Results of the IGY: Aeronomy, Glaciology, Meteorology, and Oceanography

Aeronomy

In conjunction with the triennial meeting of the International Union of Geodesy and Geophysics in Berkeley, California (20–29 August), the National Academy of Sciences organized a symposium at the University of California at Los Angeles (12–16 August) on the scientific results of the International Geophysical Year and its extension, the International Geophysical Cooperation. These great ventures extended from July 1957 through December 1959, and the organizers felt that a symposium consisting of critical reviews of the results of the entire operation would now be timely. My report concerns the reviews of the general field of aeronomy: the physics and chemistry of the upper atmosphere.

Marcel Nicolet (Brussels) opened with a summary of the structure of the upper atmosphere, an area of research that received great impetus with the advent of earth satellites. The first Soviet Sputnik of October 1957 was followed by the U.S. Vanguard and Explorer series. Gradually the irregular and puzzling atmospheric drag on the satellites became understood in terms of variations in atmospheric density. The density and, therefore, the temperature of the upper atmosphere were found to vary with time of day, with the 27-day solar-rotation period, with season, through the solar cycle, and sporadically with geomagnetic disturbances.

With the principal facts thus assembled, Nicolet went on to a lucid discussion of the theory of atmospheric structure, with, appropriately, emphasis on the variations. One of the most important results established by satellite data and their analysis by Jacchia, Nicolet, and others is that over the solar cycle the temperature of the upper thermosphere, where atmospheric evaporation occurs, varies between a minimum of about 650°K and a steady maximum of 1500°K, with brief excursions up to 1700°K.

Herbert Friedman (Washington) described the physical processes and constitution of the ionosphere. Rockets and satellites have played a dominating role in research on this subject as well, but any attempt at a detailed understanding still encounters large uncertainties. The observational results of outstanding importance include Soviet measurements of the height profile of electron density below the peak of ionization and the NASA measurements above it, mass spectrometer flights to isolate the ion species, and a variety of observations on the solar flux in different wavelength regions that are inaccessible from the ground.

In constructing theoretical models one is hampered by the strong variations in the neutral atmosphere discussed in Nicolet's paper; by variability in the solar spectrum, especially in the x-rays; and by a pitiful lack of knowledge on the pertinent reaction rates. Nevertheless, an impressive amount of information has been assembled on the specific photoionizations and other principal reactions governing the ionosphere at all heights. The experimental facts and theoretical arguments on the important question of whether particle bombardment supplements solar radiation in heating the atmosphere still appear inconclusive.

In a discussion of the geocorona or hydrogen exosphere of the earth Joseph Chamberlain (Tucson) noted that rocket photometry and spectroscopy on Lyman α radiation in the night sky by Friedman and his associates, just before and just after the IGY-IGC, provided direct evidence for an extremely tenuous and distended outermost atmosphere. The same techniques promise exciting advances in the study of planetary atmospheres in general. Theoretical and interpretational work by Johnson, Donahue, Brandt, and others has provided conflicting models of the detailed distribution of hydrogen in the space around the earth, and more definitive measurements will be required before an understanding can be attained.

Sydney Chapman (College and Boulder) reviewed auroral physics. After a fascinating account of the ancient history of the topic, he briefly discussed some of the studies of auroral morphology carried out in Alaska. The great aurora of 11 February 1958 was a fabulous display, made to order for the far-flung network of auroral all-sky cameras. Balloons and rockets contributed to this subject also, especially in measurements of auroral x-rays and the energy dispersion of auroral particles striking the atmosphere. The IGY also witnessed high-altitude explosions of nuclear bombs which produced artificial auroras at low latitudes.

Because of the time available, spectroscopic and radio studies received little attention from Chapman; they provided, however, many basic data on auroral particles, as well as on physical processes. (Indeed, the existence of an energy dispersion in auroral protons was first established through ground-based spectroscopy near the beginning of the IGY.) Chapman concluded with a summary of the auroral theory of Chapman and Akasofu. Some other theorists who contributed new ideas were listed alphabetically.

Daniel Barbier (Paris) summarized the airglow phenomenon and reported how helium and a number of other spectroscopic emissions in the sunlit airglow were first discovered during the IGY. Discussing the abundance of the rare alkali metals in the upper atmosphere, he noted the relatively high intensity of lithium associated with high-altitude nuclear explosions. A number of rocket flights helped fix precise altitudes for the layers emitting nightglow. During the IGY observers began to demonstrate the practical usefulness of ground-based spectroscopy for inexpensive measurements of temperature variations in the upper atmosphere with latitude, season, and sunspot cycles.

Morphological studies of the green and red lines of atomic oxygen were especially emphasized in the IGY, and Barbier gave an interesting account of the main advances. As the excitation of the various emissions becomes understood, airglow serves increasingly as a tool for exploring ionospheric reactions, temperatures, circulation, and their important variations. The work of Barbier in exploiting the red line in this fashion stands as a fine example. He concluded with a recommendation for better calibration and distribution of instruments in the forthcoming International Year of the Quiet Sun.

I left the symposium with the feeling that perhaps, after all, the IGY had been worth the expenditure of time, at least in aeronomical subjects. The really exciting advances came largely from rockets and satellites and from other observing programs that were dominated by the most competent researchers in the subject. Other, less important efforts amounted to research by committee: observing stations were established and data were collected by semitrained technicians only because it was clearly the thing to do. The driving force of an individual who knows what he wants to do with the data was often absent. The IGY could not have occurred without the foresight and organizational skill of such men as Nicolet and Chapman or the selfless, time-consuming contributions to planning by a host of highly competent scientists at the national and international levels. But if the IGY was a real success, it was because observers and experimenters such as Barbier, Friedman, Gringauz, Krassovsky, Kvifte, Roach, and countless others made such a large personal effort to secure the data they needed to help solve their particular research problems and because they managed somehow to inspire their students and associates to that task.

The National Academy of Sciences plans to publish the papers in a special symposium volume.

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Glaciology

Scientific advances in glaciology made during the International Geophysical Year were reviewed at a symposium held 12–16 August at the University of California, Los Angeles, in connection with the centennial of the National Academy of Sciences.

In summarizing present glacial variations, P. A. Shumsky (Moscow) pointed out that since mid-century there has been a decrease in the number of retreating glaciers, and even a general advance in some areas. As mentioned by H. C. Hoinkes (Innsbruck), however, care should be taken not to confuse these glacial variations with changes in the total mass of ice on the earth, which depend overwhelmingly on the budgets of the Antarctic and Greenland ice caps. Estimates of total annual gain and loss of ice in the Antarctic have come closer together as data have accumulated; a net increase in mass is suggested, but far from certain (C. R. Bentley, Wisconsin; M. J. Rubin, U.S. Weather Bureau). An increase in accumulation rates over the last 200 years is shown by analyses of Antarctic and Greenland snow stratigraphy (Hoinkes), but a detailed study suggests that precipitation rates have been below average since the 1930's (H. Bader, Miami). A climatic warming in the last few centuries is indicated by decreasing temperatures with depth in the polar ice caps; these gradients cannot be explained by glacial flow alone (Bader).

The relationship between glacial regimen and climate is a complicated one. In the heat budget of most glaciers radiation plays a much more important part than does sensible heat transfer (Hoinkes, Shumsky). This is clear despite persistent instrumental difficulties in radiation measurements which may force a re-evaluation of some IGY data. Hoinkes pointed out that incoming short-wave radiation is generally high in glacierized regions, thus making surface albedo of great importance in the heat budget. Since the albedo of snow is much higher than that of ice, the position of the equilibrium line dividing the accumulation and ablation areas is critical. For several glaciers in balance the ratio of accumulation area to ablation area has been found to be nearly the same, suggesting that a comparison of these areas from aerial photographs may provide a simple method of estimating the condition of a large number of glaciers. Further, it has been found that the net budget gradient in both accumulation and ablation zones tends to remain constant as the equilibrium line shifts its position and to differ little from one glacier to another within the same region. Thus quantitative budget estimates for many glaciers may be possible by detailed examination of a few, together with aerial photography.

The albedo difference between snow and ice complicates the response of glaciers to climatic changes (Hoinkes). Since high accumulation tends to decrease subsequent ablation, several successive seasons of abnormally high or low accumulation may have an amplified effect on glacial budgets. Minor changes in temperature can determine whether rain or snow falls during a few days in an ablation season and can, therefore, determine a positive or negative net budget for a whole year.

The variations in mass and energy exchange between the earth's ice and atmosphere are sufficiently important, Shumsky believes, to cause both large scale glacial variations and climatic changes. The glacial retreat in the first half of the 20th century thus resulted from an increase in the interchange of air masses between glacierized and non-glacierized regions. Even ice ages can, in Shumsky's view, be brought about with no alteration in the energy supplied to the earth from outside.

Shumsky reported that great advances have been made in recent years in the theoretical analysis of glaciers. Theories relating to flow and deformation of ice, heat flow in ice sheets, and the reaction of glaciers to changes in regimen have shown substantial success. A new theory of densification of ice fits well with observations in deep drill holes (Bader).

According to Bader, much significant information should be derived from the present program to drill to depths of thousands of meters in the Greenland and Antarctic ice caps with a thermal coring device. A stratigraphic record reaching back tens of thousands of years will permit analyses of the rates of accumulation of snow and deposition of terrestrial and extra-terrestrial dust, of past atmospheric composition from air trapped in bubbles, of paleotemperatures, and of the processes of ice deformation. Oxygen isotope ratios reflect accurately annual layers in Greenland, and variations in the electrical conductivity of meltwater and in particulate content of the ice hold promise as stratigraphic indicators. In the Antarctic, however, all methods are less reliable, and the problem of dating layers deep in the Antarctic ice has not yet been solved.

In reviewing the great increase in knowledge about the nature and extent of the Antarctic ice sheet, Bentley emphasized the difficulties of recording clear seismic echoes in the high interior plateaus. Some determinations of ice thickness, particularly those reported from early traverses which preceded the development of effective techniques, will have to be considered incorrect. Failure to indicate quality of results rather than deficiencies in the seismic method has caused the apparent disagreement between ice thickness values reported for the South Pole. G. de Q. Robin (Cambridge) emphasized the importance of adhering to the recommendation by the Scientific Committee on Antarctic Research concerning the publication of reflection seismograms.

Bentley also reported that the vast

bulk of seismic shooting has produced results of unquestionable validity. In East Antarctica a large subglacial plateau is bordered by a region of buried mountains. Before the formation of the ice sheet a large part of West Antarctica was open water separating several large islands, including what are now Marie Byrd Land and the Antarctic Peninsula, from the main part of the continent. Major ice drainage from East Antarctica is into the Amery, Filchner, and Ross Ice shelves, whereas most of the ice in West Antarctica flows into the Ross Ice Shelf and the Amundsen Sea. Widespread evidence from West Antarctica of a relatively low seismic wave velocity in the basal few hundred meters of ice might indicate a disseminated rock load of several percent. If verified, this discovery would contribute significantly to the understanding of erosion and transport by continental ice sheets.

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Meteorology

Recent findings in meteorological research were discussed at a special symposium, held at the University of California, Los Angeles, 12–16 August, on the results of the International Geophysical Year and its continuation, the International Geophysical Cooperation.

A report by Budyko and Kondratyev (U.S.S.R.; presented by Kondratyev) on the heat balance of the earth was limited mainly to the atmosphere-earth interface. The new worldwide charts of the several components of the heat budget and the water budget, based upon the expanded IGY-IGC networks, were presented. The earth as a planet annually absorbs 168×10^3 cal/cm^2, of which 112 is absorbed at the earth's surface and 56 in the atmosphere. This latter value is higher than previous estimates. Net long-wave radiation accounts for 40×10^3 cal/cm^2 loss from the surface; 59×10^3 cal/cm^2 is used in evaporation of a mean value of 100 cc of water from precipitation; and 13×10^3 cal/cm^2 is put into the atmosphere through turbulent exchange. Of the radiation balance, 90 percent is expended in evaporation over water surfaces while 50 percent is expended in evaporating water from land surfaces. Further attention now must be given to obtaining vertical profiles of the components of the radiation balance and a more detailed geographical distribution of the heat balance and its components through observations from meteorological satellites.

It was pointed out by Bolin (Sweden) that tracers, radioactive or otherwise, are only an aid to improving our knowledge of the general circulation and are no substitute for other atmospheric observations. Their transfer rate gives only a measure of the integrated motion and not much about the specific processes which effect the transfer. In order to determine whether a mean meridional cell or turbulent transfer in the vertical is responsible for the observed transfers of tracers, at least three or four carefully selected natural tracers (O_3, Be^7, H_2O, and CO_2) are required.

Teweles (U.S.), in reviewing the stratosphere-mesosphere, concluded that the IGY-IGC data have provided (i) the possibility of selecting boundary conditions leading to more realistic theoretical models of the stratosphere, which appears to differ radically from the troposphere; (ii) more accurate determinations of the radiative balance and energy budget; (iii) improved weather forecasts; and (iv) a possibility of studying many heretofore inadequately understood or unsuspected features. In winter at high latitudes, horizontal eddy transport seems to play a major role and leads to the conclusion that the vertical circulation in meridional planes is thermally indirect; sudden stratospheric warmings may be more extensively developed at high stratospheric levels than previously imagined; the autumnal reversal of stratospheric winds from summer easterly to winter westerly is very regular and tends to move southward and downward from 40 kilometers at high latitudes. A clear definition has been achieved concerning the biennial equatorial wind reversal, northward moving subtropical shear lines, the mean meridional circulation, sudden wintertime warmings, and diurnal wind variations.

Rubin (U.S.) reviewed the results of the Antarctic meteorological research based on the IGY-IGC network. A new concept of the tropospheric and stratospheric circulation, rather different from each other, and the character of the large-scale meridional and eddy heat exchanges has been developed. There is a net poleward transport of heat amounting to about 10^{22} calories per year and a net downward motion over the continent. The addition of latent heat through precipitation is about 10^{21} calories per year, with some reason to believe that the net annual ice-mass input approximately equals the outflow at the present time.

In addition to the purely meteorological reviews, papers by Shumsky, Krenke, and Zotikov (U.S.S.R.) and Kort (U.S.S.R.) discussed the interactions between atmosphere and ice, and atmosphere and ocean, respectively. Shumsky *et al.* intimate that the ice on earth, through the heat of fusion and transfer to lower latitude by drifting and melting, effects a redistribution of heat amounting to 7.65×10^{25} calories per year—"almost 35 percent of the total external heat exchange of the earth as a planet." Bader (U.S.) reviewed the deep drilling programs and emphasized the use of "thermal" drills in future borings. He explained promising methods of analysis of cores 2 kilometers in depth for determining the paleoclimate, composition of the atmosphere back to 25,000 years, natural fallout, and so forth. From subsurface temperature curves in Greenland and Antarctica he considers that these regions have been growing warmer, but no estimate of the time scale was attempted.

In his discussion of the mass budgets of glaciers, Hoinkes (Austria) pointed out that the effective radiation at the snow surface, and not the air temperature, is the significant factor in ablation. Glaciers with a ratio of 2.6 between area of nourishment and area of wastage appear to be in balance under present climatic conditions; any area with a higher ratio will undergo new glacierization. Some recent advances of glaciers at about the same longitude in the north as compared with the retreat of glaciers in the south seem to be adequately explained by the existence and persistence of particular low-index atmospheric circulation patterns, but the general worldwide advance of the 1920's will have to be explained by another mechanism, probably a worldwide decrease in effective radiation. Hoinkes proposes that the continued existence of the Greenland and Antarctic Ice Caps is that they are "protected" by the oceans which surround them since glaciers surrounded by dry land have lower albedo and "consume" more heat.

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Oceanography

Major aspects of the oceanographic program of the IGY were summarized at a National Academy of Sciences symposium on the results of the IGY-IGC. Los Angeles. Five papers were presented. Hence a comprehensive summary of the exploratory geology and geophysical expeditions, was obviously impossible. A typical expedition included two ships working together, traversing an area of several million square kilometers and using a variety of oceanographic instruments and techniques such as echo soundings, bottom cores, rock dredges, bottom photography, gravity meters, magnetometers, heat probes, seismic refraction, and others. A comprehensive review of such a wide-ranging program would either be very long or little more than a listing of names and places. R. W. Raitt (Scripps Institution of Oceanography) limited his discussion to exploratory work in the South Pacific by Scripps expeditions. Of particular interest have been the observations relevant to the problem of convective currents in the earth's mantle. Work was concentrated in the trenches that ring the Pacific basin, and on the East Pacific Rise which, in the South Pacific, runs in a general north-south direction along longitude 115°W. Spectacularly high heat flow has been recorded on the Rise, while lower than normal heat flow is the rule under the trenches. Lower than normal mantle velocities of 7.6 kilometers per second are recorded under the East Pacific Rise.

A second major program was the study of the deviation of sea level from the mean. In numbers of persons and countries participating it was probably the largest. Some old tide stations were reactivated, and many new ones were established. An effort was made to improve the geographical distribution of tide stations, and some were put on remote Pacific islands.

The analysis of the data has been done by relatively few researchers (E. Lisitzin, Finland; J. G. Pattullo, Oregon State University; and W. L. Donn, Lamont Geological Observatory). After subtraction of the astronomical tides, sea level at any given time may be the result of a combination of factors, including local wind and storm surges. On the average, however, sea level is apparently determined by two factors. One is the barometer effect: for every decrease of 1 millibar in pressure, sea level rises 1 centimeter. The second is the volume effect: heated water expands and sea level rises. The barometer effect is predominant at high latitudes, the volume effect south of 40°N. The combination of the two accounts for most of the observed change. It has not yet been possible to identify clearly any seasonal change in mass, such as might be caused by redistribution of the water within the oceans, or between the oceans and the land.

The three remaining papers focused on different aspects (at least different geographic aspects) of ocean circulation. G. Dietrich (University of Kiel) spoke about the 25 ships from many countries which were engaged in the Polar Front Survey of the North Atlantic. It is at Dietrich's laboratory at Kiel that the summary atlas of this work is being prepared. Even though the region north of the Gulf Stream is near many of the countries which support major work in oceanography, few data have been obtained from the region in the winter, perhaps because, as Dietrich noted, the wind is force 8 or greater 50 percent of the time at that time of year.

Dietrich was not the first speaker, or the last, to note that the IGY raised more problems than it solved. There have been three expeditions in the area subsequent to the IGY for studying the convection and renewal of the deep water off Greenland and the flow of the cold, heavy water from the Norwegian Sea over the Faroe-Shetland ridge and into the deep North Atlantic.

The Polar Front Survey and subsequent work in the area was planned systematically. The work in Antarctica reported on by V. G. Kort (Institute of Oceanology, Moscow) was generally done in conjunction with Antarctic resupply expeditions. However, these expeditions did provide many more hydrographic data. Although Kort's summary of transport and heat budget estimates for the zonal and particularly the meridional currents is controversial, there was certainly general agreement with his belief that further progress in this region requires expeditions whose primary purpose is the study of specific features of Antarctic circulation.

Until recently most of our knowledge of subsurface currents came from indirect measurements. During the IGY and since, more and more direct observations have been made, and the results of several of these programs were discussed by J. A. Knauss (University of Rhode Island). One finding was the verification of a prediction by H. Stommel (Woods Hole) that there should be a southward-flowing western boundary current in the deep water of the North Atlantic. Such a current, flowing at speeds between 9 and 18 centimeters per second below 2000 meters, was observed off the Blake Plateau.

Of even greater interest, however, have been the more recent measurements of J. W. Swallow (England) which suggest that the deep water of the entire western North Atlantic is in a state of turbulent unrest. The role of these large-scale eddies is still unclear, but it appears possible that many of our ideas about the general circulation will have to be reexamined. Turbulent motion, on a scale greater than was expected, but still considerably less than that in the western North Atlantic, has been observed also in the eastern North Atlantic.

During the IGY and since, information on equatorial undercurrents has increased. These eastward-flowing currents with speeds of 1 to 1½ meters per second are found just below the surface along the equator and are among the largest currents in the ocean. They are also the most perplexing. The Cromwell Current has been traced for at least 10,000 kilometers across the Pacific. The Atlantic Equatorial Undercurrent appears to be analogous to the Cromwell Current. Recent attempts to find a similar current in the Indian Ocean have shown that there is a profound difference in the current structure at the equator between the two monsoon seasons. Such observations give additional credence to the idea that these undercurrents are wind-driven. During the northeast monsoon a weak undercurrent appears to develop, but during the southwest monsoon the current structure appears to be very unsteady.

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Forthcoming Events

October

23–24. **Industrial Hygiene** Foundation, 28th annual, Pittsburgh, Pa. (R. T. P. de-Treville, 4400 Fifth Ave., Pittsburgh 13)

23–25. **Design of Experiments** (invitation only), Huntsville, Ala. (F. G. Dressel,