aggressive responses are suppressed (*15*). Neural analogs for modulation include cells in the cat superior colliculus that respond to visual stimuli alone but not to auditory stimuli alone. Auditory and visual stimuli together elicit enhanced responses in some neurons, leave some unchanged, and leave others depressed (*12*).

Finally, the combination of two nonredundant components can produce an entirely new response (emergence). When a vocal stimulus (human phoneme "ba") is mismatched with a visual stimulus (face articulating "ga"), subjects may perceive a new phoneme, "da" (*4*). Aromatic pyrazines and red and yellow coloration are commonly associated with noxious insects. Presented alone, neither cue produces aversion in chicks; aversion appears only when the odor and color occur simultaneously (*2*). Here, multimodal stimuli evoke a response not elicited by the unimodal components. Similarly, some cat superior colliculus cells respond to multimodal but not unimodal stimuli (*12*). The provision of a common terminology for discussion of multimodal signaling and its underlying integrative neural processing may encourage efforts to unify physiologic and behavioral research in this area.

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PERSPECTIVES: CLIMATE CHANGE

Solving the Aerosol Puzzle

Jeffrey T. Kiehl

How do aerosol particles affect climate? This is one of the key questions that has to be answered if we are to understand how humans influence Earth's climate. The burning of fossil fuels and biomass (in natural and man-made fires) leads to the production of substantial amounts of aerosols in the atmosphere. These particles increase the reflection of sunlight back to space directly and also indirectly by increasing the brightness of clouds. Both of these effects reduce the amount of solar energy available to the climate system, a phenomenon called negative climate forcing (that is, a cooling of the atmosphere). On page 1299 of this issue, Haywood *et al.* (*1*) use a new approach to determining the direct effect of aerosols on Earth's climate. By combining satellite data of reflected sunlight with results from numerical models, they calculate how aerosols alter the amount of solar radiation available to Earth's climate system. Their unique integration of observations and models shows how a better understanding of the aerosol problem can be reached.

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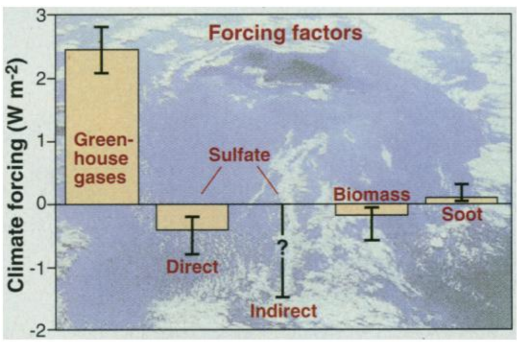
Emissions from industry are a major source of aerosols in the atmosphere. In fact, studies indicate that the cooling effect of these anthropogenic aerosols could offset a substantial amount of the forcing by greenhouse gases, which causes global warming. Unfortunately, the magnitude and spatial extent of the anthropogenic aerosol forcing effect are highly uncertain (see figure), and this uncertainty is a major hurdle in advancing our understanding of how humans have altered, and may in the future alter Earth's climate.



A question of uncertainties. Climate forcing from 1850 to the present, based on (*6*). Positive forcing corresponds to warming and negative forcing to cooling of the atmosphere. Large uncertainties exist, particularly in the aerosol forcing.

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The complexity of this problem seems to grow with each new study. Uncertainties in the direct effect arise from the amount and distribution of aerosols in the atmosphere and their chemical and physical properties, which determine their effectiveness at reflecting sunlight back to space. Interactions between different types of aerosols may also affect the magnitude of direct forcing. Recent observation and modeling studies (*2*, *3*) indicate that gas phase sulfur species readily attach to sea-salt particles, leading to composite particles that are larger in size than pure sulfate particles. Larger particles reflect less sunlight, and formation of sulfate on sea salt therefore reduces the overall magnitude of the sulfate forcing. Sulfate formation can also occur on mineral dust and carbon aerosols, again reducing the sulfate forcing. At present, there is little information on how this masking effect alters estimates of sulfate aerosol forcing. Despite these caveats, direct forcing by sulfate aerosols is clearly an important factor in anthropogenic climate forcing.

The indirect effect is plagued with even greater uncertainties. Field observations indicate that an increase in sulfate below a cloud leads to an increase in the number of cloud droplets within the cloud. A higher number of small cloud droplets increase the cloud's brightness; that is, more sunlight is reflected back to space. Unfortunately, the predicted number of cloud droplets for a given amount of sulfate aerosol varies widely from model to model, leading to a fivefold uncertainty in indirect forcing by aerosols (*4*), due to the uncertainty in predicted cloud drop number for a given below-cloud sulfate mass. The variability may result from many factors, such as the chemical properties of the aerosol, sources of other particles that can make cloud droplets, and variations in cloud properties.

How can we better understand the ways in which aerosols affect climate? Satellite

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observations can provide near-global monitoring of aerosol distribution, but cannot separate natural aerosols from those associated with human activity. Observations made from Earth's surface are thus important for validating and improving observations from space. In situ measurements can be made from the ground or from aircraft and balloons. In conjunction with laboratory studies, they can provide important information on the precise chemical composition and physical properties of aerosols, which are necessary for determining how efficiently aerosols scatter and absorb sunlight. However, such observations can never be global in extent and are restricted to small areas that cannot be resolved by global climate models. Data regarding the vertical distribution of aerosols are also important for understanding radiative forcing, but few such observations are currently available from aircraft campaigns and ground- or balloon-based remote sensing techniques. All of these data can then be used to test the validity of three-dimensional chemical transport models (CTMs), which are numerical tools that employ observed or analyzed meteorological conditions (such as winds, moisture, and temperature) to model the transport and reactions of atmospheric species as a function of time. These models include processes that transform chemical species into aerosols, that remove chemical species and aerosols through rain out processes, and that transport them through the atmosphere. They produce three-dimensional distributions of aerosols as they vary with time.

Reduced uncertainties in aerosol forcing will only be achieved through coordinated integration of these observational and modeling techniques. Haywood *et al.*'s approach is a step toward this coordination. They combine results from various CTMs along with satellite measurements of reflected sunlight to directly determine the forcing effect due to various aerosol types. Additional observations on chemical composition would further improve their estimates of aerosol direct forcing.

Is there reason for optimism in solving the aerosol problem? Haywood *et al.*'s study, in conjunction with some new observational programs, gives reason to believe there is. In February and March of this year, a major field campaign will take place in the Indian Ocean near the Maldives. The Indian Ocean Experiment (INDOEX) is an international field program designed to observe the direct and indirect effects of aerosols. The experiment includes surface, aircraft, and satellite observing systems and aerosol simulations with CTMs. Also, NASA will soon launch the Earth Observing System (EOS), a satellite that carries several instruments for measuring aerosol properties. Finally, a joint U.S.-French satellite called PICASSO-CENA will measure aerosols with a two-wavelength laser that will provide high–vertical resolution profiles of aerosol properties. A prototype of this instrument flew on the space shuttle in 1994 and gave a glimpse of the three-dimensional distribution of aerosols in Earth's atmosphere.

These studies will be invaluable for solving the aerosol puzzle. Nevertheless, as Haywood *et al.* have demonstrated, the ultimate success of putting the pieces together rests on close integration of observations and modeling programs (*5*).

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PERSPECTIVES: GEOCHEMISTRY

A Slippery Problem with Explosive Consequences

Frank Spera

Although its ultimate planetary origin is debated, there is no doubt regarding the important role played by water in many geological processes. The properties of water, either as a condensed low-temperature fluid or dissolved in crystalline, glassy, or molten silicates, influence myriad geochemical phenomena extending from Earth's surface to its deep interior. On page 1314 of this issue, Ochs and Lange (*1*) report important new results on the behavior of water-bearing silicate liquids.

In surficial processes, the role of water-rich fluids is self-evident. Geothermal waters, brines, and fluids within both continental and oceanic crust act to transport chemicals and heat in many lithospheric environments, including sedimentary basins, orogenic belts, crustal fault zones, and hydrothermal systems. In deep-seated environments, even small amounts of water—a fraction of a weight percent—can drastically influence the properties of geomaterials. For instance, the heat capacity of glassy silica increases by 30% as the concentration of water (as hydroxyl) increases from several parts per million by mass (ppm) to 1000 ppm (*2*).

The effects of water on the rheological properties of materials are remarkable. Small concentrations of water in the range of 100 to 1000 ppm dramatically weaken strong crystalline silicates, making them prone to ductile flow at temperatures typical of the crust and mantle (*3*). Recent experiments (*4*) show that 200 to 500 ppm of water can be dissolved in garnet and carried to transition zone or lower mantle depths (depths exceeding 400 km) within Earth. Integrated over the past 2.5 billion years, a substantial fraction of the hydrosphere could have been recycled by subduction of water-bearing lithosphere (and perhaps even some continental lithosphere). Water's lubricating action facilitates the plate tectonic cycle responsible for earthquakes, mountain building, subduction, and the growth of continents. The tectonic role of water may even extend to Earth's closest planetary neighbor, Venus. Differences in the tectonics of Venus and Earth have been ascribed to the relative dryness of Earth's twin and its attendant lack of a ductile asthenosphere (*5*).

Because the effects of dissolved water on the properties of magma are critical for analysis of many magma transport phenomena as well as an understanding of the atomic structure of hydrous silicate liquids, these conclusions are of broad interest. In particular, magma density is relevant to the segregation and ascent of magma, compositionally driven mixing of magma, and the dynamics of explosive eruptions driven by volatile exsolution. Ochs and Lange (*1*) address the volumetric properties of water dissolved in silicate melts at magmatic conditions, a relatively poorly known quantity. They have measured the density of hydrous glasses from which they infer the partial molar volume of water component ($\bar{V}_{H_2O}$) dissolved in silicate melts at elevated temperatures and pres-

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