out by Cecil Leith of NCAR. In order to fully establish the statistical significance of a particular numerical experiment, many repetitions with randomly varying initial data are required—in essence a determination of the climatology of the model—so that particular results can be compared against the average behavior of the simulated weather patterns. This statistical limitation, some investigators believe, may raise the amount of computer time needed by a factor of 10.

Size and computing time are not the only problems. In a review of climate models, Stephen Schneider and Robert Dickinson of NCAR observe that most general circulation models simulate the atmosphere in great detail but treat its interaction with the solar flux, the oceans, and the earth's surface much more crudely. No models, for example, simultaneously calculate the distribution of clouds and sea-surface temperature; instead one or more of these features are specified in the model on the basis of climatological data. This may not be a severe limitation, Schneider and Dickinson believe, for very short range climate predictions (a few weeks to a few months), the period for which they believe general circulation models are ideally suited and which may also be of the greatest social and economic importance. The models also have an important role, they believe, in testing simpler models.

Smaller models need not be at a disadvantage compared to general circulation models for simulating gross climatic features, according to Peter Stone of the Massachusetts Institute of Technology, even though they do not explicitly include all details of atmospheric motions. Much of the atmospheric transport of heat toward the poles is due, in mid-latitudes, to large atmospheric eddies that appear on the weather map as high- and low-pressure systems. This heat transport is climatologically important, since, along with other dynamic processes, oceanic heat transport, and radiative processes, it effectively determines the temperature at the earth's surface. Stone and, independently, J. Green of the Imperial College, London, devised methods of calculating this transport without simulating the eddies themselves.

Stone has compared the calculated heat fluxes to those produced by general circulation models and to observational data, and he finds them qualitatively and quantitatively similar. More significantly, he finds that the eddy fluxes have a strong negative feedback. In response to changes in external climatic forces, Stone believes, the eddies act to increase or decrease the heat transport in such a way as to maintain the stability of the atmosphere, limit its response to the new conditions, and hence inhibit climate change.

Not all climatic processes are stabilizing, however. W. Sellers of the University of Arizona and, independently, M. Budyko of the Main Geophysical Observatory, Leningrad, have modeled the effect of albedo changes due to variations in the ice and snow cover on the earth's surface. They find a positive feedback in response to external changes. According to their models, very small changes in the earth's energy budget, such as a decrease in the sun's output of heat, might increase the ice cover, which would reflect more sunlight back into space and cool the earth still further, leading eventually to an "ice catastrophe"—an ice-covered earth —if not mitigated by other mechanisms.

Other specific mechanisms remain to be investigated. The oceans, for example, are thought to be a stabilizing influence on climate because they undergo change on a time scale about 100 times as long as that of the atmosphere. The uppermost layer of the ocean, however, may have a much shorter time scale and may act to drive change. Because of growing evidence that sea-surface temperature anomalies play an important role in climate over short time periods, there is growing belief that investigations of the upper layer of the oceans ought to have a high priority. Thinking about the climate is a relatively new business for oceanographers, however, and despite pressure from their meteorological colleagues many believe that global monitoring and modeling of the oceans—a necessity for realistic predictions of more than a few years at a time—is simply beyond the present capacity of the field.

However limited at present, climate modeling appears to be the only way to go. Climatic processes, in the opinion of many scientists, are simply too complicated and too interrelated to be amenable to casual analysis. More deductive tests of climate mechanisms, such as models provide, are consequently to be preferred, they believe, to inductive reasoning based on past events. Indeed, for assessing man's impact on climate, there is no alternative to models. And, it would appear, modeling efforts are not far from adding greatly to the understanding of climatic phenomena of no little practical interest.—ALLEN L. HAMMOND

Planetary Science: First Meeting on Moons of the Solar System

The great age of planetary satellites was the 17th century, when the four largest moons of Jupiter were discovered by Galileo and the major satellites of Saturn were discovered by Huygens and Cassini. In the 300 years since then, the moons have been for the most part neglected. But in the last 3 years new observations from the ground and spacecraft have renewed astronomers' interest. Last month, when 150 scientists met at Cornell University, Ithaca, New York, for the First International Conference on Planetary Satellites, it seemed clear that the subject of satellites had become almost as important as the subject of planets.

While most of the efforts of the U.S. space program has been directed toward the earth's moon, which appears to be a unique object with a complex origin, it was not a principal topic of the conference. The two tiny moons of Mars, Phobos and Deimos, were discussed at more length because Mariners 7 and 9 had obtained good pictures of them and raised questions about their composition—whether it is basalt or carbonaceous chondrite. But most of the conference was devoted to the satellites of the outer planets, particularly Jupiter, Saturn, and Uranus. The larger moons of these planets are found in systems with such regular orbits that they look almost like miniature solar systems. Among the 12 moons of Jupiter, the 10 moons of Saturn, and the 5 moons of Uranus, at least 4 of the number for each planet have nearly circular orbits that lie almost in the same plane. The densest Galilean moons of Jupiter are found nearest the center of the satellite system, which is similar to the distribution of the planets from the sun. Perhaps the three satellite systems were formed by a process similar to that which formed the planetary system. If that is the case, Carl Sagan of Cornell noted, then scientists may have available not one but four sets of data to test models for the evolution of the solar nebula into the planetary forms of the present epoch. The origin of the solar system is probably as uncertain as any topic in science, and projections from a single example could be perilous.

Because the satellites of the outer planets were probably formed in the outer reaches of the solar nebula, they should have very different compositions from the inner planets, which are predominantly silicates and iron and magnesium oxides. Instead of such dense minerals, the outer satellites are probably composed of liquids and ices of such light molecules as water, ammonia, and methane. To those used to thinking of planets as rocky, such fragile substances may seem unlikely, but icy models of the satellites, proposed by John Lewis of the Massachusetts Institute of Technology, have been largely supported by the data that are available.

Although the origin of the solar system was the most fascinating topic of the Cornell conference, the greatest portion of the conference was devoted to the findings with which better models can ultimately be tested—the properties of individual satellites. Not even the masses and diameters of many small satellites are known, so their densities cannot be estimated. Even for satellites larger than the moon, such as Titan, the sixth satellite of Saturn, the density may be uncertain. A new determination of the diameter of Titan, from its rate of disappearance behind the moon during an occultation on 30 March 1974, changes its density enough to revise the estimates of Titan's composition (which would be mostly methane) and atmosphere (escaping faster than previously thought). The new measurement of the diameter, by Joseph Veverka and associates at Cornell, is 5800 kilometers, an increase of 800 kilometers.

Titan is particularly fascinating because it has an atmosphere at least 25 times as dense as the atmosphere of Mars, apparently composed of methane and molecular hydrogen. The large methane component, discovered in 1944, has given hope to many that Titan may be a likely place to find prebiotic molecules and possibly life. Although Jupiter and Saturn also have large methane components, Titan, with its relatively weak gravity, is a far easier body to probe with a spacecraft. The hydrogen component of Titan's atmosphere, reported 3 years ago by Laurence Trafton at the University of Texas, presents a problem because hydrogen is not bound to the satellite by gravity, and so it escapes. Although molecular hydrogen produced by photolysis of methane or ammonia could replenish the escaping atmosphere, Don Hunten of the Kitt Peak National Observatory noted that these sources of supply are probably inadequate. The suggestion that the hydrogen in the atmosphere may produce a greenhouse effect is not borne out by the infared thermal emission spectrum, Hunten noted, but a weak greenhouse effect due to methane may occur.

Atmospheres of Galilean Satellites

If the planetary satellites conference had been held 20 months ago, there would have been little discussion of the atmospheres of the four Galilean satellites of Jupiter, but now Io is known from Pioneer 10 measurements to have a trace atmosphere, and many scientists expect that Ganymede and Europa do too. The discovery of sodium vapor in the vicinity of Io (*Science*, 25 January) has provoked continued discussion. Recent spectroscopic measurements by Denis Matson and Torrance Johnson at the Jet Propulsion Laboratory suggest that the sodium is excited by scattered sunlight rather than an auroral mechanism.

A partial torus of atomic hydrogen in the orbit of Io was found by Pioneer 10 observations, as predicted by Thomas McDonough and Neil Brice at Cornell. The partial torus fills only about one-third of the orbit of Io because hydrogen atoms originating from the satellite eventually ionize by interaction with the plasma in Jupiter's magnetosphere, according to McDonough, and stop shining. An additional component in the vicinity of Io, reported by Carl Pilcher and Dale Cruikshank of the University of Hawaii, is helium, which they observed at 1.083 micrometers.

While no one has directly observed an atmosphere on Europa or Ganymede, Pilcher has found features unique to water frost in the infrared absorption spectra of both satellites. He concludes that least 50 percent of the surface of Ganymede and Europa is covered with water frost. The necessity of this conclusion was questioned by Tom Gehrels of the University of Arizona, who cited polarization measurements from Pioneer 10. But most of the participants at the conference seemed disposed to believe that the infrared absorption measurements are strong evidence that frost is there.

One of the greatest puzzles of all the satellites is Iapetus, the eighth moon of Saturn, which has two faces, one very bright and the other almost dark. This astronomical anomaly was depicted in the movie *2001: A Space Odyssey*, and planetary astronomers are no closer to explaining its two faces now than they were then.

The primitive state of knowledge of the satellites was noted by Al Cameron of Harvard University, who commented that the participants were "anything but unanimous" in their evaluations of the measurements that have been made. The vague images of the Galilean satellites from Pioneer 10 reminded Cameron of the best views of Mars and Mercury available only a few years ago. The outer satellites are so far away, at least eight times the distance from the earth to Mars, that more spacecraft measurements will almost certainly be required before planetary scientists can reach a consensus on the properties of the satellites.

Pioneer 11 has already been launched, and should reach Jupiter in December, then Saturn 2 years later. But the imaging devices on Pioneer spacecraft, which have a total instrument payload of only 30 kilograms, are crude instruments. Two Mariner spacecraft with high-resolution television systems are scheduled to be launched toward Jupiter and Saturn in 1977 (the MJS mission), and the satellites will be prime targets for observation. Another Mariner flyby mission in 1979 (MJU) is scheduled to observe Jupiter and eventually Uranus. In the 1980's missions to orbit Jupiter with both Mariner (MJO) and Pioneer (PJO) spacecraft are planned.

The planets of the outer solar system are clearly different from the planets we have come to know in the last few years. Whereas the rocky inner planets have proved to be laden with enduring records, perhaps even still-preserved primordial material, the outer planets are mostly gaseous and unlikely to have any hard artifacts recording their histories. The moons of the outer solar system may be more enlightening remnants of that region than the planets. If so, this is fortunate, for the moons are in many ways easier to study.

—William D. Metz