development, but would also prevent these cells from reverting to a harmful, cancerous state. However, the usefulness of FOXO4-DRI would probably be limited to those tumours that express functional p53, given the drug's mechanism of action.

The current study adds a new member to the short list of known senolytic compounds that have therapeutic activity in mice. The next challenge is human clinical trials — if senolytic therapies see success here, they could open a new chapter in medicine. ■

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In Retrospect

Half a century of robust climate models

A classic paper in 1967 reported key advances in climate modelling that enabled a convincing quantification of the global-warming effects of carbon dioxide — laying foundations for the models that underpin climate research today.

PIERS FORSTER

Fifty years ago this month, the climate modellers Syukuro Manabe and Richard Wetherald[1] published arguably the greatest climate-science paper of all time in the *Journal of the Atmospheric Sciences*. The authors essentially settled the debate on whether carbon dioxide causes global warming, building a mathematically sound climate model that was the first to yield physically realistic results. Their work spawned both the development of modern climate models and the use of radiative forcing — a measure of the alteration in Earth's energy balance resulting from human or natural changes — to understand historical causes of climate change.

Climate science was something of a slow burner. The fact that CO_2 is a greenhouse gas has been known since the work of physicist John Tyndall in 1861 (ref. 2). Crude estimates of the warming effect of CO_2 were subsequently made by the chemist Svante Arrhenius in 1896 (ref. 3), and by the engineer Guy Stewart Callendar in 1938 (ref. 4). But it was only in the 1950s that measurements showed atmospheric CO_2 levels to be rising[5], and that the physics of 'radiative transfer' was beginning to be understood. Radiative transfer quantifies how solar radiation and the thermal infrared spectrum emitted by Earth's surface are scattered, absorbed and re-emitted by gases in the atmosphere, and is fundamental to quantifying the warming effect of greenhouse gases.

In 1963, Manabe's colleague Fritz Möller used the latest developments in the science of radiative transfer to question how important the global-warming effect of CO_2 is[6]. This work, along with other early studies, happened to make reasonable estimates of the CO_2-induced warming that would occur if the climate system did not alter in some way, but did not account properly for how the system might respond. In particular, they failed to account correctly for how the distribution of atmospheric water vapour would change in a warming world.

By contrast, Manabe and Wetherald properly understood how this water-vapour feedback worked, and used that information in their new one-dimensional radiative–convective equilibrium model. This model, developed from earlier work[7], divided the atmosphere into multiple levels and redistributed energy between them in the vertical dimension from the surface, using a combination of radiation and convection. The authors used their model to estimate the warming that would occur if CO_2 levels doubled from 150 to 300 parts per million (p.p.m.) and from 300 to 600 p.p.m. From these results, they estimated that a warming of about 2.3 °C would occur for a doubling of CO_2 — in good agreement with modern estimates[8].

In fact, Manabe and Wetherald's paper was

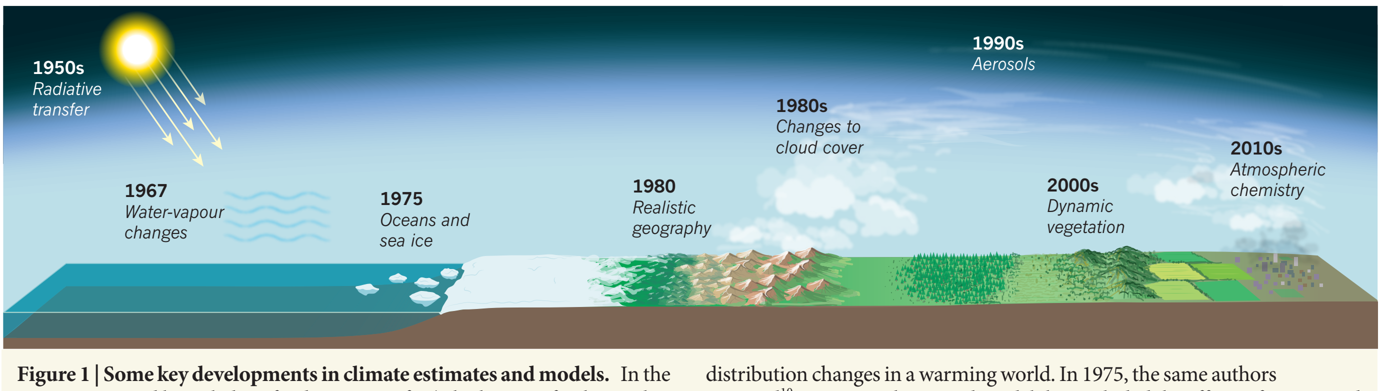

Figure 1 | Some key developments in climate estimates and models. In the 1950s, improved knowledge of radiative transfer (which quantifies how solar radiation and the infrared spectrum emitted by Earth's surface interact with gases in the atmosphere) allowed estimates of the warming effect of carbon dioxide to be made, but these were not realistic. The first robust estimate was published in 1967, when Manabe and Wetherald[1] used a computational model that included a realistic representation of how water-vapour distribution changes in a warming world. In 1975, the same authors reported[10] a more-sophisticated model that included the effects of oceans and sea-ice cover. Climate models have since become increasingly complex. Some milestones have included the incorporation of: realistic geography (rather than a grossly simplified representation of land masses) in 1980; changes to cloud cover in the mid-1980s; aerosols in the 1990s; the effects of dynamic vegetation in the 2000s; and atmospheric chemistry in the 2010s.

not focused on CO_2 and global warming at all. The researchers worked at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, which had acquired one of the first commercial computers. Manabe had been brought in to lead the development of the world's first general circulation model (a computational climate model underpinned by a numerical description of atmospheric and ocean circulation), and a few years later built the first climate model that combined oceanic and atmospheric processes[9]. The 1967 paper described a crucial step in the construction of that model: how best to link the different levels of the atmosphere with Earth's surface, taking into account radiative transfer, convection and water-vapour feedback.

What raises the paper to greatness in my mind is not its estimate of CO_2-induced warming, but how it exemplifies good practice in climate-modelling studies. First, its results are reproducible using a transparent and well-justified set of assumptions. For example, the authors used the latest observations of water vapour to justify their assumption that relative humidity will not be affected by climate change, and then used this assumption to model the water-vapour feedback. Second, the resulting model included just enough detail of physical processes to give first-order estimates of the surface and atmospheric temperature changes expected from several possible human or natural perturbations (such as changes to solar output, CO_2 concentration and clouds), but was not too complex so as to make it difficult to run on early computers, or to muddy interpretation of the results. Moreover, the authors' radiative–convective model was entirely fit for purpose.

The comprehensiveness of Manabe and Wetherald's paper also puts much subsequent work to shame: it was just as concerned with the effects of supersonic aircraft on temperatures in the upper atmosphere as it was about the effects of CO_2 at Earth's surface. It was also the first paper to find that CO_2 not only warms the surface of the planet, but also cools the stratosphere — although the authors devoted just 17 words to this major discovery.

Nevertheless, it took some time for climate scientists to warm to the paper, and Manabe himself, keen to add more sophistication to his approach, never really used his 1D radiative–convective model in this way again. Instead, Manabe and Wetherald successfully repeated their calculation in 1975 using their fledgling general circulation model[10], which could also account for high-latitude warming and changes to snow cover and sea ice.

I believe that this more-sophisticated calculation was partly responsible for building trust in their earlier approach using the 1D radiative–convective model, so that other scientists then began to use such models to great effect to probe the multiple possible causes of observed increases in surface temperature during the twentieth century[11,12]. For example, a study[11] published in 1981 concluded that twentieth-century temperature variations were probably due to a combination of human-induced changes (in land use and in atmospheric levels of greenhouse gases, ozone and aerosols) and natural phenomena (changes in solar radiation and volcanic emissions). Such work fostered international concern about climate change, and eventually led to the establishment of the Intergovernmental Panel on Climate Change in 1988.

Depending on your bent, Manabe and Wetherald's legacy can be interpreted as a justification for the ever-increasing sophistication of climate models (Fig. 1) or as a champion of simple modelling approaches. Today, radiative–convective models have been largely superseded by complex Earth-system models, or by even simpler concepts such as radiative forcing (developed in the 1970s from the radiative–convective modelling experiments highlighted above). This is a pity. Radiative–convective models are a great way of elucidating key climate processes and can still provide useful insights that other approaches cannot, especially into the uncertain role of clouds in climate[13]. Fifty years on, the time is right for their resurgence. ■

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BEHAVIOURAL ECONOMICS

Occasional errors can benefit coordination

The chances of solving a problem that involves coordination between people are increased by introducing robotic players that sometimes make mistakes. This finding has implications for real-world coordination problems. **SEE LETTER P.370**

SIMON GÄCHTER

Complex human societies exist because people cooperate with each other and coordinate their activities[1]. Cooperation involves collaborating for common benefit, whereas coordination requires people to match their collaborative activities in appropriate ways. This often entails solving small, local coordination problems to achieve global coordination. As an example, consider the production of complex goods, which involves coordinating the division of labour across sites. In this instance, error-prone people must solve many, often intricate, local problems such as work processes, or the logistics of production and supply chains, to achieve global coordination. On page 370, Shirado and Christakis[2] use network experiments to highlight the ways in which errors can help to improve global coordination.

The authors set up 230 randomly generated networks, each with 20 nodes. They allocated each of 4,000 participants to a node, and asked them to solve a colour-coordination game[3], in which the aim is to make each node one of three colours that differs from the colour of every neighbouring node (Fig. 1).

Players know that they are part of a large network, but see only the colours of their neighbours. They can change their node's colour as often as they like within five minutes. Thus, a player can remove local colour conflicts without solving all colour conflicts globally. People are paid according to how long it takes to solve all colour conflicts in the network. This set-up is an abstract representation of many real-world coordination problems[3], in which the choices optimal for an individual might not solve a global coordination problem whose resolution is in the collective interest.

In addition to human participants, Shirado and Christakis included three autonomous software agents called bots as players in many of the networks. They programmed the bots to play a locally optimal strategy, but to make a random colour choice a certain amount of the time. The authors tested three levels of