Persisting cold extremes under 21st-century warming scenarios

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[1]   Analyses of climate model simulations and observations reveal that extreme cold events are likely to persist across each land-continent even under 21st-century warming scenarios. The grid-based intensity, duration and frequency of cold extreme events are calculated annually through three indices: the coldest annual consecutive three-day average of daily maximum temperature, the annual maximum of consecutive frost days, and the total number of frost days. Nine global climate models forced with a moderate greenhouse-gas emissions scenario compares the indices over 2091–2100 versus 1991–2000. The credibility of model-simulated cold extremes is evaluated through both bias scores relative to reanalysis data in the past and multi-model agreement in the future. The number of times the value of each annual index in 2091–2100 exceeds the decadal average of the corresponding index in 1991–2000 is counted. The results indicate that intensity and duration of grid-based cold extremes, when viewed as a global total, will often be as severe as current typical conditions in many regions, but the corresponding frequency does not show this persistence. While the models agree on the projected persistence of cold extremes in terms of global counts, regionally, inter-model variability and disparity in model performance tends to dominate. Our findings suggest that, despite a general warming trend, regional preparedness for extreme cold events cannot be compromised even towards the end of the century. **Citation:** Kodra, E., K. Steinhaeuser, and A. R. Ganguly (2011), Persisting cold extremes under 21st-century warming scenarios, *Geophys. Res. Lett.*, *38*, L08705, doi:10.1029/2011GL047103.

1. Introduction

[2] Decadal or multi-decadal periods of global mean cooling within an overall anthropogenic warming trend have been previously investigated, and the possibility of such cooling periods persisting into the 21st century even under higher-than-moderate emissions scenarios has been shown [*Easterling and Wehner*, 2009]. Here we examine cold extremes, or the statistical attributes of cold events that are relatively shorter in duration; specifically, we consider events typically lasting from a day to several weeks. Previous studies with model simulations [*Hegerl et al.*, 2004; *Meehl et al.*, 2004; *Meehl and Tebaldi*, 2004; *Christidis et al.*, 2005; *Tebaldi et al.*, 2006; *Kharin et al.*, 2007; *Ganguly et al.*, 2009] and observations [*Easterling et al.*, 2000; *Easterling*, 2002; *Frich et al.*, 2002; *Klein Tank and Können*, 2003; *Zhai and Pan*, 2003; *Alexander et al.*, 2006] have used multiple definitions for climate-related extremes. One study on cold-air outbreaks (CAOs) using seven global climate models suggested that while mean wintertime temperature will significantly increase by the end of the 21st century, extreme cold events will not disappear, and that models even project an increase in CAOs for some regions [*Vavrus et al.*, 2006]. While definitions based on statistically rigorous extreme value theory [*Kharin et al.*, 2007] are useful, measuring cold extremes which are more intense, longer-lasting, or occur more frequently may have important consequences in many sectors and thus may be of interest as well.

[3] Specific attributes of cold temperature extremes have been examined through impacts-relevant indices. Frost days (*frequency*) have been noted as an important indicator for agriculture, recreation, and gardening [*Frich et al.*, 2002], and unusual, unexpected frost may have long-lasting effects on certain plant and animal population distributions and the reproduction ability of certain plant life [*Inouye*, 2000]. Two model studies [*Tebaldi et al.*, 2006; *Meehl et al.*, 2004] suggest that by the end of the 21st century, total number of frost days will decrease substantially almost everywhere. However, a study using observations showed that some regions experienced increases in frost days during the second half of the 20th century, despite an overall warming trend [*Frich et al.*, 2002]. *Duration*, or consecutive frost days, and *intensity*, or several consecutive days with unusually low temperature, may also have important implications for human mortality [*Huynen et al.*, 2001] as well as agriculture, recreation, and gardening. In temperate regions where there is seasonal variation in mortality rates, those in the winter are estimated to be 10–25% higher than summer rates and are usually seen where people are not typically accustomed to and prepared for extremely cold weather [*McMichael et al.*, 2003].

[4] Here we investigate cold temperature extremes through the following attributes:

[5] 1. Intensity: Cold Extremes Intensity (CEI) is defined as an analogue of heat wave intensity [*Meehl and Tebaldi*, 2004; *Ganguly et al.*, 2009] with relevance to human impacts [*Huynen et al.*, 2001]. The CEI is calculated as the coldest 3-day average of daily maximum temperature in a given year.

[6] 2. Duration: Cold Extremes Duration (CED) is defined as the annual maximum of consecutive frost days, defined in turn as days where minimum temperature is less than or equal to 0°C. This index has been used in studies related to observed regional climate change [*Villaroel et al.*, 2006].

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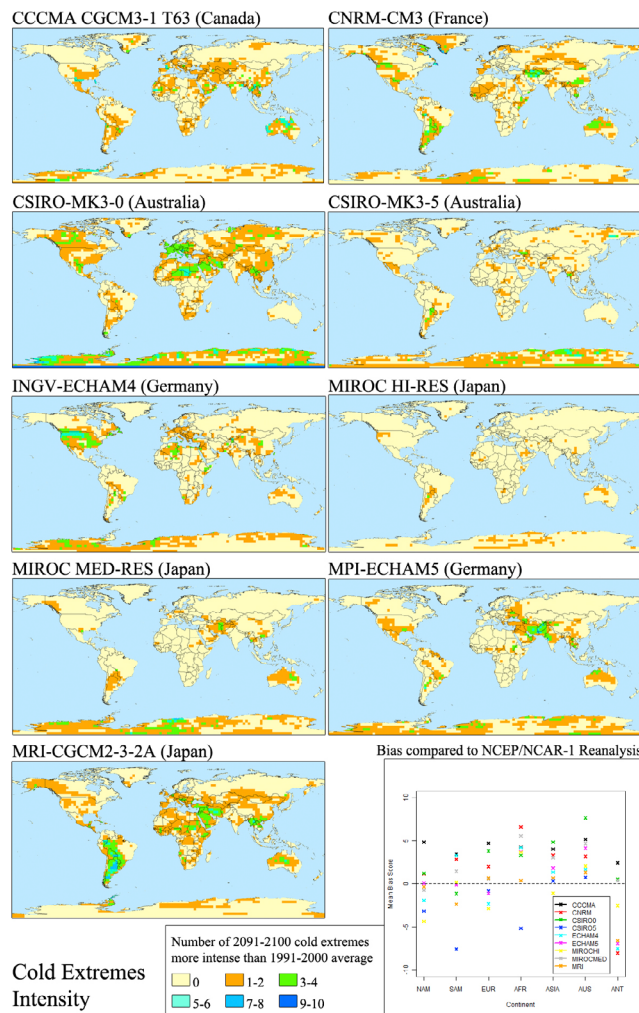
Figure 1. Persistence of Cold Extremes Duration in the twenty-first century. Cold Extremes Intensity (CEI) is computed annually and for each grid as the average daily maximum temperatures for the three consecutive days in the year when this three-day maximum has the lowest value over the year. The CEI number presented in the first nine panels from the nine global climate modes takes a value from 0–10 and indicates the number of years during 2091–2100 when this annual index is greater than the decadal average of the annual index from 1991–2000. The climate models individually project at least a few years in 2091–2100 when the CEI equals or exceeds 1991–2000 averages over specific grids. However, the inter-model differences appear significant both for total global counts and particularly at regional scales. The mean bias scores in the tenth panel calculated as a difference of decadal average of the model hindcasts compared to surrogate observations, or reanalysis datasets, during 1991–2000 indicate that the CEI from MRI-CGCM-3-2A hindcasts have been most consistently close to observations over almost all continents other than Antarctica. Incidentally, MRI-CGCM-3-2A appears to project the quite persistent CEI.

[7] 3. Frequency (Cold Extremes Frequency, CEF): The total number of frost days in a given year, as defined in previous impact-relevant studies with model-simulations

[Tebaldi et al., 2006; Meehl et al., 2004] and observations [Frich et al., 2002; Inouye, 2000].

[8] Cold extremes have been investigated to date often with spatial and/or temporal averaging of cold extreme indices [Kharin et al., 2007; Tebaldi et al., 2006]. Here we take a different perspective by exploring the attributes of cold extreme events under a warming environment in the 21st century that equal or exceed the average cold extremes attributes in the 20th century. We rely on the notion that, in the context of extremes, climate variability is more important than mean climate [Katz and Brown, 1992]. The results presented here show that the intensity and duration of cold extremes are projected to at least occasionally persist at or exceed present levels, making a case for cold-weather preparedness late into the 21st century.

2. Results

[9] Here we examine the question: What happens to the cold extreme attributes intensity, duration, and frequency (IDF) under global warming scenarios? Using one initial condition run from each of nine IPCC AR4 climate models, we test the hypotheses that under global warming scenarios, cold extremes will become less severe, which can in turn cause relaxation of regional preparedness for cold extremes even as readiness levels are enhanced for regional temperature increase and worsening heat waves. An assessment of the reliability of cold extremes projections may be developed by comparing model hindcasts with observations in the past as well as through multi-model agreement in the future [Ganguly et al., 2009; Knutti et al., 2010].

[10] Recent attribution studies [Pierce et al., 2009; Santer et al., 2009] in the context of regional climate or hydrologic assessments, specifically over the Western United States, appear to suggest that multi-model ensembles work better than any individual model. Here we use a nine-member IPCC AR4 multi-model ensemble forced with the SRES A1B scenario (see Text S1 of the auxiliary material).[1] The models were selected and one initial-condition member each was used as in recent studies of this nature [Knutti et al., 2010; Pierce et al., 2009]. The NCEP/NCAR-1 reanalysis temperature data [Kalnay et al., 1996] are used as surrogates for observations. The last decade of the 20th century were used for hindcast-observation comparison, especially since this is the last decade for which hindcast data are available for all models. Multi-model agreements are tested based on the final decade of the 21st century. According to the IPCC SRES A1B, the warmest conditions in this century are projected to happen in the final decade of the 21st century. Thus, examining the attributes of cold extremes for this last decade would help understand their persistence. The following results may seem particularly non-intuitive and surprising given all nine models project warming in 2091–2100 compared to 1991–2000 (Figure S1).

2.1. Intensity

[11] The number of years in 2091–2100 for which the CEI is more intense than the mean CEI from 1991–2000 is calculated to yield a number between 0–10 (each called an
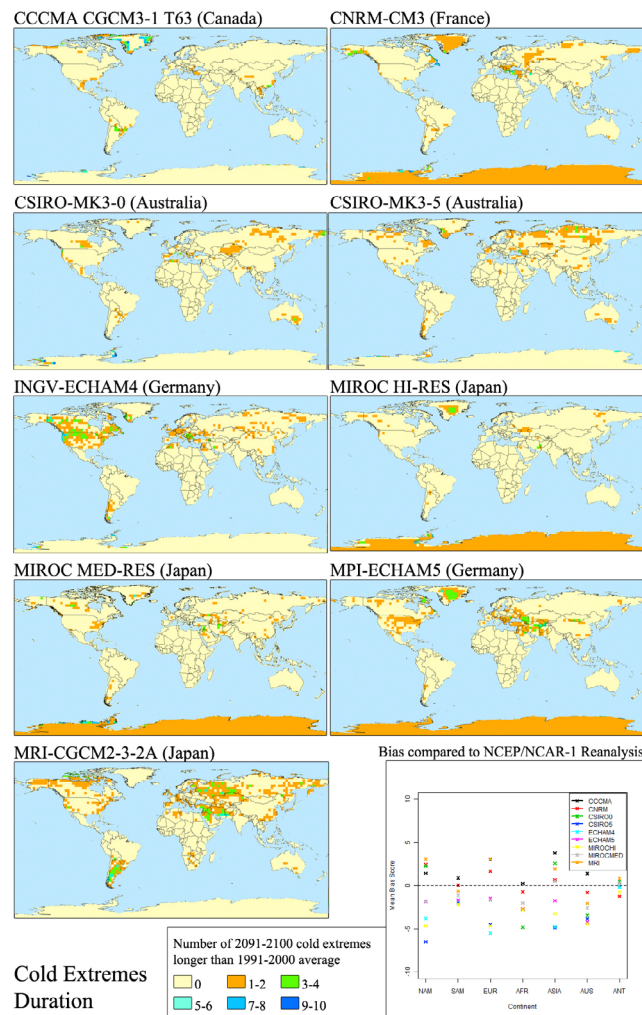

Figure 2. Persistence of Cold Extremes Duration in the twenty-first century. The Cold Extremes Duration (CED) is computed for each grid as the annual maximum of consecutive frost days (i.e., days when the minimum nighttime temperatures falls below zero degree Celsius). The CED number, decadal model comparisons and bias scores are computed in an identical manner as the CEI discussed in Figure 1.

'event'). Figure 1 shows that a substantial portion of landmass is projected to experience at least one year, even at the end of the 21st century, when cold extremes will be more intense than the 20th century average; several models show, for some regions, a substantial number of years (~3–6) where cold extremes are more intense than the 20th century average. While many models only project 1–2 events in many areas, they nevertheless suggest the necessity for cold weather preparedness into the 21st century. This insight is not apparent if just the decadal mean changes in CEI are examined. For example, the intense cold extremes projected by ECHAM4 over the Western United States are not visible in the decadal mean change map (Figure S2). The bias scores (auxiliary material) calculated in a manner similar to heat waves [*Meehl and Tebaldi*, 2004; *Ganguly et al.*, 2009] suggest that multi-model averaging may be able to effectively constrain CEI projections.

2.2. Duration

[12] The number of years in 2091–2100 for which the CED is more intense than the average CED from 1991–2000 is calculated to yield a number between 0–10. Figure 2 shows that portions of the land-mass are projected to experience at least one year, even at the end of the 21st century, when the cold extremes will be longer-lasting that the 20th century average duration. The corresponding 21st century CED events are typically less than those for CEI. In regions such as the Western United States and the Middle East, projections from ECHAM4 and MRI, respectively, suggest that CED events (Figure 2) will mirror that of the CEI (Figure 1). However, not all models (e.g., CNRM) show this correspondence. In fact, CNRM projects more CED events than CEI over Eastern Europe. Again, the bias scores may indicate that multi-model averaging may be able to constrain CED projections.

2.3. Frequency

[13] CEF projections agree with previously published projections [*Meehl et al.*, 2004; *Tebaldi et al.*, 2006] and do not show persistence in the 21st century (Figures S3 and S4). Overall, our IDF examination suggests that cold extremes may be expected to occur less frequently under a warming environment. However, those that do occur will occasionally, or in some regions perhaps often, be as (or more) intense and/or last as long as (or longer than) current mean cold extremes.

2.4. Multi-model Projection Bounds

[14] Figure 3 shows the highest, lowest and median projections of CEI and CED events at each grid, which may be interpreted as analogous to maximum and minimum bounds and most likely projections, assuming the nine models capture the range of possible future behavior. The multi-model ensemble projects many CEI events and less but nonetheless several CED events at the end of the 21st century. The minimum bound maps seem to be dominated by MIROC-HI; this model has a warm bias (Figures 1 and 2) for most continents, and thus may understate cold extremes. The maximum bound maps suggest the possibility for a substantial number of CEI and CED events.

3. Discussion

[15] We find evidence from nine climate models that intensity and duration of cold extremes may occasionally, or in some cases quite often, persist at end-of-20th-century levels late into the 21st century in many regions (Table S1 displays the proportions of land-mass projected to be affected by cold extremes for each continent). This is expected despite unanimous projections of relatively significant mean warming trends (Figure S1). Our results suggest that in many regions cold extremes may not be less severe or shorter than they have been in the recent past on average, despite global warming, although the frequency of such extremes are likely to decrease. (Figures S5–S7 explore a comparison of future and past cold extremes, both relative to the past mean, for another perspective on the change in extremes). These results do not appear to be sensitive to initial conditions of models on a global or continental scale (Figure S8). The implications for decision-makers are that, even as regional preparedness efforts are made for warming conditions, our ability to
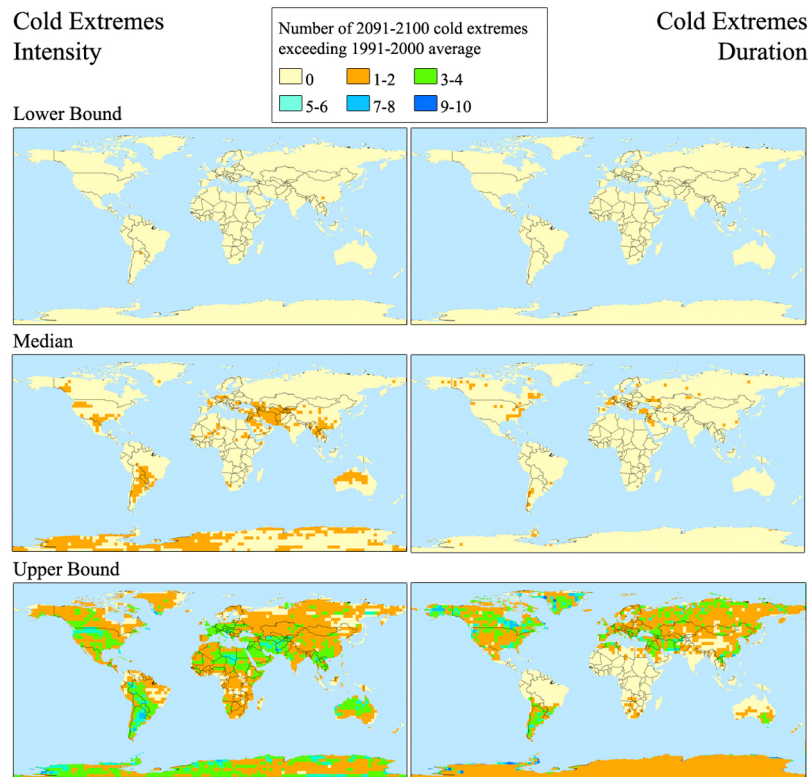
Figure 3. Central tendency and bounds for cold extremes persistence. The persistence of CEI and CED are calculated from each of the nine models per grid in the manner described in Figures 1 and 2. The minimum, median, and maximum of the nine numbers at each grid are presented, providing a measure of a minimum bound, central tendency and maximum bound respectively, for each grid. The bounds appear large, with the minimum hardly showing persistence of cold extremes, but the maximum showing widespread persistence.

respond to cold extremes cannot be compromised. Model projections for persistence of cold extremes seem to agree relatively well at continental scales as well as perhaps over certain regions like South America and the East, especially for CEI. However, considerable inter-model variability is seen over other regions and especially at local scales.

[16] Our confidence in regional projections of cold extremes persistence may be enhanced through a better understanding of the underlying physical drivers and the ability of climate models to capture them. A process-based model evaluation for guiding regional projections may be relevant since non-stationary conditions are expected under climate change and given the regional-scale multi-model variability previously noted in this paper. Investigations of physical bases may be particularly important for regions where cold extremes are expected to have significant impacts: This includes the Western United States, where snow water equivalent is critical for water-resources planning [*Cayan*, 1996; *Barnett et al.*, 2004; *Barnett et al.*, 2008], and Europe (specifically the United Kingdom), where human vulnerability to cold weather is high [*McMichael et al.*, 2003]. Downstream weather impacts in North America and Europe associated with atmospheric blocking [*Carrera et al.*, 2004; *Vavrus et al.*, 2006] as well as milder winters in Europe compared to North America resulting from advection of mean winds [*Seager et al.*, 2002] are examples of cold extremes related processes which may be used as benchmarks for model diagnostics leading to the generation of

credible regional-scale projections. In many situations, the bounds on multi-model projections may be at least as important for regional preparedness efforts as the most likely multi-model projections of persistent cold extremes. Future research into improving multi-model projections or downscaled assessments of cold temperature events may be important for effectively informing local to regional preparedness decisions. In addition to the moderate A1B emissions scenario considered here, other higher and lower emissions scenarios need to be investigated to develop comprehensive adaptation guidelines.

References

Alexander, L. V., et al. (2006), Global observed changes in daily climate extremes of temperature and precipitation, *J. Geophys. Res.*, *111*, D05109, doi:10.1029/2005JD006290.

Barnett, T. P., et al. (2004), The effects of climate change on water resources in the west: Introduction and overview, *Clim. Change*, *62*, 1–11, doi:10.1023/B:CLIM.0000013695.21726.b8.

Barnett, T. P., et al. (2008), Human-induced changes in the hydrology of the western United States, *Science*, *319*, 1080–1083, doi:10.1126/science.1152538.

Carrera, M. L., R. W. Higgins, and V. E. Kousky (2004), Downstream weather impacts associated with atmospheric blocking over the northeast Pacific, *J. Clim.*, *17*, 4823–4839, doi:10.1175/JCLI-3237.1.

Cayan, D. R. (1996), Interannual climate variability and snowpack in the western United States, *J. Clim.*, *9*, 928–948, doi:10.1175/1520-0442 (1996)009<0928:ICVASI>2.0.CO;2.

Christidis, N., P. A. Stott, S. Brown, G. C. Hegerl, and J. Caesar (2005), Detection of changes in temperature extremes during the second half of the 20th century, *Geophys. Res. Lett.*, *32*, L20716, doi:10.1029/ 2005GL023885.

Easterling, D. (2002), Recent changes in frost days and the frost-free season in the United States, *Bull. Am. Meteorol. Soc.*, *83*, 1327–1332.

Easterling, D., and M. Wehner (2009), Is the climate warming or cooling?, *Geophys. Res. Lett.*, *36*, L08706, doi:10.1029/2009GL037810.

Easterling, D., et al. (2000), Observed variability and trends in extreme climate events: A brief review, *Bull. Am. Meteorol. Soc.*, *81*, 417–425, doi:10.1175/1520-0477(2000)081<0417:OVATIE>2.3.CO;2.

Frich, P., et al. (2002), Observed coherent changes in climatic extremes during the second half of the twentieth century, *Clim. Res.*, *19*, 193–212, doi:10.3354/cr019193.

Ganguly, A. R., et al. (2009), Higher trends but larger uncertainty and geographic variability in 21st century temperature and heat waves, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(37), 15,555–15,559, doi:10.1073/ pnas.0904495106.

Hegerl, G. C., F. W. Zwiers, P. A. Stott, and V. V. Kharin (2004), Detectability of anthropogenic changes in annual temperature and precipitation extremes, *J. Clim.*, *17*, 3683–3700, doi:10.1175/1520-0442(2004) 017<3683:DOACIA>2.0.CO;2.

Huynen, M. M., P. Martens, D. Schram, M. P. Weijenberg, and A. E. Kunst (2001), The impact of heat waves and cold spells on mortality rates in the Dutch population, *Environ. Health Perspect.*, *109*(5), 463–470, doi:10.1289/ehp.01109463.

Inouye, D. (2000), The ecological and evolutionary significance of frost in the context of climate change, *Ecol. Lett.*, *3*(5), 457–463, doi:10.1046/ j.1461-0248.2000.00165.x.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, doi:10.1175/1520-0477(1996) 077<0437:TNYRP>2.0.CO;2.

Katz, R. W., and B. G. Brown (1992), Extreme events in a changing climate: Variability is more important than averages, *Clim. Change*, *21*, 289–302, doi:10.1007/BF00139728.

Kharin, V. V., F. W. Zwiers, X. Zhang, and G. C. Hegerl (2007), Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations, *J. Clim.*, *20*, 1419–1444, doi:10.1175/JCLI4066.1.

Klein Tank, A. M. G., and G. P. Können (2003), Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99, *J. Clim.*, *16*, 3665–3680, doi:10.1175/1520-0442(2003)016<3665:TIIODT>2.0. CO;2.

Knutti, R., R. Furrer, C. Tebaldi, J. Cermak, and G. A. Meehl (2010), Challenges in combining projections from multiple climate models, *J. Clim.*, *23*, 2739–2758, doi:10.1175/2009JCLI3361.1.

McMichael, A. J., et al. (2003), *Climate Change and Human Health: Risks and Responses*, World Health Organ., Geneva, Switzerland.

Meehl, G. A., and C. Tebaldi (2004), More intense, more frequent, and longer lasting heat waves in the 21st century, *Science*, *305*, 994–997, doi:10.1126/science.1098704.

Meehl, G. A., C. Tebaldi, and D. Nychka (2004), Changes in frost days in simulations of twenty-first century climate, *Clim. Dyn.*, *23*, 495–511, doi:10.1007/s00382-004-0442-9.

Pierce, D. W., T. P. Barnett, B. D. Santer, and P. J. Gleckler (2009), Selecting global climate models for regional climate change studies, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(21), 8441–8446.

Santer, B., et al. (2009), Incorporating model quality information in climate change detection and attribution studies, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(35), 14,778–14,783, doi:10.1073/pnas.0901736106.

Seager, R., et al. (2002), Is the Gulf Stream responsible for Europe's mild winters?, *Q. J. R. Meteorol. Soc.*, *128*(586), 2563–2586, doi:10.1256/ qj.01.128.

Tebaldi, C., K. Hayhoe, J. M. Arblaster, and G. A. Meehl (2006), Going to the extremes, *Clim. Change*, *79*, 185–211, doi:10.1007/s10584-006-9051-4.

Vavrus, S., J. E. Walsh, W. L. Chapman, and D. Portis (2006), The behavior of extreme cold air outbreaks under greenhouse warming, *Int. J. Climatol.*, *26*(9), 1133–1147, doi:10.1002/joc.1301.

Villaroel, C. P., B. Rosenbluth, and P. Aceituno (2006), Climate change along the extratropical west coast of South America (Chile): Daily max/min temperatures, in *Proceedings of 8 ICSHMO*, pp. 487–489, Natl. Inst. for Space Res., São José dos Campos, Brazil.

Zhai, P. M., and X. H. Pan (2003), Trends in temperature extremes during 1951–1999 in China, *Geophys. Res. Lett.*, *30*(17), 1913, doi:10.1029/ 2003GL018004.

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