whereas current practice dictates the use of standardized tables. This, in turn, may lead to more comfortable and better estimated thermal conditions, and a lower energy consumption in summer, as less cooling capacity may be required for female office workers. The biophysical approach would enable the study of thermal comfort for specific subpopulations or individuals.

This would, in practice, mean that building services engineers have to abandon their current practice of applying the PMV model which was based on tests with approximately 1,300 students mainly engaged in sedentary activity and represents a mean comfort prediction for groups.

Kingma and van Marken Lichtenbelt[1] say that an accurate representation of the thermal demand of all occupants leads to real energy savings for buildings that are designed and operated by the buildings services community. The effects on energy consumption of increasing the design indoor temperature will become greater over time as climate change leads to increased outdoor temperatures, requiring more intense cooling of buildings. Apart from saving energy, the improved comfort of both male and female office workers may improve productivity in some of their tasks[10].

These findings could be significant for the next round of revisions of thermal comfort standards — which are on a constant cycle of revision and public review — because of the opportunities to improve the comfort of office workers and the potential for reducing energy consumption.

Although Kingma and van Marken Lichtenbelt[1] provide concrete clues for practice and consistency in the direction of change in standards, the overall study samples of the work they build on are small. A large-scale re-evaluation in field studies may be needed in order to sufficiently convince real-estate developers, standard committees and building services engineers to revise their practices. In addition, the building services community needs to come up with solutions for dealing with different preferences in practice, for instance with the emergence of individualized micro-climatization systems. ❐

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EARTH SYSTEM MODELLING

Restoration of the oceans

Undoing the effects of continuing high carbon dioxide emissions on the oceans could take centuries, if it is possible at all.

Richard Matear and Andrew Lenton

Evidence is mounting that the climate is changing because of rising atmospheric carbon dioxide[1] with the potential that global warming and ocean acidification may significantly harm the ocean environment and the ecosystem services we depend on[2]. In the absence of a global agreement to limit emissions, all options must be considered to minimize these potential impacts[1]. Carbon dioxide removal (CDR), which requires the capture and storage of atmospheric carbon, is one potential technological solution to help mitigate high atmospheric carbon dioxide. Writing in *Nature Climate Change*, Sabine Mathesius and colleagues explore the ability of CDR to mitigate global warming and ocean acidification[3]. Although the thought of deliberately manipulating the climate by CDR may be unpalatable to many, it is necessary that such options be evaluated to enable informed choices of the viable ways to tackle our carbon dioxide problem.

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The study by Mathesius *et al.*[3] explores whether CDR under high CO_2 emissions can achieve an environmental outcome similar to a rapid transition to low-carbon energy use (that is, the Representative Concentration Pathway (RCP) 2.6 scenario). For their reference simulation with CDR they use the 'business as usual' high carbon emissions scenario (RCP8.5 extended[4]) from the present day to 2700. They show, consistent with other computer simulations, that under such a scenario the ocean environment will undergo substantial changes. By the year 2500, the global surface ocean warms by more than 5 °C and the global surface pH declines by more than 0.6 units from the pre-industrial values. Such large changes in the ocean environment have the potential to be catastrophic for many marine organisms, as is evident from the numerous species extinctions that occurred during the Paleocene–Eocene Thermal Maximum, when global temperatures and carbon dioxide levels had a similar magnitude of change[5].

Mathesius *et al.*[3] show that aggressive CDR can only undo the effects of high emissions (RCP8.5) and return the marine environment to either its pre-industrial state or the low emission scenario (RCP2.6) on the timescale of many human generations. The inability to quickly restore the oceans to their previous state reflects the inherent timescales involved in the ocean circulation and its carbon cycle — the ocean intermediate water takes centuries to re-stabilize, and the deep ocean takes millennia. This temporal behaviour of the ocean means that reversing the atmospheric CO_2 perturbation once it has been maintained for over a century is slow and requires many centuries. Simply put, once the carbon has entered the ocean it cannot be quickly extracted; avoiding the carbon emissions in the first place is a much more effective option.

Although the study by Mathesius *et al.*[3] is theoretical in nature it provides an important perspective on the ability of mankind to engineer the climate system and undo the effects of high CO_2 levels in the atmosphere. Although the focus of the study was on reversing the environmental changes in the ocean, the climate system is complex and the possibility that mitigation options like CDR could produce unforeseen impacts is high. For example, with CDR the study shows massive swings in the ocean pH, which may induce biological changes that fail to recover once the environmental changes are returned to their original state. Such irreversibility of the system is an important consequence and the study provides valuable information to consider as we tackle the CO_2 problem. It also demonstrates that proposed technological solutions, like CDR, to the problems of global warming and ocean acidification are no substitute for reducing carbon emissions, which remains the safest and most reliable path for avoiding dangerous climate change. ❒

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