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1 Introduction

My name is Claudia Tebaldi, I work as a Project Scientist at NCAR, the National Center for Atmospheric Research, in Boulder, Colorado. I have a PhD in Statistics, and in the last years, while working at NCAR, I developed expertise in analyzing climate records, both observed and simulated by General Circulation Models. It is in this capacity that I offer my testimony today and I want to thank you for this opportunity. It is a true honor.

Dr. Gerald A. Meehl, senior scientist at NCAR, and I have just published a study in the journal *Science* (1) the title of which well summarizes our findings: "More Intense, More Frequent and Longer Lasting Heat Waves in the 21st century." Many studies in the last decade have addressed projected changes in global average temperature, precipitation, and other general climate indicators. These studies use global coupled climate model experiments run under specific scenarios of future anthropogenic emissions. In the last few years, increasingly accurate

and more reliable climate models have let us ask, and answer, more specific questions with a more direct relevance for impacts on society and ecosystems at regional scales. The more recent focus on extreme climate events and their impacts has been galvanized by the perceived gap between climate and impacts sciences that became apparent in the IPCC's Third Assessment Report published in 2001. Thus, even if our study was made urgent by the devastating effects of the heat wave that plagued Europe in the Summer of 2003, it is just one of a new and growing series that focus on projected regional climate change, and in particular, extreme events and their impacts on society (2a,b,c and references therein).

To turn then to our study in particular, the key finding is this: Heat waves are projected to become worse at the end of the 21st century: more intense, more frequent and longer lasting. With this testimony, I substantiate this claim by presenting the major findings in some detail and support it by showing how we gathered confidence in our model results.

2 More intense, more frequent and longer lasting heat waves in the 21st century

We used the global climate model developed at NCAR with support from the Department of Energy, the Parallel Climate Model (PCM). Though the model is global, we focused on the continental United States and Europe in our analysis of observed and simulated climate. There is not one standard definition of a "heat wave". We used two definitions that characterize in statistical terms what was observed in Chicago during July 1995 and in Paris in August 2003. Linking the characteristics of the two historic events — both having catastrophic effects on the populations of these two cities — to the statistics that we derived from observations and model output is a way of making our findings immediately relevant for potential impacts assessment.

Our data consists of records of temperatures and height of the 500 mb. atmospheric pres-

sure surface, the latter describing patterns of the atmospheric circulation, that we derive from observations and computer model simulations. The observational dataset was obtained from the archives of the NCAR/NCEP reanalyis project (3). The two sets of simulations by the PCM are:

1. Climate simulations under a set of forcings representative of the historic conditions during the past century. We take the period between 1961 and 1990 as a reference period against which to compare changes at the end of the 21st century.

2. Future climate simulations, under the "business as usual" scenario (4). This scenario assumes no policy intervention to mitigate the current rate of anthropogenic emissions, i.e., a scenario in which emissions are projected to continue at the current rate. This leads to a doubling of CO_2 concentration in the atmosphere, relative to pre-industrial levels, by the end of the 21st century.

To quantify the uncertainty in the model simulations, the 20th century experiment was run four separate times, and the 21st century experiment was run five times.

The first step in our analysis was a diagnostic one: we validated the statistics of heat wave intensity, frequency and duration under current climate conditions as simulated by the PCM by comparing them to the observed statistics. Figure 1, taken from our *Science* paper, shows in the panels of the first two rows the extremely good agreement in the intensity of heat waves and its spatial distribution, for both the United States and Europe. The panels in the first row depict the spatial distribution and values of the average "worst three-day event,"[1] as observed during the period between 1961 and 1990. The corresponding panels in the second row show the same statistics but derived from climate model output. The agreement between corresponding panels is evident both in terms of spatial features and of actual values.

[1]Defined as the warmest three consecutive days each summer, relative to daily minimum temperature.

We also validated statistics of heat wave duration and frequency. With respect to these statistics, too, the model simulation is well in agreement with observations.

The agreement in the temperature statistics (i.e., the characteristics of heat waves) between modeled and observed data gives us confidence in the accuracy of our model simulations for current climate conditions. Additional confidence was gathered by comparing the atmospheric processes that are known to cause the onset and duration of heat waves. The question we were asking here is this: are the reasons why our model produces these heat waves the same as in nature? And, what we found is that the internally consistent dynamics that produce heat waves in the model are indeed the same as those that produced the actual heat waves in Chicago and Paris. Thus, we can state that the model produces an accurate simulation of present-day heat wave frequency, duration and intensity, and it does so for the right dynamical reasons. Having substantiated the reliability of our model, we can now look at future simulations.

The prognostic step in our analysis quantified the changes in heat wave characteristics under future climate conditions. Our results show that heat waves are projected to become more intense, more frequent, and longer lasting. We see statistically significant shifts in the average values characterizing the worst three-day events at every location in the United States and Europe, and this is shown in the third row of panels in Figure 1. We see heat wave frequency becoming higher by, on average, 25% in the Chicago area and 30% in the Paris region. We see heat wave duration increasing.[2]

Similar to our analysis of current conditions, we also sought to explain the changes in heat waves characteristics as a result of changes in the mean state of the dynamical processes that underlie them, again by looking at the 500mb. height patterns. We already know that such changes in atmospheric pressure can result from higher greenhouse gas concentrations. The

[2]We actually performed these kinds of analyses for many more areas around the globe, and the results consistently indicate a worsening of the expected heat wave characteristics for all regions of the world.

results show that the pattern of changes in heat waves is related to the mean change in atmospheric circulation due to increased greenhouse gases. To further strengthen our analysis of future changes in heat waves we computed the same statistics of change in the average 500mb height under increased CO_2 concentrations for a suite of climate model runs. These runs have been made available by a number of research centers, through the Coupled Model Intercomparison Project (5). With the increasing availability of comparable climate change simulations from groups around the world, we can now better quantify uncertainty in model responses through analysis of different models. The good agreement between the Parallel Climate Model and the other global climate models with regard to the simulation of the dynamical processes further strengthened our confidence that our results are not model artifacts.

3 We already know warming is happening, so what's new here?

Spatial details of our analysis add important information to the now generally accepted consensus that the climate will warm in the future. Average temperatures will increase and we are likely to see worse heat-related extreme events, but some areas are expected to see larger changes than others. Heat waves are going to worsen everywhere, but likely more so in the western United States and in the Southeast, and less so over the Northeast. Similarly, the whole of Europe will see greater intensity of heat waves, but likely more so along the Mediterranean coasts, spreading northward and affecting France and Germany – regions that were less prone to such events in the past. Some of these areas are already used to coping with intense heat during the summer. Others face greater challenges in adaptation to a changing climate because they do not currently experience severe heat waves. The extent and rate to which adaptation occurs will determine the actual consequences for the well-being of the human population and the health of natural ecosystems and resources (agriculture, wildlife, etc.).

References

(1) Meehl G. A. and C. Tebaldi, More Intense, More Frequent and Longer Lasting Heat Waves in the 21st century. *Science*, Vol. 305, No. 5686, pp. 994-997.

(2a) Hayhoe K., *et al.*, Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences*, Vol. 101, No. 34, pp. 12422-12427.

(2b) Meehl G. A., Tebaldi C. and D. Nychka, Changes in frost days in simulations of 21st century climate. *Climate Dynamics, online first*, DOI: 10.1007/s00382-004-0442-9.

(2c) Parmesan C., Root T.L. and M. R. Willig, Impacts of Extreme Weather and Climate on Terrestrial Biota, *Bulletin of the American Meteorological Society*, Vol. 81, No. 3, pp. 443-450. See also references therein.

(3) NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/

(4) Dai, A. *et al.* Climates of the Twentieth and Twenty-First Centuries Simulated by the NCAR Climate System Model. *J. of Climate*, Vol. 14, No. 6, pp. 1092-1111.

(5) Coupled Model Intercomparison Project: `http://www-pcmdi.llnl.gov/old/cmip/`

Figure 1: From "More Intense, More Frequent and Longer Lasting Heat Waves in the 21st century". *Science*, Vol. 305.