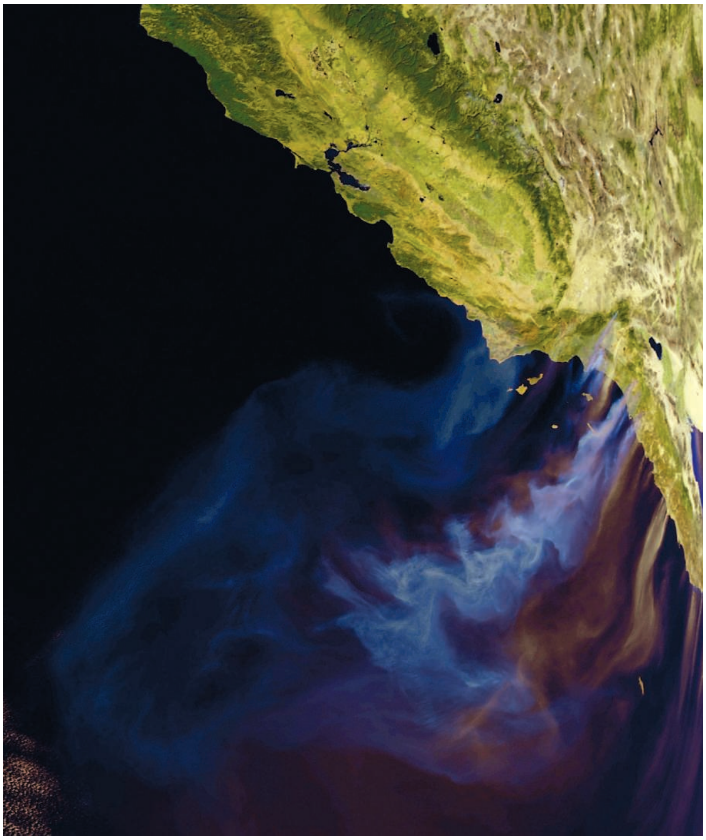
ATMOSPHERE

Smoke and Climate Change

Since preindustrial times, increasing soot concentrations have strongly reduced cooling by anthropogenic aerosols.

Johannes Quaas

Anthropogenic pollution forms small liquid or solid particles in the atmosphere. These aerosols—emitted directly, for example, as soot particles from smoke (see the figure), or formed from pollution gases, such as sulfate particles—are of nanometer to micrometer size. Some particles absorb sunlight, contributing to climate warming; others reflect sunlight, leading to a relative cooling. The global mean effect of anthropogenic aerosols is a cooling, but the relative contributions of the different types of aerosols determine the magnitude of this cooling. On page 187 of this issue, Myhre (*1*) offers new insights into these aerosol effects on climate by showing that the relative increase in light absorption by anthropogenic smoke since preindustrial times was larger than the increase in light scattering by other anthropogenic aerosols. His results substantially advance the level of scientific understanding of how aerosols affect climate.



Going up in smoke. Light absorption by smoke—such as from forest fires in California, observed here by EUMETSAT's MetOp satellite (*13*)—is key to understanding how anthropogenic aerosols affect climate change.

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For more than a decade, climate models have been used to assess the climate effects of aerosols (*2*). Over the 20th century, aerosol cooling has offset a part of the warming induced by anthropogenic greenhouse gases. Indeed, whereas early climate change simulations neglecting the aerosol cooling effect overestimated the anthropogenic warming relative to the observed temperature record, current climate models can reproduce the observed warming over the 20th century.

In such models, the global-mean warming is determined by the balance of the "radiative forcings" (warming by greenhouse gases and cooling by aerosols) and climate sensitivity (the surface temperature change for a given radiative forcing). Given that the greenhouse-gas forcing is well understood and can be predicted skillfully (*2*), uncertainties in the 20th-century aerosol cooling and climate sensitivity in the models balance each other. A large aerosol cooling implies a large climate sensitivity (*3*). The greenhouse-gas forcing must have been larger than aerosol cooling because overall, climate warmed over the 20th century (*4*).

A large fraction of anthropogenic aerosols consists of sulfate, which forms through chemical processing from sulfur dioxide, emitted jointly with carbon dioxide in fossil fuel combustion. In many regions of Earth, the sulfate aerosol concentration has declined in recent decades after pollution-reduction legislation was introduced (*5*). Because sulfate aerosols remain in the atmosphere for days, whereas carbon dioxide remains there for a century or more, the greenhouse-gas effect accumulates, whereas aerosol cooling is tightly linked to current emissions. Aerosol cooling thus offsets part of the greenhouse-gas warming—a masking effect that may be removed suddenly when fossil fuel combustion emissions are cleaned up or fuel combustion is stopped (*6*).

A reliable quantification of the aerosol radiative forcing thus is essential to understand climate change. Recent improvements in satellite observations have enabled measurement-based estimates of the global aerosol forcing (*7*–*9*). These estimates yielded systematically larger aerosol cooling than do climate model calculations. Part of this discrepancy can be explained by different assumptions made in the two approaches (*10*); for example, models and satellite data interpretations may use different estimates of the anthropogenic fraction of aerosol, or make different assumptions about aerosol forcing in cloudy skies and above bright surfaces. However, a large part of the discrepancy has remained unexplained.

Myhre now convincingly explains most of the remainder of the discrepancy. With a systematic set of sensitivity studies, he determines the relative importance of the various assumptions. He shows that with a consistent data set of anthropogenic aerosol distributions and properties, the data-based and model-based approaches converge.

The author argues that since preindustrial times, the soot particle concentration increased much more than did the rest of the aerosols. Most aerosols mainly scatter sunlight, but soot also strongly absorbs solar radiation. In both cases, the effect at Earth's surface is less incoming radiation; but at the top of the atmosphere, where the Earth system's energy balance is determined, scattering has a cooling effect, whereas absorption has a warming effect. If soot—and thus absorption—increases more than does scattering, the aerosol cooling of the Earth system is smaller than it would otherwise be. Myhre shows that when this absorption effect is properly represented in the satellite-based approach, the global-mean forcing is reduced, in better agreement with the model-based computation.

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The study by Myhre is an important advance toward quantifying the aerosol radiative forcing (and hence climate sensitivity), but many questions remain. Models continue to give diverging results, particularly with respect to regional aerosol effects (*11*). Furthermore, aerosols affect the energy balance not only directly (the effect studied by Myrhe) but also indirectly, particularly by altering cloud brightness, abundance, and geometry, as well as the distribution of precipitation (*2*, *12*). These indirect effects may be substantial but are not well understood. Better understanding of the physical processes of aerosol-cloud interactions is essential for improving their representation in climate models. This has to involve observations and modeling at the process scale, as well as constraints at the large scale through better use of improving satellite data.

References and Notes

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13. EUMETSAT is the European Organisation for the Exploitation of Meteorological Satellites. Its MetOp satellite is the first European polar-orbiting satellite dedicated to operational meteorology (www.esa.int/esaME/index.html).

10.1126/science.1176991

EVOLUTION

How Did the Turtle Get Its Shell?

Details of embryonic skeletal and muscular organization provide evidence for the evolution of the turtle shell.

Olivier Rieppel

In *On the Origin of Species*, Darwin asserted: "Monstrosities cannot be separated by any clear line of distinction from mere variations" (*1*). But encased in its shell, the turtle appears to be just such a monstrosity. No other animal, living or extinct, has its body enclosed within a bony shell that is similarly constructed in its entirety. Over the last few years, developmental biologists have started to tackle the question of how the turtle shell evolved. On page 193 of this issue, Nagashima *et al*. (*2*) provide a detailed account of muscular and skeletal changes during the embryogenesis of the modern turtle, and in drawing parallels between these early developmental changes and what is seen in ancestral turtles, provide insights into how turtle shell evolution might have occurred.

Nagashima *et al*. show that formation of the dorsal part of the turtle shell (carapace) results from complex changes in developmental pathways. Yet, commenting on the turtle shell in his classic textbook on *Vertebrate Paleontology and Evolution*, paleontologist Robert Carroll maintained that "developmental specialization does not provide any hint as to the way in which this pattern evolved phylogenetically" (*3*). The clash here is between a transformationist as opposed to an emergentist view of morphological evolution.

The classic transformationist approach sees morphological evolution as a result of natural selection working on variation manifest in reproducing organisms. Under this paradigm, the turtle carapace would have evolved from osteoderms. These are small bony plates that develop (ossify) within the deep layer of the skin (dermis) of reptiles such as crocodiles or some lizards. The lineage ancestral to turtles would have developed a dense osteoderm covering, the individual elements eventually coalescing to form larger bony plates. Fusion of osteoderms with the underlying ribs would explain how the ribs became incorporated in the carapace (*4*, *5*). Two problems remain unexplained in this scenario: How do bones that form in the skin fuse with underlying ribs that normally grow into the lateral body wall? And why is it that uniquely in turtles the shoulder blade lies inside the ribcage, instead of being located outside the ribcage as in all other tetrapods?

Origin of the shell. Skeletal and muscular development during early turtle embryogenesis provides insights into how the modern turtle shell evolved. Shown is the Chinese soft-shelled turtle, *Pelodiscus sinensis*.

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The assumption of the transformationist view is that the shoulder girdle moved backward during the evolution of turtles, so that it would be located inside the shell, which itself incorporates the ribs. But modern turtle embryos do not show any posterior dislocation of the shoulder girdle during development (*6*), drawing this hypothesis into question.

The emergentist approach seeks to understand the origin of genuinely novel structures such as the turtle shell as a result of developmental modifications. It is under this paradigm that the study by Nagashima *et al*. gains merit. A distinctive feature of the turtle embryo is a disk-shaped thickening of the dermis on the back that forms a carapacial disk (precursor to the carapace). Differentiation of epithelial cells in the margin of the carapacial disk (the carapacial ridge) is thought to organize carapace development. This is based on similarity to the regulation of tetrapod limb development by cells at the apical ridge of limb buds (*7*). The ribs then grow into the carapacial disk to initiate ossification (*8*–*10*) of the costal plates that will constitute parts of the mature shell. A similar function is assigned to embryonic trunk vertebrae, whose spines grow into the carapacial disk to induce the formation of the neural plates of the carapace.

Nagashima *et al*. observed that during early development of the Chinese soft-shelled turtle *Pelodiscus sinensis* (see the figure), translocation of the ribs to a position outside the shoulder blade involves folding of the lateral body wall along a line that defines the later formation of the carapacial ridge.

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