At larger wavelengths, the Coriolis force — which deflects large scale motions relative to a rotating planet and is strongest at the planet's poles — becomes important and a diverse group of waves emerge. For example, Rossby waves oscillate in the north–south direction (rather than up-and-down like gravity waves), and the variation in Coriolis force with latitude is the primary restoring force. Atmospheric Rossby waves on Earth are familiar as the source of long-wavelength meanders in the jetstream that strongly influence mid-latitude weather patterns. Rossby's analysis was confined to the tangent plane[9], but was soon extended to a full spherical geometry[10]; the corresponding waves are often referred to as Rossby–Haurwitz waves.

Robert Tyler, in contrast to conventional ideas for planetary tidal-excitation, invokes a tidal response to obliquity — the tilt of the equatorial plane relative to the orbital plane. In the course of an obliquity-forcing tidal cycle, the point on the satellite closest to the parent planet moves in a north–south direction, rather than east–west, as with an eccentricity tide. Tyler's key innovation is to note that the obliquity-forcing function is a perfect match to one of the Rossby-Haurwitz wave modes, and hence the obliquity tide is resonantly enhanced. Even in cases where the obliquity tide is small, the resulting fluid flow can be quite substantial.

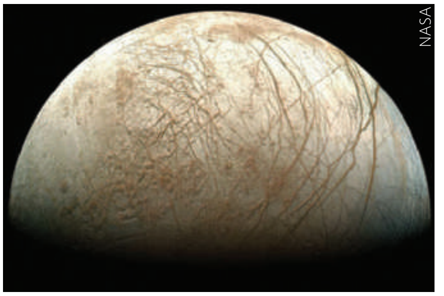

Figure 1 | Flow below the ice. Jupiter's moon Europa is thought to have liquid oceans underneath its ice surface. Robert Tyler suggests that obliquity tides, in resonance with Rossby waves, generate sufficient heat to keep the oceans flowing[4].

This proposed mechanism for tide generation makes it more difficult to estimate rates of tidal heating in planetary satellites, because the flow field in a liquid ocean forced by an obliquity tide is not entirely expressed in changes of sea-surface height. In addition to changing the shape of the satellite's surface, as the eccentricity tide does, the obliquity tide can also drive a toroidal flow of the sub-surface ocean, which means fluid particles travel along paths of a fixed distance from the satellite's centre. Such motion is hard to measure remotely, and it is not clear how future missions to Europa could estimate this tidal component.

So why is such an obliquity-induced wave not dominant on Earth? The answer is simple: the continents spoil the global ocean pattern required for this particular wave. However, the free-oscillation period (or natural-sloshing period) of the Atlantic Ocean is near to 12 h, which is roughly the period of the dominant tide excited by the Moon. This coincidence in periods produces anomalously high tides that contribute to a global rate of tidal energy dissipation in excess of 3×10^{12} W.

Tyler's theory opens up a new avenue for investigating tidal effects on Earth and other planets and satellites. Future applications of this theory, for example to Titan and Enceladus in the Saturn system, should help explain evidence for significant energy dissipation within these bodies. ❐

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ATMOSPHERIC DYNAMICS

The age of stratospheric air

Climate models predict that increasing greenhouse gas levels will invigorate the circulation in the upper atmosphere. But a close look at observations of the age of stratospheric air over 30 years reveals no acceleration in the circulation.

Darryn Waugh

The distribution of ozone and other greenhouse gases in the atmosphere depends critically on the transport of air into, within, and out of the stratosphere, the layer of the atmosphere between about 10 and 50 km above the surface (Fig. 1a). Numerical models predict that the stratospheric circulation will accelerate because of the increase in atmospheric concentrations of greenhouse gases, as will the transport of air into the stratosphere from the troposphere, the lower layer of the atmosphere[1–6]. One consequence of this acceleration is a shorter mean transport time of air from the troposphere up into the stratosphere. This transport time is termed the 'mean age' of stratospheric air, and the model simulations imply that this mean age should have decreased in recent decades. However, on page 28 of this issue, Engel and colleagues[7] present observational evidence that the mean age of stratospheric air has, if anything, increased slightly over the past 30 years.

The mean age of stratospheric air cannot be measured directly, but it can be inferred from stratospheric measurements of carbon dioxide and sulphur hexafluoride (SF_6). These gases are conserved within the troposphere and stratosphere, and there has been a steady, long-term increase of their concentrations over the past three decades. This increase originates in the troposphere where emissions occur, and is then transported upwards. The stratospheric concentrations therefore lag behind those in the troposphere, and this delay time provides an estimate of the mean age of air (Fig. 1b).

Engel and colleagues evaluated measurements of these gases made from balloon flights over the past 30 years with the aim of estimating mean age in the mid-latitudes of the Northern Hemisphere. They arrive at a trend in mean age of 0.24 ± 0.22 years per decade — a small increase in the age of mean air that is statistically significant at the 68% confidence level but indistinguishable from zero at the 90% confidence limit. This observational estimate is not in agreement with the model predictions of an accelerating circulation with a decrease in mean age. In particular, the chemistry–climate models in the latest international scientific assessment of ozone depletion[8] that simulated the mean age of stratospheric air all showed a negative trend in mean age[3–6], with changes between –0.05 and –0.20 years per decade for the time period and location considered by Engel and co-workers (Fig. 1c). Simulations with a more recent version of the model with the largest negative trend are closer to the trends derived with the other three models (J. Austin, personal communication).

The models are the first suspect for the cause of the difference between simulations and observations. Simulations of the mean age of air have historically been problematic, and even though there have been improvements in the most recent generation of models, they still do not fully agree with observations[9]. In addition, there is a spread in the simulated trend in mean age, and there is as yet no general agreement about the mechanisms that cause the simulated circulation changes.

But the uncertainties in the observed trend in the mean age (Fig. 1c) should not be forgotten either. As discussed by Engel and colleagues, many different uncertainties need to be considered when calculating the mean age of air from observations, and there are considerable variations in age estimates made in the same or adjacent years. In addition, only 27 balloon flights measured age tracers over a period of 30 years. Therefore, even a decrease in the mean age of air over the past three decades would be part of the uncertainty range if the confidence level was increased, for example to 95% as is often used.

Observed trends in tropical lower stratospheric ozone, water vapour and temperature over the past decades[10] provide some indirect, observational support for an increase in the tropical upwelling. With no other change in the circulation, this increased upwelling is expected to result in a decrease in mean age throughout the stratosphere. But as discussed by Engel and colleagues, it is possible that changes in the poleward transport in the lower stratosphere, below the altitudes of the measurements that they used, could compensate for this increased tropical upwelling, and result in the lack of a trend in the mean age of air that they observe in the middle stratosphere.

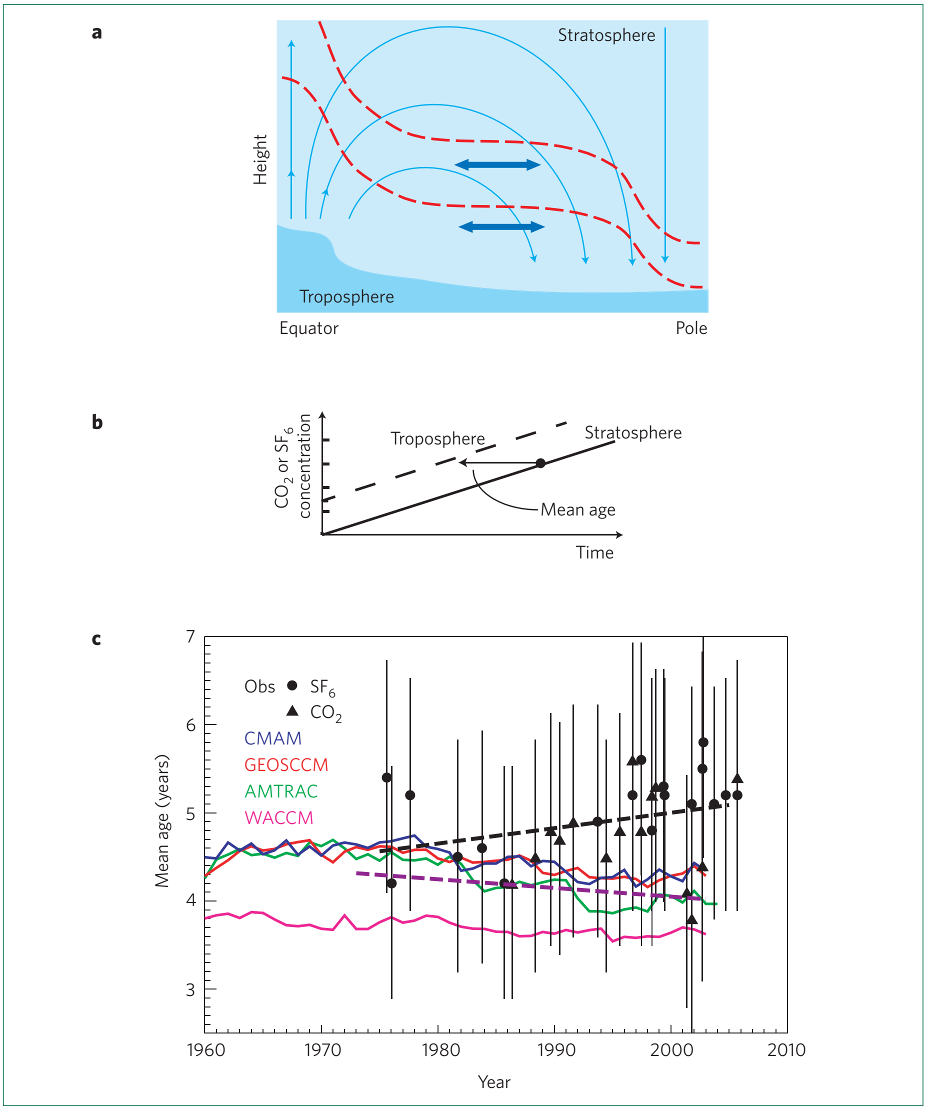

Figure 1 | Age of stratospheric air. **a**, Air masses move upwards in the tropics and circulate through the stratosphere (thin blue arrows) towards the pole. At the same time, air is mixed horizontally (thick blue arrows). The lines depicting air of a constant age (isochrones, dashed lines) are at the highest altitude near the Equator, with a downward trend towards the pole. **b**, Concentrations of conservative age tracers increase with time in both the troposphere and stratosphere. Comparison of stratospheric measurement with historical tropospheric measurments allow determination of the delay time, and hence mean age. **c**, Engel and colleagues[7] provide observational estimates (from SF_6- and CO_2-derived data) of the mean age of stratospheric air over the past 30 years (black; uncertainties 1 standard deviation). The derived trend (black dashed line) does not agree with trends derived from model simulations (solid curves are individual models[3–6] and purple dashed line is mean model trend).

Resolving this discrepancy between the observations by Engel and colleagues[7] and the models is very important. The simulated acceleration in the circulation (and decrease in mean age) is predicted to extend into and throughout the twenty-first century, with significant effects on stratospheric ozone concentrations and climate change. An accelerated circulation leads to earlier removal of ozone-depleting substances from the stratosphere[11] and, in general, to an earlier return of stratospheric ozone to historical values. However, an early 'recovery' of ozone is not expected to be uniform: the increased tropical upwelling could cause ozone levels in the tropical lower stratosphere to decrease throughout the century, even if ozone-depleting substances go back down to natural levels[12]. An accelerated circulation could also cause an increase in the transport of ozone from the stratosphere into the troposphere, with potential impacts on climate and air quality.

Given the above lack of agreement between models and data, and the large uncertainty in the observed trends, there is a pressing need for more measurements of 'age' tracers to quantify more precisely past changes in age and hence better constrain the models used to make ozone and climate projections. ❐

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