carrying with it past the mainland a narrow strip of the California coast. The third and most complicated type of boundary occurs when two plates converge and one plate overrides the other and pushes it deep into the mantle where it is heated and assimilated. Because continental rocks are generally lighter than the rock of the sea floor, the plate with continental rock tends to be the overriding plate, and the one with ocean floor tends to be thrust downward. A deep ocean trench is usually formed where a plate descends.

Since the revolution in the earth sciences is now accepted by most U.S. investigators, the authors of the report took considerable care to differentiate those aspects of plate tectonics that seem established from those still not understood. (Interestingly, Russian geodynamicists, who generally have devoted more time to continental than ocean studies, are about evenly divided between those who accept plate tectonics and those who reject it.)

The best known aspects of plate tectonics are the shapes, locations, and relative movements of the major plates at the present time. (By geological reckoning, the "present time" is approximately the last 10 million years.) But many phenomena in the interior regions of plates are difficult to explain by plate tectonics, and the processes that occur at plate boundaries are seldom understood in detail. The configurations and motions of plates at times further in the past are much more difficult to determine, and perhaps the greatest puzzle for any epoch is why plates move at all. Many scientists think that the most important questions remaining to be answered are, When did the plates begin to move? and What are the driving forces that keep them going?

Of all the types of plate boundaries, the ridges where new crust is formed (diverging boundaries) are probably the best understood, according to the report, although variations along the world's ridge zones are still puzzling. Converging plate boundaries seem to be much more complex. The primary process that occurs, underthrusting, takes place at such a great depth that it is extremely difficult to measure. Furthermore, the intense deformation of crust produced by two plates colliding results in very complex geological features, such as island arcs and mountain belts. When the collision occurs between two continents or bits of continental crust, the interaction seems to be still more complicated. The Himalayas, for example, are thought to have been formed when the Indian subcontinent collided with the Eurasian plate, probably after breaking away from Australia 100 million years ago, and the geology of the Himalayas and ad-

Speaking of Science

Frontiers of Research in Atmospheric and Marine Science

The dedication of new academic buildings is traditionally an occasion for taking stock of past accomplishments and future prospects. Ceremonies held last November at Texas A & M University in celebration of a towering new oceanography-meteorology building included such a look at research areas of growing importance to atmospheric and marine scientists. The subjects ranged from paleo-oceanography to long-range weather forecasting and—not to ignore topical themes—even to the potential role of the oceans in solving the energy crisis.

Jerome Namias of Scripps Institution of Oceanography (and a former head of the Weather Service's long-range forecast group) spoke on the problems of predicting weather patterns months, and even years, in advance. Anomalous weather such as the cold winters of the eastern United States in the 1960's or the record number of tornadoes in the Midwest in 1973 is blamed on many things, from solar activity to lunar influence (neither explanation had, at last report, gained many adherents in the meteorological community).

Namias pointed toward another extra-atmospheric influence—the oceans, whose high heat capacity makes them excellent sources and sinks of energy for the atmosphere. He reviewed evidence that thermal anomalies (hot and cold spots) in the upper layers of the oceans can persist for several seasons and suggested not only that wind patterns may help generate such anomalies, but that storm systems may intensify by drawing energy from the sea. The mechanism of the interaction is still unknown, but since the ocean changes less rapidly than does the atmosphere, it may be possible, Namias speculates, to monitor the oceans and hence to predict shifts in atmospheric patterns. In any case, the investigation of how the ocean and the atmosphere are coupled, Namias concluded, is an increasingly important research frontier.

Air-sea interaction on a smaller scale—the exchange of heat, momentum, oxygen, and carbon dioxide across the surface layer of the ocean—was also singled out as an important area. Owen Phillips of Johns Hopkins University spoke on breaking waves in the open ocean, which he characterized as one of the most widespread but least understood processes occurring at the sea surface. He pointed out that interaction among short waves, long waves, and wind-induced drift can markedly increase the chances that a wave will break and hence disrupt the surface layer that can otherwise be a barrier to air-sea exchange.

Jule Charney of the Massachusetts Institute of Technology spoke on predicting turbulent flows in the atmosphere. Turbulence is poorly understood—there is no acceptable theory of turbulence—and its irregular, aperiodic character makes it difficult to model. The question of whether turbulent flows such as those in the atmosphere are predictable even in principle is thus a key one for atmospheric scientists (Charney called it as fundamental a question as there is in all of science). Both numerical and theoretical calculations done to date indicate that atmospheric motions become essentially random (that is, unpredictable) when forecast more than a week. It happens, however, that large-scale fluctuations in the atmosphere are more energetic than small ones, and energy seems to propagate from large to smaller scales of motion while uncertainty propagates from small to larger scales. The distribution of energy among the differing scales of motion therefore deterjacent regions from Tadzhikistan to Mongolia is exceedingly complex. But the Himalayas are one of the more recently formed mountain belts in the world, and it is clear, say many geophysicists, that to unravel the tectonic details of an older mountain belt like the Appalachians would be even more difficult. Even when small bits of continental crust collide, such as along the Alpine fault in New Zealand, the processes at the boundary became much more complicated than when oceanic crust is involved. As one researcher noted, "It's clear that things get much more complicated when you get to continents, and it's also clear that it's not just because you can see them better."

If plates are moving, it seems easy —at least in principle—to explain active geological features at plate boundaries, but active features within plates appear to be inconsistent with the simple plate tectonic theory now in use. Vertical motions are sometimes almost as rapid as horizontal motions. The Rocky Mountains and the Appalachian Mountains are rising a few millimeters per year, and the very mountainous region of Tadzhikistan is moving upward at 1 to 2 centimeters per year. To a geologist, that is a huge velocity, described by one as "shooting up," and no one knows whether plate tectonics or some other process will be required to explain it. Other mid-plate phenomena that may not be consistent with plate tectonics are mid-ocean volcanism, such as in the Hawaiian islands, and the occurrence of large underwater ocean ridges that do not seem to be plate boundaries because they are free of earthquake activity. On land, the largest earthquakes in North America in modern times occurred in the Mississippi Valley in 1811, far from the boundaries of the Americas plate. So there are many phenomena that occur in the interior regions of plates that do not easily fit into the plate tectonic model.

According to the report, it is essential to find out when plate tectonics started. Our present knowledge can only be extrapolated back about 200 million years to the end of the Paleozoic era, when the continents as we now know them were probably joined together in one large land mass, called Gondwanaland. All ocean floors that now exist were apparently formed out of the ridges that opened up when Gondwanaland split apart, so the ocean floors are too young to have any record of tectonics in the Paleozoic era. If old convergence boundaries could be found on land, they could prove tectonics to be older than 200 million years, but there are no agreed upon criteria for finding such boundaries.

No one knows how to answer the basic question of plate tectonics, but

mines the predictability, according to Charney, and he proposed new methods of estimating energy transfer from one scale of motion to another. He believes that it will be possible to forecast some features of the atmosphere at times longer than a week.

Archie Kahan of the Bureau of Reclamation in Denver spoke on weather modification. He characterized it as a frontier involving more than just science—there is now a wide spectrum of opinion and intense public involvement in the question of whether or not to seed clouds. Selecting particular clouds to seed is increasingly done on the basis of numerical models, but the key problem, according to Kahan, is still in evaluating the results and in determining whether precipitation really was increased. Even experiments that are statistically designed and randomized have not settled all questions.

In oceanography, a growing area of research is the study of upwelling ecosystems—the interaction of winds and currents that bring bottom water and nutrients to the surface, thereby supporting vigorous biological communities. John J. Walsh of the University of Washington described numerical models of upwelling systems that are being used to sort out the relative roles of phytoplankton, zooplankton, and fish in the food chain, as well as the extent to which light, nutrients, and the time of year control the ecosystem. Better models of these systems, according to Walsh, may provide more accurate estimates of the anchovy production off the coast of Peru and an explanation of why a similar upwelling system off the coast of northwest Africa has not evolved a similar, harvestable species.

Karl Turekian of Yale spoke on the geochemistry of estuarine and deep-sea environments. He pointed out that uranium and thorium isotopes and the products of their radioactive decay can be used to study the effects of dumping hostile materials in the ocean. Sediments in Long Island Sound, for example, show a rise in the concentration of metals following the beginning of human habitation of the area. Uranium and a few other metals that form anionic complexes appear to find their way out of the sediments, but most do not, Turekian finds. He believes these estuarine results can be applied to deep-sea sediments, which are more difficult to study in detail, while other geochemical processes, such as those that regulate calcium carbonate, are more readily studied far from sources of continental debris.

Another growing field is that of paleo-oceanography, the study of the oceans, and, implicitly, of the climate in earlier times. James Hays of the Lamont-Doherty Geological Observatory described how analysis of sediment in the Antarctic has provided a picture of conditions 18,000 years ago. At that time, according to Hays, the cold polar water extended much farther north in the summers, as, probably, did the sea ice—in effect, the Antarctic endured winter conditions all year long. Similar events occurred in the North Atlantic—the sea extended as far south as the glacial ice that at the time covered much of the northern continents. These conditions of extreme cold have occurred about eight times in the past 700,000 years, according to Hays, in regular alternation with the periods of warmth (like the present climate). The study of the process seems important, if only, Hays indicated, because it seems very likely that a new glacial period will eventually recur— perhaps within a few thousand years.

Finally, Jacques Cousteau addressed the energy crisis and its relationship with the sea. He pointed out that nature concentrates energy in winds, currents, and tides, and he proposed that serious consideration be given to power plants operating on the tides, on the mechanical energy of ocean currents, and on the thermal gradient between surface and deep waters. In all, a selection of subjects indicative of the growing vigor of atmospheric and marine science.—ALLEN L. HAMMOND