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LETTER

Regional climate change and national responsibilities

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Global warming since preindustrial time, barely 1 °C, is small compared to weather fluctuations, yet seasonal mean temperature anomalies in most land areas are now large enough to noticeably load the 'climate dice'. The public should notice that climate is changing, because warming of recent decades has shifted the 'bell curve' describing seasonal mean local temperature anomalies over the summer hemisphere by about one standard deviation (Hansen *et al* 2012). What were once unusually warm conditions now occur more frequently, and the most extreme warm events now are more extreme than before. However, the magnitude of change varies around the globe.

Here we update the hemispheric analysis and illustrate regional changes, each shown by the bell curve for the frequency of occurrence of a given seasonal mean temperature anomaly relative to a climatological (base) period, 1951–1980, which largely preceded the rapid global warming trend of the past four decades. Results differ little if we use a longer base period, 1931–1980 (Hansen *et al* 2013a). The rationale for the bell curve presentation is that it provides a simple clear indication of significant change.

We find that recent warming during summer in arid and semi-arid subtropical regions such as the Mediterranean and Middle East is at least two standard deviations, far exceeding natural variability. Warming is similarly large in all seasons in the tropics. Large low latitude warming has been reported earlier by Diffenbaugh and Scherer (2011) and Mahlstein *et al* (2011, 2012). Added to natural subtropical aridity and high temperatures at low latitudes, this large warming contributes to drought intensification in the subtropics and makes living and working conditions more difficult in low latitudes. We will note works suggesting that higher temperatures affect economic production, contribute to human health problems, and tend to increase human conflict, perhaps increasing pressures for migration, but mainly we point to the need for research on these topics. In contrast, we can be quantitative in updating national responsibilities for fossil fuel CO_2 emissions, which are known to be the principal cause of global warming.

In updating results for Northern and Southern Hemisphere land areas (figure 1) we break the 66-year period 1950–2015 into six 11 year periods, so the periods have equal statistical significance. For clarity not all 11 year periods are included in our figures. Warming is larger in winter than in summer (Hansen *et al* 2010, IPCC 2013), but year-to-year temperature variability is much larger in winter (see global maps of interannual standard deviation of seasonal mean temperature in figure 2 of Hansen *et al* 2012). Thus the shift of the 'bell curve' (distribution of temperature anomalies in units of standard deviation) is larger in summer than in winter (figure 1), implying that climate change is easier to detect in summer than in winter. However, seasonal variation of the bell curve shift (figure 1) is small in the Southern Hemisphere, because a large fraction of Southern Hemisphere land is at low latitudes where seasonal change is small and because the dominance of ocean area in the Southern Hemisphere moderates seasonal change.

We calculate the 'shift' and the 'width' of the bell curve for each 11 year period relative to the 1951–1980 base period by finding the μ and σ yielding best least-mean-square fit of the data to

$$\exp[-(x-\mu)^2/2\sigma^2]/[\sigma\sqrt{(2\pi)}].$$

The 'shift' for any 11 year period is the difference between the seasonal mean temperature during that 11 year period and the climatology period (1951–1980) in units of the standard deviation of seasonal mean temperature during 1951–1980. The 'width' is the ratio of the standard deviation in the 11 year period and in 1951–1980. The shift and width for the 2005–2015 bell curves are given in the upper right hand corner of the graphs.

Shift of seasonal mean temperature in units of standard deviation usefully characterizes local climate change, as it measures change relative to the range of conditions that humans and other species at that locale are adapted to. Global temperature is now probably

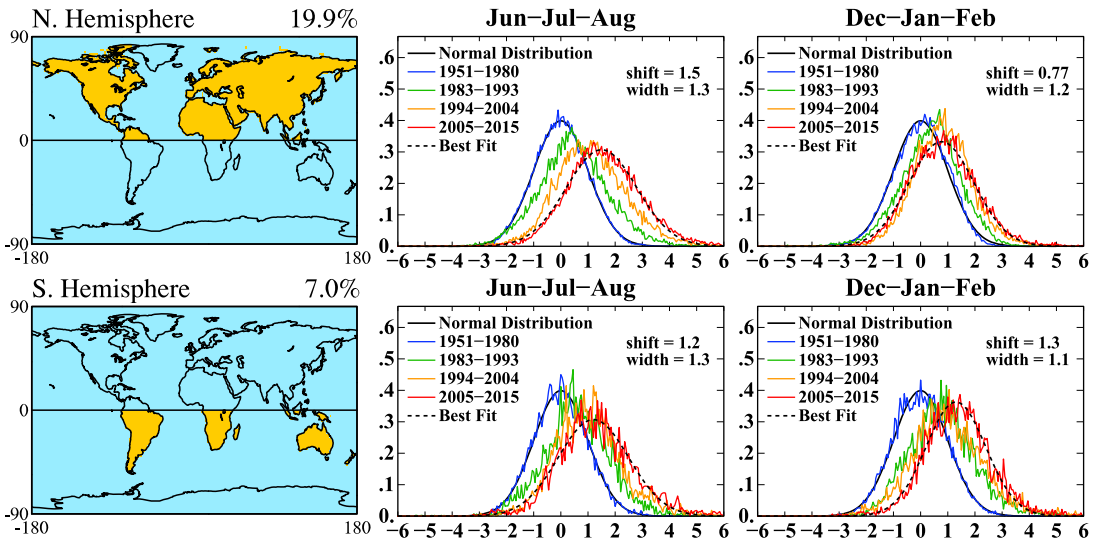

Figure 1. Frequency of occurrence of local temperature anomalies (relative to 1951–1980 mean) divided by local standard deviation (horizontal axis) for land areas shown on map. Area under each curve is unity. Numbers above the maps are percent of the globe covered by the selected region. 'Shift' and 'width' refer to the dashed curve fit to 2005–2015 data and are relative to the 1951–1980 base period (see text).

slightly above the prior Holocene maximum (Hansen *et al* 2013b), and despite regional Holocene variability (Mayewski *et al* 2004), in most regions further warming will take temperature to levels not experienced since at least the prior interglacial, more than 100 000 years ago. A question of interest is thus how large the temperature change is relative to the historic variability at that location.

The bell curve width increases with global warming and the curve tends to become slightly asymmetric with an increasingly long tail on the 'hot' side. The bell curve would become a near-symmetric normal distribution if we defined anomalies relative to the most recent decades rather than 1951–1980 (Rhines and Huybers 2013, Hansen *et al* 2013c), but it is appropriate to define anomalies relative to the time before the sharp warming trend for reasons given above.

Our analysis is of seasonal mean temperature, but emergence from noise of seasonal and daily extremes are tightly coupled, with seasonal change preceding daily change (King *et al* 2015). Our analysis (figure 1) agrees with the conclusion of Seneviratne *et al* (2014) and Sillmann *et al* (2014) that the trend toward increasingly hot extremes has continued in the most recent decade, despite evidence of a slowdown or hiatus in global surface warming (Meehl *et al* 2011, IPCC 2013). Existence of a global warming hiatus has also been questioned (Karl *et al* 2015).

Now we examine the bell curve changes in various geographical regions (figure 2). The curves become 'noiser' as the regions becomes smaller, yet the effect of warming is easily discernable.

The summer bell curves for the United States and (North and Central) Europe are shifted more than one standard deviation (1σ), while the shift in the winter is only about half of a standard deviation. The shift in summer is enough to increase the frequency of summers warmer than $+2\sigma$ from less than 1% to greater than 10%. The perceptive public may be able to notice this degree of change, but there is a geographical variation of the signal within the United States, as we will discuss. The bell curve shift in winter is too small to be easily noticed. The changes in Europe are only slightly larger than those in the United States.

The bell curve shifts are larger in China and India, being about one and one-half standard deviations in summer and one standard deviation in winter. The area that we employed for the India region includes the neighboring countries of Pakistan, Bangladesh and Sri Lanka, thus reducing the noise by achieving an area of about 0.7% of the globe. These bell curve shifts should be noticeable and have practical effects, which we will discuss.

This climate change signal, measured in units of the normal variability, becomes even stronger at lower latitudes, as we move well into the subtropics and tropics (figure 3). The summer bell curve shift is $+2.4\sigma$ in the Mediterranean and Middle East region, which means that almost every summer is warmer than average conditions in 1951–1980 and most summers are at least $+2\sigma$ relative to the climate of 50 years earlier. Warming in the Sahara and Sahel is similar to that in the Mediterraen and Middle East, although noisier because of more limited data.

South-East Asia and the African Rainforest, moist tropical regions, have bell curve shifts toward warmer temperatures exceeding $+2\sigma$ in June–July–August, i.e., a warming signal as large as the shift in the subtropical dry belt and desert. Moreover the shift in these tropical regions is as large or almost as large in the

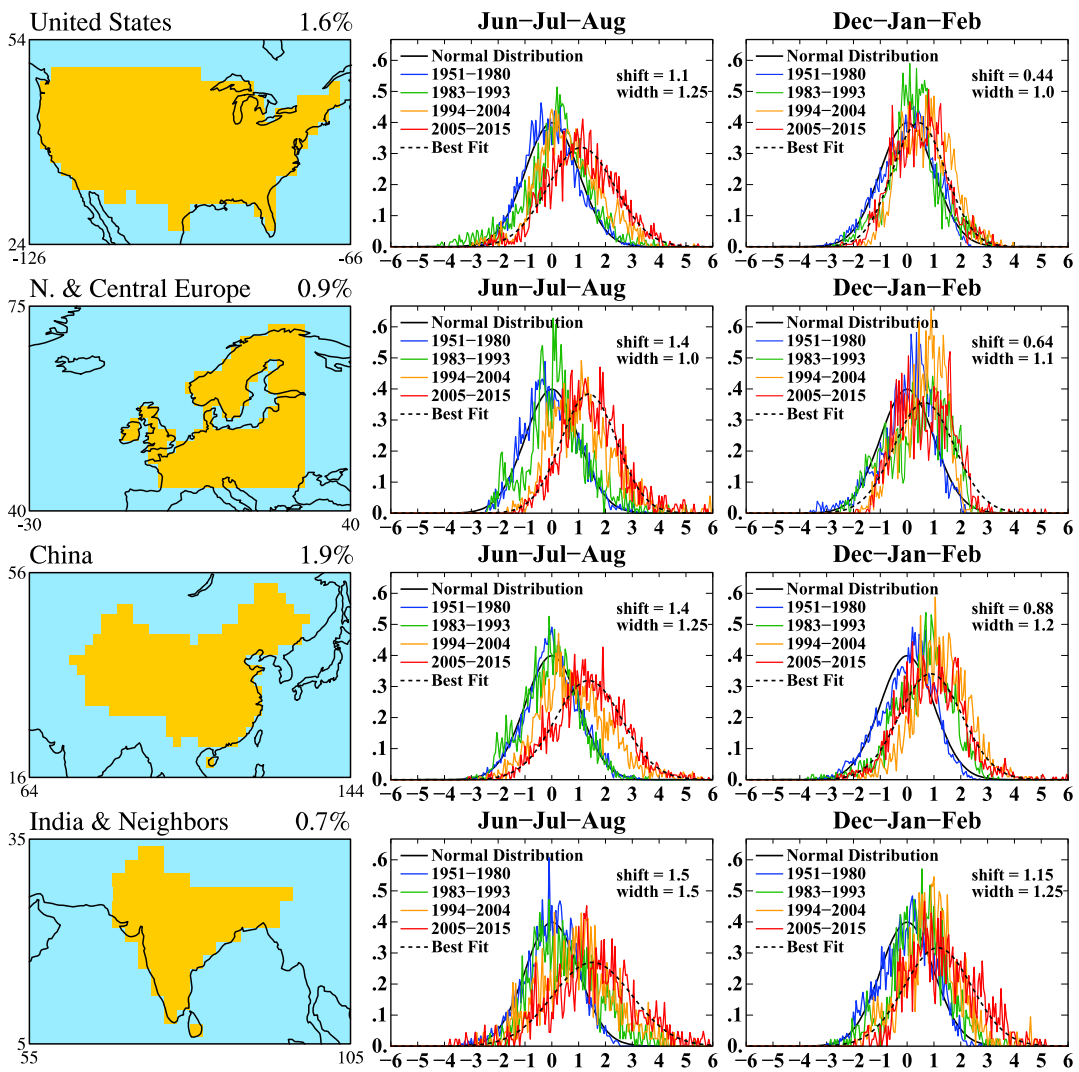

Figure 2. Shifting bell curves that define the frequency of local temperature anomalies relative to the 1951–1980 base period for four regions, with definitions and nomenclature as in figure 1.

other seasons, as shown for December–January–February (figure 3).

We do not illustrate the results for the three individual regions in the Southern Hemisphere (Australia, South America and the southern part of Africa) because we find the bell curves and their shifts for all three regions are very similar to those for the three areas together. The results for these areas are thus adequately described by the lower half of figure 1.

Global warming that leads to the large shift of the regional bell curves has been definitively associated with increasing atmospheric greenhouse gases (GHGs), principally CO_2 from fossil fuel burning (e.g., IPCC 2013, Hansen *et al* 2013b). Although global warming is only approaching 1 °C, the regional bell curves reveal that the warming signal has emphatically emerged on regional scales. The conclusion that the signal should emerge first at low latitudes in summer was reached already by Diffenbaugh and Scherer (2011) and Mahlstein *et al* (2011, 2012).

Regional bell curves, in addition to being 'noisy' because of small areas, are affected more by dynamical phenomena such as the El Nino/Southern Oscillation (Rasmusson and Wallace 1983) and North Atlantic Oscillation (Hurrell 1995). Thus decade-to-decade shifting of the bell curve is more irregular for regions than for a hemisphere. For this reason we emphasize total change from the base period to the most recent decade, minimizing the effect of regional dynamics.

Insight is provided by global maps of the temperature change that gives rise to the shifting bell curves. The temperature data that we employ is NASA/GISS surface temperature analysis (Hansen *et al* 2010) over land areas at 250 km resolution (figure 4). This analysis is based on the latest GHCN (Global Historical Climatology Network) data obtained from NOAA, GHCN version 3.3.0. We note that GHCN land data have been very stable in sucessive updates, and thus the updates do not alter our prior analyses. Sea surface temperature (SST) data have undergone greater

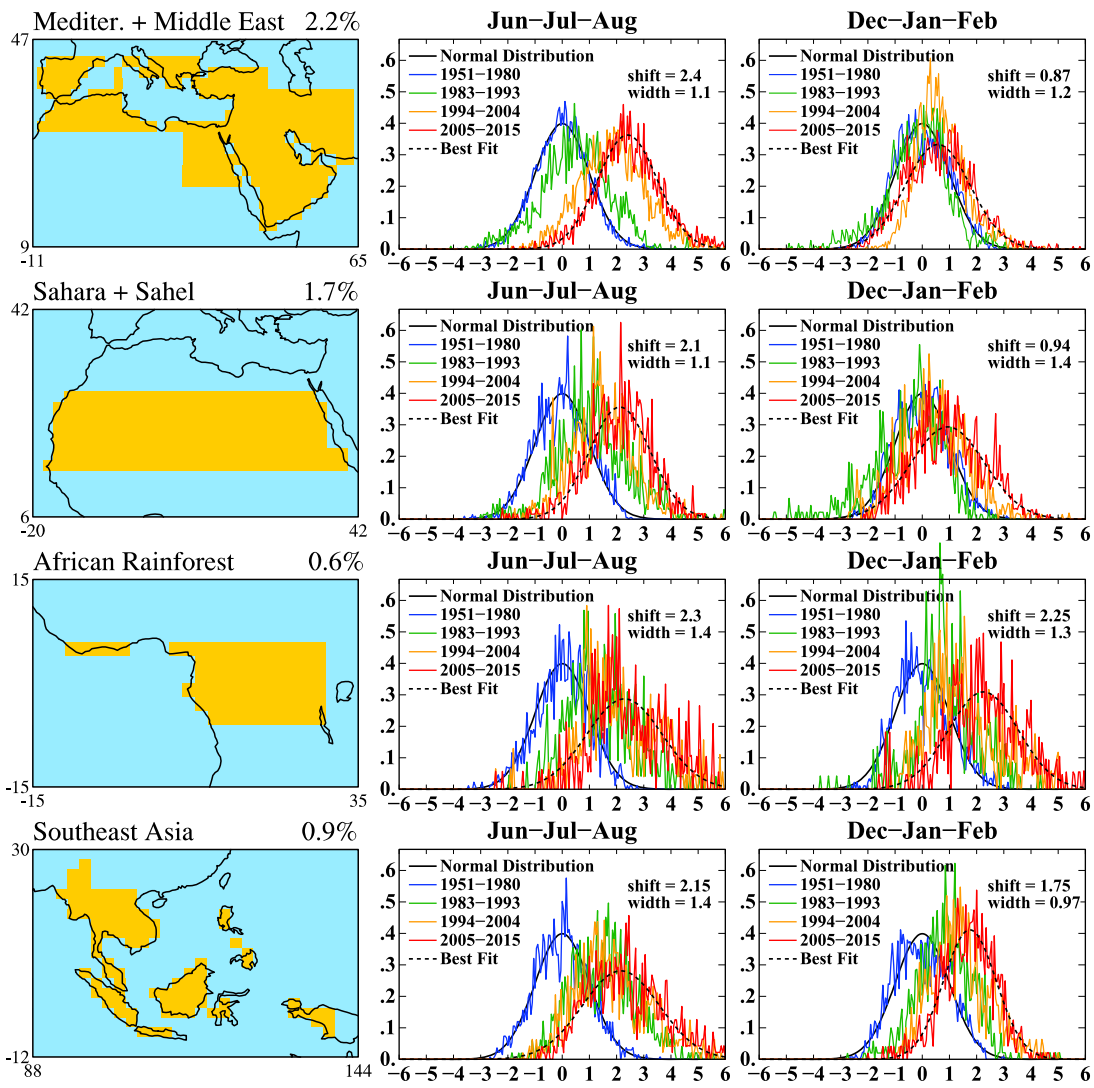

Figure 3. Shifting bell curves that define the frequency of local temperature anomalies relative to the 1951–1980 base period for four regions, with definitions and nomenclature as in figure 1.

changes in recent years, but SST data are not employed in our present study.

Large warming in 2005–2015 exists not only in the Mediterranean, Middle-East, Sahara region but also in the Gobi Desert and Southwest United States. Amplified warming in desert regions (Cook and Vizy 2015) and a tendency for increasing heatwaves and strong droughts to coincide (Mazdiyasni and Agha-Kouchak 2015) are expected consequences of increased global warming. Generally, as global warming increases, climatologically wet regions tend to get wetter and dry regions get hotter and drier (figure 2.33 in IPCC 2013). Polar amplification of surface warming is also apparent (figure 4), but that warming occurs where interannual climate variabitily is very large, so the signal-to-noise ratio and bell curve shifts are smaller at high latitudes.

Next, based on available peer-reviewed studies, we briefly review practical impacts expected to result from the shifting temperature bell curves discussed above.

Livlihoods are affected by higher temperature and associated absolute humidity, especially at latitudes with conditions already near the tolerance limit for outdoor work, as more than half of non-household labor-hours occur outdoors (ILO 2013, IPCC 2014, section 13.2). Developing countries in the tropics are affected disproportionately (Dunne *et al* 2013, Kjellstrom *et al* 2013, Lundgren *et al* 2013), but workers in places such as southern United States and eastern China are also affected by increasing temperature and absolute humidity (Luginbuhl *et al* 2008).

Human health is affected by higher temperature via impacts on heat waves, drought, fires, floods and storms, and indirectly by ecological disruptions brought on by climate change including shifting patterns of disease (Lafferty 2009, Altizer *et al* 2013, IPCC 2014, ch 11). Vector-borne diseases, usually involving infections transmitted by blood-sucking

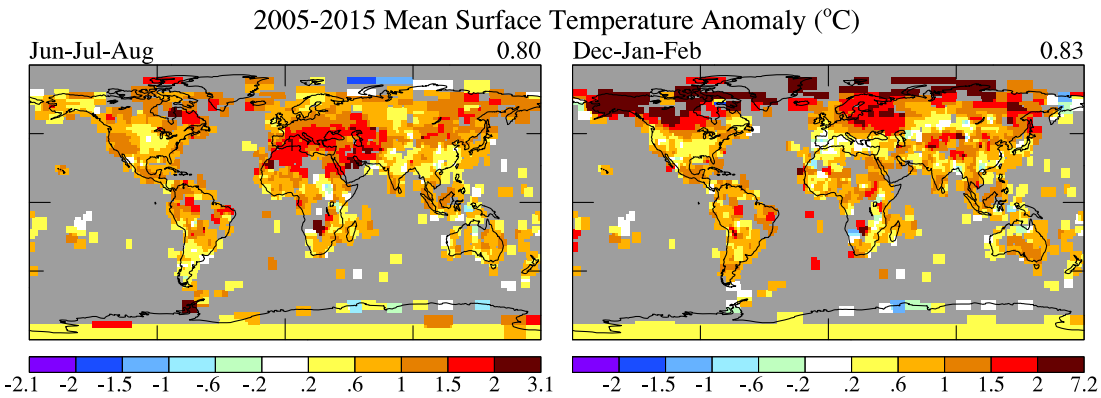

Figure 4. Surface air temperature anomalies in 2005–2015 relative to base period 1951–1980.

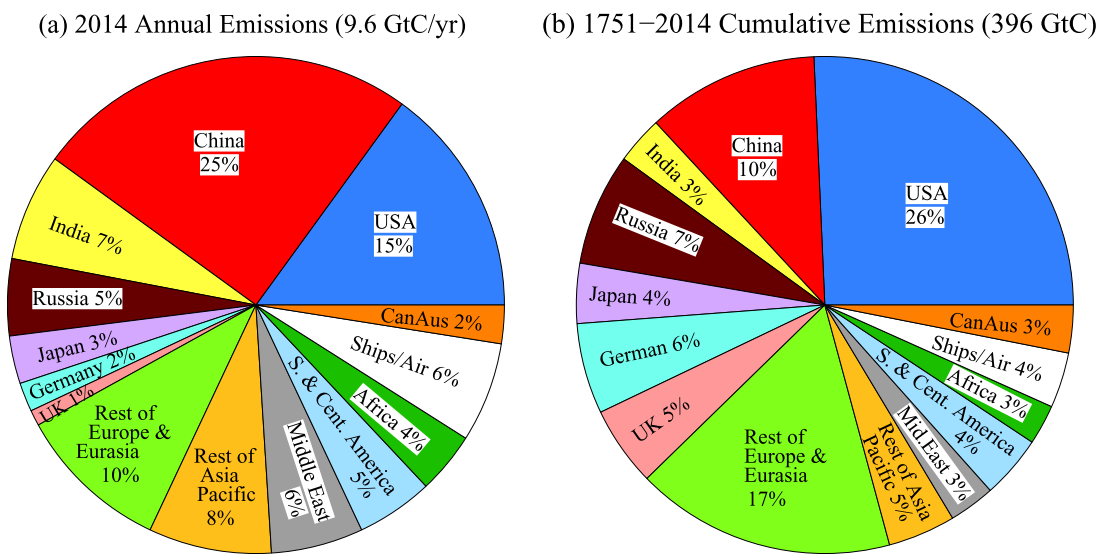

Figure 5. Fossil fuel CO_2 emissions by source in 2014 and cumulative 1751–2014. Results are an update of figure 10 of Hansen *et al* (2013b) using data of Boden *et al* (2015) and BP (2015).

mosquitoes or ticks, are sensitive to changing climate (IPCC 2014, section 11.5). Other factors will affect future disease incidence, but it can be concluded that higher temperatures allow the spread of some disease vectors to greater altitudes and higher latitudes (IPCC 2014, section 11.5).

National responsibilities for global warming can be assigned under the premise that fossil fuel CO_2 emissions are the primary issue for long-term warming. Deforestation and agricultural activities also contribute to atmospheric CO_2, but potential restoration of carbon into the soil and biosphere has comparable magnitude; indeed, assumption of such restoration via improved agricultural and forestry practices, including reforestation of lands that are of marginal value for crops, seems required if climate is to be stabilized at a level close to the Holocene temperature range (Hansen *et al* 2008, National Research Council 2015). In contrast, carbon released in fossil fuel burning will not be naturally removed from the climate system for millennia (Archer 2005, IPCC 2013, ch 6). CH_4, N_2O, O_3 and other gases also contribute to human-made climate change, but CO_2 contributes about 80% of the increase of GHG climate forcing in the past two decades (see figure 5 of Hansen *et al* 2013d) and much of the increase of the other 20% is related to fossil fuel mining or fossil fuel use.

Current fossil fuel CO_2 emissions are shown in figure 5(a). China is the largest source of current emissions, with the United States second and India a rapidly growing third. However, climate change is accurately proportional to cumulative emissions (Hansen *et al* 2007, Matthews *et al* 2009), shown in figure 5(b). The United States and Europe, including their portions of air and ship emissions, are each responsible for more than one-quarter of the climate change, China about 10% and India about 3%. Consumption-based accounting for emissions (Peters 2008) increases this disparity between developed and developing country emissions.

Per capita fossil fuel emissions (figure 6(a)) and cumulative emissions (figure 6(b)) provide a useful

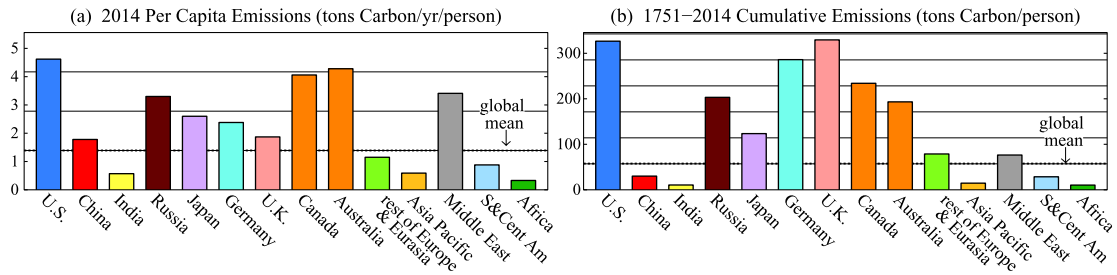

Figure 6. Per capita fossil fuel CO_2 emissions in 2014 and cumulative. Data sources as in figure 5. Results for additional individual nations are available at www.columbia.edu/~mhs119/CO2Emissions/.

perspective on emission responsibilities. Despite China's high current emissions, on a per capita basis they remain lower than many western nations, and slightly larger than the global average. Cumulative per capita emissions by China are an order of magnitude smaller than US emissions, and India's cumulative per capita emissions are even smaller.

Results similar to figures 5 and 6 have been reported many places. Our figures, available at www.columbia.edu/~mhs119/CO2Emissions/, are normally updated annually using indicated sources. Uncertainties in Chinese emissions include probable overestimate of coal emission factors (Liu *et al* 2015) and possible underreeporting of coal use (Buckley 2015).

There is striking incongruity between locations of largest climate change and fossil fuel emission sources, as noted by Diffenbaugh and Scherer (2011) and Mahlstein *et al* (2011, 2012). Largest bell curve shift is in tropical rainforest, South-East Asia, the Sahara and Sahel (figure 3). Largest temperature shift, in units of its natural variability, does not necessarily imply largest impact on local inhabitants. However, the fact that largest changes occur in places already near the limits of human heat tolerance suggests that added heat may be a problem. Fossil fuel emissions from nations in these areas are very small (Boden *et al* 2015). The only nation in these regions with current emissions as large as the global mean (figure 6(a)) is Malyasia, with current per capita emissions of about 2 tonsC/year/person. However, the cumulative emissions from these nations are all very small in comparison with developed nations, with African emissions even less than that of India (figure 6(b)). In other words, the nations experiencing the largest change of prior normal climate bear negligible responsibility for causing the climate change.

An equally large climate shift is occurring in the Mediterranean + Middle East region. The large shift is confined to the lengthening warm season, when temperatures are already near the limit of human heat tolerance. At minimum the added heat makes life more difficult in the summer and reduces productivity; it also intensifies drought conditions such as those in Syria in recent years, if not being a principal cause of the drought (Kelley *et al* 2015). As for emission responsibility, unlike most of Africa and South-East Asia, per capita emissions from the Middle East are among the largest in the world (figure 6(a)) and the fastest growing as the price of fossil fuels is kept low in many countries via government subsidies. Qatar, Kuwait, Oman, United Arab Emirates and Saudi Arabia have per capita emissions ranging from 12 to 5 tons of carbon per person per year, all greater than per capita emissions in the United States (figure 6(a)). Cumulative emissions per capita by Middle Eastern nations are not as large as in countries that developed earlier, but they are larger than the global mean (figure 6(b)).

The bell curve shifts in 2005–2015 are only about one-third of the shift that will occur with 2 °C global warming. (Although warming of land areas in 2005–2015 is ~0.8 °C, figure 4, global mean warming is only ~0.6 °C relative to 1951–80; 1951–80 is ~0.3 °C warmer than pre-industrial, Hansen *et al* (2010), so 2 °C warming above pre-industrial implies 1.7 °C relative to 1951–1980.) Given the approximate linearity between mean temperature increase and bell curve shift, 2 °C global warming would yield a shift of about six standard deviations during summer in the Mediteranean, Middle East, Sahara and Sahel regions and a similar shift in all seasons in the African Rainforest and Southeast Asia (figure 3).

Implications of these regional climate shifts are manifold. We note several consequences, focusing on their geographically uneven impact, especially the difference between developing countries at low latitudes and more developed northern nations. The examples and not a review of these burgeoning research areas, but they are sufficient to introduce discussion of relevance of these regional changes to the issue of dangerous human-made climate change.

Hsiang *et al* (2013) assemble the results of 60 quantitative studies of the relation between climate change and human conflict spanning the last 10 000 years and all major world regions. They find that interpersonal violence increases by 4% and intergroup conflict by 14% for each standard deviation change in temperature toward warmer temperatures. Such findings do not constitute natural laws, but they provide a useful

empirical estimate of impacts that can be used for at least a limited range of temperature increase. Increases we infer of 2–6 standard deviations with 2 °C global warming imply significant effects in all regions, but with larger effects at lower latitudes. Conflicts in turn tend to result in migrations with effects on both displaced and host populations (McMichael *et al* 2012).

Temperature rise itself imposes a strong disproportionately large effect on low latitude countries. Pal and Eltahir (2015) note that business-as-usual fossil fuel emissions result in some regions in the Middle East becoming practically uninhabitable by the end of this century as the wet bulb temperature approaches the level at which the human body is unable to cool itself under even well-ventilated outdoor conditions (Sherwood and Huber 2010). Today's global temperature distribution has notable nonlinear effect on economic productivity (Burke *et al* 2015). Middle latitude countries have near-optimum temperature and limited impact from projected temperature change, but, in contrast, warmer countries, such as Indonesia, India and Nigeria are on a steep slope with rapidly declining productivity as temperature rises (figure 2, Burke *et al* 2015).

These regional consequences of warming are accompanied by a threat that sea level rise poses to global coastlines, thus jointly creating a need for prompt strong actions to avoid tragic results. Earth's history suggests that warming of even 1 °C above pre-industrial levels could eventually lead to 6–9 m sea level rise (Dutton *et al* 2015). IPCC (2013) estimates that about 1 m or less sea level rise would occur by 2100, but Hansen *et al* (2015) argue that amplifying feedbacks make a highly nonlinear response likely with potential for several meters of sea level rise this century and recent ice sheet models explore mechanisms that may contribute to rapid ice sheet collapse (Pollard *et al* 2015). If the ocean continues to accumulate heat and increase melting of marine-terminating ice shelves of Antarctica and Greenland, a point may be reached at which it is impossible to avoid large scale ice sheet disintegration. Given that a majority of large global cities are located on coastlines, sea level rise would add another source of migration pressure.

The United Nations 1992 Framework Convention on Climate Change (UNFCCC 1992) stated its objective as '…stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. The 15th Conference of the Parties (Copenhagen Accord 2009) changed the focus to a goal to '…reduce global emissions so as to hold the increase of global temperature below 2 °C…', and the 21st Conference of the parties added an aspirational goal of below 1.5 °C (Davenport 2015). However, we suggest that the UNFCCC (1992) objective to stabilize GHG concentrations is fundamental and starkly informs policy requirements.

Atmospheric CO_2 amount, in particular, is a great challenge in limiting GHG concentration. Earth's paleoclimate history, especially the sensitivity of sea level to global temperature (Dutton *et al* 2015), and knowledge of Earth's carbon cycle (Archer 2005, IPCC 2013, ch 6) provide a strong constraint, which Hansen *et al* (2008) use to infer that CO_2 must be restored to a level no higher than ~350 ppm, with restoration prompt enough to avoid practically irreversible ocean warming and ice sheet disintegration. This estimate for the CO_2 ceiling was affirmed by accurate measurements of Earth's present energy imbalance (Hansen *et al* 2011, von Schuckmann *et al* 2016).

Restoration of CO_2 to a level at or below 350 ppm within a century, even with optimistic assumptions about restoration of biospheric and soil carbon, would require reductions of fossil fuel emissions by 5%–7% per year if reductions are started promptly (Hansen *et al* 2013b). Failure to achieve such reduction will result in continued long-term energy imbalance with Earth's surface and ocean continuing to warm, growing regional climate impacts, accelerating ice sheet disintegration, and more rapidly rising sea level. As evidence of the situation and consequences grows, there may be increasing calls for climate 'geo-engineering' (Royal Society 2009) with unknown consequences (Sillmann *et al* 2015).

Country-by-country goals, the approach of the 21st Conference of the Parties (Davenport 2015), will not lead to planetary energy balance and climate stabilization if fossil fuels are the cheapest energy. It is necessary to include 'external' costs to society in the fossil fuel price, especially the costs of climate change and air and water pollution (Ackerman and Stanton 2012), so that carbon-free energies and energy efficiency can supplant fossil fuels more rapidly. Such inclusive pricing of fossil fuels makes economies more efficient and reduces net economic hardships, if the carbon fee, collected from fossil fuel companies at domestic mines and ports of entry, rises gradually and if the funds are distributed uniformly to the public (Hansen 2014).

A carbon fee can be initiated by a few major economic powers and spread to most nations via border duties on fossil-fuel-derived products from non-participating nations and fee rebates to domestic manufacturers for goods shipped to non-participating nations (Hsu 2011). Issues raised by 'coercive cooperation' implicit in border adjustments (Bohringer *et al* 2012) will be subdued, once the severity and urgency of the climate threat is widely appreciated, by realization that fossil fuels cannot be phased out if some countries are allowed to export products made with untaxed fossil fuels. Developing countries have rights, recognized in the concept of common but differentiated responsibilities, and leverage to achieve economic assistance, which should be tied to the improved agricultural and forestry practices needed to

limit trace gas emissions and store more carbon in the soil and biosphere. Finally, international cooperation in generating more affordable carbon-free energies is needed, or economic development in many nations will continue to be based on fossil fuels, despite pollution and climate impacts.

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