the scope and capabilities of current generation ESMs, while quantitatively incorporating expert judgment to account for observational and model limitations.

Boyd *et al.*[2] take an innovative approach to build and use such a roadmap (Fig. 1), through application of a statistical tool (principle component analysis with factor rotation) to cluster biogeochemical impacts on 15 stressors into 6 global patterns and assess their relative contributions over 14 biogeographical provinces. This biome-level grouping of systems among the potential biogeochemical stressors facilitates comprehensive assessment of regional change. The fundamental advantage of this approach is in maximizing the information on ESM biome-level biogeochemical change in which the authors have more confidence, while minimizing reliance on model-dependent regional phytoplankton physiology and biodiversity representations in which they have less confidence. Boyd *et al.* then exercise this roadmap with a suite of observationally motivated interpretations of these biome-level changes through key phytoplankton taxa including coccolithophores, diatoms, and cyanobacteria. Their results are generally grim news for diatoms, but highlight a potentially growing niche for coccolithophores, despite decreasing rates of calcification.

The roadmap provided by this study[2] certainly has impressive potential to expand the community of observational and laboratory scientists directed at regional assessment, however, much work still remains. From the current examination of an individual model response for one scenario at a single centennial timescale, future investigation of ensembles of models with several scenarios on a continuum of timescales is needed to assess the sign and magnitude of change from the current generation of models. Advanced statistical approaches that mechanistically determine the physiological impact of multiple stressors[7] are needed for robust synthesis of multi-stressor, single-species response. Incorporation of more realistic biodiversity at the phytoplankton level is necessary to begin validating ecosystem models against observations. Most challenging, these comparisons must move beyond phytoplankton to the broader ecosystem context[8] to turn the breadth of biogeochemical understanding into relevant and actionable information for managers[9].

This work by Boyd *et al.*[2] is an innovative and threshold advance in integrative marine ecosystem study to address the challenges of environmental change. Just as a new generation of ESMs has recently emerged with the Fifth Coupled Model Intercomparison Project[10], an expansion of interdisciplinary engagement in analytical tools demonstrated by Boyd *et al.*[2] will be required to fully assess LMR impacts. This nexus of field and laboratory observations, theory, modelling, statistics, and knowledge synthesis across the physical, biological, and mathematical sciences has unveiled new challenges and opportunities to understand our environment, its sensitivity and resilience, and the role of humans. ❒

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ATMOSPHERIC CHEMISTRY

Climate's chemical sensitivity

Constraining climate sensitivity is a top priority for climate science. Now research shows that the details of how stratospheric ozone is represented in models can have a strong influence on warming projections.

David S. Stevenson

To predict how climate will change we need to know just two things: the future forcings on the Earth system, and the feedbacks that will ensue. The first requires forecasts of socioeconomics, technology, and human behaviour to be translated into changes in the planetary energy budget; for example, via changes in anthropogenic emissions and atmospheric composition. The second requires understanding of how processes interact to either amplify or damp climate response to the forcing, together with the timescales over which they operate. This response is encapsulated by a parameter called the climate sensitivity. Warmer air can (and generally does) accommodate more water vapour molecules. As water vapour is a greenhouse gas, any warming is amplified: this represents a positive feedback — it increases climate sensitivity. Several other feedbacks operate in the Earth system, including those associated with sea ice and clouds; most are positive. Negative feedbacks appear to be less common. Writing in *Nature Climate Change*, Peer Nowack and co-authors[2] report a large negative feedback, which causes a significant (in the order of 20%) reduction in climate sensitivity, resulting from a more comprehensive model representation of stratospheric ozone chemistry.

Quantifying climate sensitivity could hardly be more important. Equilibrium climate sensitivity (ECS) is defined by the surface warming in a world with doubled pre-industrial atmospheric CO_2 levels, once the system has returned to equilibrium. Current estimates of ECS are wide[1]: 1.5–4.5 °C. If Earth's climate sensitivity is high, then rapid and severe cuts in emissions are needed to have any chance of avoiding dangerous climate change[3].

Climate sensitivity can be estimated in a variety of ways, from both observations and models[1]. One commonly employed method involves subjecting a range of climate models to an abrupt quadrupling of atmospheric CO_2, and following their simulated surface temperature response over at least the next century[4]. Different representations of key Earth system processes, such as convection, cause each model to have an individual response to the atmospheric forcing. These result in different simulation of feedbacks, and consequently some models project more warming than others. Together with poorly

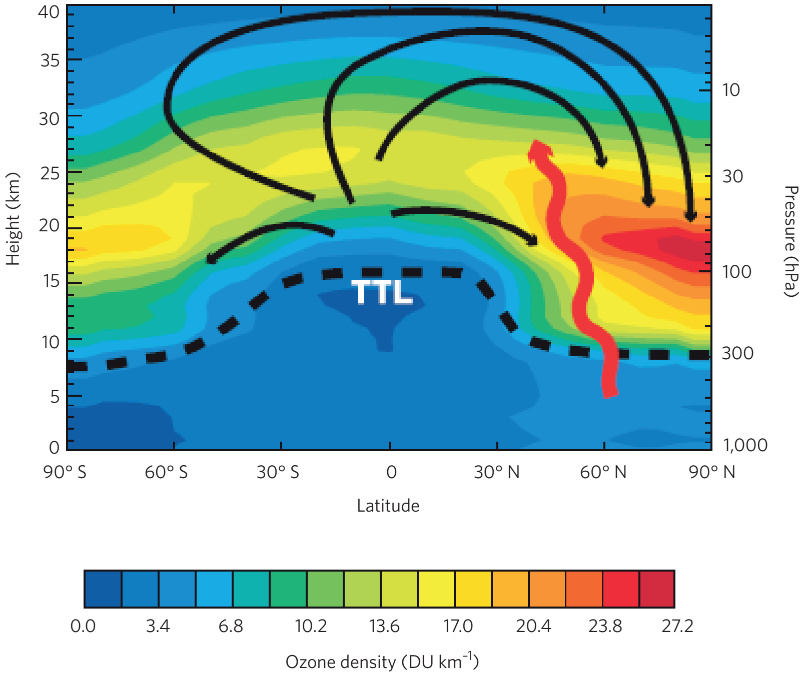

Figure 1 | Climatological longitudinally averaged ozone distribution for January–March. Black arrows indicate the Brewer–Dobson circulation. The dashed black line is the tropopause and TTL is the tropical tropopause layer. The wiggly red arrow represents planetary waves that propagate from the troposphere into the stratosphere, where they break, driving the Brewer–Dobson circulation. Note the logarithmic scale of the right-hand *y* axis. Figure reproduced with permission from ref. 7, © 2005 IPCC/TEAP.

constrained future emissions, this range of model responses generates uncertainty in climate projections.

Ever increasing computing power offers climate modellers the opportunity to make their models more accurate representations of the real world. Development has followed two (overlapping) paths: increasing spatial resolution; and increasing the number and/or complexity of processes represented. The latter path has resulted in the development of 'Earth system models' — these incorporate chemical and biological processes into the (almost entirely) physical framework of the earlier generation of climate models. Broadening the scope of Earth system models allows a wider range of potential feedbacks to spontaneously emerge — including climate feedbacks beyond those of a purely physical nature, first expounded by James Lovelock in his pioneering Gaia hypothesis[5].

Nowack *et al.*[2] use an Earth system model to investigate how inclusion of interactive chemistry influences climate sensitivity. Interactive chemistry allows distributions of radiatively active gases (in this case, ozone) to change in step with the climate, rather than prescribing them. By conducting the same experiment in two model versions (one with and one without interactive stratospheric chemistry), they isolate the impact of interactive stratospheric chemistry, and find that it induces a strong negative climate feedback. The mechanism is linked to the Brewer–Dobson circulation[6,7], which moves stratospheric air from the tropics to higher latitudes (Fig. 1). Models consistently predict a strengthening of this circulation as surface climate warms[6]. A stronger circulation lifts the tropical tropopause (the boundary between the troposphere and stratosphere), decreasing ozone in the tropical lower stratosphere. As ozone is a greenhouse gas, less ozone leads to surface cooling — a negative feedback. Temperatures also decrease locally in the layer of the atmosphere where the ozone is reduced, around the tropopause. Colder tropopause temperatures enhance the freeze-drying of air entering the stratosphere, reducing stratospheric water vapour, generating yet more surface cooling — a further negative feedback. However, decreased upper tropospheric temperatures promote cirrus cloud formation. More high cloud leads to surface warming, so the increase in cirrus represents a positive feedback. The overall impact of all these processes is dominated by the reduction in ozone and water vapour, resulting in a net negative feedback, with Nowack *et al.*[2] finding about 20% less warming in their experiment with fully interactive chemistry.

The models used in the latest IPCC report[1] represented ozone in a variety of ways — some using prescribed distributions and some incorporating interactive chemistry[8]. Hence some would have included the feedback mechanism described by Nowack *et al.*[2] whilst others did not. These differences will have contributed to the IPCC range in model climate sensitivities. It is currently unclear if the large feedback found by this study[2] occurs within all the 'interactive' models. A similar study[9] using a different model reported smaller feedback effects, although that model had a less explicitly resolved stratosphere. A key task for modellers is to check how their models simulate the relevant processes, and to devise evaluation methods to determine which models behave most like the real world.

The study by Nowack *et al.*[2] highlights an important challenge for Earth system modellers. There are undoubtedly further, important feedbacks that remain to be uncovered and quantified. For example, a stronger Brewer–Dobson circulation results in both younger stratospheric air (due to faster upwards transport), and more UV radiation reaching the troposphere (due to less ozone). Both of these effects will alter the atmospheric lifetimes of several greenhouse gases, potentially introducing further feedbacks. We know of many interactions between chemistry, the biosphere and climate[10,11], but their implications for climate sensitivity have yet to be explored comprehensively. The analysis framework used by Nowack *et al.*[2] to diagnose and quantify the ozone-circulation feedback provides an important template for future studies. Only by further exploring and understanding the behaviour of Earth system models will we narrow uncertainties in our estimates of Earth's climate sensitivity, thereby allowing us to make more robust projections of the effects of anthropogenic activities on future climate. ❐

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