The influence of the ocean and the stratosphere on climate persistence in the North Atlantic region

Tarjei Breiteig

Dissertation for the degree of Philosophiae Doctor (PhD)
Geophysical Institute, University of Bergen, Norway

July 7. 2009

All that is now
and all that is gone
and all that's to come
and everything under the sun is in tune
but the sun is eclipsed by the moon

Pink Floyd, Eclipse

Acknowledgements

During the course of seven years at Geophysical Institute, I have come across so many people that deserves thanks for helping and inspiring me. First and foremost, I would like to thank my supervisor through more than five years, Nils Gunnar Kvamstø. You have been a great support through my studies – and your optimism and understanding have been essential for this work to be completed. Thanks also to my co-supervisor David B. Stephenson for spending much of your time teaching me statistics – and for hosting me several times in Exeter. Also, thanks to co-supervisor Jürgen Bader for being interested in, and raising critical questions about my work, and to Gudrun Magnusdottir for nice discussions and for hosting me at University of California, Irvine. I would also like to thank Erik Kolstad for including me in your research. Our scientific collaboration during the last year has been very meaningful and interesting. Thanks also for being supportive and helpful in general. I would also like to thank Ivar Seierstad and Justin Wettstein for insightful comments and nice discussions.

Jeg vil også takke Ole Henrik – for uendelige vitenskapelige og ikke-vitenskapelige diskusjoner, for intense kontor-fotballkamper, for vår delte fascinasjon for visse typer kake og for å redde meg fra fysisk forfall. Jeg vil også takke alle andre studenter og ansatte for å være med å lage et flott og sosialt arbeidsmiljø. Jeg er takknemlig til alle mine forelesere, som har latt meg få lære noe så fascinerende som meteorologi. Mine tanker går spesielt til minnet om Elmer Raustein, som var en glimrende foreleser og en flott person.

Jeg vil til slutt takke min kjære Anne, familien min og mine gode venner, for hjelp, støtte og trivselsskaping av mange ulike format.

Tarjei Breiteig
Bergen, 7. July 2009

Abstract

The North Atlantic Oscillation (NAO) is generally regarded to largely be a product of processes internal to the troposphere. This thesis investigates various aspects of how the NAO and related climatical fields are influenced by two of the tropospheric boundary components; the stratosphere above and the ocean below. The thesis consists of five manuscripts, three considering the role of the stratosphere, and two considering the role of the ocean.

Data provided by the NCEP/NCAR re-analyses is used to investigate how anomalies in the stratospheric circulation relate to subsequent anomalies in various important climatic fields. The mean storm tracks are found to shift meridionally, although not symmetrically between the Pacific and the Atlantic regions (paper I). Following events of anomalously weak stratospheric circulation, a statistically significant shift in the storm track is found only over the Atlantic. The spatial temperature distribution is found to go through several spatially and temporally distinct stages (paper II). In key regions, including northern Asia, Europe and the oceanic areas off the east coast of North America, the probability of cold air outbreaks increases by 50 – 80% at various stages relative to the negative stratospheric circulation anomaly peak. The strongest cold air outbreak appears in Northern Asia several weeks before the stratospheric anomaly peaks. This cooling is associated with cold, northwesterly winds due to a strong high pressure anomaly centered above Northern Scandinavia. In a separate study (paper III), it is shown that this high pressure anomaly is a typical precursor of negative stratospheric circulation anomalies. It is found that it is associated with enhanced vertical wave propagation – which is known to favour negative stratospheric circulation anomalies. When the Scandinavian high precedes negative stratospheric circulation anomalies, the stratospheric anomalies become more intense, and stronger subsequent surface climate signals arise compared to events without a preceding Scandinavian high.

The oceanic influence on the NAO is investigated by using both re-analysed and modeled data. The feedback by North Atlantic Sea Surface Temperatures (SSTs) on the NAO is quantified by applying lagged regression models on daily, re-analysed data (paper IV). It is found that interactions between the SSTs and the NAO on daily time scale provide predictive information about the NAO in excess of what is provided by the NAO alone. SSTs along the coast of Northern America, coinciding partly with the Gulf Stream, are especially important, and are in particular found to help account for decadal NAO variability. The Gulf Stream SSTs are found to provide more prediction skill to the NAO than the well-known SST Tripole is able to.

The relation between a continuously weakening Atlantic meridional overturning circulation and interannual variability in the NAO is investigated by using data produced by the Bergen Climate Model (BCM) (paper V). It is found that the NAO develops a pronounced biennial cycle in the phase of a continuously weakening overturning circulation. A corresponding biennial signal is found also in El Niño-Southern Oscillation (ENSO). Although several hypotheses are tested, the exact processes involved in the NAO and ENSO responses are yet to be disclosed.

Contents

1 **Background** 8
1.1 Tropospheric internal variability 9
1.2 The role of the stratosphere 10
1.3 The role of the ocean 11
1.4 Other boundary effects and external processes 12

2 **Aim** 12

3 **Outline** 12
3.1 List of papers 13
3.2 Summary of papers 14

4 **Conclusions and general perspectives** 14

References 21

Manuscripts

1 Background

In principle, the earth's atmosphere constitutes a deterministic system. This means that its future state is fully defined by the initial conditions and the laws of nature. Theoretically, the atmospheric future state is thus deterministically predictable as long as the initial conditions are accurately described. Although small initially, some of the unavoidable uncertainties in the initial state will ultimately grow large enough to considerably affect the future state of the system – and thus introduce a degree of chaos in the system. In practice, deterministic predictability is therefore limited to two or three weeks (Smagorinsky 1969). In addition to an inaccurate description of the initial conditions, inadequate knowledge of how the system evolves further limits our ability to predict its future state.

Even though deterministic predictability is limited, atmospheric variability is found on a wide range of time scales, including monthly, interannual, decadal, centiennial and millennial time scales. The existence of tropospheric variability on time scales exceeding two or three weeks offers a hope that the future state could still be predicted in some way. This can naturally not be done deterministically – but merely through a statistical approach by estimating various statistical properties such as the time mean and variance of specific atmospheric variables.

Much of the atmospheric variability is accounted for by processes internal to the troposphere – which is the lower 10–15 kilometres of the atmosphere. A substantial amount is, however, also provided by processes in tropospheric boundary components that are somehow coupled to the troposphere, and to external processes that is fully de-coupled from the atmospheric system. If these boundary and external components vary more slowly than the troposphere, they may provide a degree of statistical predictability to the tropospheric system. In this thesis, the influence of two major tropospheric boundary components – the ocean and the stratosphere – on the tropospheric variability on time scales ranging from weeks to decades is studied.

1.1 Tropospheric internal variability

Besides the obvious variability associated with seasonal and diurnal variations in solar insolation, the dominating source of variability in the extra-tropical troposphere is baroclinic instability. Baroclinic instability gives rise to relatively small wave-like deviations from the mean flow, also known as baroclinic eddies, or synoptic cyclones and anti-cyclones. The lifetime of baroclinic eddies is about 7–10 days. Deterministic predictability in the extra-tropics is in practice limited to this time scale. However, baroclinic eddies interact with the large-scale mean, background flow. This interaction introduces enhanced persistence to the atmospheric system. Also, without directly involving eddy-mean flow interactions, large-scale waves in the mean flow may propagate slowly in a manner that gives rise to fluctuations slower than those associated with baroclinic eddies. The associated potential predictability on these time scales is confined to the statistical properties of the atmosphere, such as the average value of a given parameter over a given period. As an example, the exact paths of individual synoptic cyclones and associated precipitation distribution cannot be foreseen on long time scales. Rather, the mean cyclone track over some weeks or so could potentially be predicted within some uncertainty range.

The noisy extra-tropical atmospheric variability can, by means of statistical techniques, be represented by modes of variability. This offers a condensed view of the most prominent variability in the system. One widely used technique is the method of Empirical Orthogonal Functions (EOF). Using this method, it is possible to extract modes of variability that are individually independent, and whose variability is represented by a spatial loading pattern and a time-series (the principal components) that describes the temporal evolution of the spatial pattern. By applying this method on daily, monthly or seasonal sea level pressure data in the North Atlantic region, the North Atlantic Oscillation (NAO) pattern represents the largest fraction of the total variability in the region. Depending on the temporal resolution of the data, the NAO represents about 20–40 % of the regional sea level pressure variability. One should keep in mind that this means that 60–80% of the data cannot be explained by the NAO pattern. Furthermore, what is identified as modes by the EOF method, might mereley be statistical modes not reflecting any dynamical processes. Still, the NAO is well documented as a highly dynamical process (see e.g. Vallis and Gerber 2008).

The NAO represents an oscillation between pressure anomalies centred over the Greenland-Iceland region and over a region extending westwards from the Iberian Peninsula. Its prominence allowed it to be introduced as a meridional pressure dipole by Walker already in 1924. It is normally regarded as a winter phenomenon, although it has a strong influence on the summer circulation as well (Folland et al. 2009). The NAO is associated with hemispheric-wide weather and climate anomalies (Thompson and Wallace 2001). The positive phase of the NAO is, by convention, related to lower than normal sea level pressure in the northern North Atlantic region, and higher than normal pressure in a large region extending westwards from the Mediterranean Sea. The positive phase of the NAO is thus associated with strong westerlies in the northern North Atlantic region, yielding mild and wet winters in Northern Europe and deep into the northern Eurasia, dry conditions in Southern Europe and Northwestern Africa and cold conditions in the area around the Labrador Sea, including Greenland. For a comprehensive review of the climatic impacts of the NAO, see Hurrell et al. (2003).

Like the atmosphere in general, the NAO varies on a wide range of time scales. As noted by Vallis and Gerber (2008), NAO variability of less then ten days mainly reflects variability in the storm track. On weekly time scales, much of the NAO variability stems from variations in the stationary wave patterns and their interaction with baroclinic eddies. Still, some variability and persistence in the NAO exist on seasonal, interannual and decadal time scales. Although this variability might primarily reflect tropospheric internal processes, it is believed that some amount, yet to be determined, of the NAO variability on these time scales is provided by slower-varying interactive processes between the troposphere and its boundaries, or by processes strictly external to the troposphere.

1.2 The role of the stratosphere

Some boundary effects are believed to be associated with the stratosphere – the stable lid of air that resides above the troposphere. The troposphere and the stratosphere are separated by the tropopause, an interface of very strong static stability through which rising or sinking air is resisted. In winter, the extra-tropical stratospheric circulation is dominated by strong circumpolar westerly winds. The lower stratosphere represents a region of overlap between this circumpolar flow and tropospheric waves. Interactions at these levels may supply persistence from the stratosphere to the troposphere. Due to its large static stability, the stratosphere acts as a reservoir of potential vorticity. Potential vorticity inversion – which relates upper level potential vorticity anomalies to the wind field at lower levels (see e.g. Holton 2004) – can affect the tropospheric wind field directly (Ambaum and Hoskins 2002; Black 2002). Furthermore, upper-level stratospheric circulation anomalies generated by interaction with large waves of tropospheric origin have been found to feed back on the tropospheric circulation (Baldwin and Dunkerton 1999). The subsequent signal in the troposphere projects onto the Northern Annular Mode (NAM), which is a hemispheric variability pattern closely associated with the NAO. By means of the above processes, the stratosphere represents a source of persistence that may influence the troposphere through interactions across the tropospheric upper boundary.

1.3 The role of the ocean

Due mostly to the large thermal inertia of the ocean, the time scales of oceanic variability are longer than those of the atmosphere. To a large extent, atmospheric processes drive the oceanic variability. The ocean filters out the highest frequencies of variability that act upon it. Thus, when the atmospheric forcing is aggregated over time, only relatively slow oceanic variations are induced. If some kind of feedback from the ocean to the atmosphere takes place, variability of lower frequency than that provided by atmospheric internal processes alone may be introduced to the atmosphere. In fact, the ocean is normally regarded as the primary provider of atmospheric persistence, especially in the tropics where the atmospheric internal variability is less pronounced than in the extra-tropics. Still, the ocean has a great influence on the extra-tropical atmosphere as well. Most prominently, the ocean influences the atmospheric climatology by reducing the seasonal and diurnal temperature variability in coastal regions and areas downstream of mean marine winds. Furthermore, the presence of large oceanic basins next to large continents in the extra-tropics leads to a zonally asymmetric thermal forcing, which may create large meanders in the atmospheric flow (Smagorinsky 1953). Due to interaction between synoptic cyclones and large-scale waves, this asymmetry will also affect the climatological storm track. In addition to a climatological atmospheric response, studies show that sea surface temperature anomalies may also influence atmospheric variability in general, as well as the NAO (see e.g. the review by Kushnir et al. 2002).

1.4 Other boundary effects and external processes

Other boundary effects and external processes may as well influence tropospheric variability on monthly to decadal time scales. These include variability in solar insolation, the sea-ice distribution (Magnusdottir et al. 2004; Kvamstø et al. 2004), volcanic activity (Robock 2000; Christiansen 2008), soil moisture (Koster et al. 2004) and continental snow cover (Cohen and Entekhabi 1999). In the present study, we limit the analyses to the role of the ocean and the stratosphere.

2 Aim

The influence of the stratosphere and the ocean on extra-tropical tropospheric variability beyond the tropospheric internal time scale is not yet completely revealed in the scientific literature. Motivated by this, and by the important role of the NAO in shaping the weather and climate in the North Atlantic region, this thesis specifically aims to answer the following question: How and to what extent do the ocean and the stratosphere influence variability and persistence in the tropospheric climate beyond the baroclinic time scale of about ten days?

In terms of the tropospheric response, the focus will be primarily on the NAO, or when more conveniently, its hemispheric analogue, the NAM. Responses in other important climatical fields, such as surface air temperature, precipitation and storm tracks will also be visited. Although NAO and NAM are defined differently, it is generally acknowledged that they largely describe the same phenomenon. The NAO/NAM explain only parts of the total extra-tropical variability in the Northern Hemisphere, but are still among very few tropospheric phenomena for which some hope of predictability can be tracked in the literature.

3 Outline

A collection of five papers constitutes this thesis, dealing with several aspects of the question that was raised in the previous section. A list of the papers is provided immediately below, followed by a short presentation of their contents. Section 4 provides the principal conclusions of this thesis, together with some general perspectives regarding the main findings. The papers are finally presented in the remainder of the thesis.

3.1 List of papers

Paper 1
Extra-tropical synoptic cyclones and downward propagating anomalies in the Northern Annular Mode[1]
Breiteig, T. (2008)
Geophysical Research Letters (35), L07809

Paper II
The association between stratospheric weak polar vortex events and cold air outbreaks
Kolstad, E. W., Breiteig, T. and Scaife, A. A. (2009)
Submitted to Quarterly Journal of the Royal Meteorological Society

Paper III
Tropospheric precursors of downward propagating anomalies in the Northern Annular Mode
Breiteig, T. (2009)
Submitted to Climate Dynamics

Paper IV
Local interactions between the North Atlantic Ocean and the NAO
Breiteig, T., Stephenson, D. B. and Kvamstø, N. G. (2009)
Manuscript

Paper V
The association between a weakening AMOC and the ENSO and NAO inter-annual variability
Breiteig, T. (2009)
Manuscript

---

[1] Reproduced by permission of American Geophysical Union

3.2 Summary of papers

The first thematical part of the thesis (papers I–III) investigates the association between stratospheric circulation anomalies and the Northern Hemisphere extra-tropical troposphere. Most analyses are applied to data representing the recent 50 years or so. The analyses consider tropospheric processes ranging from baroclinic to seasonal time scales, and thus illuminate the higher-frequency end of the NAO spectrum. In paper I, the association between wintertime stratospheric circulation anomalies and synoptic cyclones in the Northern Hemisphere is investigated. Both the contribution from the cyclones in transmitting circulation anomalies from the stratosphere to the troposphere and their subsequent response to the circulation anomalies are examined. In paper II, it is investigated how cold air outbreaks relate to negative stratospheric circulation anomalies, both in terms of spatial extent and temporal development. In paper III, it is investigated whether the presence of a high-pressure anomaly above Northern Scandinavia might favour negative stratospheric anomalies and a subsequent feedback on the tropospheric climate.

In the second part of the thesis (papers IV–V), the oceanic impact on NAO variability is assessed. While papers I–III consider tropospheric variability on time scales up to seasons, papers IV–V examine the seasonal, interannual and decadal time scales. In paper IV, it is investigated if interactions between the NAO and sea surface temperatures in the North Atlantic Ocean on short time scales can help account for persistence in the NAO on long time scales. The analysis is applied to data representing the last 60 years or so. In paper V, it is examined if a continuous reduction of the oceanic northwards heat transport in the Atlantic Ocean, manifested as the Atlantic Meridional Overturning Circulation (AMOC), might affect the interannual variability of the NAO. The study is motivated by the fact that a continuous cooling trend in the North Atlantic Ocean, associated with the reduction in northwards oceanic heat transport, reduces the oceanic persistence, with a potential subsequent effect also on the atmospheric persistence. The study is performed on data from a general circulation model experiment.

4 Conclusions and general perspectives

As the above presentation of papers indicates, the thesis aims to address the influence through the tropospheric boundaries on the NAO persistence on a range of time scales. Overall, the findings support the view that interactions between the troposphere and both the ocean and the stratosphere add persistence to the NAO.

The main conclusions of this study are:

(i) Anomalies in the stratospheric flow are, in the mean sense, followed by significant tropospheric anomalies in the following weeks. Anomalies in precipitation, temperature, cold air outbreaks and the tracks of synoptic cyclones are found. The response in terms of cold air outbreaks is found to vary substantially throughout the life cycle of stratospheric anomalies. Significant responses in cyclone tracks are confined to the Atlantic region during negative stratospheric circulation events (negative NAO/NAM), while responses are found in both the Atlantic and the Pacific basins during positive events (positive NAO/NAM).

(ii) Besides responding to the stratospheric circulation anomalies, variability in cyclone density is also found to lead tropospheric NAM variability by some days during events of downward propagating stratospheric circulation anomalies. This likely reflects that the cyclones help transmitting circulation anomalies from the lower stratosphere to the troposphere through their interaction with the mean flow. Cyclones in the Atlantic sector are primarily associated with the development of an anomalously strong tropospheric circulation (positive NAM conditions) some days later, while those in the Pacific sector are primarily associated with the development of an anomalously weak tropospheric circulation (negative NAM conditions).

(iii) A persistent high pressure anomaly above the northern Scandinavia favours the development of negative stratospheric circulation anomalies and their downward propagation within the stratosphere. The expectation of subsequent responses in the troposphere – like those described in conclusion (i), and by means of the interaction processes described in conclusion (ii) – yield a potential for weather prediction on weekly to monthly time scales.

(iv) More than in any other area of the North Atlantic Ocean, sea-surface temperature variability along the coast of Northern America, coinciding partly with the Gulf Stream path, and in an area south of Greenland help explain long-term persistence and decadal variability of the NAO.

(v) In a model experiment in which the AMOC was continuously losing strength, the NAO developed periodic, biennial oscillations. In the control integration, no preferred frequency of variability was found. This may suggest that the presence of a stable AMOC and persistent sea surface temperatures in the North Atlantic suppresses interannual NAO variability in the control integration of the model. A biennial signal was also found in the El Niño-Southern Oscillation (ENSO). The results lend support from only one model realization, and model ensembles need to be applied before final conclusions can be made.

The exact importance of the tropospheric boundary components relative to the internal tropospheric variability can still be questioned. It is shown in paper I–III that stratospheric anomalies are associated with significant tropospheric anomalies. Still, it is possible that the stratospheric anomalies are just by-products of internal, persistent tropospheric anomalies, and that what appears to be a downward influence from the stratosphere, simply reflects a slowly propagating tropospheric wave pattern, solely accounted for by tropospheric internal processes. This should, of course, be regarded as a highly speculative hypothesis. Imagine, for instance, that a planetary wave is oriented in a way that allows a blocking high pressure anomaly to develop above the northern Scandinavia. As conclusion (iii) states, this situation favours the development of negative stratospheric NAM anomalies. The stationary wave might then propagate slightly westwards, so that, after some time, the ridge leaves Scandinavia and enters the Greenland region. Such a wave orientation would be associated with a negative surface NAM/NAO phase. One could then be tempted to conclude that the NAO/NAM response was forced by the concurrent stratospheric NAM anomaly, while it in reality was just a consequence of horizontal Rossby wave propagation internal to the troposphere. Although highly speculative, one can perhaps find some support for this hypothesis in the study by Woolings et al. (2008). They suggested that a blocking high pressure anomaly above the northern Scandinavia enhances the upper tropospheric Rossby wave breaking, which subsequently gives rise to negative NAO events. Thus, the relation between the Scandinavian precursor pattern and the negative NAO can be understood without invoking stratospheric processes. This speculation is also supported by the findings reported in paper II. There, events of anomalously weak stratospheric circulation in an ensemble of GCMs used in the latest IPCC report were examined. The models were found to reproduce both the Scandinavian high pressure anomaly prior to the stratospheric events and the subsequent negative tropospheric NAO conditions. Considered that the models might not resolve stratospheric dynamics properly as a consequence of the coarse vertical resolution at these levels, one might speculate that the subsequent negative NAO conditions can be attributed to the preceding high pressure anomaly without involving stratospheric processes. To investigate this possibility, it would be of interest to force an atmospheric model with an imposed Scandinavian anticyclone, in one run where the stratosphere is well resolved, and in one run where the stratosphere is forced to be passive. This would indicate if tropospheric processes alone are responsible for what is generally believed to be a signal communicated via the stratosphere.

Considered that stratospheric impact on the tropospheric climate is a relatively new discipline, I believe that the results of this thesis can increase the understanding of the processes involved and their climatic impacts. The results also suggest that, by considering the Scandinavian pressure conditions in concert with stratospheric conditions, the tropospheric prediction skill on weekly to monthly time scales might be enhanced. However, the Scandinavian anticyclone is also interesting in itself, regardless of possible long-term implications. Its climatic impact was thoroughly addressed in the study of Bueh and Nakamura (2007). As was shown in Paper II, the Scandinavian anticyclone significantly affects the European temperature distribution, leading to anomalously warm conditions around Greenland and Iceland, and cold air outbreaks in Central Europe. Furthermore, Breiteig (2005) showed that the Scandinavian anticyclone leads to a large increase in the genesis of synoptic cyclones at the northeastern tip of Greenland – which actually makes this the region of most frequent cyclogenesis in the entire hemisphere in situations with a Scandinavian precursor. The general relation between the Scandinavian anticyclone and stratospheric anomalous events is further supported in a series of recent studies that are yet to be published (Woollings et al. 2009; Garfinkel et al. 2009; Martius et al. 2009).

The results of paper III suffer somewhat from having only 50 years of re-analysed data available. The composite sizes are small, which limits the robustness of the results. Furthermore, the effectiveness of the Scandinavian precursor pattern is tested on the same data set from which it was derived. This may imply that the answer is to some extent built into the method. Although the span of available data is short, one way to overcome this problem could be to construct the precursor pattern from one half of the data set, and test it on the other half. Such a test may be incorporated in a revised version of the manuscript.

The spatial temperature response to negative stratospheric circulation anomalies has to my knowledge only been investigated in a temporally mean sense previously. The results of paper II suggest that the temporally averaged temperature signal found by others actually consists of several well-defined and statistically robust stages, with the strongest signals appearing before the stratospheric circulation anomaly peaks. This suggests the possibility for more accurate prediction of surface temperature conditions during events with anomalously weak stratospheric circulation. It would be of interest to group the surface responses according to the type and structure of the stratospheric anomaly or to the antecedent tropospheric state, to see if some of the surface responses can be attributed to a certain type of stratospheric anomaly or to a certain state of the preceding troposphere.

In paper IV, the ocean is found to significantly help explain variability in the NAO. Still, the importance of the ocean-atmosphere interactions relative to the variability within the troposphere is yet to be determined. The principal message of paper IV is that, when considering interaction processes on shorter time scales than what is normally done in the literature, we are able to extract an influence by the ocean on the NAO that differs from the existing literature. These short-term interactions help explain even the decadal variability of the NAO. The exact mechanism by which the Gulf Stream SSTs impact the NAO could not be identified. A pathway through altered cyclone statistics was investigated, but the results were inconclusive. It is acknowledged that the influence by Gulf Stream SSTs on the NAO may be very weak compared to tropospheric internal processes, and that the exact mechanism is yet to be determined.

Paper V presents some interesting results regarding possible influences of the AMOC rate of change on the interannual NAO and ENSO variability. Since the AMOC is expected to weaken in response to global warming, the results may apply also to NAO and ENSO variability in the transient state between the present and the future climate. The results suffer, however, from being based on only one GCM realization. Studies have shown that the simulated future state of the AMOC differs substantially between various GCMs. If the NAO and/or ENSO variability response turns out to be very sensitive to the exact AMOC rate of change, the significance of the response is substantially weakened. An ensemble of corresponding GCM experiments needs to be considered to further assess the significance of the results.

References

Ambaum, M. and B. Hoskins (2002). The NAO troposphere-stratosphere connection. *Journal of Climate 15*(14), 1969–1978.

Baldwin, M. and T. Dunkerton (1999, DEC 27). Propagation of the arctic Oscillation from the stratosphere to the troposphere. *Journal of Geophysical Research - Atmospheres 104*(D24), 30937–30946.

Black, R. (2002). Stratospheric forcing of surface climate in the Arctic Oscillation. *Journal of Climate 15*(3), 268–277.

Breiteig, T. (2005, May). Synoptiske lavtrykks rolle i vekselvirkningen mellom stratosfære og troposfære. Master's thesis, Geophysical Institute, University of Bergen.

Bueh, C. and H. Nakamura (2007). Scandinavian pattern and its climatic impact. *Quarterly Journal of the Royal Meteorological Society 133*, 2117–2131.

Christiansen, B. (2008). Volcanic eruptions, large-scale modes in the Northern Hemisphere, and the El Niño-Southern Oscillation. *Journal of Climate 21*, 910–922.

Cohen, J. and D. Entekhabi (1999). Eurasian snow cover variability and Northern Hemisphere climate predictability. *Geophysical Research Letters 26*, 345–348.

Folland, C. K., J. Knight, W. Linderholm, H, D. Fereday, S. Ineson, and J. W. Hurrell (2009). The summer North Atlantic Oscillation: Past, present, and future. *Journal of Climate 22*, 1082–1103.

Garfinkel, C. I., D. L. Hartmann, and F. Sassi (2009). Tropospheric precursors of anomalous Northern Hemisphere stratospheric polar vortices. *Journal of Climate*, submitted.

Holton, J. (2004). *An Introduction to Dynamic Meteorology* (Fourth ed.). San Diego, CA, US: Academic Press.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck (2003). *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, Volume 134 of *Geophysical Monograph Series*, Chapter An Overview of the North Atlantic Oscillation, pp. 1–35. Washington, DC, US: American Geophysical Union.

Koster, R. D., P. A. Dirmeyer, and Z. Guo et al. (2004). Regions of strong coupling between soil moisture and precipitation. *Science 305*, 1138–1140.

Kushnir, Y., W. A. Robinson, and I. Bladé et al. (2002). Atmospheric GCM response to extratropical SST anomalies: Synthesis and evaluation. *Journal of Climate 15*, 2233–2256.

Kvamstø, N. G., P. Skeie, and D. B. Stephenson (2004). Impact of Labrador sea-ice extent on the North Atlantic Oscillation. *International Journal of Climatology 24*, 603–612.

Magnusdottir, G., C. Deser, and R. Saravanan (2004). The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. part I: Main features and storm track characteristics of the response. *Journal of Climate 17*, 857–876.

Martius, O., M. Polvani, and H. C. Davies (2009). Blocking precursors to stratospheric sudden warming events. *Geophysical Research Letters (in press)*.

Robock, A. (2000). The life cycles of some non-linear baroclinic waves. *Reviews of Geophysics 38*, 191–219.

Smagorinsky, J. (1953). The dynamical influence of large-scale heat sources and sinks on the quasi-stationary mean motions of the atmosphere. *Quarterly Journal of the Royal Meteorological Society 79*, 342–366.

Smagorinsky, J. (1969). Problems and promises of deterministic extended range forecasting. *Bulletin of the American Meteorological Society 50*, 286–311.

Thompson, D. W. J. and J. M. Wallace (2001). Regional climate impacts of the Northern Hemisphere Annular mode. *Science 293*, 85–89.

Vallis, G. K. and E. P. Gerber (2008). Local and hemispheric dynamics of the North Atlantic Oscillation, Annular patterns and the zonal index. *Dynamics of atmospheres and oceans 44*(3-4), 184–212.

Walker, G. T. (1924). Correlation in seasonal variation of weather IX. *Mem. Indian Meteorol. Dept. 24*, 275–332.

Woolings, T., B. Hoskins, M. Blackburn, and P. Berrisford (2008). A new Rossby wave-breaking interpretation of the North Atlantic Oscillation. *Journal of the Atmospheric Sciences 65*, 609–626.

Woollings, T., A. Charlton-Perez, S. Ineson, A. Marshall, and G. Masato (2009). Associations between stratospheric variability and tropospheric blocking. *In preparation*.