GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L12803, doi:10.1029/2011GL047764, 2011

Influence of subtropical and polar sea-surface temperature anomalies on temperatures in Eurasia

Jan Sedláček,[1] Olivia Martius,[2] and Reto Knutti[1]

Received 12 April 2011; revised 11 May 2011; accepted 12 May 2011; published 23 June 2011.

[1] In summer 2010 an exceptional heatwave occurred over western Russia. At the same time sea-surface temperatures (SSTs) were anomalously warm in the Barents Sea and the Arabian Sea. We investigate a possible link between these two SST anomalies by prescribing SST anomalies separately and combined in an ensemble of climate model simulations. The positive surface air temperature response over western Russia is strengthened if both SST forcings are combined. While the SST anomalies in the Arabian Sea are likely due to natural variability the sea surface in the Barents Sea is expected to warm in future and the sea-ice cover to decline enhancing the warming. Thus, we hypothesize that heatwaves over Europe and Russia will likely become more frequent as a result of the dynamic response of the atmosphere in addition to what is expected from the change in mean temperature. **Citation:** Sedláček, J., O. Martius, and R. Knutti (2011), Influence of subtropical and polar sea-surface temperature anomalies on temperatures in Eurasia, *Geophys. Res. Lett.*, *38*, L12803, doi:10.1029/2011GL047764.

1. Introduction

[2] During the summer of 2010 several extreme weather events occurred in the Northern Hemisphere. A heatwave in western Russia with record temperatures led to severe forest fires. *Barriopedro et al.* [2011] show that the heatwave over Russia was unprecedented compared to temperature reconstructions from the last half millennia. In Pakistan several intense precipitation events resulted in severe floods, further west Japan recorded the warmest summer since 1898, and heavy precipitation events in China caused land slides (http://www.ncdc.noaa.gov/oa/reports/weather-events.html).

[3] In late spring the sea-ice cover in the Barents Sea was anomalously low and sea-surface temperatures (SSTs) were approximately 3°C warmer than the 1980–2009 climatology. *Stroeve et al.* [2011] report a 40% decrease in sea-ice concentration and 2–3°C warmer surface air temperatures (SATs) in the Barents Sea during the previous winter, mostly due to atmospheric circulation changes. Concomitantly, the Indian Ocean was warmer than climatology during summer 2010 as it is often observed when a La Niña is present in the Pacific Ocean [e.g., *Yoo et al.*, 2010]. Using observed SST and ice concentration, *Dole et al.* [2011] suggest that the heatwave in summer 2010 was not predictable or at least only on short lead time [*Matsueda*, 2011].

[4] SST anomalies in the Indian Ocean can affect SATs over Europe and Asia [e.g., *Black and Sutton*, 2007; *Yun et al.*, 2010]. Positive SST anomalies can invigorate convection. The resulting upper-level response is an anticyclone located to the northwest of the heating maximum [*Hoskins and Karoly*, 1981]. The interaction of this anticyclone with the upper-level jet leads to areas of dynamically forced descent and warming over the Mediterranean and the Sahara [e.g., *Rodwell and Hoskins*, 1996]. Common to all the studies mentioned above is that the location of the SAT response to a SST anomaly is dependent on the background flow.

[5] The effect of extratropical SST anomalies on the circulation is more complex and often two-tiered. An initially shallow baroclinic response in the form of a local surface pressure reduction is gradually replaced by larger-amplitude barotropic anomalies forced through eddy vorticity fluxes [e.g., *Deser et al.*, 2007; *Kushnir et al.*, 2002, and references therein]. In winter the barotropic response typically projects strongly onto the leading modes of internal variability. Few studies have investigated the response of the summer circulation to a reduction of sea-ice concentration and anomalies in the SST fields in the polar region. *Bhatt et al.* [2008] find that summertime flow response to sea-ice anomalies does not project on the internal variability.

[6] Here we study the individual and combined role of the SST anomalies in the Barents Sea and the Arabian Sea in influencing the SAT over Eurasia, by forcing the CCSM (Community Climate System Model) with SST anomalies.

2. Model and Experimental Setup

[7] We use the NCAR CCSM4 model with prescribed ocean and ice components and interactive atmospheric and land components. The resolution is 1.9° in latitude and 2.5° in longitude. We branch every two to three years three experiments from a long equilibrium control simulation with climatological SSTs and sea-ice concentrations, leading to 36 ensembles per experiment.

[8] In the BAR experiment the SSTs are increased by 2°C from May to August in a box in the Barents Sea. Additionally, the sea-ice concentration in the Barents Sea is modified to roughly correspond to the satellite observations. In the IND experiment the SSTs in the Arabian Sea are increased by 2°C from May to August. The reanalysis shows a warm anomaly of about 3°C in the Barents Sea and an anomaly of about 1.5°C in the Arabian Sea. The SST anomalies are shown in Figure S1 of the auxiliary material.[1] Finally, the BAR and IND anomalies combined form the

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.
[2]Oeschger Center for Climate Change Research, University of Berne, Bern, Switzerland.

0094-8276/11/2011GL047764

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047764.

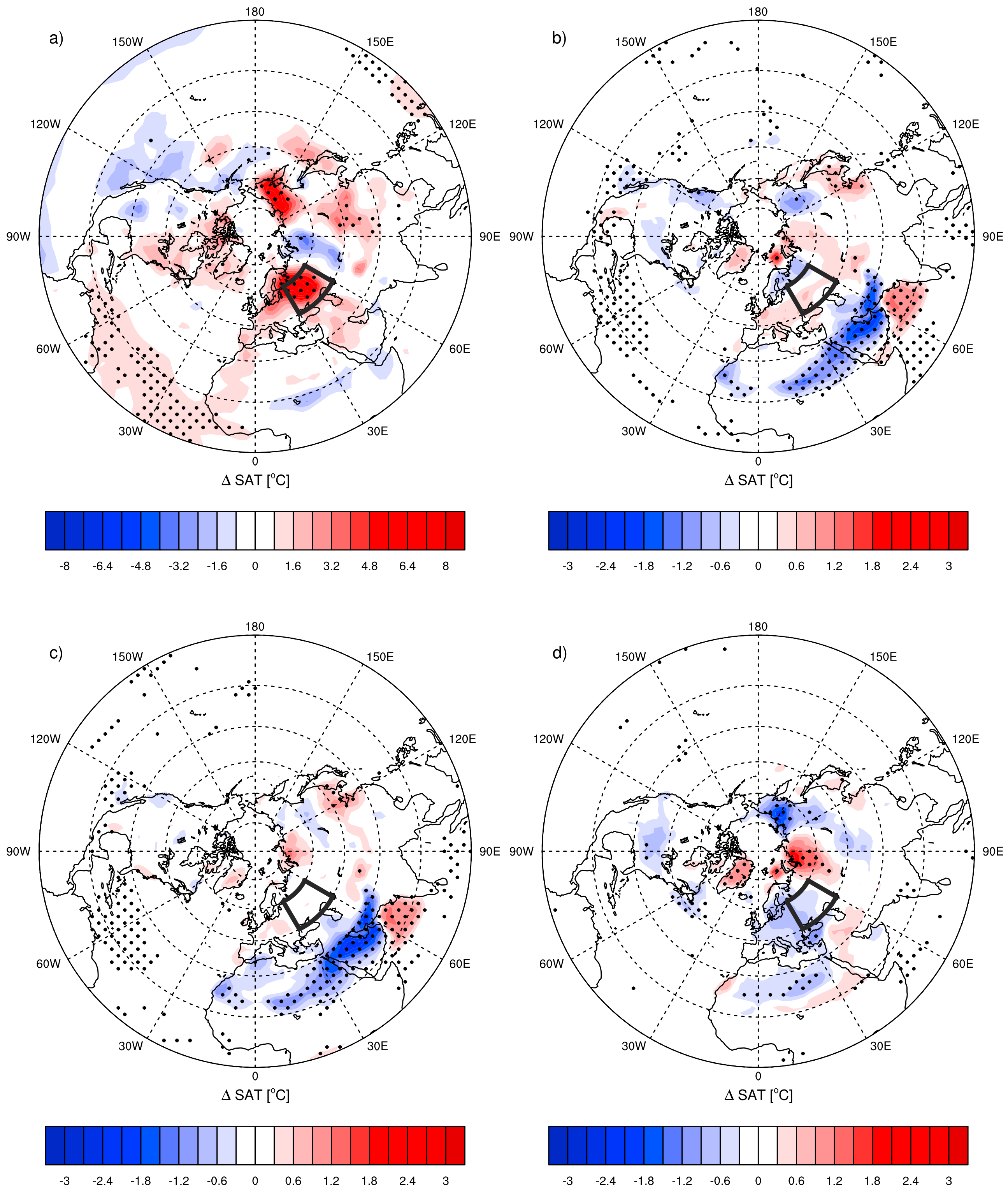

Figure 1. SAT anomalies for July (a) NCEP/NCAR anomalies with respect to the climatology of 1980–2009, ensemble means of (b) the TOT simulation, (c) the IND simulation, and (d) the BAR simulation. Note the different color bars. The dots in Figure 1a denote regions where the anomalies exceed the 95% percentile of the climatological variability. In Figures 1b–1d the dots denote regions where the anomalies are significant at 95% confidence using a t-test. The boxes mark the region from 45°N to 60°N and from 30°E to 60°E.

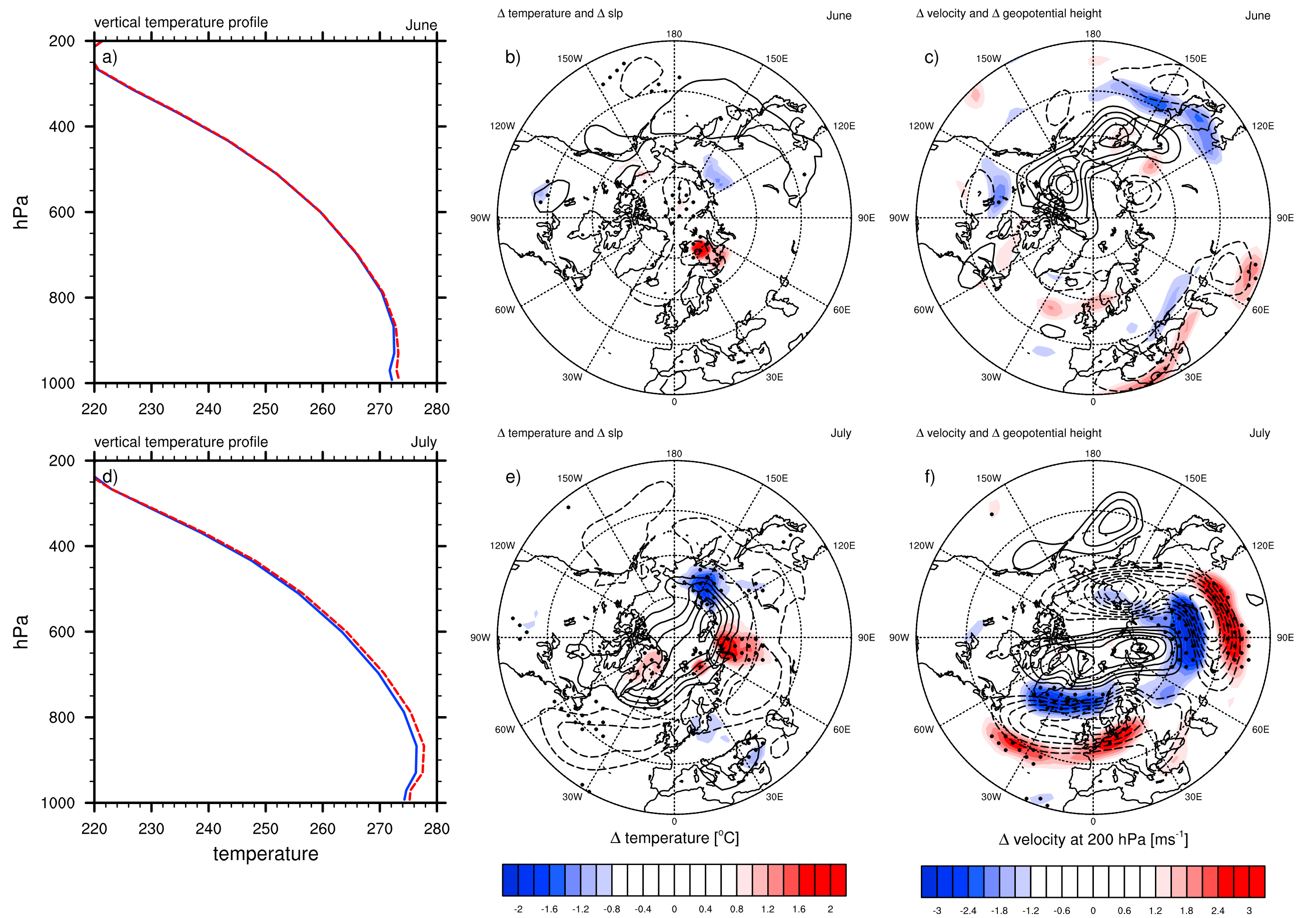

Figure 2. Atmospheric fields for the BAR simulations. (top) The June anomalies and (bottom) the July anomalies. (a, d) The vertical temperature profiles over the region of the SST perturbation. The blue line is the unperturbed ensemble mean and the red line denotes the perturbed ensemble mean. (b, e) The temperature (colored contours) and pressure (contour lines; interval 0.6 hPa, zero contour is not plotted) anomalies at the surface. (c, f) The velocity (colored contours) and geopotential height (contour lines; interval 5 m, contour lines between −10 m and 10 m are not plotted) anomalies at 200 hPa. The negative contour lines are dashed. The values plotted are ensemble mean values and the dots denote regions where the anomalies are significant at 95% confidence using a t-test.

TOT simulation. Note, that we are not prescribing explicitly a La Niña state in the Pacific which was in place in summer 2010. However, positive SST anomalies in the Indian Ocean are linked to La Niña events [e.g., *Yoo et al.*, 2010].

3. Results

3.1. Surface Air Temperature Response

[9] The July SAT anomalies from NCEP/NCAR and the modeled SAT anomalies are shown in Figure 1. The NCEP/NCAR anomalies are calculated with respect to the 1980–2009 climatology. The observed SAT anomalies show a wave-like pattern over Eurasia with a significant positive anomaly over Russia. The TOT simulations reproduce the warm anomalies over Russia and near Japan. The distinct cold anomaly located over the Arabian Peninsula and northern Africa is a response to the SST forcing in the Arabian Sea (see Figure 1c) and is discussed in section 3.3. In the IND experiments there is a slight warming over Europe. The BAR experiment shows a wave-like sequence of anomalies resembling those found in NCEP/NCAR but with inverse polarity and much smaller amplitude. Since our forcing is idealized we do not expect to reproduce the exact climatic fields of summer 2010. Even for prescribed SST and sea ice in 2010 one would not expect to fully reproduce the observed heat wave [*Dole et al.*, 2011] given the large internal variability. The aim of this study is to investigate the mechanism by which the BAR and IND anomalies change the probability or magnitude of such an event, which is similar to the idea of single event attribution [e.g., *Stott et al.*, 2004].

[10] In our experimental setup the SST anomalies are imposed on a climatological SST field. Hence, feedbacks with the ocean are not possible. Apart from the forcing areas, the SAT response over the ocean will be damped.

3.2. Positive SST and Negative Sea-Ice Anomalies in the Barents Sea

[11] In the model climatology a low-level inversion is present in June over the Barents Sea. The SST forcing overcomes the inversion (Figure 2a) and leads to the formation of a small cyclonic anomaly over the Barents Sea which

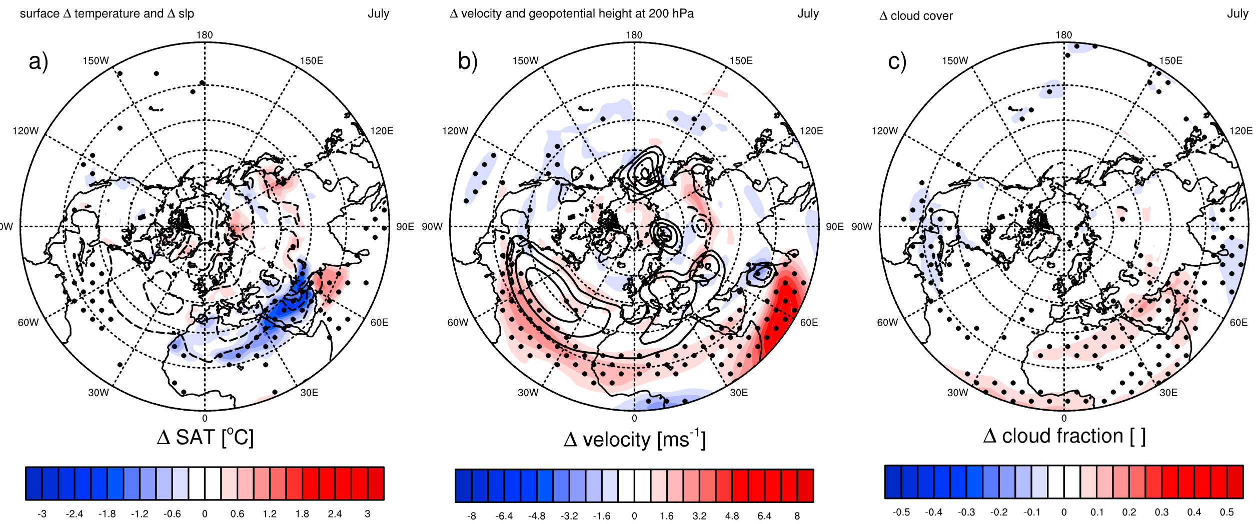

Figure 3. Ensemble mean of the July anomaly fields for the IND simulation. (a) The temperature (colored) and pressure (contour lines; interval 0.8 hPa, zero contour is not plotted) at the surface, (b) velocity (colored) and geopotential at 200 hPa (contour lines; interval 10 m, contour lines between −20 m and 20 m are not plotted), and (c) cloud cover fraction. The dots denote regions where the anomalies are significant at 95% confidence using a t-test.

advects warm continental air northwards (Figure 2b). A second cyclonic anomaly in the Arctic Basin advects colder Arctic air southwards. The vertical structure of the response to the SST anomaly is baroclinic (compare Figures 2b and 2c).

[12] In July the baroclinic response becomes barotropic. A similar transition time period was reported by *Deser et al.* [2007] for a winter anomaly. The barotropic response at upper-levels resembles a negative Arctic Oscillation (AO)-like pattern, shifting the jet southward (Figure 2f). The SAT anomaly pattern is driven by temperature advection (Figure 2e). The structure of the anomaly pattern strongly resembles the primary pattern of model variability (not shown).

[13] The mean temperature response at the surface is weak and exhibits large variability. Hence, we compute two composites of nine members each to investigate why some BAR simulations show a warming over Russia while others show a cooling. The cold composite behaves similar to the whole ensemble (see Figure S2 of the auxiliary material). The warm composite on the other hand, shows no inversion near the ground in the unperturbed state and the barotropic response in July produces a wave-like response aloft (see Figure S3 of the auxiliary material). Near the ground a cyclonic (anticyclonic) anomaly in the cold (warm) composite results in cold (warm) temperature advection over Russia. It is interesting that in the two composites the SAT anomalies are of opposite sign in June and July, i.e., a warm July over Russia is preceded by a cold June over that region.

3.3. Positive SST Anomaly in the Arabian Sea

[14] In the IND simulations there is a significant positive SAT anomaly over the region of the positive SST anomaly and a negative SAT anomaly over the Arabian Peninsula and northern Africa (Figure 3a). The weaker positive SAT anomaly over Europe is not statistically significant.

[15] The warm SST anomaly in the Arabian Sea enhances convection over that region. The resulting divergent motion at upper levels induces an anticyclonic flow anomaly to the northwest extending from the Caspian Sea towards Europe and northern Africa (Figure 3b). This anomaly enhances the climatological subtropical anticyclone and affects the subtropical jet located at the northern edge of the anticyclone. Compared to the control experiment the jet is shifted northwards over western Russia (Figure 3b).

[16] Anomalously high cloud fractions (mainly high clouds) cover the area of the negative SAT anomalies, indicating that a decrease in incoming shortwave radiation might be responsible for the negative temperature anomaly (Figure 3c).

4. Discussion and Conclusion

[17] The SAT anomaly pattern of the TOT simulation is not a linear combination of the BAR and IND experiments. The perturbation from the Arabian Sea dominates the response (Figure 1). This may be due to several reasons. The spatial extent of the anomaly in the Arabian Sea is roughly five times larger than the one in the Barents Sea. Thus, the amount of heat inserted into the atmosphere is much larger over the Arabian Sea. Furthermore, the SST anomaly in the Barents Sea can only trigger a significant disturbance of the upper-level flow once the baroclinic response affects the storm track and the barotropic, eddy driven response sets in [e.g., *Deser et al.*, 2007]. The subtropical anomaly on the other hand is affecting the upper-level flow directly and instantaneously.

[18] The response to the Barents Sea SST anomaly is linked to the disappearance of the low-level stability of the atmosphere. *Serreze et al.* [1992] report that in summer, the strength of the inversion over the Barents Sea is about 2°C. Thus, as in our experiments, a SST anomaly of 2°C can sometimes overcome the inversion and sometimes not. *DeWeaver and Bitz* [2006] found that the CCSM overestimates subsidence over the polar region and thus, potentially the strength and frequency of the inversion near

the ground. This could result in a bias for the cold composite in the model.

[19] The most interesting aspect of the non-linear response in our simulations is that the warm anomaly over Russia is strengthened if both SST anomalies are included. The dynamical link between the two anomalies is the upper-level jet which serves as waveguide for the synoptic-scale eddies that are crucial for establishing the barotropic response [e.g., *Deser et al.*, 2007; *Bhatt et al.*, 2008]. The SST anomaly over the Arabian Sea leads to a northward shift of the jet over western Russia. This can have two effects: i) A meridional shift of the jet affects the preferred type of life-cycle of the baroclinic eddies on the jet [*Rivière*, 2009]. The prevalence of one type of life-cycle over the other is central for establishing and maintaining one or the other AO phase [e.g., *Feldstein and Franzke*, 2006]. ii) The jet is in closer proximity to the circulation anomalies over the Barents Sea which potentially modifies their influence on the barotropic response.

[20] As shown in section 3.2 the barotropic response of the atmosphere to heating in the Barents Sea has an AO-like or wave-like structure with a slight preference for the negative AO anomaly pattern resulting in a negative SAT anomaly over Russia. The variability among the 36 ensemble members, however, is large and a substantial fraction of members fall into the wave-like and positive SAT anomaly category. We argue that the northward shift of the jet over Russia due to heating in the subtropics results in a preference for the wave-like anomaly pattern and positive SAT anomalies over Russia. However, the detailed role of the Barents Sea anomaly in reinforcing the barotropic response is still an open question and will be the focus of future research.

[21] The SATs in the region where the reanalysis indicates the largest warming show indeed that including both forcings yields higher temperatures as compared to the single forcing simulations (see boxes in Figure 1). The mean temperature in this region is 0.2°C and 0.5°C warmer as simulated with the Arabian Sea and Barents Sea SST forcings only. However, the median of the 90th percentile temperature of TOT is about 1°C and 1.2°C warmer as the IND and BAR.

[22] The amplitude of the SAT anomalies in the simulations is much lower than in the observations. One possibility is that this is due to model averaging. However, more likely it suggests that additional feedback mechanisms are important. Such mechanisms include land-atmosphere interactions which depend for example on the soil-moisture content [e.g., *Fischer et al.*, 2007] and land snow-cover [e.g., *Hall et al.*, 2008]. Although, the model has an interactive land component, the experimental setup does not include preconditioning.

[23] The impact of climate change on extreme weather events is a hotly debated question. The warm SST anomaly and the low sea-ice concentration in the Barents Sea in early summer seamlessly fit into the trends observed in recent years and could be an emerging climate change signal. *Steele et al.* [2008] report a warming of the peripheral Arctic Seas since 1965 and *Meier et al.* [2007] report a significant downward trend in Barents Sea-ice extent during the satellite era. A reduced sea-ice cover in the Barents Sea increases the likelihood of warm SST anomalies in that region. The SST anomaly in the Arabian Sea on the other hand is linked to the El Niño - Southern Oscillation pattern and tied to natural variability.

[24] An event like the 2010 heatwave in Russia could result from internal variability only [*Dole et al.*, 2011]. However, *Stott et al.* [2004] show that an increase in mean temperature due to greenhouse gas emissions will lead to more frequent and longer lasting heatwaves in future. In addition to that, the dynamical response to a negative trend of sea-ice concentration and a positive trend in SSTs in the Barents Sea could increase the probability of heatwaves in Russia and Europe beyond what would be expected from a shift in mean temperature.

[25] **Acknowledgments.** We thank Dennis Hartmann for the fruitful discussion in the early stage of the study, and thank Tom Chase and an anonymous reviewer for their suggestions and comments which helped to improve the paper.

[26] The Editor thanks the anonymous reviewer for their assistance in evaluating this paper.

References

Barriopedro, D., E. M. Fischer, J. Luterbacher, R. M. Trigo, and R. García-Herrera (2011), The hot summer of 2010: redrawing the temperature record map of Europe, *Science*, *332*(6026), 220–224, doi:10.1126/science.1201224.

Bhatt, U. S., M. A. Alexander, C. Deser, J. E. Walsh, J. S. Miller, M. S. Timlin, J. Scott, and R. A. Tomas (2008), The atmospheric response to realistic reduced summer Arctic sea ice anomalies, in *Arctic Sea Ice Decline: Observations, Mechanisms, and Implications*, *Geophysical Monograph Ser.*, vol. 180, edited by E. T. DeWeaver, C. M. Bitz, and L.-B. Tremblay, pp. 91–110, AGU, Washington, D. C.

Black, E., and R. Sutton (2007), The influence of oceanic conditions on the hot European summer of 2003, *Clim. Dyn.*, *28*(1), 53–66, doi:10.1007/s00382-006-0179-8.

Deser, C., R. A. Tomas, and S. Peng (2007), The transient atmospheric circulation response to North Atlantic SST and sea ice anomalies, *J. Clim.*, *20*, 4751–4767, doi:10.1175/JCLI4278.1.

DeWeaver, E. T., and C. M. Bitz (2006), Atmospheric circulation and its effect on Arctic sea ice in CCSM3 simulations at medium and high resolution, *J. Clim.*, *19*, 2415–2436.

Dole, R., M. Hoerling, J. Perlwitz, J. Eischeid, P. Pegion, T. Zhang, X.-W. Quan, T. Xu, and D. Murray (2011), Was there a basis for anticipating the 2010 Russian heat wave?, *Geophys. Res. Lett.*, *38*, L06702, doi:10.1029/2010GL046582.

Feldstein, S. B., and C. Franzke (2006), Are the North Atlantic Oscillation and the Northern Annular Mode distinguishable?, *J. Atmos. Sci.*, *63*, 2915–2930, doi:10.1175/JAS3798.1.

Fischer, E. M., S. I. Seneviratne, D. Lüthi, and C. Schär (2007), Contribution of land-atmosphere coupling to recent European summer heat waves, *Geophys. Res. Lett.*, *34*, L06707, doi:10.1029/2006GL029068.

Hall, A., X. Qu, and J. D. Neelin (2008), Improving predictions of summer climate change in the United States, *Geophys. Res. Lett.*, *35*, L01702, doi:10.1029/2007GL032012.

Hoskins, B., and D. J. Karoly (1981), The steady linear response of a spherical atmosphere to thermal and orographic forcing, *J. Atmos. Sci.*, *38*, 1179–1196.

Kushnir, Y., W. A. Robinson, I. Bladé, N. M. J. Hall, S. Peng, and R. Sutton (2002), Atmospheric GCM response to extratropical SST anomalies: Synthesis and evaluation, *J. Clim.*, *15*(16), 2233–2256.

Matsueda, M. (2011), Predictability of Euro-Russian blocking in summer of 2010, *Geophys. Res. Lett.*, *38*, L06801, doi:10.1029/2010GL046557.

Meier, W. N., J. Stroeve, and F. Fetterer (2007), Whither Arctic sea ice? A clear signal of decline regionally, seasonally and extending beyond the satellite record, *Ann. Glaciol.*, *46*(1), 428–434.

Rivière, G. (2009), Effect of latitudinal variations in low-level baroclinicity on eddy life cycles and upper-tropospheric wave-breaking processes, *J. Atmos. Sci.*, *66*, 1569–1592, doi:10.1175/2008JAS2919.1.

Rodwell, M. J., and B. J. Hoskins (1996), Monsoons and the dynamics of deserts, *Q. J. R. Meteorol. Soc.*, *122*, 1385–1404.

Serreze, M., J. Kahl, and R. Schnell (1992), Low-level temperature inversions of the Eurasian Arctic and comparisons with Soviet drifting station data, *J. Clim.*, *5*, 615–629.

Steele, M., W. Ermold, and J. Zhang (2008), Arctic Ocean surface warming trends over the past 100 years, *Geophys. Res. Lett.*, *35*, L02614, doi:10.1029/2007GL031651.

Stott, P. A., D. A. Stone, and M. R. Allen (2004), Human contribution to the European heatwave of 2003, *Nature*, *432*, 610–614.

Stroeve, J. C., J. Maslanik, M. C. Serreze, I. Rigor, W. Meier, and C. Fowler (2011), Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010, *Geophys. Res. Lett.*, *38*, L02502, doi:10.1029/2010GL045662.

Yoo, S.-H., J. Fasullo, S. Yang, and C.-H. Ho (2010), On the relationship between Indian Ocean sea surface temperature and the transition from El Niño to La Niña, *J. Geophys. Res.*, *115*, D15114, doi:10.1029/2009JD012978.

Yun, K.-S., K.-J. Ha, and B. Wang (2010), Impacts of tropical ocean warming on East Asian summer climate, *Geophys. Res. Lett.*, *37*, L20809, doi:10.1029/2010GL044931.

R. Knutti and J. Sedláček, Institute of Atmospheric and Climate Science, ETH Zurich, Universitästrasse 16, CH-8092 Zürich, Switzerland. (jan.sedlacek@env.ethz.ch)

O. Martius, Oeschger Centre for Climate Change Research, University of Berne, Zähringerstrasse 25, CH-3012 Bern, Switzerland.