or to rubber tappers in the Amazon[7] indeed demonstrate delayed bedtimes and reduced sleep duration. And evidence from a study comparing US residents in daily life and on a camping trip away from artificial light suggests that access to electric light not only shifts the circadian clock but also exaggerates the natural individual variability of sleep timing[8]. At an extreme, perhaps the owl-like tendencies of adolescents, and the resulting debate on shifting school timing to later starts, are to a considerable extent a direct result of our manipulation of our light environment.

Yetish and colleagues also point to the influence of a second environmental cycle on sleep timing: temperature. Core body temperature rises and falls over each 24 hours, with sleep generally occurring as the body temperature falls. Because we are a diurnal species, awake during the day and asleep during the night, and because environmental temperature tends to drop during the hours of darkness, the rhythm of our core body temperature tends to align with that of the environmental temperature. From an energetic perspective, this makes sense — keep the difference between environment and body temperature as small as possible and you reduce the amount of energy needed to stay warm. This link between environmental temperature, metabolic demands and the timing of the sleep–wake cycle has received attention in the animal and human sleep literature[9,10]. Yetish and colleagues found that the timing of waking is closely associated with the environmental minimum temperature; in the one group that woke after sunrise, the San, this pattern occurred only during summer, when the environmental-temperature minimum also occurred after sunrise.

We are beginning to understand the impact of our artificial world on our sleep–wake rhythms. Although we have tantalizing hints about how the light environment of our modern world affects our sleep patterns, there are few data on how we manipulate our temperature environment and the effects of such manipulation on sleep. Yetish *et al.* have provided findings that alter our assumptions about sleep in our ancestors, and have opened the door to further studies of the effects of light and temperature on sleep today. ■

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ECONOMICS

Higher costs of climate change

An attempt to reconcile the effects of temperature on economic productivity at the micro and macro levels produces predictions of global economic losses due to climate change that are much higher than previous estimates. SEE LETTER P.235

THOMAS STERNER

We are already experiencing the economic impacts of climate change — heatwaves, for example, are increasing health costs and employee absenteeism, as well as reducing crop yields. But attempts to calculate the costs of warmer temperatures have produced conflicting results, particularly between estimates at the micro versus the macro scale in wealthy countries. Aggregating cost estimates from many different instances of micro-scale damage to obtain a single macro-scale estimate for the whole economy is very hard. In this issue, Burke *et al.*[1] (page 235) show that these inconsistencies can be reconciled if nonlinearity in the relationship between temperature and economic productivity is taken into account at the macro scale. Furthermore, their results imply that the damages from climate change are much more serious than is generally believed.

If a cyclone hits your house, the correct cost of the damage is not what the house originally cost but the cost of the best replacement you can make that will leave you equally well

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Figure 1 | Dry fields in Shanxi province, northern China. Many micro-level economic outputs, such as crop yields, show abrupt, nonlinear or even discontinuous relationships with temperature, decreasing dramatically at high temperatures. Burke *et al.*[1] find that a smooth but nonlinear response to temperature also applies to macro-level economic productivity in both wealthy and poor countries.

off. Now extrapolate this example to climate change. If you realize that your house was badly designed or badly located to withstand a changing climate, then the best replacement might be to rebuild the house somewhere else or even to spend the money in an entirely different way. This example shows how damage motivates adaptation. But adaptation can, in turn, change the cost of damage. Thus, in the aftermath of major events related to climate change, we recalculate the future course of action and reallocate resources. This is one of the reasons why simply looking at the micro-level costs of any disastrous event gives an incomplete picture, and why macro-level evidence is needed.

Burke and colleagues set themselves the task of connecting micro- and macro-level estimates of the costs related to changes in temperature and other climate variables. A small, but increasing, number of studies have shown that various micro-level components of the economy exhibit a highly nonlinear response to local temperature in a wide variety of countries, both rich and poor (see, for instance, refs 2 and 3). For example, worker productivity and crop yields are both relatively stable at temperatures between 0 and 25 °C, but decline steeply at higher temperatures (see Fig. 1 of the paper[1]). The question is how to aggregate such effects to cover the whole economy without double counting or missing vital parts. One seminal study[4] found no correlation between macroeconomic productivity and temperature in rich countries, but a linear correlation in low-income countries (that is, the higher the temperature, the bigger the costs).

Burke *et al.* find several differences from that study. They analysed updated and slightly different data covering several additional years (2004–10). They also used a different (and I believe improved) approach to handling confounding variables in their models, together with other methodological details that give somewhat higher precision in their estimates. The main result is an overall nonlinear pattern in the relationship between temperature and economic growth. Almost all low-income countries are in 'warm' regions, and thus are predicted to suffer strong effects when temperatures go even higher, whereas rich industrialized countries are typically closer to the 'optimal' average temperature and thus show a weaker and more varied response. There are many possible ways of running such regression analyses, but the authors chose to focus on estimates that do not compare one country with another (which would risk inviting the influence of many confounding factors), but instead compare each country with itself during years with different temperatures.

The authors also sought to reconcile their aggregate finding with evidence from micro-level economic activities that exhibit different temperature dependencies. Although these relationships vary and are typically strongly nonlinear, aggregation of these effects can smooth the pattern, resulting in a nonlinear macro-level response to temperature that is essentially applicable to all countries (Fig. 1). According to the authors' modelling, overall economic productivity peaks at an annual average temperature of 13 °C and declines strongly at higher (and lower) temperatures. This relationship seems to apply to all countries, to be constant since 1960 and to be applicable to both agricultural and non-agricultural activities. The implication is that all kinds of economic activity in all kinds of countries are heavily influenced by changes in our global climate.

The authors take great care to check the robustness of their findings but there will, no doubt, be attempts to look for other data and approaches, which may give different results. But such is the scientific process and, should these conclusions stand up or even be strengthened, they will have far-reaching implications. For example, unmitigated warming is predicted to lead to a (population weighted) average temperature increase of 4.3 °C by 2100: Burke and colleagues' model predicts that the accompanying climate changes would lead to a decline in average global incomes by a quarter compared with a scenario without climate change. Global income would also become more unequal, because some regions would benefit (particularly those that have a cold climate today, which tend to be countries with quite high incomes) whereas others, especially the (warmest and) poorest, would be hit very hard.

All told, these estimates equate to much larger economic losses than most leading models suggest (assuming that we do not find completely new ways to adapt), and hence give even more reason to mitigate damages today. The current leading models, referred to as integrated assessment models (IAMs), are already being used as a basis for policy. In the United States, there have been considerable battles, even in Congress, concerning the 'social cost of carbon', which is based on the three most prominent IAMs (see, for example ref. 5). Burke and colleagues' results suggest that these damage predictions, and thus also the social cost of carbon, need to be raised by several hundred per cent.

The conclusion that temperature-associated costs will be higher than previously calculated will cause a stir, and should have stark repercussions for policy. Another major significance of this paper will be to expand this emerging field of work. Future assessments of the relationship between economics and temperature will inevitably change details and expose nuances, particularly concerning the role of adaptation. My feeling is that we are only beginning to understand just how much damage a changed climate can wreak. ■

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