Regional climate engineering by radiation management: Prerequisites and prospects

Johannes Quaas, Martin F Quaas, Olivier F Boucher, Wilfried Rickels

To cite this version:

Johannes Quaas, Martin F Quaas, Olivier F Boucher, Wilfried Rickels. Regional climate engineering by radiation management: Prerequisites and prospects. Earth's Future, 2016, 4 (12), pp.618-625. 10.1002/2016EF000440 . hal-01478786

AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2016EF000440

Special Section:

Crutzen +10: Reflecting upon 10 years of geoengineering research

Key Points:

- The article introduces the concept of regional radiation management and its prospects
- Regional-scale economic incentives are demonstrated on the basis of published data
- Feasibility and traceability of regional climate modification need to be investigated and new governance options have to be conceived

Corresponding author:

J. Quaas, johannes.quaas@uni-leipzig.de

Citation:

Quaas, J., M. F. Quaas, O. Boucher, and W. Rickels (2016), Regional climate engineering by radiation management: Prerequisites and prospects, *Earth's Future*, *4*, 618–625, doi:10.1002/2016EF000440.

Received 24 AUG 2016
Accepted 4 NOV 2016
Accepted article online 17 NOV 2016
Published online 21 DEC 2016

Regional climate engineering by radiation management: Prerequisites and prospects

Johannes Quaas[1], **Martin F. Quaas**[2], **Olivier Boucher**[3], **and Wilfried Rickels**[4]

[1]Institute for Meteorology, Universität Leipzig, Leipzig, Germany, [2]Department of Economics, University of Kiel, Kiel, Germany, [3]Laboratoire de Météorologie Dynamique, Université Pierre et Marie Curie/CNRS, Paris, France, [4]Kiel Institute for the World Economy, Kiel, Germany

Abstract Radiation management (RM), as an option to engineer the climate, is highly controversial and suffers from a number of ethical and regulatory concerns, usually studied in the context of the objective to mitigate the global mean temperature. In this article, we discuss the idea that RM can be differentiated and scaled in several dimensions with potential objectives being to influence a certain climate parameter in a specific region. Some short-lived climate forcers (e.g., tropospheric aerosols) exhibit strong geographical and temporal variability, potentially leading to limited-area climate responses. Marine cloud brightening and thinning or dissolution of cirrus clouds could be operated at a rather local scale. It is therefore conceivable that such schemes could be applied with the objective to influence the climate at a regional scale. From a governance perspective, it is desirable to avoid any substantial climate effects of regional RM outside the target region. This, however, could prove impossible for a sustained, long-term RM. In turn, regional RM during limited time periods could prove more feasible without effects beyond the target area. It may be attractive as it potentially provides the opportunity to target the suppression of some extreme events such as heat waves. Research is needed on the traceability of regional RM, for example, using detection and attribution methods. Incentives and implications of regional RM need to be examined, and new governance options have to be conceived.

1. Introduction

Radiation management (RM) has been proposed as a means of last resort to combat the dangerous global change. However, numerous concerns arise when considering a possible implementation. RM is usually conceived to tackle climate change in a global context, in order to suppress the global mean surface temperature increase [*Crutzen*, 2006; *Sillmann et al.*, 2015]. So far, research on RM has mostly focused on long time scales of ∂ (30 years), for which the climate system may essentially be considered as a deterministic, boundary-conditions problem. At the same time, climate modeling studies have shown that RM is not optimally suited to mitigate the most detrimental aspects of changing climate, namely the changes in climate extremes [*Curry et al.*, 2014; *Aswathy et al.*, 2015].

Yet, RM can be differentiated and scaled in several dimensions. Even though the climate system is global, with forcing in one region potentially affecting the climate in another region, RM measures are conceivable that target (1) climate parameters other than the global mean surface temperature, (2) climate variables in a specific region, or (3) specific meteorological events (i.e., limited also in time). To what extent different RM measures, or a portfolio of different RM measures, will make such a differentiation possible is so far an open scientific question.

Many of the socioeconomic incentives about RM would have to be reassessed in the context of regional, rather than global, RM, taking into account the extent to which it might be possible to modify the climate regionally and possibly also for limited time periods, with little or no significant effect beyond. Here, we discuss prospects and limitations of potential regional RM application and elaborate on avenues for future research to address the various research questions.

From an economic point of view, a possibility to decorrelate the increase in global mean surface temperature and local to regional climate extremes would be particularly attractive, as extremes tend to cause particularly severe climate damages [*Sherwood and Huber*, 2010; *Dunne et al.*, 2013; *Lobell et al.*, 2013; *Zander et al.*, 2015]. It should, however, be noted that not all climate extremes could be addressed by this kind of intervention: coastal surges for instance are local in nature but are strongly related to mean sea-level rise which is a global phenomenon. An important question in this regard is, to what extent incentives for societies emerge so that options of regional RM might be utilized. A first step in this direction is to estimate how strongly economic preferences with respect to climate-related variables such as mean temperature, temperature extremes, and precipitation are correlated in space. This question is discussed in Section 2.

From a physical point of view, it has to be established that whether RM is feasible for a limited region, that is, whether an RM method can be conceived that would have the intended impact in the targeted area but only with limited detrimental effects beyond it. To which extent this is possible for substantial levels of climate engineering is an open question. A possibility is that sustained, long-term regional RM is impossible without substantial effect in adjacent regions, but it might still be attractive to perform regional RM for limited time periods, certain detrimental weather conditions only. These questions are discussed in Section 3.

Depending on the feasibility of a regional control of relevant climate variables, and given the preferences of the regions of the world with respect to these variables, the next question is to what extent countries or clubs of countries might make use of regional RM, and to what extent this would influence mitigation efforts in the absence of global cooperation on climate policy. One may expect that welfare effects strongly depend on the feasibility of limiting the RM effect in space and time. The availability of limited-area RM measures may lead to outcomes that range from almost solving the climate change problem regionally to making it worse than in case of uncoordinated emissions of greenhouse gases. This relates to the question of how to regulate the deployment of regional RM and the possibility to attribute the intended regional outcomes to the RM measures applied and exclude damages outside the targeted area. These questions are discussed in Section 4. Finally Section 5 concludes and proposes avenues for future research.

2. Incentives for Regional RM

Regional RM could be economically particularly attractive, because it might open the possibility to decorrelate the increase in global mean surface temperature and local climate extremes. The crucial point is that different countries and regions of the world may face different manifestations of climate change. The incentives for applying regional RM depend on the match between the spatial scales at which the climate may be engineered and the spatial scales of variability in preferences with respect to climate-related variables.

There is an increasing body of literature that empirically investigates impacts of the climate on specific socio-economic aspects such as agricultural production [*Aufhammer and Schlenker*, 2014], energy consumption [*Aufhammer and Mansur*, 2014], labor productivity [*Heal and Park*, 2015], political conflicts [*Burke et al*., 2015a], and general economic output [*Dell et al*., 2014; *Burke et al*., 2015b]. A robust finding across studies seems to be the existence of an "optimal temperature" or "optimal climate" with respect to the economic output. As long as regional climate is tied to global climate and its change, different regions of the world may prefer quite different global climates such that their regional climate is close to their optimal climate.

Nordhaus [2006] has set up a Geographically based Economic database (G-Econ, http://gecon.yale.edu/) which provides information on gross cell product (i.e., gross domestic product [GDP] in grid cells, at a 1° × 1° resolution on a global longitude–latitude grid) and can be used to investigate the influence of temperature and precipitation, and geographic variables (e.g., elevation, roughness of surface, distance to coast) on gross cell product. Using the cross-sectional data for GDP_i in all grid cells i in 2005 (approximately representative for the present-day GDP distribution) and long-term averages for temperature T_i and precipitation P_i (1980–2008) from the G-Econ database, we apply an estimation approach in line with that of *Nordhaus* [2006],

$$ln\left(\mathrm{GDP}_i\right) = a_0 + a_1 T_i + a_2 T_i^2 + a_3 T_i^3 + a_4 P_i + a_5 P_i^2 + c_{\mathrm{country}} + \sum_{i=6}^{7} a_i G_i + \sum_{i=8}^{14} a_i D_i + \varepsilon_i, \tag{1}$$

where c_{country} captures country-fixed effects, G_i are two geographic variables (accounting for the elevation and the grid-cell area within country), D_i are seven dummy variables (accounting for being an island, being in the high latitudes, for different distances to the coast [three dummy variables], accounting for extreme rich grid cells [two dummy variables]), and ε_i is the error term. The equation is estimated by means of

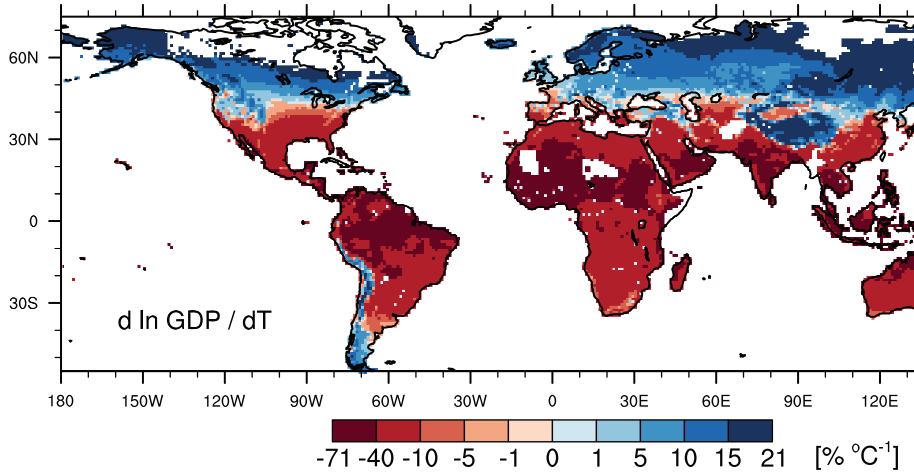

Figure 1. Marginal relative changes in grid-cell GDP with respect to temperature change in 2100 in the RCP8.5 scenario.

weighted ordinary least squares whereby we rely on Newey-West-based determination for the coefficient covariance matrix to obtain consistent estimates with respect to heteroskedasticity in the data. Like *Nordhaus* [2006], we find a significantly positive estimate for a_1 and significantly negative estimates for a_2 and a_3 , which indicates that the cells typically have an "optimal temperature" that maximizes gross cell product. Similarly, we find a significantly positive estimate for a_4 and negative estimate for a_5, which indicates that the cells typically also have "optimal precipitation." Such "optimal temperature" and/or "optimal precipitation" gives an indication of the region's economic preferences with respect to the application of regional RM.

The incentives for regional RM are indicated by the marginal change of grid-cell GDP with respect to temperature and precipitation. For illustrative purposes, we consider the incentives under rather extreme climate, like it is projected in the RCP8.5 scenario. We focus here on temperature changes since it seems even more challenging to intentionally alter regional precipitation than temperature patterns. The temperature change between the observed present-day temperatures and 2100 is taken from the multimodel mean (the average of the ensemble means of 11 climate models for which the relevant output was available) difference between the annual mean temperatures for 2100 and 2010 for the RCP8.5 scenario in the 5th Coupled Model Intercomparison Project [CMIP5; see *Taylor et al*., 2012 for a description of the simulations]. Results shown in Figure 1 demonstrate that the effect of temperature changes on GDP in 2100 will go in opposite directions for different regions. It should be noted that the projection shown in Figure 1 are an estimation based on current economic structures in combination with the projected temperature changes. Accordingly our approach provides (at best) a snapshot for economic impacts of climate change.

Regions in mid- to high latitudes, and at high altitudes, tend to be economically more successful with even warmer temperatures, while regions in low latitudes perform better at colder temperatures. The relative decrease in GDP with warming temperatures at low latitudes is larger than the increase at high latitudes.

Obviously, using such an estimation approach provides only a rough forecast for the economic impacts of a changing climate. Issues like changes in interannual variability or drastic unforeseeable changes cannot be included. Accordingly, the complex cause-effect chains between regional climate and economic output are only roughly approximated by such empirical investigations of the climate-economy link. Furthermore, the macroeconomic price system, global trade-flows, and allocation of labor and capital may change substantially in a fundamentally different climate. In addition, such an approach neglects the adaptation potential. The combination of these economic processes may strongly influence the effects of climate-related variables on GDP. Nevertheless, the approach clearly identifies certain regions with significant gains and losses due to climate change, where it is rather unlikely that adaption and price effects will overcompensate the general productivity loss or gain, indicating that we can indeed expect spatially heterogeneous preferences with regard to regional RM.

3. Feasibility of Limited-Area RM

It is an open question to which extent regional RM is feasible. Perturbations to the atmospheric composition in general lead to nonlocal responses. These responses depend on the weather or climate regime since propagation of the response to a given perturbation is modulated by the atmospheric circulation. A stable weather regime is conducive to more localized responses than a strong zonal or meridional flow. With regard to regional RM, options to mitigate climate extremes are particularly relevant. Heat waves are of central interest because they are (1) expected to increase in occurrence and intensity and (2) particularly detrimental to human health [e.g., *Sheridan and Allen*, 2015]. While regional RM is unlikely to decrease the likelihood of large-scale conditions favoring heat waves, it could help to mitigate the intensity of individual events. Temperature extremes may be more manageable than precipitation extremes [*Aswathy et al*., 2015], although temperature and precipitation are of course not unrelated. For precipitation, the large body of weather modification research shows little skill in changing either the frequency of occurrence or the intensity at will [*National Research Council*, 2003]. It is important to note that only certain climate extremes can be addressed by regional RM. For instance, sea-level rise that to a large extent responds to nonlocal forcings [*Hu et al*., 2013] leads to regional climate extreme events such as coastal floodings [*Tebaldi et al*., 2012] that would be conceivably difficult to mitigate with regional RM.

Radiative forcing is a measure of the perturbation to the energy budget that results in climate effects, the latter usually measured by the change in the global-mean surface temperature [*Gregory et al*., 2004]. Although the radiative forcing concept is often applied to global mean quantities, some short-lived climate forcers (e.g., tropospheric aerosols) exhibit strong geographical and temporal variability, potentially leading to nonuniform climate responses. Marine cloud brightening, which consists of seeding low-level clouds in order to enhance planetary albedo [*Latham*, 1990; *Latham et al*., 2012], is expected to exert a radiative forcing that is essentially localized to the region of seeding [*Jones et al*., 2009, 2011; *Alterskjær et al*., 2013; *Aswathy et al*., 2015]. Similarly, thinning or dissolution of cirrus clouds would be operated at a rather local scale [*Mitchell and Finnegan*, 2009; *Storelvmo et al*., 2013; *Storelvmo and Herger*, 2014]. It is therefore conceivable that such schemes could be applied in a way that targets climate modification at the regional scale. It may also be applied during a limited period, and thus might allow to target a suppression of certain extreme events such as heat waves. In this sense, RM could become a mixed initial-boundary condition problem rather than simply a boundary condition problem.

It is well known, however, that the intertwined processes in the Earth system and the circulation lead to a response of the climate system that is not simply following the forcing pattern [*Boer and Yu*, 2003; *Xie et al*., 2013]. The dissimilarity of the forcing and response patterns is nevertheless largest over the oceanic regions of the winter hemispheres [*Persad et al*., 2014]. Thinking about potential deployment of regional RM, the continental regions of the summer hemispheres are therefore of particular interest.

As a starting point, it is useful to refer to *Shindell et al*. [2010], who analyzed the temperature response to present-day aerosol and CO_2 emissions in four climate models, in comparison to preindustrial levels. The patterns showed a spatial autocorrelation with the forcing pattern that was very long (>10,000 km) in the zonal direction, but dropped at length scales of about 3500 km in the meridional direction. Temperature change in individual zonal belts, as simulated by climate models, is related to the forcing patterns, especially those by anthropogenic aerosols [*Shindell and Faluvegi*, 2009; *Voulgarakis and Shindell*, 2010]. It is an open question whether a forcing configuration is possible for which the response is even more localized in the meridional direction, and also substantially more localized in the zonal direction. The problem is further complicated by the fact that there is a large uncertainty in the response pattern to a localized forcing as evident in the differing responses different models simulate for the same regional forcing [*Kasoar et al*., 2016].

In the mid-latitudes with a prevailing westerly zonal flow, one may anticipate that a targeted RM during weather regimes with little zonal flow may be better suited to affect preferentially the region of interest. In mid-latitudes, extreme weather, in terms of heat waves, often coincides with blocking situations, or persistent high pressure systems [*Hoskins and Woollings*, 2015]. This offers prospects to target blocking situations in which zonal flow is weak and their associated climate extremes. An initial study by *Bernstein et al*. [2013] showed the potential to mitigate a heat wave in a modeling case study with a regional climate model applying stratospheric sulfur injections. Due to the large technical effort, the long lifetime and thus large spatiotemporal distribution for stratospheric sulfate, it seems, however, more plausible to employ a shorter-lived climate engineering mechanism, such as cloud seeding, to address particular extreme events or climate change mitigation at a regional scale.

It has been demonstrated that heat waves become more frequent due to anthropogenic emissions of greenhouse gases [*Schär et al*., 2004; *Jones et al*., 2008; *Christidis et al*., 2012; *Morak et al*., 2013; *Herring et al*., 2014; *Sun et al*., 2014]. *Sillmann et al*. [2013] document that climate models are increasingly able to reproduce temperature extremes as well as their response to forcings. Atmospheric models are thus promising tools to further investigate the feasibility of regional RM.

4. Welfare Implications and Scope for Governing Regional RM

If regional RM would become an option, it may be expected that every player (e.g., a country or region) has an incentive to unilaterally implement their most-preferred RM measure to the most-preferred extent. If every actor could perfectly engineer the local climate, and if regional RM has purely local effects, one may expect that the global availability of regional RM options would lead to a pareto-efficient outcome. If, however, regional RM was feasible in only some regions there may well remain large unmitigated damages of climate change in other parts of the world. One important example may be the unmitigated warming in the Arctic [e.g., *Aswathy et al*., 2015]. General theory of second best [*Lipsey and Lancaster*, 1956] tells us that, absent a globally first-best solution to the climate change problem, the option of regional RM may decrease welfare at a global scale, that is, for the majority of regions outside the target region. In that vein, if the areas where regional RM is feasible are large emitters of greenhouse gases, the availability of regional RM may significantly decrease their incentives to mitigate greenhouse gas emissions. Thus, the unmitigated climate damages outside the regions where regional RM is feasible may even increase and, it is even conceivable that global welfare may be reduced by the availability of the regional RM option for only some countries. This calls for studying the question of how to regulate the deployment of regional RM.

The scope for a global regulation of regional RM measures depends on the possibility to attribute intended local outcomes to regional RM measures and to exclude damages outside the targeted area. For applying standard regulation approaches (e.g., based on liability law) to regional RM efforts, one needs to be able to reliably attribute the intended outcome to a RM measure in the targeted area [*Sillmann et al*., 2015], and to reliably reject the hypothesis that particular weather events somewhere else are caused by a RM measure. These possibilities could be studied, building on the available extensive experience with detection and attribution studies assessing (inadvertent) anthropogenic forcings, and making use of novel approaches exploiting ensemble climate forecasts at short time scales.

This can build on the fact that a central question in anthropogenic climate change is the detection of climate change signals in observations, and the attribution of aspects of climate change to specific forcings [*Bindoff et al*., 2013]. In climate model simulations, patterns of climate change are analyzed in simulations that apply or not a specific forcing signal to identify the “fingerprint” of climate responses attributable to the specific forcing agent [*Hasselmann*, 1997; *Hegerl et al*., 1997; *Bürger and Cubasch*, 2015]. The question becomes especially relevant when considering liability for climate change [*Allen*, 2003; *Prather et al*., 2009].

However, rather than the attribution of a large-scale, long-term trend, liability requires the assessment of specific events. Again, extreme events are of particular interest [*Allen*, 2003]. Detection and attribution of climate change at a regional to local scale remains challenging [*Stott et al*., 2010]. Due to the chaotic character of weather, and due to the complexity of the Earth system, an unequivocal assertion of causality is virtually impossible. Rather, the change in risk, or frequency of occurrence, of a given climatic event can be assessed and quantified [*Stone and Allen*, 2005].

The attribution of an altered risk for a given climate event relies on an accurate simulation of the probability distribution function of the climate at a given location, with and without the anthropogenic agent. This can be based on a large model ensemble [*Massey et al*., 2015]. In attributing a climate event to anthropogenic activity, it is important to assess both the likelihood and the magnitude [*Otto et al*., 2012]. Detection and attribution for RM targeting continental heat waves may be more feasible than for other weather conditions. *Christidis et al*. [2013] were particularly skillful in probabilistically attributing a continental heat wave in the Moscow area in 2010 to anthropogenic emissions. *Hegerl et al*. [2011] show particular skill in detecting and attributing the summer cooling after volcanic eruptions. *Stott et al*. [2004] demonstrated that the probability of a heat wave such as the one over Europe in 2003 at least doubled due to anthropogenic emissions of greenhouse gases. On the basis of this evidence, it seems in general plausible that the attribution of a heat wave, or the mitigation of a heat wave, to a specific forcing may be feasible in probabilistic terms.

Innovative regulation approaches may provide some scope for governance that leads to mutual advantages for the heterogeneous regions of the world, even if an attribution is feasible only to a limited extent. Such a mutually advantageous regulation could have the strongest potential to be implemented at a global scale. A subsequent question is which regulatory approaches could lead to a pareto-improvement compared to the uncoordinated outcome.

5. Conclusion and Future Research

RM, as an option to engineer the climate, is highly controversial and suffers from a number of ethical and regulatory concerns. To the extent that regional RM is feasible, some concerns may have to be reassessed. However, it is unclear to what extent a limited-area application might be possible that is both locally effective and harmless outside the targeted region. Incentives and implications of regional RM need to be examined, and new governance options have to be conceived.

In this paper, we have discussed the state of the literature on regional RM. In conclusion we state five overarching research questions and avenues how to address these questions in future research:

1. *Feasibility*: To which extent is it possible to generate a localized climate response to a localized forcing? Can a time-varying forcing, involving increased intervention only during carefully selected weather regimes, help to spatially contain the climate response?

2. *Incentives*: What is the spatial correlation of economic preferences with respect to climate variables? To which extent are regional preferences with respect to different climate variables (temperature, precipitation) correlated?

3. *Economic implications*: What are possible welfare implications of having regional RM technology available when countries would implement regional RM and mitigate greenhouse gas emissions in an uncoordinated way? Such a study would have to apply theory of differential games to study equilibrium outcomes in an integrated assessment model.

4. *Traceability*: What does it take to detect and attribute a limited-area effect of a RM measure, and to reject the hypothesis that climate events outside the targeted area are affected by the RM measure? Such an analysis could build on, and advance, existing detection and attribution methods. Based on ensemble modeling, it would provide probability distributions for the socioeconomic assessment.

5. *Governance*: How to regulate regional RM most efficiently, given the uncertainties in predictability and traceability? Such a study could make use of economic theories of mechanism design.

Acknowledgments
This study was funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) in Priority Programme 1689 “Climate Engineering - Risks, Challenges, Opportunities?” project LEAC-II (GZ QU 311/10-2 and QU 357/3-2). We thank the climate modeling community and PCMDI for providing the CMIP5 results via the ESGF/WDCC (https://www.dkrz.de/daten-en/wdcc/wdc-cluster-earth-system-research), and the G-Econ project for providing their data at http://gecon.yale.edu. Two anonymous reviewers are acknowledged for constructive and useful comments on the first version of the manuscript. We acknowledge financial support from the German Research Foundation (DFG) and Universität Leipzig within the program of Open Access Publishing.

References

Allen, M. (2003), Liability for climate change, *Nature*, *421*, 891–892, doi:10.1038/421891a.

Alterskjær, K., J. E. Kristjánsson, O. Boucher, H. Muri, U. Niemeier, H. Schmidt, M. Schulz, and C. Timmreck (2013), Sea-salt injections into the low-latitude marine boundary layer: The transient response in three Earth system models, *J. Geophys. Res.*, *118*(21), 12,195–12,206, doi:10.1002/2013JD020432.

Aswathy, V. N., O. Boucher, M. Quaas, U. Niemeier, H. Muri, J. Mülmenstädt, and J. Quaas (2015), Climate extremes in multi-model simulations of stratospheric aerosol and marine cloud brightening climate engineering, *Atmos. Chem. Phys.*, *15*(16), 9593–9610, doi:10.5194/acp-15-9593-2015.

Aufhammer, M., and E. Mansur (2014), Measuring climate impacts on energy consumption: A review of the empirical literature, *Energy Econ.*, *46*, 522–530, doi:10.1016/j.eneco.2014.04.017.

Aufhammer, M., and W. Schlenker (2014), Empirical studies on agricultural impacts and adaptation, *Energy Econ.*, *46*, 555–561, doi:10.1016/j.eneco.2014.09.010.

Bernstein, D. N., J. D. Neelin, Q. B. Li, and D. Chen (2013), Could aerosol emissions be used for regional heat wave mitigation? *Atmos. Chem. Phys.*, *13*, 6373–6390, doi:10.5194/acp-13-6373-2013.

Bindoff, N., et al. (2013), Detection and attribution of climate change: From global to regional, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgle , pp. 867–952 , Cambridge Univ. Press, Cambridge, U. K.

Boer, G., and B. Yu (2003), Climate sensitivity and response, *Clim. Dyn.*, *20*(4), 415–429, doi:10.1007/s00382-002-0283-3.

Bürger, G., and U. Cubasch (2015), The detectability of climate engineering, *J. Geophys. Res.*, *120*, 11,404–11,418, doi:10.1002/2015JD023954.

Burke, M., S. Hsiang, and E. Miguel (2015a), Climate and conflict, *Annu. Rev. Econ.*, *7*, 577–617, doi:10.1146/annurev-economics-080614-115430.

Burke, M., S. Hsiang, and E. Miguel (2015b), Global non-linear effect of temperature on economic production, *Nature*, *527*, 235–239, doi:10.1038/nature15725.

Christidis, N., P. A. Stott, G. S. Jones, H. Shiogama, T. Nozawa, and J. Luterbacher (2012), Human activity and anomalously warm seasons in Europe, *Int. J. Climatol.*, *32*(2), 225–239, doi:10.1002/joc.2262.

Christidis, N., P. A. Stott, A. A. Scaife, A. Arribas, G. S. Jones, D. Copsey, J. R. Knight, and W. J. Tennant (2013), A new HADGEM3-a-based system for attribution of weather- and climate-related extreme events, *J. Clim.*, *26*(9), 2756–2783, doi:10.1175/JCLI-D-12-00169.1.

Crutzen, P. J. (2006), Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Clim. Change*, *77*(3–4), 211–219, doi:10.1007/s10584-006-9101-y.

Curry, C. L., et al. (2014), A multi-model examination of climate extremes in an idealized geoengineering experiment, *J. Geophys. Res. Atmos.*, *119*, 3900–3923, doi:10.1002/2013JD020648.

Dell, M., B. Jones, and B. Olken (2014), What do we learn from the weather? The new climate-economcy literature, *J. Econ. Literat.*, *52*, 740–798, doi:10.1257/jel.52.3.740.

Dunne, J. P., R. J. Stouffer, and J. G. John (2013), Reductions in labour capacity from heat stress under climate warming, *Nat. Clim. Change*, *3*(6), 563–566, doi:10.1038/nclimate1827.

Gregory, J. M., W. J. Ingram, M. A. Palmer, G. S. Jones, P. A. Stott, R. B. Thorpe, J. A. Lowe, T. C. Johns, and K. D. Williams (2004), A new method for diagnosing radiative forcing and climate sensitivity, *Geophys. Res. Lett.*, *31*, 2–5, doi:10.1029/2003GL018747.

Hasselmann, K. (1997), Multi-pattern fingerprint method for detection and attribution of climate change, *Clim. Dyn.*, *13*, 601–611, doi:10.1007/s003820050185.

Heal, G., and J. Park. (2015), Godilocks economics? Temperature stress and the direct impact of climate change, *Working Paper 21119*, *National Bureau Econ*. *Res*., doi:10.3386/w21119.

Hegerl, G. C., K. Hasselmann, U. Cubasch, J. F. B. Mitchell, E. Roeckner, R. Voss, and J. Waszkewitz (1997), Multi-fingerprint direction and attribution analysis of greenhouse gas, greenhouse gas-plus-aerosol and solar forced climate change, *Clim. Dyn.*, *14*(1), 71–72, doi:10.1007/s003820050186.

Hegerl, G., J. Luterbacher, F. González-Rouco, S. F. B. Tett, T. Crowley, and E. Xoplaki (2011), Influence of human and natural forcing on European seasonal temperatures, *Nat. Geosci.*, *4*(2), 99–103, doi:10.1038/ngeo1057.

Herring, S. C., M. P. Hoerling, T. C. Peterson, and P. A. Stott (2014), Explaining extreme events of 2013 from a climate perspective, *Bull. Am. Meteorol. Soc.*, *95*(9), S1–S96, doi:10.1175/1520-0477-95.9.S1.1.

Hoskins, B. J., and T. Woollings (2015), Persistent extratropical regimes and climate extremes, *Curr. Clim. Change Rep.*, *1*, 115–124, doi:10.1007/s40641-015-0020-8.

Hu, A., Y. Xu, C. Tebaldi, W. M. Washington, and V. Ramanathan (2013), Mitigation of short-lived climate pollutants slows sea-level rise, *Nat. Clim. Change*, *3*(8), 730–734, doi:10.1038/nclimate1869.

Jones, A., J. Haywood, and O. Boucher (2009), Climate impacts of geoengineering marine stratocumulus clouds, *J. Geophys. Res. Atmos.*, *114*(10), D10106, doi:10.1029/2008JD011450.

Jones, G. S., P. A. Stott, and N. Christidis (2008), Human contribution to rapidly increasing frequency of very warm Northern Hemisphere summers, *J. Geophys. Res. Atmos.*, *113*(2), 1–17, doi:10.1029/2007JD008914.

Jones, G. S., N. Christidis, and P. A. Stott (2011), Detecting the influence of fossil fuel and bio-fuel black carbon aerosols on near surface temperature changes, *Atmos. Chem. Phys.*, *11*(2), 799–816, doi:10.5194/acp-11-799-2011.

Kasoar, M., A. Voulgarakis, J.-F. Lamarque, D. T. Shindell, N. Bellouin, W. J. Collins, G. Faluvegi, and K. Tsigaridis (2016), Regional and global climate response to anthropogenic SO2 emissions from China in three climate models, *Atmos. Chem. Phys.*, *16*, 9785–9804, doi:10.5194/acp-16-9785-2016.

Latham, J. (1990), Control of global warming? *Nature*, *347*(6291), 339–340, doi:10.1038/347339b0.

Latham, J., et al. (2012), Marine cloud brightening, *Philos. Trans. R. Soc. A*, *370*(1974), 4217–4262, doi:10.1098/rsta.2012.0086.

Lipsey, R., and K. Lancaster (1956), The general theory of second best, *Rev. Econ. Stud.*, *24*, 11–32, doi:10.2307/2296233.

Lobell, D. B., G. L. Hammer, G. McLean, C. Messina, M. J. Roberts, and W. Schlenker (2013), The critical role of extreme heat for maize production in the United States, *Nat. Clim. Change*, *3*(5), 497–501, doi:10.1038/nclimate1832.

Massey, N., R. Jones, F. E. L. Otto, T. Aina, S. Wilson, J. M. Murphy, D. Hassell, Y. H. Yamazaki, and M. R. Allen (2015), Weather@home-development and validation of a very large ensemble modelling system for probabilistic event attribution, *Q. J. R. Meteorol. Soc.*, *141*(690), 1528–1545, doi:10.1002/qj.2455.

Mitchell, D. L., and W. Finnegan (2009), Modification of cirrus clouds to reduce global warming, *Environ. Res. Lett.*, *4*(4), 045102, doi:10.1088/1748-9326/4/4/045102.

Morak, S., G. C. Hegerl, and N. Christidis (2013), Detectable changes in the frequency of temperature extremes, *J. Clim.*, *26*(5), 1561–1574, doi:10.1175/JCLI-D-11-00678.1.

National Research Council (2003), *Critical Issues in Weather Modification Research*, The National Academies Press, Washington, D. C, 144 pp.

Nordhaus, W. D. (2006), Geography and macroeconomics: new data and new findings, *Proc. Natl. Acad. Sci. U. S. A.*, *103*(10), 3510–3517, doi:10.1073/pnas.0509842103.

Otto, F. E. L., N. Massey, G. J. Van Oldenborgh, R. G. Jones, and M. R. Allen (2012), Reconciling two approaches to attribution of the 2010 Russian heat wave, *Geophys. Res. Lett.*, *39*(4), L04702, doi:10.1029/2011GL050422.

Persad, G. G., Y. Ming, and V. Ramaswamy. (2014), Spatial similarities in the surface energy flux response to present-day greenhouse gases and aerosols. *AGU General Fall Meeting*, San Francisco, Calif., 15–19 Dec. [Available at http://membership.agu.org/files/2015/01/Persad_AGU_2014.pdf].

Prather, M. J., et al. (2009), Tracking uncertainties in the causal chain from human activities to climate, *Geophys. Res. Lett.*, *36*(5), L05707, doi:10.1029/2008GL036474.

Schär, C., P. L. Vidale, D. Luthi, C. Frei, C. Haberli, M. A. Liniger, and C. Appenzeller (2004), The role of increasing temperature variability in European summer heatwaves, *Nature*, *427*(6972), 332–336, doi:10.1038/nature02300.

Sheridan, S. C., and M. J. Allen (2015), Changes in the frequency and intensity of extreme temperature events and human health concerns, *Curr. Clim. Change Rep.*, *1*, 155–162, doi:10.1007/s40641-015-0017-3.

Sherwood, S. C., and M. Huber (2010), An adaptability limit to climate change due to heat stress, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(21), 9552–9555, doi:10.1073/pnas.0913352107.

Shindell, D., and G. Faluvegi (2009), Climate response to regional radiative forcing during the twentieth century, *Nat. Geosci.*, *2*(4), 294–300, doi:10.1073/pnas.0913352107.

Shindell, D., M. Schulz, Y. Ming, T. Takemura, G. Faluvegi, and V. Ramaswamy (2010), Spatial scales of climate response to inhomogeneous radiative forcing, *J. Geophys. Res. Atmos.*, *115*(19), D19110, doi:10.1029/2010JD014108.

Sillmann, J., V. V. Kharin, X. Zhang, F. W. Zwiers, and D. Bronaugh (2013), Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate, *J. Geophys. Res. Atmos.*, *118*(4), 1716–1733, doi:10.1002/jgrd.50203.

Sillmann, J., T. M. Lenton, A. Levermann, K. Ott, M. Hulme, F. F. Benduhn, and J. B. Horton (2015), Climate emergencies do not justify engineering the climate, *Nat. Clim. Change*, *5*(4), 290–292, doi:10.1038/nclimate2539.

Stone, D. A., and M. R. Allen (2005), The end-to-end attribution problem: From emissions to impacts, *Clim. Change*, *71*(3), 303–318, doi:10.1007/s10584-005-6778-2.

Storelvmo, T., and N. Herger (2014), Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere, *J. Geophys. Res. Atmos.*, *119*(5), 2375–2389, doi:10.1002/2013JD020816.

Storelvmo, T., J. E. Kristjansson, H. Muri, M. Pfeffer, D. Barahona, and A. Nenes (2013), Cirrus cloud seeding has potential to cool climate, *Geophys. Res. Lett.*, *40*(1), 178–182, doi:10.1029/2012GL054201.

Stott, P. A., D. A. Stone, and M. R. Allen (2004), Human contribution to the European heatwave of 2003, *Nature*, *432*, 610–614, doi:10.1038/nature03089.

Stott, P. A., N. P. Gillett, G. C. Hegerl, D. J. Karoly, D. A. Stone, X. Zhang, and F. Zwiers (2010), Detection and attribution of climate change: A regional perspective, *WIREs Clim. Change*, *1*(2), 192–211, doi:10.1002/wcc.34.

Sun, Y., X. Zhang, F. W. Zwiers, L. Song, H. Wan, T. Hu, H. Yin, and G. Ren (2014), Rapid increase in the risk of extreme summer heat in Eastern China, *Nat. Clim. Change*, *4*(12), 1082–1085, doi:10.1038/nclimate2410.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*(4), 485–498, doi:10.1175/BAMS-D-11-00094.1.

Tebaldi, C., B. H. Strauss, and C. E. Zervas (2012), Modelling sea level rise impacts on storm surges along US coasts, *Environ. Res. Lett.*, *7*(3), 014032, doi:10.1088/1748-9326/7/1/014032.

Voulgarakis, A., and D. T. Shindell (2010), Constraining the sensitivity of regional climate with the use of historical observations, *J. Clim.*, *23*(22), 6068–6073, doi:10.1175/2010JCLI3623.1.

Xie, S.-P., B. Lu, and B. Xiang (2013), Similar spatial patterns of climate responses to aerosol and greenhouse gas changes, *Nat. Geosci.*, *6*(10), 828–832, doi:10.1038/ngeo1931.

Zander, K. K., W. J. W. Botzen, E. Oppermann, T. Kjellstrom, and S. T. Garnett (2015), Heat stress causes substantial labour productivity loss in Australia, *Nat. Clim. Change*, *5*(May), 1–6, doi:10.1038/nclimate2623.