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A volcanically triggered regime shift in the subpolar North Atlantic ocean as a possible origin of the Little Ice Age

C. F. Schleussner[1,2] **and G. Feulner**[1]

[1]Potsdam Institute for Climate Impact Research, Telegrafenberg A62,
14473 Potsdam, Germany
[2]Physics Institute, Potsdam University, Potsdam, Germany

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Correspondence to: C. F. Schleussner (schleussner@pik-potsdam.de)

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Abstract

Among the climatological events of the last millennium, the Northern Hemisphere Medieval Climate Anomaly (MCA), succeeded by the Little Ice Age (LIA) are of exceptional importance. The origin of these regional climate anomalies remains however a subject of debate and besides external influences like solar and volcanic activity, internal dynamics of the climate system might have also played a dominant role. Here, we present transient last millennium simulations of the fully-coupled model Climber 3α forced with stochastically reconstructed wind fields. Our results indicate that short-lived volcanic eruptions might have triggered a cascade of sea-ice – ocean feedbacks in the North Atlantic, ultimately leading to a persistent regime shift in the ocean circulation. We find that an increase in the Nordic Sea sea-ice extent on decadal timescales as a consequence of major volcanic eruptions leads to a spin-up of the subpolar gyre (SPG) and a weakened Atlantic Meridional Overturning Circulation, eventually causing a persistent, basin-wide cooling. These results highlight the importance of regional climate feedbacks such as a regime shift in the subpolar gyre circulation for past and future climate.

1 Introduction

The so-called Little Ice Age (LIA), a period of cool temperatures over the Northern Hemisphere, is among the most debated climatological events of the Holocene. Tree-ring reconstructions from central Europe reveal a reduction in summer temperature of at least 1 K and more (Büntgen, 2011) and successive agro-ecological and socioeconomic down-turn might have set the field for the outbreak of the “Thirty Years’ War”, one of the most destructive episodes in pre-industrial Europe (Zhang et al., 2011a). Even though the term Little Ice Age is widely used in literature, a coherent definition did not emerge due to a substantial variance in the climate signal between different geographical regions and records. Jones and Mann (2004) define it as a period from

1300–1450 AD to 1850–1900 including several warmer and colder episodes. Since the LIA coincides with a series of minima in sunspot activity, it has been interpreted as an example of the importance of multi-decadal variations in the total solar irradiance (TSI) to the earth's climate (Eddy, 1976). Recent TSI reconstructions, however, estimate the changes in the radiative forcing over the last millennium to be of the order of 0.2–0.7 W m^{-2} as compared to the 2008/2009 solar minimum with a tendency towards the lower end (Jansen et al., 2007; Gray et al., 2010). In a modeling study, these low estimates have been shown to yield results that are consistent with Northern hemisphere temperature reconstructions (Feulner, 2011). In these simulations, LIA cooling is dominated by the effect of volcanic eruptions, an alternative hypothesis that has been suggested earlier (Robock, 1979; Crowley, 2000).

Regarding possible mechanisms for regional cooling, reconstructions suggest a slowing down of the Atlantic meridional overturning circulation (AMOC) during the LIA (e.g., Broecker, 2000; Lund et al., 2006) and model results as well as observations reveal a multi-decadal to centennial internal variability of the AMOC (Parker et al., 2007; Menary et al., 2011). Otterå et al. (2010) presented model results indicating that volcanic eruptions, despite the short life-time of their atmospheric imprint, may be an important driver of multi-decadal AMOC variability. Decadally-paced volcanic forcing has been reported to result in persistent changes in North Atlantic climate on centennial time-scales (Zhong et al., 2010), caused by a coupled ocean-ice mechanism. In contrast, other studies find little imprint of volcanic eruptions on the AMOC (Ortega et al., 2011; Hofer et al., 2011) or report a diverse set of responses over the last millennium (Mignot et al., 2011). In a model intercomparison, even more contradictory findings between different models and reconstructions are reported making the question of the origins of the LIA puzzling (Fernández-Donado et al., 2012).

Reconstructions suggest that the MCA was characterized by a persistent positive North-Atlantic Oscillation (NAO) as the dominant atmospheric mode (Trouet et al., 2009; Olsen et al., 2012), followed by a transition into a more variable state including strongly negative episodes during the LIA. An increase in sea-ice extent was found in the western Nordic Seas, interrupted by short periods of greatly reduced ice cover (Macias Fauria et al., 2009). Reconstructions for the whole Arctic ocean even suggest an overall decrease in sea-ice extent over the LIA (Kinnard et al., 2011), again illustrating the irregular spatial pattern of climate anomalies during this episode and highlighting the importance of regional climate feedbacks.

Here, we present a systematic approach to separate the impacts of changes in TSI, volcanism, greenhouse gas emissions and reconstructed wind-stress variability on the North Atlantic ocean during the last millennium. We compare our outcome to multi-proxy reconstructions and suggest a mechanism for the MCA-LIA transition.

2 Model and experiments

2.1 Model description

The simulations presented in this study where performed with the intermediate-complexity climate model CLIMBER-3α (Montoya et al., 2005). Its oceanic component is based on the GFDL MOM-3 code (Pacanowski and Griffies, 1999), with 24 variably spaced vertical levels, a coarse horizontal resolution of 3.75°, a background vertical diffusivity of $\kappa_h = 0.3 \times 10^{-4}\,\mathrm{m}^2\,\mathrm{s}^{-1}$ and an eddy-induced tracer advection with a thickness diffusion coefficient of $\kappa_{\mathrm{gm}} = 250\,\mathrm{m}^2\,\mathrm{s}^{-1}$. It contains a coarse resolution statistical dynamical atmosphere (Petoukhov et al., 2000) and a thermodynamic/dynamic sea-ice component (Fichefet and Maqueda, 1997).

Due to the coarse resolution, the SPG circulation does not extend to the Labrador Sea and therefore subpolar convection is limited to the central Irminger basin. The area of deep convection in the Greenland Basin compares well with observations of mixed layer depth (de Boyer Montégut et al., 2004). CLIMBER-3α was used in a variety of model intercomparison studies on the last millennium (Jansen et al., 2007; Eby et al., 2012) and investigating AMOC stability (Gregory et al., 2005; Stouffer et al., 2006).

2.2 Experiment design

In our modeling study of the last-millennium, the TSI reconstruction by Steinhilber et al. (2009) is used, supplemented by the record by Wang et al. (2008) from 1850 onwards as recommended by the Paleoclimate Modeling Intercomparison Project (PMIP3). This reconstructed time series has been shown to yield hemispheric temperatures in CLIMBER-3α close to ensemble reconstructions over the last millennium (Feulner, 2011).

For the volcanic forcing, the time series by Crowley (2000) is used and anthropogenic aerosols and greenhouse gas forcings follow the PMIP3 recommendations (Schmidt et al., 2011). The time series for the TSI only and the combined short-wave forcing is shown in Fig. 1a. Aerosol forcing is only considered in its direct impact on the TSI, since our atmospheric component lacks a sufficient representation of other climate impacts of aerosol release.

Since our statistical-dynamical atmosphere does not produce internal variability, we externally prescribed wind-fields by a stochastically construction method utilizing the 1049 to 1995 winter NAO reconstruction index by Trouet et al. (2009) and the annual surface wind stress anomalies from the National Centers for Atmospheric Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis data from 1948 to 2009 (Kalnay et al., 1996). The North-Atlantic Oscillation (NAO) is the leading atmospheric mode of North Atlantic climate variability (Hurrell and Deser, 2009). In a first step, we derived the standard deviation of the winter NAO index as provided by Hurrel (2012) giving a standard deviation of 1 for the period 1899 to 2012. Assuming that the distribution provides a statistically independent probability for the index of a mean state, it allows us to construct wind stress time series for the entire 1049 to 1995 period. For each year in the Trouet et al. (2009) time series, the index is set as the mean of a normal distribution with the derived standard deviation. This distribution is taken as the probability distribution to sample years out of the NCEP 1948 to 2009 period using inverse transform sampling. A resulting time series is shown in Fig. 1b in comparison with the reconstructions by Trouet et al. (2009).

It is unlikely that North Atlantic wind-fields over the last millennium with greatly varying regional climate conditions will be sufficiently represented by a construction procedure based on a 60 yr time series. In particular, for the reconstructed persistent positive NAO-phase during the MCA, this method leads to weaker NAO reconstructions, due to the lack of particular high NAO years in the time series. The comparison of an ensemble constructed using this stochastic procedure can however yield interesting insights into how the atmospheric component influences North Atlantic oceanic variability. An ensemble of 10 stochastic wind-field time series is created and all experiments are performed for all ensemble members. These wind-field time series are added to a prescribed climatology (Trenberth et al., 1989). From 1948 onwards, the anomalies according to the NCEP reconstruction are applied for all ensemble members.

Subpolar oceanic resonance to atmospheric forcing in our model is enhanced to reproduce observed variability, when a constant freshwater forcing offset is applied over the convective region in the Nordic Seas (63.75°-78.75° N and 11.25° W–10° E) as shown in Mengel et al. (2012). The offset applied in their model study is 15 mSv and thereby within the range of natural variability as estimated by Curry and Mauritzen (2005) for the second half of the 20th century. In addition to the experiment described above, we present results for runs with a smaller constant 5 mSv offset.

All runs were started from an equilibrium simulation with a constant CO_2 concentration of 277 ppm and a solar constant of 1361 W m^{-2} according to Kopp and Lean (2011), which was spun-up in a period of 200 years starting in the year 850 with a constant freshwater offset. During the spin-up time, repeated NCEP wind-field variability was applied as in Mengel et al. (2012) and the volcanic forcing mirrored from the years 1000–1150 was applied for the 850–1000 period.

3 Results

As depicted in Fig. 1c, the ensemble mean without a freshwater offset exhibits a persistent switch in the circulation regime of the subpolar gyre (SPG) during the late 17th century with a large spread for the different stochastic wind-stress forcing reconstructions. This SPG regime shift is accompanied by an increase in sea-ice in the Nordic Seas (Fig. 1d) that is consistent with sea-ice reconstructions by Macias Fauria et al. (2009). A spin-up of the SPG is closely linked to subpolar convection strength (Levermann and Born, 2007) in our model and has been reported for a variety of climate models (Born et al., 2012; Schulz et al., 2007). Furthermore, SPG variability has been found to dominate the multi-decadal AMOC variability signal in various model studies (e.g. Msadek and Frankignoul, 2009; Park and Latif, 2011). Such an SPG spin-up is based on a threshold in the subpolar circulation regime in our model (Mengel et al., 2012) and is very sensitive to small changes in the western Nordic Seas freshwater budget and atmospheric variability. Therefore, the timing of this transition should not be over-interpreted but rather be seen as a proof of concept. We conducted the same model ensemble simulations with an additional freshwater offset in the Nordic Seas of 5 mSv (blue, as described above) and found a switch in the ensemble mean around 1450 in line with the onset time of the LIA in most climate records. Consequently, when comparing model ensemble results with an AMO reconstruction index by Mann et al. (2009), we find better agreement between the 5 mSv offset ensemble and the reconstructions in the 16th and 17th century (Fig. 1e). The North Atlantic Sea-Ice Extent (NASIE) over the Nordic Seas (40° W–20° E, 64° N–80° N) is depicted in Fig. 1d.

To identify the driving processes behind this basin-wide circulation shift, we decomposed the external forcings for all reconstructed wind-fields (Fig. 2) without additional freshwater offset. Again, great variations between the ensemble members are found, indicating the importance of atmospheric forcing on North Atlantic ocean dynamics. Our method also incorporates atmospheric variability induced by external forcing, because imprints of both TSI changes and volcanic eruptions have shaped our reconstructed NAO timeseries. In our modeling study however, wind-field forcing alone (WIND, grey curve) did not lead to a full spin-up of the SPG in the LIA and only leads to a moderate strengthening in the 18th century. When compared to the reference AMO signal (Fig. 2c), atmospheric forcing alone also lacks some prominent features of the reconstruction, most importantly the cooling over the LIA. This picture does not change much, if TSI plus anthropogenic CO_2 changes are applied (blue curve), ruling out changes of the TSI as the major origin of LIA cooling of the North Atlantic in our model. In contrast to the weak response to TSI forcing, volcanic and wind-field forcing combined (VOLC, in red) already leads to dynamics very similar to the full forcing case until 1850 (FULL, purple). Since the atmospheric response to volcanic forcing is incorporated in the wind-field reconstructions, we can conclude that the direct sea ice-oceanic response is of major importance to Northern Hemisphere climate variability over the last millennium. From this forcing decomposition, we find in accordance with Otterå et al. (2010) and Miller et al. (2012) volcanic forcing to be the dominant driver of pre-industrial North Atlantic variability with both an atmospheric as well as an oceanic response being evident.

In our model simulations, anthropogenic aerosol emissions, which are only incorporated in the FULL case, have a profound impact on the North Atlantic climate system. In TSI and VOLC, the increase in anthropogenic CO_2 emissions after 1850 immediately results in a NASIE reduction, SPG weakening and AMO increase that is greatly delayed in FULL, whereas the NASIE reaches MCA levels in the late 20th century in good agreement with reconstructions (Kinnard et al., 2011). Additionally, we can conclude that profound NASIE reduction leads to SPG weakening in our model simulations.

To support these findings, we conducted the last millennium simulations without prescribed atmospheric variability for TSI and volcanic forcing separately (including anthropogenic CO_2 forcing). As shown in Fig. 3, there is little to no variability in the TSI forcing only scenario, whereas in the volcanic forcing only run a sea-ice increase, SPG spin-up and AMO reduction cascade is induced by a series of volcanic eruptions in the early 17th century.

4 Discussion

The AMOC has been found to be very sensitive to the sea-ice extent in the northern convection region in a variety of climate models (Oka et al., 2012), and it has been proposed by Zhong et al. (2010) that the sea-ice increase due to decadally paced volcanism might have been the trigger of a persistent AMOC weakening during the LIA. As an initial response to a major volcanic eruption we also find a substantial increase in sea-ice extent in the western Nordic Seas, in particular over the Nordic Seas convection sites as shown in Fig. 4a. This increase in sea-ice cover reduces ocean heat release and thereby hinders convection (Marotzke, 2012). Consequently, overflows over the Greenland-Scotland-ridge are reduced, and a cascade of feedbacks leads to increased subpolar convection and a spin-up of the SPG as described in Levermann and Born (2007). Nevertheless, like in the CCSM3 model investigated in Zhong et al. (2010), the impact of single volcanic eruptions is too short-lived to trigger such a regime shift, but a cascade of volcanic eruptions with only a few years distance between the individual eruptions appears to be sufficient. Our findings are in line with results of a modeling study by Goosse et al. (2012), who report a SPG regime change between MCA and LIA in the LOVECLIM model.

To test this hypothesis we prescribed JFM winter sea-ice coverage over the northern convection region (Fig. 4a grey box) to be fully covered as after volcanic eruptions in a control run with constant TSI and without prescribed atmospheric variability. As depicted in Fig. 4b, such an abrupt increase in sea-ice leads to a reduction in the overflows with a lag of several years, a slowing down of the AMOC and a spin-up of the SPG on multi-decadal time-scales (solid line). We stopped this artificial prescription after 15 yr (dashed line) and found this forcing period to be sufficient to trigger the feedback cascade. Unlike the abrupt strengthening of the SPG in the continuous scenario after 50 yr (Fig. 4e), the SPG spin-up for the 15-yr scenario is more uniform. The persistent increase in sea-ice for the continuous scenario leads to an increased sea-ice export to the subpolar North Atlantic that weakens subpolar convection and blocks the SPG spin-up for several decades.

A sea-ice forcing period of 5 yr that can be taken as a single-eruption scenario (Fig. 4 dotted lines) is found to be insufficient to trigger our sea ice-ocean feedbacks and all relevant quantities are found to recover on decadal timescales. Our conceptual experiment therefore supports the suggestion by Zhong et al. (2010) that decadally paced volcanic forcing can lead to North Atlantic regime shifts that persist on a centennial time-scale. However, the dynamic of the SPG in the experiments deduced by Zhong et al. (2010) are opposite to our findings. They report a weakening of the overflows and the subpolar overturning cell as a reaction to volcanic forcing, the latter induced by increased sea-ice export to the Labrador Sea through the East Greenland Current. Even though we also find an increase in the annual Nordic Seas sea-ice export from 12.6 mSv freshwater equivalent in the 12th century to 15.6 mSv freshwater equivalent in the 19th century, this additional sea-ice is not reaching our subpolar convection site but is limited to the boundary current. We cannot rule out that this result is due to the displacement of our subpolar convection site from the Labrador Sea to the central Irminger Sea, but recent results of a high resolution model study support our finding of an anti-correlation of AMOC and SPG dynamics (Zhang et al., 2011b). Additionally, observations combined with high-resolution modeling do not indicate a correlation between AMO and SPG over the last 50 yr (Hátún et al., 2009). Model studies of the North Atlantic during the Eemian also highlight the importance of sea-ice dynamics for the AMOC (Born et al., 2009).

5 Conclusions

There is a growing body of evidence for the importance of volcanic eruptions as a pacemaker of North Atlantic climate variability on centennial timescales (e.g. Otterå et al., 2010; Mignot et al., 2011; Zhong et al., 2010) and that changes in the TSI are of minor importance. Here, we conducted model experiments indicating that pure TSI changes alone can not explain the pronounced North Atlantic cooling during the LIA, but that volcanic eruptions triggered local sea ice-ocean feedbacks that ultimately led to a persistent hemisphere-wide cooling. This finding highlights the importance of the AMOC internal variability and the North Atlantic and Arctic circulation system for the global climate. By utilizing reconstructions of atmospheric variability we were also able to identify a sea ice-oceanic feedback that was found to be crucial to reproduce a slowing down of the AMOC during the LIA as it is present in multi-proxy reconstructions. This is in good agreement with Palastanga et al. (2011), who report that a persistent negative NAO phase alone is insufficient to explain the LIA in a model study, but that additional AMOC weakening is necessary.

We also found our model experiment to be very sensitive to small changes in the Nordic Seas freshwater budget and sea-ice extent. This sensitivity might in part be model dependent, but in the light of the major changes in both Arctic freshwater budget (Curry and Mauritzen, 2005) and sea-ice extent (NSIDC, 2012) due to anthropogenic global warming, it raises the question, if these regional changes might have hemispheric impacts as they presumably had in the past.

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References

Born, A., Nisancioglu, K. H., and Braconnot, P.: Sea ice induced changes in ocean circulation during the Eemian, Clim. Dynam., 35, 1361–1371, doi:10.1007/s00382-009-0709-2, 2009. 6208

Born, A., Stocker, T. F., Raible, C. C., and Levermann, A.: Is the Atlantic subpolar gyre bistable in comprehensive coupled climate models?, Clim. Dynam., online first: doi:10.1007/s00382-012-1525-7, 2012. 6205

Broecker, W.: Was a change in thermohaline circulation responsible for the Little Ice Age?, P. Natl. Acad. Sci., 97, 1339–1342, 2000. 6201

Büntgen, U.: 2500 Years of European Climate Variability and Human Susceptibility, Science, 331, 578–582, doi:10.1126/science.1197175, 2011. 6200

Crowley, T.: Causes of climate change over the past 1000 years, Science, 289, 270–277, doi:10.1126/science.289.5477.270, 2000. 6201, 6203

Curry, R. and Mauritzen, C.: Dilution of the northern North Atlantic Ocean in recent decades, Science, 308, 1772–1774, doi:10.1126/science.1109477, 2005. 6204, 6209

de Boyer Montégut, C., Madec, G., Fischer, A., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, J. Geophys. Res., 109, C12003, doi:10.1029/2004JC002378, 2004. 6202

Eby, M., Weaver, A. J., Alexander, K., Zickfeld, K., Abe-Ouchi, A., Cimatoribus, A. A., Crespin, E., Drijfhout, S. S., Edwards, N. R., Eliseev, A. V., Feulner, G., Fichefet, T., Forest, C. E., Goosse, H., Holden, P. B., Joos, F., Kawamiya, M., Kicklighter, D., Kienert, H., Matsumoto, K., Mokhov, I. I., Monier, E., Olsen, S. M., Pedersen, J. O. P., Perrette, M., Philippon-Berthier, G., Ridgwell, A., Schlosser, A., Schneider von Deimling, T., Shaffer, G., Smith, R. S., Spahni, R., Sokolov, A. P., Steinacher, M., Tachiiri, K., Tokos, K., Yoshimori, M., Zeng, N., and Zhao, F.: Historical and idealized climate model experiments: an EMIC intercomparison, Clim. Past Discuss., 8, 4121–4181, doi:10.5194/cpd-8-4121-2012, 2012. 6202

Eddy, J.: The maunder minimum, Science, 192, 1189–1202, 1976. 6201

Fernández-Donado, L., González-Rouco, J. F., Raible, C. C., Ammann, C. M., Barriopedro, D., García-Bustamante, E., Jungclaus, J. H., Lorenz, S. J., Luterbacher, J., Phipps, S. J., Servonnat, J., Swingedouw, D., Tett, S. F. B., Wagner, S., Yiou, P., and Zorita, E.: Temperature response to external forcing in simulations and reconstructions of the last millennium, Clim. Past Discuss., 8, 4003–4073, doi:10.5194/cpd-8-4003-2012, 2012. 6201

Feulner, G.: Are the most recent estimates for Maunder Minimum solar irradiance in agreement with temperature reconstructions?, Geophys. Res. Lett., 38, L16706, doi:10.1029/2011GL048529, 2011. 6201, 6203

Fichefet, T. and Maqueda, M. A. M.: Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics, J. Geophys. Res., 102, 12609–12646, 1997. 6202

Goosse, H., Crespin, E., Dubinkina, S., Loutre, M.-F., Mann, M. E., Renssen, H., Sallaz-Damaz, Y., and Shindell, D.: The role of forcing and internal dynamics in explaining the “Medieval

Climate Anomaly”, Clim. Dynam., 39, 2847–2866, doi:10.1007/s00382-012-1297-0, 2012. 6207

Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G. A., Shindell, D., Geel, B. V., and White, W.: Solar influences on climate, Rev. Geophys., 48, RG4001, doi:10.1029/2009RG000282, 2010. 6201

Gregory, J. M., Dixon, K. W., Stouffer, R., Weaver, A., Driesschaert, E., Eby, M., Fichefet, T., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. H., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Sokolov, A. P., and Thorpe, R. B.: A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration, Geophys. Res. Lett., 32, L12703, doi:10.1029/2005GL023209, 2005. 6202

Hátún, H., Payne, M., Beaugrand, G., Reid, P., Sandø, A., Drange, H.,Hansen, B., Jacobsen, J., and Bloch, D.: Large bio-geographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales, Prog. Oceanogr., 80, 149–162, doi:10.1016/j.pocean.2009.03.001, 2009. 6208

Hofer, D., Raible, C. C., and Stocker, T. F.: Variations of the Atlantic meridional overturning circulation in control and transient simulations of the last millennium, Clim. Past, 7, 133–150, doi:10.5194/cp-7-133-2011, 2011. 6201

Hurrel, J.: NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA. Updated regularly available at: http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-pc-based (last access: 20 May 2012), 2012. 6203

Hurrell, J. and Deser, C.: North Atlantic climate variability: the role of the North Atlantic Oscillation, J. Marine Syst., 78, 28–41, doi:10.1016/j.jmarsys.2008.11.026, 2009. 6203

Jansen, E., Overpeck, J., Briffa, K. R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W. R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., and Zhang, D.: Palaeoclimate, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007. 6201, 6202

Jones, P. and Mann, M.: Climate over past millennia, Rev. Geophys., 42, RG2002, doi:10.1029/2003RG000143, 2004. 6200

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, B. Am. Meteorol. Soc., 77, 437–471, 1996. 6203

Kinnard, C., Zdanowicz, C. M., Fisher, D. A., Isaksson, E., de Vernal, A., and Thompson, L. G.: Reconstructed changes in Arctic sea ice over the past 1,450 years, Nature, 479, 509–512, doi:10.1038/nature10581, 2011. 6202, 6206

Kopp, G. and Lean, J.: A new, lower value of total solar irradiance: evidence and climate significance, Geophys. Res. Lett., 38, L01706, doi:10.1029/2010GL045777, 2011. 6204

Levermann, A. and Born, A.: Bistability of the subpolar gyre in a coarse resolution climate model, Geophys. Res. Lett., 34, L24605, doi:10.1029/2007GL031732, 2007. 6205, 6207

Lund, D., Lynch-Stieglitz, J., and Curry, W.: Gulf Stream density structure and transport during the past millennium, Nature, 444, 601–604, doi:10.1038/nature05277, 2006. 6201

Macias Fauria, M., Grinsted, A., Helama, S., Moore, J., Timonen, M., Martma, T., Isaksson, E., and Eronen, M.: Unprecedented low twentieth century winter sea ice extent in the Western Nordic Seas since A.D. 1200, Clim. Dynam., 34, 781–795, doi:10.1007/s00382-009-0610-z, 2009. 6202, 6205

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256–60, doi:10.1126/science.1177303, 2009. 6205, 6216, 6217

Marotzke, J.: Climate science: A grip on ice-age ocean circulation, Nature, 485, 180–181, doi:10.1038/485180a, 2012. 6207

Menary, M. B., Park, W., Lohmann, K., Vellinga, M., Palmer, M. D., Latif, M., and Jungclaus, J. H.: A multimodel comparison of centennial Atlantic meridional overturning circulation variability, Clim. Dynam., 38, 2377–2388, doi:10.1007/s00382-011-1172-4, 2011. 6201

Mengel, M., Levermann, A., Schleussner, C.-F., and Born, A.: Enhanced Atlantic subpolar gyre variability through baroclinic threshold in a coarse resolution model, Earth Syst. Dynam., 3, 189–197, doi:10.5194/esd-3-189-2012, 2012. 6204, 6205

Mignot, J., Khodri, M., Frankignoul, C., and Servonnat, J.: Volcanic impact on the Atlantic Ocean over the last millennium, Clim. Past, 7, 1439–1455, doi:10.5194/cp-7-1439-2011, 2011. 6201, 6208

Miller, G. H., Geirsdóttir, A., Zhong, Y., Larsen, D. J., Otto, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., and John, R.: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, Geophys. Res. Lett, 39, L02708, doi:10.1029/2011GL050168, 2012. 6206

Montoya, M., Griesel, A., Levermann, A., Mignot, J., Hofmann, M., Ganopolski, A., and Rahmstorf, S.: The Earth System Model of Intermediate Complexity CLIM*BER*-3α. Part I: description and performance for present day conditions, Clim. Dynam., 25, 237–263, doi:10.1007/s00382-005-0044-1,2005. 6202

Msadek, R. and Frankignoul, C.: Atlantic multidecadal oceanic variability and its influence on the atmosphere in a climate model, Clim. Dynam., 33, 45–62, doi:10.1007/s00382-008-0452-0, 2009. 6205

NSIDC: The National Snow and Ice Data Center University of Colorado, Boulder, available at: http://www.nsidc.org/ (last access: 14 October 2012), 2012. 6209

Oka, A., Hasumi, H., and Abe-Ouchi, A.: The thermal threshold of the Atlantic meridional overturning circulation and its control by wind stress forcing during glacial climate, Geophys. Res. Lett., 39, L09709, doi:10.1029/2012GL051421, 2012. 6207

Olsen, J., Anderson, N. J., and Knudsen, M. F.: Variability of the North Atlantic Oscillation over the past 5,200 years, Nat. Geosci., 5, 808–812, doi:10.1038/ngeo1589, 2012. 6201

Ortega, P., Montoya, M., González-Rouco, F., Mignot, J., and Legutke, S.: Variability of the Atlantic meridional overturning circulation in the last millennium and two IPCC scenarios, Clim. Dynam., 38, 1925–1947, doi:10.1007/s00382-011-1081-6, 2011. 6201

Otterå, O., Bentsen, M., Drange, H., and Suo, L.: External forcing as a metronome for Atlantic multidecadal variability, Nat. Geosci., 3, 688–694, doi:10.1038/ngeo955, 2010. 6201, 6206, 6208

Pacanowski, R. C. and Griffies, S. M.: The MOM-3 manual, Tech. Rep. Tech. Rep. 4, NOAA/Geophyical Fluid Dynamics Laboratory, Princeton, NJ, USA, 1999. 6202

Palastanga, V., Van der Schrier, G., Weber, S., Kleinen, T., Briffa, K., and Osborn, T.: Atmosphere and ocean dynamics: contributors to the European Little Ice Age?, Clim. Dynam., 36, 973–987, doi:10.1007/s00382-010-0751-0, 2011. 6209

Park, W. and Latif, M.: Atlantic Meridional Overturning Circulation response to idealized external forcing, Clim. Dynam., 39, 1709–1726, doi:10.1007/s00382-011-1212-0, 2011. 6205

Parker, D., Folland, C., Scaife, A., Knight, J., Colman, A., Baines, P., and Dong, B.: Decadal to multidecadal variability and the climate change background, J. Geophys. Res., 112, 1–18, D18115, doi:10.1029/2007JD008411, 2007. 6201

Petoukhov, V., Ganopolski, A., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., and Rahmstorf, S.: CLIMBER-2: a climate system model of intermediate complexity. Part I: model description and performance for present climate, Clim. Dynam., 16, 1–17, doi:2000.10.1007/PL00007919 2000. 6202

Robock, A.: The "little ice age": northern hemisphere average observations and model calculations., Science, 206, 1402–1404, doi:10.1126/science.206.4425.1402, 1979. 6201

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0), Geosci. Model Dev., 4, 33–45, doi:10.5194/gmd-4-33-2011, 2011. 6203

Schulz, M., Prange, M., and Klocker, A.: Low-frequency oscillations of the Atlantic Ocean meridional overturning circulation in a coupled climate model, Clim. Past, 3, 97–107, doi:10.5194/cp-3-97-2007, 2007. 6205

Steinhilber, F., Beer, J., and Fröhlich, C.: Total solar irradiance during the Holocene, Geophys. Res. Lett., 36, L19704, doi:10.1029/2009GL040142, 2009. 6203, 6216

Stouffer, R. J., Yin, J., Gregory, J. M., Dixon, K. W., Spelman, M. J., Hurlin, W., Weaver, A. J., Eby, M., Flato, G. M., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Peltier, W. R., Robitaille, D. Y., Sokolov, A. P., Vettoretti, G., and Weber, S. L.: Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes, J. Climate, 19, 1365–1387, doi:10.1175/JCLI3689.1, 2006. 6202

Trenberth, K., Olson, J., and Large, W.: A Global Ocean Wind Stress Climatology based on ECMWF Analysis, Tech. Rep. NCAR/TN-338+STR, National Center for Atmospheric Research, Boulder, Colorado, USA, 1989. 6204

Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., and Frank, D. C.: Persistent positive North Atlantic oscillation mode dominated the Medieval Climate Anomaly, Science, 324, 78–80, doi:10.1126/science.1166349, 2009. 6201, 6203, 6204, 6216

Wang, Y., Lean, J., and Sheeley Jr., N.: Modeling the sun's magnetic field and irradiance since 1713, Astrophys. J., 625, p. 522, doi:10.1086/429689, 2008. 6203

Zhang, D. D., Lee, H. F., Wang, C., Li, B., Pei, Q., Zhang, J., and An, Y.: The causality analysis of climate change and large-scale human crisis, 108, 17296–17301, doi:10.1073/pnas.1104268108, 2011. 6200

Zhang, R., Delworth, T., Rosati, A., Anderson, W., Dixon, K., Lee, H., and Zeng, F.: Sensitivity of the North Atlantic Ocean Circulation to an abrupt change in the Nordic Sea overflow in a high resolution global coupled climate model, J. Geophys. Res., 116, 1–14, C12024, doi:10.1029/2011JC007240, 2011. 6208

Zhong, Y., Miller, G. H., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Schneider, D. P., Geirsdottir, A., and Dyn, C.: Centennial-scale climate change from decadally-paced explosive volcanism: a coupled sea ice-ocean mechanism, Clim. Dynam., 37, 2373–2387, doi:10.1007/s00382-010-0967-z, 2010. 6201, 6207, 6208

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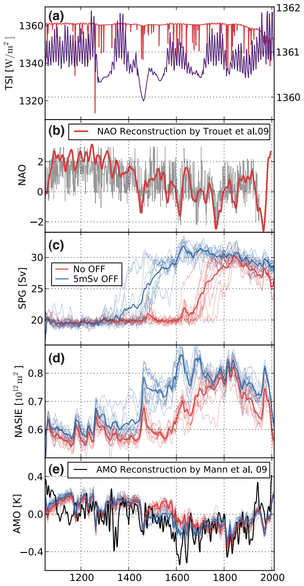

Fig. 1. Transient model results of the last millennium with prescribed TSI, CO_2 and wind-field forcing applied. **(a)** The TSI forcing time series by Steinhilber et al. (2009) (purple) and the full top-of-the-atmosphere short-wave TSI forcing including aerosols from volcanic eruptions and anthropogenic emission (red). **(b)** Based on NAO reconstructions by Trouet et al. (2009) (red) and NCEP/NCAR reanalysis data, wind-field patterns were stochastically constructed as described in Sect. 2. Out of ten ensemble members, one NAO time series is shown in grey for comparison. **(c)** The SPG dynamics for an ensemble with an additional 5mSv freshwater offset in the Nordic Seas (blue) and without freshwater offset (red, individual ensemble members in light red, thick lines: ensemble mean). **(d)** The North Atlantic Sea-Ice Extent (NASIE) with and without freshwater offset. **(e)** AMO anomalies in comparison with the reconstructed AMO index by Mann et al. (2009).

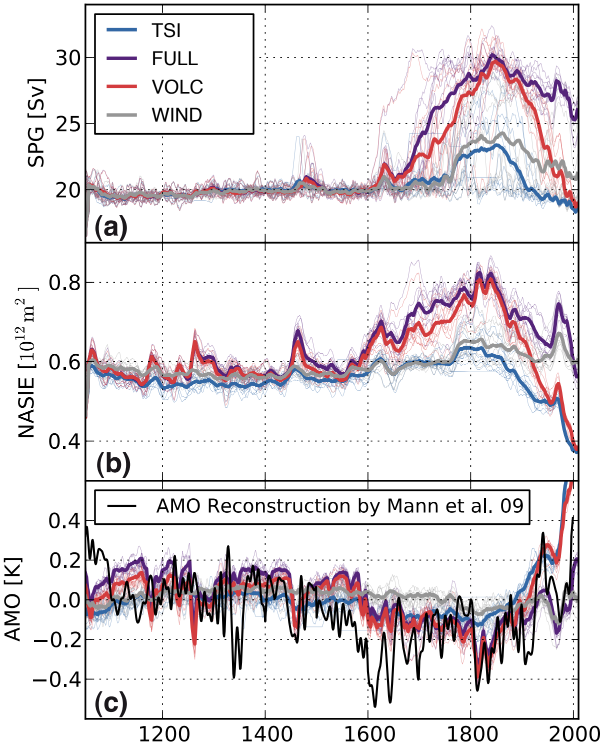

Fig. 2. To identify the driving processes behind SPG and AMO dynamics, the different forcings applied are treated separately (bold: ensemble mean, light: individual members). Pure prescribed wind forcing (WIND) is shown in grey, wind plus changes in the solar irradiance only (TSI) in blue, wind plus volcanic forcing in red (VOLC) and the combination of all forcings (FULL) in purple. Anthropogenic CO_2 is applied in TSI, VOLC and FULL. **(a)** SPG, **(b)** NASIE and **(c)** AMO anomalies in comparison with the reconstruction time series by Mann et al. (2009).

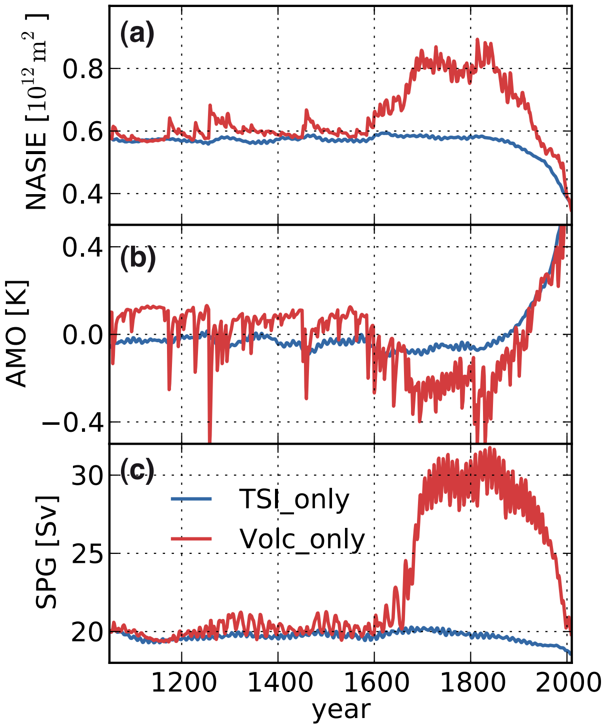

Fig. 3. Last millennium simulations for TSI (blue) and volcanic (red) forcing only without prescribed winds. **(a)** NASIE, **(b)** AMO anomalies and **(c)** SPG.

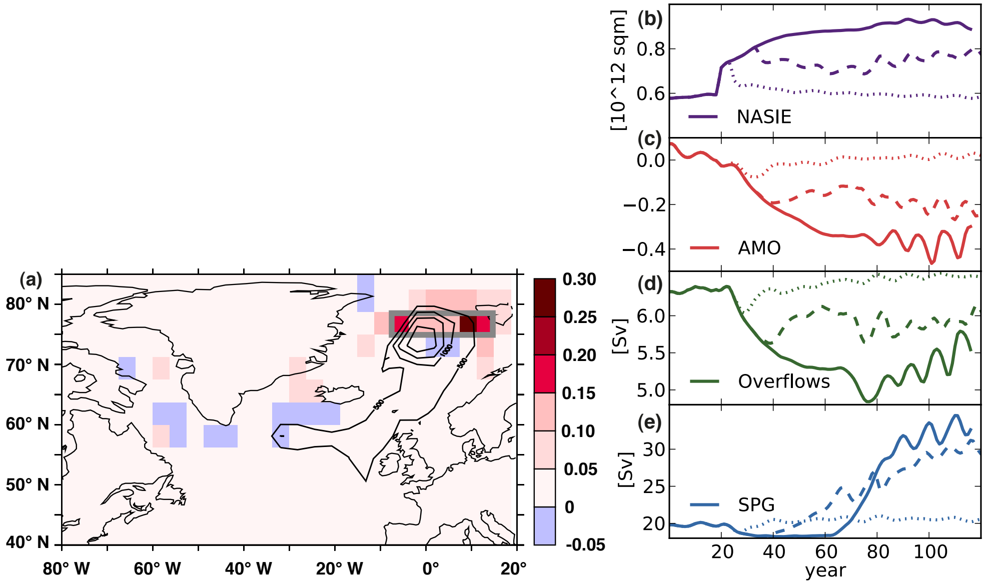

Fig. 4. (a) Difference in annual NASIE between a decade following a major volcanic eruption (1460–1470) and a reference decade (1440–1450). The overall NASIE increase is particularly strong west from Svalbard, which is a key region for deep water formation in our model (February mixed layer depth of the control run overlaid). In a conceptual experiment, the sea-ice extent in this region (grey box) was artificially set to LIA – levels starting from the year 1050. Continuous (straight line), 15 yr (dashed) and 5 yr forcings (dotted) are compared. Constant and 15 yr forcing eventually leads to a rapid increase of NASIE **(a)**, to a reduction in the GSR-overflows **(b)**, in the AMO **(c)** and to a SPG spin-up **(d)**.