in the semiconductor (bandgap energy) makes the Raman scattering process more efficient. Because of this resonant enhancement effect, the lower powers characteristic of cw lasers can be sufficiently converted to be observable.

Progress which is also being made in the development of lasers and coherent sources in the vacuum ultraviolet (where light is rapidly absorbed in the atmosphere and can be propagated only in a nonabsorbing medium, such as a vacuum) will be reviewed in a second article.—ARTHUR L. ROBINSON

Long-Range Weather Forecasting: Sea Temperature Anomalies

When the Arab oil embargo of last fall left the United States facing the possibility of serious shortages of heating oil, the question of how severe the winter would be was suddenly far from academic. One U.S. science official, reportedly under intense pressure to advise energy planners on the weather, made a desperate phone call to a West Coast meteorologist who is studying long-range weather prediction. After several days of hurried analysis of sea-surface temperature patterns in the Pacific and other data, the scientist ventured the opinion that the eastern United States would experience a mild winter, a guess subsequently and fortunately confirmed by events. The incident underscores both the limits to our understanding of climatic processes and the role which weather patterns can play in national policy. It also illustrates the growing conviction of many scientists that it is the oceans and not the atmosphere which hold the best clues to climatic change.

Warmer weather, heavier rains, and similar changes of climate are experienced largely as shifts in atmospheric weather patterns. The oceans, however, also undergo shifts in circulation patterns and temperature which influence human commerce. The reappearance 2 years ago of el Niño, the temporary cessation of the upwelling of nutrient-rich waters off the Peruvian coast, led to the collapse of anchovy fishery in that region and a subsequent boom in soybean futures as that crop became a substitute source of protein. Recently oceanographers have found that el Niño is only a coastal manifestation of major, nonseasonal changes in currents, wind patterns, and rainfall throughout the equatorial Pacific. Smaller but similar variations in sea-surface temperature occur further north in the Pacific, and it is these variations which appear to be linked with weather patterns over the North Pacific, the United States, and possibly more remote areas.

The temperature variations appear in the form of patches of water 1° to 2°C above or below normal, 100 meters or more in depth, and covering as much as 1 million square kilometers. These patches typically persist throughout a Pacific winter and may recur in successive years in the same region. As reservoirs of an enormous amount of thermal energy, these patches of anomalously warm or cool water are thought to be evidence of air-sea heat exchange or other phenomena on a scale that is large enough to influence weather patterns, although the specific mechanisms involved are not understood. Indeed, whether the hot and cold patches or other oceanic phenomena can initiate shifts in climate or are merely passive responses to atmospheric changes is still uncertain. In a series of experiments and theoretical studies that constitute the North Pacific Experiment (NORPAX), meteorologists and oceanographers are attempting to find out how the patches are formed and what their role is in the exchange of heat with the atmosphere. In the long run, NORPAX investigators hope to be able to monitor ocean temperature variations by satellite and subsurface sensors and then to predict some features of weather patterns and climatic shifts months and perhaps years in advance—predictions that, if accurate, would be of inestimable value to farmers and national policy-makers alike.

The possibility of long-range weather forecasting arises from the fact that changes in the ocean occur more slowly than those in the atmosphere, and from the development of statistical (as opposed to mechanistic) forecasting techniques in the NORPAX program. Daily weather forecasts in the United States are now based primarily on mechanistic models of atmospheric processes, a preference anecdotally attributed by meteorologists to the outcome of a debate between mathematicians John von Neumann and Norbert Wiener during the years after World War II, when computers were first being applied to weather prediction. According to the story, von Neumann was much more persuasive in his advocacy of mechanistic forecasting than Wiener, who favored statistical methods. But despite the undoubted successes of mechanistic or "dynamic" forecasting, studies by E. Lorenz, of the Massachusetts Institute of Technology, and others indicate that the method is not likely to be extendible in detail beyond a week or two even with greatly improved data. The limitation arises because small errors in the computed forecast grow with time (a property of the nonlinear equations on which the models are based) and eventually produce an essentially random weather pattern. Nor is the difficulty purely an artifact of the models used—the predictability of turbulent flows such as those in the atmosphere is not established, even in principle. But if atmospheric motions cannot be forecast weeks or months ahead in detail, some statistical properties may nonetheless be predictable. Indeed, precipitation and other weather phenomena that are too small to show up on existing computational grids are now forecast statistically, so the methods are not completely distinct.

Reliable long-range prediction is still many years away, but statistical analysis of more than 25 years of data on sea-surface temperatures by J. Namias of Scripps Institution of Oceanography and other NORPAX scientists has turned up some interesting features. Namias finds that variations from the long-term temperature averages tend to occur as large, spatially coherent patches 1000 km or more across. Definite patterns emerge from the data—a tendency, for example, to have an anomalously cold patch in mid-Pacific and an anomalously warm patch off the California coast, or the reverse—although anomalies occur in all parts of the Pacific. Namias also finds correlations between oceanic and atmospheric data in which wind patterns are statistically associated with sea-surface temperature patterns. This association of air and sea phenomena is particularly likely in certain regions such as that from north of Hawaii to the Aleutians, which Namias speculates may be due in part to cold polar air sweeping down and picking up heat from the relatively warm water in such a way as to reinforce the wind and temperature patterns.

One of the more intriguing results of the NORPAX statistical work is the finding that, in six of the most extreme years for which data are available, there appears to be a distinct relationship between the sea-surface temperature pattern and the winter weather pattern over the United States. A cold patch of water in mid-Pacific and a warm patch off the California coast occurred in association with colder than normal winters in the eastern United States and warmer than usual winters in the western half of the country. The reverse pattern (abnormally warm water in mid-Pacific and mild winter weather in the eastern United States) also occurred. With only six instances, as Namias points out, the relationship is not statistically significant, however suggestive it may be of a link between the Pacific temperature anomalies and the climate downwind.

Many oceanographers are cautious about accepting the results because they believe their statistical significance is questionable. Others have criticized the sea-surface temperature data as not that accurate to begin with. Even though it does not in itself prove cause and effect, the statistical evidence is useful in pointing out particular regions of the ocean for study and in suggesting patterns and associations between variables for which experiments may establish a physical basis. There is also general agreement that the anomalies are evidence of some significant processes occurring in the North Pacific. Even without a well-established mechanism, a statistical relationship can be used for forecasting. Namias has been able to construct formulas, based on historical data, for predicting how sea-surface temperature will change; given December temperatures, for example, he has been able to forecast January temperatures with some success. More ambitious forecasting efforts for both sea and air are being developed.

A second major part of the NORPAX effort consists of experiments designed to discover the physical mechanisms by which the anomalies are created. This involves measuring heat fluxes in the upper layer of the ocean—the so-called mixed layer in which temperatures are relatively uniform. In summer the mixed layer in the North Pacific is often less than 25 meters thick, but in winter it grows to 100 meters or more. It is in winter that the strongest interaction between the atmosphere and the ocean takes place—the winds are stronger, and the atmosphere can extract heat from the ocean, for short periods, at the prodigious rate of 90 million joules per square meter per day (six times the solar flux reaching the earth's surface). But whether the sea-surface temperature anomalies come from air-sea heat exchange, from vertical mixing with the colder water underneath the mixed layer, or from horizontal transport of water from the north or south is still uncertain. All of these mechanisms, according to NORPAX director C. Cox of Scripps, will be investigated in a series of experiments.

The first such experiment, designated Pole, took place in the North Pacific for 3 weeks in February 1974. Intensive measurements of heat fluxes, temperature, currents, and other variables were made in a column of water at one location with Flip, a semisubmergible vessel designed for just such purposes. Less detailed data were gathered within a radius of 100 km by a ship and within 200 km by a plane with the aid of instrument packages lowered or dropped through the mixed layer. Although the experimenters did not encounter as stormy weather as they had hoped, they did succeed in collecting a good set of data against which to compare theoretical models and to test monitoring devices, according to R. Davis of Scripps. Later experiments will survey still larger sections of ocean, eventually with the aim of being able to watch an anomaly form and to observe how the mixed layer responds to atmospheric changes.

Ocean Physics Still Uncertain

One difficulty with developing a detailed physical understanding of the processes by which anomalies form is that there is no acceptable theory of the general circulation of the oceans, or even of the formation and decay of the mixed layer. Attempts to construct such theories and numerical experiments with coupled ocean-atmosphere models are under way as part of NORPAX, but the program is not expected to produce a mechanistic solution capable of explaining the anomalies and their interaction with the atmosphere in the near future. Rather the hope is to understand enough about the processes involved to design a reliable monitoring system for use with statistical and mechanistic forecasting techniques.

Monitoring in the past has been restricted to data collected on "ships of opportunity," but an extensive network of tide gauges and meteorological sensors is now being installed around the Pacific by K. Wyrtki of the University of Hawaii, and others. Additional efforts to compare shipboard temperature measurements and satellite radiometer observations and to design a monitoring system that could gather data for forecasting are under way. NORPAX oceanographers believe that satellite observations have not yet achieved their potential accuracy, largely because of problems with adjusting for cloudiness, but that they will eventually be extremely valuable sources of data for long-range forecasting. Other uncertainties in monitoring include the frequency and spacing of data samples, determination of the most relevant variables other than sea-surface temperature, and the development of reliable instruments.

The NORPAX program represents something that is still relatively new for oceanographers and meteorologists—a large-scale integrated research effort involving many institutions. The move up to big science has brought with it, in the case of NORPAX, additional stresses for the participants, and not everything has gone smoothly. There is also considerable disagreement among the participants as to the relative importance of, for example, statistical and physical studies. Nonetheless, the program appears to be making some progress in tackling a problem that would be beyond the capabilities of individual investigators.

The sea-surface temperature anomalies in the Pacific are only one instance of large-scale persistent fluctuations in the oceans. Similar fluctuations in temperature and salinity have been observed in the Atlantic and also seem to be associated with changes in weather patterns. Whether the atmosphere drives the oceans or vice versa is uncertain (it may be that instabilities in the coupled ocean-atmosphere system cause the fluctuations), but the anomalies do represent changes large enough to have significant effects on climate. Indeed, many oceanographers believe that the oceans may be the best place to look for indications of shifts in climate, because they change much more slowly than the atmosphere and are less affected by seasonal fluctuations that tend to mask climatic changes. If climate predictions are still a long way off, the anomalies are still, as Cox describes them, "immense phenomena, immensely important to man."

—Allen L. Hammond