

Decadal-scale modulation of the NAO/AO by external forcing: Current state of understanding^(*)

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Summary. — Analyses of observations show correlations between the mean state of indices representing either the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO, also called Northern Annular Mode) with various external forcings. These include volcanic eruptions, solar variability, greenhouse gas levels and stratospheric ozone depletion. Climate model simulations have been able to reproduce many aspects of these correlations over a variety of time scales ranging from inter-annual to century scale. This has allowed some insight to be gained into how external forcings modulate these intrinsic variability patterns. I review current understanding derived from comparisons of a range of models with observations to highlight areas of commonality as well as remaining uncertainties. Contrasts between the Northern and Southern Hemispheres suggest that much of the response to external forcing occurs via wave-driven processes. Comparison of the response to forcings at different levels in the atmosphere indicate a sizeable role for both stratospheric and surface-level perturbations. Implications for forcing of changes in Mediterranean climate are presented for pre-industrial times during the last millennium, for the twentieth century, and for the potential future.

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1. – Introduction

The patterns that account for the most variance in meteorological observations are ENSO, followed by the Northern and Southern Annular Modes (NAM, also called the Arctic Oscillation (AO), and SAM). The latter two patterns are especially dominant in extratropical wintertime variability in their respective hemispheres. The AO/NAM pattern is extremely similar to the North Atlantic Oscillation in the Atlantic sector, where it is most strongly expressed, and will be hereafter treated as the same phenomenon.

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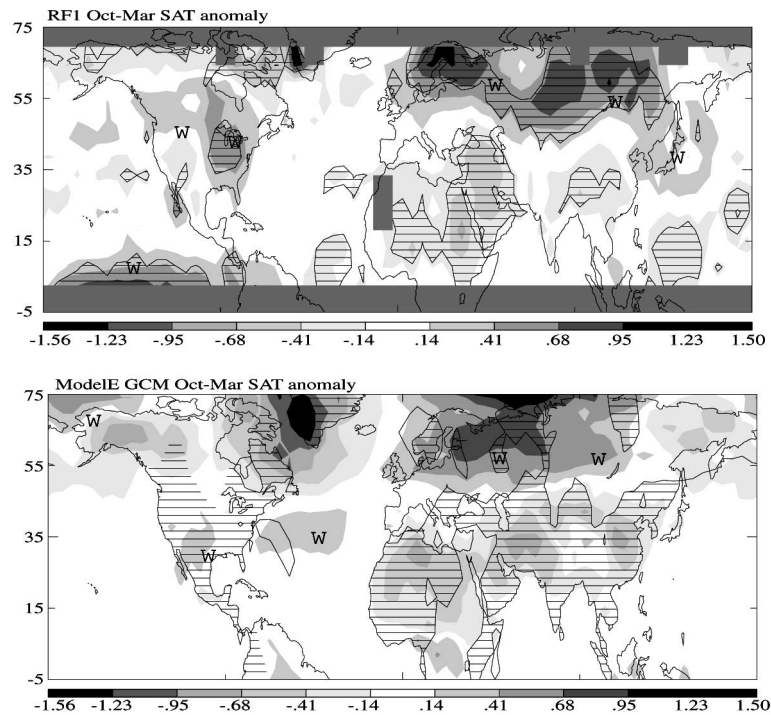


Fig. 1. – Surface temperature anomalies during the cold season (October-March) following large tropical volcanic eruptions in historical reconstructions-observations and the GISS GCM. Historical values (top) are averaged over 11 known eruptions with a negative radiative forcing of at least 1 W/m^2 (mean forcing -3.77 W/m^2). Model values (bottom) are the mean response averaged over the cold-seasons following the eruptions of Pinatubo, Santa Maria, and Krakatau (mean forcing -3.68 W/m^2) in 5-member ensemble runs with the GISS modelE GCM (*i.e.* 15 eruptions). Hatched regions indicate areas where the response is significant at the 95% confidence level. Observations are taken from proxy network reconstructions through 1980 and meteorological data thereafter. Darker colors indicate greater temperature changes, with areas exhibiting warming marked with the letter W. Grey bands along the top and bottom of the upper panel indicate regions where data was not available. Figure modified from [20].

While these patterns are intrinsic variability modes of the coupled atmosphere-ocean system, growing evidence indicates that they are also responsive to external forcing. Shifts in the AO/NAM at both short (annual) and long (multi-decadal) timescales appear in the historical record, and have a substantial effect on regional Northern Hemisphere extratropical surface temperature and precipitation anomalies. A better understanding of the AO/NAM response to external forcing will thus aid in interpretation of the causes of historical climate changes in the Mediterranean region.

2. – Response to external forcing

One of the clearest examples of the response of the AO/NAM to external forcing is the increased westerly circulation (the AO/NAM “high” phase) during the two winters immediately following large tropical volcanic eruptions. In prior work [20] we analyzed

the mean climate response pattern following large tropical volcanic eruptions back to the beginning of the 17th century using a combination of proxy-based reconstructions and modern instrumental records of cold-season surface air temperature. Warm anomalies occurred throughout northern Eurasia while cool anomalies cover northern Africa and the Middle East, extending all the way to China. In North America, the northern portion of the continent cools, with the anomalies extending out over the Labrador Sea and southern Greenland (fig. 1). The analyses confirmed that for two years following eruptions the anomalies strongly resemble the AO/NAM in the Atlantic-Eurasian sector. With our four century record, the mean response is statistically significant at the 95% confidence level over much of the Northern Hemisphere land area (fig. 1). Both the mean response and the variability can be successfully reproduced in general circulation model simulations (fig. 1) [3,11,20,24]. Driven by the solar heating induced by the stratospheric aerosols, which also cool the surface, these models produce enhanced westerlies from the lower stratosphere down to the surface. During the cold season, this results in enhanced westerly advection of relatively warm oceanic air over the continents and of cooler air from continental interiors to their eastern coasts. In some regions, meridional winds are modulated along with the increased westerlies, leading to enhanced warming over Siberia and cooling over the Middle East, for example. This behavior is consistent with the seesaw of mass between the polar cap and mid-latitudes typically used to define the AO or NAO. The climate response to volcanic eruptions thus strongly suggests that stratospheric temperature and wind anomalies can affect surface climate by forcing a shift in the AO/NAM.

Though the short-term continental winter warming response to volcanism is clear in the historical record, we have found that in our model the long-term (decadal mean) regional response is not significant compared to unforced variability for either the winter or the annual average [21]. This is due to opposing dynamical and radiative effects. The radiative impact of volcanic aerosols is both to cool the surface and to warm the lower stratosphere. For example, after Pinatubo, the model simulates a large winter warming in the sunlit portion of the lower stratosphere ($\sim 2^{\circ}\text{C}$), similar to NCEP observations [24]. This increases the meridional temperature gradient between mid-latitudes and the Arctic in that region. Since the eruption takes place in June, the ocean has relatively little time to adjust to the radiative forcing by the following winter, and the tropical surface cooling then is only -0.1°C . This leads to a very small cooling of the tropical upper troposphere (due to its close connection with the surface in convective regions), which marginally reduces the meridional temperature gradient in the tropopause region that occurs naturally due to the reduction of tropopause height with increasing latitude. However, this has a weaker impact than the much larger lower stratospheric heating in the sunlit atmosphere at slightly higher altitudes. The gradient change increases the westerly winds in this region, which increases the refraction of upward propagating planetary waves towards the equator [23]. This in turn leads to an increase in poleward angular momentum flow, which drives the stronger surface westerlies associated with a positive AO/NAM anomaly. This dynamical planetary wave feedback via the stratosphere has been seen in response to volcanic eruptions in both observations and GCM simulations [12,17,23]. Over the longer term, however, the opposite effect takes place. The aerosols, being relatively large and therefore heavy, fall out of the stratosphere in a few years, while the ocean cooling maximizes a couple years following the eruption and persists for several years subsequently. The cooler sea surface leads to cooling in the tropical upper troposphere, which reduces the meridional temperature gradient in the tropopause region, forcing a tendency towards the AO/NAM “low” phase. Thus the circulation changes largely cancel one an-

other out over longer timescales, leaving a fairly spatially homogeneous cooling pattern as the response to volcanic eruptions [21]. Since most historical datasets are predominantly land-based, it is important also to note that while cold-season temperatures typically warm over large areas immediately following eruptions, warm-season temperatures cool owing to the purely radiative effect of the volcanic aerosols. This opposing seasonality leads to annual average signals that are quite small. During the few centuries prior to the industrial era, externally driven climate change is thought to have been forced primarily by volcanic eruptions and solar variability. In contrast with volcanism, the long-term (decadal mean) regional response to solar forcing greatly exceeds unforced variability for both winter and annual averages. Long-term decreases in solar irradiance lead to a strong negative AO response in our model [21, 22], for example comparing the Maunder Minimum with a century later, which causes significant wintertime continental cooling (fig. 2). A similar signal is present in the summer (fig. 2) due to the long-term persistence of sea-surface temperature (SST) anomalies and radiative cooling of the continents, but with reduced amplitude compared with the winter since there is no dynamical enhancement. Another GCM has also reported an enhanced temperature response to solar forcing over NH continents, consistent with a reduced AO [5]. The two primary forcings for climate in the pre-industrial period, solar variations and volcanic eruptions, thus have quite different impacts in the model. For both volcanic eruptions and decreased solar irradiance the global average response is cooling. The regional responses are dissimilar, however (fig. 2). Decreased solar irradiance of course cools the surface. At the same time, the lower stratosphere cools due to decreased absorption of incoming solar radiation by ozone owing to both the irradiance reduction and to reduced photochemical production of ozone in the lower stratosphere (radiation at ultraviolet (UV) wavelengths varies much more than that at longer wavelengths, and this UV plays a major role in formation of the stratospheric ozone layer). In the example of the Maunder Minimum *vs.* a century later, the sunlit portion of the lower stratosphere cooled by 0.2 to 0.4 °C during winter. The upper tropical troposphere cooled by 0.6 to 0.8 °C in response to the tropical surface cooling. These persistent coolings led to a reduced temperature gradient between NH middle and high latitudes in both the lower stratosphere and the upper troposphere, forcing a negative AO [22]. In contrast, volcanic eruptions cool the surface, but aerosol heating warms the sunlit lower stratosphere. This leads to an increased meridional gradient in the lower stratosphere, but a reduced gradient in the tropopause region. These may separately cause enhancements of the AO on one to two year timescales via the stratospheric warming, and reductions on decadal timescales via the surface cooling. However, in light of these opposing physical drivers of AO changes, and the short-term nature of the large dynamical response to eruptions, it is not surprising that the long-term net dynamical effect of volcanic eruptions is minimal. Additionally, the typically short timescale of volcanic perturbations does not allow their radiative impact to be fully felt by the oceans or sea ice, in contrast to multi-decadal solar forcing, further weakening their long-term effect. Since the impact of the volcanically-induced dynamical changes on the annual average temperatures is also reduced by the seasonally opposed influences of the radiative response (summer continental cooling) and stratospherically-forced dynamical response (winter continental warming), it is reasonable that the long-term annual average impact of volcanoes is relatively homogeneous spatially.

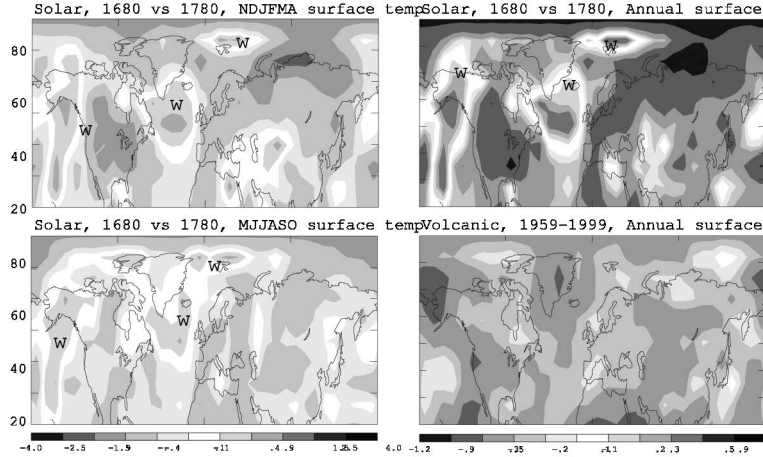


Fig. 2. – Surface temperature response (K) to decreased solar irradiance during 1680 relative to 1780 and in the volcanic transient experiments. Values are given for solar simulations for November–April (top left), May–October (bottom left), and the annual average (top right). An annual average over 5 ensemble members of transient volcanic runs (1959–1999) is shown for comparison (bottom right). Note the difference in scale between the two columns. Cold-season temperature responses are significant in the subtropics for values greater than about 0.2 K, at mid-latitudes for values greater than about 0.3 K, and poleward of 75° N for values greater than about 0.6 K. Warm-season and annual average values greater than about 0.2 to 0.3 K are significant. The solar forcing was -0.32 W/m^2 , while the average volcanic forcing was -0.44 W/m^2 . Darker colors indicate greater temperature changes, with areas exhibiting warming marked with the letter W. Figure modified from [21].

3. – Model comparison with historical reconstructions

The simulated external forcing of regional surface temperature anomalies can also be compared with patterns derived from a compilation of diverse proxy climate indicators. A comparison of surface temperatures during the late Maunder Minimum, when the ocean has had sufficient time to respond to the solar irradiance anomaly, with a century later is an ideal test of models. These periods are both well before external forcing became predominantly anthropogenic, so that uncertainties in forcings such as the indirect effect of aerosols are not important. We use model results from simulations forced with reduced solar irradiance during the Maunder Minimum compared with a century later, and from volcanic simulations of the response to the 20th century transients, and to Pinatubo. The latter serve as a generalized response to volcanic forcing, which was ~ 0.16 W/m^2 more negative during the late 17th century (1660–1690) than the late 18th century (1770–1790) [4]. Proxy data have been averaged over these same decades to obtain decadal timescale patterns.

Given that the long-term volcanic influence on the non-linear AO/NAM and hence on regional changes is very weak, the surface temperature response to the volcanic forcing can be added to that due to reconstructed solar irradiance changes during this same period [13]. This provides an estimate of the total change (fig. 3). The result shows a regional pattern of continental cooling due to a forced negative AO/NAM anomaly. While the global mean surface temperature change is 75% due to solar forcing and 25% to volcanic forcing, all of the AO reduction is attributable to the solar forcing, as the

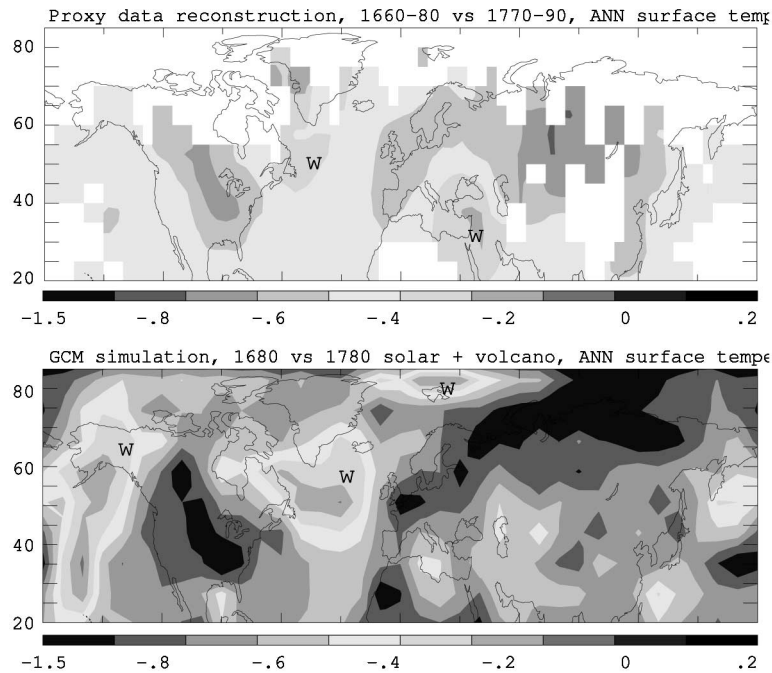


Fig. 3. – Reconstructed (top) and simulated (bottom) annual average temperature difference between 1660-1680 and 1770-1790. The reconstructed surface temperatures are based on a multi-proxy estimate using tree-rings, ice cores, corals and historical data [15]. Model results are based on the sum of the response in two simulations, one incorporating reconstructed solar irradiance changes during this period and one using volcanic forcing scaled to changes over this time. Darker colors indicate greater temperature changes, with areas exhibiting warming marked with the letter W. No proxy data is available at high latitudes. Figure modified from [21].

volcanic forcing actually gave a weak AO increase.

We compare the total response with that derived from surface temperature pattern reconstructions based on diverse proxy data [15]. A favorable agreement is found between the simulated and reconstructed temperature anomalies over this period (fig. 3), with both showing large, spatially coherent anomalies in mid-latitudes. Agreement is especially good over North America, where the impact of reduced northwesterlies moving around the Rockies is clearly visible in both cooling patterns. The model also reproduces the cooling which arcs up through western Europe into Asia, though the Middle East does not show the warming seen in the reconstruction (it is relatively warm compared to Eurasia, however, and the newer GISS modelE now captures this behavior in the volcanic case shown in fig. 1). While both the GCM and the reconstruction show warming over parts of the North Atlantic, the reconstructed anomaly is less than the unforced variability, which is quite large in this region. Additionally, we regard the model simulation results as being less reliable over the oceans, as they do not include changes in ocean dynamics, which may be an important feedback, at least in the Atlantic where surface anomalies are buffered by communication with the deep ocean [6]. The model results also do not account for possible changes in the El Niño-Southern Oscillation and potential extratropical responses, particularly with regard to the Pacific region. Nevertheless,

the basic pattern of anomalously cold continents is clear in both the paleoclimate data and the model response, and it is in these areas that both values are most reliable. The amplitude of the cooling is larger in the model, however. This version of the GISS GCM has a climate sensitivity at the high end of the modelled range (~ 1 per W/m^2). Additionally, the proxy reconstruction is implicitly spatially smoothed through the use of a limited eigenvector basis set to approximate large-scale temperature changes. Moreover, data availability limits the size of this basis set in earlier centuries, leading to a greater smoothing of regional temperature variations prior to the 18th century in particular. Note that there is some independent evidence for a reduced NAO during the late 17th and 18th centuries from European historical reconstructions [14]. Additional support for Atlantic sector circulation change consistent with a reduced AO/NAO during the LIA comes from sediment cores [10] and from historical evidence for greater northeasterly flow of continental air into Europe [25].

While paleoclimate reconstructions of surface temperatures in past centuries are uncertain, there is broad agreement among different methods and data sources, at least at the level of the NH mean temperature variations [2, 4, 9, 16]. On the regional scale, European temperature estimates are most reliable, as historical and a few long instrumental data series augment the more widespread proxy-data such as tree-rings in the proxy network reconstruction. The reconstructed European regional temperature anomaly is thus a key test of a model's regional response to forcing. Comparing the Maunder Minimum period with a century later, the more negative volcanic forcing fails to produce even the right sign of temperature change in this region, as all the volcanic simulations generate a warming relative to the NH extratropical mean while the proxy data and the response to solar forcing show cooling outside the range of unforced variability. Thus we believe solar forcing represents a much more plausible explanation for historical temperature variations resulting from external forcing.

4. – Conclusion

Decadal and longer-term regional climate changes during the pre-industrial appear to be attributable largely to solar rather than volcanic forcing as persistent solar anomalies are able to cause a sustained shift in the AO/NAM shift. While land use changes may have contributed to regional climate changes, the gradual clearing of native forests would be expected to lead to cooler temperatures, so would not account for the European warming associated with the end of the Little Ice Age, for example. For centennial-scale hemispheric mean changes, however, volcanic and solar forcing appear to have comparable magnitudes which are for the most part simply proportional to their effect on the Earth's energy budget.

Regional climate changes in the Mediterranean appear to have been greatly influenced by shifts in the AO/NAM (NAO) pattern. There is a sizeable body of evidence indicating that stratosphere-troposphere dynamic feedbacks are important in this response, with analyses of recent observations indicating that anomalies in the stratosphere indeed proceed those at lower levels [1], and simplified model simulations showing that stratospheric heating anomalies lead to subsequent alterations of surface climate [7, 18, 26]. Clearly, however, the SST response to external forcing is also important, as demonstrated by opposing behavior of the long- and short-term responses to volcanic eruptions. Another example is the similarity between the surface responses to stratospheric ozone depletion and greenhouse gas increases for the SAM. Ozone has a large effect in the stratosphere (in fact, it changes temperatures almost exclusively in the stratosphere, providing another

example of stratospheric anomalies affecting surface climate). While greenhouse gases have a much smaller effect in the stratosphere, they have a comparable effect on surface climate, presumably through their much larger effect on SSTs [19]. These results may also be consistent with the implications of studies showing that recent North Atlantic climate changes can be reproduced by models driven by tropical SST changes [8].

Despite the overall progress in understanding forcing of pre-existing variability patterns, substantial uncertainties remain. The exact magnitudes of regional changes are difficult to ascertain. The historical reconstructions suffer from the geographic limits of proxy climate data, as well as the potential underestimate of variance discussed previously. The models must be driven by estimates of the historical variation of solar and volcanic forcing, but both of these are not well known. For solar forcing especially, calibration of cosmogenic proxies or sunspots used to reconstruct historical variations is quite uncertain, and the variations as a function of wavelength are very poorly known. The models themselves are subject to uncertainties in the level of climate sensitivity, and to limitations in both the model domain (*e.g.*, inclusion of the stratosphere or mesosphere, inclusion of a full dynamic ocean) and the physical processes included (*e.g.*, chemistry), primarily as a result of limited computational resources. Thus we can hope for qualitative agreement between the patterns seen in reconstructions and in GCMs, but quantitative agreement is probably not a meaningful objective. Nevertheless, recent results suggest that interpretation of historical climate variability through the paradigm of dominant variability patterns provides a useful method to gauge the importance of various external forcings in the Northern Hemisphere extratropics.

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REFERENCES

- [1] BALDWIN M. P. and T. J. DUNKERTON, Propagation of the Arctic Oscillation from stratosphere to the troposphere, *J. Geophys. Res.*, **104** (1999) 30, 937, 946.
- [2] BRIFFA K. R. *et al.*, Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years, *Nature*, **393** (1998) 350.
- [3] COLLINS M., *Predictions of climate following volcanic eruptions, in Volcanoes and the Earth's Atmosphere* (American Geophysical Union) 2003.
- [4] CROWLEY T. J., Causes of climate change over the past 1000 years, *Science*, **289** (2000) 270.
- [5] CUBASCH U. *et al.*, Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model, *Clim. Dynam.*, **13** (1997) 757.
- [6] DELWORTH T. L. and K. W. DIXON, Implications of the recent trend in the Arctic/North Atlantic oscillation for the North Atlantic thermohaline circulation, *J. Climate*, **13** (2000) 3721.
- [7] EICHELBERGER S. J. and J. R. HOLTON, A mechanistic model of the northern annular mode, *J. Geophys. Res.*, **107** (D19) (2002) 4388, doi: 10.1029/2001JD001092.
- [8] HOERLING M. P., J. HURRELL and T. XU, Tropical origins for North Atlantic climate change, *Science*, **292** (2001) 90.

- [9] JONES P. *et al.* High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures, *Holocene*, **8** (1998) 455.
- [10] KIEGWIN L. D. and R. S. PICKART, Slope water current over the Laurentian Fan on Interannual to Millennial Time Scales, *Science*, **286** (1999) 520.
- [11] KIRCHNER I., G. L. STECHNIKOV, H.-F. GRAF, A. ROBOCK and J. C. ANTUNA, Climate model simulation of winter warming and summer cooling following the 1991 Mount Pinatubo volcanic eruption, *J. Geophys. Res.*, **104** (1999) 19039.
- [12] KODERA K., Influence of volcanic eruptions on the troposphere through stratospheric dynamical processes in the Northern Hemisphere winter, *J. Geophys. Res.*, **99** (1994) 1273.
- [13] LEAN J., J. BEER and R. BRADLEY, Reconstruction of solar irradiance since 1610: Implications for climate change, *Geophys. Res. Lett.*, **22** (1995) 3195.
- [14] LUTERBACHER J., C. SCHMUTZ, D. GYALISTRAS, E. XOPLAKI and H. WANNER, Reconstruction of monthly NAO and EU indices back to AD 1675, *Geophys. Res. Lett.*, **26** (1999) 2745.
- [15] MANN M. E., R. S. BRADLEY and M. K. HUGHES, Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, **392** (1998) 779.
- [16] MANN M. E., R. S. BRADLEY and M. K. HUGHES, Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations, *Geophys. Res. Lett.*, **26**, (1999) 759.
- [17] PERLWITZ J. and H.-F. GRAF, The statistical connection between tropospheric and stratospheric circulation of the Northern Hemisphere in winter, *J. Climate*, **8** (1995) 2281.
- [18] POLVANI L. M. and P. J. KUSHNER, Tropospheric response to stratospheric perturbations in a relatively simple general circulation model, *Geophys. Res. Lett.*, **29** (2002), doi:10.1029/2001GL014284.
- [19] SHINDELL D. T. and G. A. SCHMIDT, Southern Hemisphere climate response to ozone changes and greenhouse gas increases, *Geophys. Res. Lett.*, **31** (2004) L18209, doi:10.1029/2004GL020724.
- [20] SHINDELL D. T., G. A. SCHMIDT, M. E. MANN and G. FALUVEGI, Dynamic winter climate response to large tropical volcanic eruptions since 1600, *J. Geophys. Res.*, **109** (2004) D05104, doi:10.1029/2003JD004151.
- [21] SHINDELL D. T., G. A. SCHMIDT, R. L. MILLER and M. E. MANN, Volcanic and Solar Forcing of Climate Change during the Preindustrial Era, *J. Clim.*, **16** (2003) 4094.
- [22] SHINDELL D. T., G. A. SCHMIDT, M. E. MANN, D. RIND and A. WAPLE, Solar forcing of regional climate change during the Maunder Minimum, *Science*, **294** (2001) 2149.
- [23] SHINDELL D. T., G. A. SCHMIDT, R. L. MILLER and D. RIND, Northern Hemisphere winter climate response to greenhouse gas, volcanic, ozone and solar forcing, *J. Geophys. Res.*, **106** (2001) 7193.
- [24] STENCHIKOV G., A. ROBOCK, V. RAMASWAMY, M. D. SCHWARZKOPF, K. HAMILTON and S. RAMACHANDRAN, Arctic Oscillation response to the 1991 Mount Pinatubo eruption: Effects of volcanic aerosols and ozone depletion, *J. Geophys. Res.*, **107** (2002) 4803, doi:10.1029/2002JD002090.
- [25] WANNER H. *et al.*, Wintertime European circulation patterns during the late Maunder minimum cooling period (1675-1704), *Theor. Appl. Climatol.*, **51** (1995) 167.
- [26] WITTMAN M. A. H., L. M. POLVANI, R. K. SCOTT and A. J. CHARLTON, Stratospheric Influence on Baroclinic Lifecycles and its Connection to the Arctic Oscillation, *Geophys. Res. Lett.*, **31** (2004), doi:10.1029/2004GL020503.