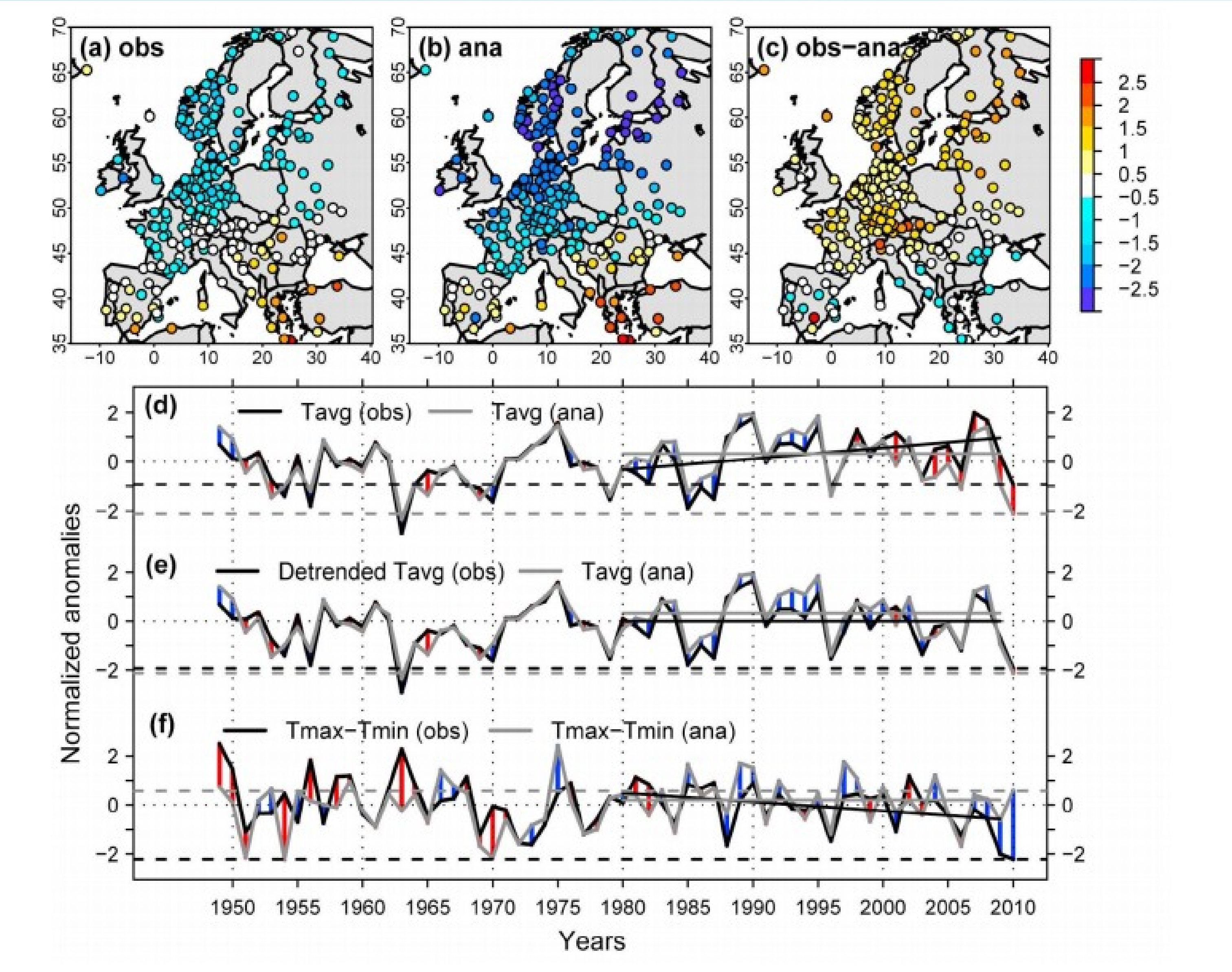


It seems we had not only the lowest winter NAO values since meteorology started but also the second longest blockings (see panel a) since 1949 (the longest were in 1963).

Cattiaux et al 2010 (GRL)

"Winter 2010 in Europe: A cold extreme in a warming climate" published on October 22

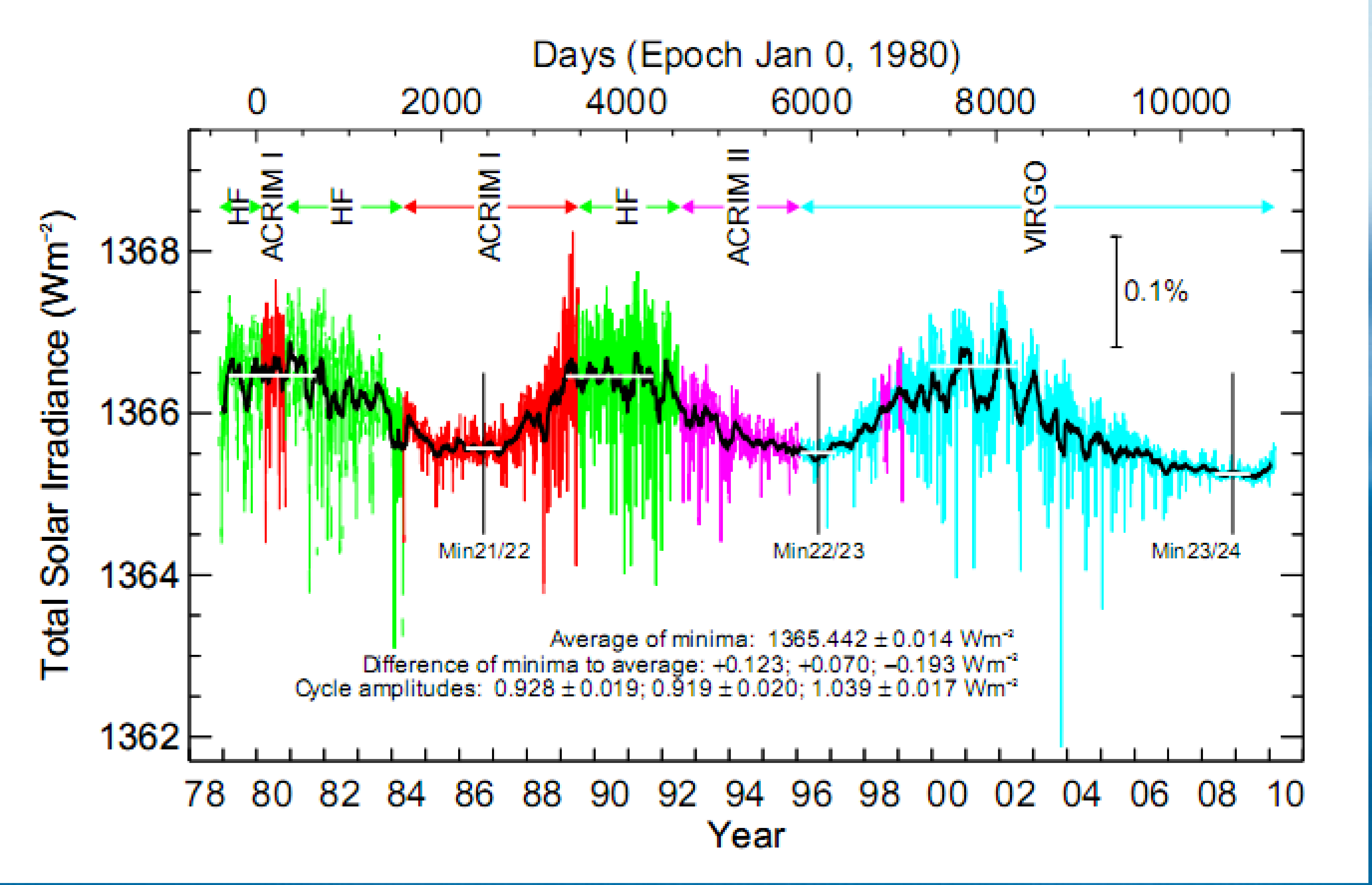
But it was only the 13th coldest one. Why?



Comparing the synoptic situation of every winter day with most similar (analogous") days in 1949-2009 shows that the observed "obs" values started to diverge from "ana" since 1980. This may be interpreted as the effect of global warming making winters less cold than similar ones in the past and decreasing day-night amplitudes (f)

Cattiaux et al 2010 (GRL)
"Winter 2010 in Europe: A cold extreme in a warming climate" published on October 22

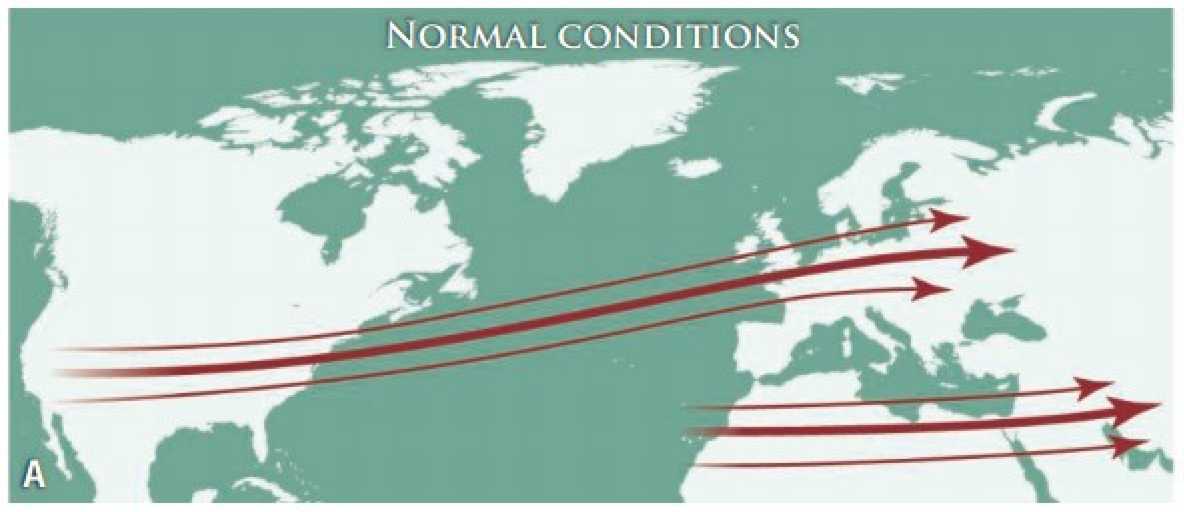
Solar activity in 2009/10 lowest since 1913

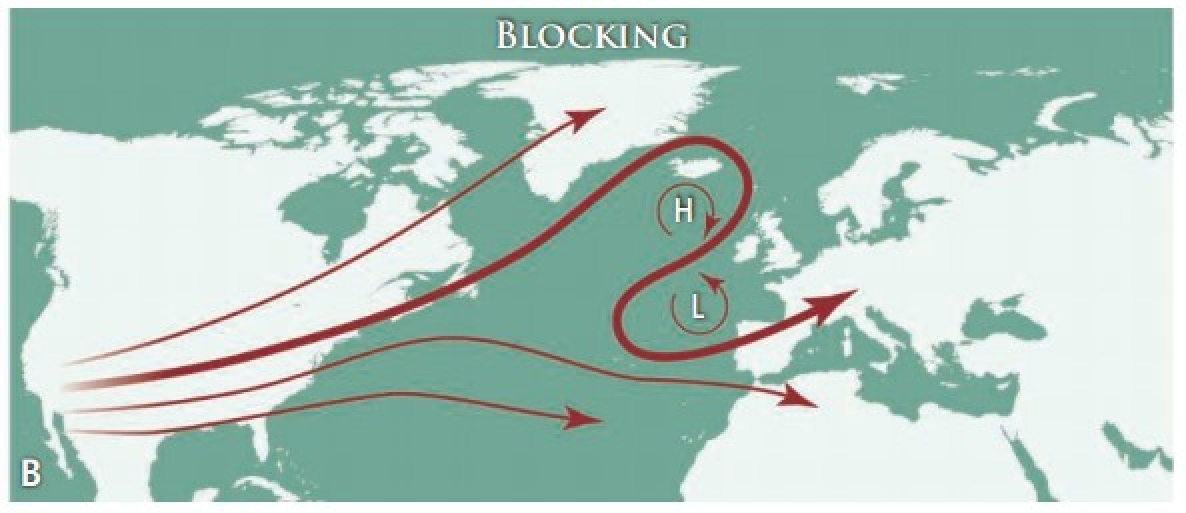


The PMOD composite Total Solar Irradiation as daily values plotted in different colors for the different originating experiments. The difference between the minima values is also indicated, together with amplitudes of the three cycles

http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant

What is a blocking?

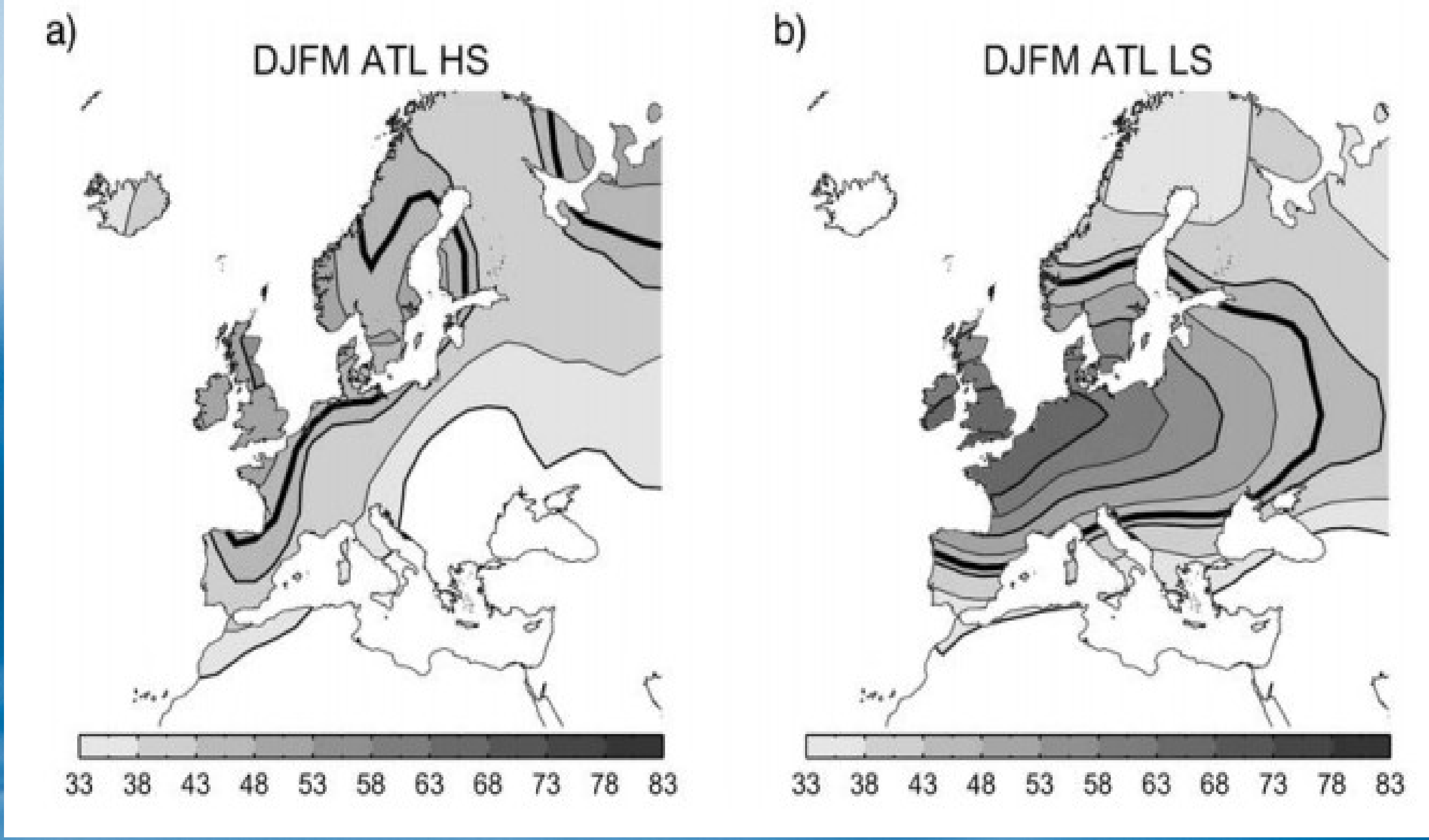




Diverting the jet stream. (A) In the normal weather pattern, the jet stream carries air from North America across the Atlantic to Europe. The wind shear on the flanks of the jet acts to maintain the ocean gyre circulations. (B) During a blocking weather pattern, the strong westerly winds of the jet stream are diverted north and south around a dramatic reversal of streamlines.

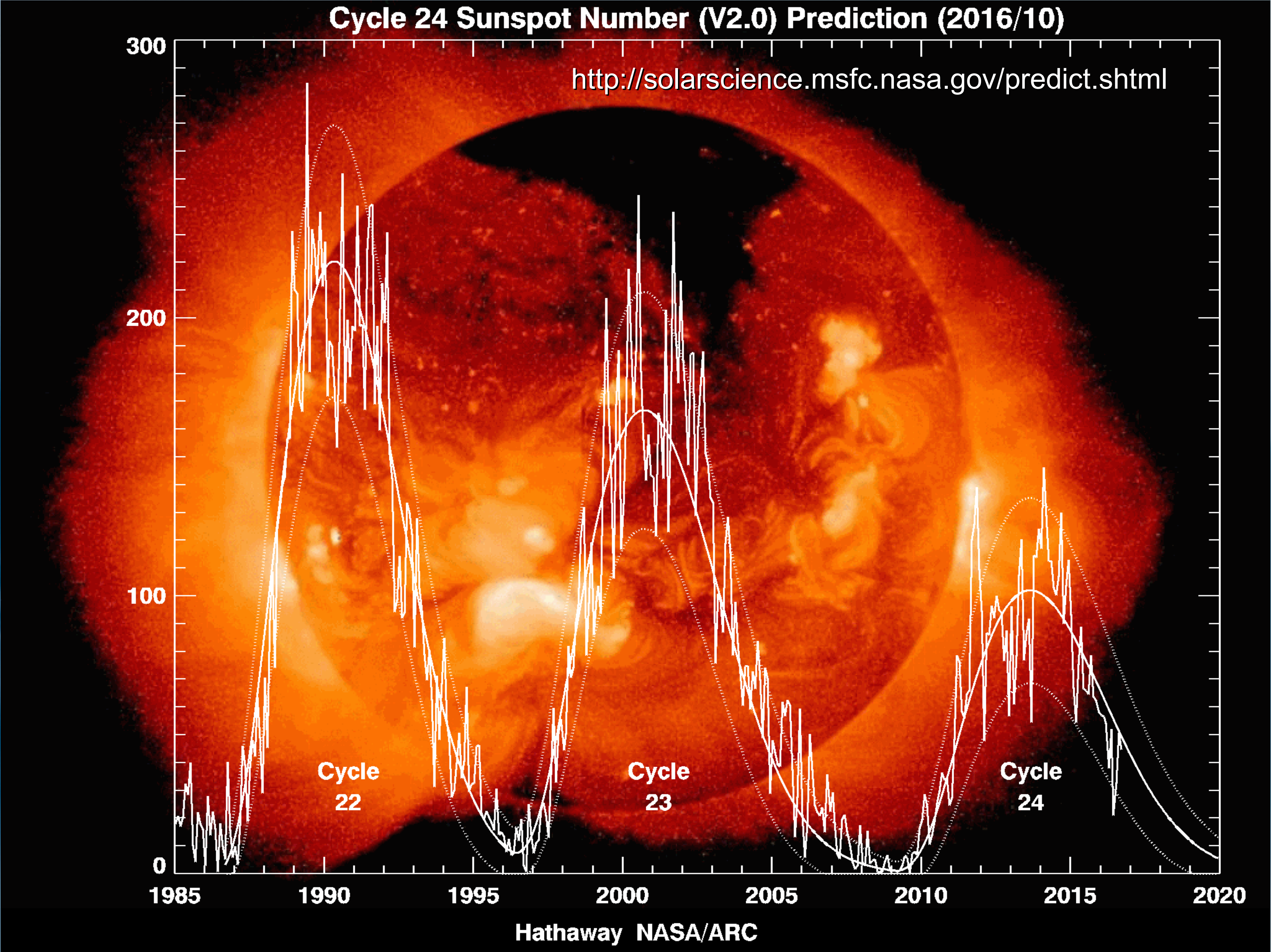
Woolings. 2011 (Science)

Blocking is more effective with low solar activity



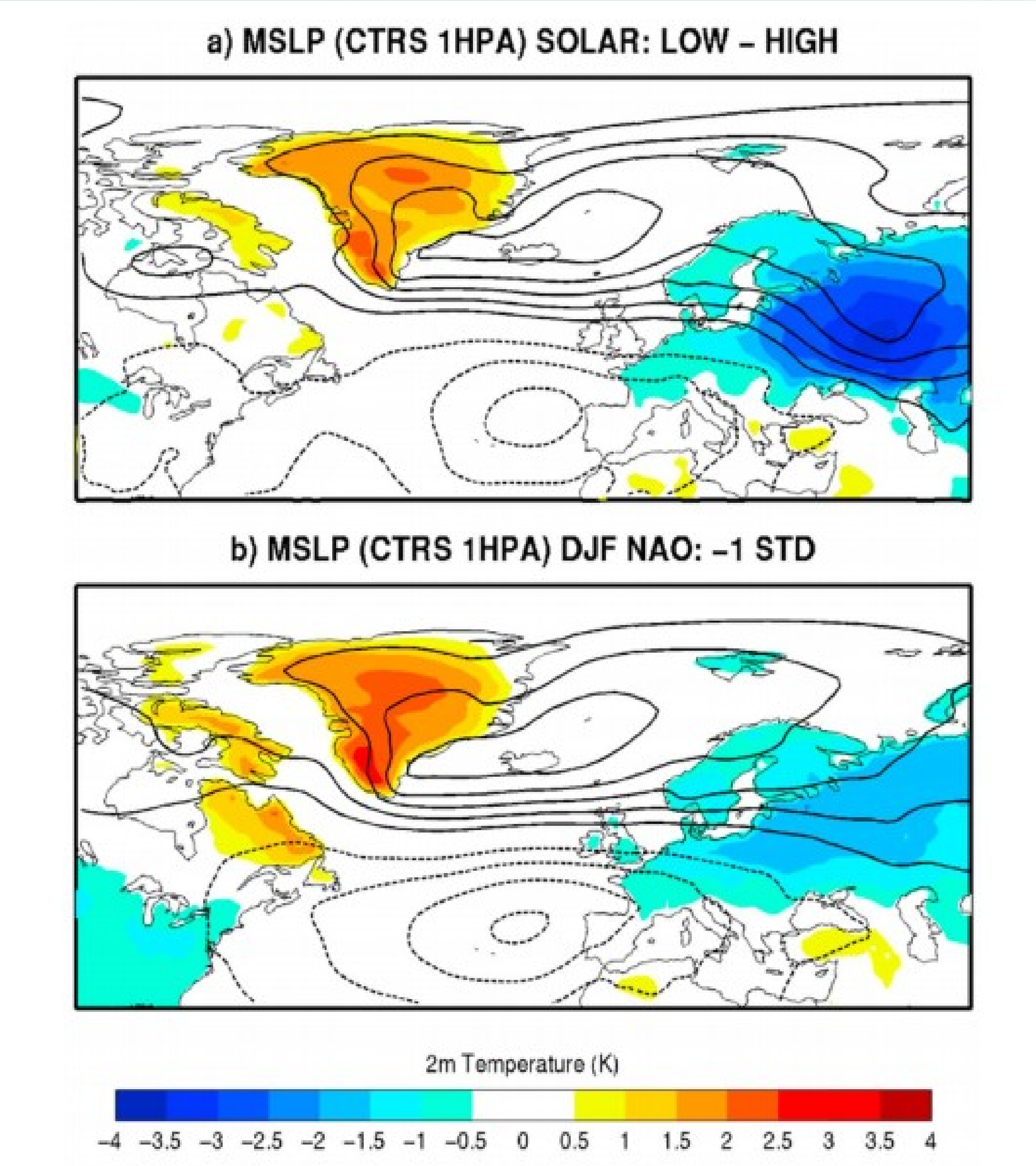
Solar modulation of the blocking impacts in the temperature distribution. Percentage of Atlantic blocking days with daily mean 2-m temperature anomalies in the lower tercile of its winter distribution under: (a) HS and (b) LS. Solid lines and shaded areas denote those values exceeding the expected value (33.3%) with 5% contour interval. The thick solid line denotes the 95% confidence threshold based upon a binomial test. The quartile solar stratification is used

Barriopedro et al. 2008 (JGR)



Cycle 24 Sunspot Number (V2.0) Prediction (2016/10)
http://solarscience.msfc.nasa.gov/predict.shtml
300
200
100
0
Cycle 22
Cycle 23
Cycle 24
1985
1990
1995
2000
2005
2010
2015
2020
Hathaway NASA/ARC

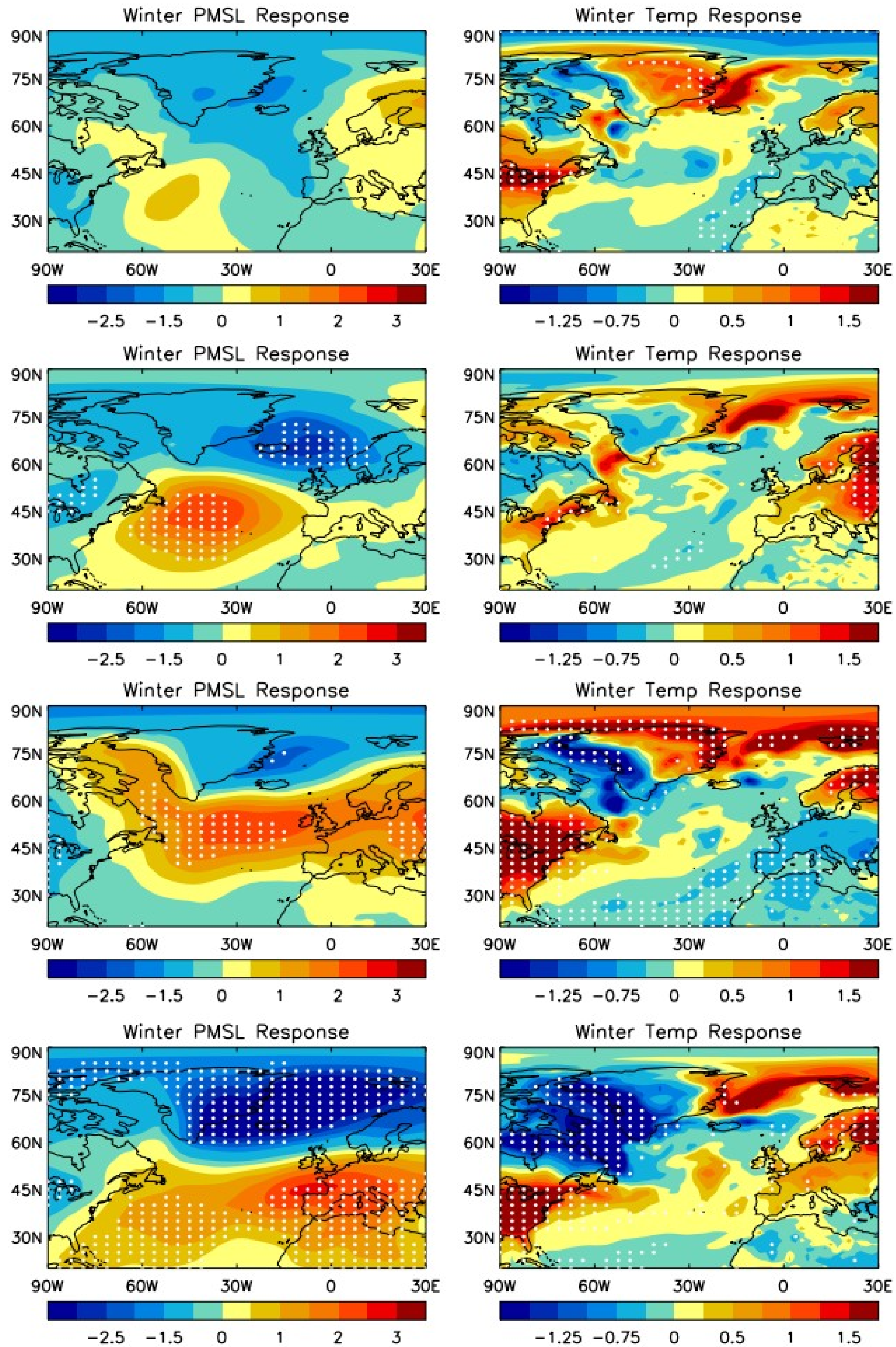
Is the effect of Solar activity similar but distinct from NAO?



Comparison of mean winter surface pressure (contours) and 2m temperature (colors) between low- and high- solar activity years (upper panel) and low and high NAO (lower panel).

The patterns are similar but the effects of low solar activity extend more to the East towards Central Europe. The two patterns seen statistically different.

Woolings et al 2010 (GRL)



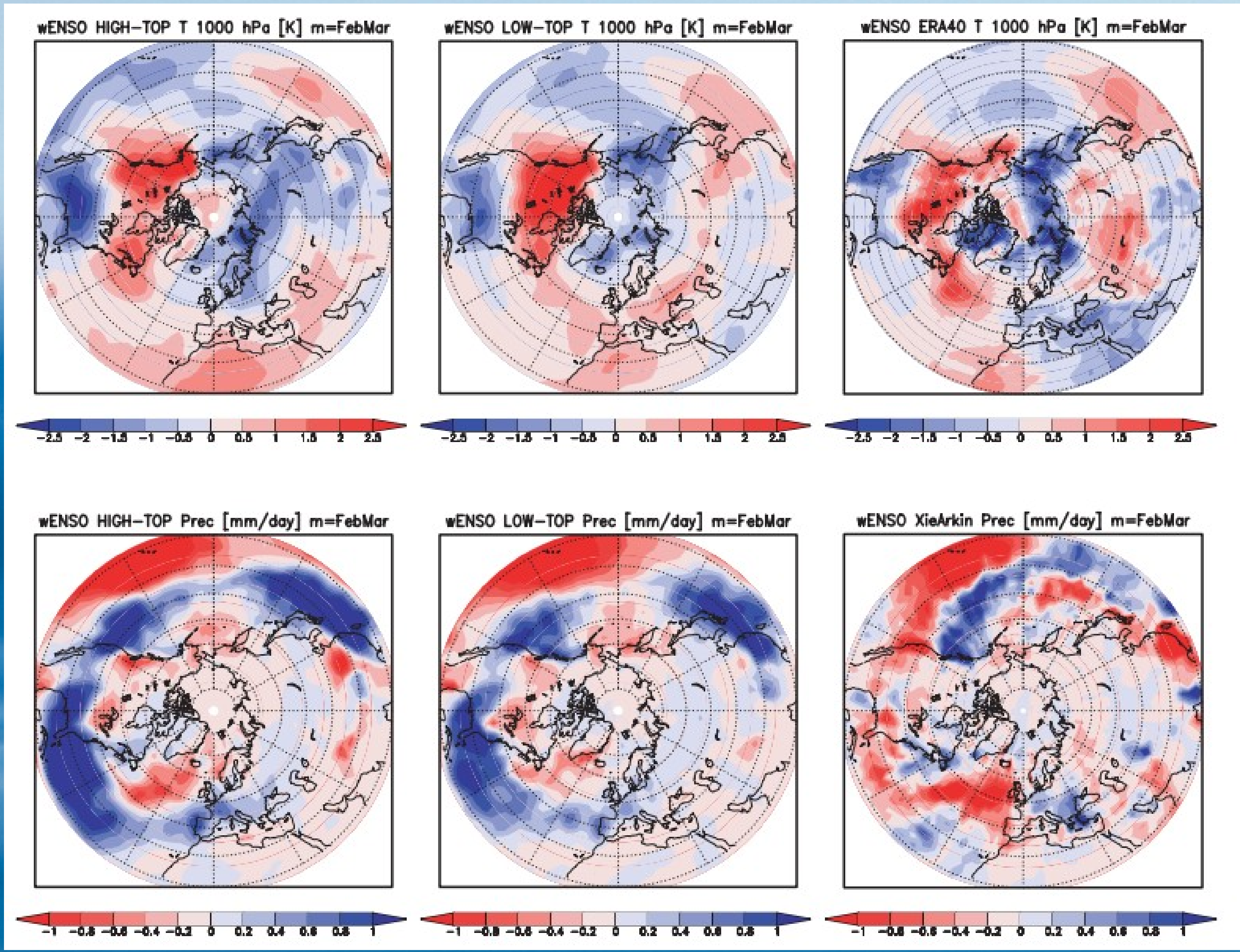
Lagged solar effect on NAO?

Model results showing the effect of stepwise 1.2 W/m2 increase in solar UV flux, after 1, 2, 3 & 4 years (from top to bottom). The left column are changes in winter surface pressure and right in winter surface temperature.

Is the delayed response the reason for "smearing out" of the solar signal which makes the 11-year oscillation undetectable in the NAO time series?

Scaife et al 2013 (GRL)

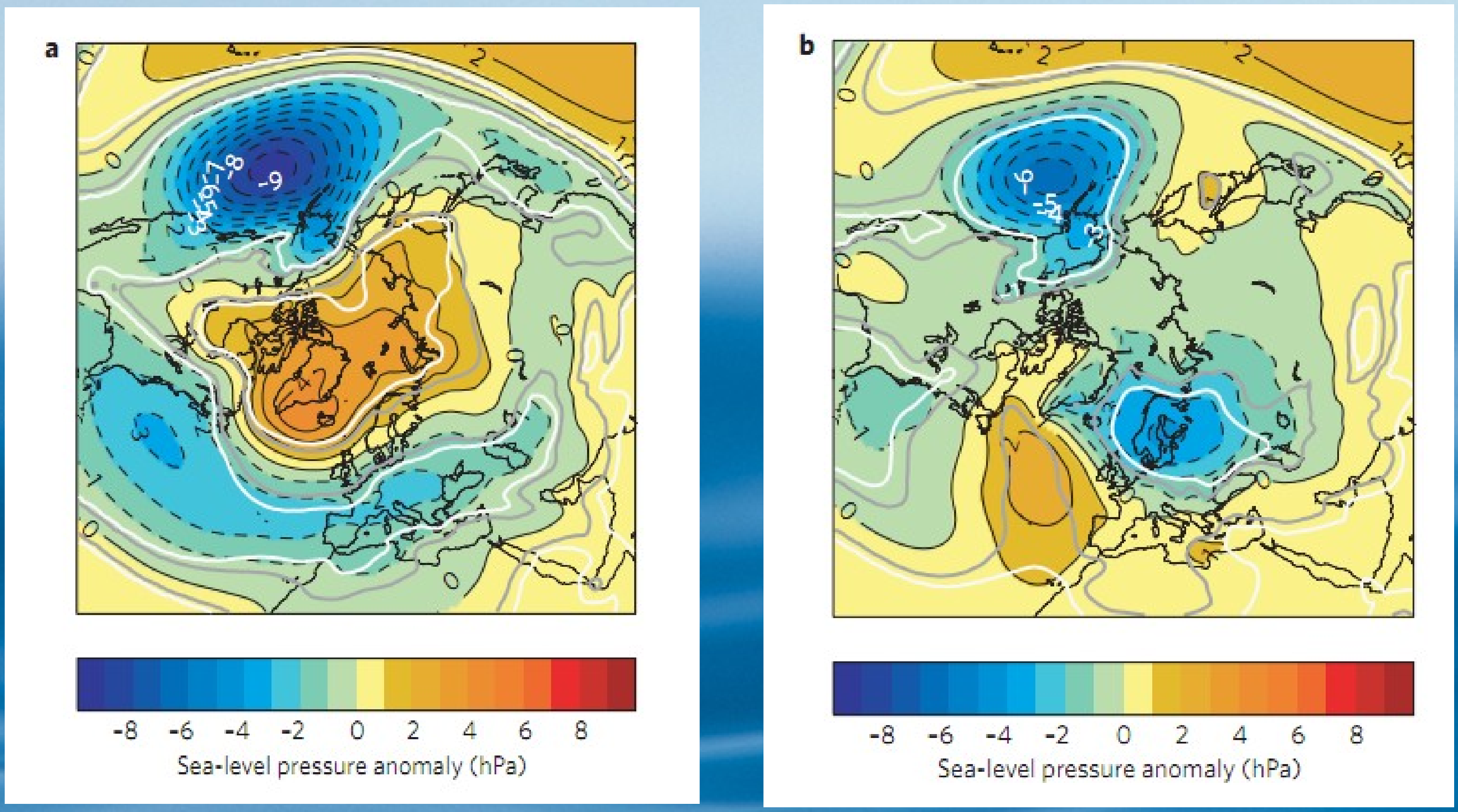
ENSO also influences North Hemisphere winter?



FM ENSO anomaly in (top) 1000-hPa temperature (K), and (bottom) precipitation (mm day^{-1}) for (left) high-top model, (middle) low-top model, and (right) ERA-40 data for SLP and 1000-hPa temperature; precipitation data from observations.

Cagnazzo & Manzini 2009 (J. Climate)

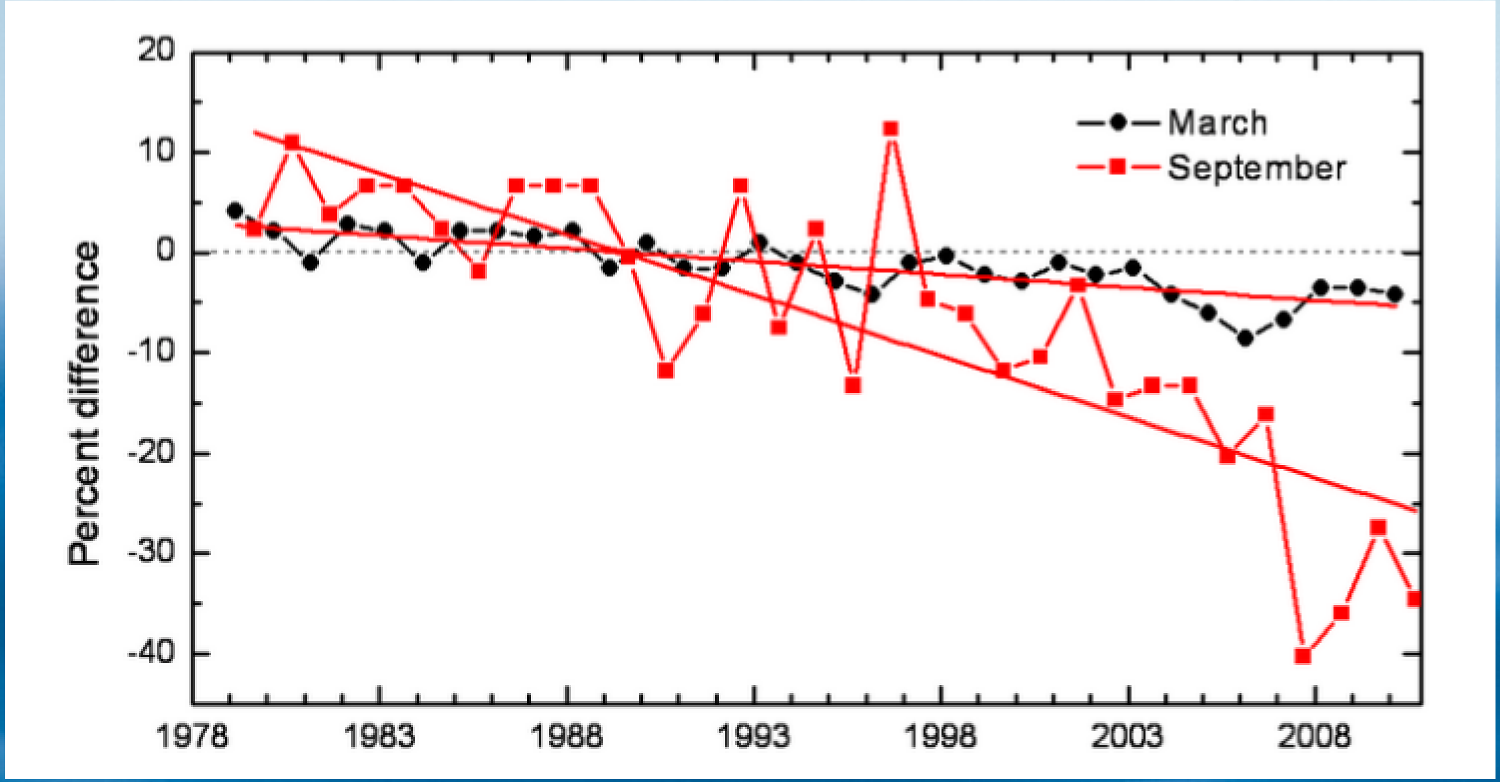
Yes but only in years with Sudden Stratospheric Warmings



Modelled surface climate response to El Niño associated with a weak and strong polar vortex. Composite sea-level pressure anomaly (hPa) for El Niño years with sudden stratospheric warmings (a) and El Niño years with no sudden stratospheric warmings (b). Anomalies are for January–March. Grey and white contours indicate significance at the 95% and 99% confidence levels.

Ineson & Scaife 2010 (Nature Geoscience)

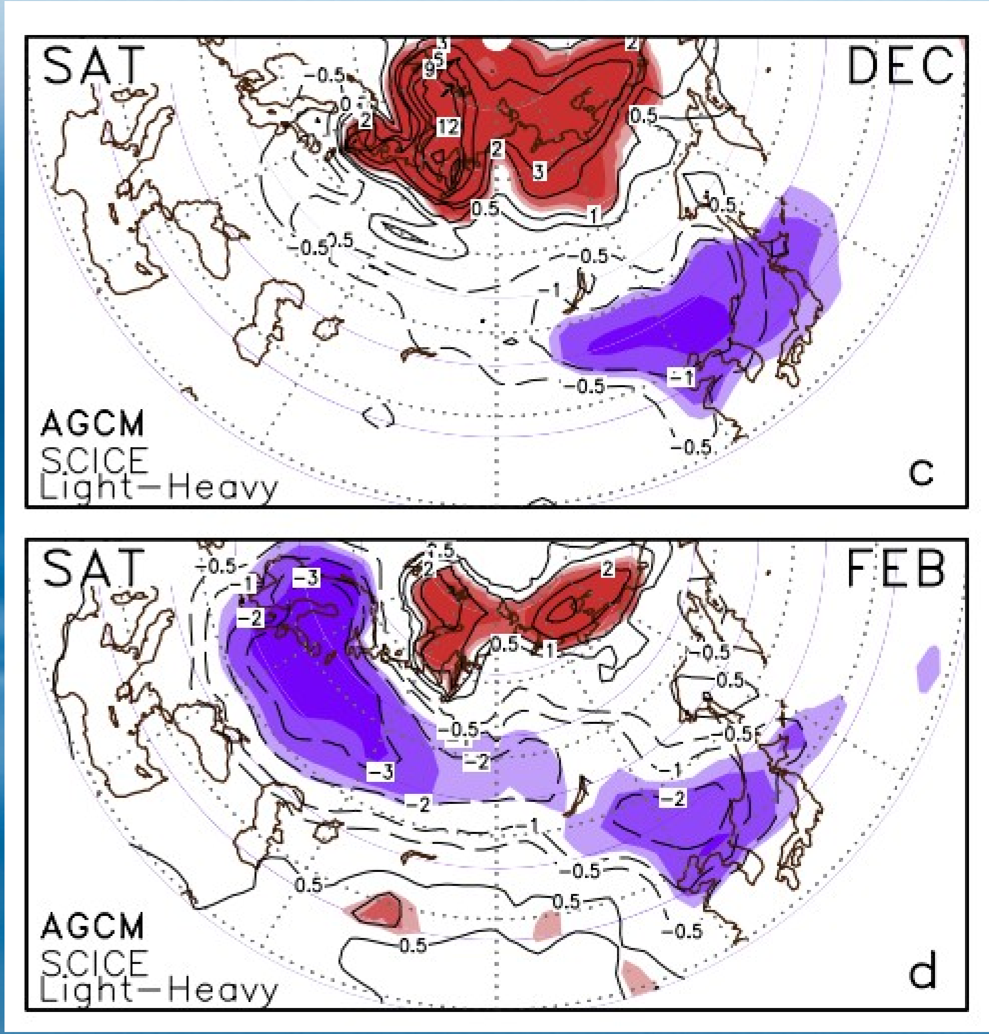
Arctic sea-ice loss



Time series of the percent difference in ice extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) relative to the mean values for the period 1979–2000. Based on a least squares linear regression for the period 1979-2009, the rate of decrease for the March and September ice extents is –2.7% and –11.6% per decade, respectively.

Richter-Menge, J., and J.E. Overland, Eds., 2010: Arctic Report Card 2010, http://www.arctic.noaa.gov/reportcard

Less summer Arctic sea-ice means colder Eurasian winter?

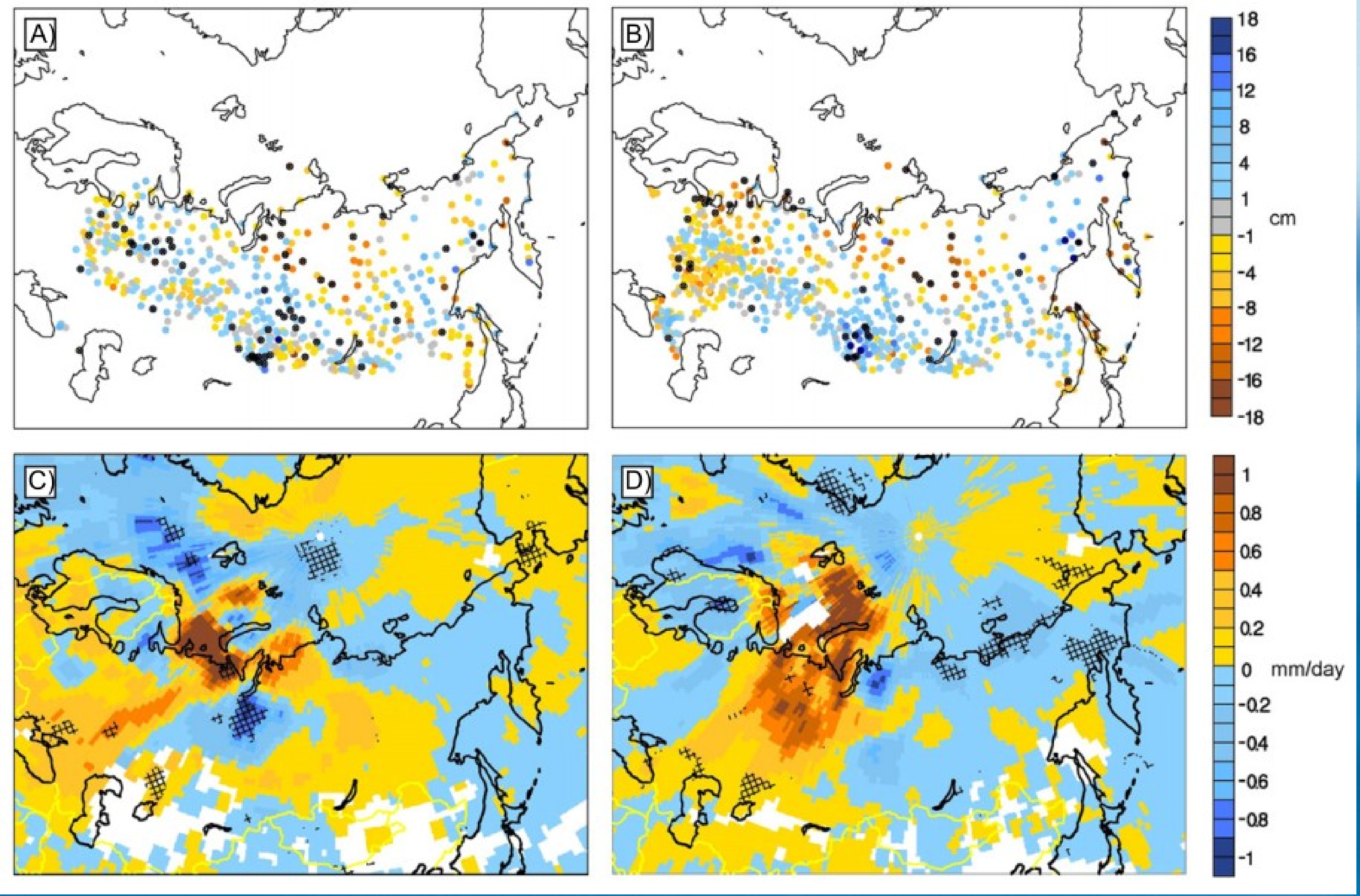


Maps of monthly near-surface temperatures for December and February (1978/9 – 2005/6) regressed on sea-ice concentration in previous September (with reversed signs!).

Less Summer sea-ice means warmer wintertime Arctic and colder Eurasia in a zonal area similar to the 2009/10 winter anomaly (especially in February).

Honda, Inoue & Yamane 2009 (GRL)

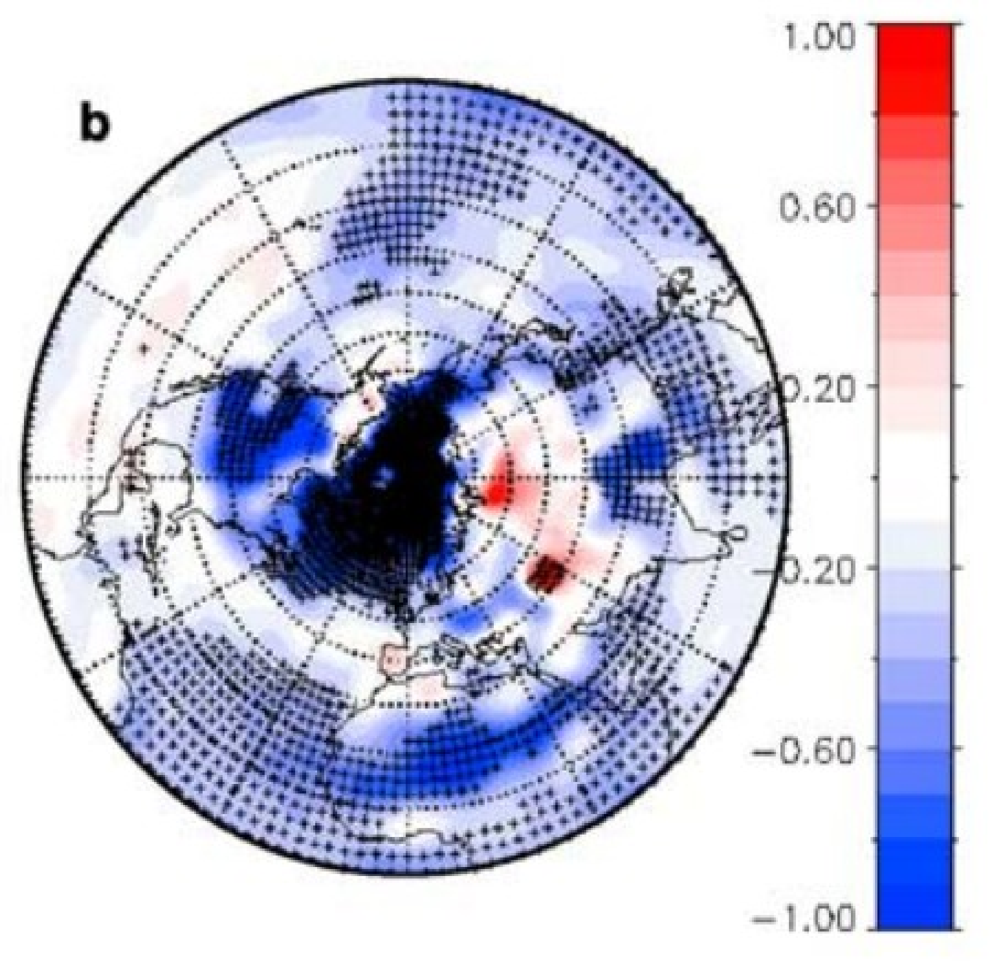
Less summer Kara Sea ice means more snow in Siberia



Difference between low and high BKS station measurement of snow for a) October and b) November and *E-P* differences from forward trajectories starting in the BKS region for c) October and d) November.

Wegmann et al 2015 (ERL)

Less summer Arctic sea-ice means colder Eurasian winter?

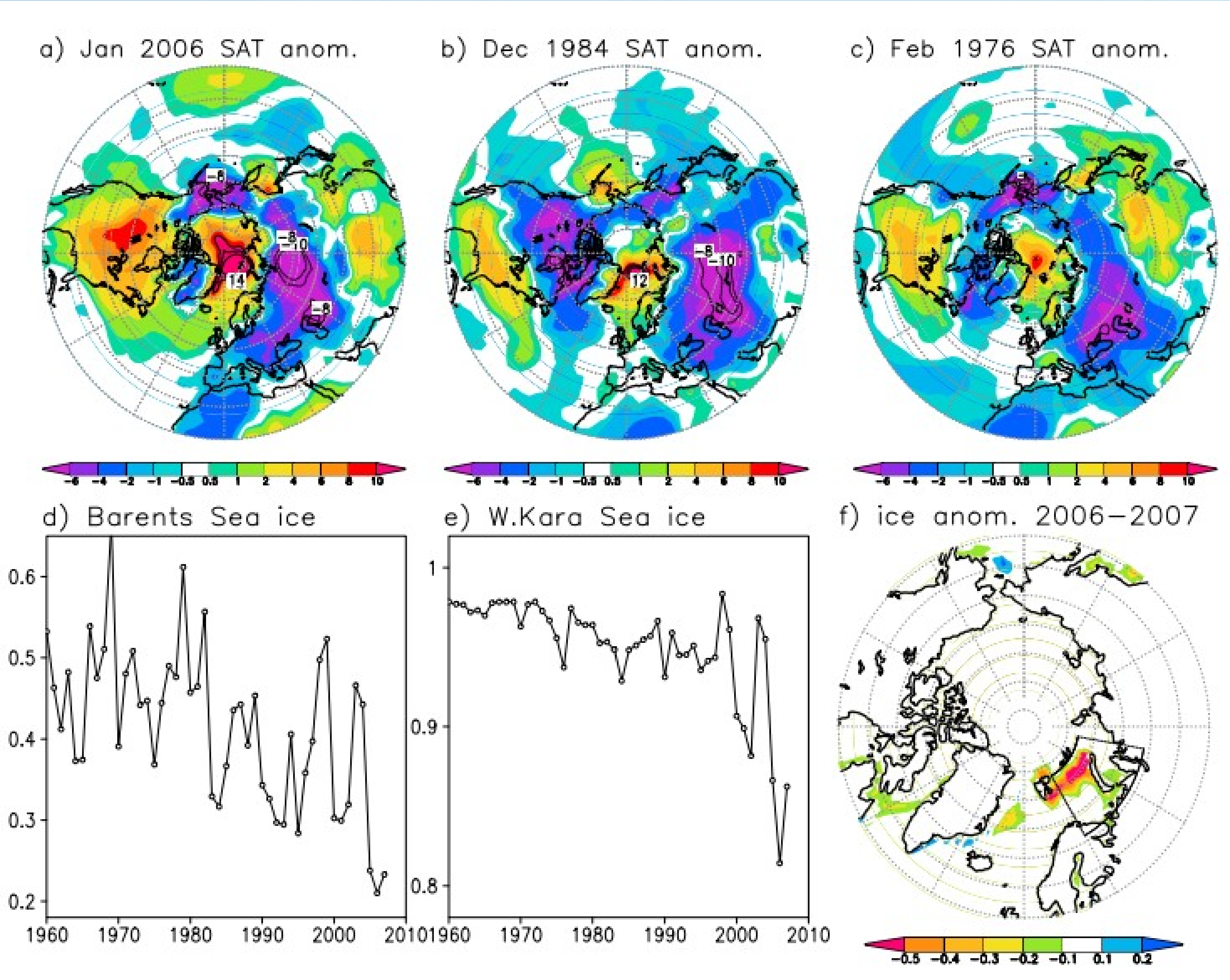


Linear regressions between actual September sea-ice extent and the surface air temperature in $K/10^6$ km during the following winter (Nov – Jan)

Here the sign of the correlation is not changed!

Francis et al. 2009 (GRL)

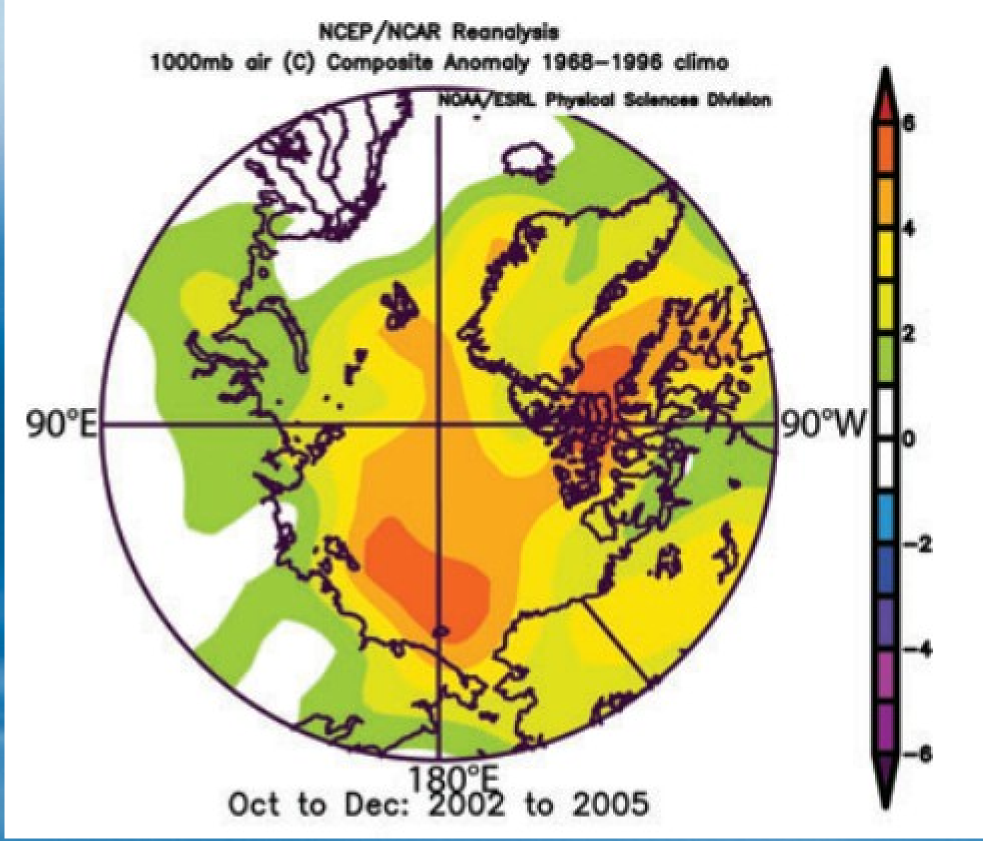
Possibly it is also the Barents-Kara sector sea-ice loss

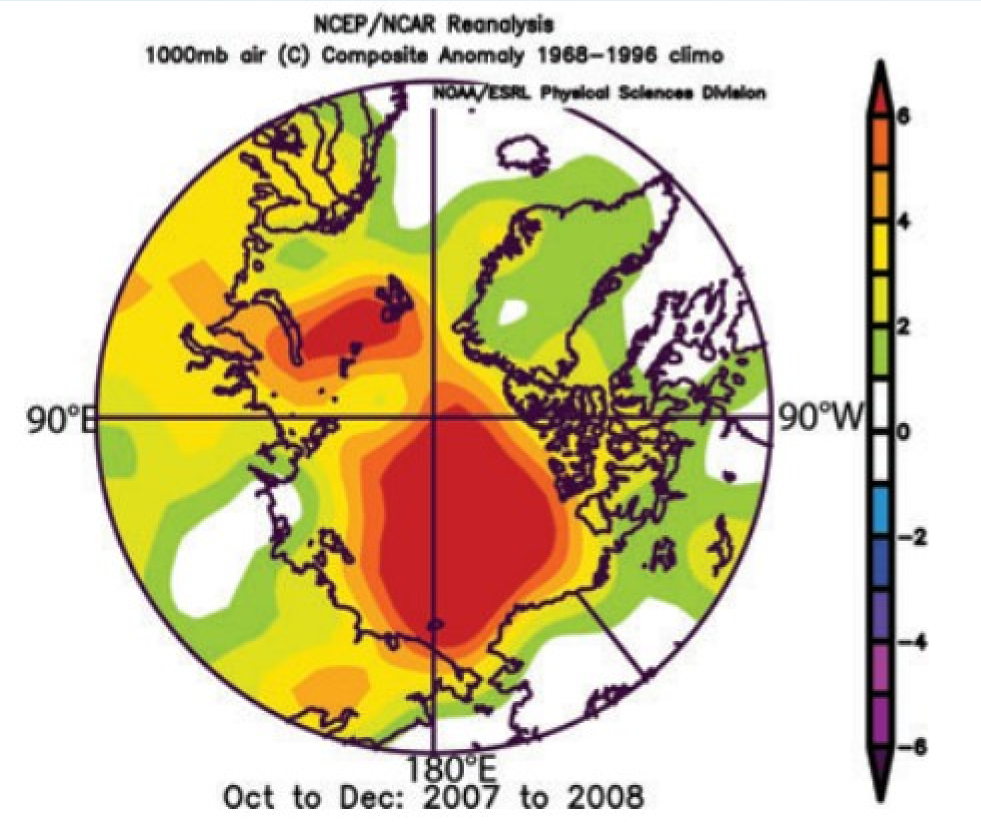


Petoukhov and Semenev (2010) explain extremely cold Eurasian winters by the loss of sea-ice in Barents and Kara Seas. Interestingly they submitted their paper **before** the cold 2010 winter!

Petoukhov Semenov 2010 (GRL)

Arctic October-December near-surface air temperature anomaly

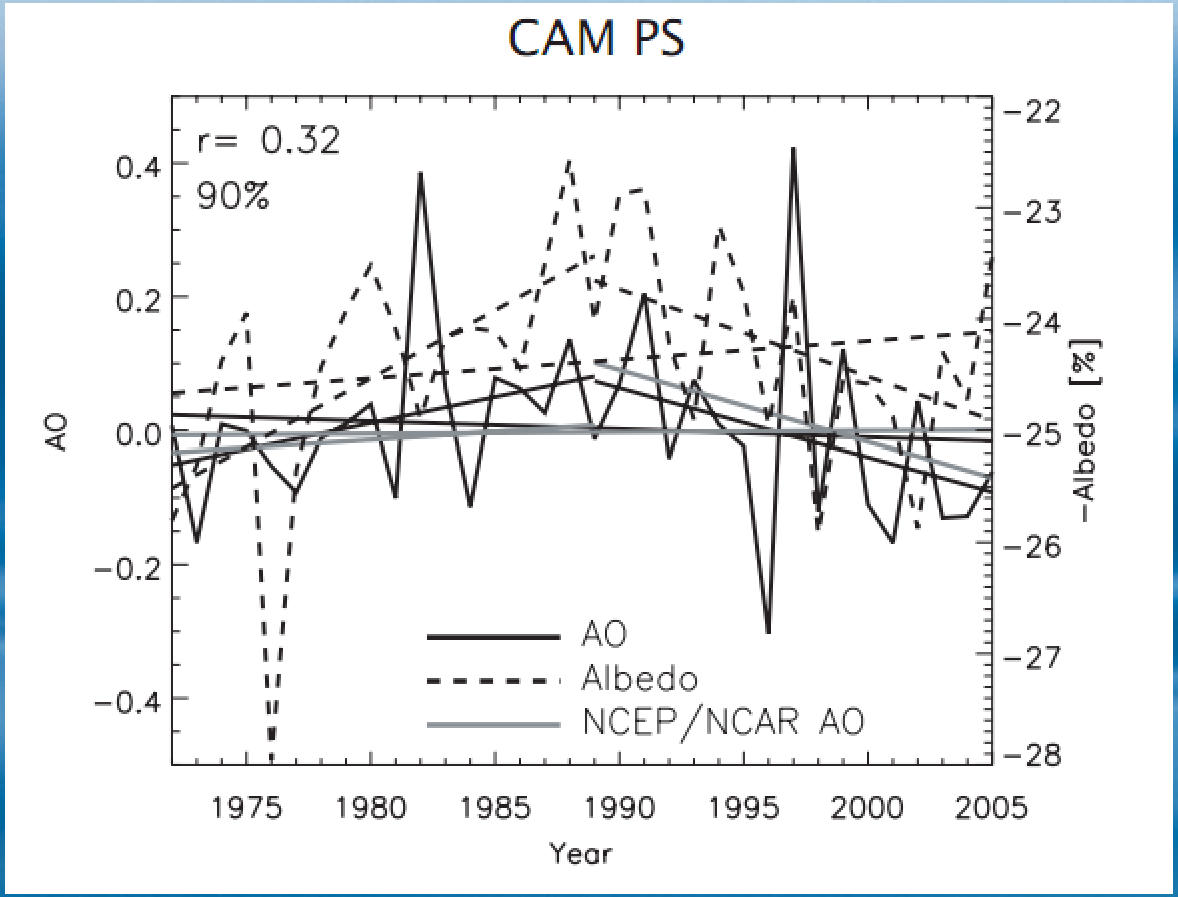




Near surface air temperature anomaly multiyear composites (˚C) for (left panel) October–December 2002–2005 and (right panel) October–December 2007–2008,

Richter-Menge, J., and J.E. Overland, Eds., 2010: Arctic Report Card 2010, http://www.arctic.noaa.gov/reportcard

More Eurasian snow means lower NAO/AO?

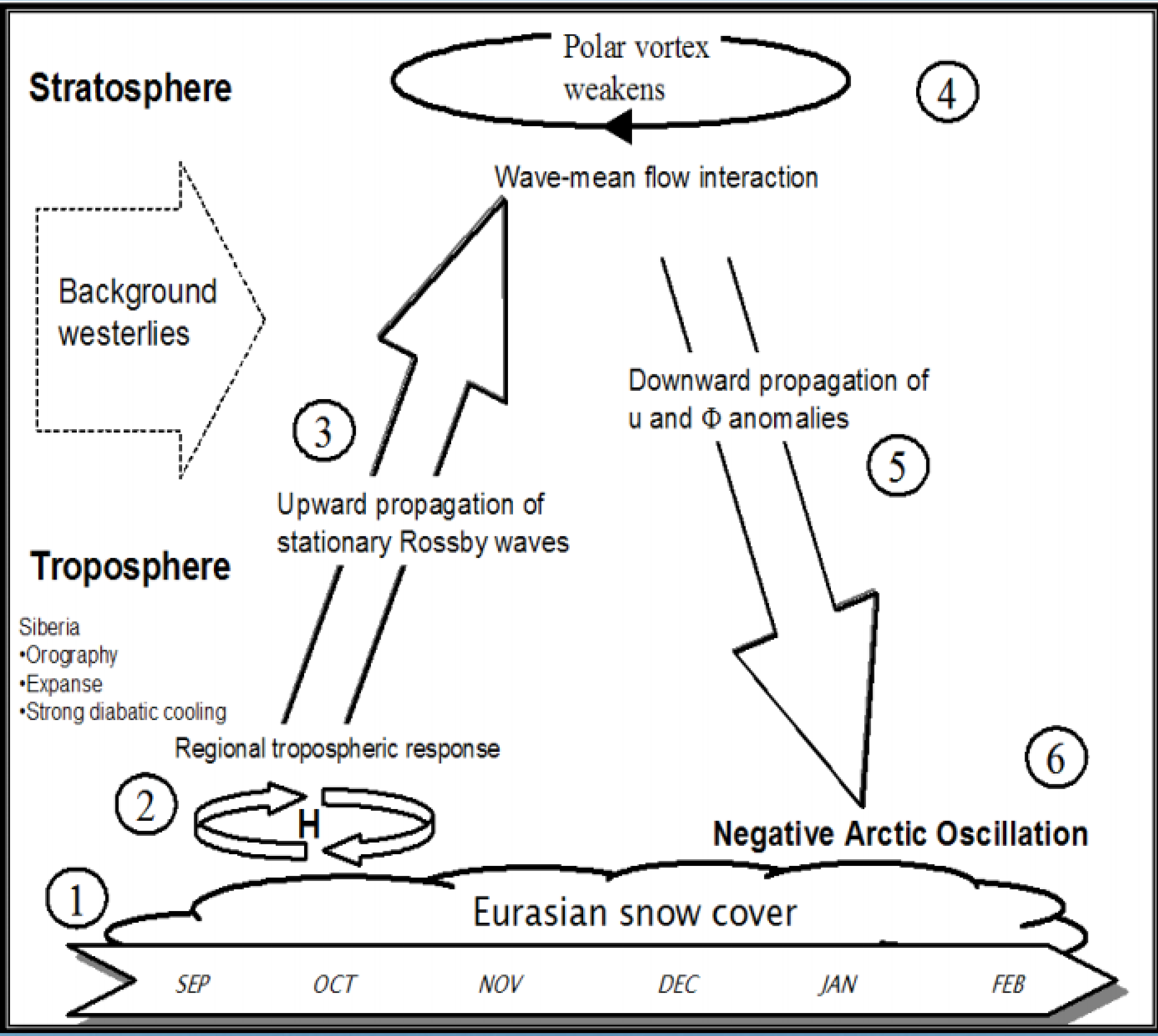


Forcing a climate model (CAM3) with satellite derived wintertime snow extent and calculating the corresponding albedo (inverted!) one can obtain AO wintertime values similar to observations.

Does it mean the Eurasian snow cover really drives the winter AO/NAO values? Maybe, but both can also respond to the same forcings. For example the Arctic sea ice?

Allen & Zender 2012 (J. Climate)

The proposed mechanism of Eurasia autumn snow cover on winter NAO index

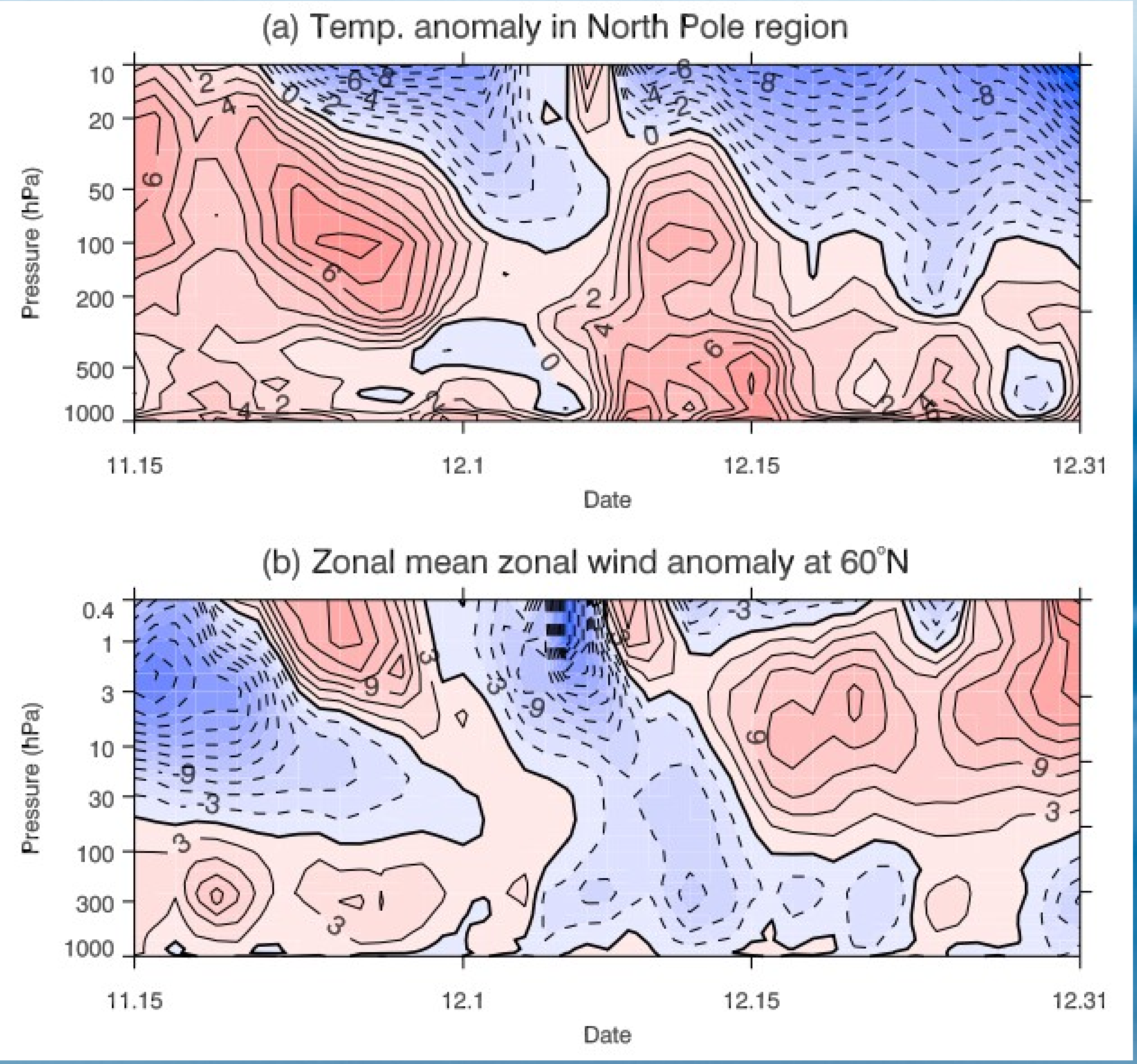


The mechanism, involving a stratospheric sudden warming (3) and downward propagation of zonal wind and potential temperature anomalies (5) seems well documented.

However it does not exclude the possibility of a (0) phase: summer Arctic sea-ice anomaly results in an Autumn SST anomaly, influencing Siberian snowfall.

Cohen et al. 2010 (GRL) supplement after Cohen et al. 2007

The stratospheric link has been observed

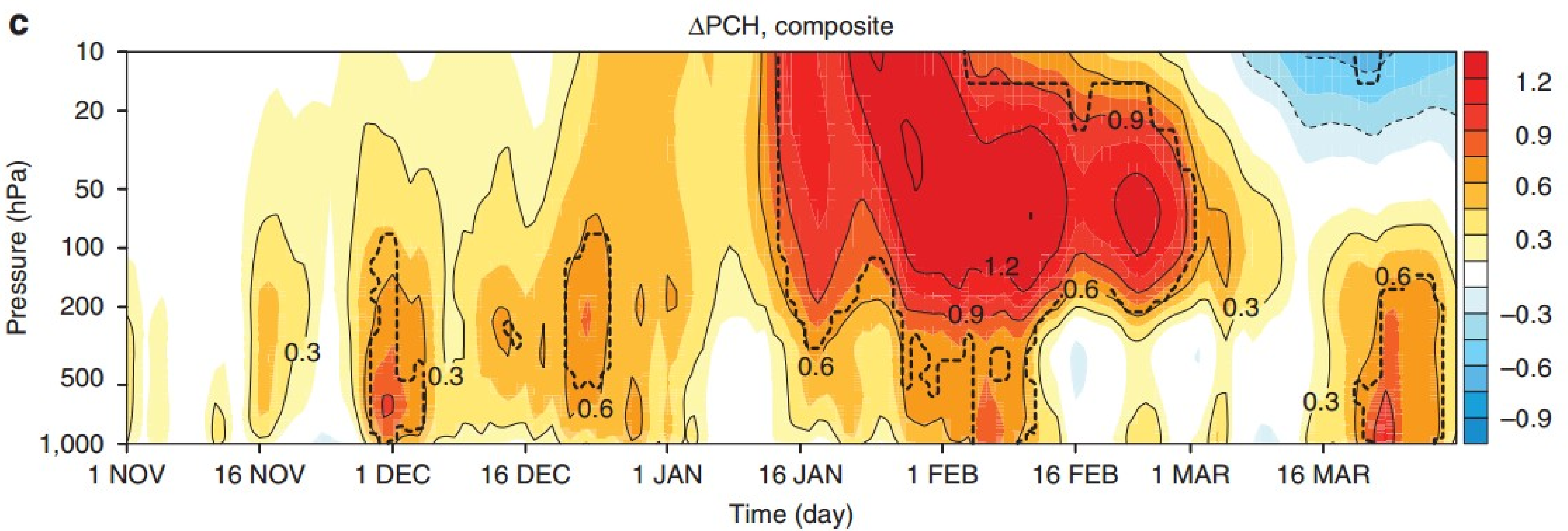


The changes in temperature and zonal winds anomalies during the 2010 winter did start from the stratosphere.

One can observe two events starting in mid-November and early December

Wang & Chen 2010 (GRL)

Even better: stratospheric link starting from the surface has been observed

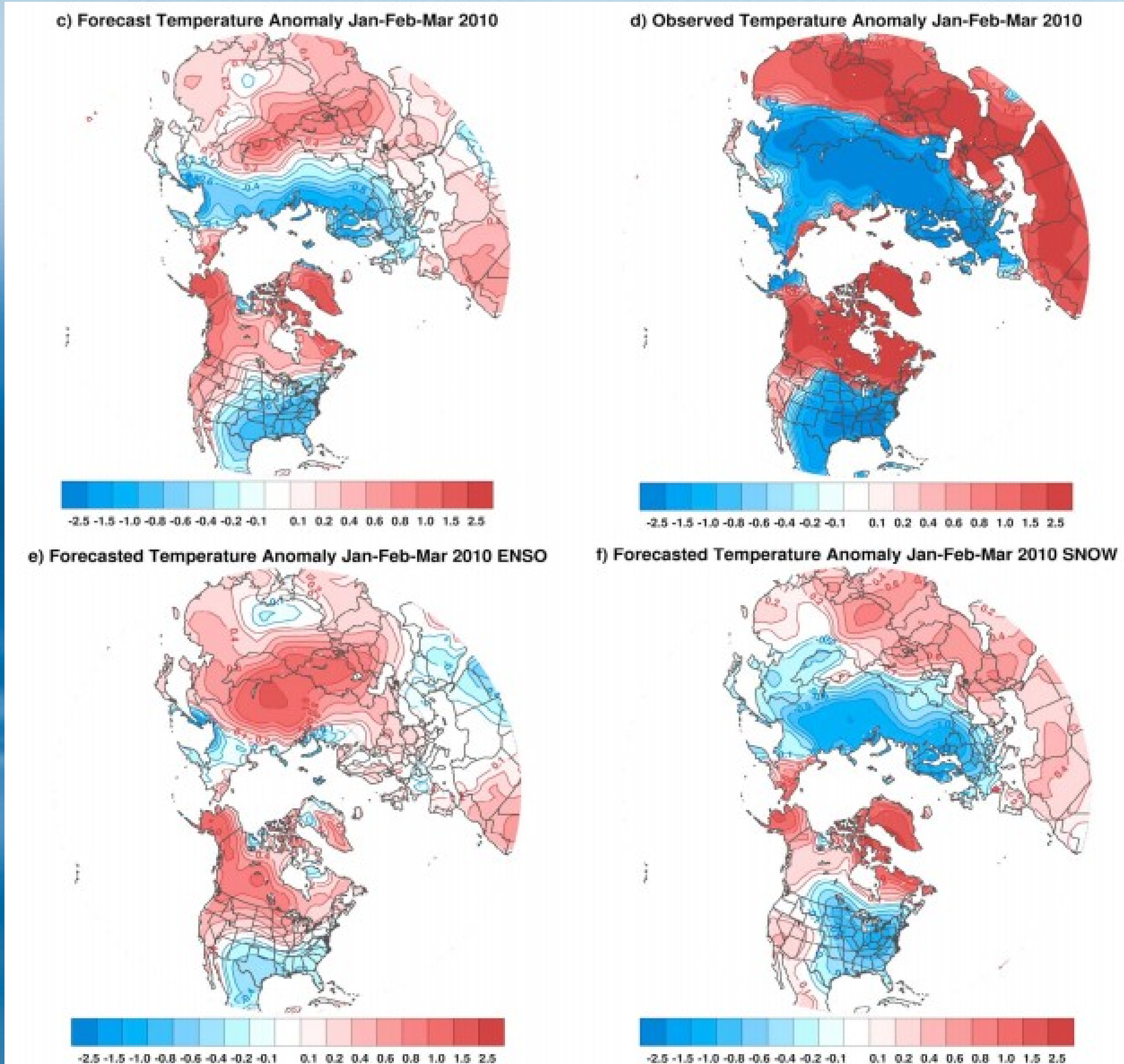


The “seasonal evolution of the composite PCH anomaly for the years of anomalously low SIC over the B–K seas”.

PHC = polar cap height (a measure of weakened polar vortex); SIC = sea ice concentration; B-K = Barents-Kara seas

Kim et al 2014 (Nature Communications)

Eurasian snow as a good winter predictor

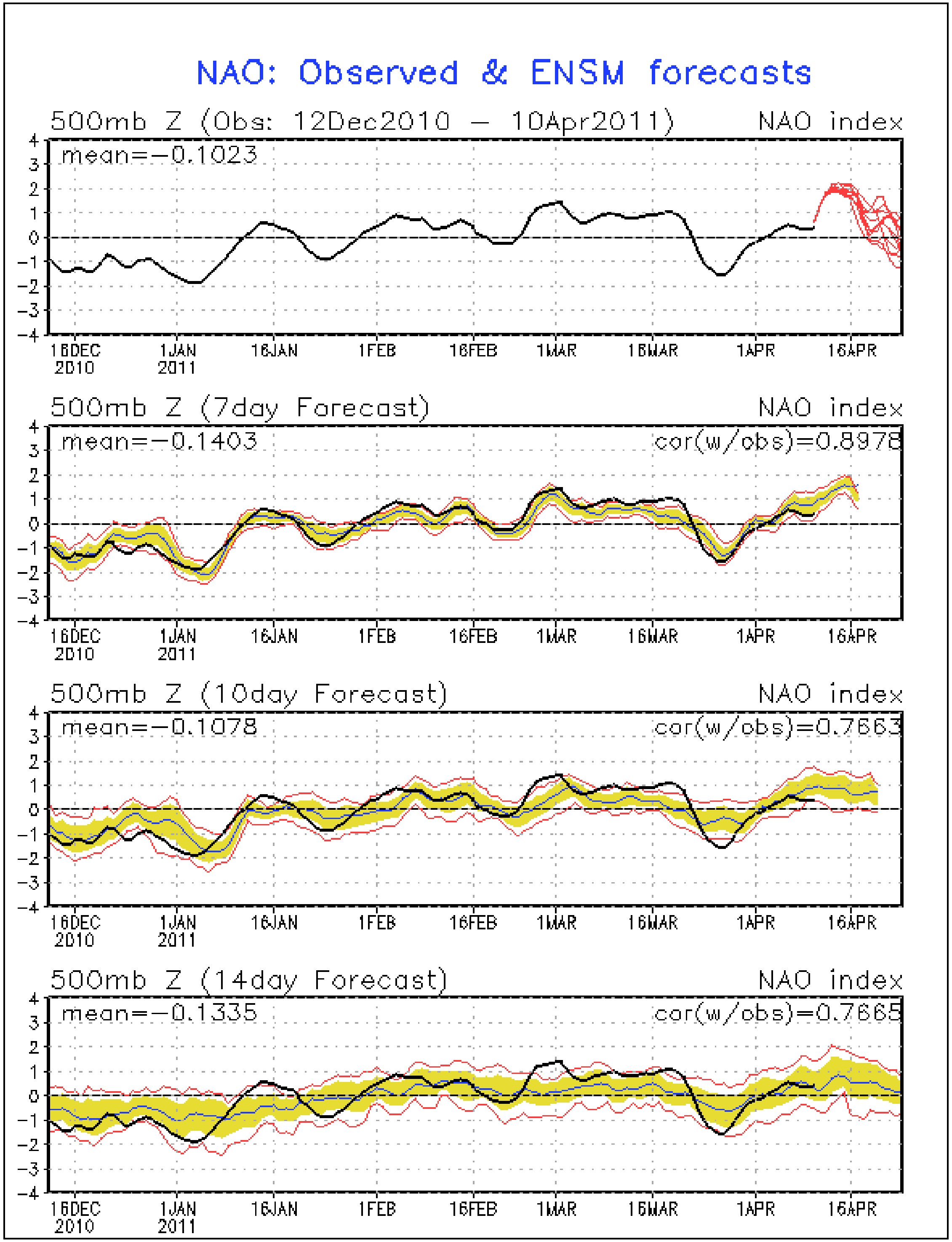


Cohen et al 2010 predicted c) the 2010 winter temperatures d) using only three parameters: Eurasian snow extent, surface pressure and an ENSO index.

Because the model is linear it is possible to discern the effect of the predictors. While an ENSO only e) prediction was clearly wrong, an Eurasian snow extent one f) was surprisingly good.

But is snow the real climate forcing here?

Cohen et al. 2010 (GRL)

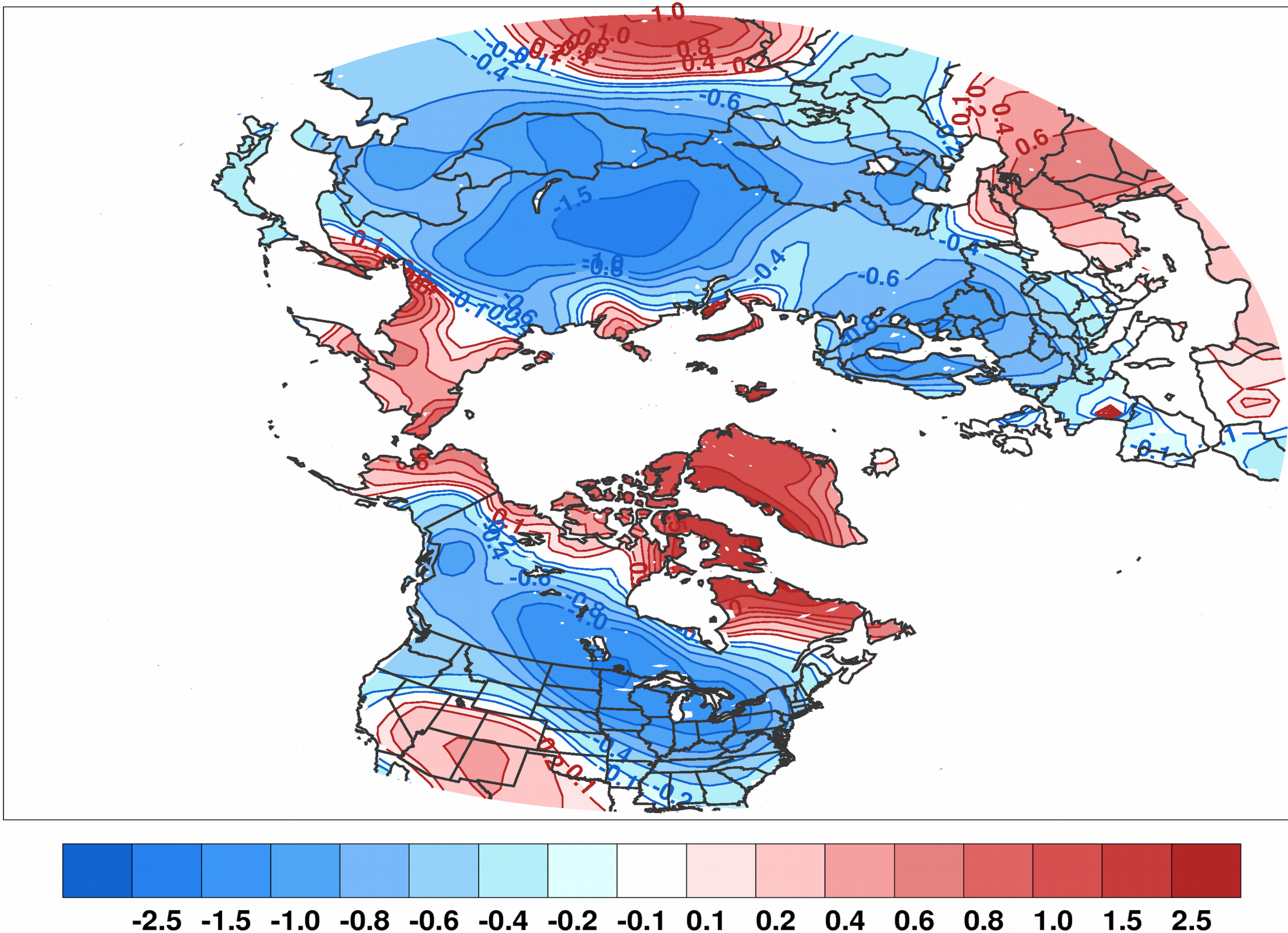


And what about this winter?

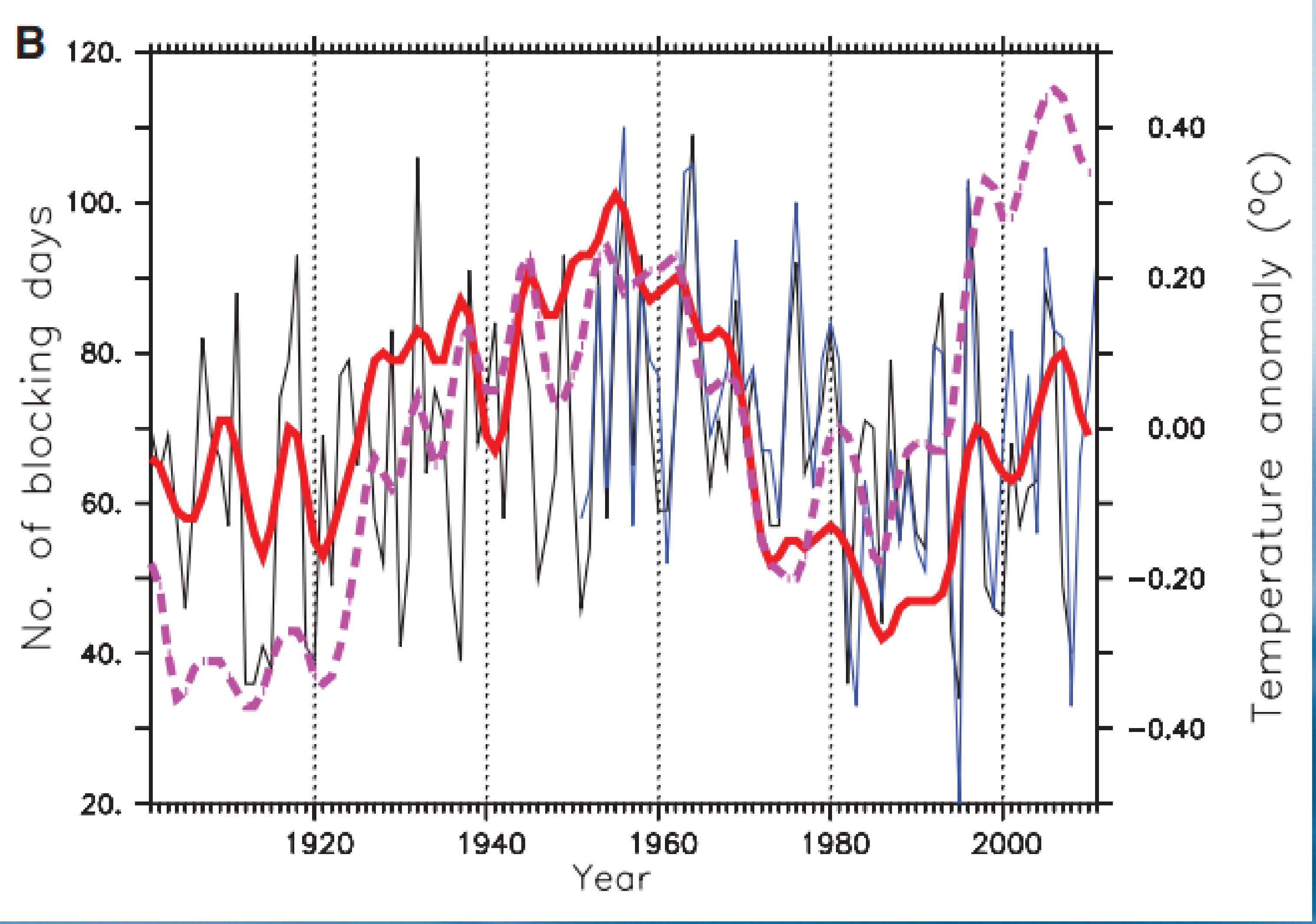
The observed NAO values for December 2010 to present day and forecasts for the next weeks.

http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao.sprd2.gif

Forecast Temperature Anomaly Dec-Jan-Feb 2011



Cohen 2010 (private communication)



Does blocking cause AMO variability?

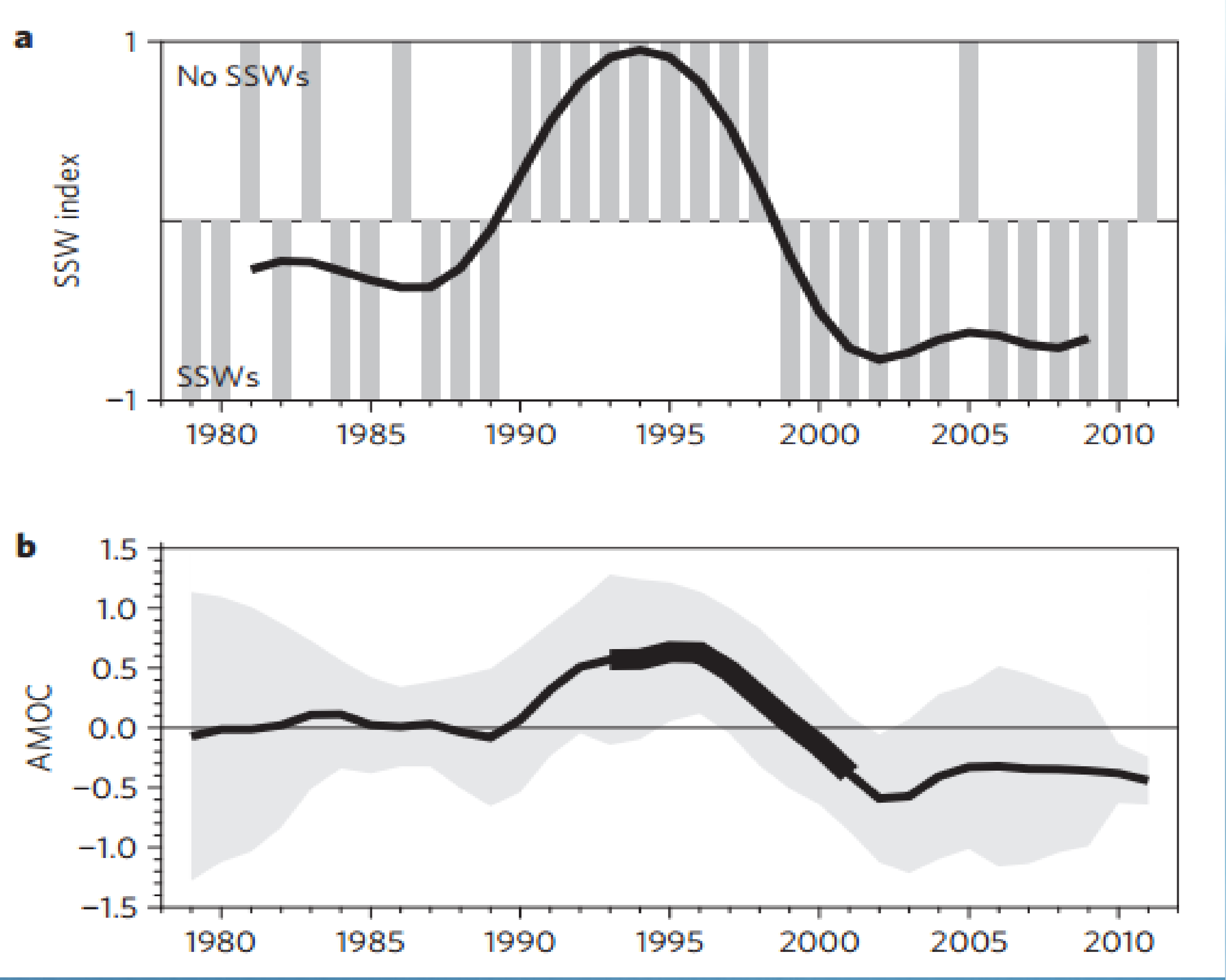
Really?!

DJFM blocking days in the region from 10°E to 70°W and 45°N to 75°N from the 20th century reanalysis (black) and from NCEP/NCAR reanalysis (blue). The two blocking time series have a correlation of 0.85 over the overlapping time period 1949–2008. The AMO index (dashed pink) is an area-averaged SST from 0°N t o 60°N and 10°E to 80°W. The AMO index with global surface temperature evolution removed is shown in solid red.

Häkkinen, Rhines, Worthen 2011 (Science)

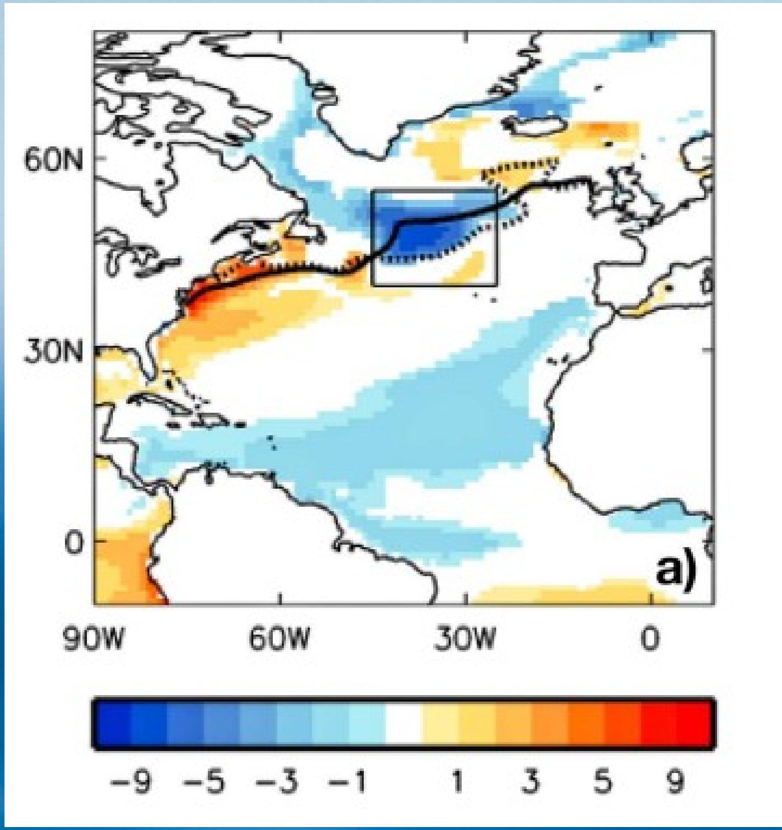
A stratospheric connection to Atlantic climate variability (?)

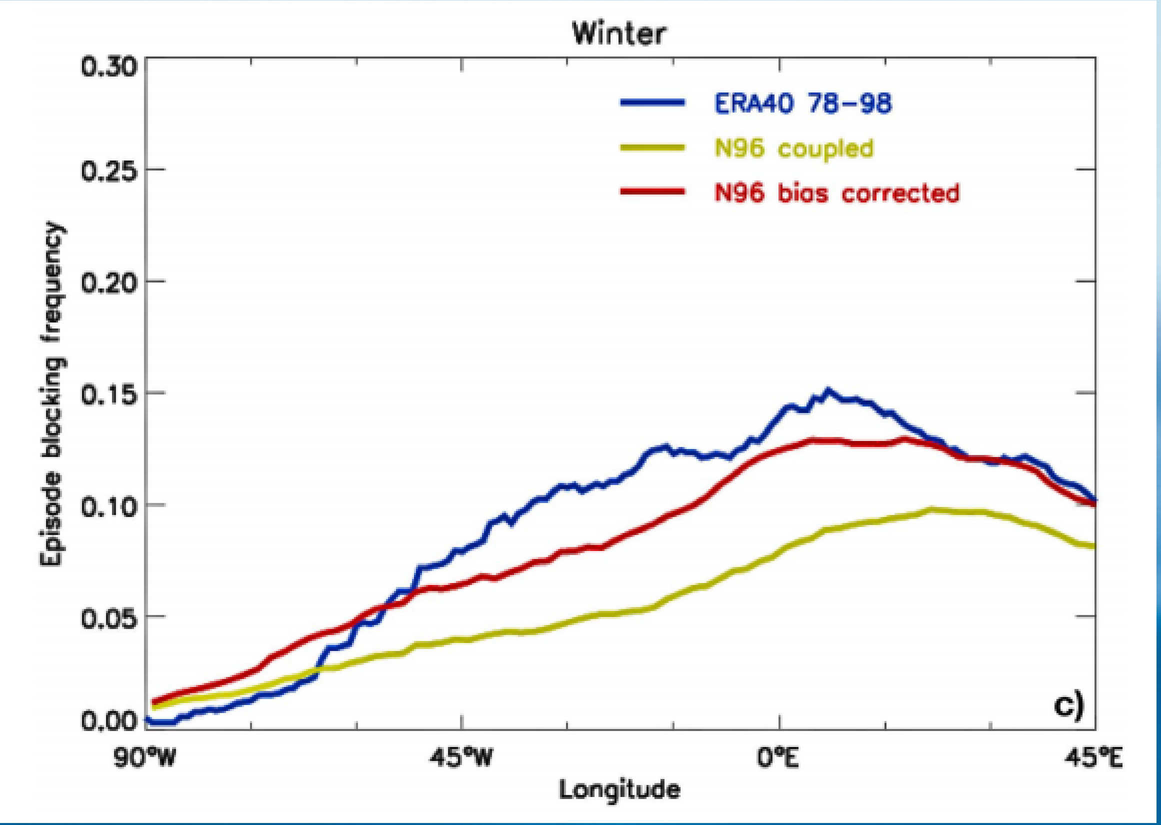
(a) Annual time series of the Stratospheric Sudden Warming (SSW) index; grey bars mark years with (-1) and without (+1) major SSWs; the black line is a smoothed version of this. (b) Multi-reanalysis estimate of annual mean AMOC variations at 45 N; thick black line denotes the common period for all 12 reanalyses and grey shading is the 1σ uncertainty interval



Reichler et al 2012 (Nature Geoscience)

Better SST values improve blocking in models



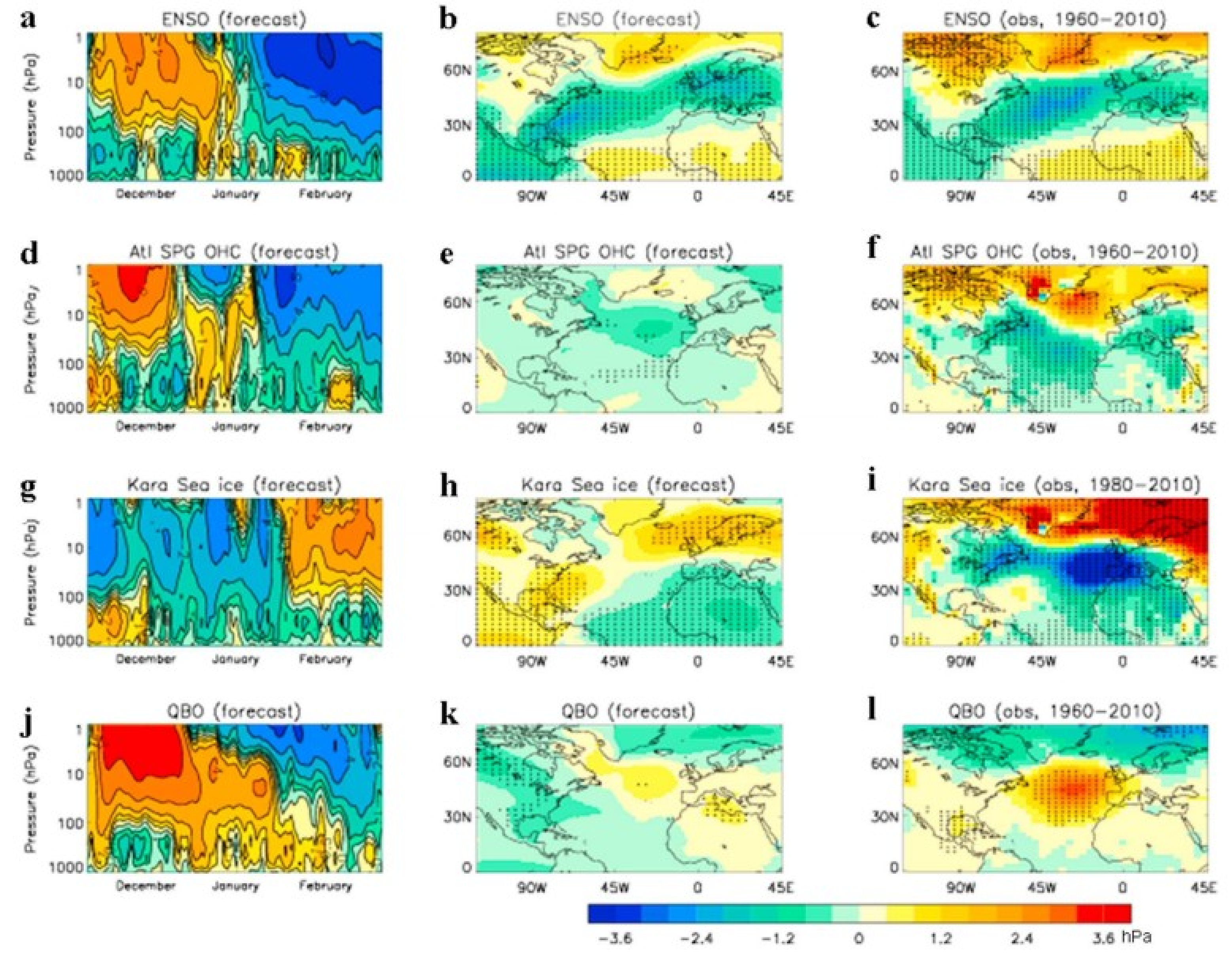


Most coupled circulations models underestimate winter SST values by up to 5 ºC south of Greenland and overestimate off New England (left). Correcting this bias strongly improves the modeled blocking frequency. Right panel shows Atlantic blocking frequency in the model (green), after mean bias correction (red) and observations (blue). A similar improvement is achieved by increasing the resolution of the ocean part of the model.

This result implies that SST controls blocking rather than the other way.

Scaife et al 2011 (GRL)

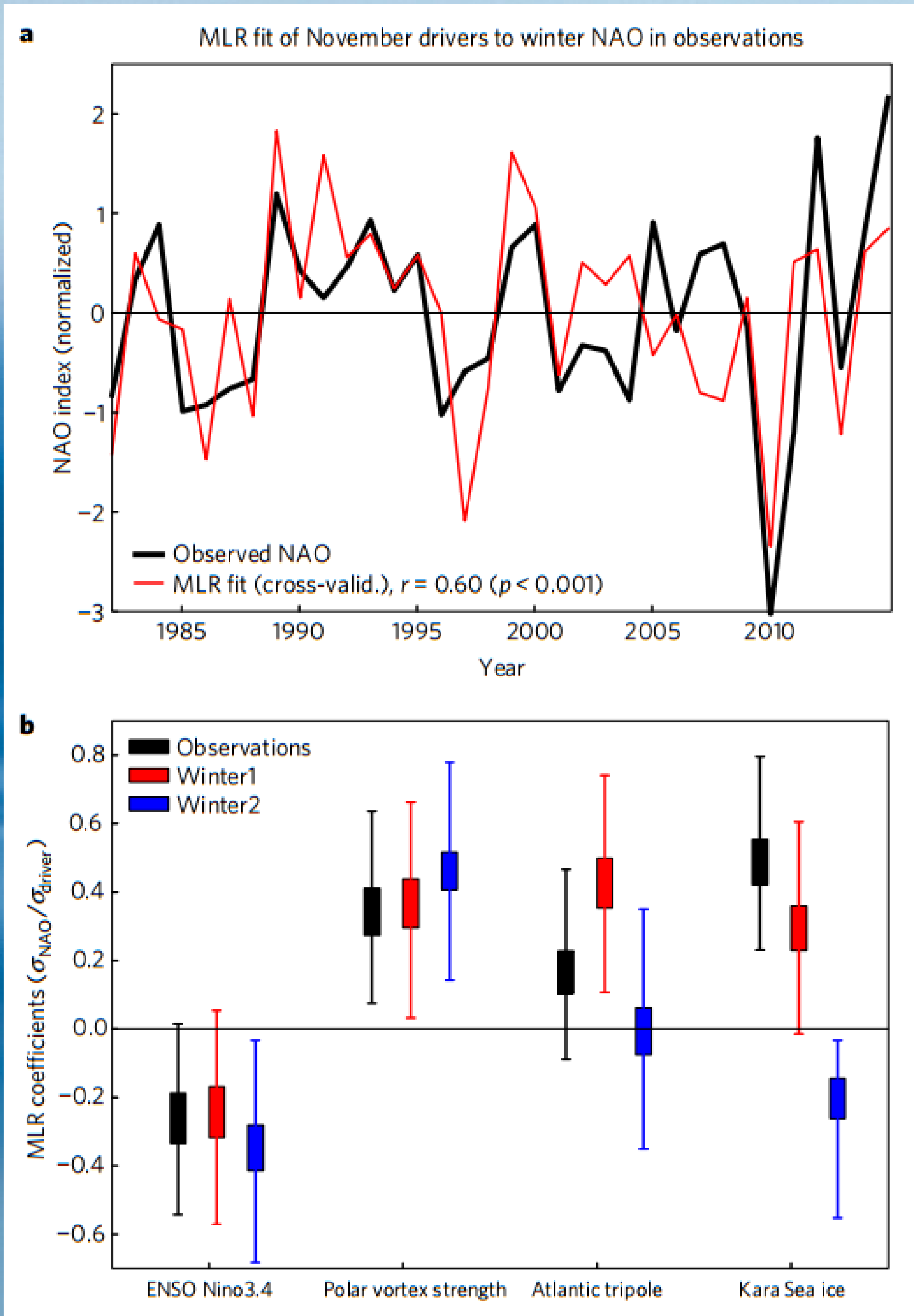
So can one predict wintertime NAO?



The best results so far has been achieved by a combination of ENSO, Subtropical Gyre heat content, Kara Sea ice and QBO (Quasi Biennale oscillation of tropical temperatures).

Scaife et al 2014 (GRL)

Is it possible to predict NAO one year before?



Multiple linear regression analysis. **a**, The cross-validated MLR fit to the observed winter NAO using the four observed November indices as predictors, see Supplementary Fig. 4 for equivalent MLR fits to the model first and second winters. **b**, Box and whisker plots to show the coecients for each of the four indices, for observations and both the first- and second-winter model predictions. The filled boxes show the range of coeficient values resulting from the cross-validation procedure, whereas the whiskers give the mean 5–95% confidence intervals

Dunstone et al 2016 (Nature Geoscience)

Zatem jaka będzie zima?

- Zeszłej zimy sprzysięgło się przeciw nam wszystko: niska aktywność słońca, El Nino, mało lodu w Arktyce i malejący AMO
- Lód w Arktyce, AMO (i ozon) nie zmieniają się z roku na rok ale obecnie mamy La Ninę i większą aktywność słońca
- Jednak NAO lubi mieć podobne wartości w sąsiednich latach
- Zatem czego się spodziewać?

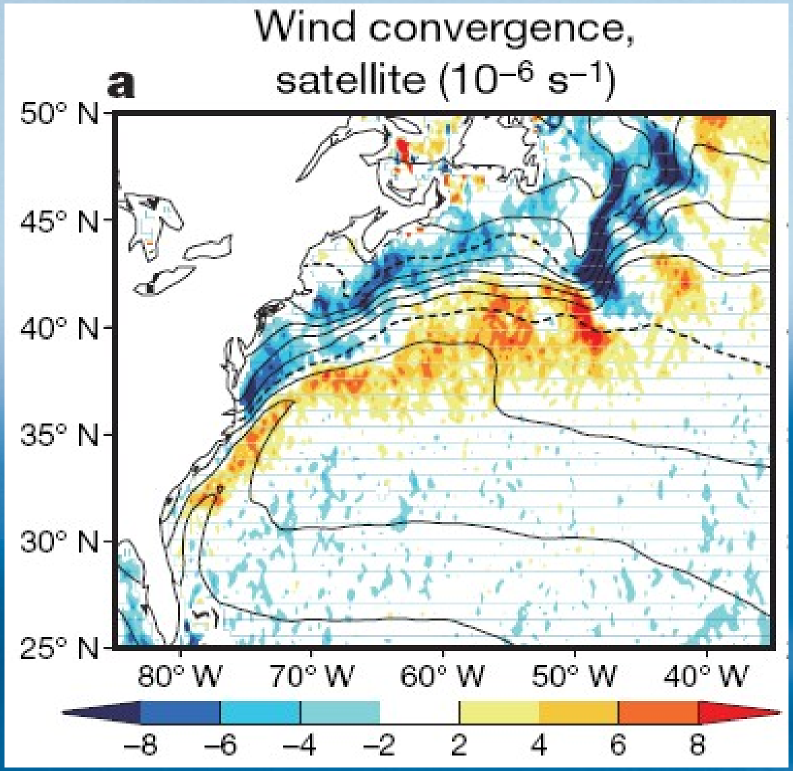
Układ temperatur Atlantyku, duża ilość lodu arktycznego latem, brak El Nino oraz maksimum aktywności słonecznej – wzzystko to sugeruje ciepłą zimę 2013/14 (dodatnie NAO).

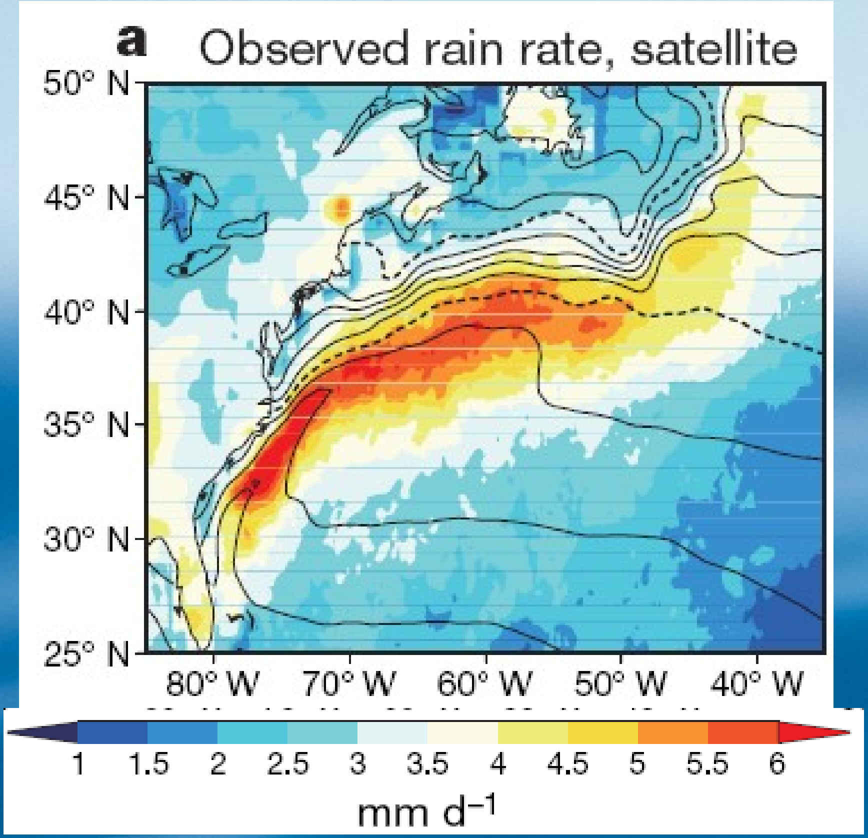
Dziękuję za uwagę

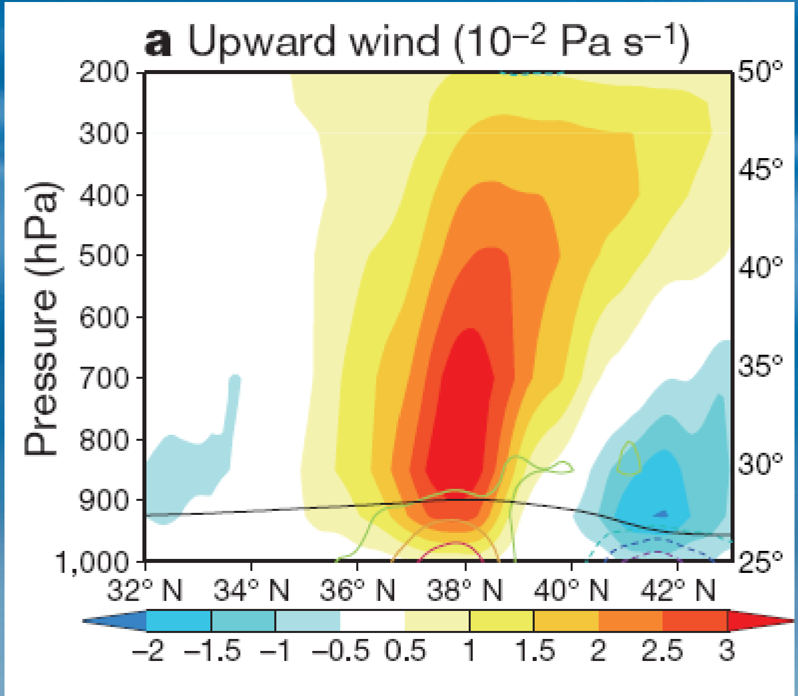
Za **tydzień** (12.12.2016 r.):

Tropiki a zmienność klimatu (ENSO, huragany, monsuny)

The Gulf Stream influences the whole troposphere



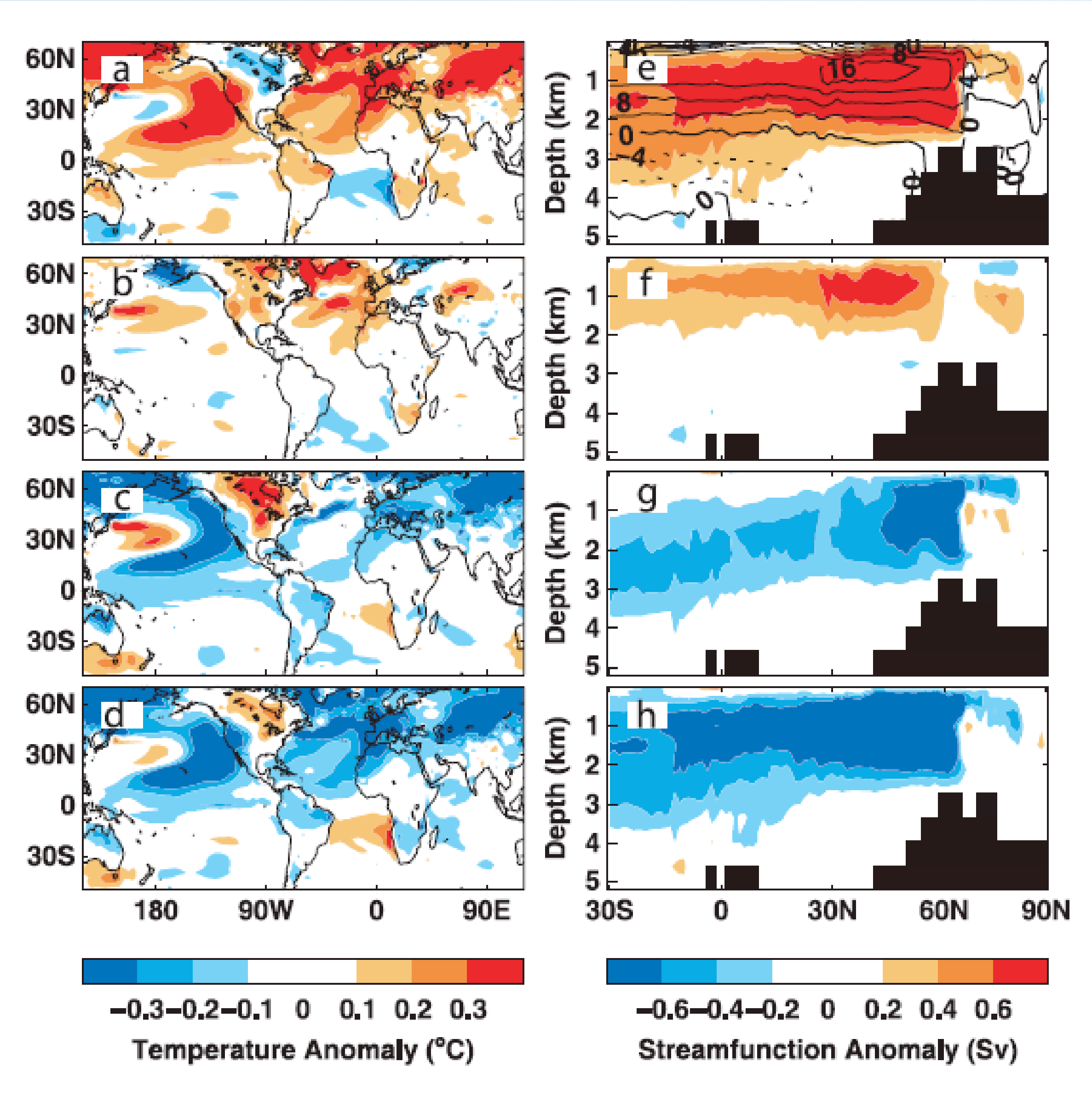




The observed average yearly surface wind convergence and rain rates along the Gulf Stream as well as the vertical wind cross-section (upward is positive) with the boundary layer marked as a black line.

Minobe et al. 2008 (Nature)

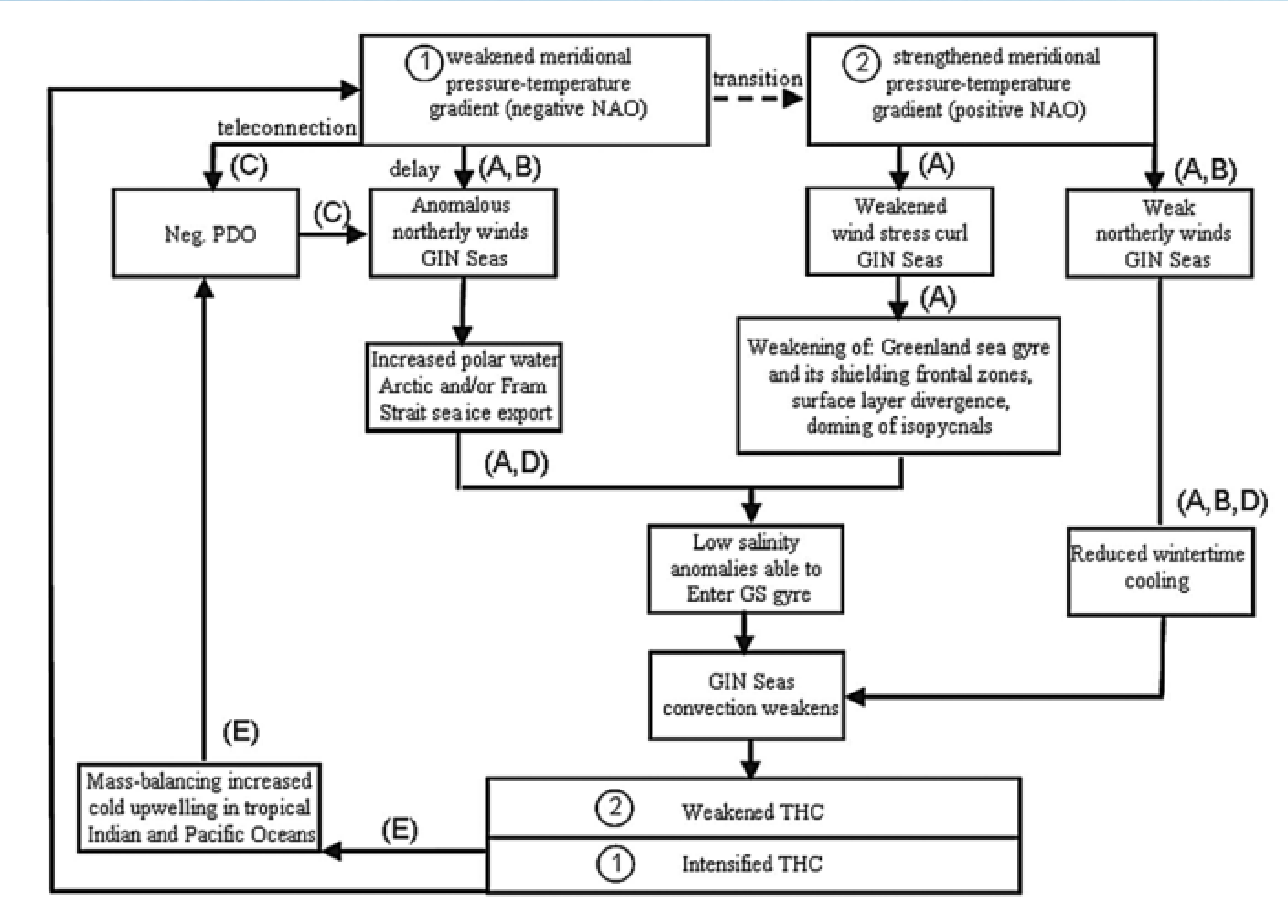
Modeled AMO: surface temperature and THC



Simulated temperature and THC anomalies at 0º, 60º, 120º and 180º of the modeled cycle.

Knight et al. 2005 (Geophysical Research Letters)

We have even more than one possible mechanism

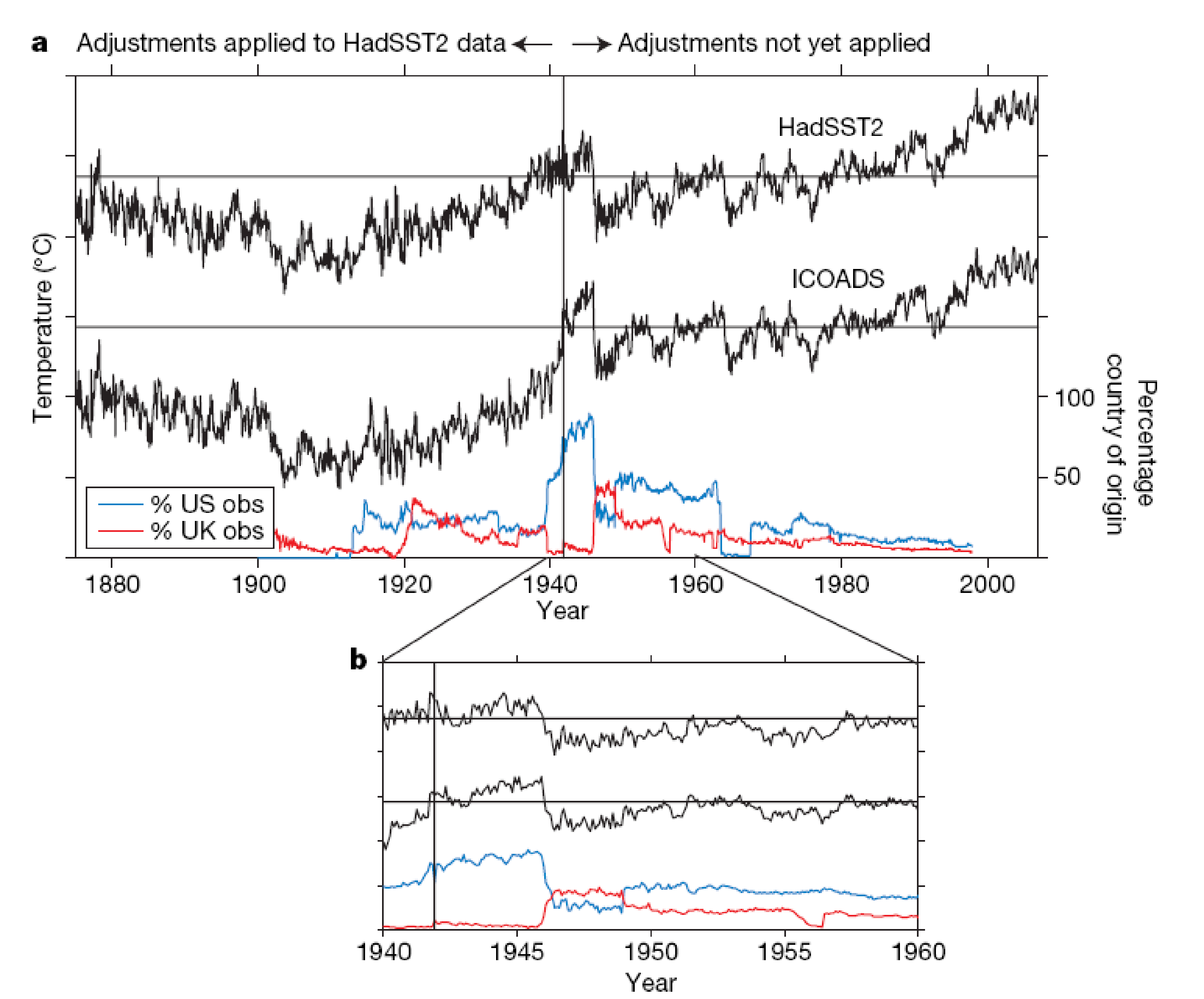


Dima and Lohmann proposed a more complicated mechanism involving NAO changes influencing freshwater inflows from the Arctic. The above graph is supposed to explain at least part of it.

Grossmann Klotzbach 2009 (JGR) explaining the mechanism proposed by Dima & Lohmann 2007 (or rather part of it)

Back to square one?

Published on May 29, 2008

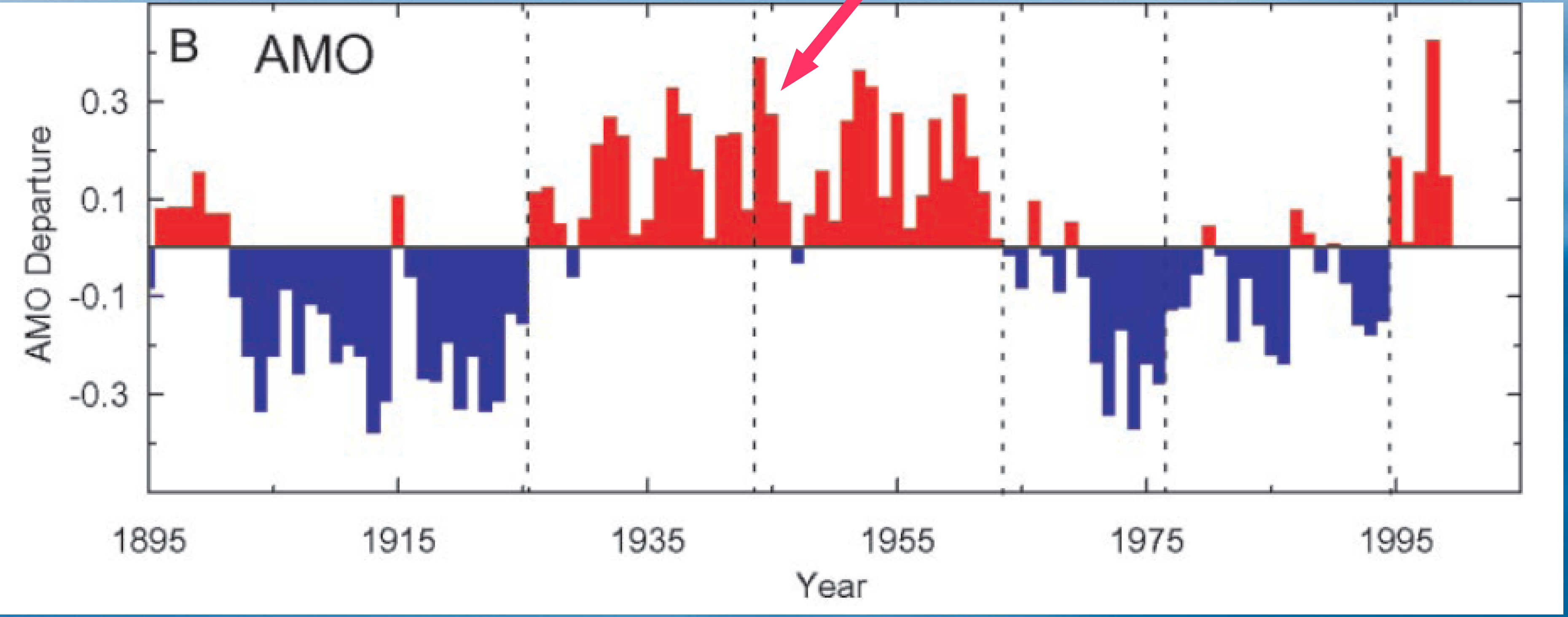


It seems that the mid-20th century SST discontinuity (not visible in land data), a 0.3º C drop in 6 months from August 1945, was an artifact caused by the British not measuring SST during the war. The British open bucket method was biased down while the US engine room intake method biased up.

If continuation of the HadSST2 reanalysis of original (but ENSO "cleaned") ICOADS dataset erases out the 1940-1945 bulge, would there be still any 20th century AMO to explain? *Thompson et al. 2008 (Nature)*

Probably AMO is still with us

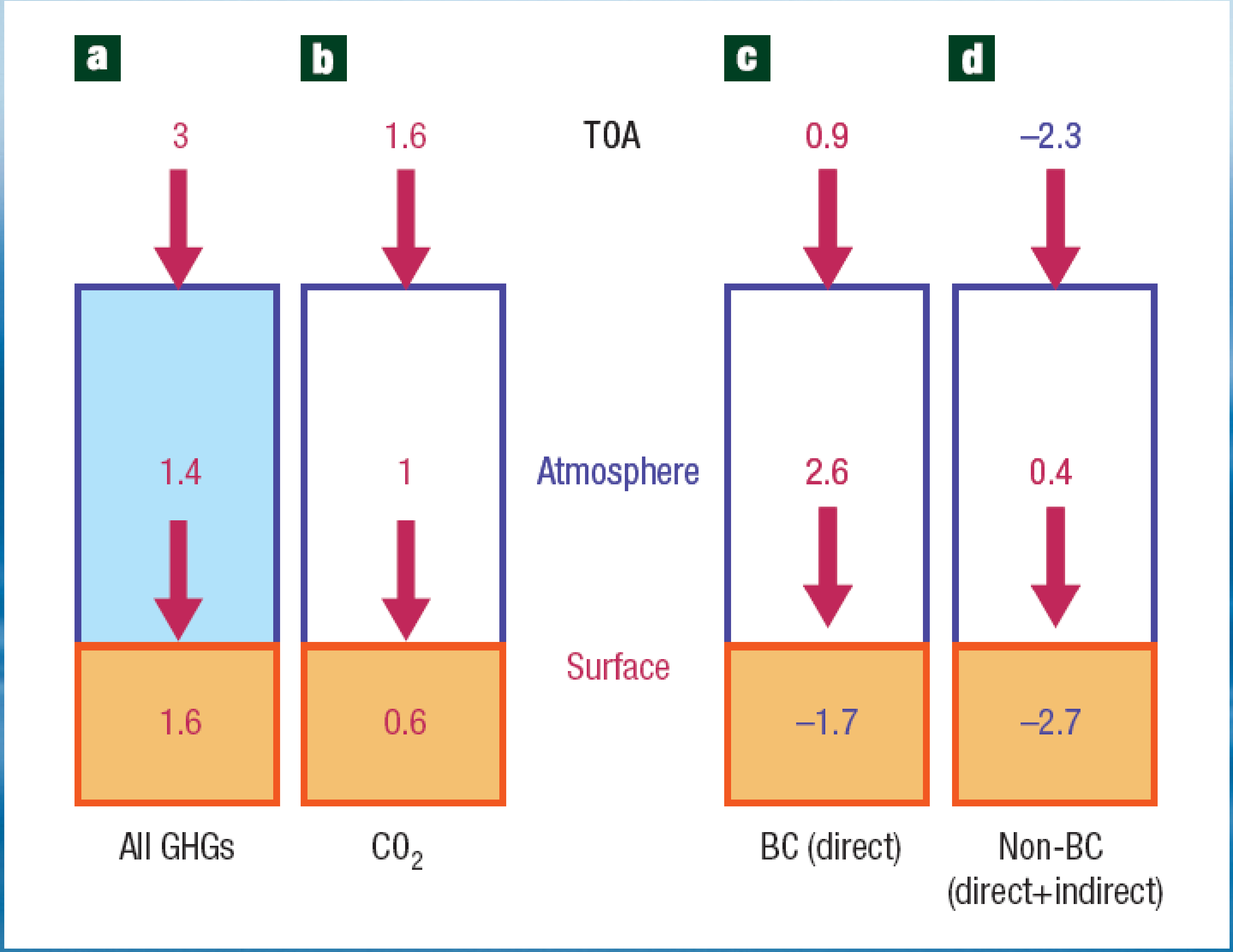
The “British bucket” dip ?



Filling out the 0.3º C “British bucket” dip would seem to make the AMO signal even stronger. Moving the left (“pre-dip”) part of the graph down by 0.3 º C would make an even bigger minimum tn the 1970s (after correcting the detrending). So it seems there is still an AMO to account for.

McCabe Palecki McCourt 2004 (PNAS)

... then suddenly black carbon enters the scene.



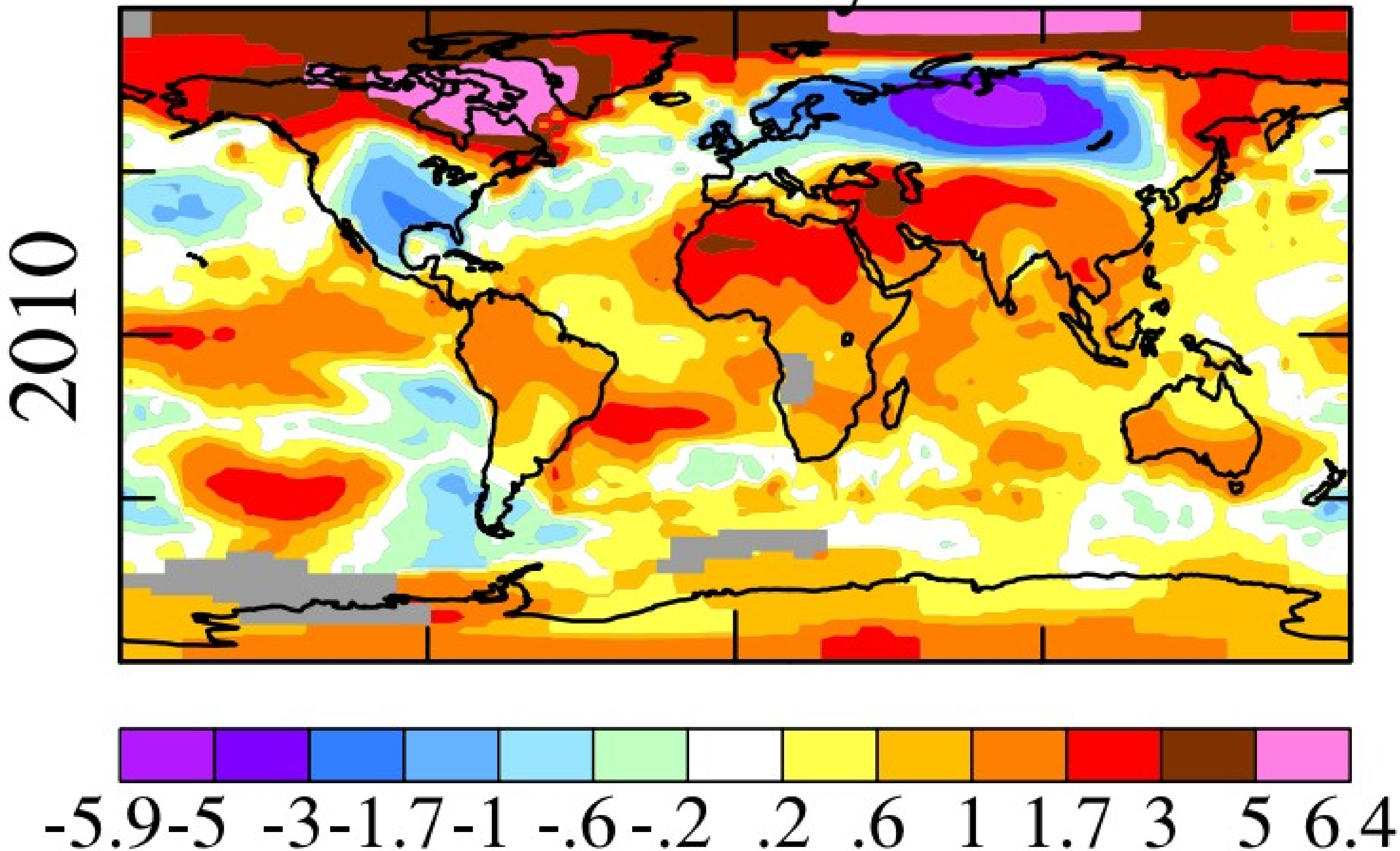
Radiative forcing ($W\ m^{-2}$) of:
a) all greenhouse gases, b) CO_2 only, c) black carbon (soot), d) other aerosols.

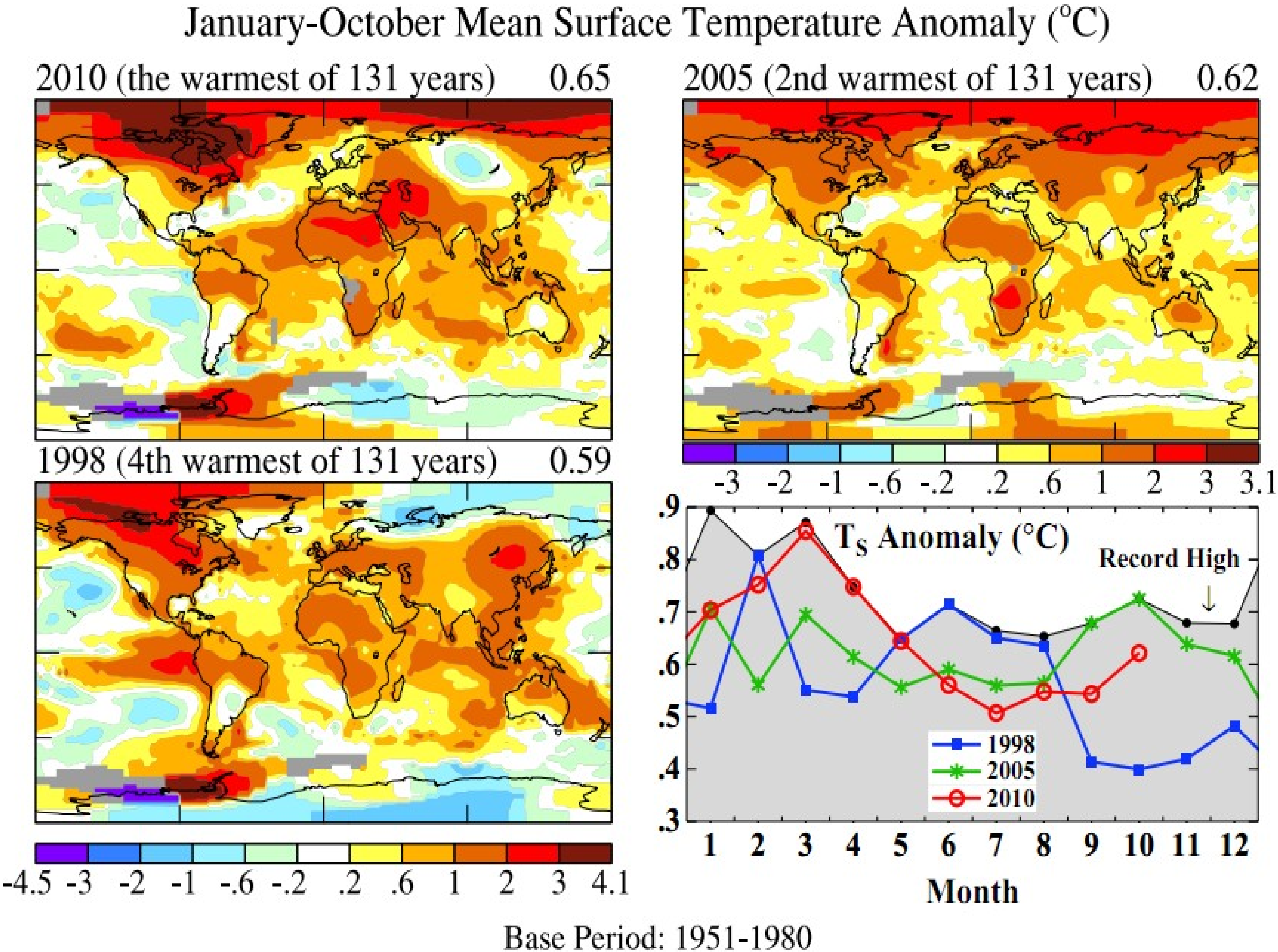
This additional warming of the planet (see TOA values) with direct surface cooling and troposphere warming complicates the aerosol -> climate influence even more.

Ramanathan & Carmichael 2008 (Nature Geoscience)

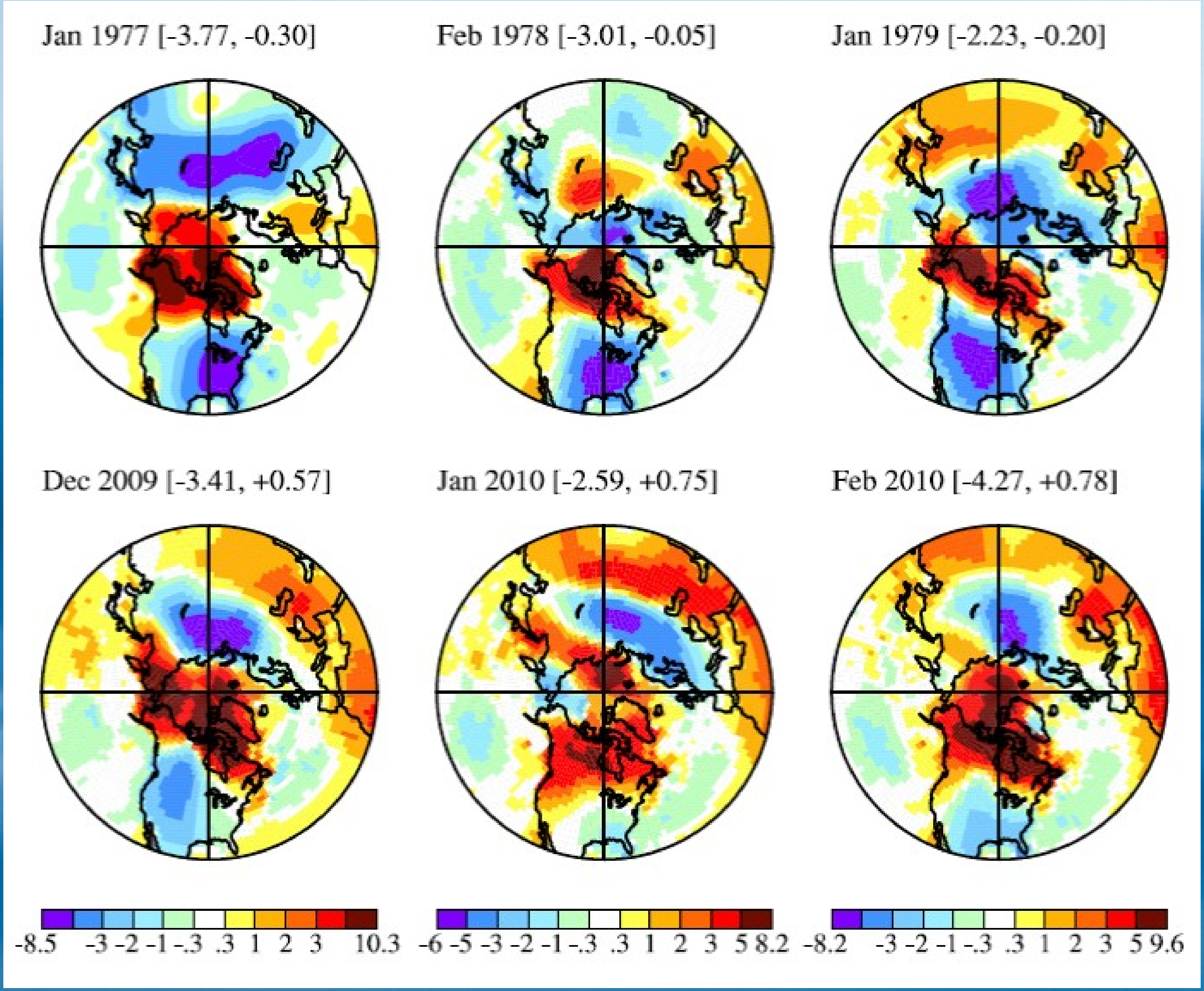
N.H. Winter (Dec-Jan-Feb)

2nd warmest of 130 years 0.68




January-October Mean Surface Temperature Anomaly (°C)
2010 (the warmest of 131 years) 0.65
2005 (2nd warmest of 131 years) 0.62
1998 (4th warmest of 131 years) 0.59
-3 -2 -1 -.6 -.2 .2 .6 1 2 3 3.1
-4.5 -3 -2 -1 -.6 -.2 .2 .6 1 2 3 4.1
Ts Anomaly (°C)
Record High
.9
.8
.7
.6
.5
.4
.3
1 2 3 4 5 6 7 8 9 10 11 12
Month
1998
2005
2010
Base Period: 1951-1980

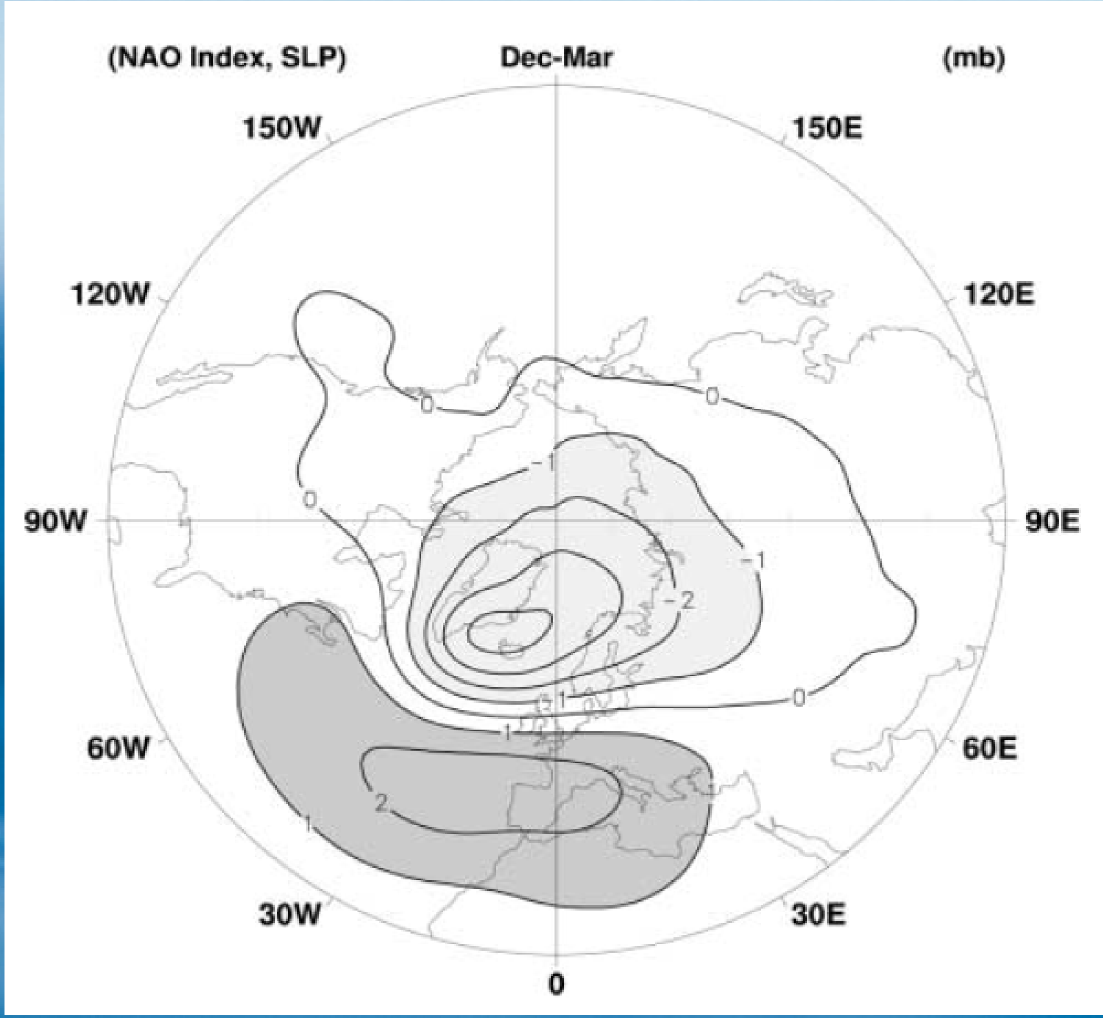
Low AO values lead to this kind of winters



90-24 N temperature anomaly for months with extremely negative AO Index

Hansen 2010 (unpublished)

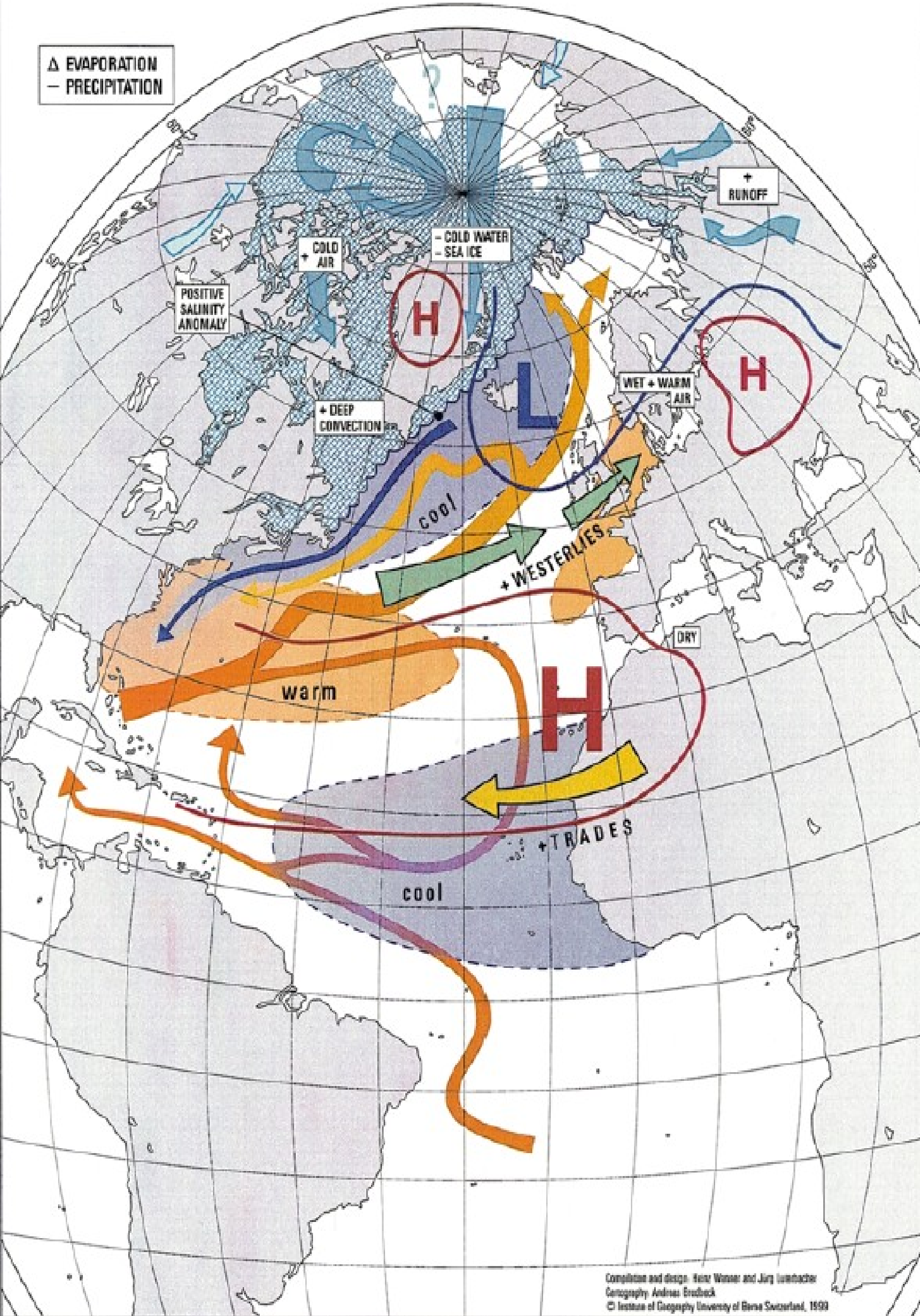
North Atlantic Oscillation (NAO)



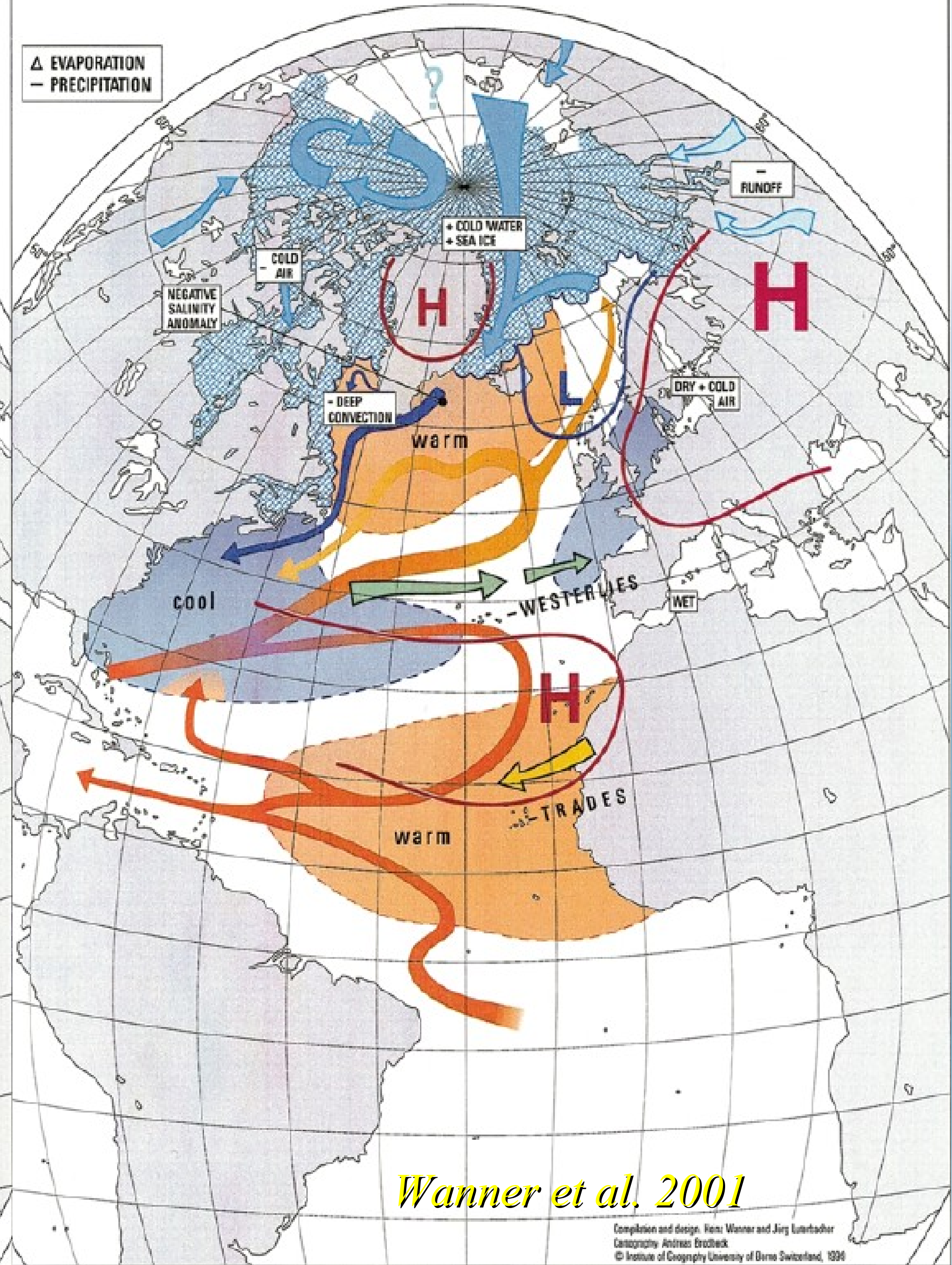
NAO index, identified by Walker (1924), was historically defined as the surface air pressure difference between Lisbon, Portugal and Reykjavik, Iceland (the graph shows a positive NAO pressure pattern). NAO explains 31% variability in winter temperatures north of 20º N.

Greatbatch 2000

NAO +

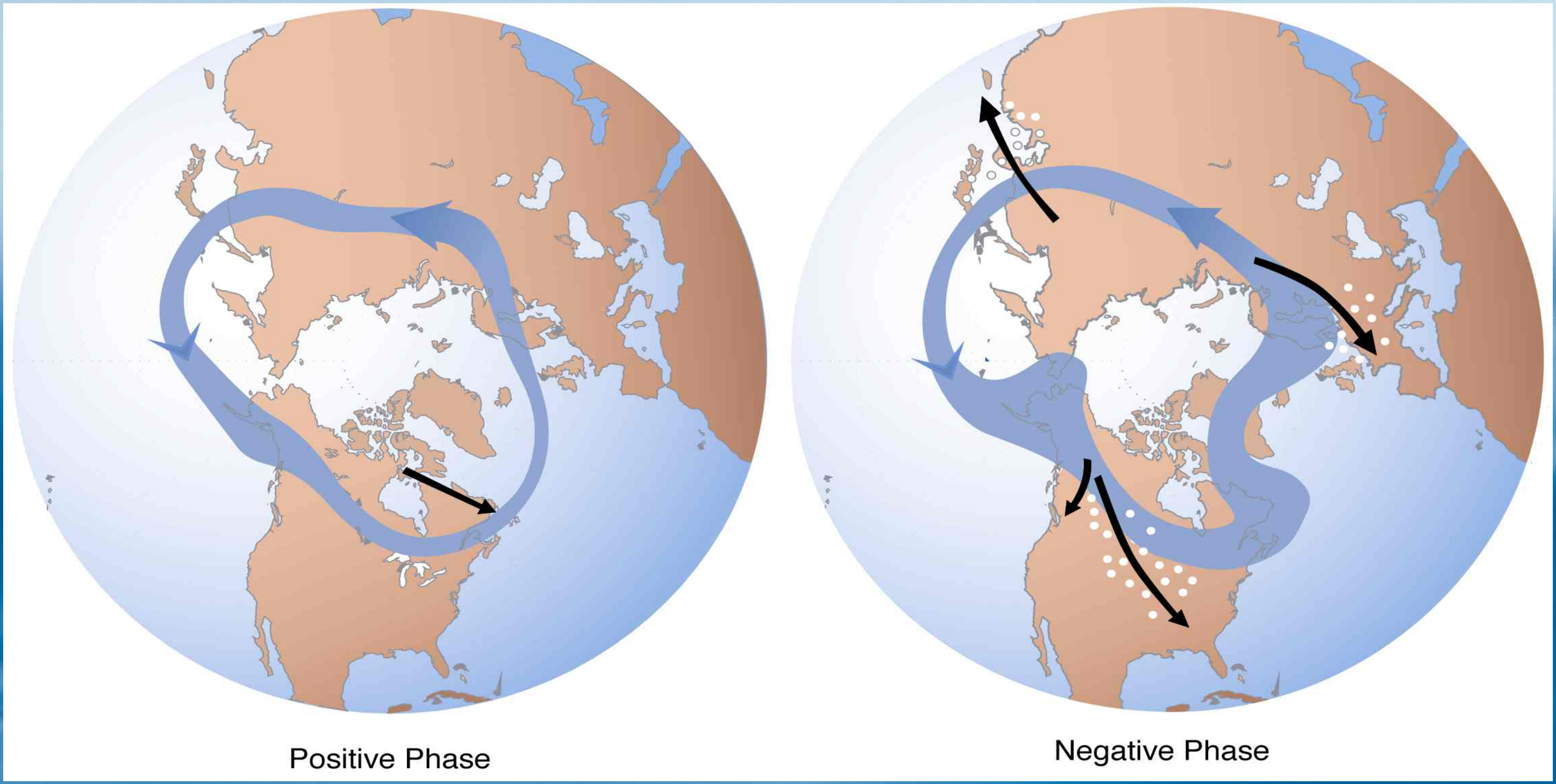


NAO -



Wanner et al. 2001

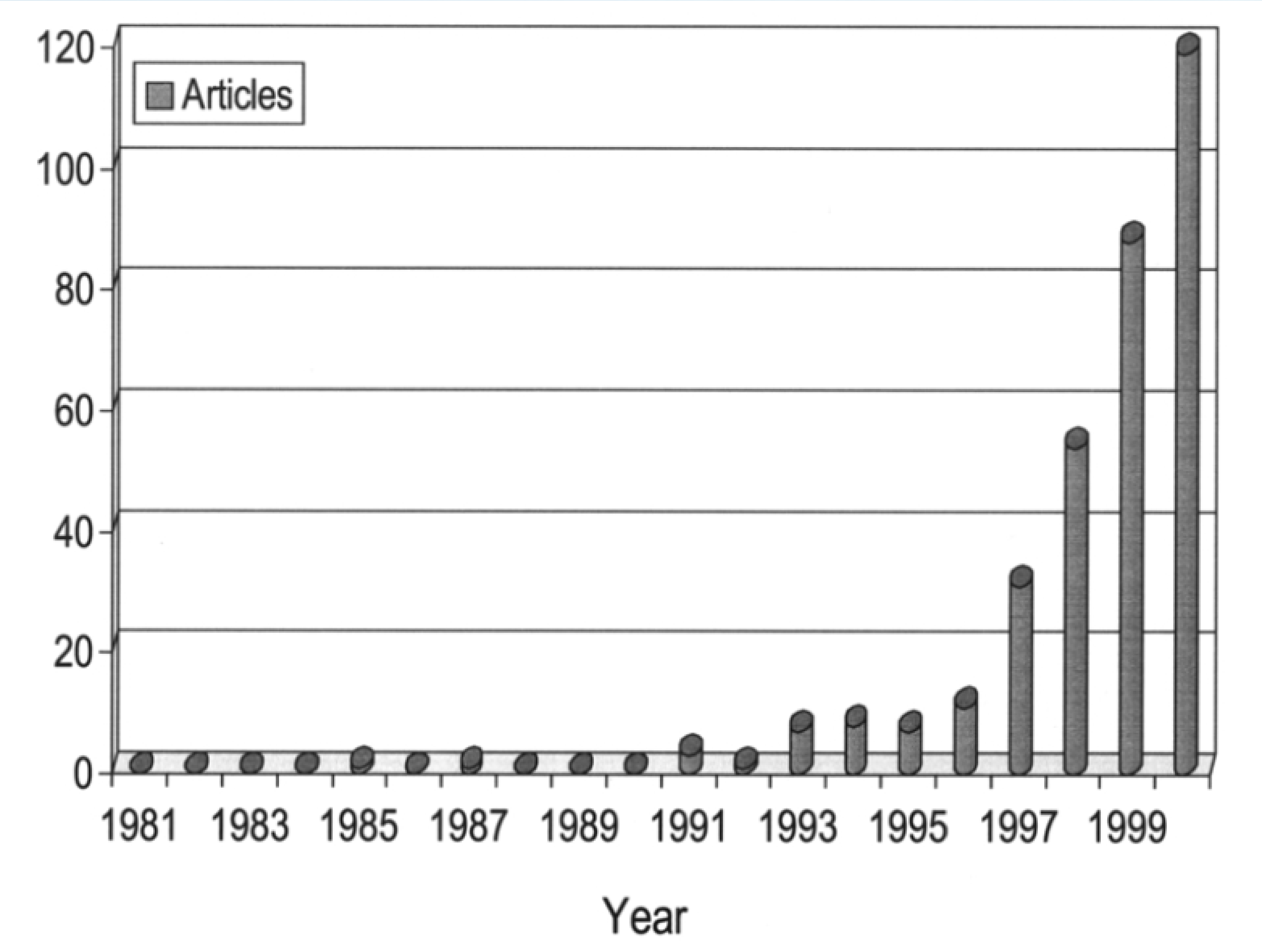
Arctic Oscillation (AO) and storm tracks



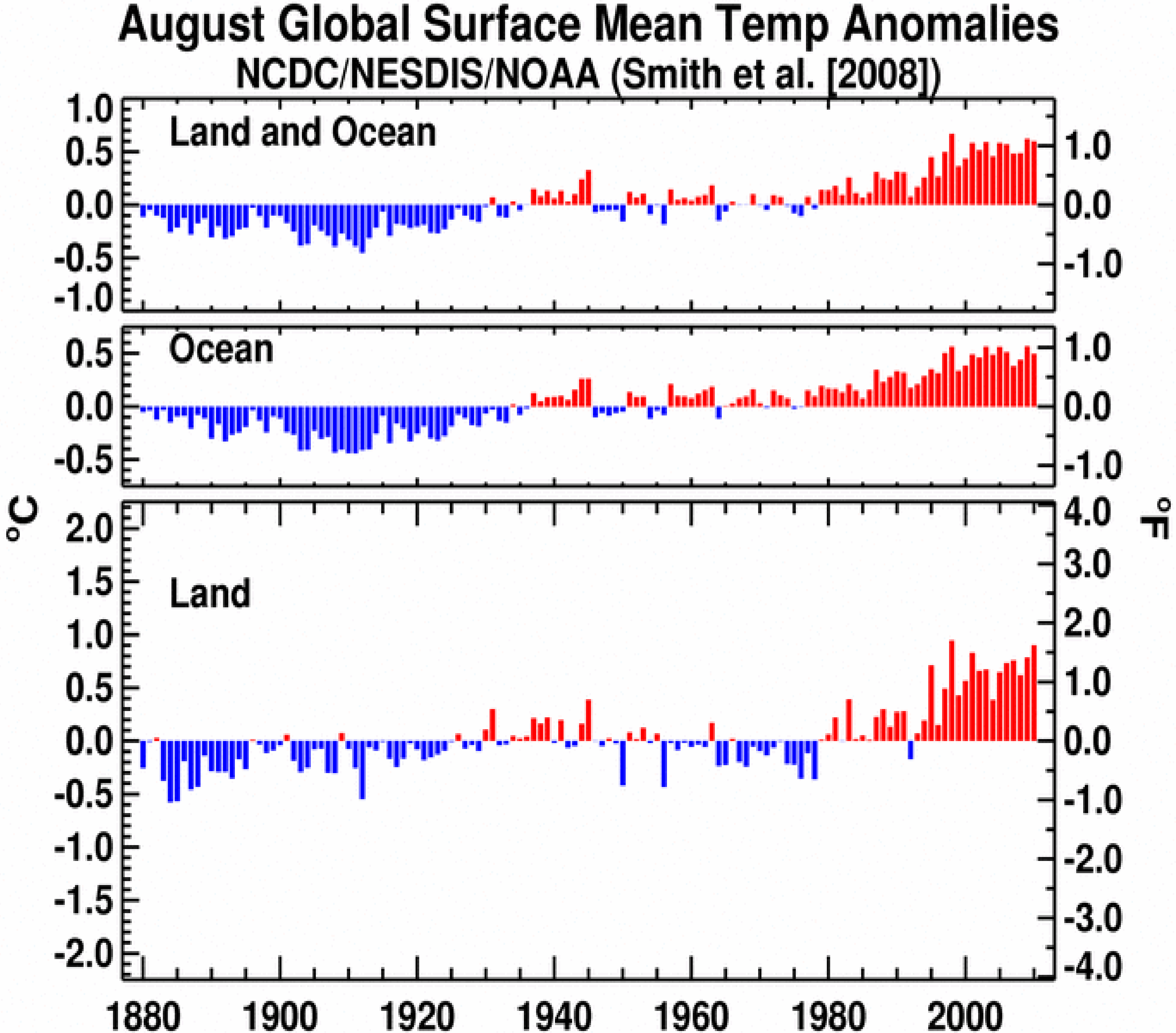
Another index, highly correlated wit NAO is Arctic Oscillation – difference of air pressure between 37º-45º N zone and the polar vortex (and therefore a measure of its intensity). With positive AO, polar vortex is stronger ans the storm tracks are closer to the pole.
Most researchers treat NAO as the local Atlantic chapter of AO.

Ganopolski i Rahmstorf, 2002

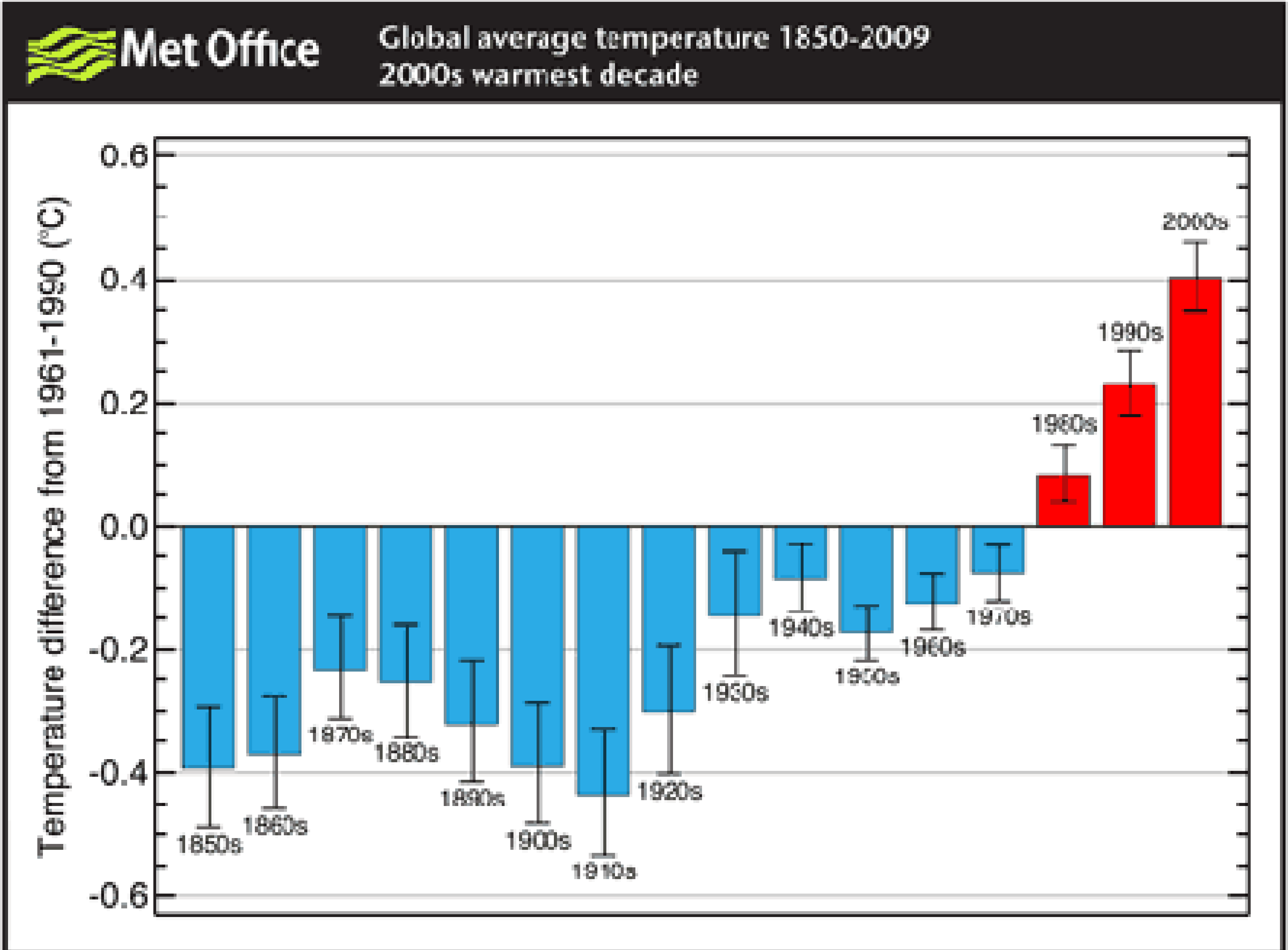
The number of scientific articles on NAO



Wanner et al. 2001



August Global Surface Mean Temp Anomalies
NCDC/NESDIS/NOAA (Smith et al. [2008])
Land and Ocean
Ocean
Land
°C
°F
1.0
0.5
0.0
-0.5
-1.0
2.0
1.5
-1.5
-2.0
3.0
4.0
-3.0
-4.0
1880
1900
1920
1940
1960
1980
2000

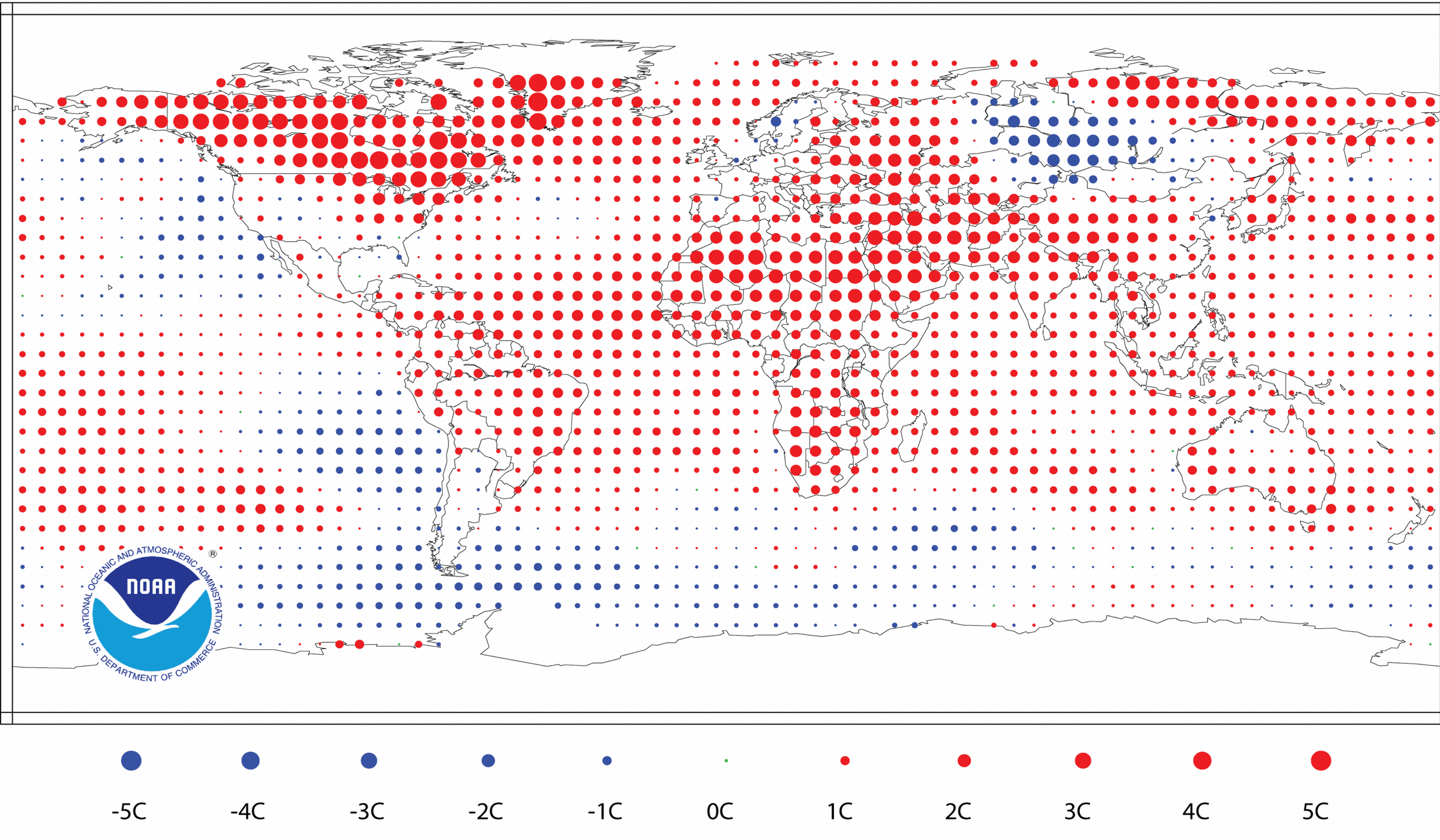


Met Office
Global average temperature 1850-2009
2000s warmest decade
Temperature difference from 1961-1990 (°C)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
1850s
1860s
1870s
1880s
1890s
1900s
1910s
1920s
1930s
1940s
1950s
1960s
1970s
1980s
1990s
2000s

Temperature Anomalies Jan-Aug 2010

(with respect to a 1971-2000 base period)

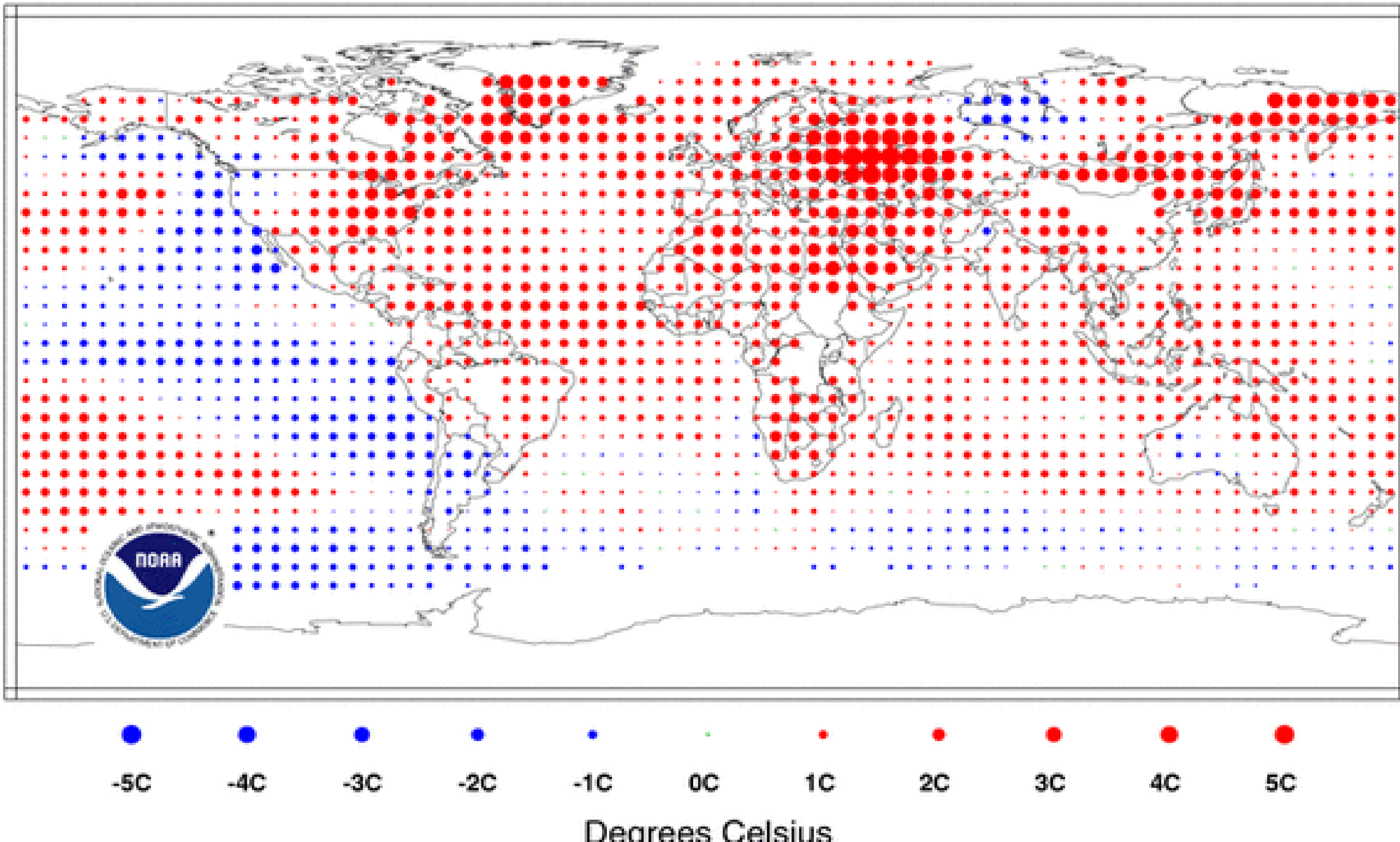
National Climatic Data Center/NESDIS/NOAA



Temperature Anomalies Jun-Aug 2010

(with respect to a 1971-2000 base period)

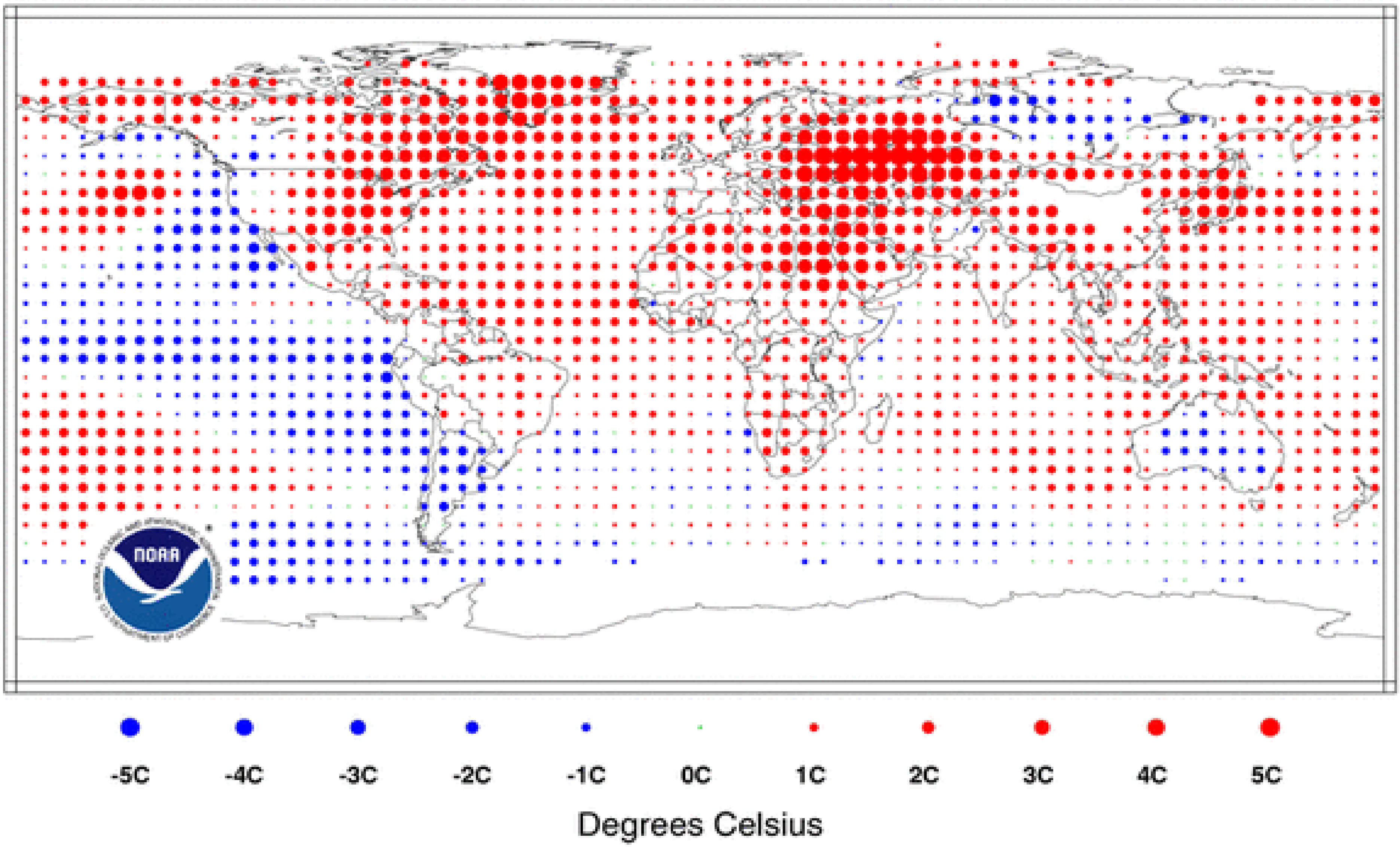
National Climatic Data Center/NESDIS/NOAA

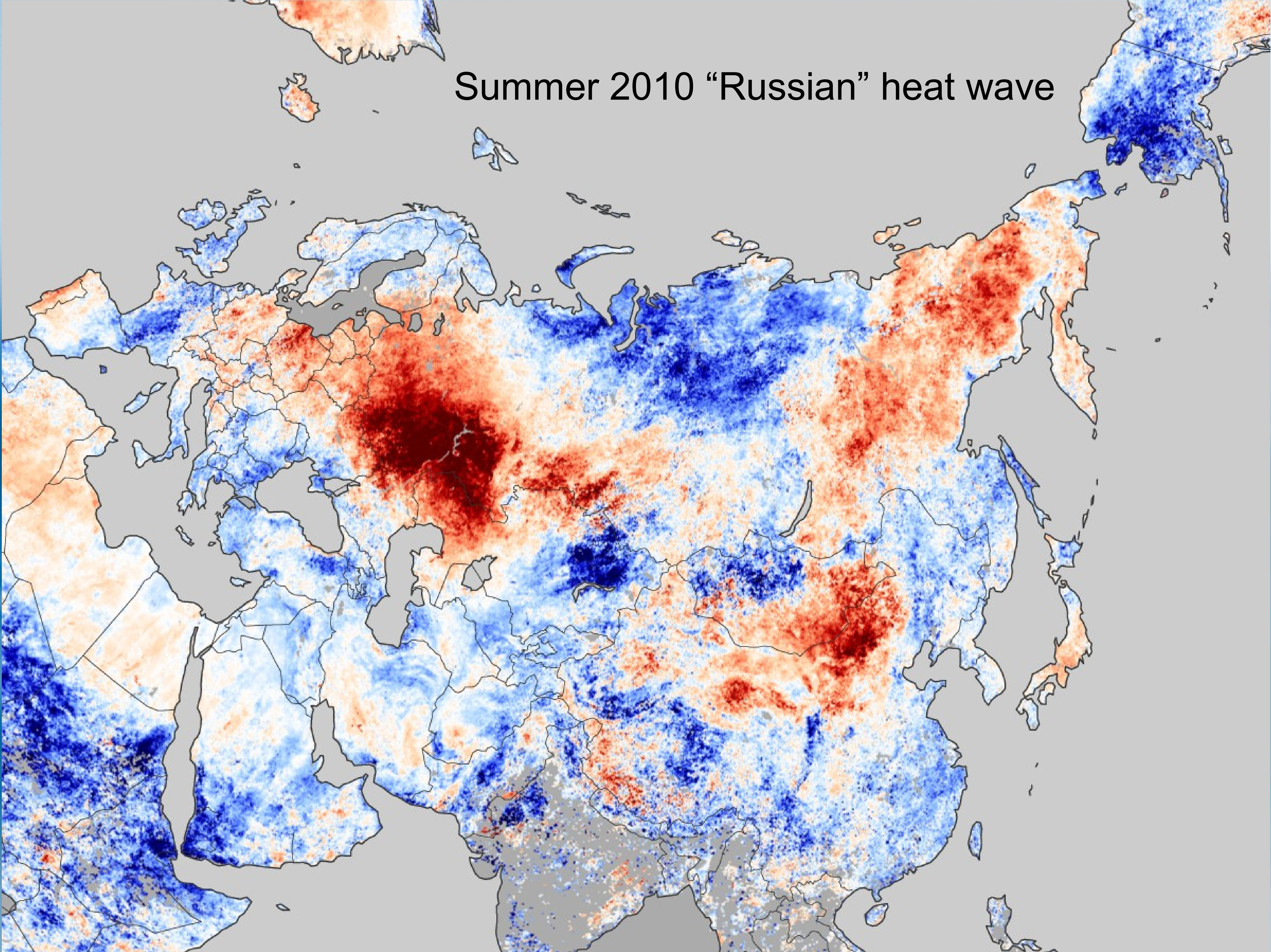


Temperature Anomalies August 2010

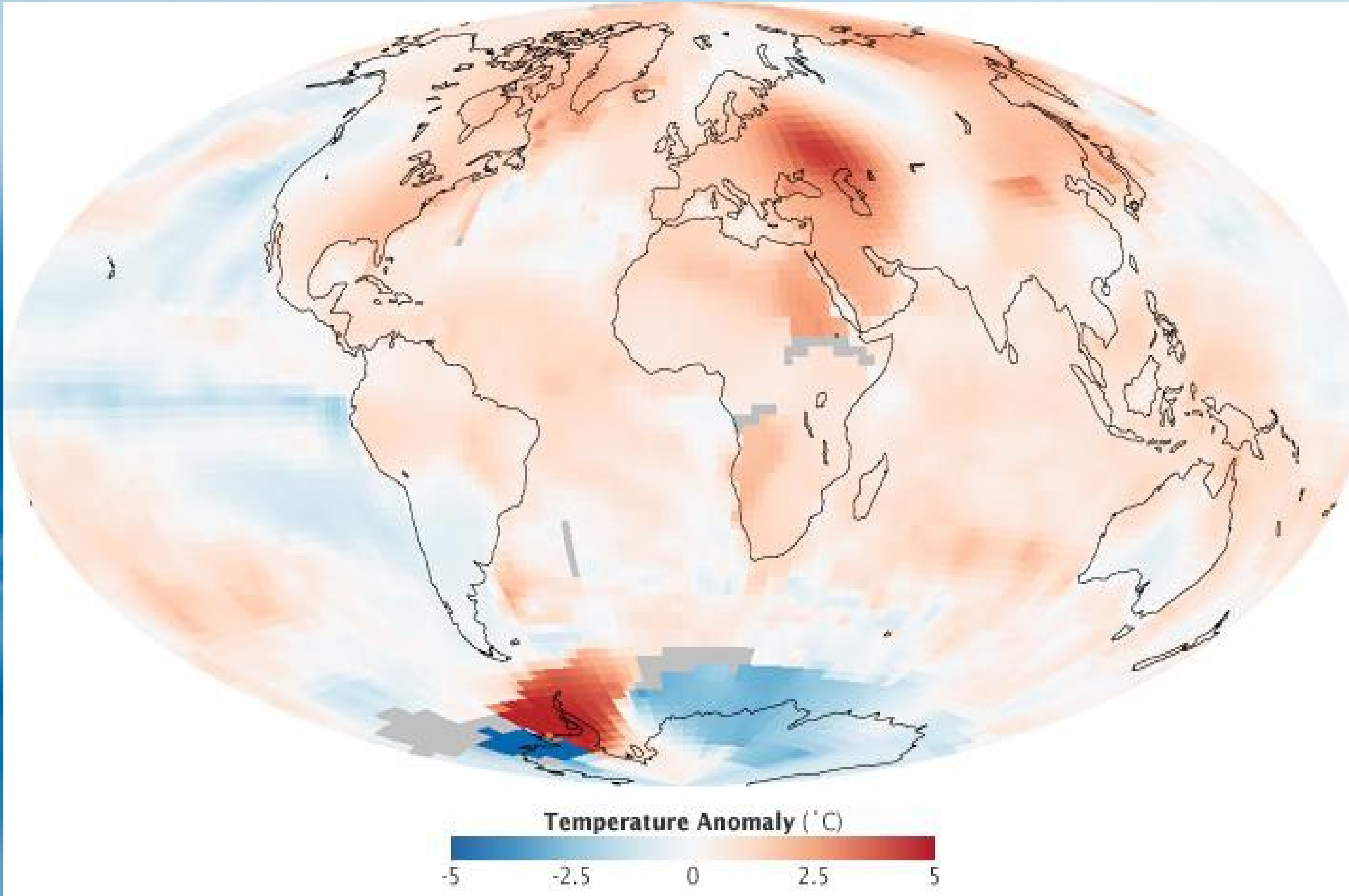
(with respect to a 1971-2000 base period)

National Climatic Data Center/NESDIS/NOAA




Summer 2010 “Russian” heat wave

A global summer 2010 heat wave ?



Possibly to add in future:

- Evan et al 2009
- Park & Latif 2008
- Hofman Maqueda 2009 (to the previous one)
- Thompson et al 2010