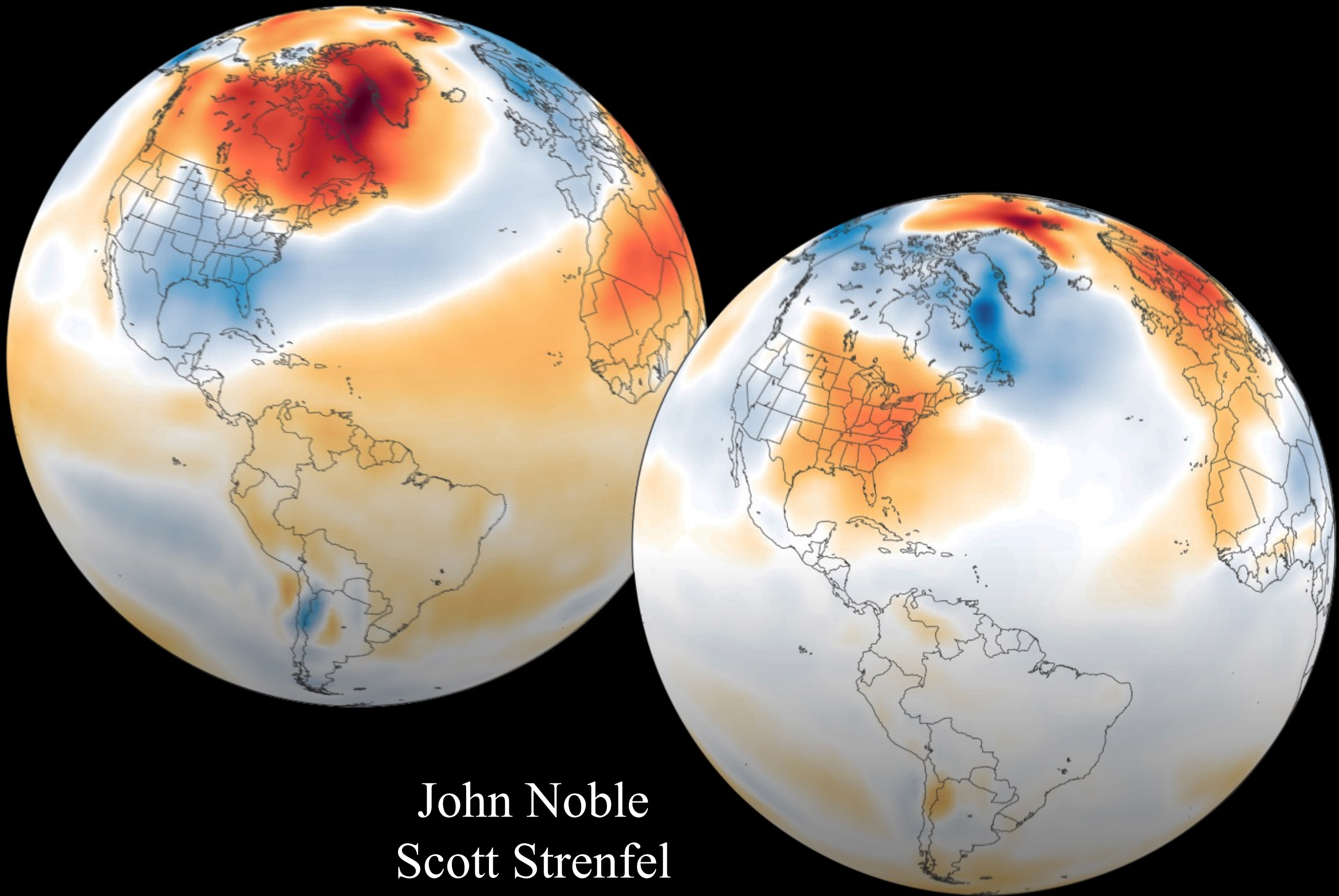
North Atlantic Oscillation (NAO)



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Meteorology 205B
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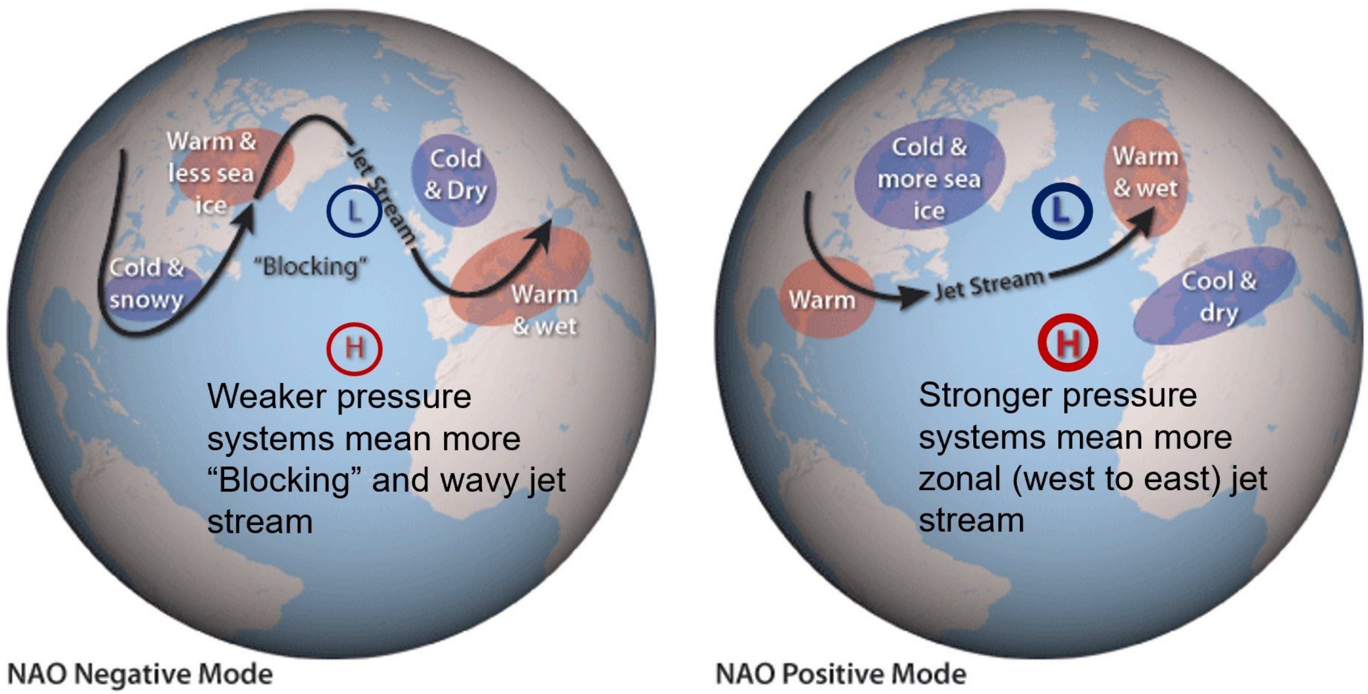
Overview

- The North Atlantic Oscillation (NAO) is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe.

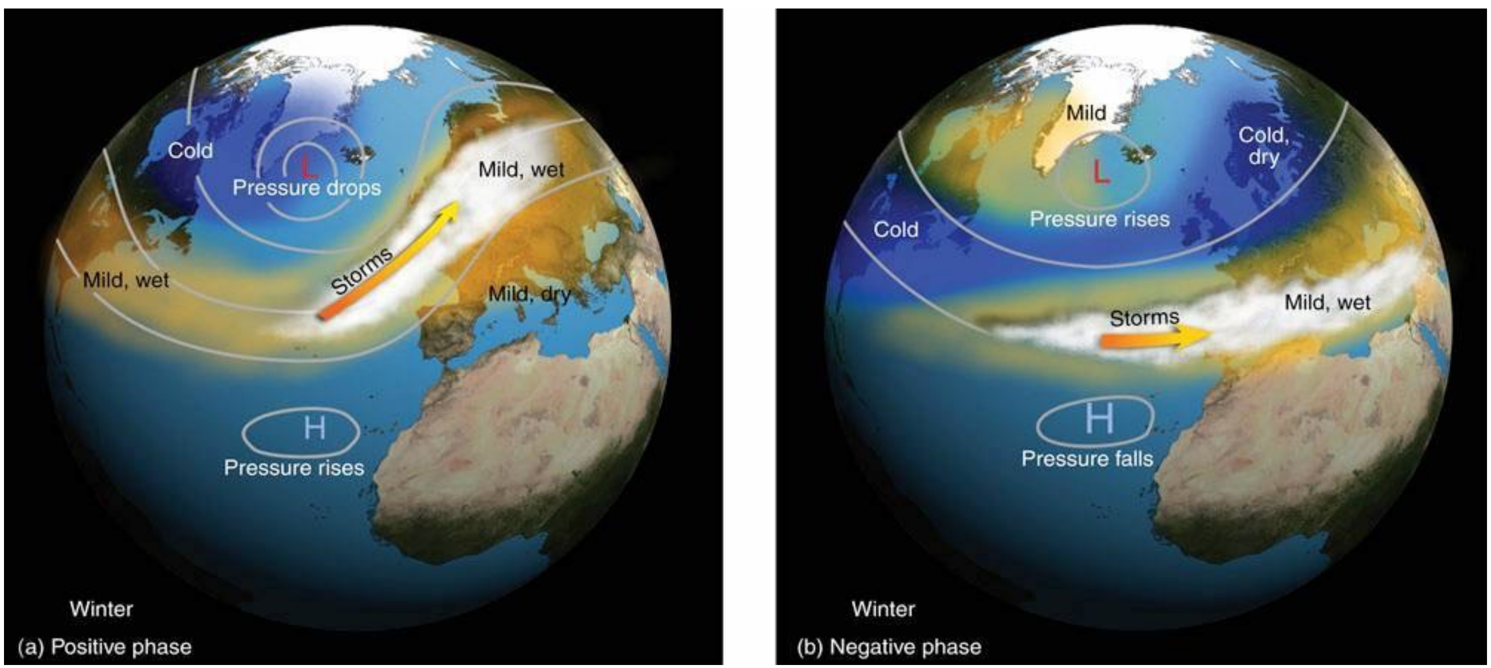
- The NAO is a large scale seesaw in atmospheric mass between the subtropical high and the polar low.



Overview

- NAO is a mode of variability internal to the atmosphere (Hurrell *et al.* 2003)

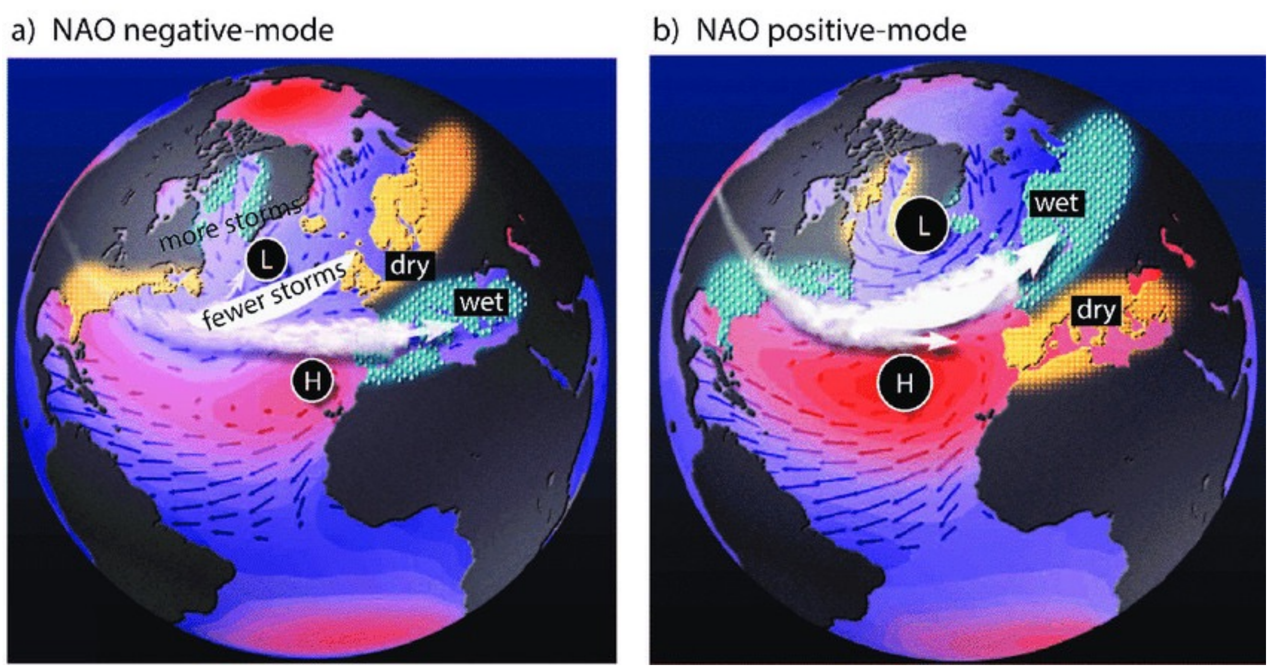
- However, indices of it exhibit decadal variability and trends.
    - Indicates a role of external forcing in NAO?
    - Maybe a small, but useful amount of predictability.



NAO early history

Earliest description of the NAO was made by seafaring Scandinavians (Stephenson *et al*. 2003).

Missionary Hans Egede Saabye (1770–78) made this observation in his diary: ‘When the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely’.
(Loon and Rogers 1978)



NAO early history

- Gronau (1811) documented winters between Greenland and Germany as being above or below normal (Stephenson *et al*. 2003)
- Early 'seesaw' studies (Dove 1839; Dannmeyer 1948).
- Hildebrandsson (1897) investigated time-series of pressure in NH and found an inverse relationship between pressure at Iceland and the Azores.
- NAO first defined by the famous Sir Gilbert Walker in 1920s.

	Winter	
Year	Greenland	Germany
1709	very mild	extraordinarily severe
1740	very mild	unusually cold
1746	mild	cold
1756	very harsh and severe	very mild
1758	hardly winter at all	very cold
1759	not really cold	very cold
1764	very cold	very mild
1765	very cold	moderate
1766	very mild	very cold
1767	mild	very cold
1768	mild	cold
1790	cold	mild
1792	very mild	very cold
1799	extraordinarily mild	unusually cold
1800	extraordinarily mild	unusually cold

(Loon and Rogers 1978)

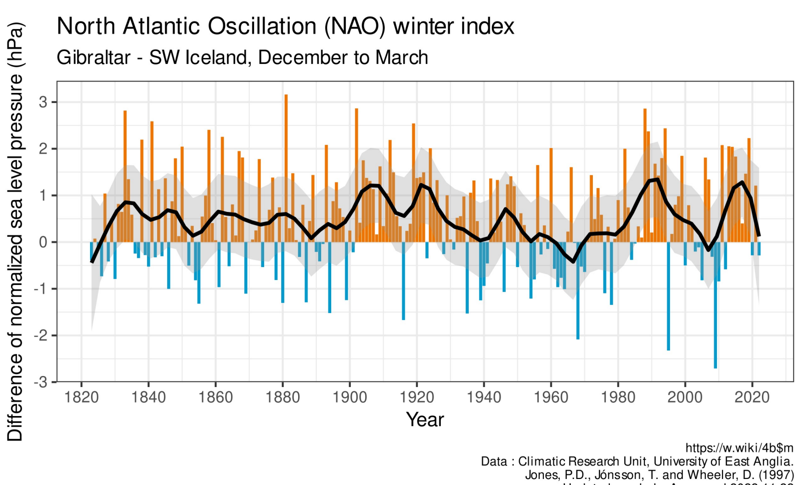
NAO index

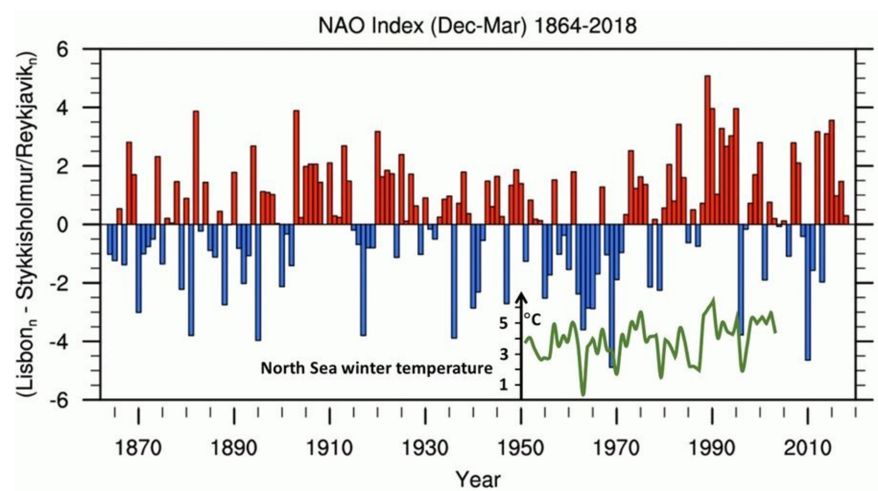
The NAO index is defined as the anomalies difference between the polar low and the subtropical high during the winter season (December through March).

The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years.

An Index can be constructed that represents the phase of the NAO. Most commonly the NAO index is based on the surface pressure (SLP) difference between the Subtropical (Azores) high and the Subpolar (Island) low.

Very often the pressure readings from two stations, one on Iceland and the other either the Azores, Lisbon or Gibraltar, are used to construct the NAO index. The twice daily reading are averaged from November through March and the difference is then the winter NAO index.

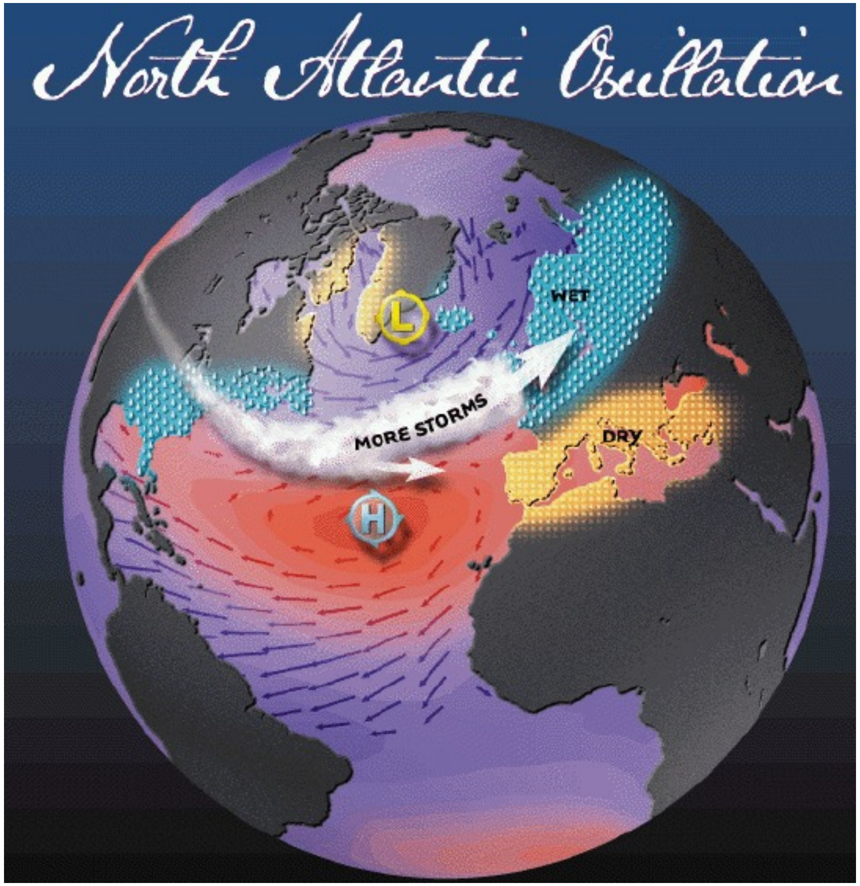




NAO index

Positive NAO Index

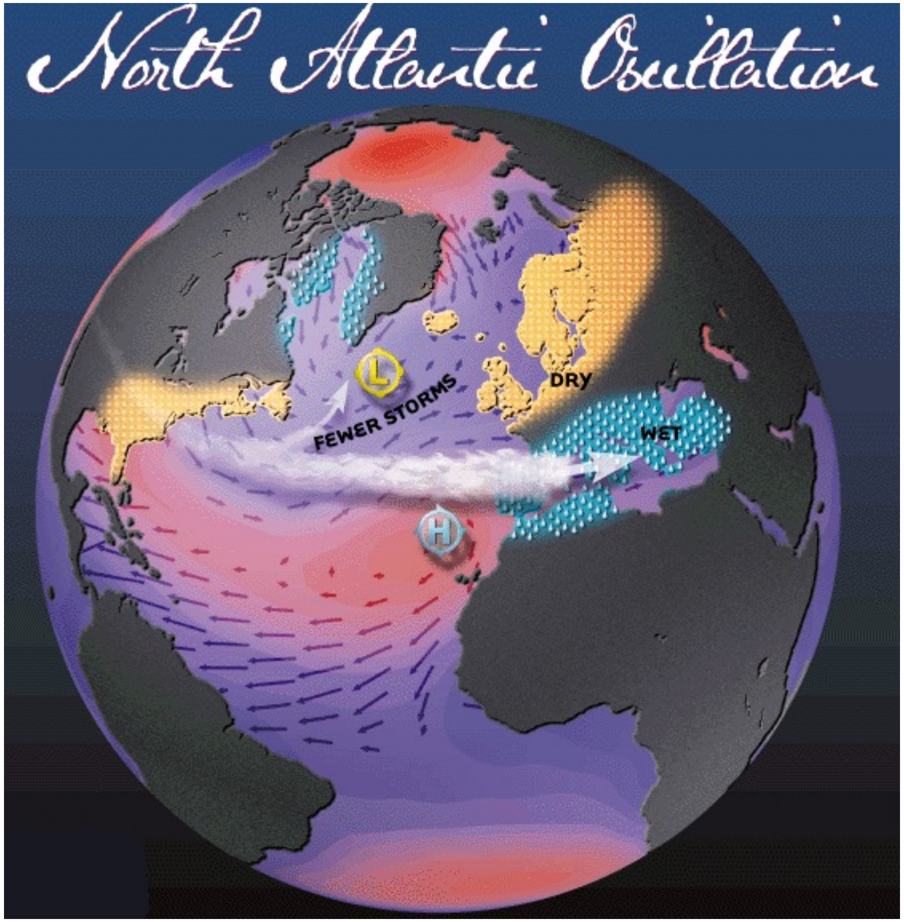
- The positive NAO index phase shows a stronger than usual subtropical high pressure center and a deeper than normal Icelandic low.
- The increased pressure different results in more stronger winter storms crossing the Atlantic Ocean on a more northerly track.



NAO index

Negative NAO Index

- The negative NAO index phase shows a weak subtropical high and a weak Icelandic low.
- The reduced pressure gradient results in fewer and weaker winter storms crossing on a more west-east pathway.



Impacts of the NAO

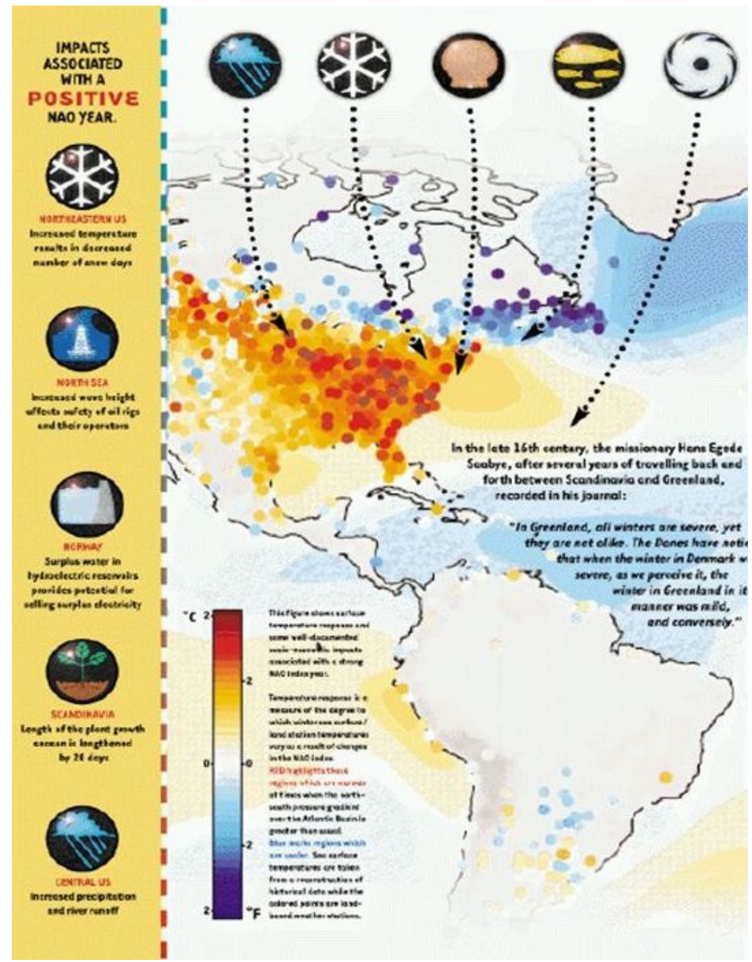
The US East coast experiences milder winter conditions during a positive NAO index phase.

The amount of snow cover is reduced.

Warmer than usual ocean temperatures cause more frequent occurrence of "red tides" in the summer.

Colder than usual tropical ocean temperatures reduce the number of hurricanes in the following summer.

Cold ocean temperatures in the spawning grounds over the Grand Banks cause less cod reproduction.



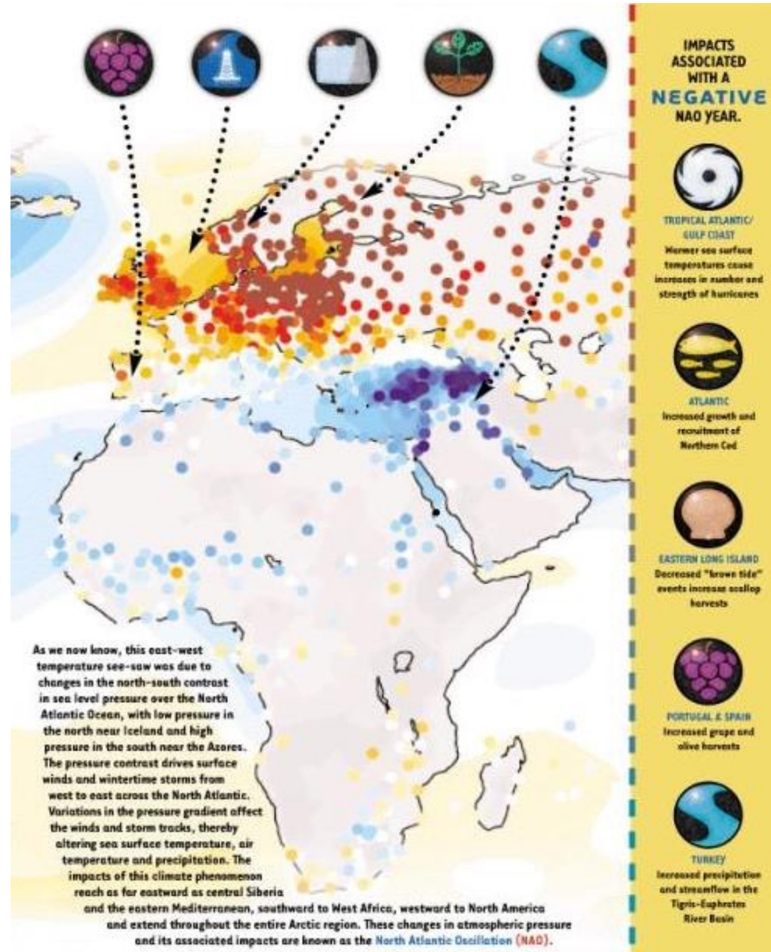
(Visbeck 2008)

Impacts of the NAO

Northern Europe experiences mild and wet winter during the positive NAO index phase.

South-Eastern Europe receives less rain and hence causes significant problems with drinking water supply and reduced stream flow volume in the Middle East (Positive NAO).

Harvest yield of grapes and olives have been shown to depend significantly on the NAO.



(Visbeck 2008)

NAO temperature impacts

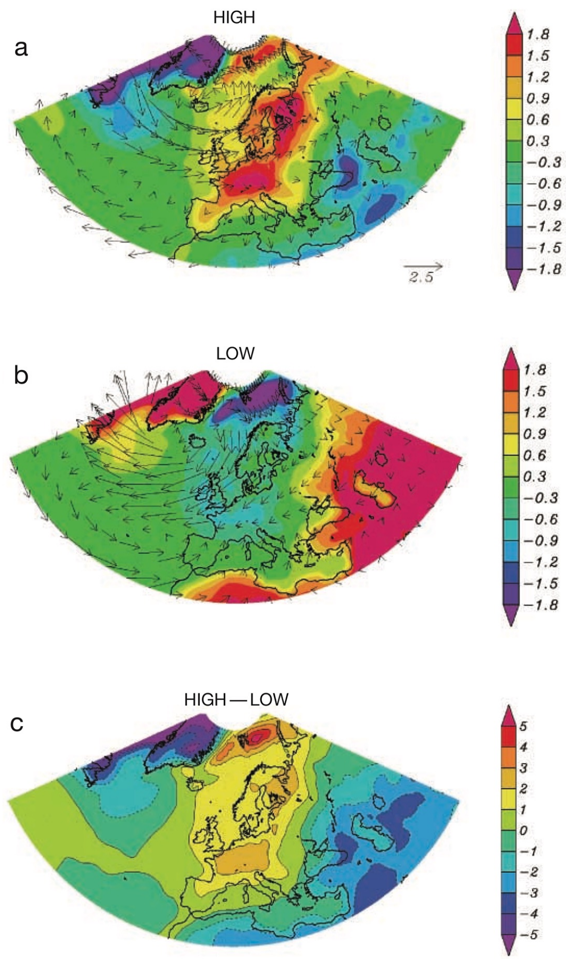


Fig. 3. Tmax anomaly fields (°C) for winter months with (a) high NAO index >1.0, (b) low NAO index <−1.0, and (c) their difference. Vectors of the anomaly 10 m wind field (m s^{-1}) for months with (a) high and (b) low NAO indices are also represented

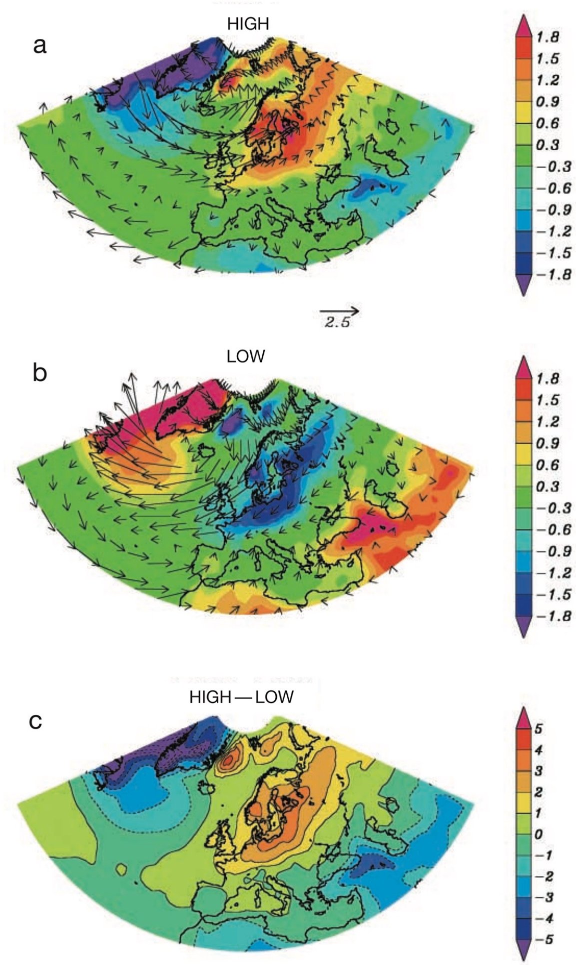


Fig. 4. Tmin anomaly fields. Legend as for Fig. 3

(Trigo *et al.* 2002)

NAO precipitation impacts

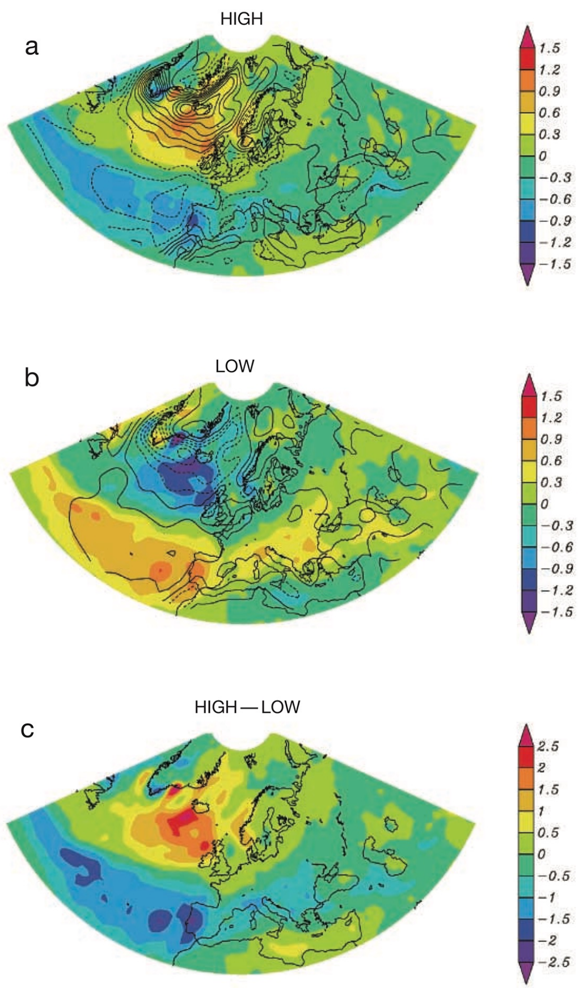


Fig. 6. Precipitation rate anomaly fields (mm d^{-1}) for winter months with (a) high NAO index > 1.0, (b) low NAO index < −1.0, and (c) their difference. Positive (solid) and negative (dashed) isolines of the 10 m anomaly vorticity field, for months with (a) high and (b) low NAO indices are also represented

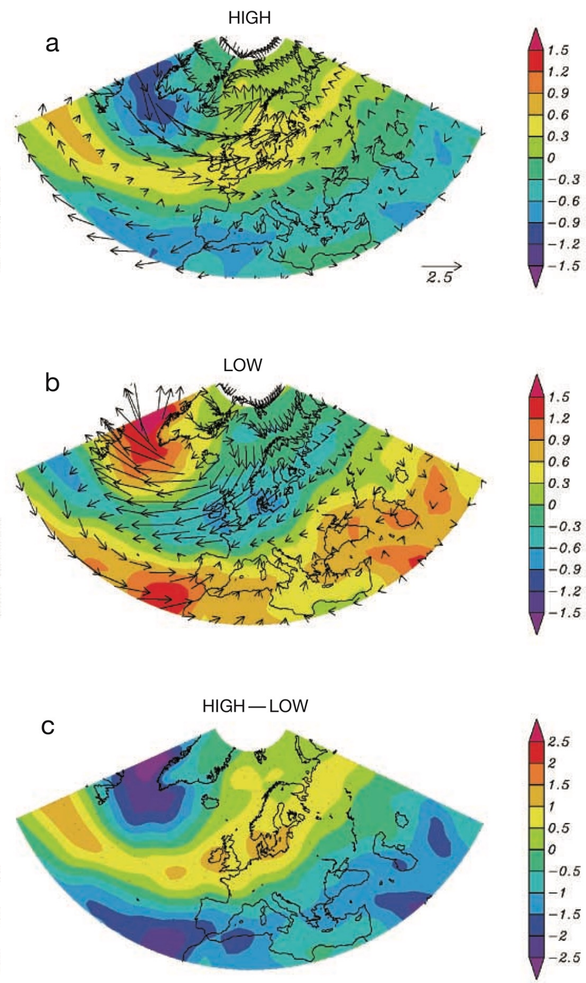


Fig. 7. Precipitable water anomaly fields (mm d^{-1}). Legend as for Fig. 3

(Trigo *et al.* 2002)

NAO precipitation impacts

Table II

Stations (latitude, longitude) that contain records of December–March precipitation for at least 40 winters. The correlation coefficients r(NAO, P) with the NAO index (Figure 5) and the total number of winters (n) that were included in the correlations are indicated. Also indicated are the mean precipitation rate $\overline{P}$ over the total number of winters (n), and the difference in precipitation rate between winters with a NAO index > 1.0 and those with an index < -1.0. One asterisk indicates statistical significance at the 5% level and two indicate significance at the 1% level

Station	r(NAO, P)	n	$\overline{P}$(mm day^{-1})	ΔP(mm day^{-1})
Bergen (60.4° N, 5.3° E)	0.77**	72	5.8	3.6**
Stornoway (58.2° N, 6.3° W)	0.75**	63	3.5	1.4**
Tiree (56.6° N, 6.9° W)	0.67**	63	3.4	1.2**
Stavanger (58.9° N, 5.6° E)	0.66**	43	2.7	1.4**
Thorshavn (62.0° N, 6.8° W)	0.53**	116	4.8	1.1**
Lerwick (60.1° N, 1.2° W)	0.49**	63	3.6	0.8**
Reykjavik (64.1° N, 21.9° W)	0.48**	73	2.7	0.9**
Akureyri (65.7° N, 18.1° W)	0.43**	63	1.6	0.4*
Stykkisholmur (65.1° N, 22.7° W)	0.40**	117	2.2	0.7**
Haparanda (65.8° N, 24.2° E)	0.37**	130	1.2	0.4**
Karesuando (68.5° N, 22.5° E)	0.21*	115	0.6	0.1
Oslo (60.2° N, 11.1° E)	0.21*	125	1.3	0.2
Helsinki (60.3° N, 25.0° E)	0.18*	130	1.5	0.1
Edinburgh (56.0° N, 3.4° W)	0.14	130	1.7	0.2
Stockholm (59.4° N, 18.0° E)	0.14	126	1.1	0.1
Copenhagen (55.7° N, 12.6° E)	0.14	129	1.3	0.1
Valentia (51.9° N, 10.3° W)	0.09	123	4.5	0.1
De Bilt (52.1° N, 5.2° E)	0.08	130	1.9	0.1
Belfast (54.7° N, 6.2° W)	0.01	63	2.3	0.0
London (51.2° N, 0.2° W)	–0.02	129	1.7	–0.0
Angmagssalik (65.6° N, 37.6° W)	–0.02	90	2.6	–0.0
Athens (38.0° N, 23.7° E)	–0.11	98	1.7	–0.1
Egedesminde (68.7° N, 52.8° W)	–0.13	38	0.6	–0.1
Paris (49.0° N, 2.5° E)	–0.19*	119	1.5	–0.3**
Frankfurt (50.1° N, 8.7° W)	–0.19*	130	1.4	–0.2*
Godthåb (64.2° N, 51.8° W)	–0.20*	100	1.1	–0.4
Jakobshavn (69.2° N, 51.1° W)	–0.21*	95	0.4	–0.1
Ivigtut (61.2° N, 48.2° W)	–0.31*	89	2.8	–0.9*
Marseille (43.5° N, 5.2° E)	–0.32**	120	1.5	–0.5*
Milan (45.4° N, 9.3° E)	–0.35**	130	2.2	–0.8**
Istanbul (41.0° N, 29.1° E)	–0.36**	64	2.7	–0.7**
Lyon (45.7° N, 5.0° E)	–0.37**	129	1.6	–0.5**
Rome (41.8° N, 12.2° E)	–0.37**	119	2.6	–0.8**
Ajaccio (41.9° N, 8.8° E)	–0.48**	42	2.2	–1.1**
Ponta Delgado (37.8° N, 25.7° W)	–0.49**	98	3.2	–1.1**
Belgrade (44.8° N, 20.5° E)	–0.50**	94	1.4	–0.6**
Casablanca (33.6° N, 7.7° W)	–0.61**	82	2.0	–1.1**
Lisbon (38.8° N, 9.1° W)	–0.64**	130	3.0	–1.8**
Madrid (40.4° N, 3.7° W)	–0.69**	129	1.3	–1.0**

Statistical significance

* 5% level (95% CI)

** 1% level (99% CI)

(Hurrell 1997)

NAO wind and temperature impacts

During high NAO winters (Hurrell 1995)

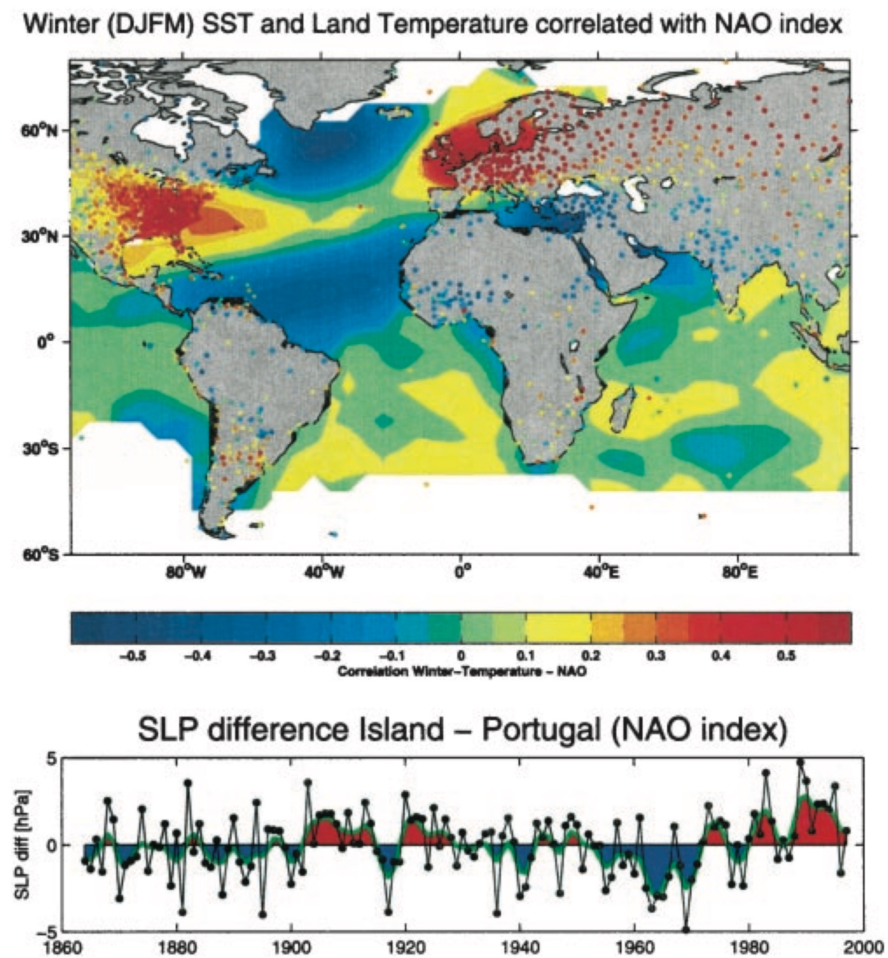
- Westerlies onto Europe over 8 ms^{-1} stronger than low NAO
- Anomalous southerly flow over Eastern US
- Anomalous northerly flow over:
    - Western Greenland
    - Canadian Arctic
    - Mediterranean

Variability of NAO winters (Hurrell 2001)

- NAO variability explains about one-third of the Northern Hemisphere interannual surface temperature variance.

Correlation between NAO and SSTs

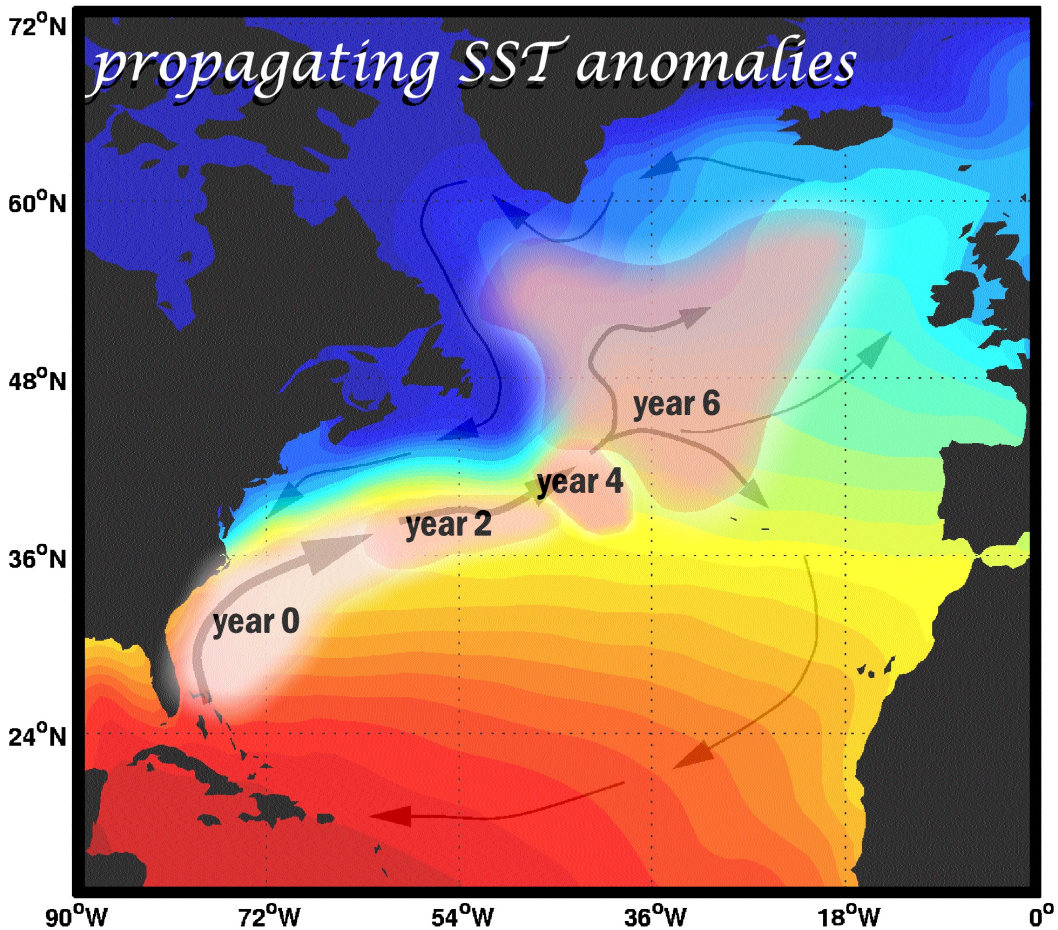
Spatial correlation map of mean winter (DJFM) station temperature and sea surface temperature (SST) correlated against the NAO index (Lower). The NAO index is defined by Hurrell (2) as the difference between the normalized DJFM sea level pressure (SLP) anomaly at Lisbon, Portugal and Stykkisholmur, Iceland. During a positive NAO, colder conditions prevail over western Greenland and the Mediterranean region, whereas warmer conditions prevail in northern Europe, the northeast United States, and parts of Scandinavia. SST reflects a tripole pattern with a cold anomaly in the subpolar region, a warm anomaly in the mid-latitudes centered off Cape Hatteras, and a cold subtropical anomaly between the equator and 30°N. (Visbeck *et al.* 2001)



Atlantic Ocean SSTs and the NAO

Some scientist have suggested that the storage and propagation of temperature anomalies by the ocean gives an important feedback to the atmosphere and is responsible for the decadal signal in NAO.

If correct, one could make use of the "slow ocean dynamics" to predict aspects of the NAO.

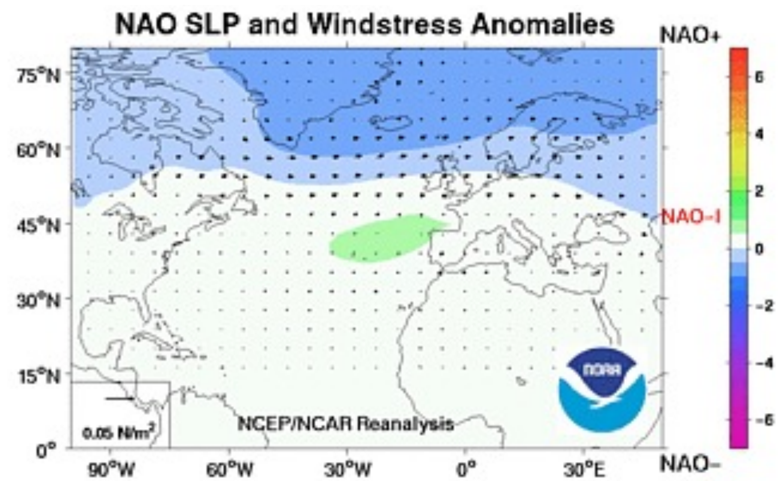


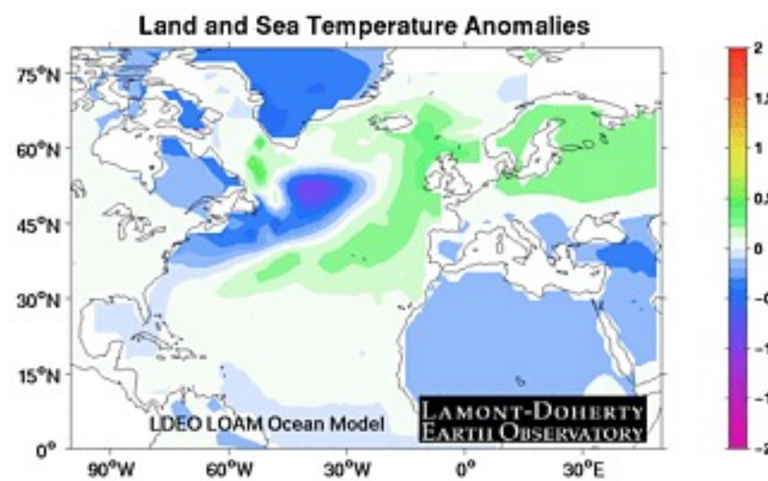
SLP, windstress, & temperature anomalies

Animation of sea level pressure and surface winds during an idealized NAO cycle of 12 year duration.

The lower panel shows the land temperature response and the propagation of SST anomalies in the ocean.

The ocean is simulated by the Lamont Ocean model (LOAM) All other data are regressions from the NCEP/NCAR reanalysis.





(Visbeck 2008)

NAO-ENSO connection with solar cycle

- Both NAO and ENSO undergo long-term variations closely related to the secular solar activity variations (Kirov and Georgieva 2002).

- Solar cycle drives both these large-scale features?

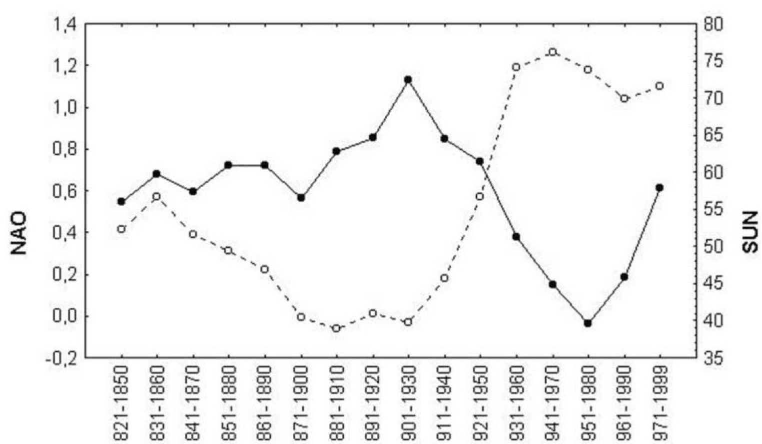


Fig. 1 Long-term variations of NAO (solid line) and international sunspot numbers (broken line), 30-year averages. (Kirov and Georgieva 2002)

r = –0.90 with NAO lag of 10 years

r = –0.73, concurrent

$p < .01$

NAO-ENSO connection with solar cycle

Are ENSO/NAO both driven by the solar cycle/ number of sunspots?

Authors state the statistical evidence is there but the mechanisms through which solar activity affects atmospheric circulation and baric systems, and long-term variations in ENSO are still a matter of controversy.

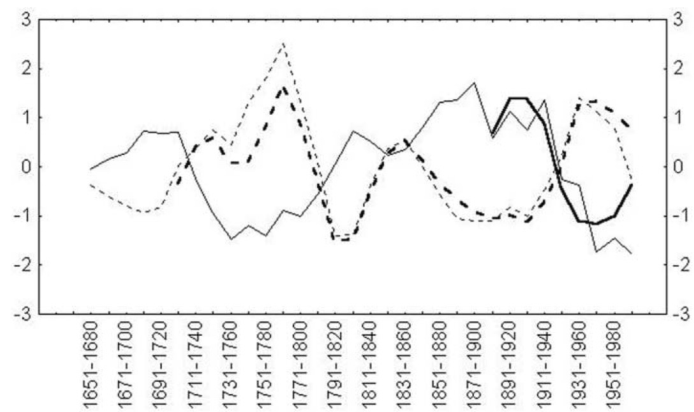


Fig. 2. Comparison between El Niño and solar activity: Quinn's El Niño index – thin solid line and Cold Tongue Index (CTI) – thick solid line; the grouped sunspot numbers Rg – thin broken line and international sunspot numbers – thick broken line, in units of standard deviations, 30-year averages, detrended. (Kirov and Georgieva 2002)

$r = -0.73$, concurrent

$p < 0.01$

Conclusions

The North Atlantic Oscillation is the largest mode of climate variability in the Atlantic Sector, and possibly in the whole northern hemisphere.

Its impacts reach from the upper atmosphere to the bottom of the ocean and reach from America over to Europe and far into Asia.

NAO may ultimately be driven by the solar cycle.

The dynamics of the NAO are not fully understood, and in particular its sensitivity to ocean, land, and changes in the sea-ice conditions need more study.

It has also been suggested that tropical ocean temperatures can influence the phase of the NAO.

Climate change and the NAO

- Questions:
    - Has the NAO exhibited significant changes in recent decades?
    - How do NAO variations manifest in other quantities?
    - What are the mechanisms by which NAO responses come about?
    - Are NAO changes masking or enhancing anthropogenic climate change?
- Motivations
    - Understanding relationship between climate change (CC) and the NAO is necessary to improve predictions
- Methodology
    - NAO index definitions
        - Station-based vs EOF-based
    - Use estimates of internal variability from historical observations, paleoclimate data, simulations
- Observations
    - Limitations:
        - 1. Short
        - 2. Contaminated by anthropogenic forcing

(Gillett *et al.* 2003)

NAO index formulations

- Station-based NAO index
  - Differences in sea level pressure (SLP) at two stations (Jones 2003)
- EOF-based NAO index
  - Derived by projecting SLP onto an EOF pattern
    - *e.g.* November-April monthly SLP northward of 20^{o} N (Thompson and Wallace 1998)
    - *i.e.* Arctic Oscillation index, or Northern Hemisphere Annular Mode index (Thompson *et al.* 2003).

Observed NAO changes

- The NAO boreal winter (BW) index has exhibited an upward trend over recent decades, corresponding to decreased surface pressure over the Arctic and increased surface pressure over the subtropical North Atlantic (Gillett *et al.* 2003).

- First apparent in the mid-1990s.

- Increasing greenhouse gas concentrations were thought to be a contributing factor (Palmer 1993; Hurrell 1995; Graf *et al.* 1995).

- Winter surface pressure over Iceland has fallen by ~ 7 hPa over the past thirty years and has been as associated with over half the Eurasian winter surface temperature increase over the same period (Hurrell 1996), and much of the observed trend in precipitation over Western Europe.

Observed NAO changes

- This trend has been associated with over half the winter surface warming in Eurasia over the past 30 years, as well as strong regional trends in precipitation over Western Europe (Gillett *et al.* 2003).

- Thompson *et al.* (2000) concluded that the observed positive trend between January and March is significant compared to its own internal variability, assuming that variability is uncorrelated.

NAO response to varied forcing

- Graf *et al.* (1995) speculate that greenhouse gases may have contributed to the observed upward trend in the BW NAO index.

- Hypothesis is tested by forcing a coupled ocean-atmosphere model (ECHAM1) with increased CO_2 concentrations and other anthropogenic forcings.

- No significant circulation response was detected, model failings were speculated to be a possible factor (Graf *et al.* 1995).

Model limitations

- Existing climate models have limited horizontal and vertical resolution that may limit their ability to properly simulate features such as baroclinic disturbances or stratospheric processes.

- GCMs, however, are the best available tools to investigate these questions (Gillett *et al* 2003).

Model simulations

- Ulbrich and Christoph (1999) used a later version (ECHAM4), and found a significant change towards the positive index phase, linearly proportional to the applied radiative forcing.
- They also noted a northeastward shift of the northern center of action of the NAO in response to increasing greenhouse gas concentrations.
- Osborn *et al.* (1999) examined changes in a station-based NAO index in HadCM2 with prescribed increases in greenhouse gases, and found a decrease in the NAO index.
- Other studies using this model, however, have since found either no significant change (Gillett *et al.* 2000) or a weak increase (Osborn 2002) depending on the definition of the NAO index used.

Observed and simulated trends

Observed trend is outside the 5–95% range of simulated internal variability for almost all trend lengths between 20 and 60 years (Gillett *et al.* 2000).

Osborn *et al.* (1999) demonstrated that observed positive 30-yr winter NAO index trends beginning between 1960 and 1967 were outside the 95% range of variability simulated during a 1400-year control run of the HadCM2 coupled climate model.

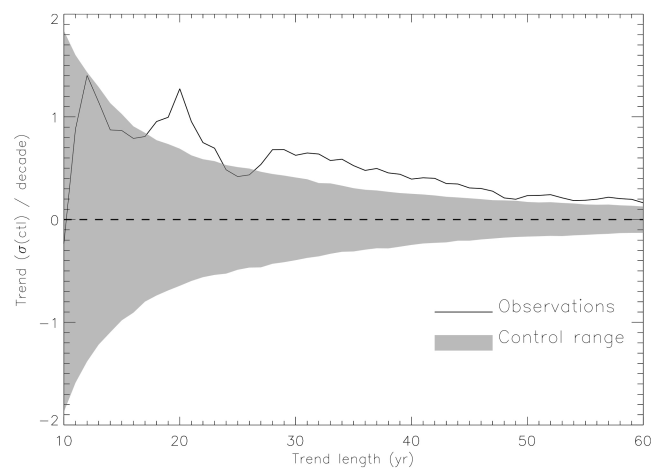


Figure 1. A comparison of the trend in the observed December-February EOF-based NAO index with the corresponding trend in HadCM2 control. The solid line shows the observed trend as a function of the length of time over which it is measured, always ending in 1997. The grey band shows the 5%–95% range of trends in 1091 years of HadCM2 control. Adapted from *Gillett et al.* [2000].

(Gillett *et al.* 2003)

Stratospheric mechanisms

- Shindell *et al.* (2006) found that a 9-level model with a 10 hPa upper boundary showed no NAO response to a GG increase.
- However, a second model with 23 levels and an upper boundary at 0.002 hPa showed an increase in the NAO index of an amplitude similar to that observed.
- Stratospheric mechanisms were then considered, though other models without a well-resolved stratosphere have since also been found to produce a similar response (Shindell *et al*. 2006, Gillett 2003).

Trends and natural variability

- Several studies have shown this trend to be inconsistent with simulated natural variability.
- Most climate models simulate some increase in the winter NAO index in response to increasing concentrations of greenhouse gases, though the modeled changes are generally smaller than those seen in the real atmosphere.

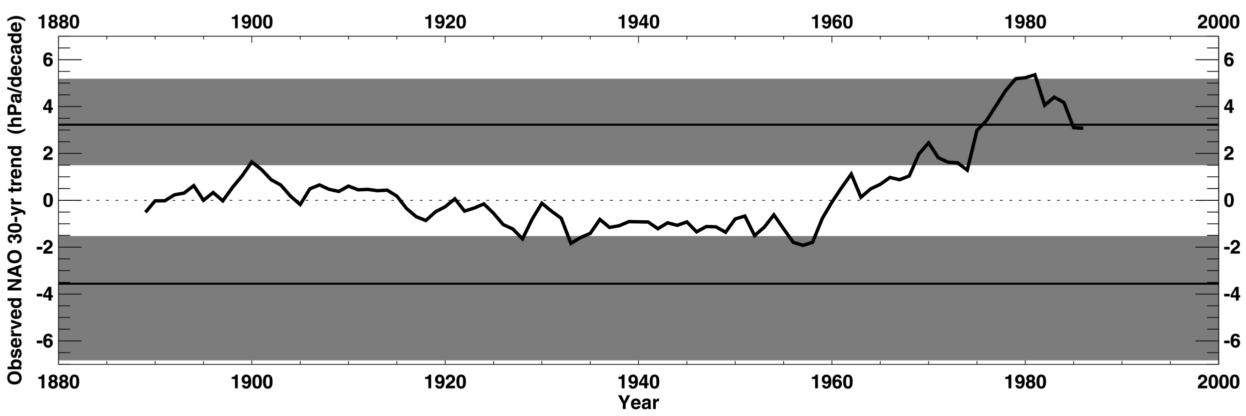


Figure 2. 30-year trend (black line, expressed as hPa/decade) in the observed EOF-based NAO index, computed in a sliding window and plotted against the central year of the window. Grey shading shows the ranges of 2.5 and 97.5 percentiles of 30-year trends computed during seven multi-century control simulations, with the solid horizontal lines indicating the mean 2.5 and 97.5 percentiles computed across the seven models.

(Gillett *et al.* 2003)

BW NAO index and surface temperature

Strong positive correlation between the winter NAO index and the average NH extratropical winter temperature.

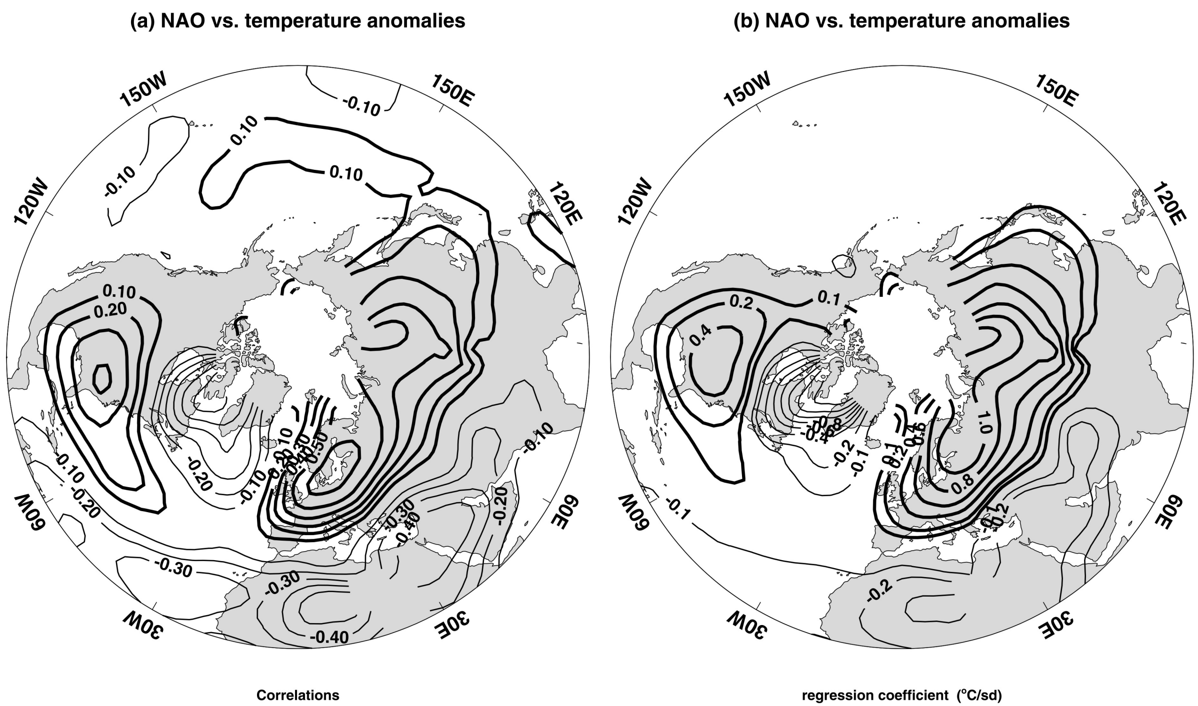


Figure 3. Correlation (a) and regression coefficient (b) of near surface air temperature on the NAO index.

(Gillett *et al.* 2003)

NAO response to forcing changes

Table 1. North Atlantic Oscillation index response to greenhouse gas increases in several general circulation models. Upward arrows indicate an increase in the NAO index, corresponding to a decrease in Arctic SLP, in response to increasing greenhouse gas concentrations (and changes in sulphate aerosol in the case of the CCCma model). A '.' indicates either no significant change, or that the sign of the change has been shown to be dependent on the definition of the NAO index. Note that authors use various different EOF and station-based measures of the NAO, and vary in the rigor of their estimates of the significance of the trend. Adapted from *Gillett et al.* [2002a].

Model	NAO response	Source	Model description
HadCM2	.	1, 2, 3, 4, 12	14
HadCM3	↑	4,12	15
ECHAM3	↑	4, 5	16
ECHAM4	↑	2, 4, 6, 7, 12	6
CCCma	↑	8,12	17
GISS-S	↑	4, 9, 10	18
GISS-T	.	9, 10	9
CSIRO	↑	11,12	19
CCSR	↑	11,12	20
NCAR-CSM	.	7, 12	21
NCAR-PCM	↑	12	22
GFDL	↑	13	23

Sources: 1, *Gillett et al.* [2000]; 2, *Zorita and González-Rouco* [2000]; 3, *Osborn et al.* [1999]; 4, *Gillett et al.* [2002a]; 5, *Paeth et al.* [1999]; 6, *Ulbrich and Christoph* [1999]; 7, *Robertson* [2001]; 8, *Fyfe et al.* [1999]; 9, *Shindell et al.* [1999a]; 10, *Shindell et al.* [2001b]; 11, E. Zorita (pers. comm.); 12, *Osborn* [2002]; 13, *Stone et al.* [2001]; 14, *Johns et al.* [1997]; 15, *Gordon et al.* [2000]; 16, *Voss et al.* [1998]; 17, *Flato et al.* [2000]; 18, *Shindell et al.* [1998]; 19, *Gordon and O'Farrell* [1997]; 20, *Emori et al.* [1999]; 21, *Boville and Gent* [1998]; 22, *Washington et al.* [2000]; 23, *Stouffer and Manabe* [1999]. GISS-S denotes the 23 level GISS model with a model top at 0.002 hPa, and GISS-T the 9 level GISS model with a model top at 10 hPa.

(Gillett *et al.* 2003)

Observations vs. simulations

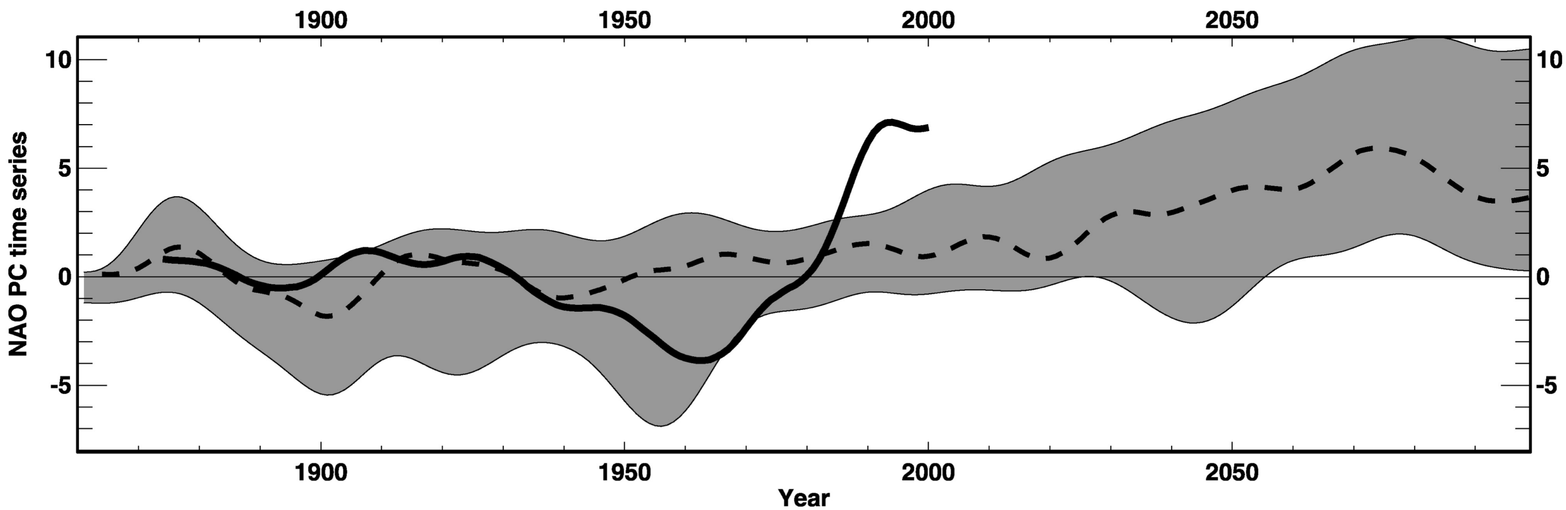


Figure 6. The observed NAO index (solid line) and the average (dashed line) of the NAO indices from seven climate model simulations under increasing greenhouse gas forcing (1% per annum compounded increase in [CO_2] after 1990), together with an envelope containing the individual model simulations (grey shading). All series have been smoothed with a 30-year low-pass filter. The NAO index is the scaled principal component time series associated with each model's leading EOF of the Atlantic-sector SLP field (defined during the control run of each model).

(Gillett *et al.* 2003)

Natural forcings

- Natural forcings may have also had an impact on the atmospheric circulation: volcanic aerosols induce the westerly (positive index) phase of the NAO in the 1–2 years following major eruptions.

- Multi-decadal changes in the NAO have also in part been attributed to changes in solar irradiance.

- Experiments using climate models forced only with changes in tropical sea surface temperatures suggest that at least part of this trend may be due to remote forcing from the tropics.

- Natural forcings are unlikely to account for a substantial component of the recently observed positive NAO index trend.

Natural forcings

- Hoerling *et al.* (2001) argued that the upward trend in the boreal winter NAO index is linked to a warming of tropical SSTs, particularly over the Indian and Pacific oceans.

- By prescribing observed SSTs since 1950 over the tropics, and fixed seasonally varying climatological SSTs elsewhere, they were able to explain roughly half the magnitude of observed mid-tropospheric height trends in the Northern Hemisphere.

- This was similar to the trend explained when global observed SSTs were specified.

Prescribed SSTs

- Prescribed SSTs in a model closely constrain the temperature of the whole tropospheric column, thus it may be that warming tropical SSTs are just a reflection of greenhouse gas forcing in the atmosphere, and it is this atmospheric change that is more directly responsible for the upward trend in the NAO index.

- These results do, however, suggest that greenhouse gas forcing could modulate the NAO merely through changes in the tropical circulation. (Gillett *et al.* 2003)

Anthropogenic forcing

- Increasing greenhouse gas concentrations are most probably responsible for anomalous increase (Gillett *et al.* 2003).

- Some authors have argued that greenhouse gas-induced changes in the meridional temperature gradient in the lower stratosphere may be responsible for the upward NAO index trend, but over-all the mechanism of response to greenhouse gases remains open to debate.

- Sulphate aerosol and stratospheric ozone depletion are generally found to have little significant effect on the NAO (Gillett *et al.* 2003).

Anthropogenic forcing

- Stenchikov *et al.* (2002) suggested that aerosol stratospheric warming in the tropical lower stratosphere is not the dominant NAO-forcing mechanism. Stratospheric aerosols can also induce tropospheric cooling, which is strongest in low latitudes especially in winter.

- This could then influence the NAO directly through a tropospheric mechanism, or via the stratosphere through a reduction in the tropospheric meridional temperature gradient.

- This may lead to a decrease of the mean zonal energy and amplitudes of planetary waves in the troposphere.

- The corresponding decrease in wave driving in the lower stratosphere may then cause a strengthening of the polar vortex.

Model comparisons

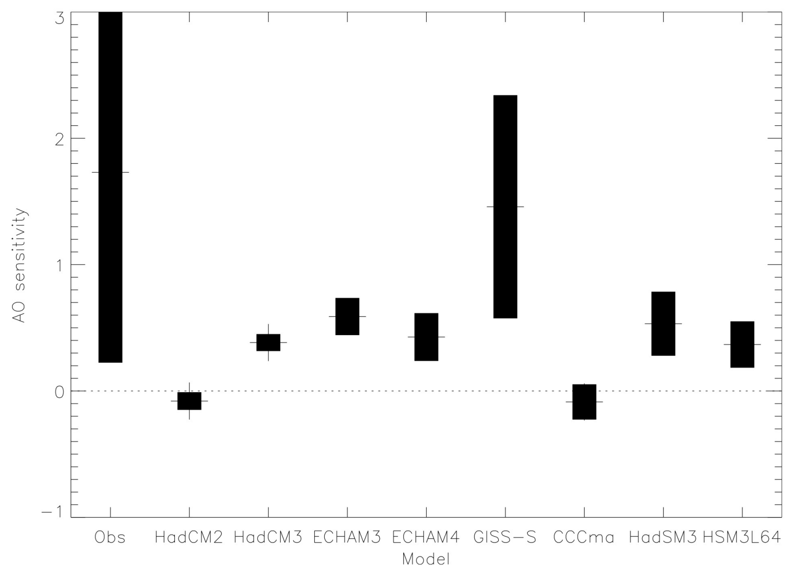


Figure 7. The mean sensitivity of a hemispheric EOF-based NAO index to net radiative forcing at the tropopause due to greenhouse gases in eight GCMs and observations. Black bars show 5-95% uncertainty ranges estimated using control variability. Adapted from *Gillett et al*. [2002a].

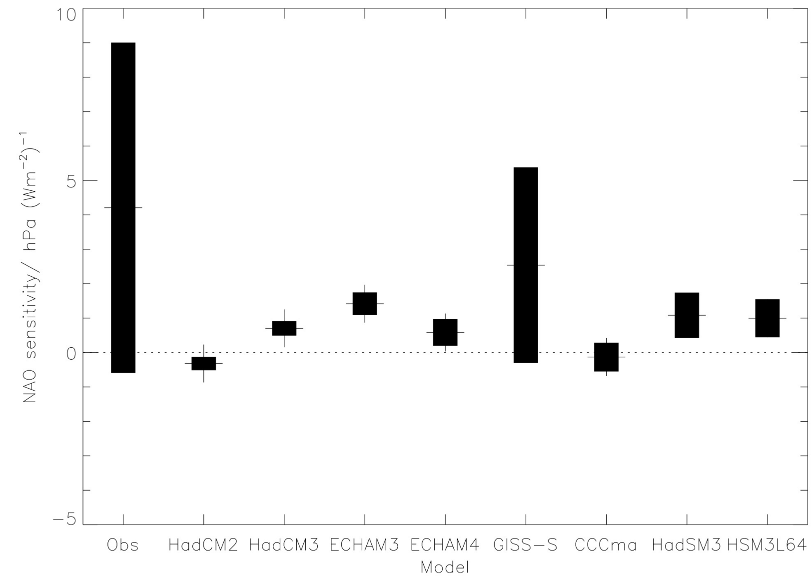


Figure 8. The mean sensitivity of a station-based NAO index to net radiative forcing at the tropopause due to greenhouse gases in eight GCMs and observations. Adapted from *Gillett et al.* [2002a].

(Gillett *et al.* 2003)

Conclusions

- The NAO boreal winter (BW) index has exhibited an upward trend over recent decades, corresponding to decreased surface pressure over the Arctic and increased surface pressure over the subtropical North Atlantic (Gillett *et al.* 2003).

- While the dominant effect of ↑ GG concentrations is tropospheric warming and stratospheric cooling (Cubasch *et al.* 2001), the exact influence on the NAO is still uncertain.

- Understanding the relationship between climate change and the NAO is necessary to make accurate climate predictions (Gillett *et al.* 2003).

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