Challenges and Research Needs in Climate Change and Human Health:

A Case Study on Heat Waves

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October 8, 2010

NSF workshop on "Mathematical Challenges in Sustainability"

DIMACS (Rutgers)

November 15-17, 2010

Subtheme: Human well-being and the natural environment

Introduction

Climate change is anticipated to influence public health through a wide range of pathways, largely through exacerbating health risks that exist in the current day (NIEHS 2010). Air pollution levels may be affected, especially for pollutants with photochemical formation such as ozone (Chang et al. 2010, Bell et al. 2007). The distribution of infectious diseases, such as malaria and dengue fever, may shift into populations that have not been previously affected (Parham and Michael 2010, Johansson et al. 2009, Tanser et al. 2003). Changes in temperature and precipitation patterns as well as in the frequency, intensity, and distribution of floods and droughts may affect water-borne diseases, including cholera (Patz et al. 1996). Impacts on natural disasters (e.g., floods, hurricanes) can result in displacement, resulting in infectious disease and conflict (Watson et al. 2003). Altered weather patterns can affect agriculture, thereby impacting nutrition and hunger (Wesche and Chan, in press).

Efforts to quantify the health impacts from a changing climate face several challenges. A key challenge is estimating future conditions, which is often achieved through use of global circulation models (GCMs), often on conjunction with regional modeling systems. Researchers have extensively evaluated GCMs and improved the representation of the climate system and estimates of extreme conditions (IPCC 2007). Still limitations remain and some weaknesses of GCMs are known, such as an underestimation of the frequency and quantity of precipitation during extreme events. Uncertainties in the estimation of health impacts from climate change involves uncertainties inherent in the GCMs, linking of multiple systems (e.g., GCM output to be used in regional weather models), and downscaling output from GCM models to a finer spatial resolution. To estimate health consequences from climate change in the future, we must understand current day impacts. Thus, the uncertainties associated with models to estimate present day effects (e.g., how infectious disease spreads) also play a role. Other key challenges are the untestable assumptions regarding scenarios used as inputs to the GCMs and baseline health status with respect to population growth, emissions of greenhouse gases, the rate of technological development and implementation, changing demographics (e.g., age, race) that relate to susceptibilities, and urbanization.

Perhaps the most direct link between climate change and human health is through changes in weather patterns, with anticipated higher overall temperatures and more frequent and severe extreme events (Meehl and Tebaldi 2004). Several studies have examined how heat and heat waves affect temperature in the current day (Anderson and Bell 2009 and in press, Ostro et al. 2009, Curriero et al. 2002) and some have explored heat-related mortality impacts under a changing climate (Gosling et al. 2007). However, new approaches to generate quantitative estimates are needed (Xun et al. 2010, Kinney et al. 2008). Specifically, mathematical models for estimating current day effects and how to apply such models to future conditions are limited. Below, we describe many of the challenges to quantitative estimation of the human health consequences of higher temperatures under a changing climate, with a focus on the potential contributions of mathematical modeling. Many of the challenges discussed apply more broadly to the study of human health and climate change in general.

Challenges and Research Needs on the Effects of Heat Waves on Human Health

The majority of heat wave studies have retrospectively analyzed the adverse health impact associated with very extreme heat events. Studies are needed that investigate the health effects of heat waves in multiple locations over time in order to quantify the risks attributable to less extreme, but still potentially harmful, heat wave events. However, studies of health effects of heat waves are challenged by several factors inherent to how to: 1) specify the mathematical model for the association between temperature variables and health outcomes; 2) investigate susceptibility; 3) quantify adaptation; and 4) characterize sources of uncertainties in the data, the statistical model, and the parameters of the model. With adequate data, mathematical modeling of the relationship between temperature conditions and health outcome could substantially advance this research topic. Some of these challenges are described below.

Defining a heat wave: The definitions of heat waves generally involve specifying the following quantities: 1) exceedances of percentiles of the temperature distribution; 2) exceedances of specific absolute temperature levels; 3) continuous stretches of high temperature; and/or 4) high humidity. For example Meehl and Tebaldi in their paper in *Science* (2004) used the following definition: a heat wave is defined as the longest period of consecutive days satisfying: a) daily maximum temperature is above T1 for $\geq$ 3 days; b) daily maximum temperature is above T2 for the entire period; and c) average of daily maximum temperature over the period is $\geq$ T1, where T1 is the 97.5th percentile of the distribution of daily maximum temperatures; and T2 is the 81st percentile of daily max temperatures. In a recent analysis of heat and cold effects in 107 U.S. communities, Anderson and Bell (2009) considered 6 possible definitions of a heat wave with duration defined as periods of $\geq$2 or $\geq$4 consecutive days of temperatures above the 98.5th, 99th, or 99.5th percentile of the community's temperature, and these categorizations were used previously in analysis of 3 European cities (Hajat et al. 2006). Decisions regarding the definition of a heat wave should consider multiple ways of categorizing elevated temperatures, such as the absolute temperature levels or percentiles. These different ways of defining heat affect the interpretation of results regarding adaptation, such as whether a community is experiencing a temperature that is elevated compared to the city's more typical conditions.

Disentangling the health risk of a heat wave episode from the health risks of other environmental factors such as temperature and ambient pollutants: Statistical models for estimating the relative risks of heat waves published in the literature typically include both temperature terms as well as an indicator of a heat wave day (Anderson and Bell 2009). Under these models, the regression coefficient of the indicator provides an estimate of the heat wave effect beyond (e.g. adjusted by) the effect of temperature. Since heat waves are functions of temperature, inclusion of both variables in the model may introduce multicollinearity. In addition, it is more desirable to estimate a "global" or "cumulative" effect of heat wave that is not adjusted by temperature. However, since temperature is highly associated with mortality (see for example Curriero et al. 2002), omitting the temperature variable in a regression model having a heat wave day indicator yields a model with poor fit. Alternatively, to estimate a cumulative effect of temperature in the past few days before the adverse health event, temperature has been modeled with distributed lag models of both linear and nonlinear temperature covariates having time-varying regression coefficients (Welty and Zeger 2005). To estimate the effect of a heat wave event on mortality risk, studies have included as confounders day of week and smooth functions of calendar time (Anderson and Bell 2009, Hajat et al. 2006) and sometimes adjustment for air pollutants. The inclusion of pollutants as covariates in weather-risk models is complex given the role of temperature in the formation of tropospheric ozone and secondary particles. In summary, substantial uncertainty still remains about how to model the heat wave-health exposure response in presence of complex interaction terms and potentially many unmeasured confounders.

Studying adaptation: The ability of people to adapt to increasing long-term average temperatures as well as increasing frequency and severity of heat waves is one of many interrelated variables contributing to the uncertainty about the human health impact of climate change (Patz et al. 2000). We consider adaptation to mean a person's ability to adapt to temperature patterns that they commonly experience, thereby mitigating potentially negative health effects. Adaptation pathways can be biological, structural (e.g., differences in building designs), or behavioral (e.g., changes in clothing or indoor/outdoor activity patterns). Studies of temperature and mortality have quantified aspects of adaptation in many different ways, and there exists no mathematical framework that can quantify adaptation in a comprehensive fashion.

For example, one study of 11 large cities in the eastern U.S. found that for the years 1973–1994, compared to northern cities, southern cities (where climate is generally warmer) had higher minimum mortality temperatures (MMT), which is the point at which the association between temperature and mortality is zero in a nonlinear dose-response curve. Southern cities also had larger effects of cold temperature than northern cities. Northern cities tended to have lower MMTs and generally had larger effects of hot temperature (Curriero et al. 2002). The presence of central air conditioning (AC) in the household is an adaptive factor that has been shown in some studies to be associated with decreasing the effect of extreme heat (Bouchama et al. 2007). A decrease in the effect of hot temperatures was observed in a national study of temperature and mortality for the 14-year period of 1987–2000 (Barnett 2007). That study employed a time-varying coefficient statistical model stratified by season and found that the effect of temperature generally decreased over the 14-year period for the summer season but was relatively constant for other seasons. This decrease in the effect of hot temperatures appears to correlate with a general increase in the use of AC in the U.S. However, a formal connection between long-term trends in temperature-related health effects and trends in AC usage has not been explored.

Characterizing susceptibility: A key question of interest is whether extreme heat affects individuals and populations equally. Retrospective studies of major heat waves in the U.S. and Europe have identified a number of factors that make people more susceptible to dying from or being hospitalized for heat-related illnesses (Bouchama et al. 2007). Some of these factors are medical conditions which can be thought of as generally weakening the body's physical response to extreme heat while other factors are non-medical characteristics such as race, age, and socio-economic factors. However, results have not been completely in agreement. In determining factors that make individuals more or less susceptible to heat waves, current approaches have a number of deficiencies. For example, retrospective studies of heat waves have been limited to isolated incidents with relatively small study population sizes. It is not always clear whether differences between studies of heat waves are attributable to differences in study populations, temperature characteristics, or statistical methodology. Epidemiological studies of susceptibility factors have not been in full agreement to date, possibly due to a location-specific or regional focus of the studies. With a national database of health and weather information, risk estimates could be obtained using consistent methodology and heterogeneity in risks could potentially be explained using various location-specific socio-economic or other variables, thereby mitigating many of the problems with interpreting current studies.

Providing evidence for (or against) the mortality displacement hypothesis: A few studies have examined whether some heat related deaths would have occurred only a few days later even without the elevated exposures, in this case, elevated temperatures, a concept known as "mortality displacement". Again, results for previous epidemiological studies are mixed. Mathematical models could be developed to better characterize the time course of temperature effects on mortality. For example, distributed lag models allow one to make inferences about the cumulative health effect of a heat wave over a multi-day period after the heat wave episode, and these methods have been applied in the context of time-series studies of air pollution and mortality (Welty and Zeger 2005, Schwartz 2000). In the mortality displacement scenario we would expect to obtain a shape of the distributed lag function that indicates a large risk on the same day (day 0) of an increase in temperature, followed by a period where the risk of death is negative. One interpretation of the negative risk is that the pool of susceptible people is depleted on day 0 and therefore mortality is less than expected on subsequent days.

Developing a comprehensive treatment of both statistical and model uncertainty: Understanding the contribution of the different sources of uncertainty is an integral part of a systematic assessment of future health risks under climate change. In order to combine estimates of present and historical relative risk of mortality associated with heat waves with output from climate simulation models, a measure of the corresponding uncertainty is desired. This measure should include both model uncertainty as well as statistical uncertainty conditional on a given model. Information regarding the sensitivity of results to various types of uncertainties is needed.

Building a surveillance model to track adverse health effects associated with extreme temperatures: The surveillance model could include a linked national data base with information on weather, health, and potential confounders (e.g., air pollution, demographics). These national data should be updated routinely to monitor health effects of environmental exposures to estimate how weather affects health in the current day and how these risk change over time. In addition these national data set and statistical and mathematical models could be used to: 1) routinely estimate the association between extreme temperature events and health using national data sets; and then 2) predict the health impact of future climate change scenarios.

Quantifying the co-benefits from climate change and short-term air pollution policies: Many of the policies aimed at lowering emissions of greenhouse gases would also lower levels of ambient air pollutants in the near term and vice versa (Markandya et al. 2009, Wilkinson et al. 2009, Bell et al. 2008, Cifuentes et al. 2001). However, most analyses of the health impacts of climate change policies do not incorporate the benefits, and costs, of changes in air quality in the short term. As an example, most discussion largely ignored the potential for cap and trade legislation to contribute to reductions in levels of other harmful air pollutants, such as sulfur dioxide, particulate matter, and ozone precursors, which share emission sources with greenhouse gases (Barr et al. 2010). Mathematical models could be developed to understand to what degree reduction of greenhouse gases could lead to: 1) an immediate reduction in harmful air pollutants, thereby improving public health in the short term; and 2) a mitigation of climate change, thereby improving public health in the long term. In summary, a full understanding of how a climate change scenario impacts health would incorporate the short-term health benefits from the climate change policies assume in the scenario development.

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