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Key Points:
- Attribution statements for temperature extremes are consistently strong
- Attribution statements increase as event duration increases
- Attribution statements for temperature extremes are strongest at the equator

Supporting Information:
- Readme
- Figure S1
- Figure S2

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Attribution of extreme weather to anthropogenic greenhouse gas emissions: Sensitivity to spatial and temporal scales

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Abstract Recent studies have examined the anthropogenic contribution to specific extreme weather events, such as the European (2003) and Russian (2010) heat waves. While these targeted studies examine the attributable risk of an event occurring over a specified temporal and spatial domain, it is unclear how effectively their attribution statements can serve as a proxy for similar events occurring at different temporal and spatial scales. Here we test the sensitivity of attribution results to the temporal and spatial scales of extreme precipitation and temperature events by applying a probabilistic event attribution framework to the output of two global climate models, each run with and without anthropogenic greenhouse gas emissions. Attributable risk tends to be more sensitive to the temporal than spatial scale of the event, increasing as event duration increases. Globally, correlations between attribution statements at different spatial scales are very strong for temperature extremes and moderate for heavy precipitation extremes.

1. Introduction

In the aftermath of catastrophic weather events, scientists are often called to investigate whether anthropogenic greenhouse gas (GHG) emissions played a role in causing the event. A typical scientific analysis responding to these questions has been to examine how anthropogenic emissions have altered the chance of an event over a specific spatial and temporal domain, corresponding to the observed event [*Dole et al.*, 2011; *Pall et al.*, 2011; *Stott et al.*, 2004]. Although these studies can provide scientifically robust attribution statements, the process is often time consuming, sometimes taking years after the occurrence of the event. It would be convenient if attribution conclusions for previously studied events could be considered as proxies for other events occurring in the vicinity of the studied event, even if the other events are not identical in their spatial and temporal extent. Here we use the term "event" to describe a notable weather or climate extreme in rainfall or temperature, ignoring the potential compound effects of multiple meteorological variables. The conclusions from these targeted studies apply to a specific definition of the event and may be sensitive to this definition. However, the robustness of attribution conclusions to variations in the spatial and temporal extent of the event remains largely unexplored.

While other attribution concepts have been used in some recent studies, this paper specifically examines the sensitivities for the popular attribution approach of assessing how the probability of an event has been altered by emissions [*Stott et al.*, 2013; *Otto et al.*, 2012]. We examine attribution results over a range of spatial and temporal scales for areas around the globe in order to determine the sensitivity of results to definition of the extent in both space and time. As such, it is intended to provide a general guideline on how to interpret analyses of the attributable risk from anthropogenic GHG emissions to the occurrence of an event, by the way of similar events occurring at different spatial and temporal domains (e.g., a more local 1 week heat wave within a regional hot summer, given analyses of the latter) in the same region of the world, that is, influenced by the same fundamental weather and climate dynamics. Because it is impossible to attribute any single weather event to anthropogenic emissions, since the event could have occurred in the absence of external forcing, we use a probabilistic attribution framework comparing ensembles of atmospheric climate model simulations for the November 2008 to October 2011 period, both with and without climate forcings from anthropogenic GHG emissions [*Allen*, 2003; *Stone and Allen*, 2005]. During this period, both positive and negative El Niño–Southern Oscillation phases were simulated and the results are therefore indicative of what would be expected under a reasonable (though restricted) range of climate variability.

2. Data

To allow for different model representations of the climate system, we use data generated by two Atmospheric Global Climate Models. Output of daily mean surface temperature and precipitation were generated by CAM5.1 and HadAM3P-N96, at resolutions of ∼2° and ∼1.5°, respectively. Each ensemble is composed of 56 realizations of the November 2008 to October 2011 period, run either with observed atmospheric GHG concentrations ("real world") or a hypothetical scenario assuming anthropogenic GHG emissions had never influenced the climate system ("non-GHG world"). Each realization in a scenario differs from the others only in its initial state. For all simulations, at least 1 month before 1 November was discarded to allow sufficient time for divergence from the similar initial conditions.

Forcings for the real-world scenario were prescribed to represent November 2008 to October 2011 conditions, with observed values for GHG concentrations and sea surface temperatures (SSTs) for both models (supplementary information for *Pall et al.* [2011]), as well as volcanic aerosols, solar luminosity, ozone, and sea ice concentrations. The CAM5.1-2degree simulations were also driven with the year-2000 annual cycle in tropospheric aerosols, while the HadAM3P-N96 simulations were driven with the climatological annual cycle in sea ice concentration. Under the hypothetical non-GHG-world scenario, GHG concentrations were reduced to preindustrial levels, while SSTs were cooled according to the seasonally varying pattern estimated from simulations of the HadCM3 atmosphere-ocean model driven by historical changes in greenhouse gas concentrations, with a global adjustment in magnitude estimated through an optimal detection analysis against observed trends. Aerosol forcings were not considered in the HadCM3 simulations as we are primarily looking at the signal attributable to greenhouse gases. Sea ice advance was estimated from the cooled SSTs according to the algorithm of *Pall et al.* [2011].

3. Method

We select rainfall and cold event thresholds for daily, 5 day, and monthly extremes (sampled using a running window with a 1 day step) from the ensembles driven by the real-world scenario. Because the hot extremes selected from the real-world scenario barely occur in the non-GHG scenario, we select these thresholds from the ensembles driven by the non-GHG scenario. Both one-in-one-year and one-in-ten-year rainfall thresholds are chosen, while only one-in-one-year temperature thresholds are selected. The risk ratio (RR) is a metric characterizing the anthropogenic contribution to the occurrence of the extreme event. It is given by the percentage of days that exceed the threshold in the real world scenario (P_{real}) divided by the percentage of days that exceed that same threshold in the non-GHG scenario ($P_{\text{non-GHG}}$), i.e., it is defined only in terms of frequency of occurrence, not impact. Since we use the non-GHG scenario to define the hot thresholds, P_{real} and $P_{\text{non-GHG}}$ exchange positions in the equation. Because the thresholds have been defined as either one-in-one-year or one-in-ten-year events, $P_{\text{real}} = 0.27\%$ or 0.027%, respectively. This method is used to infer RRs for events occurring at the resolution of the model, as well as at the regional scale. For the latter, rainfall and temperature grid cell values are aggregated across 58 regions demarcated by the Weather Risk Attribution Forecast (WRAF), the spatial scale for each being about $2 \cdot 10^6$ km^2 and comparable to the size of synoptic systems in the extratropics (http://www.csag.uct.ac.za/~daithi/forecast).

In cases for which $P_{\text{non-GHG}} = 0\%$, we have artificially adjusted $P_{\text{non-GHG}}$ to 1 day (one in 56×3 years), exceeding the threshold in the sample of simulations in order to prevent infinities interfering with the calculations. The actual statistical calculations were performed with these cases removed. There is, however, a question of biasing results if we continue to remove the more extreme cases. For this reason we used thresholds from either the real-world or non-GHG scenario that did not result in these cases. The investigation of attribution statements for one-in-ten-year precipitation events was, however, an exception: a severe bias existed when considering one-in-ten-year monthly precipitation events, due to an omission of a large number of cases. Finally, we estimate uncertainty in the results from a 20,000-member Monte Carlo sampling procedure. This entails randomly selecting individual simulations from our ensembles of 56 simulations, with replacement, to produce pseudo-ensembles of 56 simulations for which we then reperform the calculations.

4. Results

The maps in Figure 1 depict RRs at grid cell resolution calculated from the HadAM3P-N96 simulations for four different weather event types. Warm and cold colors suggest anthropogenic GHGs have increased or

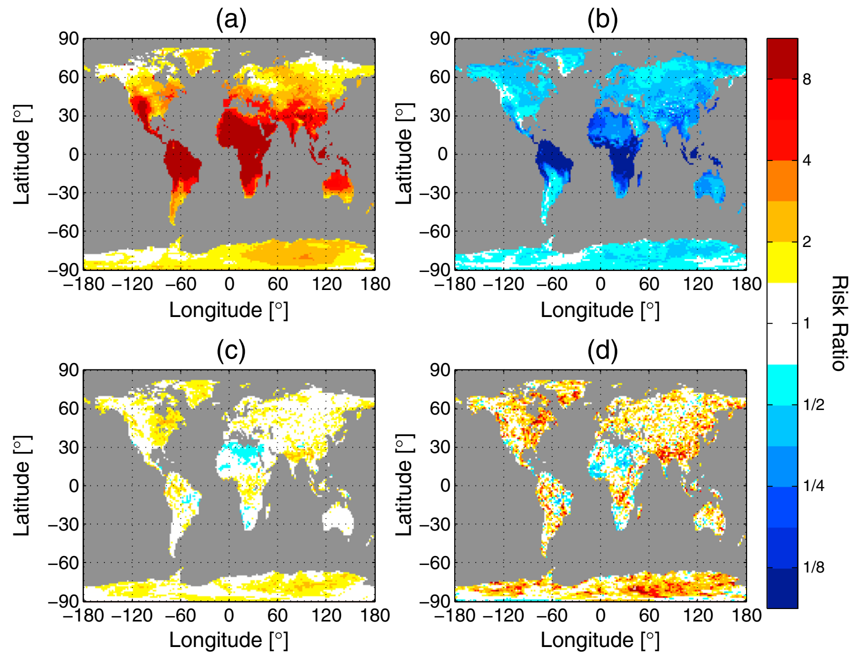

Figure 1. (a) RRs for one-in-one-year hot days, (b) one-in-one-year cold days, (c) one-in-one-year wet days, and (d) one-in-ten-year wet days. Maps were generated using output from HadAM3P. See Figure S1 in the supporting information for maps using output from CAM5.1

decreased the probability of event occurrence, respectively, while whites suggest these emissions have had no or a relatively low influence on the probability. The attributable risk for the chance of one-in-one-year hot and cold day events to anthropogenic GHG emissions is strongly influenced by latitude, as estimated from both climate models. The tendency for GHG emissions to contribute to a higher chance of hot events and a lower chance of cold events is strongest at low latitudes, reflecting a fairly uniform global warming occurring against the background of the lower variability of the tropics. Early emergence of warming at low latitudes, as a result of low interannual variability, has for example been shown by *Mahlstein et al.* [2011]. RRs for one-in-one-year wet days (Figure 1c) are less extreme. However, on the whole, anthropogenic emissions are responsible for increasing the probability of the event over most land areas of the world (warm colors dominate). The RRs regarding one-in-ten-year wet days (Figure 1d) suggest that greenhouse gases have a stronger impact on the occurrence of these more extreme events. Examination of the Monte Carlo samples shows that poorer sampling is mostly responsible for the greater patchiness of the map for these rarer events (not shown).

Maps for 5 day extremes and monthly extremes share the same general pattern as those for 1 day extremes in Figure 1, with some differences in the overall magnitudes described below. Maps calculated with the CAM5.1-2degree simulations (see Figure S1 in the supporting information) are also similar but with stronger RRs in the high latitudes than from the HadAM3P-N96 simulations, consistent with the more extensive sea ice coverage in the CAM5.1-2degree non-GHG-world simulations.

Regression analysis was performed at the regional scale between RRs for grid-scale events and for regional-scale events, for rainfall and temperature (hot and cold) events lasting 1 day, 5 days, and 1 month, to examine how the spatial and temporal scales of the event influence the RR. Figure 2 shows the RRs of 1 day events derived at both spatial scales over each of the 58 WRAF regions, calculated from the HadAM3P-N96 data. The calculated RRs for extremely wet days are mostly greater than unity at both spatial scales, indicating that anthropogenic greenhouse gas emissions have increased the chance of these events. The high correlation coefficients of 0.95 for hot and cold temperature events suggest that attribution calculations performed at an arbitrary spatial scale can serve as a proxy for events occurring at similar spatial scales and over neighboring regions. Given that the slopes are slightly less than unity, a small and apparently systematic adjustment to attribution results as a function of spatial scale would improve the accuracy of results estimated from such proxy analyses. However, for wet extremes the slope of the linear

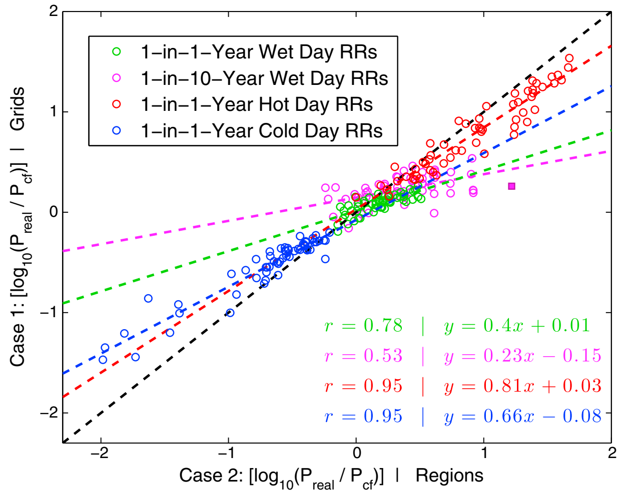

Figure 2. Regressions between risk ratios derived at grid and regional scales over each of the 58 WRAF regions for one-in-one-year wet day RRs (green), one-in-ten-year wet day RRs (magenta), one-in-one-year hot day RRs (red), and one-in-one-year cold day RRs (blue). Square markers have been artificially adjusted and indicate WRAF regions over which $P_{\text{non-GHG}} = 0\%$ at the regional scale. Only data from HadAM3P-N96 are shown here, with distributions of CAM5.1-2degree results being nearly identical (see Figure S2 in the supporting information).

fit is considerably less than unity, indicating that an adjustment would be necessary when interpreting attribution conclusions over a smaller or larger area. We argue that the moderate correlation coefficients suggest that the use of a linear adjustment could at least improve the accuracy of an attribution statement for an event, considering analysis of a similar event occurring at a different spatial scale. For one-in-ten year events there is only a weaker correlation between RRs at the two spatial scales ($r = 0.53$). The correlation for one-in-one-year events is higher at 0.78. One hypothesis for the general contrast in correlation coefficients between temperature and rainfall events, the latter being lower, is that the dynamics responsible for the temperature RRs vary at larger spatial scales (e.g., radiation balance), whereas the dynamical changes responsible for the rainfall RRs tend to vary at smaller spatial scales (e.g., convective cells).

The lower correlations for one-in-ten-year wet events than for one-in-one-year wet events appear to be mostly a consequence of sampling accuracy. When studying the rarer events, $P_{\text{non-GHG}} = 0\%$ in some cases (or in many cases when event duration is longer), which implies that when we do capture events exceeding the threshold, they are possibly, in many cases, not being captured frequently, thereby increasing the uncertainty of the results. On the other hand, when we study cold events, we expect $P_{\text{non-GHG}}$ to be greater than P_{real} ($= 0.27$). To avoid similar sampling issues, we experience with one-in-ten-year wet events, we reverse the procedure for hot events by obtaining one-in-ten-year thresholds from the non-GHG scenario. Now by definition, $P_{\text{non-GHG}} = 0.27\%$, and we expect P_{real} to be greater. We find that the correlation coefficients for daily, 5 day, and monthly events (hot and cold) for results from both models are greater than 0.9. Supposing the hot thresholds had been obtained from the real-world scenario as opposed to the non-GHG scenario, the correlation coefficients would then be 0.83, 0.84, and 0.7 (0.73, 0.75, and 0.6 from CAM5.1 output) for daily, 5 day, and monthly events, respectively. Thus, we argue, mainly in the case of one-in-ten-year wet events, that if it was not for reduced sampling accuracy as a consequence of the methodology, the correlations would most likely be stronger.

Figure 3 provides a summary of the global average magnitude of the RRs for the various event durations, scales, and climate models. Each symbol denotes the global average of the regional RR values, where those regional RRs are in turn either averages of grid cell RRs or the RRs of the regional average values. In Figure 3d, the monthly results are not shown since uncertainty as a consequence of poor sampling strongly increases. When sampling is poor, a bias tends to emerge. The number of regions over which $P_{\text{non-GHG}} = 0\%$ increases, and these regions are discarded before averaging. However, regions over which $P_{\text{non-GHG}} > 0\%$ are not discarded before averaging, and as a consequence, the count (over some of these regions), of grid cells over which $P_{\text{non-GHG}} = 0\%$, may be high. Because these values are then artificially changed assuming 1 day exceeded the threshold, the averaged RRs at the grid scale tend to be exaggerated. If Figure 3a was to be

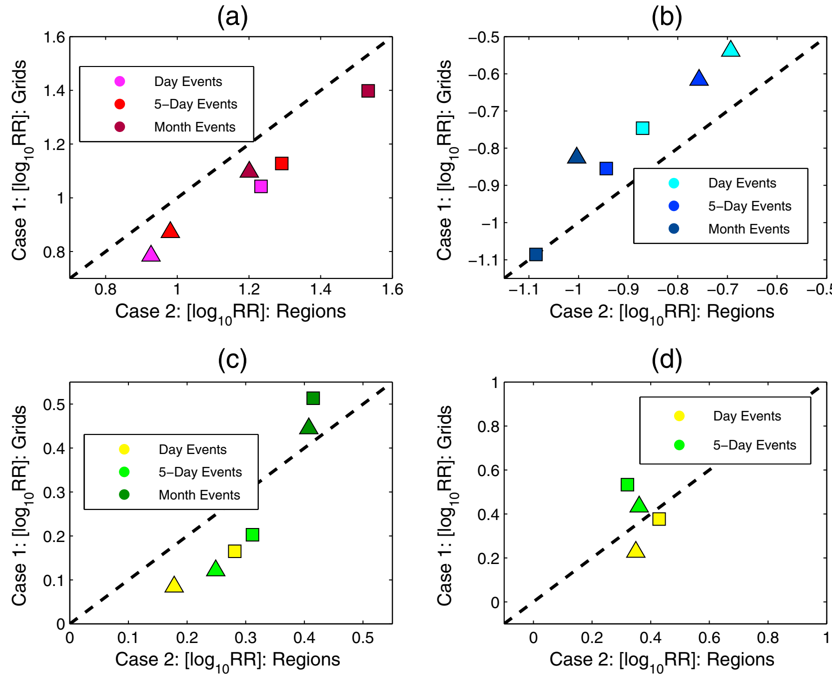

Figure 3. Summaries of the influence of spatial and temporal scale on RRs. Each marker is the average of the regional and grid cell values over WRAF regions such as those seen in Figure 2. RRs for one-in-one-year (a) hot, (b) cold, and (c) wet events, and (d) one-in-ten-year wet events, are shown. Square markers are results from CAM5.1-2degree; triangular markers are results from HadAM3P-N96.

regenerated using thresholds from the real-world scenario, the bias emerges, positioning the six markers further from the 45° line and mostly above it. The panel shown suggests that anthropogenic emissions hold a marginally greater responsibility for increasing the risk of hot extremes occurring at the regional scale.

A common characteristic in all panels in Figure 3 is that as the event duration increases, the RRs become more extreme. As with the more extreme RRs near the equator being a consequence of low interannual variability, here the reduction in variability arises through averaging over time. While the absolute magnitudes differ between estimates made with either of the two climate models, the relative progression of average RR values through the temporal and spatial scales is strikingly similar. Part of the difference in absolute magnitude probably arises because sea ice coverage was adjusted in the non-GHG scenario of CAM5.1-2degree, while it was not in HadAM3P-N96.

5. Discussion

The implications of the results shown here for studies using different attribution concepts remains unclear. RRs calculated in this study follow directly from the experimental design and analysis. In this respect, the values cannot be taken at face value to represent the true role of anthropogenic greenhouse gas emissions in changing the probability of extreme events. For instance, there remains a considerable uncertainty in the global magnitude, spatial pattern, and seasonal pattern of the ocean warming attributable to greenhouse gas emissions, meaning that CAM5.1-2degree effectively sees cooler surface boundary conditions in its non-GHG simulations in areas along the sea ice edge in the observed real world. Only one estimate was used here; thus, uncertainty in this factor has not been explored. We can see no reason, however, why a different estimate for the attributable ocean warming would affect the statistical properties in which attribution statements respond to changes in temporal and spatial scales of the event.

The two climate models used in this study differ in their date of issue by a decade (with HadAM3P-N96 being older), and they have been developed at different centers in different institutional environments. Their related atmosphere-ocean models do not share common behavioral characteristics in comparison with other climate models [*Masson and Knutti*, 2011]. The similarity of results between these two models thus suggests a robustness across recent and current generations of climate models. Exploration of this robustness will be possible when similar large-ensemble attribution experiments performed under the International CLIVAR Climate of the 20th Century Project become available in the coming year [*Kinter and Folland*, 2011]. The increasing and decreasing frequencies of extremely hot and cold events shown in this study, respectively (over almost all land areas of the world as a consequence of anthropogenic GHG emissions), are consistent with the results by *Fischer et al.* [2013] and *Sillmann et al.* [2013].

Results from this study indicate that the degree to which anthropogenic emissions have contributed to increasing or decreasing the chance of an event depends strongly on the duration of the event, but in a way that may follow a straightforward systematic relationship. A similar property also appears to hold for the dependence on the spatial extent when temperature extremes are concerned. However, there are mostly moderate correlations between attribution results of different spatial domains for precipitation extremes, suggesting that the dependence of attribution conclusions for precipitation events may be sensitive to the specified spatial extent of the event. In this sense, results from attribution analyses for temperature extremes can probably be used as a proxy for attribution statements regarding similar events occurring at different spatial and temporal scales, and possibly even for events occurring beyond the resolution of the climate model, while analyses for precipitation extremes require a sensitivity analysis to ensure that conclusions are not overly dependent on the analysis method.

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