jet stream during cold European winter of 2005/6 (250HPa dyn. height)

frequent blocks over central Europe from late Dec to Mar

note apparent precursors possibly as far upwind as the Gulf of Alaska
Atlantic multidecadal variability and sea-surface height: observations and atmospheric connections.

Sirpa Häkkinen\textsuperscript{1}, Peter B. Rhines\textsuperscript{2} with Denise L. Worthen\textsuperscript{1}

(1) NASA Goddard Space Flight Center, Code 614.1, Greenbelt, MD 20771
(2) University of Washington, Seattle, PO Box 357940, WA 98195
Climatic episodes of warm, saline northern Atlantic Ocean occur at decadal to century timescales. They co-vary with

- weak subpolar ocean gyre,
- warm subpolar steric height anomaly
- increased advection of warm subtropical waters north to the subpolar gyre (strengthened AMOC merid heat transport)
- weak windstress-curl over the SP gyre

and

- extreme, breaking jet-stream meanders overhead => Atlantic blocking anticyclones (*Hakkinen & Rhines, Science 2011*)
- positive feedback of warm oceanic SST on the atmospheric circulation (*Croci-Maspoli & Davies MWR 2009*)
Atlantic SST (sea-surface temperature) and salinity: extreme warming in late 1990s – 2000s

Holliday et al
GRL 2008
AMO/AMV index and spatial SST field based on Atlantic SST ‘north of Equator’, regressed on global SST; similar to 1st rotated EOF of N Atlantic SST

*Enfield GRL 2001*
AMO/AMV index and spatial SST field based on Atlantic SST ‘north of Equator’, regressed on global SST; similar to 1st rotated EOF of N Atlantic SST  

*Enfield GRL 2001*
**Fig. 3. Climate indices.** Annual averages of: the Atlantic Multi-decadal Oscillation (AMO) (Enfield et al., 2001), the SST west of the British Isles (Rayner et al., 2006) (see text), the inverted gyre index (GI) (Hátún et al., 2005b) and the North Atlantic Oscillation (NAO, inverted) (http://www.cdc.noaa.gov) are shown. The Central England Temperature (CET) (Parker and Horton, 2005) during the spring months March and April has been plotted over the SST series. The CET is low-pass filtered using an 8-year filter width. The two temperature time series (black) are to scale, the others are not.

**Hátún et al.** Prog. in Oceanography 2009 connects these time series with ecosystem shifts, fisheries
Focus on the subpolar N Atlantic: water-column heat content EOF 1 (NODC WOA data)
SEA SURFACE HEIGHT FROM ALTIMETRY

SSH EOF1 17.5%

DATA FROM NASA MEASURES PROJECT; PROVIDED BY BRIAN BECKLEY SAIC/GSFC to 03/2011

SSH INCREASE OF ~ 13cm IN THE IRMINGER SEA

dual role of altimetry: surface geostrophic circulation and ocean water column heat content

The subpolar cyclonic gyre weakened and warmed steadily
SSH INCREASE OF ~ 13cm IN THEIRMINGER SEA

SSH PC1

The subpolar cyclonic gyre weakened and warmed steadily

SSH EOF1 17.5%

dual role of altimetry: surface geostrophic circulation and ocean water column heat content

DATA FROM NASA MEASURES PROJECT; PROVIDED BY BRIAN BECKLEY SAIC/ GSFC to 03/2011
Europe freezes in cold winter weather
More than 120 deaths linked to temperatures as low as -32.5°C, while 11,000 villagers are trapped by snow in Serbian mountains

Peter Walker
guardian.co.uk, Thursday 2 February 2012 16.23 EST

Goran Milat, one of those residents cut off, said: "We are thankful for this help. But the snow did what it did and we are blocked here until spring."
jet stream during cold European winter of 2005/6 (250HPa dyn. height)
frequent blocks over central Europe from late Dec to Mar
note apparent precursors possibly as far upwind
В on PV-2 surface (tropopause): reversals are breaking Rossby waves on the jet stream, at the synoptic scale: connected with both orographic (Rocky Mts) and ‘thermographic’ (warm Atlantic heat content) forcing.

Note the wavetrain upwind (west) of the block

*Hoskins & Tyrliss JGR 2008* cluster plots showing east-west locations of blocking

θ on PV-2 surface (tropopause): reversals are breaking Rossby waves on the jet stream, at the synoptic scale: connected with both orographic (Rocky Mts) and ‘thermographic’ (warm Atlantic heat content) forcing.
Winter 2005/6 NAO index

PV anomaly

EU temperature

cold episodes

blocking events

_Croci-Maspoli & Davies_  
_Mon Wea Rev 2009_

study of cold EU winter of 2005/6

**FIG. 5.** The bottom curve represents the temporal evolution of the winters 2005/06 daily 2-m temperature (5-day running mean) over central Europe. Light (dark) gray shading indicates negative (positive) anomalies in respect to the ERA-40 climatology. Dashed contours represent ±1 standard deviation of the daily climatological mean. The middle thick black line indicates the mean VAPV distribution over the northern European region, and the top thick black line indicates the daily NAO index with arbitrary scaling. The five horizontal bars at the bottom signify the duration of the major blocking events in the Euro-Atlantic region.
Winter blocking days (NDJF) from Compo et al. *QJRMS* 2011

20th C reanalysis (blue) and NCEP reanalysis (red)

Based on 500hPa index of extreme jet stream meanders

(*Tibaldi & Molteni* Tellus 1990)
Winter blocking days (NDJF) from Compo et al. *QJRMS* 2011
20th C reanalysis (blue) and NCEP reanalysis (red)

Based on 500hPa index of extreme jet stream meanders
(*Tibaldi & Molteni* Tellus 1990)

One way to make long-period atmospheric variability is to involve the ocean.
Conclusion I: Atlantic wintertime blocking comes in clusters, which vary over interannual-to-multidecadal timescale.
AMV northern Atlantic SST index and Atlantic Blocking
AMV northern Atlantic SST index and Atlantic Blocking

AMO (AMV) index
index detrended

No. of blocking days

Temperature anomaly (°C)

1920 1940 1960 1980 2000
AMV northern Atlantic SST index and Atlantic Blocking

AMO (AMV) index
index detrended
Atlantic blocking index (black)
Winter blocking days (NDJF) from Compo et al. *QJRMS* 2011
20th C reanalysis (blue) and NCEP reanalysis (red)

Based on 500hPa index of extreme jet stream meanders
(*Tibaldi & Molteni* *Tellus* 1990)
Conclusion II: at 10 – 50 year timescale of AMV, blocking corresponds with a warm subpolar Atlantic ocean

(ironically causing cold central Europe winters)
Atmospheric forcing variability involves both east/west and north/south structure. Blocking, AMV, wind-stress curl and air/sea buoyancy flux all show subpolar centers of action west of England.
DJFM WIND STRESS CURL VARIABILITY

EOF1 (24%) and EOF2 (16%)

NAO-like ‘intergyre’ EOF 1

‘Gyre Mode’, EOF 2

PC1 (BLACK) and PC2 (RED)

NAO Index (Dec-Mar) 1864-2010

NAO
AVERAGE BLOCKING DAYS per winter, base on Scherrer et al, modified from Molteni & Tibaldi, 1990
(reversal of 500hPa gradient and requiring persistence of at least 5 days in sector 45N-70N, 80W-30E)

From the 20th century
Reanalysis by Compo et al. (2011) European sector blocks are most frequent; Greenland (NAO type) blocks often follow EU blocks
BLOCKING COVARIATES WITH AMO/AMV SST

blocking days per winter (DJFM) regressed on AMO/AMV time series

1939-1968 warm yrs minus 1900-1929 cold yrs
ATMOSPHERIC BLOCKING COVARIATES WITH WIND-STRESS CURL
(blocking days based on negative minus positive wind curl time series)

PC1 (top) and PC2 (bottom)

NAO-like PC1
Greenland blocks

GYRE PC2
MODE
European blocks

60% of European blocks are followed by Greenland blocks: Woollings et al JAS 2008
AIR-SEA HEAT FLUX COMPOSITE CORRESPONDING to CURL PC2 (based on negative minus positive wind curl time series; positive curl => upward heat flux)
Conclusion III: the two principal EOFs of wind-stress-curl correlate with winter blocking frequency, separately Greenland (NAO-like) and European (gyre-mode) blocks.

Air-sea heat flux is also well correlated with EOF-2, the ‘gyre mode’.

Severe blocking winters are less well correlated with NAO.
What is the relation between AMO/AMV and AMOC?
What is the relation between AMO/AMV and AMOC?

Surface drifter tracks passing from subtropical gyre warm water north to subpolar gyre (Rockall Trough). SST in color:

Sparse yet mostly between 1996 and 2005

(Hakkinen & Rhines JGR 2009)
What is the relation between AMO/AMV and AMOC?

surface drifter tracks passing from subtropical gyre warm water north to subpolar gyre (Rockall Trough).
SST in color:
Sparse yet mostly between 1996 and 2005

(Hakkinen & Rhines JGR 2009)
Warm AMOC branch:
Poleward salinity transport at 55-60N  \((\text{Hakkinen} & \text{Rhines JGR 2011})\)
from SODA reanalysis  \(0.25^\circ \times 0.4^\circ \times 40\) levels 1958-2007
\((\text{Carton} \& \text{Giese, MWR 2008})\)
Despite the diverse model results, the connection between AMV and AMOC seems to exist in the recent dramatic warming of the subpolar Atlantic: the warm branch of AMOC (northward flowing warm, saline waters from subtropics to subpolar latitudes) has occurred (Hakkinen & Rhines, JGR 2011).
RAPID AMOC (Sv.) at 26.5N with Ekman/GS related 2010 event
RAPID AMOC (Sv.) at 26.5N with Ekman/GS related 2010 event
Eastward wind-stress anomaly: Nov 2009 to Feb 2012
(large dip in Ekman contribution to AMOC at 26.5N in Dec 2010, Feb 2010)
SSH INCREASE OF ~ 13cm IN THE IRMINGER SEA

dual role of altimetry: surface geostrophic circulation and ocean water column heat content
Blocking frequency (days per winter) .. NCEP data

Historic low 1996 NAO
Blocking frequency (days per winter) .. NCEP data
Conclusion I: Clusters of Atlantic wintertime blocking vary over 10-50 year (multi-decadal) timescale

Conclusion II: at 10 – 50 year timescale, warm Atlantic ocean corresponds to increased blocking episodes, weak subpolar gyre circulation (and, ironically, cold central Europe winters)

Conclusion III: the two principal EOFs of wind-stress-curl correlate with winter blocking frequency, separately Greenland and European blocks. These EOFs and other combinations of EOFs better describe the east-west phase of blocking than does the simple NAO….see Hurrell & Deser, J.Marine Sys 2009, Woollings, Hannachi & Hoskins, QJRoyal Met Soc 2010: NAO + EA

Conclusion IV: the warm, northward flowing branch of AMOC meridional circulation has been active in creating the most recent AMV warm period in the subpolar Atlantic: Hakkinen & Rhines JGR 2009, 2011. Extreme atmospheric blocking events occurred in the late 2000s, corresponding to sudden lurches of AMOC$_{26.5N}$. 
Conclusion I: Clusters of Atlantic wintertime blocking vary over 10-50 year (multi-decadal) timescale

Conclusion II: at 10 – 50 year timescale, warm Atlantic ocean corresponds to increased blocking episodes, weak subpolar gyre circulation (and, ironically, cold central Europe winters)

Conclusion III: the two principal EOFs of wind-stress-curl correlate with winter blocking frequency, separately Greenland and European blocks. These EOFs and other combinations of EOFs better describe the east-west phase of blocking than does the simple NAO….see Hurrell & Deser, J.Marine Sys 2009, Woollings, Hannachi & Hoskins, QJRoyal Met Soc 2010: NAO + EA

Conclusion IV: the warm, northward flowing branch of AMOC meridional circulation has been active in creating the most recent AMV warm period in the subpolar Atlantic: Hakkinen & Rhines JGR 2009, 2011. Extreme atmospheric blocking events occurred in the late 2000s, corresponding to sudden lurches of AMOC$_{26.5N}$. 
Conclusion I: Clusters of Atlantic wintertime blocking vary over 10-50 year (multi-decadal) timescale

Conclusion II: at 10 – 50 year timescale, warm Atlantic ocean corresponds to increased blocking episodes, weak subpolar gyre circulation (and, ironically, cold central Europe winters)

Conclusion III: the two principal EOFs of wind-stress-curl correlate with winter blocking frequency, separately Greenland and European blocks. These EOFs and other combinations of EOFs better describe the east-west phase of blocking than does the simple NAO….see Hurrell & Deser, J.Marine Sys 2009, Woollings, Hannachi & Hoskins, QJRoyal Met Soc 2010: NAO + EA

Conclusion IV: the warm, northward flowing branch of AMOC meridional circulation has been active in creating the most recent AMV warm period in the subpolar Atlantic: Hakkinen & Rhines JGR 2009, 2011. Extreme atmospheric blocking events occurred in the late 2000s, corresponding to sudden lurches of AMOC$_{26.5N}$
Conclusion I: Clusters of Atlantic wintertime blocking vary over 10-50 year (multi-decadal) timescale

Conclusion II: at 10 – 50 year timescale, warm Atlantic ocean corresponds to increased blocking episodes, weak subpolar gyre circulation (and, ironically, cold central Europe winters)

Conclusion III: the two principal EOFs of wind-stress-curl correlate with winter blocking frequency, separately Greenland and European blocks. These EOFs and other combinations of EOFs better describe the east-west phase of blocking than does the simple NAO….see Hurrell & Deser, J.Marine Sys 2009, Woollings, Hannachi & Hoskins, QJRoyal Met Soc 2010: NAO + EA

Conclusion IV: the warm, northward flowing branch of AMOC meridional circulation has been active in creating the most recent AMV warm period in the subpolar Atlantic: Hakkinen & Rhines JGR 2009, 2011. Extreme atmospheric blocking events occurred in the late 2000s, corresponding to sudden lurches of AMOC_{26.5N}.
The End

2005/6 winter

Z250 dyn height (contours);
Z850 temperature (colors)
SUPPLEMENTAL MATERIAL!
Eastward winter wind-stress averaged over N Atlantic vs. latitude:
dips in 2009, strengthens in 2010, 2011
Figure 2. Trajectories of the 71 floats used in this study, during July 1997–December 2002. Bold dots indicate the deployment position for each float. Different colors are assigned to each float. Trajectory and deployment position for each float have the same color.
ERA40 atlas:

diagnosed heating of the lower atmosphere (DJF) heating integrated 700hPa to the ground

largely due to warm ocean
Winter 2005/6 NAO index
PV anomaly
EU temperature
cold episodes
blocking events

Croci-Maspoli & Davies
Mon Wea Rev 2009
study of cold EU winter of 2005/6
Ocean SST forcing of atmospheric blocks
Intensification of blocking anticyclonic ridge by upward ocean heat/moisture flux

Atmos. simulation with prescribed air/sea fluxes
Intensification of blocking anticyclonic ridge by upward ocean heat/moisture flux: time evolution of intensity of block (PV minimum)

strong block (control with SST heating, evap)
Intensification of blocking anticyclonic ridge by upward ocean heat/moisture flux: time evolution of intensity of block (PV minimum)

strong block: (control with SST heating, evap)

remove heating
Intensification of blocking anticyclonic ridge by upward ocean heat/moisture flux: time evolution of intensity of block (PV minimum)

strong block: (control with SST heating, evap)

remove heating

remove evaporation
Intensification of blocking anticyclonic ridge by upward ocean heat/moisture flux: time evolution of intensity of block (PV minimum)

strong block: (control with SST heating, evap)

- remove heating
- remove evaporation
- remove both
A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents

Vladimir Petoukhov¹ and Vladimir A. Semenov²,³

change in 250 hPa dyn height due to reduced Barents Sea icecover from 80% to 60%
Anticyclonic breaking => block

Cloud images with 315K PV contours

Fig. 7. Infrared satellite image sequence from blocking formation to the mature blocking stage at 1200 UTC 23 Dec 2005–26 Dec 2005. Superimposed are PV contours at 315 K with the 2-PVU isoline in boldface (from 1 to 8 PVU with 1-PVU spacing). Note the cloud band on the upstream side of the block during formation.
Adding east/west centers of variability to NAO
Beyond NAO: accounting for east-west shifts
East Atlantic pattern + NAO
500 HPa dyn. height

Figure 10. Summary of the circulation at different locations in NAO/EA space. The horizontal axis of the grid of plots is the NAO and the vertical axis is the EA. Z500 anomalies are contoured every 20 m per standard deviation of the principal component time series, and 300 hPa zonal wind is shaded every 10 m s$^{-1}$ starting at 20 m s$^{-1}$. The corner plots are given by adding the respective NAO and EA maps and scaling by $1/\sqrt{2}$. 

Woollings, Hannachi & Hoskins
QJRMS 2010
4 SLP Weather Regimes for NCEP (DJFM 1950-2006)

Deser & Hurrell
J. Marine Sys 2010
10 year averages; VARIABILITY OF BLOCKING FREQUENCY BY DECADE CALCULATED FROM THE 20TH CENTURY REANALYSIS BY COMPO ET AL (2011)
5-year averages; PENTADAL BLOCKING VARIABILITY BASED ON NCEP REANALYSIS
Greenland blocks ~ the negative phase NAO-, (anticyclone over Greenland, warm moist air flowing into Labrador Sea, cold EU)

Woollings et al. *QJRMS* 2010: High-latitude jet has three preferred latitudes, and NAO- is the ‘southern jet’ case: then the high- and low-latitude jet streams merge into one in the 0-60°W sector
This winter, the migration of blocking westward...
18 Jan 2012  Z250, during the current EU block/cold & snow wind speed: note the spiral maximum reaching low latitude over Africa
climatology of the same plot from ERA40 atlas Dec-Feb Z250 & windspeed
Following the longitude of blocking: anticyclonic Rossby wave meanders & breaking

*Hoskins & Tyrliss JGR 2008*

cluster plots in various sectors
\( \theta \) on PV-2 surface (tropopause)

connections with both orographic (Rocky Mts) and ‘thermographic’ (warm Atlantic heat content) forcing. Note the wavetrain upwind of the block.
Fig. 1. Schematic illustration of four types of wave breaking showing the deformation of a representative $\theta$ contour on the dynamical tropopause during wave breaking. The two upper schematics show the evolution of (a) an equatorward extrusion of low-$\theta$ air and (b) a poleward extrusion of high-$\theta$ air within a zone of background anticyclonic wind shear. The two lower schematics show the evolution of (c) an equatorward extrusion of low-$\theta$ air and (d) a poleward extrusion of high-$\theta$ air within a zone of background cyclonic wind shear. The arrow marks the position of the midlatitude jet. The initial stages of each development, in which the wave-breaking nature is different in LC1 and P1, correspond to the left-hand side of each figure. The schematics and the notation for LC1 and LC2 are taken from Thornicroft et al. (1993), and those for P1 and P2 from Peters and Waugh (1996).
Why does blocking persist?

Stern (*J Marine Res* 75) modon resists Rossby wave radiation which will tear apart (disperse a single low or high pressure vortex. Potential vorticity has isolated extrema, with PV linearly related to streamfunction.

And... it alters the westward propagation speed. With the anticyclone north of the cyclone, the dipole can propagate westward relative to the mean flow, hence standing still.
Blocking ideas:

Orographic stationary waves ... mountains
‘Thermographic’ stationary waves...l warm ocean forcing

Natural tendency for large amplitude waves to slow their phase propagation

Slower westerlies => shorter Rossby wavelength for stat. waves.
   topog drag slows westerlies, shrinking length scale and blocks move from EU
to Greenland

Orographic vorticity (lee cyclones) remains strong with weak westerlies...causing
more dramatic jet stream meanders for relatively weak jet streams.

‘Billiard ball effect’: downstream development, group velocity ~ 50° longitude per day
of individual systems (Chang & Orlanski)
The billiard ball effect: downstream development of storms in the 300 hPa waveguide (20° wide) Chang, Lee & Swanson J Clim 2002. Often, synoptic systems originating in western Pacific lead to chains of systems reaching across N America to Europe.
Higher resolution models often behave differently.
WATER MASSES AT 55-60N (SODA)
SODA Model details: $0.25^0 \times 0.4^0 \times 40$ levels 1958-2007
(Carton & Giese, MWR 2008)

INTEGRATED SALT TRANSPORT

TRANSPORT AT 55N OF WATERS WITH $S > 35.3$ (red), $> 35.4$ (blue), $> 35.5$ (purple)

Monthly data
Drifters are present in the Gulf Stream box in the given time period but tracks leaving the box could be in the next time period.
Summer 2010 heat wave in Russia: blocking related
(NOAA dismisses immediate connection with global warming)

The heat wave was concentrated in western Russia – Siberia experienced much cooler than normal temperatures. The following figure shows temperature anomalies for July 20-27 relative to the average for the same dates 2000-2008 [http://earthobservatory.nasa.gov/OTD/view.php?id=45069]


“The heat wave was due primarily to a natural phenomenon called an atmospheric “blocking pattern”, in which a strong high pressure system developed and remained stationary over western Russian, keeping summer storms and cool air from sweeping through the region and leading to the extreme hot and dry conditions. While the blocking pattern associated with the 2010 event was unusually intense and persistent, its major features were similar to atmospheric patterns associated with prior extreme heat wave events in the region since 1880, the researchers found.”
Spain
Early 20th C warming: Cod 1930s in Greenland

Harry van Loon and Danish weather stations (Godthab/Huuk)
Ocean Effects of Blocking

Tim Woollings

Normal Conditions

Blocking

Atmospheric Blocking and Atlantic Multidecadal Ocean Variability

Sirpa Häkkinen, Peter B. Rhines, Denise L. Worthen

Atmospheric blocking over the northern North Atlantic, which involves isolation of large regions of air from the westerly circulation for 5 days or more, influences fundamentally the ocean circulation and upper ocean properties by affecting wind patterns. Winters with clusters of more frequent blocking between Greenland and western Europe correspond to a warmer, more saline subpolar ocean. The correspondence between blocked westerly winds and warm ocean holds in recent decadal episodes (especially 1996 to 2010). It also describes much longer time scale Atlantic multidecadal ocean variability (AMV), including the extreme pre-greenhouse-gas northern warming of the 1930s to 1960s. The space-time structure of the wind forcing associated with a blocked regime leads to weaker ocean gyres and weaker heat exchange, both of which contribute to the warm phase of AMV.
Figure 1. Extended annual mean SAT record for the Atlantic-Arctic boundary region ($T_{NA}$). 95\% confidence limits are shown. Decadal-scale variations are emphasized with a 2-way Butterworth low-pass filter constructed to remove frequencies higher than 0.1 cycles year$^{-1}$ (bold black line). The early 20th century warming (ETCW) episode is marked. Regions represented by station-based composite SAT records used in $T_{NA}$ are indicated in the map.
Figure 1. Extended annual mean SAT record for the Atlantic-Arctic boundary region ($T_{NA}$). 95% confidence limits are shown. Decadal-scale variations are emphasized with a 2-way Butterworth low-pass filter constructed to remove frequencies higher than 0.1 cycles year$^{-1}$ (bold black line). The early 20th century warming (ETCW) episode is marked. Regions represented by station-based composite SAT records used in $T_{NA}$ are indicated in the map.

Figure 2. Concurrent variations in multiple climate records. (a) $T_{NA}$. (b) Mean $\delta^{18}$O. (c) $SST_0'$. (d) Teigarhorn SST'. (e) Mean sea ice index (inverted). (f) Koch (Iceland) sea ice index [Wallevik and Sigurjónsson, 1998]. A low-pass filter was applied as in Figure 1 (bold black lines). Notable deflections are marked with dashed gray lines. The
How good is the early 20\textsuperscript{th} C reconstruction of 500 hPa height? 
\textbf{Red} dots: 1905-1938 ;  \textbf{blue} dots: 1950-present   
Kite, aircraft, pilot balloon upper air obs vs. Compo \textit{et al.} reanalysis  
(which uses only SLP and ocean SST obs)
Tropical ocean/atmosphere interaction is well established

Nward shift of Atl ICTZ => more Sahel P,
Fig. 1. Schematic illustration of four types of wave breaking showing the deformation of a representative $\theta$ contour on the dynamical tropopause during wave breaking. The two upper schematics show the evolution of (a) an equatorward extrusion of low-$\theta$ air and (b) a poleward extrusion of high-$\theta$ air within a zone of background anticyclonic wind shear. The two lower schematics show the evolution of (c) an equatorward extrusion of low-$\theta$ air and (d) a poleward extrusion of high-$\theta$ air within a zone of background cyclonic wind shear. The arrow marks the position of the midlatitude jet. The initial stages of each development, in which the wave-breaking nature is different in LC1 and P1, correspond to the left-hand side of each figure. The schematics and the notation for LC1 and LC2 are taken from Thornicroft et al. (1993), and those for P1 and P2 from Peters and Waugh (1996).
SST EOFs 1 and 2; PC 1 and 2
Hadley Ctr SST

![Graphs and maps showing SST EOFs and PC 1 and 2 for Hadley Ctr SST.](image-url)
EOF 1 and 2; PC 1 and 2 for ocean water column heat content. (NODC WOA)

EOF 1 trend like warming

EOF 2 AMV like recent warming
ATLANTIC MULTIDEcadal Variability

Linear trend and detrended SST

Ting et al 2009

locally, south of Iceland: Reverdin 2010
Short-term weather events may drive ocean variability on time scales of several decades.

Atmospheric blocking over the northern North Atlantic, which involves isolation of large regions of air from the westerly circulation for 5 days or more, influences fundamentally the ocean circulation and upper ocean properties by affecting wind patterns. Winters with clusters of more frequent blocking between Greenland and western Europe correspond to a warmer, more saline subpolar ocean. The correspondence between blocked westerly winds and warm ocean holds in recent decadal episodes (especially 1996 to 2010). It also describes much longer time scale Atlantic multidecadal ocean variability (AMV), including the extreme pre-greenhouse-gas northern warming of the 1930s to 1960s. The space-time structure of the wind forcing associated with a blocked regime leads to weaker ocean gyres and weaker heat exchange, both of which contribute to the warm phase of AMV.
The Atlantic storm track is very active, with a persistent low in eastern Canada on the upwind side of the blocking pattern.
COMPOSITE SLP CORRESPONDING NEGATIVE - POSITIVE EXTREMES OF WIND STRESS CURL PC2

Data from the 20th century
Reanalysis by Compo et al. (2011)
100 yr timescale: note 1990s-2000s increase, unlike NAO
together, various BLOCKING COMPOSITES

Gyre mode PC2 wind curl time series

AMO time series

1939-1968 warm yrs minus 1900-1929 cold yrs
The magnitude of seasonal changes in the sea surface height (SSH) exceeds the seasonal magnitude of the steric height (SH).

SH, in its turn, shows a stronger trend (growth) in the recent years ...

Is this something that warns us about horizontal mass redistribution in the North Atlantic associated with changes in circulation and gyre strength?
Surface drifters launched in subtropics which reached subpolar Rockall Trough (temperature in color).
Figure 2. Trajectories of the 71 floats used in this study, during July 1997–December 2002. Bold dots indicate the deployment position for each float. Different colors are assigned to each float. Trajectory and deployment position for each float have the same color.
meridional overturning at 30N tracks SST anomalies (40N-60N)
Higher resolution models often behave differently.
European sector blocking is more common than Greenland (Atlantic sector) blocking (frequency of blocking plotted against longitude).

**But, cold EU winters associate with Atlantic blocks**

Croci-Maspoli et al. J.Clim 2011

Greenland blocks often follow soon after EU blocks (Woollings 2010)

NOAA 500hPa blocking frequency (red: climatol, blue: el Niño)
• adds: wedge of cold subduction
• SPMW formation there
• high EKE/MKE eddy stirring (Azores trit)
• old PV SPG