Testimony for House Committee on Energy and Commerce

Subcommittee on Energy and Power

hearing entitled

"Climate Science and EPA's Greenhouse Gas Regulations"

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Summary

Observational studies show that warm temperature extremes have become hotter since the mid 20th century, cold temperature extremes have moderated, and precipitation extremes have intensified over broad areas of the world where suitable observations are gathered. There is a firm physical basis for the expectation that increasing greenhouse gas concentrations in the atmosphere should lead to such changes, and recent research that compares observations with changes predicted by climate models shows that the effects of increasing greenhouse gas concentrations provides a more plausible explanation for the observed changes in temperature and precipitation extremes than other possibilities, such as natural climate variations. While these studies do not provide the final word on the question of whether, and by how much, increasing greenhouse gas concentrations have affected the frequency and intensity of extreme climate and weather events, they suggests that human influence is now affecting the frequency and intensity of high impact events that put people and their livelihoods at risk. Moreover, studies of two specific events (the European 2003 heat wave, and flooding in the UK in the autumn of 2000) have shown that the odds of those events had been increased substantially relative to the world that would have been in the absence of human induced increases in atmospheric greenhouse gases. The approaches used in these studies are applicable to other events, and to the prediction of long- and short-term changes in the risk of damaging climate events.

Biographical Information

I am a Canadian citizen who was born in the Netherlands and immigrated to Canada with my parents as a small child. I am married with three children and currently live in Victoria, BC. I was trained as a statistician but have spent most of my professional career in climate science, primarily at Environment Canada where I have served as a Research Scientist, Chief of the Canadian Centre for Climate Modelling and Analysis, and ultimately Director of the Climate Research Division which has about 120 staff. Recently, I have taken a position at the University of Victoria as the Director of the Pacific Climate Impacts Consortium, which is a regional climate service that serves public and private stakeholders as well as the general public in the Pacific and Yukon region of Canada. I have served the IPCC in a number of capacities over my career, including as a Lead Author of Chapter 12 of the IPCC WG1 contribution to the Third Assessment Report Report (Mitchell et al., 2001), a Coordinating Lead Author of Chapter 9 of the IPCC WG1 contribution to the Fourth Assessment Report (Hegerl et al., 2007), and currently as a member of the IPCC Bureau for WG1.

Introduction

As noted in the recent U.S. Climate Change Science Program Synthesis and Assessment Product 3.3 (CCSP, 2008) "Extremes are a natural part of even a stable climate system and have associated costs ... and benefits. For example, extremes are essential in some systems to keep insect pests under control. While hurricanes cause significant disruption, including death, injury, and damage, they also provide needed rainfall to certain areas, and some tropical plant communities depend on hurricane winds toppling tall trees, allowing more sunlight to rejuvenate low-growing trees. But on balance, because systems have adapted to their historical range of extremes, the majority of events outside this range have primarily negative impacts."[i] Recently we have seen a spate of extreme climate and weather events that have drawn intense media interest, including this winter's intense storms affecting the US and Canadian eastern seaboard, similarly extreme winter storms last year, the Russian heat wave and Pakistani flooding of summer 2010, the extraordinary Australian flooding event of this past January. These events have certainly tested our ability to cope with weather and climate variations, have had significant negative impacts, and pose the question as to whether human influence on the climate system has played a role. While the research required to answer this question specifically in the context of recent events is yet to be completed, two new papers in *Nature* (Min et al., 2011; Pall et al., 2011) have presented evidence that changes in the intensity of extreme precipitation since the middle of the 20th century may be linked to human induced global warming, and that in at least in one instance, that human influence on climate had likely substantially increased the risk of flooding.

The observed intensification of precipitation extremes, and observed changes in temperature extremes, are occurring in the context of a climate that has warmed markedly over the past century. Since this change in the basic state of the climate system affects extremes, I first briefly review some of the available information on global warming. I then consider research on changes in temperature and

precipitation extremes specifically that I and my colleagues have undertaken. It should be noted that the types of events that we have considered are the simplest imaginable – heavy 1-day and 5-day precipitation accumulations, and extreme warm or cold temperatures. An important reason for this simple approach is that reliable data, gathered operationally by meteorological services in many countries, are available to define such events, assess whether they are changing in intensity or frequency, and if possible, assess causes of observed changes. While this makes the science at least somewhat tractable, it has only allowed us to begin to scratch the surface of a complex web of questions; there is a great need to better understand the complex combinations of factors that trigger impacts in humans and ecosystems (Hegerl et al., 2011) and to understand how, and why, dynamically energetic phenomena such as tornadoes and hurricanes are changing and are likely to change in the future.

Warming of the climate system

The global surface temperature record is the most thoroughly studied and scrutinized observational record used in climate research. Compiling this record is a massive undertaking that involves the assembly, quality control and adjustment of observations from thousands of locations and that are obtained with a variety of technologies. Several groups (UEA CRU/Hadley Centre, NASA GISS, NOAA NCDC, etc) independently maintain compilations of surface temperature (Brohan et al., 2006; Hansen et al., 2006; Smith et al., 2008). Differences between compilations reflect uncertainty due to incomplete global coverage, differences in approaches that are used for gridding, adjustment uncertainties, etc. The record is continually updated as new observations become available, historical data are recovered and transcribed to electronic form, errors in data entry, station location and identification, processing, etc., are identified and corrected, and adjustments techniques are improved[ii,iii]. Figure 1 shows that despite the different methods in the way they collect and process data to calculate the global-average

temperature, there is agreement on temperature trends from decade to decade (Figure 1) and they all agree global-average temperature has increased over the past century. Differences between global-average temperature anomalies estimated from the different compilations are consistent with published uncertainty estimates that accompany each of the compilations.

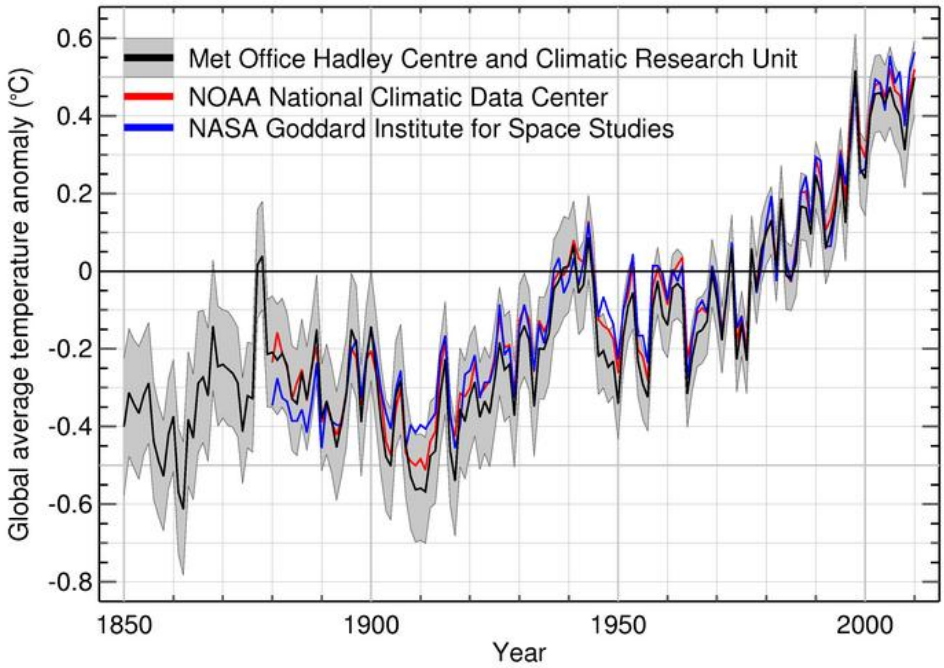

Figure 1: Estimated global-average surface temperature anomalies based on three data sets. The three data sets are: Met Office-CRU (black), produced by the Met Office Hadley Centre in collaboration with the Climatic Research Unit at the University of East Anglia; NCDC (red) produced by the National Climate Data Center; and NASA GISS (blue) produced by the Goddard Institute for Space Studies at NASA. The grey shaded area shows the approximate 95% confidence range for the Met Office-CRU data. The true global average is expected to lie outside this range around 5% of the time. Courtesy Peter Stott, Met Office Hadley Centre.

Warming over the past century is unequivocal (IPCC, 2007). This is evident not just from the surface temperature record (e.g., Figure 1), but also from observations of other parts of the climate system – information that is gathered independently of the surface temperature record using different methods and instruments from those that are used to monitor surface temperature. For example, the free atmosphere, as monitored by satellites, is warming in a manner that is consistent with surface warming (Figure 2). In addition, a recent survey of 10 key climate indicators published in the 2009 *State*

of the Climate report (Arndt et al., 2010)[iv], and based on the findings of 300 scientists from 160 research groups in 48 countries, all point to the same finding that the world is warming. The indicators include increases in atmospheric water vapour content, reductions in snow cover extent, glacier mass balance and Arctic sea ice extent (see also Min et al., 2008), warming in the interior of the global oceans leading to increases in ocean heat content, and rising sea level due to ocean warming and the melting land ice.

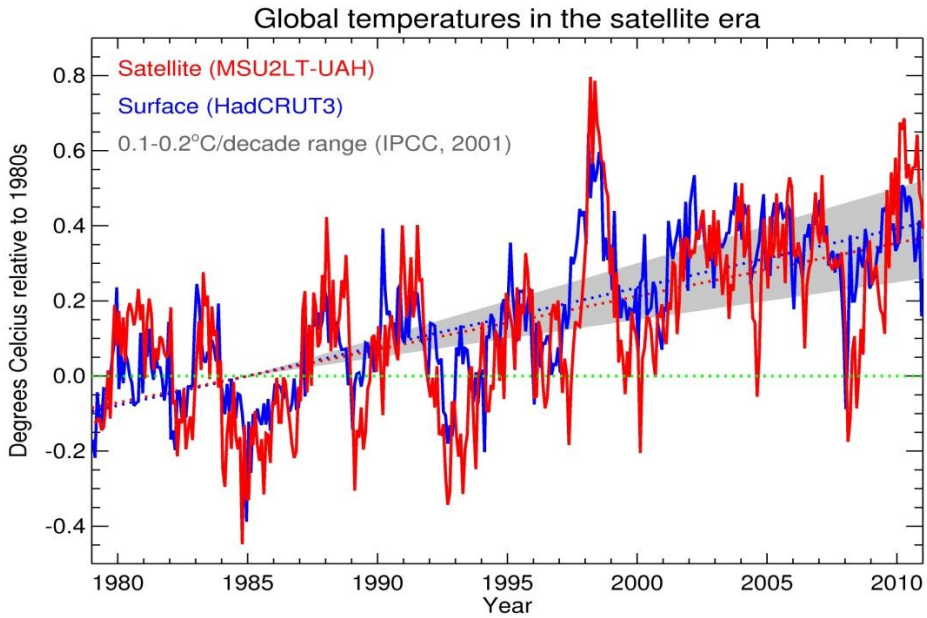

Figure 2: Monthly global mean surface temperature anomalies estimated from HadCRUT3 (blue) and global mean lower tropospheric air temperature anomalies estimated from the University of Alabama MSU2LT record (red) relative to 1980-1989 for 1979 to the present. The trends for this period are shown in dotted blue and red lines respectively, and show warming over the period of about 0.15°C per decade. Also shown is the warming range projected by the IPCC in its Third Assessment Report (IPCC, 2001). Figure courtesy Myles Allen, University of Oxford.

Figure 2 also shows the prediction that was made by the IPCC in 2001 that the decade of the 2000s would be 0.1-0.2°C warmer than the 1990s, primarily because of the influence of rising greenhouse gases. The fact that this prediction has turned out to be correct provides independent confirmation that most of the observed warming on global and continental scales can be ascribed, with a high level of scientific certainty, to increases in greenhouse gas concentrations in the atmosphere. If the upswing in temperatures from the 1970s to the 1990s had been entirely due to internally-generated variability, there would have been no reason to predict a continued warming.

The effect of greenhouse gas induced warming is modulated to some extent by other influences on the climate system, including that of aerosols, volcanic activity, and solar activity (Hegerl et al., 1997; Tett et al., 1999; Huntingford et al., 2006; Hegerl et al., 2007) as well as natural internal variability. It is acknowledged that there have likely also been influences from regionally important forcing agents, such as land use change (Portmann et al., 2009) and some types of aerosols (including black carbon – soot; Jones et al., 2011); some of which may have regional cooling influences, but the science has not yet been able to quantify the extent to which these factors have affected regional temperatures. Against this backdrop of natural variability and possible regional influences, it is not surprising that warming should be less evident at some times than others, or that it should be less evident in some regions, such as in the US "warming hole" (Kunkel et al., 2006; Portmann et al., 2009; Christidis et al., 2010).

That there should be a warming effect is an unassailable fact of science. Human use of fossil fuels and the land surface have lead to an increase in the atmospheric concentration of CO_2 from about 280 ppmv prior to industrialization to approximately 390 ppmv today (GAW, 2010). Concentrations continue to rise at a rate of about 2 ppmv per year. CO_2 is a gas that is transparent to sunlight, and thus its presence in the atmosphere does not impede the flow of energy into the Earth system. Sunlight, which powers the Earth system, is either reflected back to space (by clouds, reflective aerosols, or the Earth's surface), or absorbed and converted to heat. In order to maintain a constant temperature, the Earth must, in turn, radiate the heat that is produced from sunlight back to space. However, higher levels of CO_2 and other greenhouse gases in the atmospheric make it more difficult for heat to exit the system because these gases not fully transparent to infrared (heat) radiation. This inevitably leads to a warming, the magnitude of which depends upon various "feedback" processes. Science has been aware of this warming effect, which is now well evident in observations, since the 19th century (Fourier, 1824; Arrhenius, 1896; Harries et al., 2001).

Extreme Temperature and Precipitation Events

While observed changes in global-average temperature may not seem to be particularly harmful, it is increasingly apparent that neither the observed warming over the past century of approximately 0.75°C globally (Trenberth et al., 2007), nor the projected warming of approximately 2-4°C or more for the end of the current century (Meehl et al., 2007), is without serious impact. It has often been stated that those impacts will make themselves felt most acutely through extreme climate and weather events because such events evidently stress the coping capacity of human and natural systems. From an ecosystem perspective, extreme events may initiate responses to gradual background changes that are delayed by inertia (e.g., Jentsch and Beierkuhnlein, 2008).

Changes in extreme temperature and the intensification of extreme precipitation events are natural consequences of a warming climate. A warmer climate would inevitably have more intense warm temperature extremes than the present climate, including longer and more intense heat waves, and less intense cold temperature extremes. Further, a warmer atmosphere can, and does, hold more water vapour, which has been detected in data (Santer et al., 2007; Willett et al., 2007; Arndt et al., 2010), and which implies that more moisture is available to form precipitation in extreme events and to provide additional energy to further intensify such events[v]. Many of these expected changes have been observed, and in some instances, are beginning to be linked to human induced warming of the climate system.

A number of studies (e.g., Christidis et al., 2005, 2010; Zwiers et al., 2011) have now used various types of detection and attribution methods to determine whether the changes in temperature extremes predicted by climate models in response to historical greenhouse gas increases and other forcings are detectable in observations of extreme temperatures. This research demonstrates that this is indeed the case, both globally and in many regions, and suggests that human influence has substantially increased the frequency of rare warm events globally (such as the 20-year warm extreme in daily

maximum or minimum temperature) and substantially decreased the frequency of rare cold events (such as the 20-year cold extreme in daily maximum or minimum temperature) (Zwiers et al., 2011).

While demonstrating that human influence from increasing greenhouse gas concentrations has influenced temperature extremes on large scales is a useful advance that provides information about the impact of global warming, this alone does not answer the very frequently asked question about whether a specific event, such as the extended European heat wave of 2003 that caused approximately 40,000 deaths (García-Herrera et al., 2010), was due to human influence on the climate system. The clear answer to this question, and one that is underscored by the Meehl et al. (2009) study of the occurrence of record breaking temperatures, is that individual extreme events cannot be ascribed to human influence on the climate system in the sense that the event could not have occurred if it were not for human influence. It is, however, possible to assess how human influence on climate may be "loading the weather dice", making some events more likely, and others less likely. In the case of the European heat wave event, Stott et al. (2004) estimated that human influence had very likely at least doubled the probability of an event similar to that which occurred compared to the world that would have been if human activities had not increased greenhouse gas concentrations. Numerous factors can affect the occurrence of an extreme warm event in a given location, so answering the question, what was the role of human influence on climate in this event, requires specific research. Showing that one heat wave was made more likely by human influence does not mean this would apply to all heat waves.

Heavy and extreme precipitation events have also received a considerable amount of study. Heavy precipitation has contributed an increasing fraction of total precipitation over the regions for which good instrumental records are available (Groisman et al., 2005; Alexander et al, 2006), and particularly over the US (Karl and Knight, 1998; Kunkel et al., 2007; Peterson et al., 2008; Gleason et al., 2008), indicating an intensification of precipitation extremes. Direct examination of precipitation extremes, such as the largest annual 1-day accumulation, or the largest annual 5-day accumulation, also

shows that extreme precipitation has been intensifying over most parts of the world for which suitable records are available (Alexander et al., 2006; Min et al., 2011, Figures 3, 4), with an increase in the likelihood of a typical 2-year event of about 7 percent over the 49 year period from 1951 to 1999.

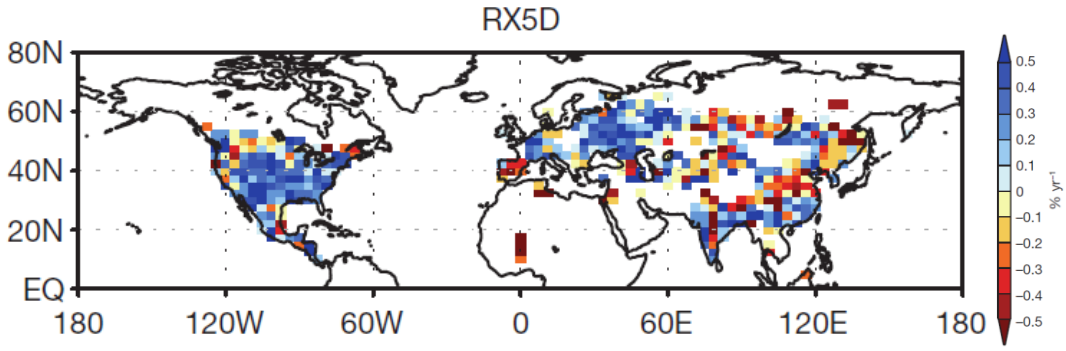

Figure 3: Geographical distribution of trends of extreme precipitation indices (PI) during 1951–99 for 5-day precipitation accumulations. Annual extremes of non-overlapping 5-day accumulations were fitted to the Generalized Extreme Value distribution which was then inverted to map the extremes onto a 0-100% probability scale. Blue colours indicate intensification of extreme precipitation, which is observed at about 2/3rds of locations. From Min et al. (2011).

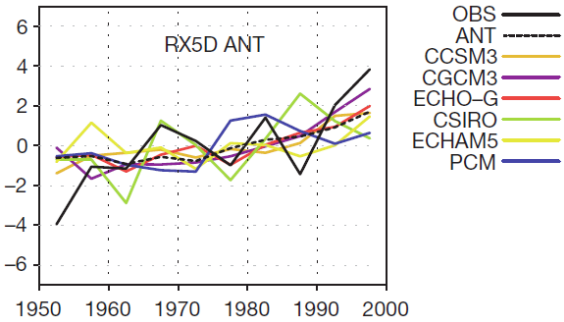

Figure 4: Time series of five-year mean area-averaged PI anomalies in percent for 5-day annual extreme precipitation anomalies over Northern Hemisphere land during 1951–99. Black solid line represents observations and the dashed line represents the multi-model mean for the models indicated in the legend. Model simulations where run with anthropogenic forcings. Coloured lines indicate results for individual model averages (see Supplementary Table 1 of Min et al. (2011) for the list of climate model simulations and Supplementary Fig. 2 of Min et al. (2011) for time series of individual simulations). Each time series is represented as anomalies with respect to its 1951–99 mean.

Climate scientists have long argued that an intensification of extreme precipitation is an expected consequence of human influence on the climate system (e.g., see Allen and Ingram, 2002; Trenberth et al., 2003). Indeed, models do intensify extreme precipitation in response to increasing greenhouse gas concentrations and Min et al. (2011) recently showed, using an ensemble of models, that the observed large-scale increase in heavy precipitation cannot be explained by climate variability, and is most likely due to human influence on climate. However, as with extreme temperature events, place and event based research is required to determine whether increasing greenhouse gas concentrations have altered the odds of a given type of event. Pall et al. (2011) demonstrate a suitable

approach, and show that human influence from increased greenhouse gas contributions had substantially increased the odds of flooding in England and Wales in the autumn of year 2000 as compared to the world that would have been if greenhouse gas concentrations had remained at pre-industrial levels (Figure 5).

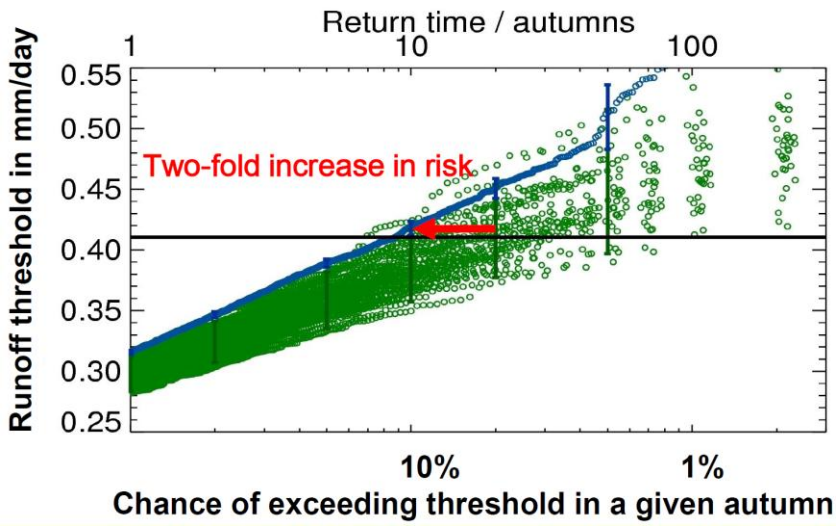

Figure 5: Change in occurrence frequency of daily river runoff for England and Wales in autumn 2000. Occurrence frequency curves of runoff (circles) synthesized from all precipitation simulations in A2000 (blue) and A2000N climates (green). A2000 climates are obtained using an atmospheric climate model run with observed year 2000 atmospheric composition (greenhouse gases and aerosols) and observed autumn 2000 sea-surface temperatures. A2000N climates are obtained using the preindustrial atmospheric composition and observed sea surface temperatures from which sea-surface temperature changes attributed to anthropogenic forcing had been removed. Four global coupled climate models (HadCM3, GFDLR30, NCARPCM1 and MIROC3.2) were used to estimate attributed sea-surface temperature changes. Top axis is equivalent return time. Horizontal lines mark the highest autumn 2000 runoff synthesized from ERA-40 precipitation (0.41 mm). Bars represent 5–95% confidence intervals. Note that 'chances' on the lower x-axis are provided to give an informal interpretation of the technical term 'return time' but do not account for the impact of multiple events occurring in a single season.After Pall et al. (2011, Supplementary Fig. 3a).

The weather events that do most damage are very often those that are most difficult to predict: we can, however, assess the impact of an external factor like human influence on climate on the odds of a weather event occurring, even if we cannot predict when it will occur (if you load a dice to double the odds of a six, you still cannot predict precisely the result of any particular roll). Hence the fact that seasonal forecasting of extreme weather is clearly very difficult does not prevent us from assessing the role of long-term drivers in extreme weather risk or attempting to predict seasonal variations in risk. El-Nino, for example, strongly influences both temperature and precipitation extremes globally (Kenyon

and Hegerl, 2008, 2010; see Figure 6), and can alter the likelihood of rare damaging precipitation events by more than a factor of 4 in some parts of the US, particularly in the southwest (Zhang et al., 2010). Any human influence on extreme weather risk combines with these episodic variations and the chance fluctuations that are inevitable when dealing with rare events: hence we should not assume that, if human influence is making a particular event more likely on average, it will necessarily do so every year.

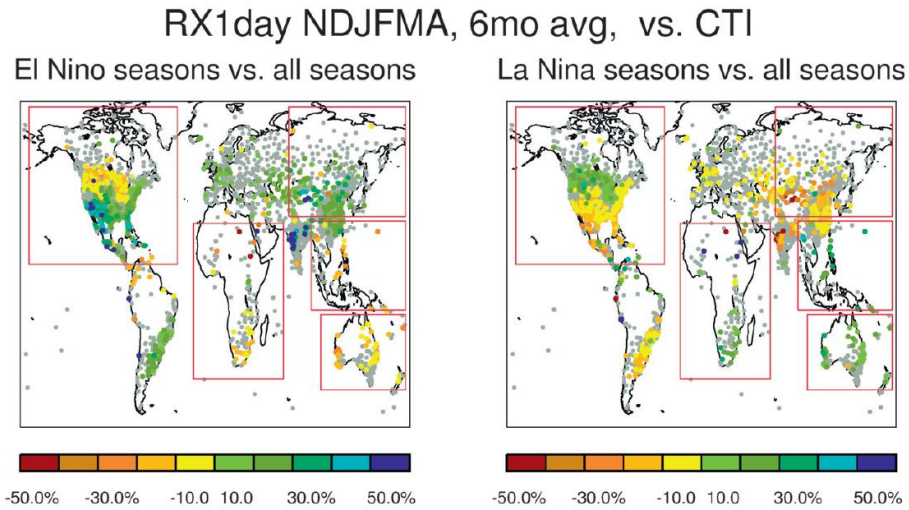

Figure 6: Impact of El-Nino (left) and La-Nina (right) on the intensity of the largest precipitation event monthly in the November to April half of the year. Based on station data from the GHCN (Global Historical Climate Network) for 1949-2003. Courtesy G. Hegerl. From Kenyon and Hegerl (2010).

The recent studies on temperature and precipitation extremes discussed in this statement are far from being the final word on the question of whether, and by how much, increasing greenhouse gas concentrations have affected the frequency and intensity of extreme climate and weather events. However, the "smoking gun" evidence from these studies suggests that human influence is now affecting the frequency and intensity of high impact events that put people and their livelihoods at risk. While assessments of the abilities of climate models to simulate temperature and precipitation extremes (e.g., Kharin et al., 2007) are sobering, there is a firm physical basis for the expectation that increasing greenhouse gases will intensify warm temperature extremes, moderate cold temperature extremes, and intensify extreme damaging precipitation events. Note that moderating cold temperature extremes are not necessarily a benefit – e.g., they have been identified as a key factor in the ongoing

devastation of western North American forests by forest beetles (see CCSP, 2008, Box 1.2). Recent research, such as that cited above, shows that these effects on climate are becoming evident in operationally gathered and reported meteorological data – scientific data that are not affected by changes in reporting policy or the intensity of media interest. While some people and regions may expect to benefit in the short term from climate change, the evidence is emerging that others, including citizens of the United States, may already be being harmed by extreme weather events that have been made more likely by human influence on climate.

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Notes

[i] CCSP (2008), pp 1-2.

[ii] The adjustment of instrumental records to remove non-climatic artefacts from, for example, instrument changes, is unavoidable if the record is to be useful for monitoring long term change. This is so both for the "insitu" instrumental record (e.g., surface temperature observations obtained with thermometers), and for satellite records, which much necessarily be constructed by piecing together readings from sequences of relatively short-lived instruments.

[iii] Corrections to errors in the CRUTEM3 dataset identified through scrutiny of CRU software and emails have virtually no impact on trends in either global-average surface temperature or global-average land surface air temperature. See http://hadobs.metoffice/com/crutem3/jan_2010_update.html for details.

[iv] See also http://www.noaanews.noaa.gov/stories2010/20100728_stateoftheclimate.html.

[v] The condensation of water vapour into precipitation releases the heat that was used initially to evaporate this water into the atmosphere. Therefore, if there is more condensation in a given event, more of this "latent" heat is released, imparting more energy to the storm.