per Kelvin of globally averaged surface warming[9]. These values for sea-level rise do not include any contributions from land ice melting, which could make the estimates even higher.

These published results have not been highlighted because of scepticism regarding the ability of early models to realistically simulate deep-ocean mixing, and the intuition of some experts that as long as land ice exists, cold water would be available to keep the deep ocean cold. In the past few years, present-day state-of-the-art climate models have revisited the early results and have found similar responses, confirming many of these results[1,10].

In their paper, Li *et al.*[1] show the various physical response timescales found in the atmosphere–ocean–land–sea-ice system (Fig. 1). As the atmosphere and upper ocean are tightly coupled, the surface air temperature and the near surface ocean temperatures have a very similar response timescale. In the deeper ocean layers, the response timescale lengthens, with the longest response timescales found near the ocean bottom. Again, broadly confirming earlier results, Li and colleagues find that the ocean warms quasi-uniformly at depth on a millennial timescale, and that the long-term warming is a substantial fraction of the equilibrium surface air temperature warming.

The large warming throughout the world ocean leads to a large sea-level rise. In the Li *et al.* model, for a fourfold increase in carbon dioxide concentration, the globally averaged surface air temperature increase is 10.8 Kelvin above pre-industrial temperatures, and the globally averaged sea-level rise due to warming water alone is 5.8 metres. The ratio of the surface warming to sea-level rise falls within the range given in the 2007 Intergovernmental Panel on Climate Change report[9], noted above.

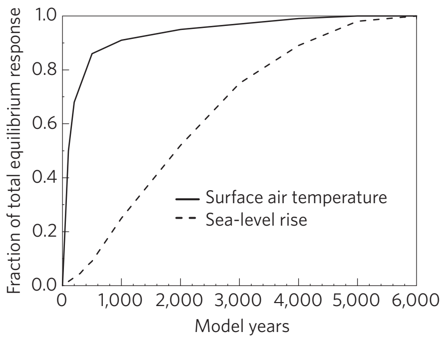

Figure 1 | The response of globally averaged surface air temperature and sea-level rise to an increase of carbon dioxide concentration in the model atmosphere. Li *et al.*[1] modelled carbon dioxide concentrations as increasing at a rate of 1% per year until it reached four times the pre-industrial value and then held it constant. To illustrate the impact of the slow penetration of heat into the ocean on the sea-level response, the fraction of the total equilibrium response is plotted. The timescale of the sea-level response is much slower than that of surface air temperature. Data taken from ref. 1.

Owing to the well-documented uncertainties in the equilibrium climate sensitivity and continuing technical issues with the models used for these studies, readers should take the precise long-term results found in this or any model study cautiously. What matters is that for any equilibrium climate change within the assessed Intergovernmental Panel on Climate Change temperature range of 2.0–4.5 Kelvin for a doubling of carbon dioxide, the equilibrium sea-level rise is quite large — 0.4–2.7 metres (ref. 9). Furthermore, most future projections of carbon dioxide have values that are more than double, which could result in greater sea-level rise. The magnitude of equilibrium sea-level rise from climate sensitivity alone is much larger than that observed over the past century, and larger than many of the projected changes for this century[9]. Again, this emphasizes the slow response of the deep oceanic layers and sea-level rise to forcing changes.

The recent work by Li and colleagues uses a present-day model to confirm earlier results that have so far been de-emphasized. As more climate models obtain similar results, climate modellers will have greater confidence in the long-term projections of deep-ocean warming and sea-level rise.

An important caveat to this discussion is that it is very difficult to predict what technological advances and mitigation strategies will be available in the next 100, 500 or 1,000 years to possibly remove significant amounts of carbon dioxide from the atmosphere. Until such options are available and while there are still significant technical issues surrounding long-term projections from models, it is clear that the decisions we make today, individually and as a society, will impact our planet for a long time. ❐

Ronald J. Stouffer is at the Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, New Jersey 08542, USA.
e-mail: ronald.stouffer@noaa.gov

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ENERGY

Analysing fossil-fuel displacement

It is commonly assumed that fossil fuels can be replaced by alternative forms of energy. Now research challenges this assumption, and highlights the role of non-technological solutions to reduce fossil-fuel consumption.

Andrew K. Jorgenson

Much attention is given by both experts and policymakers to the role of non-fossil-fuel energy in the fight against greenhouse-gas emissions. Scientific bodies, including the Intergovernmental Panel on Climate Change[1], as well as non-governmental organizations and sections of the general public, implicitly assume that each unit of alternative energy replaces a given unit of fossil-fuel energy as a form of proportional displacement. Writing in *Nature Climate Change*, Richard York[2] has tested this assumption and suggests that across most nations of the world over the past 50 years, on average, each unit of total national energy use from non-fossil-fuel sources displaced less than one quarter of a unit of fossil-fuel energy use, and the amount is even less when focusing on only fuel use for electricity.

Drawing from various areas of multidisciplinary research, including environmental sociology, ecological economics and structural human ecology, York[2] analyses annual data for 132 countries from 1960 to 2009 to assess the extent to which the per capita demand for fossil-fuel energy is affected by the amount of per capita energy produced from non-fossil-fuel sources, while controlling for known driving forces of per capita energy use, including levels of economic development and urbanization. In particular, York[2] estimates a model of per capita fossil-fuel electricity production (dependent variable) including, as explanatory variables, per capita production of non-fossil-fuel energy, gross domestic product (GDP) per capita (adjusted for inflation and in US dollars) and factors unique to each country that do not change through time. He then repeats the estimation exercise by adding other explanatory variables, such as measures of urbanization (percentage of the population living in urban areas), manufacturing (percentage of GDP from the manufacturing sector) and the age-dependency ratio of nations (the ratio of people under 15 and over 64 to those 15 to 64 years of age). Finally, he estimates the same two models again using per capita total energy production from fossil fuels as the dependent variable.

Turning to the results, if the assumption that alternative energy can proportionally displace fossil-fuel energy is indeed valid, one would expect to see an estimated regression coefficient (the 'displacement coefficient') of −1 for the non-fossil-fuel energy production variable, or something close to it. In the first of the per capita fossil-fuel electricity production models, the estimated displacement coefficient is −0.089, and decreases in absolute value to −0.079 in the second model that accounts for a broader range of drivers. These results suggest that each kilowatt hour of non-fossil-fuel electricity that is generated displaces at best only 0.089 kilowatt hours of fossil-fuel-generated electricity — a far cry from proportional displacement. In other words, to displace one kilowatt hour of fossil-fuel electricity requires generating at least 11.326 kilowatt hours of non-fossil-fuel electricity. In the first of the per capita fossil-fuel total energy production models, the estimated displacement coefficient is −0.128, and increases in absolute value to −0.219 in the second, more complete model. Although the results of this second model are closer to proportional displacement, they still suggest that more than 5.5 units of non-fossil-fuel energy are required to displace one unit of fossil-fuel total energy.

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York's findings contradict the widely held assumption that the expansion of alternative energy production will proportionally suppress fossil-fuel energy production. And the implications are quite clear. For alternative energy sources to adequately displace fossil-fuel sources, non-fossil-fuel energy would need massive global expansions, and such increases would pose unique ecological problems and human health risks[3]. For example, hydropower disrupts aquatic ecosystems, and the recent tragedy at the Fukushima Daiichi nuclear power plant in Japan, as well as the ongoing clean-up efforts at the Hanford Site in the United States, underscore the life-threatening risks associated with nuclear power. And other alternative energy sources, such as wind power, require significant material inputs for their construction as well as large amounts of area to generate nontrivial amounts of energy.

However, all well-executed research has limitations. Some recent studies indicate that forms of economic globalization contribute to national-level fossil-fuel energy consumption and greenhouse-gas emissions[4], whereas other studies suggest that militaries are additional moderate-sized drivers of fossil-fuel energy consumption[5]. Neither economic globalization variables nor national military variables are included in York's analysis. Although such exclusion is unlikely to lessen the validity of the findings, the effects of those variables on York's estimated displacement coefficients would have made his analysis more realistic and potentially increased the overall statistical significance of the models used.

Besides contradicting the proportional displacement assumption, York's research adds to the growing body of environmental social science that highlights how societies cannot only rely on technological solutions to reduce fossil-fuel use and thus anthropogenic carbon dioxide emissions[6–8]. To effectively reduce emissions, societies need to focus on reducing the consumption of energy at both the individual/household level[9] and the system level, with strategies geared towards broader changes in the economic, political and cultural spheres[10]. More broadly, York highlights the importance of integrating research on the human dimensions of climate change — such as the role of individuals and collective human behaviour, the characteristics of social institutions and the complex interrelationships between the world's nations — with research on technological solutions to tackle greenhouse-gas emissions. ❐

Andrew K. Jorgenson is in the Department of Sociology at the University of Utah, 380 South 1530 East, Room 301, Salt Lake City, Utah 84112, USA.
e-mail: andrew.jorgenson@soc.utah.edu

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