climate has equilibrated to a doubling of CO_2 concentration relative to pre-industrial levels, an equilibrium that might take a few hundred years to establish[8]. These sensitivity values are outside the range of those produced by the CMIP5 ensemble, which fed into the previous IPCC Assessment Report[8] in 2013. They seem to have arisen largely because of revisions to how cloud microphysics is represented, particularly in the parameterization of supercooled liquid water. Cloud microphysics describes the properties (such as size and relative concentration) of water and ice droplets in a cloud. On such tiny matters might our future rest.

And so, the question is this. Are we to believe these new estimates of climate sensitivity, or will they end up being reverted to earlier CMIP5 values as the models go through a further round of revisions?

Some years ago, the meteorologist Mark Rodwell and I proposed[9] a method for assessing predictions of climate sensitivity — one based on very short-range (6-hour) weather forecasts. We were motivated by startling results suggesting that warming could be as much as 11 °C for a doubling of CO_2 levels[10]. These high estimates arose in climate models in which a particular cloud-system parameter, known as convective entrainment, was set to unusually small values that could not readily be ruled out by studying the accuracy of the models' climate simulations. By showing that errors of 6-hour weather forecasts were made substantially worse using a model with these reduced values of convective entrainment, we were able to cast doubt on the credibility of these exceptionally large estimates of climate sensitivity.

We found that if we ran a state-of-the-art numerical weather-prediction system with a low convective entrainment parameter, it produced much less accurate 6-hour forecasts than when the forecast model had more-typical values plugged in. To everyone's relief, this suggested that the low values of the parameter used in the climate models were unrealistic, and thus we could discount the alarming 11 °C sensitivity estimates.

Williams *et al.* have now subjected the CMIP6 Met Office climate model to the same 6-hour weather-forecast test. The authors chose to test this model because it was one of those that produced a relatively large climate sensitivity of about 5.5 °C. The model has a revised scheme for cloud microphysics as mentioned above, in which there are more supercooled water droplets and fewer ice droplets.

The authors found that the 6-hour-forecast errors were smaller for the revised model than for a version of the model without the cloud-microphysics revisions. Hence, instead of being able to discount estimates of high sensitivity, as Rodwell and I had done, their result provides some of the best current evidence that climate sensitivity could indeed be 5 °C or greater.

In short, these results, published in a specialist journal, and probably read by few climate policymakers, carry a far-reaching message: we cannot afford to be complacent. It seems that cloud adjustment to climate change is not going to give us breathing space. Instead, we need to redouble our efforts to cut emissions.

There is a serious caveat to the general application of this technique. The test makes sense only if the model used to do the short-term forecast is the same as the one used to do the climate projection. The Met Office weather and climate models are reasonably similar (their model is often called the 'Unified Model'), but weather models do not generally correspond well with climate models.

On top of this, an accurate 6-hour weather forecast is possible only if one can come up with accurate initial conditions for the model from observations, a process known as data assimilation. This is a complex and computationally demanding optimization problem[11], and most climate institutes do not have such data-assimilation capability. Moreover, accurate data assimilation requires the spatial and time resolution of climate models to be increased to be comparable with those used for state-of-the-art weather forecasting. Conversely, the parameterizations in weather-forecast models must be as complex and comprehensive as the ones in corresponding climate models; few weather-forecast centres have the resources for this.

Thus, to reduce uncertainty in estimates of the crucial cloud feedbacks, climate institutes and weather-forecast centres should work together to ensure that their model systems are as seamless[12,13] as possible. I contend that weather and climate modelling must be rationalized worldwide, and that human and computational resources should be pooled to produce high-resolution, unified weather–climate models[14,15].

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Atomic physics

Quantum matter orbits Earth

Maike D. Lachmann & Ernst M. Rasel

Exotic ultracold gases called Bose–Einstein condensates have been created on board the International Space Station. This feat is not only a technological landmark, but could also improve our understanding of fundamental physics. **See p.193**

States of matter known as Bose–Einstein condensates (BECs) were first observed 25 years ago[1,2]. Since then, these quantum objects have become a key tool in the study of quantum physics, and they are routinely produced in hundreds of laboratories around the world. On page 193, Aveline *et al.*[3] report the generation of rubidium BECs aboard the International Space Station, which is in orbit around Earth. The condition of perpetual free fall on the station offers new methods for probing BECs and for making a wide range of high-precision measurements.

A BEC is produced when a dense cloud of trapped bosonic atoms (atoms for which a quantum property known as spin is an integer) is cooled to temperatures near absolute zero[4,5]. In these ultracold ensembles, the atoms mainly populate the lowest energy state of the trap. A central tenet of quantum mechanics is wave–particle duality, whereby every particle can be described as a wave of matter. BECs are useful objects for testing quantum mechanics because the entire cloud of atoms can be regarded as a single matter wave. This property is called quantum degeneracy.

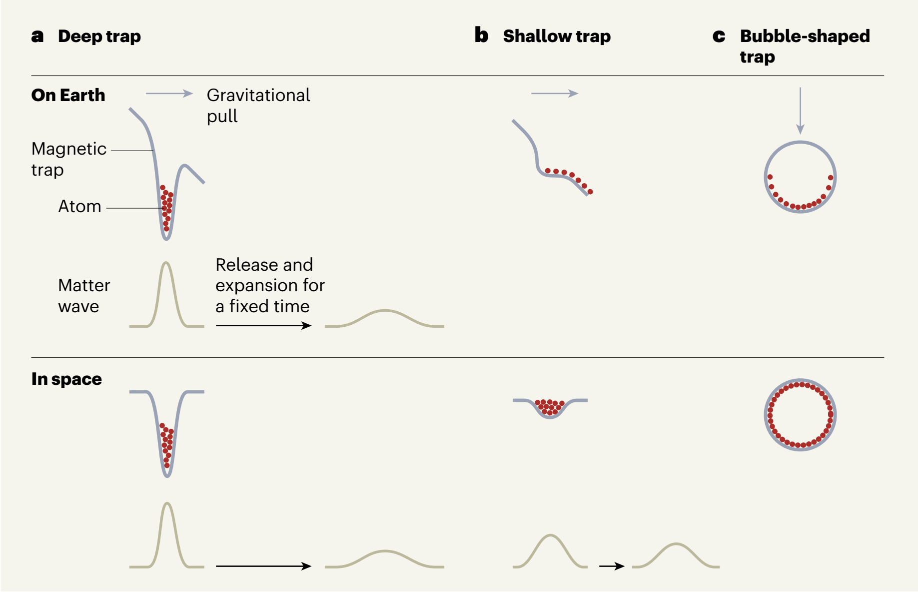

Figure 1 | Bose–Einstein condensates on Earth and in space. a, Ultracold atoms in a magnetic trap can form a state of matter called a Bose–Einstein condensate, which can be considered as a single matter wave. A deep trap can be used on Earth (where the planet's gravitational pull affects the trap's shape) and in space. However, when the condensate is released from the trap and allowed to expand freely for a relatively long fixed time, the matter-wave signal is lost. **b**, A shallow trap cannot be used on Earth because the atoms cannot be held together against the planet's gravitational pull. Aveline *et al.*[3] found that such a trap can be used in space, and that the resulting matter-wave signal is retained after the same expansion time as in **a**, owing to a slower expansion rate. **c**, A Bose–Einstein condensate could be confined uniformly across the surface of a bubble-shaped trap in space but not on Earth, where the atoms accumulate at the trap's base.

Bose–Einstein condensation is achieved by cooling the atomic cloud using several methods that involve combinations of light and magnetic fields. A commonly used final step is known as evaporative cooling[6]. In this approach, the atoms are confined in a magnetic trap, and those that have the highest kinetic energy (the 'hottest' atoms) are driven from the trap using radio-frequency radiation. The remaining atoms collide with each other and reach thermal equilibrium at a lower mean temperature than the initial temperature. This process is repeated until a BEC is formed.

As discussed, Bose–Einstein condensation requires low temperatures, at which atoms hardly move. However, when a BEC is released from a magnetic trap so that experiments can be carried out, repulsive interactions between the atoms cause the cloud to expand. Within a few seconds, the BEC becomes too dilute to be detected. The expansion rate can be reduced by decreasing the depth of the trap, and, thereby, the density of atoms in the trap.

On Earth, the planet's gravitational pull restricts the shape of possible magnetic traps in such a way that a deep trap is needed to confine a BEC (Fig. 1a,b). By contrast, Aveline and colleagues found that the extremely weak gravity (microgravity) on the International Space Station allowed rubidium BECs to be created using shallow traps. As a result, the authors could study the BECs after about one second of expansion, without needing to manipulate the atoms further.

Before releasing a BEC, Aveline *et al.* observed that the tightly trapped condensate was surrounded by, and interacting with, a halo-shaped cloud of rubidium atoms. During evaporative cooling, these atoms had been transferred to a state that is insensitive to magnetic fields. The atoms then interacted only weakly with the trap through their quantum-mechanical properties, owing to a phenomenon called the second-order Zeeman effect[7]. On Earth, such atoms would be removed from the trap by the dominant force of gravity. However, in orbit, they remain in the trap and could be used, for example, to directly produce ultracold atomic samples that have an extremely low density.

The authors' experiments mark just the beginning of many exciting studies on quantum-degenerate gases. For example, microgravity allows atoms to be confined or guided using trap shapes, such as that of a bubble[8], that cannot be used properly on Earth (Fig. 1c). Future work on the evolution of such atoms will provide insight into few-body physics. Moreover, there are planned experiments on quantum-gas mixtures of potassium and rubidium[9].

Earth-orbiting BECs could also advance atom interferometry — a measurement technique based on the interference between matter waves. The sensitivity of an atom interferometer to inertial forces is proportional to the square of the time that atoms spend in the interferometer[10]. On the ground, this time is restricted by the limited free-fall time. Microgravity facilities such as rockets[10], aeroplanes[11] and 'drop towers'[12] have been used previously to address this problem, but Earth-orbiting atom interferometers would enable many more experimental cycles.

"The authors' apparatus needed to satisfy the strict mass, volume and power-consumption requirements of the International Space Station."

For the future goal of high-precision measurements in space, a thorough analysis of all systematic effects and the implementation of techniques developed on the ground are essential. Such measurements could provide stringent tests of the universality of free fall (the principle that all objects accelerate identically in an external gravitational field) and theories of dark energy (the unknown energy that is thought to be causing the expansion of the Universe to accelerate). The expected sensitivities would also make BEC interferometry of interest for satellite navigation, exploration and Earth observation.

Aveline and colleagues' technological achievement is remarkable. Their apparatus needed to satisfy the strict mass, volume and power-consumption requirements of the International Space Station, and be robust enough to operate for years without needing to be serviced. The authors' Earth-orbiting BECs provide new opportunities for research on quantum gases, as well as for atom interferometry, and pave the way for missions that are even more ambitious.

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Correction

Quantum matter orbits Earth

Maike D. Lachmann & Ernst M. Rasel

This article gave an incorrect definition of bosonic atoms. They should have been defined as atoms for which a quantum property known as spin is an integer.

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