one of the most intensely studied sections of the entire mid-ocean ridge system. This site is characterized by relatively frequent eruptions along the axis of the ridge and volcanically driven hydrothermal activity. That a network of off-axis melt lenses has only recently been discovered in such a well-studied area underscores just how much there is yet to learn about rift magmatism.

Rioux *et al.*[2] also investigate the fast-spreading East Pacific Rise. Specifically, using U-Pb systematics, they date the timing of cooling of zircon crystals in rocks from the lower crust that are exposed at Hess Deep, a cavernous gash on the flanks of the East Pacific Rise. Given that the plates neighbouring the East Pacific Rise spread apart rapidly, Rioux *et al.* expected to find a narrow range of ages, in line with the idea that the margins of a narrow magma chamber move away rapidly to form new crust. Instead, they found that rocks at Hess Deep cooled and crystallized over prolonged timescales that are comparable to those at slow-spreading ridges such as the Mid-Atlantic Ridge[10]. The broad range of cooling ages of the zircon crystals could result from an axial magmatic system that is anomalously wide, leading to drawn-out cooling and formation of the rocks. Alternatively, the broad range of ages could stem from intrusion of young magma bodies at a distance from the rift into the surrounding older crust.

Taken together, the studies by Canales *et al.*[1] and Rioux *et al.*[2] reinforce the emerging view that magmatic accretion of new crust at fast-spreading ridges is much messier than previously thought (Fig. 1). Although the majority of new crust is certainly constructed by the axial magmatic systems, there is evidence from the Oman ophiolite — oceanic crust that is today exposed on land — that as much as 20% of crustal rocks may be intruded at off-axis locations[15,16].

Globally, 98% of Earth's spreading centres are found beneath its ocean. This watery cover is both a boon and a hindrance. Although it facilitates the use of sophisticated marine geophysical imaging experiments[1], it prevents the use of geodetic methods that use radar. Pagli *et al.*[3] demonstrate the power of interferometric synthetic aperture radar methods in their study of the slow-spreading Afar rift in Africa. They identify a body of magma that is 1 km deep and 8 km long, located at very shallow depths in the crust. Remarkably, current models of rifting predict shallow, elongate magma bodies to exist exclusively at fast-spreading ridges[8]. Because it is not covered by an ocean, Afar lacks the cooling effects of sea water and hydrothermal circulation. It is therefore likely that the shallow, elongate magma body is a mark of the high temperature of the rift, otherwise found only at fast-spreading ridges. If so, this study emphasizes that the boundary conditions applied by Earth's ocean play a central and perhaps under-appreciated role in shaping magmatic systems at rifts.

Finally, a synthesis of geodetic and seismic data from historical episodes of subaerial rifting at Afar and Iceland[17] reveals characteristics of rifting events that are unpredicted. For example, at both locations the initial emplacement of the widest and most voluminous intrusions of magma seem to occur farthest from the centre of the rift segment. Smaller intrusion episodes closer to the rift centre then follow. The observed pattern of dyking and intrusions could result from lateral variations in the mechanical strength of the crust[18], which is largely controlled by the thermal structure.

Rifting and magmatic accretion are apparently far from simple. New crust can be formed during intrusive magmatic events that occur over a broad region spanning many kilometres on either side of the rift. The plate-spreading rate may not be the sole controlling factor of the structure and geometry of a magma chamber, or of the rate at which new crust is accreted. Instead, where and how heat is delivered and removed from a rift — in the form of magma transport from the mantle below and hydrothermal interactions with the ocean above — also have important roles.

In the parable of the blind men and the elephant, the emperor remarks that the true description of the beast requires reconciliation between apparently opposing observations. The studies in this issue[1–3,17] show that so it is with rifts, too. ❐

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CLIMATE SCIENCE

Constraints on the high end

The plausibility of the high end of global warming projections in recent assessments is a subject of debate. A study of multi-model climate simulations argues that we need to take the possibility of strong warming seriously.

Isaac Held

Useful guidance on how much warming to expect requires estimates of uncertainties in climate projections. In its 2007 assessment report, the Intergovernmental Panel on Climate Change (IPCC) placed a wide uncertainty range on possible climate trajectories for the coming century. Since then, several studies have implied that the lower half of this range is more plausible than the upper half[1,2], so a re-evaluation of the high end of projected temperature increases is particularly important. Writing in *Nature Geoscience*, Rowlands and colleagues[6] conclude that by 2050, global mean temperatures are likely to be 1.4 to 3 °C warmer than during the period 1960–1990, if greenhouse gas emissions continue along a pathway without mitigation but with some reductions in sulphate aerosols.

More than a dozen climate modelling groups around the world have provided their best attempts at simulating climate over the twenty-first century and beyond — for a variety of emissions scenarios — to the Coupled Model Intercomparison Project (CMIP). This archive of model results has been utilized for the 2007 IPCC report as well as national climate assessments. These models differ in a host of ways, ranging from their treatments of small-scale moist convection to aerosol–cloud interactions and ocean mixing processes. Motivated in part by the small size and unsystematic character of the CMIP ensembles, some groups have moved towards creating 'perturbed physics' ensembles by starting with one model and systematically perturbing parameters. In this way, they have created much larger sets of climate model projections[3–5]. The CMIP and perturbed physics ensembles are complementary, and it is a challenge to optimally combine these resources with expert opinion to provide the most meaningful estimates of uncertainty.

Climate modelling is not sufficiently advanced to have reached agreement on the set of key model parameters that are uncertain yet critical, and that designers of a model ensemble should therefore focus on. Expert advice is required on the choice of which set of parameters to vary. There is no claim that these are all of the relevant uncertain parameters, or that there are no further, structural uncertainties in the model that cannot be expressed as simple parameter variations. The resulting range of simulations must then be narrowed to those that are deemed plausible, based on comparison with key observations. This comparison determines the extent to which projections from each model version deserve to be considered as part of the distribution of plausible outcomes. The definition of this filter through which the models must pass is critical to the interpretation of the results (Fig. 1).

Rowlands *et al.*[6] analyse projections from thousands of distinct climate models, under a typical scenario of greenhouse gas emissions with no mitigation. They use the simulations generated through climateprediction.net[7], the most ambitious of the efforts at perturbed physics simulations, run on computers of volunteers around the world. Selecting those models that they consider sufficiently realistic, they find that no model that passes their quality control warms less than 1 °C by 2050 as compared with their 1960–1990 baseline. On the other hand, a surprisingly large fraction (about 15%) of these models warm by as much as 3 °C.

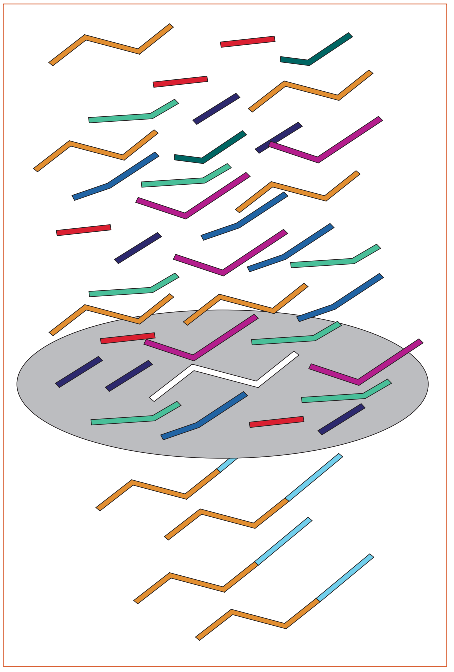

Figure 1 | Selection of the fittest models. In a perturbed physics ensemble of models, uncertain parameterizations are varied to produce a range of distinct climate models. A quality criterion — usually a comparison with observed climate variables — is then used to select viable models that are included into the projection for future change. Rowlands and colleagues[6] select models based on their agreement with regional temperature time series that correlate with future warming in previous model ensembles and the magnitude of required flux adjustments. According to projections from the remaining models, global mean temperatures by 2050 are likely to rise between 1.4 and 3 °C above the 1960—1990 average.

This work marks a significant technical advance over previous publications by this group: it is based on projections with a very large set of fully coupled atmosphere–ocean models suitable for studying the transient non-equilibrium climate states relevant for century-scale projections. However, to prevent unrealistic drifts in control simulations, artificial energy fluxes are imposed at the air–sea interface. These flux adjustments vary seasonally, but are otherwise independent of time. To define their filter for model quality control, Rowlands *et al.*[6] use the evolution of surface temperatures in more than 20 land regions and ocean basins over the past 50 years, as well as the global mean magnitude of the required flux adjustment.

Many other metrics could be contemplated for this purpose; for example, estimates of ocean heat content variations or various aspects of the observed seasonal cycle. However, the global warming in this model ensemble does not seem to be sensitive to changes in the ocean parameters, and the use of seasonally varying flux adjustments precludes a straightforward use of the observed seasonal cycle as a metric. Some of the models that pass the quality control employed by Rowlands and colleagues[6] may exhibit other disqualifying features in their mean climates, akin to the unrealistic stratospheric water vapour concentrations and water vapour feedback that characterizes extreme members in some other perturbed physics ensembles[5,8].

According to the authors, the ability of their high response models to pass through the imposed filter is typically not a consequence of a balance between exceptionally large aerosol forcing and large climate sensitivity. If it is not aerosol cooling, then internal variability must mask the large responses to increasing greenhouse gases over the period of observational constraints, to enable the models to pass the quality control. But the ability of internal variability to hide underlying forced trends is likely to decrease as the time period analysed gets longer. Indeed, the authors suggest that tests against observed temperature evolution over a longer time period might reduce the viability of some of their current high-end models.

Rowlands and colleagues[6] consider an ensemble of unprecedented size in their study, but it is nevertheless important to think of the results as a work in progress while questions of how best to confront each model with observations are addressed. Their massive perturbed physics ensemble is a valuable resource for further analysis of climate change. Eventually, it may help us not only to quantify uncertainty, but also to reduce it. ❒

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